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THE ÅLAND SEA, ITS SURFACE TOPOGRAPHY AND STATIONARY CURRENTS

by

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Abstract

For this study the hydrographic data collected 20—21 June, 1956, were used. That period was relatively calm and thus probably represented stationary conditions.

The whole Åland Sea, a sound between the Gulf of Bothnia and the Baltic proper, was found to be characterized, as expected, (1) by an isohaline, almost isothermal upper zone, (2) by a halocline, and (3) by a deeper zone. The halocline was found to consist of an upper part which was also a thermocline, and of a weaker lower part which was characterized by a temperature inversion. For obvious reasons the layer of no motion should appear close to the depth between the two distinct parts of the halocline.

In the final approximation the depth of the layer of no motion was taken to be the depth at which the curves representing the anomalies of specific volume at two neighbouring stations crossed (or were tangent to) each other. The depths thus found varied between 39 and 80 metres.

Integrating over the specific volume upwards from the depth of the layer of no motion it was found that the Swedish coast appeared to be 16 ± 4 mm higher than the west coast of Åland. The maximum mean southward current under stationary conditions (actually between stations 15 and F64) was

found to be 11.3 cm s^{-1}. The volume transport towards south above the layer of no motion was found to be 47 000 m^3 s^{-1} and the volume transport towards north to be 12 000 m^3 s^{-1}. Assuming that the discharge from rivers into the Gulf of Bothnia was 15 000 m^3 s^{-1}, the volume transport towards north through the Archipelago Sea should have been some 20 000 m^3 s^{-1} during this period.

1. Main characteristics of the Åland Sea

The water exchange between the Gulf of Bothnia and the Baltic proper proceeds both through the open Åland Sea, situated west of the main island of Åland and the east coast of Sweden, and through the Archipelago Sea, east of the main island of Åland. Basically the Åland Sea (Fig. 1) is an open sound with an elongated deep channel of more than 200 metres' depth running from southeast towards northwest and with a southern sill, approximately along the latitude 59°35′ N, having mostly a depth of some 40 metres with one deeper canyon probably causing the actual sill depth to be about 70 metres.

The exchange of water, salt and pollutants through the Åland Sea is dominated to a great extent by the meteorologically caused rapid water movements either northwards or southwards, as clearly indicated by the recent current measurements. (Ehlin and Ambjörn, [5].) Since the salinity and thus also the density of the southbound waters normally is less than those of the other waters, they tend to stay in the uppermost layers. On the other hand, the northbound waters normally have a tendency to sink into deeper water layers or to turn back southwards.

The problem of the resulting water exchange can be approached through the measurement of actual currents and ensuing computations, such measurements being, however, tedious and difficult to perform. The other possibility is to make use of a situation when the winds both are and have been weak before the observation period. In this study the latter approach has been made. Thus in the following an attempt is been made to calculate for the Åland Sea

— the surface topography or at least the height difference between the west coast of Åland and the east coast of Sweden,
— the currents through a few transversal sections,
— the volume transport through the same sections.

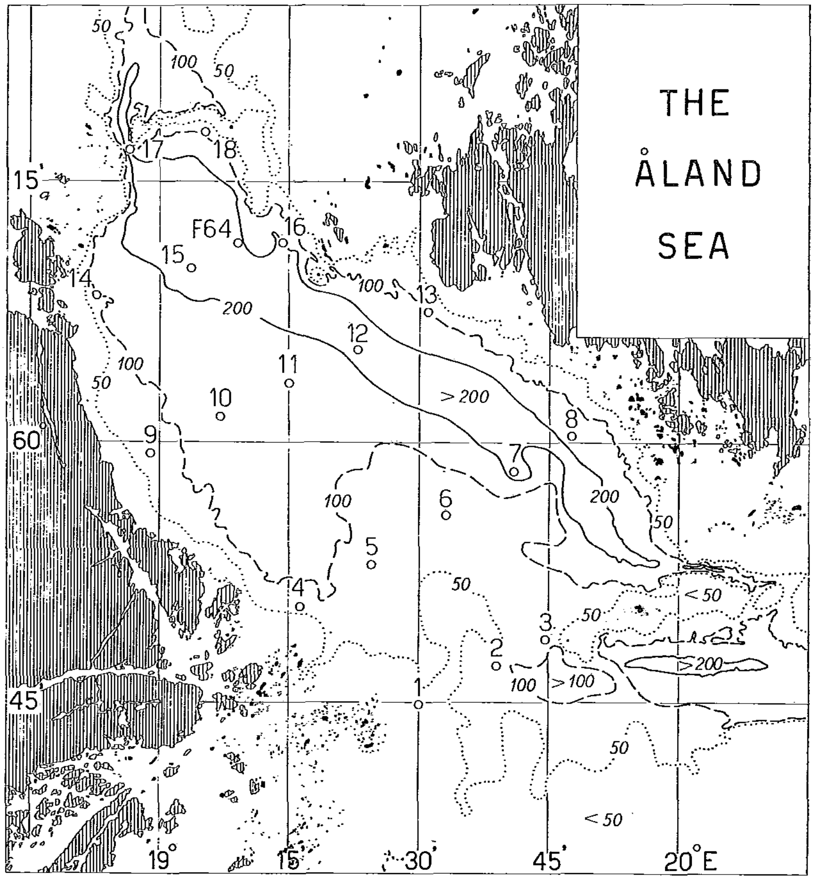

Fig. 1. The Åland Sea. The hydrographic stations, 1 to 18, including F64, were those used in this study.

The immediate reasons for this attempt were as follows:

1. The results from hydrographic levellings across the Åland Sea are required for the precision levelling by the geodetists.
2. Finnish-Swedish bilateral studies of pollution of the Gulf of Bothnia, and of measures to combat it, require information about the water exchange through the Åland Sea.
3. For the interpretation of the actual current measurements in the Åland Sea, if possible, a reference study is required, not based upon direct measurements.

4. Further hydrographic studies of the Åland Sea will be made simpler if they can be based upon an earlier interpretation of hydrography observed during idealized conditions.
5. Estimates concerning the water volume transport through the Åland Sea and, indirectly, also through the Archipelago Sea are required for numerous local purposes, including the possibilities of combatting the land-based and other pollution of the sea area in question.

The Åland Sea is obviously principally a sound connecting the Gulf of Bothnia and the Baltic proper. However, one could consider the said sea also an estuary but with some modification. BOWDEN [3] gives the following general definition:

»An estuary may be defined as a partially enclosed body of water which receives an inflow of fresh water from land drainage and which has a free connection with the open sea. The water within the estuary consists of a mixture of fresh water and sea water in proportions which vary from place to place. This definition, which follows that used by CAMERON and PRITCHARD [4], covers coastal plain estuaries and fjords, as well as certain gulfs, sounds and inlets. It also includes embayments formed behind offshore bars, provided they have a salinity significantly lower than the open sea.»

Analogously to this general definition we could define the Åland Sea as follows: »The Åland Sea may be considered a fjord-type estuary to be defined as a partially enclosed body of water, which receives an inflow of the water of Gulf of Bothnia, being a mixture of fresh water from land drainage in the catchment area of the Gulf of Bothnia and of saltier water having penetrated the Gulf of Bothnia either through the Archipelago Sea or through the Åland Sea. The water within the Åland Sea is a mixture of the water of Gulf of Bothnia and of Baltic proper water in proportions which vary from place to place.»

2. *Schematic presentation of the water masses of the Åland Sea*

HELA and KOROLEFF [8] published the hydrographical and chemical data which were collected in 1956 among others in the Åland Sea, and HELA [7] presented a hydrographical survey of the waters in the Åland Sea. The applied nineteen hydrographic stations (Fig. 1) cover the whole Åland Sea rather well. Furthermore, during the period of the field study, 20 and 21 June, 1956, the winds varied between 1 and 3 Beauf. only, mainly from the south. Moreover, during a few days immediately preceding the above period in the area of the whole Gulf of Bothnia the winds were weak or moderate. This can be concluded from the limited absolute and relative changes of the sea level of the area of the Gulf of Bothnia, taken from data of sea level in relation to the expected mean sea level, (in cm), (LISITZIN, [10]):

	June 18	19	20	21
Raahe (64°42′ N, 24°30′ E)	+10.1	+4.1	+2.9	−3.3
Pietarsaari (63°42′ N, 22°42′ E)	+ 5.4	+2.9	+1.1	−5.0
Mäntyluoto (61°36′ N, 21°29′ E)	− 3.3	−4.3	−3.8	−6.2
Degerby (60°2′ N, 20°23′ E)	− 8.4	−6.6	−5.7	−5.2

Thus the material of June 20—21, 1956, should yield results which resemble stationary conditions.

In order to systematize the hydrographic data covered by the said nineteen stations, the mean salinity, the mean temperature etc. over the whole Åland Sea were computed and the mean values plotted on semi-logarithmic scale for every depth.

Firstly, the mean vertical distribution of salinity (*cf.* TULLY, [17]) indicates (Fig. 2) an isohaline upper zone (AB) between the surface and some 10 metres, the halocline, consisting of two parts, the upper part of the halocline (BC) between some 10 and 50 metres and the lower part (CD) between some 50 and 130 metres and the lower zone (DE) between 130 metres and the bottom. The existence of the nearly isohaline lower part (CD) of the halocline seems to indicate that the relatively saline water from the south penetrates the Åland Sea in a pulsatory manner. Thus the deepest layers consist of two or several types of water having somewhat differing salinities.

For each depth also the standard deviation of the salinity was computed. As expected, the standard deviation was in the upper zone (AB) low, 0.1 $_{0/00}$, in the lower part of the halocline less than 0.1 $_{0/00}$ and in the lower zone some 0.03 $_{0/00}$ only but had a maximum of some 0.5 $_{0/00}$ in the upper part of the halocline, at the depth of 24 metres. This is in a rather good agreement with TULLY [17], who assumed that the lower limit of the halocline is regarded as the level through which transport

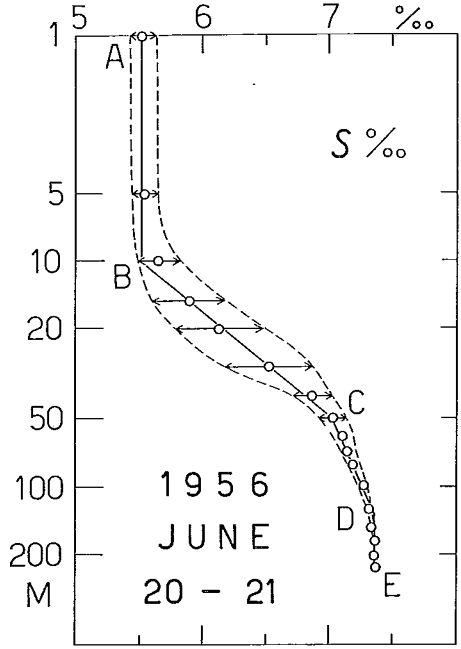

Fig. 2. The mean vertical distribution of salinity, given in semi-logarithmic scale, in the Åland Sea, June 20—21, 1956. Also the standard deviation of salinity at each depth has been given with horizontal arrows.

takes place upwards only, whereas mixing as well as entrainment occurs within the halocline.

Secondly, the mean vertical distribution of temperature is indicated in Fig. 3. In this presentation the upper zone (AB) reaches the depth of some 8.5 metres, the upper part (BC) of the halocline corresponds to a downwards decreasing temperature from 8.5 metres to some 34 metres, if an effort is made to make use of a broken line, or to some 45 metres if the point C is indicated by the vertical tangent of a curve BCD. The lower part of the halocline (CD) is observed in this presentation as an inversion layer of the temperature. Once more the lower end of the lower part (CD) of the halocline is found at the depth of 130 metres.

Next, the mean vertical distribution of σ_t is seen in Fig. 4. Here again the depths 8.5, 50 and some 130 metres correspond to the levels of B, C and D. If, however, σ_t ($= \sigma_{S,t,o}$) is replaced by $\sigma_{S,t,p}$ that is, if the compressibility of water is taken into account, the actual density

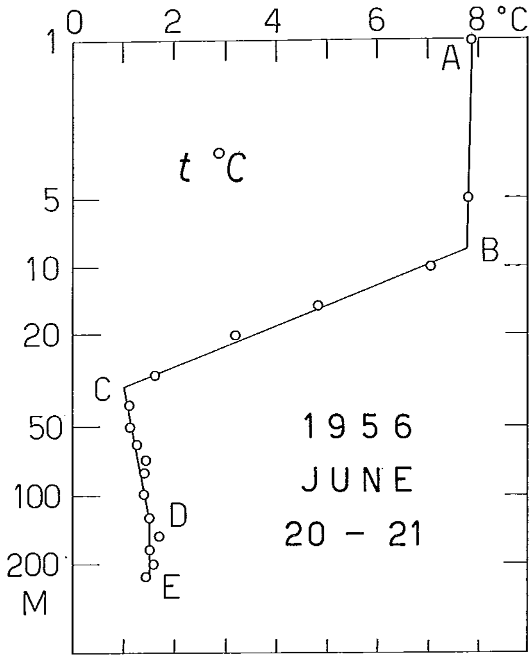

Fig. 3. The mean vertical distribution of temperature, given in semi-logarithmic scale, in the Åland Sea, June 20—21, 1956.

appears in the semi-logarithmic presentation between 8.5 metres and the bottom more or less as a straight line. This interesting observation calls for another analysis which we hope to perform at a later date.

In the corresponding mean tS-diagram (Fig. 5) the upper zone AB and, likewise, the lower zone DE appear almost as two points, while the two parts of the halocline (BC and CD) appear more or less as two straight but differing lines. Assuming that BCD really is a broken line, the significant C-layer seems to have the following characteristics: $z = 34$ metres, $S = 6.44\ {}_{0}/_{00}$ and $t = 0.6$°C. However, it seems more correct to indicate that in this presentation the point C has more or less worn off as a result from mixing. Therefore, the indicative C-layer is found as the minimum of the curve BCD with the following characteristics: $z = 45$ metres, $S = 6.94$°C, $t = 1.1$°C and $\sigma_t = 5.57$.

Finally, even the oxygen saturation percentage (Fig. 6), presented as a »function» of σ_t clearly indicates a rather sharp turning point somewhere near the values $\sigma_t = 5.75$ and $O_2 = 98$ per cent. In this con-

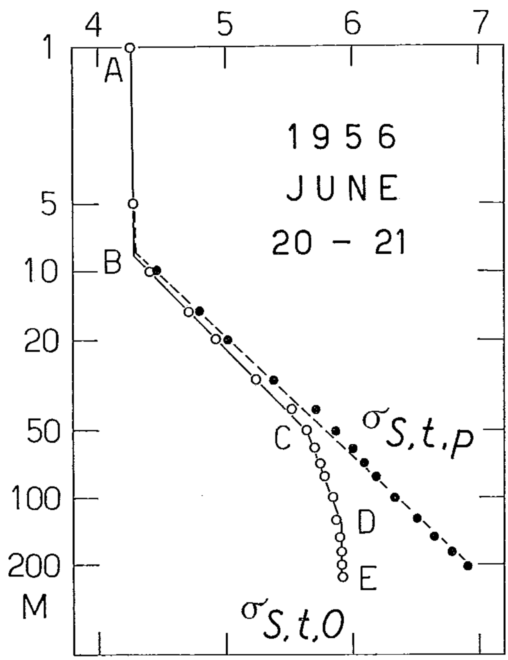

Fig. 4. The mean vertical distribution of σ_t ($= \sigma_{S,t,0}$), given in semi-logarithmic scale, in the Åland Sea, June 20—21, 1956. The corresponding values of $\sigma_{S,t,p}$ are indicated by the broken line.

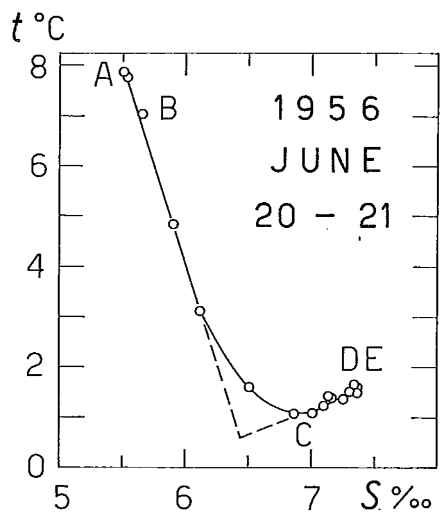

Fig. 5. The temperature-salinity diagram, based upon the mean values in Figures 2 and 3, for the Åland Sea, June 20—21, 1956.

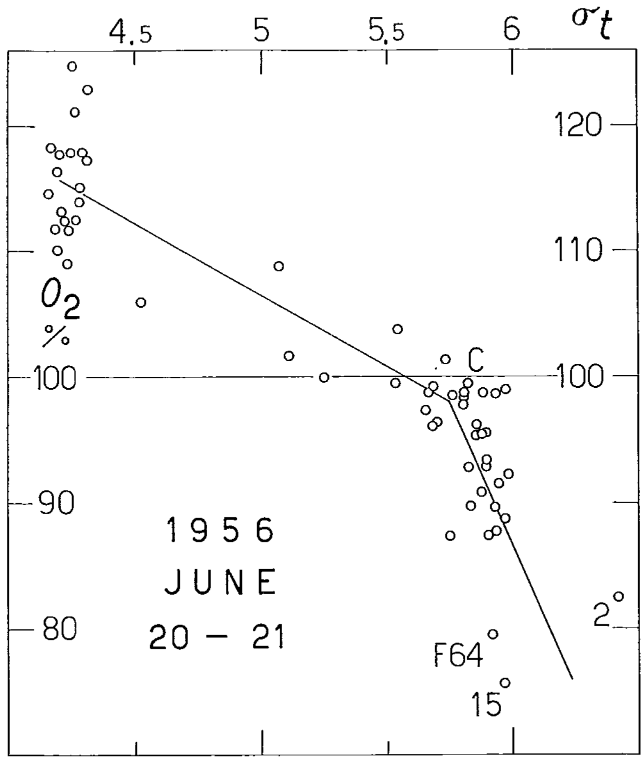

Fig. 6. The oxygen saturation, per cent, given as the »function» of σ_t, in the Åland Sea, June 20—21, 1956.

nection one must observe that in the deepest waters, where σ_t has the highest values, the scattering of oxygen saturation degree indicates the pulsatory character of the water inflow into the Åland Sea (Fig. 7). At the bottom of the station 2, at the southern edge of the Åland Sea the rather salty water is obviously »too rich» in oxygen, while at the stations F64 and 15, in the northern part of the deep valley of the Åland Sea the bottom waters show an oxygen deficit greater than one would expect.

Linking the above observations together one may now observe that the Åland Sea was 20—21 June, 1956, characterized by the following water masses and layers.

— The upper zone (AB) is isohaline, almost isothermal and oversaturated with oxygen.
— The layer B appears at the depth of 10 (or 8.5) metres.

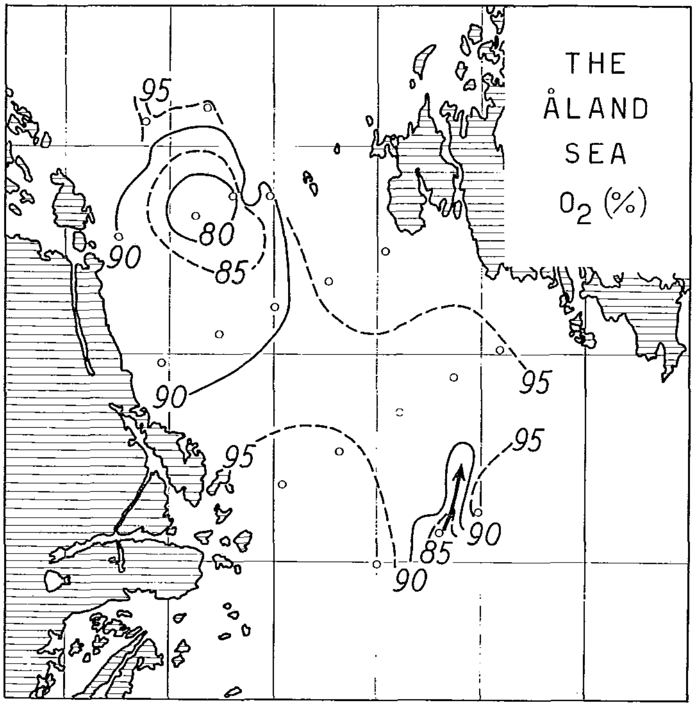

Fig. 7. The distribution of oxygen saturation, per cent, near the bottom of the Åland Sea, June 20—21, 1956.

— The upper part (BC) of the halocline appears also as a thermocline. This water mass is oversaturated with oxygen but less so than the upper zone.
— The layer C appears at the depth of 50 (or 45) metres.
— The lower part (CD) of the halocline appears as an inversion layer of thermocline. This water mass shows a slight saturation deficit of oxygen.
— The layer D appears at the depth of 130 metres.
— The lower zone DE is practically isohaline and isothermal. The saturation deficit of oxygen is more developed than in the lower part of the halocline but its scattering is quite pronounced.

One may conclude that the layer C or another depth close to it divides the waters of the Åland Sea into two basically different water bodies.

3. The application of the dynamic method

As pointed out above, an effort is made to apply the standard dynamic method. In order to avoid erroneous conclusions, particular attention must be paid to the effects of the various assumptions made. Moreover, the estimation of the accuracy of the results, if any, will be made possible by means of the said assumptions.

When the forces are given per mass unit, as always in the physical oceanography, the equation of motion has the following general form:

$$\frac{d\boldsymbol{c}}{dt} = (-\,2\boldsymbol{\Omega}\times\boldsymbol{c}) + (-\,\alpha\,\nabla\,p) + \boldsymbol{g} + \boldsymbol{F} \tag{1}$$

where $\boldsymbol{c}$ is the velocity,
$\boldsymbol{\Omega}$ is the angular velocity of the earth's rotation:

$$|\boldsymbol{\Omega}| = 0.729\times 10^{-4}\ \mathrm{s}^{-1},$$

α is the specific volume of water ($\mathrm{cm}^3\ \mathrm{g}^{-1}$),
p is the pressure ($\mathrm{dyne\ cm}^{-2}$),
$\boldsymbol{g}$ is the acceleration of gravity,
$\boldsymbol{F}$ is the frictional force.

When the above equation of motion is given by means of three components and when the minor terms are neglected following the standard procedure, the following set of equations is obtained:

$$\left\{\begin{aligned} \frac{du}{dt} &= (2\Omega\sin\phi)v - \alpha\frac{\partial p}{\partial x} + F_x \\ \frac{dv}{dt} &= (-\,2\Omega\sin\phi)u - \alpha\frac{\partial p}{\partial y} + F_y \\ \frac{dw}{dt} &= -\,\alpha\frac{\partial p}{\partial z} + g + F_z \end{aligned}\right. \tag{2}$$

It is rather obvious that when neglecting such minor terms, the errors introduced were small enough not to have affected the accuracy of the forthcoming computations.

In these equations

u, v, w are the components of $\boldsymbol{c}$,

ϕ is the latitude,

F_x, F_y, F_z are the components of $\boldsymbol{F}$.

Two further assumptions must now be made. First, it is assumed that the currents are stationary, unaccelerated. Since this assumption is relatively bold, it will affect the results of the computations and thus must be taken into account when estimating the accuracy of the results. (Implicitely it must be assumed that the observation period (von Arx, [1]) for each hydrographic section is brief enough, that is, »synoptic«. Because of the rather stationary conditions during June 20—21, 1956, and because of the rapid working methods on board, we assume that this secondary condition was fulfilled.) Secondly, it is necessary to neglect the frictional terms. Even this assumption is basically wrong, especially close to the coast lines, and its effect must be considered when estimating the final accuracy.

With these two basic assumptions the last equation gives us the hydrostatic equation, while the first two can be combined into the well-known geostrophic equation

$$\alpha \frac{\partial p}{\partial n} = (2\Omega \sin \phi) c \tag{3}$$

indicating that in this case the pressure gradient and the Coriolis force balance each other. In this equation

c is the horizontal current velocity and

n is the direction normal to the current velocity.

Taking into account the elongated form of the Åland Sea it has been assumed that the currents are mainly longitudinal, while the hydrographic stations (Fig. 1) have been placed along lines roughly following the most probable direction of n. The selection of the direction of n may erroneously reduce the computed speeds of currents but will not affect the computed height difference along a hydrographic section between the west coast of Åland and the east coast of Sweden.

For the actual computations the practical formula (4) is used

$$c_1 - c_0 = \frac{1}{2\Omega \sin \phi \,\mathrm{AB}} \left\{ \int_{p_1}^{p_0} \alpha_B \, dp - \int_{p_1}^{p_0} \alpha_A dp \right\} \tag{4}$$

where c_1 and c_0 refer to the current speeds

at the depths 1 and 0 and

A and B are indices for two hydrographic stations.

This formula obviously gives the current at level 1 in relation to the current at level 0. In order to obtain the absolute current speeds the speed differences are integrated from a layer of no motion both upwards up to the surface and, likewise, downwards. Thus the selection of the layer of no motion becomes another critical factor affecting also the results of the computations, as will be shown below.

Finally, the accuracy of the computation of specific volume has to be taken into account as another factor affecting the final results. Following the standard procedure already proposed in this form by V. BJERKNES [2] the specific volume is presented in the following manner:

$$\alpha_{S,t,p} = \alpha_{35,0,p} + \delta \tag{5}$$

where δ is called the anomaly of specific volume. Since $\alpha_{35,0,p}$ is by definition constant at every depth, the specific volume can be replaced in formula (4) by its anomaly, δ. The computations were arranged as follows:

$$\begin{aligned}
\delta &= \alpha_{S,t,p} - \alpha_{35,0,p} \\
&= (\alpha_{35,0,0} + \delta_S + \delta_t + \delta_{S,t}) + (\delta_p + \delta_{S,p}) + \delta_{t,p} + \delta_{S,t,p} - \alpha_{35,0,p} \qquad (6)\\
&\sim \alpha_{S,t,0} \qquad\qquad + \Delta_{S,p} + \delta_{t,p} \qquad - \alpha_{35,0,p} \\
&= \frac{1}{1 + 10^{-3}\sigma_t} + (\Delta_{S,p} - \alpha_{35,0,p}) + \delta_{t,p}\,.
\end{aligned}$$

Because of the relative shallowness of the Åland Sea, $\delta_{S,t,p} \sim 0$. In the limits of the salinity of the Åland Sea, $5.39 \leq S \leq 7.43$, and up to the depth of some 250 metres, $\delta_{S,p}$ is at every depth constant, while δ_p is, just like $\alpha_{35,0,p}$ as well, by definition constant at every depth, which fact makes the arrangement of computations simple.

4. Selection of the layer of no motion

As indicated above, the appropriate selection of the layer of no motion is significant for the accuracy of the final results. WITTING [18] in one of his classical works computed the surface topography of the whole Baltic Sea area in relation to the level of the North Sea. He kept separate the »anemo-baric disturbance» and the »dynamic disturbance», the latter one corresponding in principle to the varying height of the sea surface in relation to the layer of no motion. WITTING assumed for his calculations that the depth of the layer of no motion was the in Åland Sea 20 m. This and other analogous assumptions were correct enough for the computation of longitudinal height differences as can be seen indirectly from his main results according to which the surface of the southernmost part of the Gulf of Bothnia is some 33 centimetres above the level of the North Sea. This order of magnitude has been verified by the geodetic levellings; among other LEVALLOIS and MAILLARD [9] give as height difference between the southwestern coast of Finland and eastern North Sea some 30 centimetres.

When trying to find out the transversal slope of the Åland Sea with maximum accuracy we have stepwise followed three differing, more accurate methods in order to be able to be in a position of comparing internally the correctness of the said methods.

First approximation

From the mean tS-diagram (Fig. 5) we took the value $\sigma_t = 5.57$ as representing the layer of no motion. Then the vertical distribution of σ_t (or rather water density without the effect of the compressibility) was plotted semi-logarithmically for every hydrographic station and the depth, where the above σ_t appeared, was taken as the layer of no motion.

Here it is worthwhile mentioning that only in two cases it was found desirable to perform minor corrections in the plotted original σ_t-values. The corresponding corrections were then introduced either to the original temperature or salinity data and taken into account in the following calculations. All the other hydrographic data were obviously correct as required.

Second approximation

For every hydrographic station separately a tS-curve was plotted and the depth of the C-layer, that is, the layer between the upper and lower parts of the halocline, was defined graphically by means of the crossing points of two straight lines, BC and CD corresponding to the said two parts. The actual depth of the C-layer, in metres, was estimated from the position of the crossing point between the observed data at standard depths. It was then assumed that these depths indicated the layer of no motion.

This approximation made it possible to calculate also height differences between hydrographic stations not being on the same section. The smoothing of such results concerning the height differences between sections was performed as follows:

— It was assumed that the transversal differences were correct.
— The height difference between two sections was defined by means of the arithmetical mean of the computed height differences between two stations taken from two neighbouring sections. The results were as follows.

Section 1—3		
Height difference	—0.4	±0.6 mm
Section 4—8		
Height difference	+3.2	±0.4 mm
Section 9—13		
Height difference	+5.8	±0.6 mm
Section 14—16		
Height difference	+3.2	±0.7 mm
Section 17—18		

— Finally, in order to give a simple outlook to the presentation, the lowermost point was given the height 0.

The surface topography, based upon the second approximation, as explained above, is given in Fig. 8. We believe that the third approximation is more accurate than this one. However, since the last one can be applied to two sections only, it has been worthwhile presenting the surface topography as given in Fig. 8, especially since it seems to be internally rather logical.

In the same Fig. 8 the surface currents are given by means of a few arrows. The relative lengths of the arrows indicate the longitudinal current components computed by means of the second approximation. The actual direction of the currents was made to fit into the slopes of the surface topography. (Our actual current results are presented in connection with the third, final approximation.)

Third approximation

Finally, as the most reliable approach the vertical distribution of the anomalies of specific volume at two neighbouring stations was plotted and the crossing points of these two anomaly curves taken as the depth of the layer of no motion.

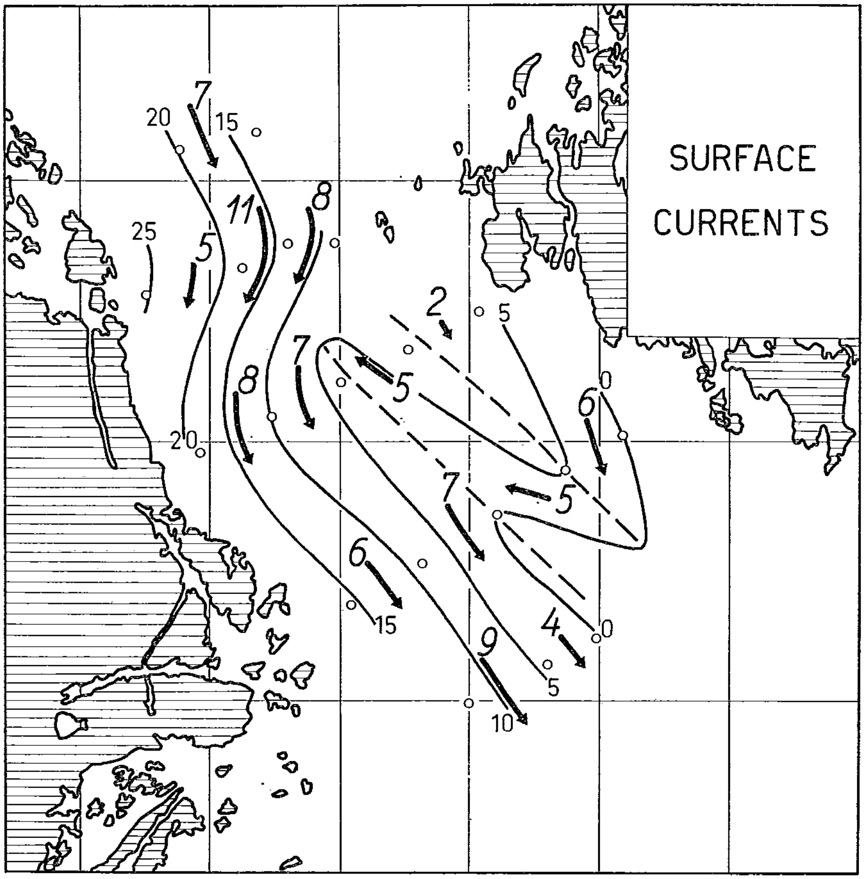

Fig. 8. The surface topography of the Åland Sea, given in millimetres, June 20—21, 1956, based upon the second approximation above. The length of the arrows indicates roughly the speed of the surface currents, in cm s^{-1}, the directions of which have been adjusted to follow the slopes of the topography used.

This approach gives results only at two sections, 9—13 and 14—16, since in other cases the anomaly curves do not cross each other. One weak point is observed even in these two sections: the anomaly curves of the stations 12 and 13, and likewise, those of F64 and 16, do not actually cross each other but are, at a reasonable depth, tangent to each other as is indirectly indicated also in Figs. 10 and 11, where the depths of the layer of no motion are shown. It is believed that this lack of actual crossing points has not affected the results.

The results of the three approximations, in millimetres, give at least an idea about the relative accuracy of the three methods used.

Section 9—13	9	10	11	12	13	9—13
First approximation	14.1	5.5	0	3.6	3.2	10.9 mm
Second approximation	15.5	6.8	0	4.1	2.8	12.7
Third approximation	16.4	7.8	0	5.6	3.3	13.1

Section 14—16	14	15	F64	16	14—16
First approximation	15.6	10.0	3.8	0	15.6
Second approximation	16.2	9.7	4.2	0	16.2
Third approximation	15.1	12.9	5.0	0	15.1

5. *The height difference between Sweden and Åland*

The results were not very much different regardless of the approximation used, however, we definitely feel that the third approximation gives the most reliable results, that is, the sea surface is at station 9 in all 13.1 mm higher than at station 13 and similarly at station 14 in all 15.1 mm higher than at station 16. When these results are finally extrapolated to reach the coast lines (or east of station 16 the outer edge of the islands), in both cases the height difference becomes with some accuracy 16 mm (Fig. 9).

As a point of comparison it is interesting to note that PROUDMAN [16] in his textbook estimated that in the Strait of Dover the resulting current is 3 nautical miles per day or 6.43 cm s^{-1} and the breadth of the

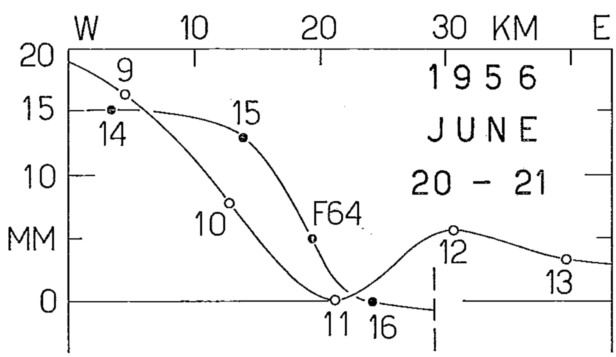

Fig. 9. The slopes of the surface of the Åland Sea, given in millimetres, at two cross sections, 14—16 and 9—13, June 20—21, 1956.

Strait 35.2 km. Thus he arrives at the conclusion that the total rise from the English coast to the French coast is 26.2 mm. He adds, however, that »from continuous observations of the water-levels on the two sides of the Strait, and simultaneous observations of currents over the Strait, the relationship between the zeros of the levelling systems of England and France could be determined». PROUDMAN's above mean slope is 7.4×10^{-7}, while ours is 3.7×10^{-7}, the order of magnitude being thus relatively similar. The non-tidal character of the Åland Sea, contrary to the Strait of Dover, the ideal conditions during our observation period and the method used in the third approximation seem to indicate that our height difference can be used to determine the relationship between the zeros of the levelling systems of Sweden and Finland across the Åland Sea, the Finnish geodetists having already performed the actual levelling through the whole Archipelago Sea from the Finnish mainland to the main island of Åland.

MÄLKKI [13] has recently estimated the accuracy of such hydrographic levellings. We could rely upon his thinking to a certain extent; however, during our observation period the conditions were ideal enough to warrant partly a greater accuracy than MÄLKKI estimates for the use of temperature, salinity, current, wind and sea level measurements over a lengthy period of time. However, most of the following results are based upon experience only or even upon pure estimates without actual computations. Further studies should clarify whether or not we have estimated the errors in a reliable manner.

Firstly, it was assumed that the currents were stationary and unaccelerated. We believe that because of rather stationary conditions the acceleration error is only $\pm$ 2 mm/40 km. Neglecting eventual short-term peaks in the air pressure field, the possible error due to the air pressure gradient should not be larger than $\pm$ 1 mm/40 km. Finally, during the observation period the wind component across the Åland Sea was on an average approximately 1 m s^{-1}, which brings about a wind error of $\pm$ 1 mm/40 km.

The friction term which in this relatively stationary case could be called »coastal term» is estimated simply from Fig. 9 to be $\pm$ 2 mm/40 km.

It is assumed that no error whatsoever was brought about when selecting the layer of no motion for the sections 9—13 and 14—16. Finally, as estimated by MÄLKKI [13], in the observations and computations of density gradients an error of $\pm$ 1 mm/10 km or $\pm$ 2 mm/40 km must be taken into account.

This brings us to believe that the east coast of Sweden was 20 to 21 June, 1956, in all 16 ± 4 mm higher than the west coast of Åland. One expects that the same would always repeat itself with some accuracy during stationary conditions, that is, towards the end of a calm or an almost calm period. The geodetists might wish to make use of this possibility.

We have not made an effort to compare our results, as far as the accuracy is concerned, with those which one would get from a long series of measurements, as explained by Mälkki [13]. Obviously, the results would not be identical even if the observation period would cover a very long period. It is not impossible, however, that our height difference result would be indicative for a corresponding result from long term measurement.

6. *The computed currents*

The above approximate surface topography of the Åland Sea (Fig. 8) and the slopes of the two final cross sections (Fig. 9) indicate a surface current pattern similar to that based upon the distribution of salinity at the surface and presented by Hela ([7], (Fig. 7)). (The only difference is that a weak northwest bound surface current along the west coast of Åland was seen in the salinity distribution, while such a current is not found in the topography.)

Using the formula (4), the currents of Figs. 10 and 11 were obtained for the two cross sections 14—16 and 9—13. In both figures the Swedish coast appears on the left. Positive current figures, given in cm s^{-1} indicate a current from the paper, that is, towards south or rather south-south-east. The mean depth of the layer of no motion is indicated for each pair of stations by means of a horizontal line at the depth of some 40 to 80 metres.

The inherited weaknesses of these computations can be listed as follows:

- As explained above, the currents are never purely geostrophic.
- The computation gives current components perpendicular to the cross section which are not necessarily identical with the true current.
- The sharp changes from station to station are bound to bring about significant inaccuracies. Among others it would have been useful to have two auxiliary stations around station 11 in order to get a more reliable picture about the current peaks. Similarly, it would have been

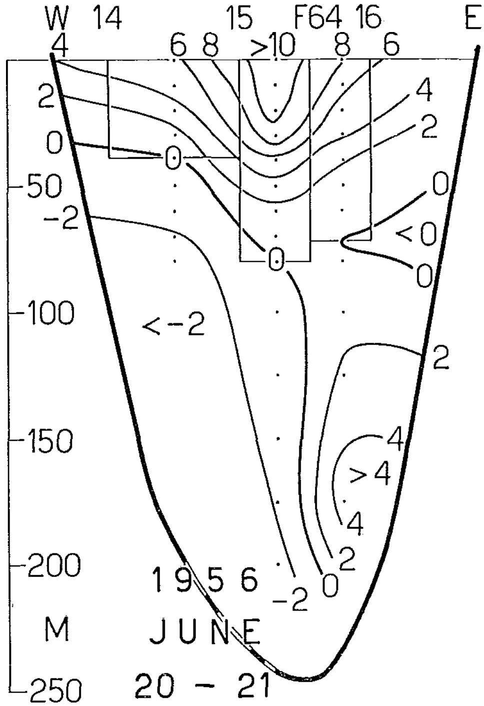

Fig. 10. The computed mean currents, in cm s^{-1}, between station pairs, at the cross section 14—16.

appropriate to have a couple of additional stations around station 15 in order to get a more detailed idea about the depth of the layer of no motion.

— Moreover, the given current figures are mean currents between two neighbouring stations and not point values. When drawing the current curves this fact was not really taken into account, in spite of the minor distortions involved.

— In reality nothing is known about the currents between the coast line and the station closest to it.

In spite of all these inherited weaknesses the two current patterns should be at least indicative. In addition, when determining the depth of the layer of no motion both between stations 12 and 13 and also between stations F64 and 16, as explained above, the curves representing the anomalies of specific volume did not really cross but were only

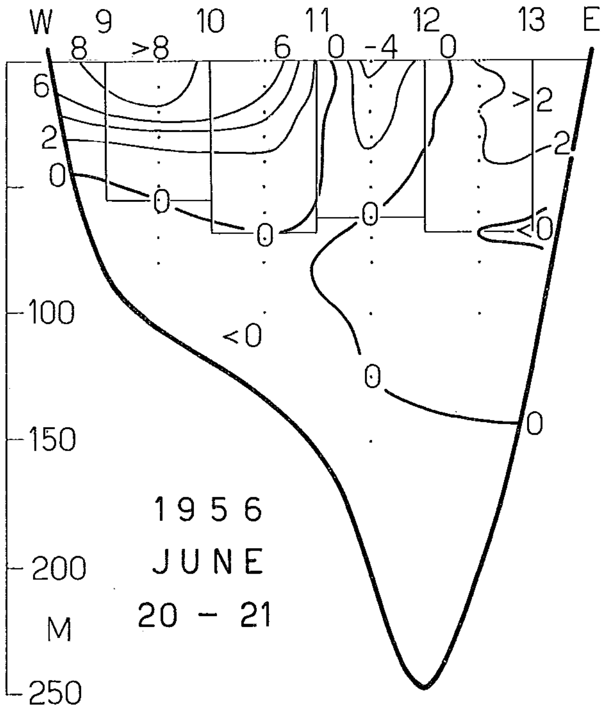

Fig. 11. The computed mean currents, in cm s^{-1}, between station pairs, at the cross section 9—13.

tangent to each other. Since the layer of no motion even in these two cases appears at a rather logical depth, we cannot but believe in the correctness of this interpretation.

The maximum speed of the southbound current is observed at cross section 14—16 between stations 15 and F64, the mean speed at the surface being 11.3 cm s^{-1}. The same current is observed at section 9—13 close to the Swedish coast, between stations 9 and 10, the mean speed at the surface being 8.3 cm s^{-1}.

It is interesting to note that PALMÉN [14] obtained the following resulting speeds for the surface currents during the years 1923—27:

»Grundkallen»	(60°34′ N, 18°58′ E)
June:	N 16 W 5.1 cm s^{-1}
October:	N 25 W 8.2 cm s^{-1}
»Svenska Björn»	(59°36′ N, 19°56′ E)
June:	N 32 E 3.4 cm s^{-1}
October:	N 9 W 6.3 cm s^{-1}

The similarity of these resulting currents (giving the direction from which the current is flowing), measured from the light vessels by means of current crosses, with our computed currents for a single synoptic, relatively calm period is encouraging.

A northbound current is observed in Fig. 11 between stations 11 and 12, with a mean speed at the surface being 5.1 cm s^{-1}. This current does not reach the section 14—16 but turns west and back southwards. In the deeper layers a northbound current component is observed especially at the western edge of the Åland Sea. — Further details on the current distribution 20—21 June, 1956, can be seen in Figs. 10 and 11.

Ehlin and Ambjörn [5] have recently published most interesting results of their oceanographic investigations in the Åland Sea during the period June—September 1973, their station S2 corresponding to our station 17 near Understen and their station S4 to our 18 near Märket. Their current and other measurements were performed mainly in the northernmost part of the Åland Sea and, moreover, their observation period is not similar to ours. They give a wealth of information especially concerning the time variation of the currents and also concerning the changes in the vertical distribution of the currents and of the thermocline. When taking into account that our observations refer to only one brief synoptic period with rather stationary conditions, while their measurements cover a long period with drastically changing conditions, the approaches as such are different, indeed. Nevertheless, it seems justified to state that nothing in these two approaches contradicts each other, except perhaps two details, as follows.

(1) The layer of no motion (although this term is not used by the said authors) seems to appear closer to the surface than we observed during our synoptic period, the second approximation giving 38 metres for stations 15 and 18.

(2) The said authors have not yet computed their resulting currents. Nevertheless, an estimate based upon their current statistics may indicate somewhat speedier resulting currents than obtained by us. To a certain extent this may be due to the various inherited weaknesses of the current computations as listed above. On the other hand, the currents between Understen and Märket must be faster than in the open Åland Sea.

In addition it is of greatest significance to point out that our results, based upon one synoptic period, may be indicative as to the resulting volume transport between the Gulf of Bothnia and the Baltic proper. However, only actual current measurements can give an idea about the material (salt, pollutants etc.) exchange between the said two sea areas.

7. *Volume transport through the Åland Sea*

During our period of study, the volume transport towards south above the layer of no motion was through the section 14—16 in all 49 000 $m^3 s^{-1}$ and through the section 9—13 in all 46 000 $m^3 s^{-1}$, the mean value being some 47 000 $m^3 s^{-1}$. Similarly, the volume transport towards north was some 12 000 $m^3 s^{-1}$.

MIKULSKY [11] has computed that the mean discharge from the rivers into the Gulf of Bothnia in June is some 11 000 $m^3 s^{-1}$. For our purpose we can estimate that the opposite effects of precipitation and evaporation, both at sea, are of the same order of magnitude. Taking into account that in 1956 the spring was delayed (*cf.* PALOSUO, [15]), the June 1956 discharge into the Gulf of Bothnia could have been 15 000 $m^3 s^{-1}$. (The late melting of snow on the Swedish mountains should explain such a delay in the discharge.)

This apparent discrepancy between the results of MIKULSKY [11] and ours can be explained either stating that our period was not representative or through the following schematic computation:

	Volume transport towards south:	Volume transport towards north:
Through Åland Sea:	47 000 $m^3 s^{-1}$	12 000 $m^3 s^{-1}$
Through the Archipelago Sea:	—	20 000 $m^3 s^{-1}$
Total:	47 000 $m^3 s^{-1}$	32 000 $m^3 s^{-1}$
Difference: towards south 15 000 $m^3 s^{-1}$		

In spite of the various uncertain factors involved, this result seems to indicate that the net volume transport through the Archipelago Sea into the Gulf of Bothnia has been greater than normally expected. This statement does not contradict the expectation expressed by EHLIN and AMBJÖRN [5] that the total material exchange between the said two areas proceeds mainly through the open and deep Åland Sea and not through the shallow Archipelago Sea with its thousands of islands.

8. *Interfacial entrainment*

ELLISON and TURNER [6] found that in a two-layer flow the interfacial entrainment upwards probably was negligible for $R_i > 0.8$, the RICHARDSON number, R_i, being defined by

$$R_i = \frac{\gamma g \bar{D}}{\bar{c}^2} \tag{7}$$

In our case

$$\gamma = \frac{\varrho_2 - \varrho_1}{\varrho_2} \sim \frac{0.00032}{1.00612} \sim 0.00032,$$

$g = 980$ cm s^{-2},
$\bar{D}$ = mean depth of the layer into which entrainment is taking place ~ 4000 cm,
$\bar{c}$ = mean velocity ~ 5 cm s^{-1},
which gives for R_i an approximative value $R_i \sim 50$.

MONIN and YAGLOM [12] observe that the RICHARDSON number in conditions of high stability may apparently assume very large values; thus there is no limiting »critical» value of R_i.

The result, in spite of its approximative character, should give a definite proof that no entrainment through the layer of no motion, in the middle portion of the Åland Sea, was going on during the observation period, as it was indirectly assumed when calculating the errors of the surface topography.

9. *Conclusions*

The actual results are presented in the Abstract in the beginning of this article.

In addition, two further general observations can be made. First, the classical hydrography still can produce useful results, with some good luck, if all the measurements and samplings are performed with great care. Secondly, only the actual current measurements, together with other pertinent data, will give really new understanding into the phenomena in the sea. When preparing such projects the results from traditional studies can be used to a certain extent as guidelines.

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