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VARIATIONS IN SALINITY AT UTÖ 1911—1961

by

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Abstract

The variations in salinity at Utö (59° 46′ 58″N; 21° 20′ 58″E) during the last 50 years are graphically analysed. The relationship between different salinity influencing factors as hydrometeors, winds and solar activity is discussed. Further a comparison is made between the severity of the winter and the salinity at Utö.

I. Introduction

Regular observations of temperature and salinity already started in the waters around Finland at the end of the last century. For many of the fixed stations there are continuous yearly series, broken by the two world wars only. Despite of the large material available, there are, however, only few works published where these data have been treated.

In this work an attempt is made to analyse the superimposed salinity variations in the Baltic, reflected in the values at Utö. This station, with observations in the depth at 59° 46′ 58″N and 21° 20′ 58″E, was chosen because of its favourable position and comparatively great depth of 90 m. It is one of the outermost Finnish stations in the south-west, in the boundary area between the Baltic proper and the Archipelago. The conditions there reflect the situations in the adjacent areas; the trench-like gully opens into the open sea in the south, and the deep samples may be taken to reflect the characteristics of the corresponding water layers in Northern Baltic.

II. Treatment of material

To obtain the actually occuring variations in salinity, which are independent of seasonal fluctuations, from every salinity value has been subtracted its corresponding mean value for the same date in a reference period. For this reference period was chosen the decade 1921—30, as the salinities (and temperatures) then observed, have been treated by harmonical analysis by GRANQVIST [2]. Later on, he himself used the same period as basis of comparison for his investigations of the increase of salinity along the coast of Finland [3].

Salinity anomalies were calculated for every tenth meter from surface to bottom for the beginning of every month. The anomalies are positive, if the salinity is greater than its corresponding average value for the years 1921—30, negative in the opposite case. The average salinity for the whole water body at Utö was 6.72‰ during the reference decade, ranging from 6.36‰ at the surface to 7.02‰ at the 90 m depth [2]. The

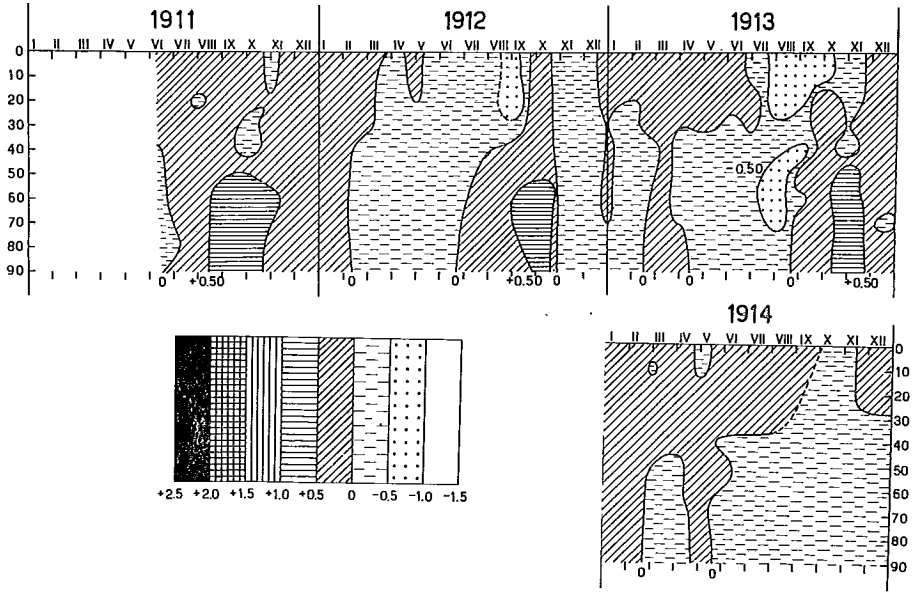

Fig. 1. Salinity deviations at Utö for the period 1911 VI—1914 XII in salinity per mille units from the average for 1921—30. The anomaly intervals are marked as above. The lines are isanomalies of salinity (the dotted lines indicate lack of observations) and the shadowings mark the intermediate values.

obtained anomalies are graphically shown in the figures by different shadowings with intervals of $0.50^0/_{00}$.

In Figure 1, showing the years before World War I, no greater anomalies, that is of the magnitude of $1.00^0/_{00}$ or more, occured. In the falls of 1911, 1912 and 1913 a deviation of more than $+ 0.50^0/_{00}$ could be noticed from the bottom up to a depth of 50 m. This deviation was greater than $0.80^0/_{00}$ from 90 to 80 meters in 1911 and from 90 to 60 m in 1913, while it was below $0.60^0/_{00}$ in 1912. In 1913 not only a positive anomaly of $0.50^0/_{00}$ but also an almost as large negative one could be noted. This minimum occured in August, September and October from the surface down to 20 m, with a maximal negative deviation of $-0.79^0/_0{}^0$ in August. This minimum in salinity then continued downwards with an anomaly of about $-0.60^0/_{00}$ from a depth of 40 m to 70 m. From this deeper minimum the salinity anomaly suddenly changed markedly in three months to the already mentioned maximum in November. Generally, salinity in these years was a little below the average reference value.

It is not known how the salinity at Utö fluctuated in the war years, as the measurements then were very few. Thus, in February 1915 there was an anomaly of $- 0.50^0/_{00}$ from 30 m to 60 m and in May 1917 a negative deviation as large as $- 1.00^0/_{00}$ occured from the bottom up to 60 m. This allows one to suppose, that the values during the war years were lower than the average.

In 1920 (Fig. 2) the areas of positive and negative anomalies were almost as large, with a positive dominance above 50 m and a negative one from that depth down to the bottom.

During the reference period 1921—30 the total amount of the anomalies according to definition was $\pm 0.00^0/_{00}$. However, the deviations during that shorter period do not differ markedly from those of the adjacent years, indicating that conditions then were quite stabile.

From October 1920 on to March 1925 the positive anomalies clearly dominated with a marked salinity maximum in 1922. Twice, in the middle depths in June and from the bottom to 40 m in November and December, the anomalies exceeded $+ 0.50^0/_{00}$ and even $+ 1.00^0/_{00}$ in December from 50 m downwards. January 1924 was an exception: The salinity was rather low in the whole water body from the surface minimum of $5.55^0/_{00}$, corresponding to an anomaly of $- 0.97^0/_{00}$, to an anomaly of $- 0.54^0/_{00}$ at the bottom.

From April 1925 a long period of decrease in salinity started. For the

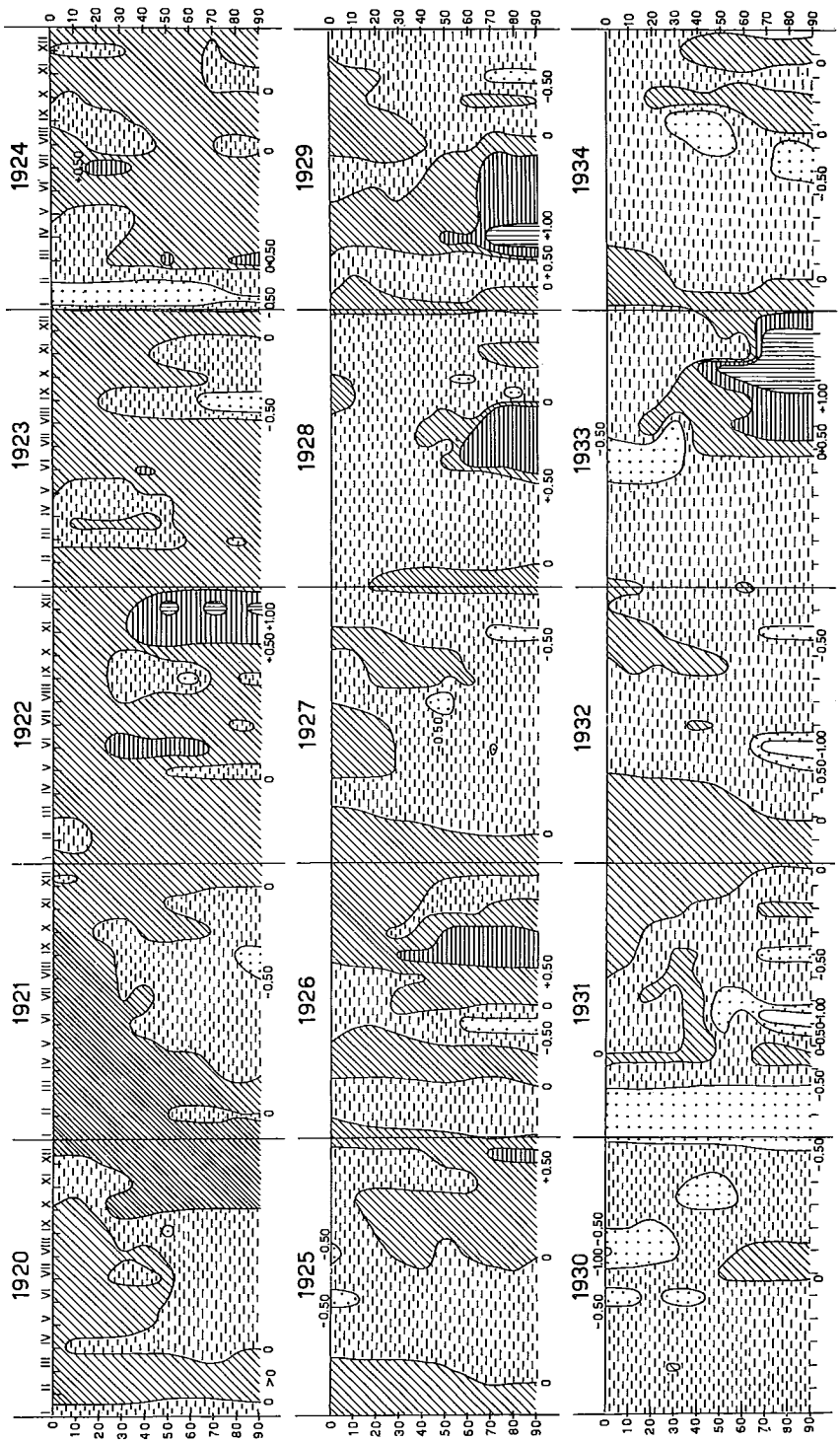

Fig. 2. Salinity deviations at Utö for the period 1920—35 in salinity per mille units from the average for 1921—30.

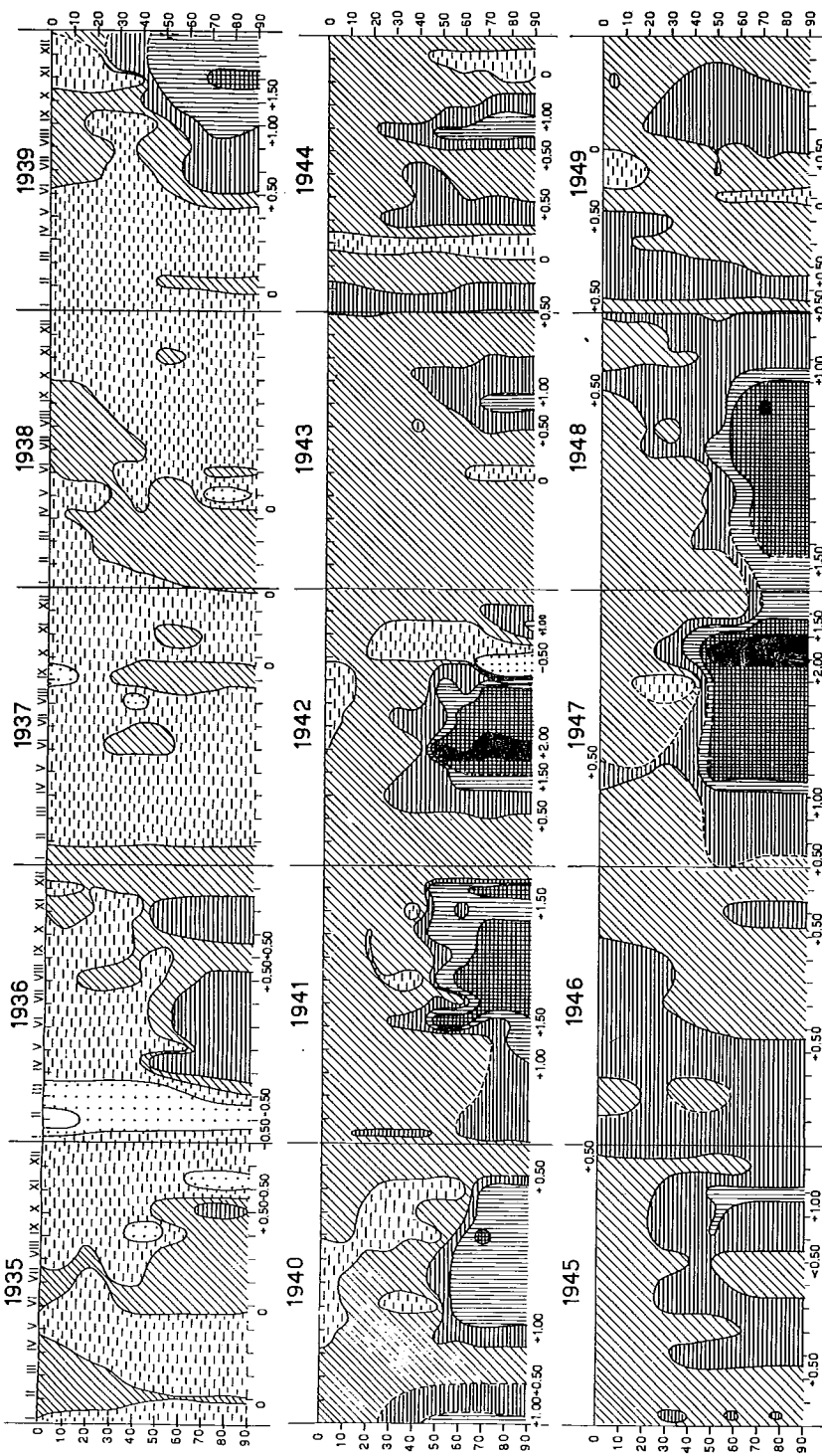

Fig. 3. Salinity deviations at Utö for the period 1935—50 in salinity per mille units from the average for 1921—30.

most part, the salinity anomalies were negative for the whole water body on to the middle of 1939. Only in the bottom layers did positive anomalies of $0.50^0/_{00}$ occur as in the years 1925, 1926, 1928, 1935 and 1936. In 1929 and 1933 the bottom anomalies even exceeded $1.00^0/_{00}$. As in these years, also in September and October 1926 and in April, October and November 1936 the increase of $+ 0.50^0/_{00}$ rose to the depth of 50 m. (Fig. 3.) This depth really seems to have some interesting properties. In April 1936 the anomaly was even closer to $+ 1.00^0/_{00}$ with the values of $+ 0.97^0/_{00}$ to $+ 0.99^0/_{00}$ from 90—70 m.

A noticeable characteristic of the maximal salinities is their slow ascent from the bottom layers towards the surface, which at Utö takes about two years as found by LISITZIN [7]. As salinity anomalies are used in order to eliminate the seasonal variations, this ascent, however, cannot be seen in the figures.

In such a period of decrease great negative deviations are expected to be found. They occur too and more frequently than the positive ones, but in contrast to those, they can be observed in all depths. However, they most commonly occur at the surface and at the bottom and only occasionally in the depth of 40—50 m. Beside the positive anomalies of $+ 0.50^0/_{00}$ in 1926 and in 1936, in both the years there occured an almost equal negative anomaly. In both cases the negative anomaly preceded the positive one. The extremely large negative deviation in 1936 will be dealt with later.

In June 1931 and 1932 some exceptional conditions prevailed and the greatest negative anomalies for the whole time of observation were noted. These anomalies of $- 1.00^0/_{00}$ in both years reached from the bottom to 70 m, with a minimum ranging from $- 1.11^0/_{00}$ at the bottom to $- 1.05^0/_{00}$ at 70 m, in both depths corresponding to a real salinity of $6.11^0/_{00}$ in 1931. In 1932 the minimum ranged from $- 1.18^0/_{00}$ ($S = 5.93^0/_{00}$) to $- 1.15^0/_{00}$ ($S = 5.90^0/_{00}$). These values, however, appear somewhat doubtful, but as they occured twice, and at the same time in different years, they might represent real, but highly exceptional conditions.

In February 1936 a similar extraordinary decrease of $- 1.00^0/_{00}$ occured, but now at the surface. The anomaly was $- 1.05^0/_{00}$ corresponding to a salinity of $5.43^0/_{00}$. This year was unusual in an other respect too. The minimum at the surface was surrounded by a set of salinities with anomalies of about $- 0.70^0/_{00}$, reaching from surface to bottom.

The same phenomenon occured as mentioned above, in January 1924

and was present in January and February 1931 too. These three years, however, were the only, when such a great salinity decrease was observed in the whole water body, and in all cases within the first three months of the year.

The long period of low salinity at Utö was broken in November 1939 by the hitherto greatest positive anomaly, + 1.50‰, from 70 to 90 m. It can be mentioned that, according to KALLE [6], in the Gotland Depth, at a depth of about 200 m, the period of decrease in salinity ended in 1933, while the great increase started in 1937. The intermediate years were characterized by unstable conditions and large fluctuations in salinity.

From this time on, high salinity is dominating the whole water body, with some minor intrusions of water with a salinity below the average. More characteristic of this period of increasing salinity are the occasionally occuring great inflows of saline water in the bottom regions up to 50 m. Every year these inflows now maintain an average salinity of 0.50‰, in most of the years even of 1.00‰. Usually these increases are to be seen in the middle or later part of the year.

In some of these years as in 1942, 1947, 1952 and 1955 (Fig. 3 + 4) salinity was exceptionally high, with an anomaly above + 2.00‰. In 1955 an anomaly of 2.00‰, however, could only be seen at 70 m and 80 m in June, while in the other years it reached up to 50 m.

In 1948 too, an anomaly of + 2.00‰ was noticed, but here it only comprised one value in September at 70 m.

The highest anomaly ever observed occured in October 1947 at 50 m. The deviation increased from + 2.24‰ at the bottom to + 2.39‰ at 50 m, corresponding to salinities of 9.40‰ at the bottom and 9.24‰ at 50 m.

The most persistent salinity increase observed, with an anomaly above 2.00‰ lasting from June to October occured in 1952. The greatest anomaly of + 2.28‰, corresponding to a salinity of 9.33‰, occured at the depth of 70 m. It was in this depth the anomaly remained above 2.00‰ for five months, ending earlier in the other depths from 90 m to 50 m.

According to FONSELIUS [1] a great inflow in the Bornholm Basin was observed in 1959, to reach the Landsort Depth in the middle of 1960. At almost the same time this inflow was observed in the bottom layers at Utö as an anomaly of + 1.70‰ (Fig. 4). Further, according to Fonselius, a new inflow in July 1961 was observed in the Gotland Basin. Our values,

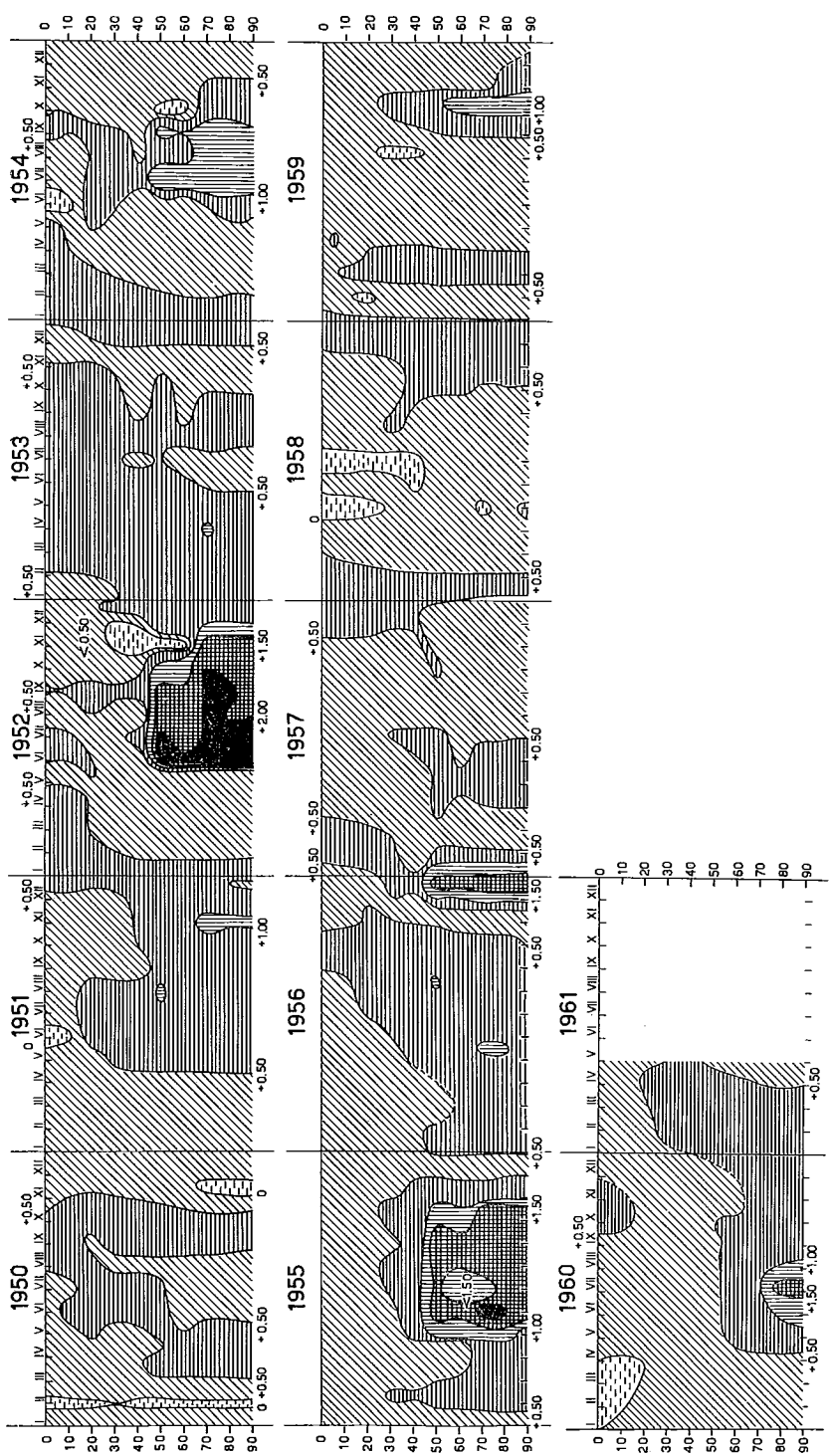

Fig. 4. Salinity deviations at Utö for the period 1950—61 V in salinity per mille units from the average for 1921—30.

now available for Utö, only cover the time to May 1961, but here salinity seems to decrease after April, when an anomaly of about + 0.50‰ almost reached the surface. Probably, the mentioned increase will later be found at Utö too, when the corresponding values from this station are received.

III. Discussion of the factors influencing salinity

1. General

In the Baltic salinity is most strongly influenced by horizontal and vertical movements of the water masses. As the greatest positive anomalies occur at or near the bottom, this fact indicates, that the origin of saline water is to be found in the bottom currents. Through the Danish Sounds heavy, warm and salt-rich North Sea water flows into the Baltic along the bottom, forming a compensatory current to the outflowing less saline surface current. The hydrography of the deep basins in the Baltic has been treated in more detail according to the salt inflows by FONSELIUS [1]. By and by the water mixes with the upper water layers, especially in autumn *i.e.* in the part of the year when the thermocline disappears and vertical turnover takes place. When the inflow is exceptionally great, it can somewhat later appear as a positive anomaly at Utö. On its way northwards the inflowing water can clearly be followed by the gradually increasing salinities and temperatures in the bottom regions.

The speed of the transport is not constant, but generally a time of about eleven months is needed for the passage of water from the region of the Danish Sounds to the vicinity of Utö. During the exceptionally strong inflows in 1941, 1951 and 1954 it happened even swifter, taking only about 7 months, while 20 months were needed for the saline water to reach Utö in 1947 and 13 months in 1922. The average time for these inflows is 11 months in agreement with the results of LISITZIN [7]. Calculating with a distance of 530 sea-miles, a mean deep current velocity of 3.4 cm/s is obtained for the inflows.

Generally, southernly currents reach the Finnish sea-area from Southern Baltic during spring and summer accounting for an increase in salinity in the bottom layers. These regularly occuring increases, however, were eliminated from the calculated anomalies by the procedure used.

The variations in salinity at Utö ($\triangle S_{\text{Utö}}$‰) are caused by the combined effect of the variations in the Sounds ($\triangle v_{\text{Sounds}}$), in the Baltic proper ($\triangle v_{\text{Baltic proper}}$) and of vertical changes ($\triangle v_z$) as convection,

vertical turnover and upwelling. As the salinity at Utö is a function (f) of these factors the relationship can be symbolized by the formula:

$$\Delta S_{\text{Utö}}\,{}^{0}/_{00} = f(\Delta v_{\text{Sounds}} + \Delta v_{\text{Baltic proper}} + \Delta v_z)$$

2. Surface influences

At the surface salinity is influenced by river run-off, precipitation, evaporation and condensation as well as of the freezing and melting of ice. These factors, however, are of minor importance in the Baltic and besides, their effect has mostly been eliminated from the observational data by the use of salinity anomalies.

Occasionally the outflowing surface current of less saline water from the Bothnian Sea may be so large, that it comprises the entire area of the Gulf of Bothnia. In this case it can be observed at Utö as a decrease in salinity as mentioned by SIMOJOKI [8]. This happens in spring and early summer if river run-off has been exceptionally large. At this time the vertical convection has decreased due to a strengthening of the thermal stratification, which prevents mixing between the water layers. The big negative anomalies at the surface in 1930 and 1933 were probably caused by this factor.

3. Westerly winds

Inflow through the Danish Sounds may be very strong during persistent westerly gales. This was the case *e.g.* in November and December 1951, when the greatest saline inflow ever observed occured at the Bornholm Depth. In June 1952 salinity suddenly rose to extraordinarily high values at Utö. This very increase was closely studied by WYRTKI [10]. In the middle of November 1951 the prevailing winds above Northwestern Europe suddenly changed direction from SE and E to the opposite zonal type of circulation. For about a month strong westerly winds prevailed forcing saline water from the North Sea into the Baltic, so leading to the said large increase in salinity.

As the formerly prevailing easterly winds had considerably lowered the water level in the Baltic, the effect of the westerly winds became stronger. Therefore, the inflow of saline water got a noticeable greater speed than the winds alone could have accounted for. On the other hand, if the water level in the Baltic is high when a westerly gale starts, the

inflowing saline water may be brought out again without penetrating into the Baltic.

When a westerly gale is strong and persistent enough, inflow under suitable conditions may take place in the whole cross section of the Sounds. The different causes of water exchange through the Sounds were closely examined by WYRTKI [11].

4. Easterly winds

Like the westerly gales, also easterly winds can contribute to an increase in salinity. Predominating NE-winds ordinarily prevail in winter time in the area of Fennoscandia. Besides making the effect of the following westerly winds stronger, as mentioned, the easterly winds create compensating bottom currents directed inwards. As the stratification of the water masses is least pronounced in winter time mixing is furthered, which contributes to the salinity increase.

At the surface the NE-winds drive the water layers in the Baltic towards the SW and W and finally out through the Danish Sounds. These winds usually carry dry continental air which furthers evaporation from the water surface especially in autumns and winters, but although the supply of fresh water is small in winters, the increase of salinity is, as seen from the figures, more marked in the deeper layers than at the surface, which proves that these effects at the surface are of secondary importance only.

5. Unstable winds

On the other hand, unstable wind directions causing fluctuating currents in the Sounds also increase the salinity in the Baltic, according to GRANQVIST [4]. Just when the direction of the current changes from outwards- to inwards-going, a strong but short injection of salt water takes place. When the currents steadily change direction in the Sounds, they bring in salt water, which always mixes a little with the inside waters before it is brought out again somewhat poorer in salt than before.

6. Secular variations of solar activity

However, there might be an outermost cause to the particular factors influencing salinity. It would be the secular variation of the solar activity, according to SOSKIN [9]. The solar activity influences the atmospheric circulation, which is connected with the hydrological conditions. Probably

a relationship does exist between the long-term hydrological variations in the Baltic and the secular variations of solar activity.

During the period of intensification of the solar activity, from the beginning of the nineteen hundred and thirties (to the middle of the sixties?), a general increase in the salinity and temperature occured. This period is characterized by factors, which all contribute to an increase in the salinity. After 1930 the frequency of the deep cyclones over Europe increased. The westerly gales became more frequent and they in turn caused strong inflows of saline water into the Baltic. In the river discharge a general decrease occured. Eliminating the effect of the westerly winds, this decrease led to a lowering of the mean sea level and a weakening of the water exchange through the Sounds, as the outflowing current became weaker. This in turn resulted in an increase in intensity of the deep compensation current.

During the period of weakening of the solar activity, the factors mentioned would change in the opposite direction, leading to a general decrease in salinity.

IV. Relationship between ice conditions in winters and salinity values

As the general distribution of atmospheric pressure is closely correlated to the wind and current conditions, a comparison is for simplicity made between its effects on the winter temperatures and salinity values. This question has already been dealt with by LISITZIN [7]. The winter temperatures are reflected in the severity of the winter, indicated by the duration of the ice cover at Utö.

The first noticeable salinity increase at Utö occured in 1922 (Fig. 2), with a positive anomaly of $1.00^0/_{00}$. Then the average salinity for the whole year, for the first time since observations started, reached the value of $7.00^0/_{00}$. The corresponding winter, preceded by a mild one, was comparatively cold, although not so cold as in the nineteen hundred and forties. The cause to this increase is found in the strong NW-winds in November and December 1921, which led to a large salt inflow observed *e.g.* at the Danish lightship Lappegrund. [12]

The intermediate years are characterized by mild winters during the whole third decade, and by comparatively low salinities with an average value of $6.78^0/_{00}$ for the years 1920—44. (LISITZIN, *loc.cit.*) Not until almost twenty years later or in 1940 (Fig. 3) did the annual mean of the salinity again rise to $7.00^0/_{00}$.

In 1939—40 the waters at Utö were ice-covered for 117 days, while in mild winters they do not freeze at all. This exceptional winter was followed by two almost as cold ones with an ice cover lasting for 113 days in 1940—41 and for 95 days in 1941—42, according to JURVA and PALOSUO [5], accompanied by mean salinities of 7.31‰ and 7.27‰. However, despite of what is indicated by the number of the ice days, the winter 1941—42 actually was the coldest hitherto in this century according to means of air temperatures for January, February and March. In 1942 the mean temperature for these months was — 11.9°C at Utö, while it in 1940 was — 8.7°C and in the mild winter 1938, + 0.8°C [13]. These cold winters show the large inflow of saline water, which in 1942 raised the anomaly with more than 2.00‰ in the bottom regions, with a maximum at 70 m. At the surface salinity decreased during the same time, in connection with the outflowing surface waters and the mixing with fresh water during the ice melting. However, the salinity increase already started in June 1939, while the cold period did not start until December 1939. The two preceding winters were exceptionally warm, and it is in this warm period the reasons are to be found. In 1937 salinity for the whole year was exceptionally high at Lappegrund. Inflow of saline water did often occur, but an inflow caused by strong W-winds did not take place until in November 1941. Thus, this inflow was the reason to the high anomalies at Utö in 1942. As strong persistent W-winds did not prevail during the preceding years, when the salinity increase started, the high anomalies then must have been connected with the severe winters and caused by the compensatory currents to the easterly winds.

During the next winter the waters at Utö did not even freeze and the average salinity accordingly dropped to 7.00‰. Then a period with mild winters followed, until in 1946—47 the waters at Utö were ice-covered for 88 days. This winter was followed by the great inflow in 1947—48 with an anomaly above 2.00‰ in October 1947 up to 50 m. The traces of this inflow could still be seen in an anomaly of 2.00‰ in 1948.

The next large inflow in 1952, already dealt with in connection with the westerly gales, was not, however, preceded by any extremely cold winter. The number of the ice days were 57 in 1950—51, but in the corresponding winter 1951—52 they were only 4.

In 1955—56 there was a really cold winter with 97 ice days, but salinity had already increased to a 2.00‰ deviation in June 1955. It then remained high, more than 0.50‰ above the average, for most part

of the next year, even increasing with more than $1.50^0/_{00}$ in December up to 50 m. In this case too, strong NW-winds which in November and December 1954 forced saline water through the Sounds, were the causing factor. From this time on, as seen from the figures (Fig. 4), salinity gradually decreased until the middle of 1958.

In October 1959 the salinity anomalies up to 50 m suddenly exceeded $1.00^0/_{00}$ as an introduction to the coming cold winter with 92 ice days at Utö. Now too, the increase above $1.50^0/_{00}$ in the bottom regions in July 1960, was preceded by a warm period and accompanied by a cold winter. Although the next extremely mild winter in 1960—61 with no ice at Utö, did not contribute to the increase, the anomaly in the bottom regions remained nearly at $1.00^0/_{00}$ on to March 1961. Until April 1961 even an ascent of salt towards the surface layers could be noticed.

As seen from the above, high salinity and severe winters accompany each other. As a rule, a large positive salinity anomaly near the bottom is preceded by a mild winter an accompanied by a severe one. Mild winters are ordinarily caused by persisting W-winds which force saline water through the Sounds. About one year later this water then reaches Utö.

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The data used have been taken from the following publications: *Merentutkimuslaitoksen Julkaisu — Havsforskningsinstitutets Skrift* from the series:

a) Regular observations of temperature and salinity in the seas around Finland.
b) A survey of the state of the ice on the coasts of Finland in the winter.