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ON THE DEEP WATER FLOW INTO THE BALTIC

by

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Abstract

The supply of deep water to the Baltic through the Bornholm Strait has been observed during a four year period. The results suggest that the deep water supply is approximately evenly distributed over a salinity range (8 ‰, 18,5 ‰) with a flow intensity 1.55×10^3 $m^3/s \cdot$ ‰. This result includes an estimated correction for flow south of Bornholm of order 0.15×10^3 $m^3/s \cdot$ ‰. The synoptic observations from the Bornholm Strait have been checked against long time records available in three points on the cross-section. This comparison is made in terms of a function $\bar{\mu}$ *(r, S)* which gives the mean contribution to the flow with salinity larger than *S* per unit area of the cross-section.

1. *Introduction*

Simultaneous observations of salinity and current speed have been performed during a four year period in the strait between Bornholm and Sweden in the southern Baltic. The theoretical background to these observations was developed by WALIN [13]. Results from the first year were reported by PETRÉN and WALIN [4].

In this paper results from the whole program is presented in a slightly modified manner. In particular the data has been organized in order to make comparisons between ship observations and recordings from automatic current meters.

The primary purpose of the observation program has been to obtain estimates of the function $\overline{M}(S)$ defined as the long term mean value of the volume flux into the Baltic having salinity exceeding S. As discussed by WALIN [13] this function is of direct usefullness *e.g.* for the calculation of various biochemical transports within the Baltic. Such calculations have also been perfomed see *e.g.* SHAFFER [9, 10, 11, 12] and RYDBERG [6, 7].

A second purpose of the investigation has been to find out whether at all it is possible to make this type of estimate from direct observations and if so how the observations should best be organized. In fact since the very beginning of this project serious doubts have been raised regarding the possibility to reach a meaningful description of the mean inflow distribution (*i.e.* from a limited number of ''snapshots'' of the flow picture).

A third purpose has been to improve our understanding of deep overflows of the kind occurring in the Bornholm Strait and also in the Stolpe Channel, further into the Baltic. Our observations have also been analysed from this point of view; see *e.g.* RYDGREN [5, 8] and LUNDBERG [3].

In the following we will not discuss the dynamical properties of the system but concentrate on our result rearding $\overline{M}(S)$ and its reliability.

2. *Observations*

The topography of the strait is shown on the map in figure 1 where the stations for shipobservation are shown as well. Figure 2 shows a cross-section of the strait through our observation points. The shaded area illustrates the location of the overflow. The salinity in this region is typically between 10—20 ‰ with an inward velocity of order 20—50 cm/sec. The flow and salinity pattern changes dramatically in time but still the overflow is a feature which dominates most of the time in the bottom layer.

Our observations are of two kinds.

(i) Observations from ship of velocity, salinity and temperature at the stations shown in fig. 2.

(ii) Observations of the same parameters at three points with recording current meters.

The total amount of measurements available is given in Tables 1 and 2.

The ship observations were performed in the following way. Days of observation were chosen essentially at random with the exception that on a few occasions observations have been taken on concequtive days. The purpose has been to obtain as far as possible an unbiased material. To achieve this goal it is of course necessary to carry through the measurements independently of weather conditions. In the beginning of the program this was not always possible since we were then operating from a small boat. Later experience

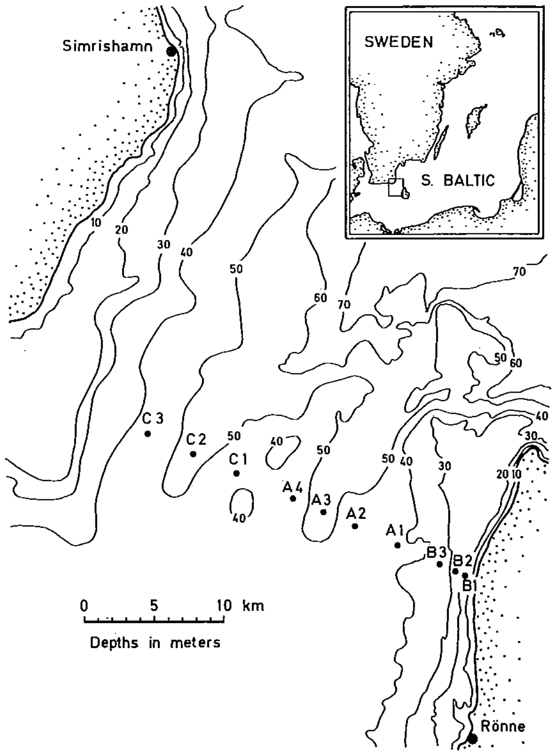

Fig. 1. Map over the region between Bornholm and Sweden. The stations for ship observations are named B1—B3, A1—A4 and C1—C4. Most important are stations A1—A3.

Table 1. Dates for ship-observations of the overflow in the Bornholm Strait.

1973	1974	1975	1976	1977
26 Sep	29 Mar	28 Apr	30 Jan	15 Feb
27 Sep	5 Jun	25 Jul	1 Feb	29 Mar
29 Sep	2 Jul	5 Nov	3 Feb	8 Jun
23 Oct	12 Aug	6 Nov	8 Apr	
26 Oct	17 Aug		15 Jun	
7 Nov	12 Sep		11 Aug	
8 Nov	21 Oct		20 Aug	
28 Nov	22 Oct			
	23 Oct			
	27 Nov			

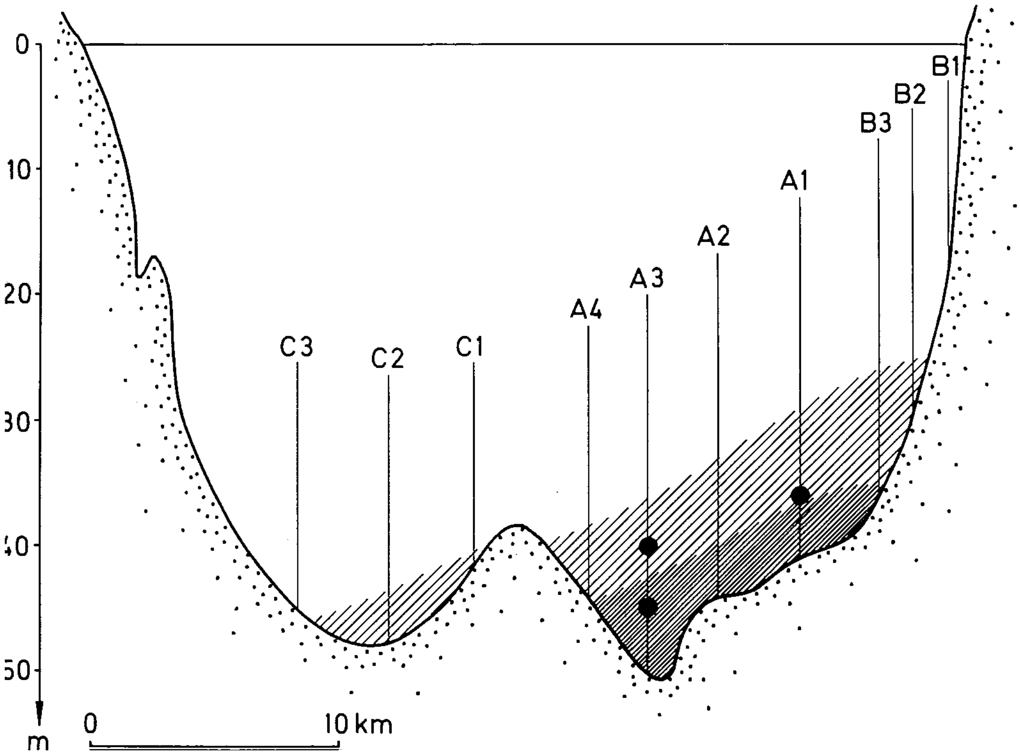

Fig. 2. Cross-section of the Bornholm Strait through the stations when observations were taken. The big dots show the position of the recording current meters. The overflow is typically occurring within the shaded area.

Table 2. Time periods when recording instruments measuring current salinity and temperature have been operating.

	On station A3 5 m above bottom	On station A3 10 m above bottom	On station A1 5 m above bottom
I	29 Jul 73 — 27 Sep 73		
II	27 Nov 74 — 24 Apr 75		27 Nov 74 — 29 Apr 75
III	26 Apr 75 — 12 Jun 75		
IV	9 Jul 75 — 5 Nov 75		
V	5 Nov 75 — 31 Jan 76	5 Nov 75 — 31 Jan 76	
VI	2 Feb 76 — 7 Apr 76	2 Feb 76 — 7 Apr 76	2 Feb 76 — 7 Apr 76
VII	7 Apr 76 — 13 Jun 76	7 Apr 76 — 14 Jun 76	7 Apr 76 — 17 Jun 76
VIII	17 Jun 76 — 10 Aug 76	17 Jun 76 — 10 Jun 76	17 Jun 76 — 10 Aug 76
IX			10 Aug 76 — 3 Nov 76
X			3 Nov 76 — 30 Dec 76
XI	26 Jan 77 — 29 Mar 77		25 Jan 77 — 30 Mar 77

have shown however that there is no systematic tendency for the overflow to maximize during storm peaks and we do not think that our inability to measure because of bad weather on a few days have influenced the result very much.

On a day of observation the cross-section was passed over in a few hours, *i.e.* essentially synoptically. On each station a salinity temperature profile was first taken. If water saltier than 8,5 ‰ was found current observations were made with one meter depth interval in this layer. We used pendulum current meters of the type constructed by HAAMER [2]. According to our experience this is the only technique available which allows current observations with comparable speed and spatial resolution. (This technique for current observation have recently (summer 1980) been used under oceanic conditions on the YMER expedition in the strait between Spetsbergen and Greenland, apparently with great success).

In total we have now collected 32 days of observations.

The automatically recording instruments used was of the type constructed by Aanderaa. The instruments were left out for periods of between 1 and 5 months length. The observation points are shown in figure 2. We had no problem with fouling of the instruments but we had extensive trouble with instruments being caught by trawlers. The automatic instruments were recording current, salinity and temperature with intervals of at most 40 minutes *i.e.* dense enough to resolve essentially all variations in time.

3. *Data handling*

From our ship observations we have obtained one snapshot of the overflow from each of the 32 days of observation. These observations give us fields of salinity and current with relatively good resolution in space.

Our intention is to estimate the function $\overline{M}(S)$ from these observations. Obviously we have reasons to worry about what has been going on in between our days of observation. Generally speaking; is it at all possible to catch the mean behaviour of a phenomenon having so many modes of variation from a number of samples in time. This raises the question of how to use our long time records (from a few points in space) to improve upon or to judge the reliability of the estimate based upon our ship observations.

The crucial tool in this contex is the function $\bar{\mu}(r, S)$ which gives the contribution to $\overline{M}(S)$ per unit area of the cross-section.

In the rest of this section we will discuss the procedure in some detail. In analogy with our definition for $\overline{M}(S)$ we define $M(S, t)$ as the volume flux in the salinity interval (S, ∞) at time t. Consequently we have

$$\overline{M}(S) = \frac{1}{T} \int_T M(S, t)\, dt \tag{3.1}$$

where the integration should be performed over a sufficiently long period of time. (How long or which time period depends on for what purpose we intend to use $\overline{M}(S)$).

We now want a function $\bar{\mu}(r, S)$ such that

$$\overline{M}(S) = \int_A \bar{\mu}(r, S)\, dA \tag{3.2}$$

where $\int_A dA$ represents integration over the whole cross-section of the strait and r denotes position on the cross-section.

From the definition of $M(S, t)$ we have

$$M(S, t) = \int_{A'(S,\, t)} u_o(r, t)\, dA \tag{3.3}$$

where

$A'(S, t)$: Part of A in which $S_o(r, t) > S$
$u_o(r, t)$: Velocity component perpendicular to cross-section at (r, t).
$S_o(r, t)$: Salinity at (r, t).

In other words: Given an arbitrarily chosen value of the independent variable S; find out where the actual salinity $S_o(r, t)$ (observed or otherwise known) exceeds S and perform the integration over that part of A only. The problem with this formula is obviously that the range of integration varies not only with S but even more important with time. Taking *e.g.* a mean value in time of (3.3) we can clearly not move the mean value operation inside the integration sign in (3.3) *i.e.*

$$\overline{M(S, t)} \neq \int_{\bar{A}'} \bar{u}_o(r, t)\, dA$$

This has the fairly obvious implication that quantities like $\bar{u}_o$, $\bar{S}_o$ or $\bar{A}'$, although describing the mean hydrographic situation, is not useful for the computation of $\overline{M}(S)$.

However the integral in (3.3) may be rewritten as an integral over the whole area A if we introduce a factor under the integral sign which is zero whenever we are outside A' and one when we are inside. Such a factor is given by the γ-function

$$\gamma(S_o(r, t) - S) = \begin{matrix} 1 \text{ when } S_o > S \\ 0 \text{ when } S_o < S \end{matrix}$$

We thus have

$$M(S, t) = \int_A u_o(r, t)\gamma(S_o(r, t) - S)\, dA \tag{3.5}$$

or taking o mean value in time

$$\overline{M}(S) = \int_A \overline{u_o(r, t)\gamma(S_o(r, t) - S)}\, dA \tag{3.6a}$$

we have thus found that the function $\bar{\mu}(r, S)$ is given by

$$\bar{\mu}(r, S) = \overline{\mu(r, S, t)} = \overline{u_o(r, t)\gamma(S_o(r, t) - S)} \tag{3.6b}$$

In the computation of $\overline{M}(S)$ we first compute $\bar{\mu}(r, S)$ from our 32 samples of the fields $u_o(r, t)$, $S_o(r, t)$. The time mean value in (3.6b) is then replaced by the arithmetic mean value of the individual samples, *i.e.*

$$\mu(r, S) \simeq \frac{1}{N} \sum_{\nu}^{N} u_o^{\nu}\gamma(S_o^{\nu} - S) \tag{3.7}$$

where N in our case equals 32 and (u_o^{ν}, S_o^{ν}) is an individual sampling of the fields $u_o(r, t)$, $S_o(r, t)$.

We then obtain a space field for $\bar{\mu}(r, S)$ for each salinity level; in our case for every 0,5 ‰. Alternatively we may say that for each point r we have a distribution with respect to S which represents the local contribution to $\overline{M}(S)$ per unit area. Note that while $\mu(r, S, t)$ is always a step function with respect to S, $\bar{\mu}(r, s)$ is a smooth function of S unless $S_o(r, t)$ is constant in time (see figure 3).

From our observation with recording current meters we have long time records of $u_o(r, t)$ and $S_o(r, t)$ at three points in the cross-section. At these points we may thus compute $\bar{\mu}(r, S)$. These estimates of $\bar{\mu}(r, S)$ can be compared with the estimates obtained from ship observations. We think this comparison provides a most valuable check on the reliability of our original estimates from ship observations for the following reasons.

(i) The observations from ship and recording instruments respectively represent completely independent information obtained with widely different methods.

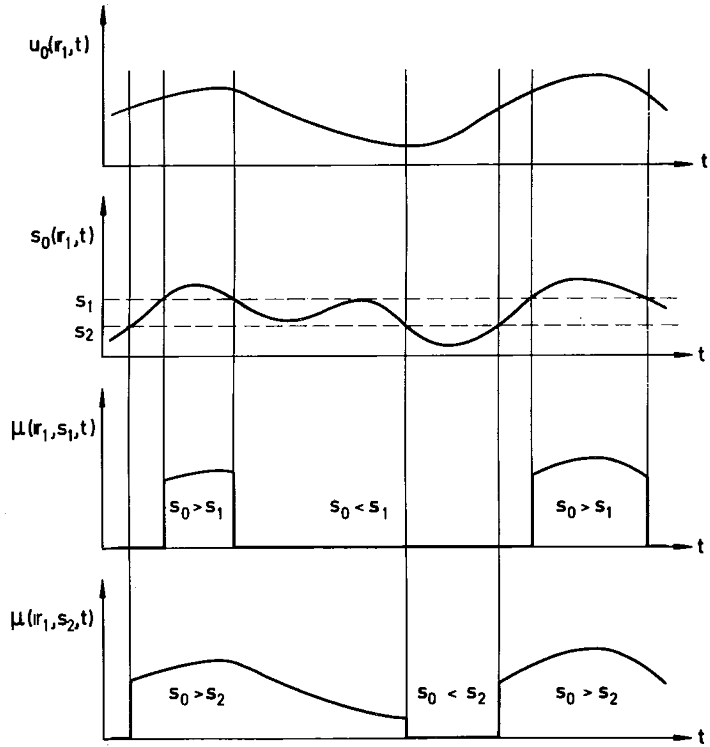

Fig. 3a. Illustration of the definition of $\mu(r, S, t) = u_o(r, t) \cdot (S_0(r, t) - S)$. From *two* functions of *r* and *t* we form one function of *r*, *t* and *S*. The formation of $\mu(r, S, t)$ is illustrated for two arbitrary choises of *S* (S_1 and S_2).

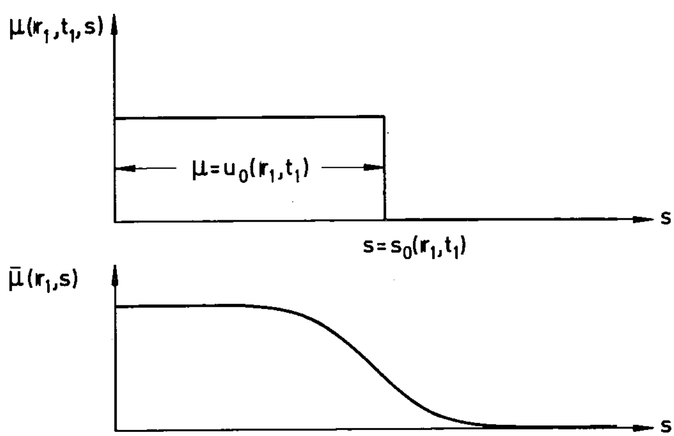

Fig. 3b. Illustration of the behaviour of $\mu(r, S, t)$ and $\bar{\mu}(r, S)$. The instantaneous shape of $\mu(r, S, t)$ is always a stepfunction plotted against *S* for fixed *r* and *t*. Taking a time average will generally smooth out the step to a gentle sloop unless $S_o(r, t)$ is independent of time.

(ii) The information from the recording instruments is based on a very large number of observations making this information reliable where it is available. In particular exceptional ''inflow events'' which might have occurred in between our ship observations should have been picked up by the recording instruments.

(iii) The function $\bar{\mu}(r, S)$ can be expected to be a well-behaved function of the space coordinates. (The typically discontinous and unpredictable behavior of $u_o(r, t)$, $S_o(r, t)$ as well as $\mu(r, t, S)$ is smoothed out in the process of time-averaging). Thus if our estimate of $\bar{\mu}(r, S)$ can be shown to be reliable in a few representative points we have good reasons to believe that the whole field is reliable.

The final result $\bar{M}(S)$ is then obtained simply by integrating $\bar{\mu}(r, S)$ over the field, *i.e.* in practice from the formula

$$\bar{M}(S) = \sum_m \bar{\mu}(r_m, S)a_m$$

where a_m is an area element ascribed to an observation point r_m and the summation is over all such points, *i.e.* over the whole area A. This procedure will give us $\bar{M}(S)$ for $S > S^o$ where S^o is the salinity of the essentially homogeneous surface layer. The range $S < S^0$ is not the primary object of the present investigation. When constructing $\bar{M}(S)$ in this range we thus simply assume that the whole outflow occurs i a narrow salinity range arounds $S = S^o \simeq 8$ ‰ and that the fresh water supply M_o to the Baltic is known. This gives $\bar{M}(S)$ the shape shown in figure 4 of the next section.

4. *Results*

Our main result $\bar{M}(S)$ is shown in figure 4. As discussed in section 3 this distribution has been obtained from 32 essentially synoptic sections across the strait with observations of the vertical distribution of salinity and velocity on at most 10 stations. Note that the curve is based on our observations for $S > S^o$ only as described in section 3. Furthermore the net outflow from the Baltic $M_o = \bar{M}(S = 0)$ has been taken as 14000 m³/s following Falkemark 1974.

As can be seen from figure 4 the curve $\bar{M}(S)$ between 8 and 18,5 ‰ is very close to a straight line. Our result may thus be given the following simple interpretation. The deep water inflow through the Bornholm strait is distributed evenly over the salinity range 8—18,5 ‰ with an intensity

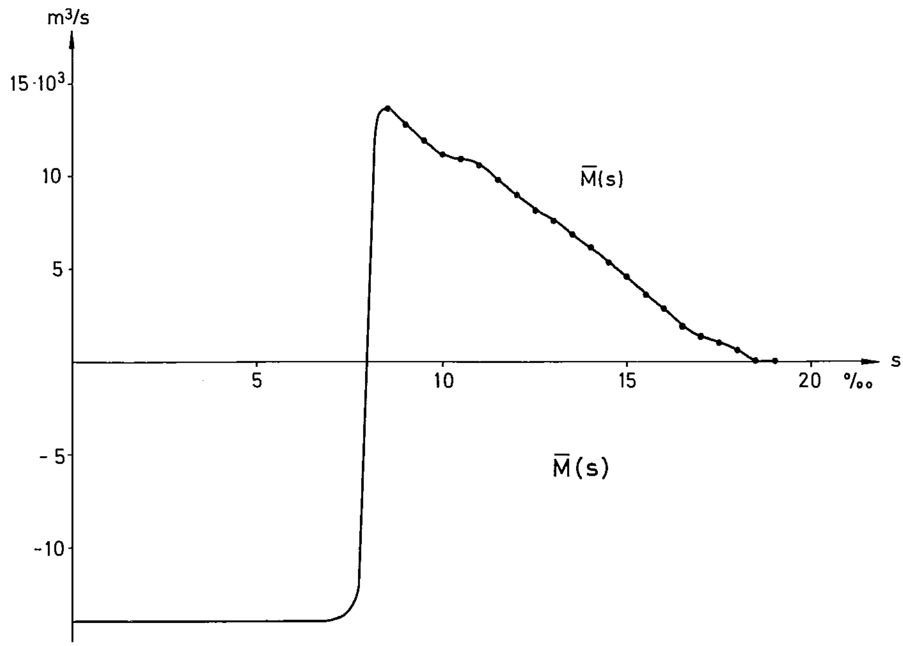

Fig. 4. The main result from our ship-observations the function $\overline{M}(S)$. Note that the flow in a particular salinity range is given by the slope of the curve. The steep part around 8 ‰ represents the outflowing surface water. This part is not based on observations. Note also that for $S \quad S^o \simeq$ 8 ‰ the curve is close to a straight line. The result may thus be given the following simple description. The inflow is evenly distributed over the salinity range (8 ‰, 18,5 ‰) with an intensity $1.4 \cdot 10^3\ m^3/s \cdot$ ‰.

$$\left(-\frac{\delta \overline{M}}{\delta S}\right) \text{ close to } 1.35 \cdot 10^3\ m^3/s \cdot \text{‰}.$$

Our main issue now is to judge how reliable the distribution shown in figure 3 can be.

One way to get an indication of the reliability of our result is to compare with the distribution function obtained from smaller number of observations. In figure 5 we have plotted the distribution $\overline{M}^{17}(S)$ which is obtained from our first 17 observations. Comparing this with our final result, which is also plotted in figure 5, gives an idea of the level of accuracy. We thus find for the local deviation

$$\left| \overline{M} - \overline{M}^{17} \right| \simeq 0.2 \left| \overline{M} \right|$$

while the "relative integral error"

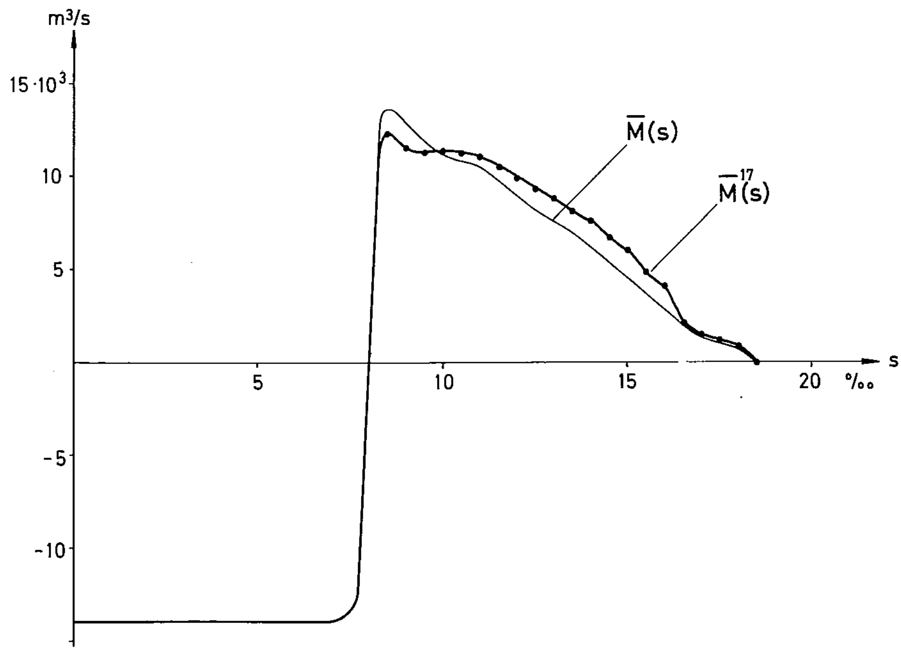

Fig. 5. The flow function $\overline{M}^{17}(S)$ obtained in the same way as $\overline{M}(S)$ based on the first 17 observations only. For comparison the function $\overline{M}(S)$ from the whole set of observations is also shown.

$$\left| \int_{S_0}^{\infty} \overline{M}\, dS - \int_{S_0}^{\infty} \overline{M}^{17}\, dS \right| < 0.1 \left| \int_{S_0}^{\infty} \overline{M}\, dS \right| .$$

We note that the deviation between $\overline{M}(S)$ and $\overline{M}^{17}(S)$ can be traced to two extreme days of observation showing respectively an unusual inflow with $S \simeq 16$ ‰ and an outflow in the range $9‰ < S < 11$ ‰. These two extreme observations occurred in the first 17 observations. The influence of the extreme outflow around $S \sim 10$ ‰ remains, though much weaker, in-our final mean function $\overline{M}(S)$.

Although we undoubtedly get the impression from figure 5 that our results are converging towards a reliable mean value one may still argue that very strong inflow events with short duration might have fallen in between our observations. It is thus of interest to make use of our long time records at a few spatial points to verify the results obtained from our 32 synoptic sections. For this purpose we make use of the function $\mu(r, S)$ defined in section 3, which represents the contribution to $\overline{M}(S)$ per unit area of the cross-section.

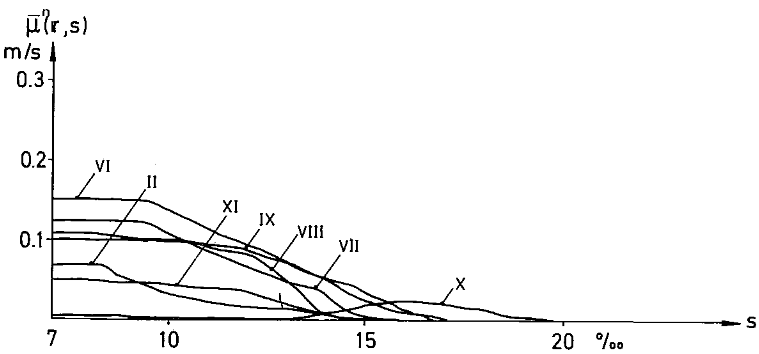

Fig. 6a. Information from station A1 5 meters above bottom. Each curve $\bar{\mu}^n(r, S)$ represents the average of $\mu(r, S, t)$ over a time period during which a particular instrument has been operating continuously. The time period corresponding to each curve I, II, III etc can be found in table 2.

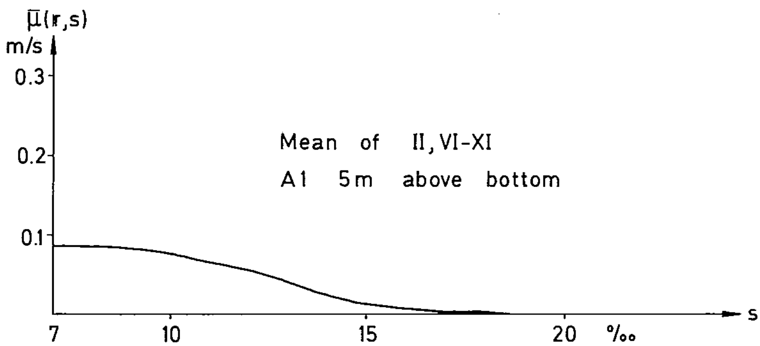

Fig. 6b. Estimate of $\bar{\mu}(r, S)$ at A1 5 meter above bottom obtained as the average of $\mu(r, S, t)$ over the whole time period covered by recording instruments, *i.e.* the mean of all $\bar{\mu}^n(r, S)$ in figure 6a.

From the observations made by the recording instruments we have calculated mean values $\bar{\mu}^n(r, S)$ for each period that an individual instrument has been operated. We thus obtain a number of curves $\bar{\mu}^n_\nu$ for each of the three measuring points. We have also calculated the mean value for these points from the whole material available. This information is shown in figures 6 a—f. We note the considerable spreading between individual ''instrument-periods'' indicating that the inflow, as expected, has a good deal of variability on time-scales of order 2—3 months.

In figures (7a—c) we have plotted $\bar{\mu}(r, S)$ as obtained from our 32 sections for the points where the information from recording instruments is available. For comparison we have also plotted the results given in figures (6b, d, f).

We thus have two empirical representations of $\bar{\mu}(r, S)$ in three points emanating from completely independent types of observation.

Noting that we expect $\bar{\mu}(r, S)$ as obtained from the synoptic sections to contain a much larger stochastic error than the integral $\int_A \bar{\mu}(r, S)\, dA$ we feel that the agreement as given by figure (7a—c) is encouraging.

We note in particular that our fear that $\overline{M}(S)$ (and thus $\bar{\mu}$) might be severely influenced by ''inflow events'' falling in between our synoptic sections does not seem to be justified; Such inflows should have been picked up by the recording instruments and thus destroyed the relative agreement shown by figures (7a—c).

Still we have to accept however the possibility that events occurring less frequent than say every second year might influence the long time averages of the inflow.

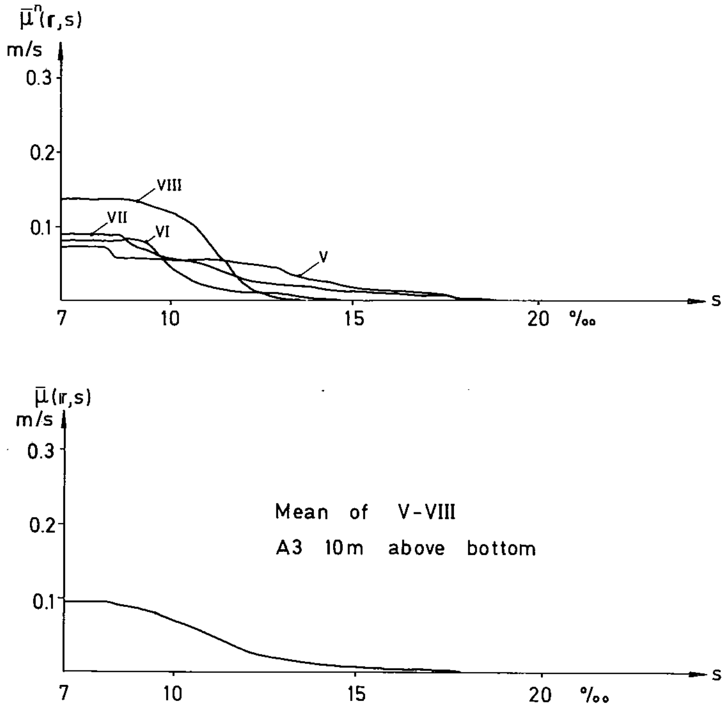

Fig. 6c, d. Same as figure 6a, b for station A3 10 meters above bottom.

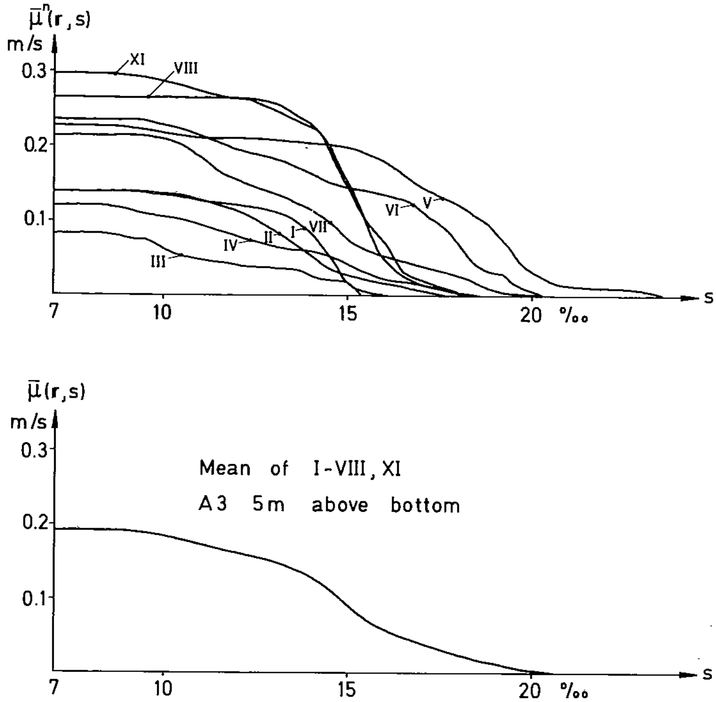

Fig 6e, f. Same as figure 6a, b for station A3 5 meters above bottom.

5. *Discussion*

Let us now discuss our result in view of the overall salt balance of the Baltic.

The requirement of no net salt flux may be written

$$\int_o^\infty \bar{m}(S) \cdot SdS + R = 0$$

where $\bar{m}(S) = - d/dS\, \bar{M}(S)$. $(m(S)\, dS)$ thus gives the volume flux in the salinity interval $(S,\, S + dS)$.

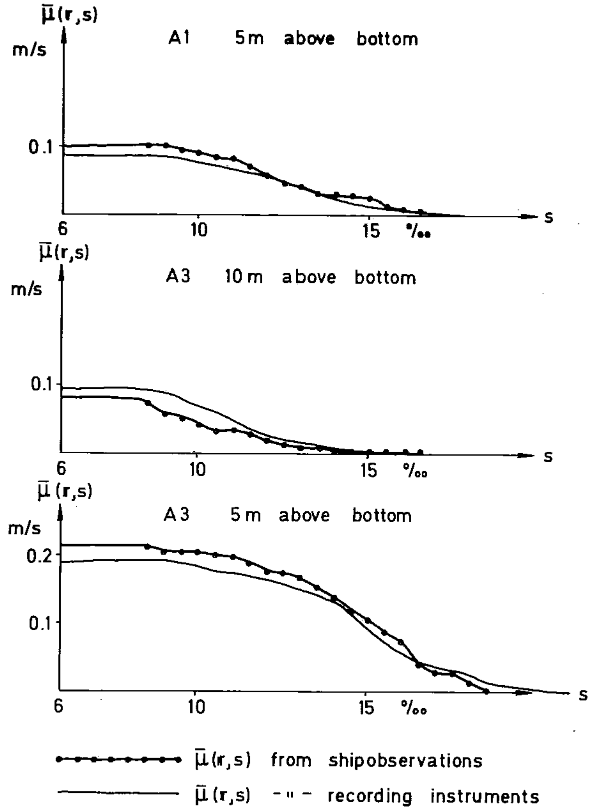

Fig. 7. Comparison of estimates of $\bar{\mu}(r, S)$ at three fixed points, station A1 5 meters above bottom (fig 7a), station A3 10 meters above bottom (fig 7b) and station A3 5 meters above bottom (fig 7c). The curves without dots are obtained from recording current meters (same as figures 6b, d, f) while the curves with dots represent the ship observations at the same points.

Integrating by parts we obtain

$$\int_{o}^{\infty} \overline{M}(S)\, dS + R = o \qquad (5.1)$$

where R represents turbulent fluxes in the surface layer. R thus depends on correlated salinity and velocity variations in the surface layer. This flux could be included in the description given by $\overline{M}(S)$. It would then appear as an extra peak on $\overline{M}(S)$ close to 8 ‰. Since we have no observation available to estimate the magnitude and shape of this peak, we have chosen to represent this flux with an extra term R. In consequence the surface layer is assumed to be homogeneous when $\overline{M}(S)$ is constructed.

Let us first assume that R may be ignored. Equation (5.1) then tells us

$$\int_{o}^{\infty} \overline{M}(S)\, dS = o$$

From figure 4 we find

$$\int_{o}^{S^o} \overline{M}(S)\, dS \simeq -112 \times 10^3 \frac{m^3\ {}^0/{}_{00}}{s} \qquad (5.2a)$$

$$\int_{S^o}^{\infty} \overline{M}(S)\, dS \simeq 75 \times 10^3 \frac{m^3\ {}^0/{}_{00}}{s} \qquad (5.2b)$$

i.e.

$$\int_{o}^{\infty} \overline{M}(S)\, dS \simeq -37 \times 10^3 \frac{m^3\ {}^0/{}_{00}}{s} \qquad (5.2c)$$

which corresponds to a net saltflux out of the Baltic of magnitude 37 ton/s.

It should be noted that the integral

$$\int_{S^o}^{\infty} \overline{M}(S)\, dS = \int_{S^o}^{\infty} \overline{m}(S)\, [S - S^o]\, dS$$

represents an ''excess salt flux'', *i.e.* the extra salt transport caused by the incoming water being saltier than S^o. Also

$$\int_{o}^{S^o} \overline{M}(S)\, dS$$

does represent only part of the total outgoing salt flux, *i.e.* the part $M_o \cdot S^o$, where M_o is the net run off from the Baltic. (The total salt fluxes into and out of the Baltic is obtained by adding to the fluxes given by (5.2a, b) the amount $\overline{M}_{max} \cdot S^0$ where $\overline{M}_{max}$ is the maximum value of $\overline{M}(S)$ for S slightly larger than S^o).

If the descrepancy

$$-37 \times 10^3 \frac{m^3\ {}^0/{}_{00}}{s}$$

is compared with the total flux in either direction it becomes less impressive.

Despite the above comment we find the deviation as given by (5.2c) remarkably large particularly in view of the promising results of section 4 regarding the accuracy of our estimate of $\bar{M}(S)$.

We may think of a number of possible explanations e.g.

(i) The turbulent surface flux represented by R.

(ii) Salt supply over the shallow areas south of Bornholm.

(iii) The salt content in the Baltic is unstationary.

(iv) The fresh water supply M_o is smaller than 14000 m³/s.

(v) Our estimate of $\bar{M}(S)$ trough the Bornholm strait in the range $S > S^o$ is too low.

In the rest of this section we will comment on these possibilities.

(i) The unknown flux R depends on variations in the surface layer salinity S^o correlated with variations of the surface outflow in time and space. For a very rough estimate let us assume that superimposed on the mean outflow in the surface layer we have typically an outlow of magnitude M' with salinity $S^o - S'$ and an inflow of the same magnitude but with salinity $S^o + S'$. This would create a salt flux

$$R \simeq 2\,M'S'$$

From observations we would guess

$$S' \approx 0.1\ ^o/oo$$

Assuming

$$R \approx 40 \times 10^3\ \frac{\mathrm{m}^3\ ^o/oo}{\mathrm{s}}$$

would then imply

$$M' \approx 200 \times 10^3\ \mathrm{m}^3/\mathrm{s}$$

This is about 7 times the total mean outflow $\bar{M}_{max} + M_o$ in the surface layer and more than 14 times the netflow out of the Baltic. This appears to be an overestimate but we can certainly not rule out that the term R accounts for at least part of the missing salt flux. Note also that whatever the magnitude of R it will always change our salt balance in the correct direction. (Since R is ''diffusive'' it will always represent a salt flux towards lower salinities *i.e.* into the Baltic).

(ii) Regarding the possibility of substantial flow south of Bornholm we presently have no way of quantitative estimate. The sill depth probably allows some deep water flow to pass under strong inflowconditions. Again we can only state that any contribution would give saltflux into the Baltic *i.e.* help to explain the missing salt flux.

(iii) Let us next assume that the saltflux predicted by our estimate $\overline{M}(S)$ is correct at least for the time period under consideration. We may then calculate the rate of change of the salinity in the Baltic during the time period in question caused by the excess outflow of salt. Using a value of 22×10^{12} m^3 for the volume of the Baltic we thus find that an excess outflow of salt amounting to 37 ton/s would lower the mean salinity by 1 ⁰/₀₀ in about 20 years.

We conclude that such an excess outflow could persist for say 5 years without being recognized as a general change in the state of the system. Such long term variations of the salt content can not be ruled out.

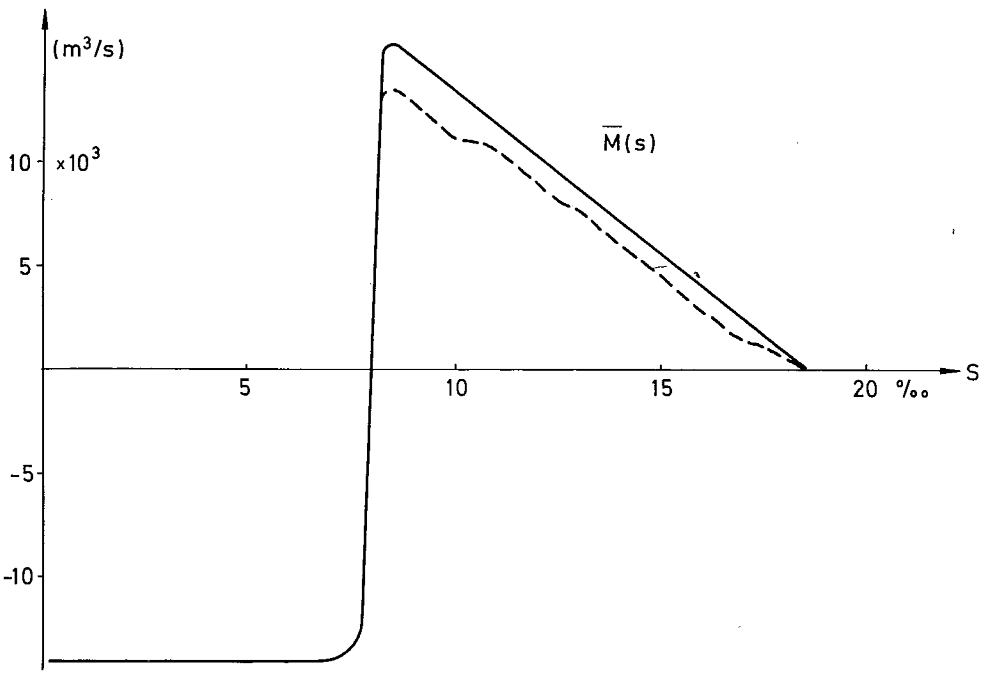

Fig. 8. A "best guess" of the function $\overline{M}(S)$ describing the total supply of deep water to the Baltic inside Bornholm (including flow south of Bornholm). The suggested modified curve (full-drawn) implies a mean flow which is evenly distributed over the salinity range (8 ⁰/₀₀, 18,5 ⁰/₀₀) with intensity 1.55×10^3 m^3/s · ⁰/₀₀. For comparison the result from figure 4 is shown (dashed curve).

(iv) Changing the fresh water supply to a lower value means that the calculated outflow of salt as given by (5.2a) decreases. In order to make $\int_0^\infty \overline{M}(S)\, dS = 0$ we have to chance M_0 from 14000 to 9000 m³/s. Although M_0depends on fairly uncertain calculations e.g. evaporation and rainfall over the Baltic we doupt that the error in M_0 is that large.

Against the background presented above a reasonable guess is that the "missing salt supply" according to (5.2c) has three equally important causes

(i) Diffusive saltflux in the surface layer as represented by the term R.

(ii) Underestimate of $\overline{M}(S)$ mainly due to negligence of flow south of Bornholm.

(iii) Other causes which may effect the salt balance in either direction, *e.g.* error in the net run off etc.

We thus suggest that our estimate of $\overline{M}(S)$ according to figure 4 should be increased somewhat for $S > S^o$ to account for flow south of Bornholm, *i.e.* when we want an estimate of the total supply of deep water to the Baltic east of Bornholm.

In figure 8 we have performed such a "reasonable" modification of $M(S)$ which decreases the "missing salt supply" as given by $|\int_0^\infty \overline{M}(S)\, dS|$ with about 30 % as compared with calculations based on figure 4. The description of the deep water flow as given by figure 8 implies a constant flow intensity 1.55×10^3 m³/s · ⁰/₀₀ in the salinity range (8 ⁰/₀₀, 18,5 ⁰/₀₀). This modified version of $\overline{M}(S)$ represents our "best guess" on the basis of the now available observations.

REFERRENCES

1. FALKENMARK, M. and Z. MIKULSKI, 1974: *Hydrology of the Baltic Sea,* IHD-project document, no 1, Sweden.
2. HAAMER, J., 1974: Current measurements with gelatin pendulums. *Vatten* 1/74.
3. LUNDBERG, P., 1977: *On the mechanics of the deep-water flow in the Bornholm channel.*
4. PETRÉN, O. and G. WALIN, 1976: Some observations of the deep flow in the Bornholm Strait during the period June 1973-December 1974. *Tellus,* **28.**
5. RYDBERG, L. 1976: Observations of the deep water flow through the Stolpe Channel during Aug 1976. *Dept. of Oceanogr., Gothenburg, Report 15.*
6. —»—, 1978: Deep water flow and oxygen consumption within the Baltic. *Dept. of Oceanogr., Gothenburg, Report 27.*
7. —»—, 1980: Omsättning och syrebalans i Östersjön. *Natural Research Council yearbook 1980.*
8. —»—, 1980: Rotating hydraulics in deep-water channel flow. *Tellus* **32.**
9. SHAFFER, G., 1975: Baltic coastal dynamics project. *Contr. from Askö lab., Univ. of Stockholm, No 7.*
10. —»—, 1977: Calculations of cross-isohaline salt exchange. *Dept. of Oceanogr. Gothenburg, Report 24.*
11. —»—, 1979: On the phosphorous and oxygen dynamics of the Baltic Sea. *Contr. from Askö lab. Univ of Stockholm No 26.*
12. —»—, 1979: Conservation calculations in Natural coordinates (with an example from the Baltic). *J. Phys. Oceanogr.* **9.**
13. WALIN, G. 1977: A theoretical framework for the description of estuaries. *Tellus* **29.**