A short note on the exchange of water and nutrients between the Skagerrak and the Kattegat

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Simultaneous measurements of velocities, salinity, oxygen, and nutrients were undertaken in the northern Kattegat, in a cross-section between the island of Læsø and Sweden. The main aim was to determine the amount of deep water flowing southwards through the Kattegat, as a part of the exchange of water between the Baltic and the ocean. Fluxes of water, nutrients, and oxygen are presented as functions of salinity. A division is made between the biologically passive winter period (November to February), when inorganic nutrients are nearly conservative, and a "summer" period from March to October. The mean flow of deep water (S > 30 PSU) was, during winter, 64,000 m³/s and, during summer, 28,000 m³/s, with a yearly mean value of 40,000 m³/s. The values are approximately 30% higher than the indirectly calculated fluxes, based on entrainment theory. The yearly mean outflow of surface water (S < 30 PSU) was approximately 20,000 m³/s, indicating a mean outflow of more than 30,000 m³/s in the shallow section west of Læsø. Salt balance calculations and old lightvessel velocity measurements confirm this conclusion.

Introduction

The Kattegat forms the outer part of the Baltic estuary (Fig. 1). It is shallow, with a mean depth of 20 m, and is characterized by a very strong vertical salinity stratification, caused by an outflow of low saline Baltic water in the surface layer and an inflow of high saline water from the Skagerrak at deeper levels (Fig. 2). The surface water salinity varies between 12 and 25 PSU, the deep water salinity between 32 and 34 PSU. The halocline depth varies both in time and space, with an average of about 15 m.

Although the local nutrient supply to the Kattegat is large, the supply of nutrients and oxygen from surrounding waters is also important for the ecology of the area. In fact, the supply of deep water from the Skagerrak, driven by upward entrainment due to local winds (Stigebrandt, 1983) is the largest single nutrient source (Ryding et al., 1990).

In 1975–1977 the Fishery Board of Sweden carried out an extensive field programme based on current and nutrient measurements in the northern Kattegat (the GF-section, see Fig. 1). The results indicated large current fluctuations in time and space. The calculated net flux exceeded the supply of freshwater to the Baltic by a factor of three (Szaron, 1979; Svansson, 1984). The reason for this discrepancy was not quite clear, but the section coincided with a front between the Kattegat surface water and the high salinity water in the Jutland current flowing eastward north of Skagen.

In this paper, the results from an intensive measuring programme which was carried out in a cross-section near Læsø (Fig. 3) in order to determine the fluxes of water, nutrients, and oxygen into the Kattegat are presented. The programme comprised simultaneous measurements on a total of 38 occasions between 1984 and 1988. To avoid the frontal area in the northern Kattegat, the cross-section in this project was chosen further south. As our main interest concerned the deep water, this section seemed more suitable, although we lost a part of the northernmost Kattegat.

Field work

Out of the 38 expeditions, 27 were considered as "full cross-sections", including all 10 stations and without any missing parameters. The results from these 27 sections comprise the database for this report. CTD profiling with a Neil Brown, MK III, was made at all stations. Current measurements with pendulum current meters were carried out at stations 2, 4, 6, 8, and 10. Water
Figure 1. Map of the Kattegat area, with the Læsø and GF sections indicated.
sampling for nutrient chemistry, salinity, and oxygen determination was carried out at every second station (2, 4, 6, 8, and 10) using a rosette water sampler attached to the CTD. The sampling depths were determined in correspondence with the CTD profile, so that at least one sample was taken in each water mass. Between three and eight samples were taken at each station. Nutrient chemistry included determination of $NO_3$, $NO_2$, $NH_4$, $(NO_3 + NO_2 + NH_4 = DIN)$, TOTN, $PO_4=(DIP)$, and TOTP.

**Data treatment**

The cross-section was divided into a grid net according to Figure 4. Each grid box was assigned a mean salinity and a mean temperature by averaging all salinity and temperature data from the CTD measurements (>10 values/m) within that box.

The results from the pendulum current meters were treated as follows: The velocity recordings from the individual pendulums were divided into cross- and lengthwise components. Each box where there was a current measurement was assigned that specific value. For the boxes in between, the velocity values were interpolated using the salinity profile, assuming that the gradients in velocity were located at the same depths as the gradients in salinity.

All chemical parameters were interpolated in the same way as the velocity data, such that each box was assigned a specific concentration. This procedure resulted in one data matrix for each parameter (velocity, salinity, temperature, oxygen, DIP, TOTP, DIN, TOTN) and each transect. The mean velocity $V_{ij}$ and mean salinity $S_{ij}$ in each grid box were then calculated for the above-mentioned matrixes. Averages including standard deviations are shown in Figures 5a, b and 6a, b respectively.

The volume fluxes, $M(S)$, perpendicular to the cross-section were calculated as functions of salinity (see Walin, 1977). $M(S)$ is the volume flux for salinities less than $S$. $M$ was determined in the following way: the velocity, $V_{ij}$ in each box was multiplied by the corresponding area, $a_{ij}$, and sorted after salinity in 0.5 PSU intervals. Thus, we got a function.

$$m(S) = \sum_{ij} V_{ij} * a_{ij}(S)$$

where $m$ is the volume flux in the salinity interval between $S$ and $S+\Delta S$ and where $\Delta S=0.5$ PSU. $M$ was then obtained by integrating $m$;

$$M(S) = \int_0^S m(S') \, ds'$$

Figure 3. Cross-section from Denmark to Sweden. Locations of the stations in the Læsø section are shown.
Figure 4. The Læsø section, including the grid-net used in the calculations.

Figure 5. (a) The mean velocity (cm/s) (PSU) (mean for all transects). (b) The standard deviation of velocity.
These functions were calculated for each transect (see Rydberg and Andersson, 1989) and averaged over winter (Nov–Feb) and summer (Mar–Oct) periods. The average M(S) for winter and summer is shown in Figure 7a, b. The volume transport M(S), average for the whole year is given in Figure 7c.

To calculate the integrated fluxes of salt and nutrients through the section, for each crossing, we used the following expressions:

$$M_s(S) = \int_0^S v_{ij} a_{ij} S_{ij} \, ds'$$

for salinity transport, and

$$M_C(S) = \int_0^S v_{ij} a_{ij} C_{ij} \, ds'$$

for transport of nutrients.

Results

Salinities. Fluxes of water and salt

The approximate net fluxes of water are shown in Figure 8; the mean outflow in the surface water is in the order of 18 000 m$^3$/s (S < 30 PSU), while the inflow of deep water is in the order of 40 000 m$^3$/s (S > 30). Thus, by assuming that the net outflow of water from the Baltic is 15 000 m$^3$/s (equal to the mean fresh water supply; see Svansson, 1975), our measurements indicate that there must be an outflow on the western side of Læsø which is well above 30 000 m$^3$/s.

A very strong seasonal variability was found in the volume fluxes across the Læsø section, mainly due to higher windstress and subsequent entrainment transport during the winter period.

Fluxes of nutrient and oxygen

The period from November to February coincides with
the biologically passive season, where the inorganic nutrient components are almost conservative. From March to October, on the other hand, we can expect low concentrations of inorganic nutrients within the surface waters.

The nutrient (DIP, TOTP, DIN, TOTN) fluxes through the cross-section are shown in Figures 9a–d (winter) and 10a–d (summer). The flux of DIN into the Kattegat within the deep water during winter is 24 000 tons N/month (S > 30 PSU), but during summer it is only 6000 tons N/month (S > 30 PSU), owing to a combination of less inflow of deep water and lower concentrations. In the surface water, the outflow during winter is c. 6000 tons N/month (S < 30 PSU), while during summer the surface water outflow is negligible. The corresponding fluxes of DIP in the deep water during winter are 4000 tons P/month and during summer 1100 tons P/month. The surface water outflow during winter is 800 tons P/month and during summer about 200 tons P/month. Thus, differing from DIN, there is a small export of DIP from the Kattegat during summer.

As the concentrations of TOTN and TOTP are relatively constant throughout the year (with only a small decrease in concentrations during summer), the transport of these constituents more directly mirrors the volume transport. During winter, however, there is a net transport of TOTN into the Kattegat of 23 000 tons N/month. The corresponding inflow of TOTP is 4 000 tons P/month. Discussing net fluxes, however, one must keep in mind that the fluxes west of Læsø are not considered in these figures. Taking this transport into consideration TOTN and TOTP are transported out of the Kattegat.

The oxygen deficit and the supply of oxygen to the Kattegat deep water is by far the most important question for the ecology of the area. Figure 11 a–c shows the fluxes of oxygen in the Læsø section. During winter the deep-water inflow is large. The oxygen concentrations in the Kattegat deep water approaches those of the surface water (Andersson and Rydberg, 1988). During summer, the supply of oxygen through the deep water is still large, and even during the period when the oxygen concentrations within the Kattegat deep water are really low (August–October), the supply is still large; more than 500 0000 tons O2/month (S> 30 PSU).

Discussion

This project was carried out with the main purpose of determining the flux of high saline (S > 30 PSU) Skagerrak water, including its salt, nutrient, and oxygen content, into the Kattegat deep water. However, measurements were taken also within the surface water, excluding only the rather small and shallow section west of Læsø (Læsø Rende, Fig. 3). It would otherwise have been impossible for us to take measurements in the whole cross-section during one, single day. We also argued, with reference to the main purpose, that no deep water would normally pass into the Kattegat across the shallows (<10 m) south and southwest of Læsø.

It is possible to obtain an indirect estimate of the flow through Læsø Rende by putting the net outflow across the whole section equal to the long-time average freshwater supply to the Baltic QF = 15 000 m3/s. This assumption implies a yearly mean outflow of surface

![Diagram](https://via.placeholder.com/150)
water in the Læsø Rende of 37 000 m$^3$/s, corresponding to a mean velocity northwards in that part of the cross-section of nearly 25 cm/s. According to Dietrich (1951) the observed mean surface velocity at the LV “Læsø Rende” was 22.6 cm/s during the period 1901–1930. In 1912–1913, J. P. Jacobsen carried out intensive current measurements at several depths from the LV “Læsø Rende”. Much later, his results were worked up by Rossiter (1968), who determined the mean velocities for a 14-month period of daily measurements. The mean northward velocity is well above 20 cm/s, thus supporting a strong mean outflow of surface water on the Danish side of Læsø.

It is of course tempting at this stage to use old data on salinity and nutrients from Læsø Rende to calculate full cross-section fluxes. This procedure is easily done for salinity. Assuming steady state, the salt flux through the full cross-section must be zero, implying that the salt transport through the Læsø Rende, $M_s$ (Læsø Rende) equals to $M_s(S = 35)$. Daily salinity measurements from

Figure 8. Average transport through the section. Positive values indicate transports into the Kattegat.

Figure 9. (a) The transport of DIN through the section as a function of salinity. Winter. Positive values indicate transports into the Kattegat. (b) As in 9a but for TOTN. (c) As in 9a but for DIP. (d) As in 9a but for TOTP.
Figure 10. (a) The transport of DIN through the section as a function of salinity. Summer. Positive values indicate transports into the Kattegat. (b) As in 10a but for TOTN. (c) As in 10a but for DIP. (d) As in 10a but for TOTP.

Figure 11. (a) The transport of oxygen through the section as a function of salinity. Winter. Positive values indicate transports into the Kattegat. (b) As in 11a but for summer. (c) As in 11a but for autumn.
several depths exist far back to the beginning of the century. Long-time salinity averages were obtained from the Danish Agency for Environmental Protection (Aertebjerg, pers. comm.). The volume transport \( V(S) \) for the full cross-section, including Læsø Rende, is shown in Figure 12. The corresponding salt transport \( M(S) \) is shown in Figure 13. As seen from this figure, the salt flux for the whole cross-section ends up at exactly zero, which is strong support for the results obtained through this project, even if our calculation on salt flux does not take into consideration that current velocities (direction) and salinities are not quite independent (a feature which is obscured by the averaging process).

Concerning nutrient fluxes, a straightforward calculation is not easily carried out. First, there are relatively few observations. In Table 1, we have summarized Danish and Swedish nutrient and oxygen measurements from Læsø Rende during 1981–1989 (SMHI, database). Flux calculations based on these measurements require a seasonal division of the volume flow through the Læsø Rende, as was done for the eastern part of the section. A seasonal division requires a seasonal estimate of the supply of water from the Baltic. Such estimates have been presented by Svansson (1975), but the variations in atmospheric pressure and sea levels are such that a four-year period, like ours, with relatively few measurements is unlikely to coincide with such long-time averages (different from the freshwater supply in itself).

Although one cannot recommend calculation of full cross-section fluxes of nutrients this is no serious drawback. The purpose of this project was to study the deep water fluxes, including the seasonal variations concerning these fluxes. The results obtained here differ significantly from estimates obtained from entrainment theory. An empirical, yearly mean value for the upward entrainment velocity in the Kattegat of \( 0.25 \text{ m/day} \) was derived by Stigebrandt (1983). The measurements presented here indicate a deep-water inflow of \( 64000 \text{ m}^3/\text{s} \) during winter and \( 28000 \text{ m}^3/\text{s} \) during summer compared to roughly \( 50000 \text{ m}^3/\text{s} \) during winter and \( 20000 \text{ m}^3/\text{s} \) during summer for the entrainment approach.

### Table 1. Salt, oxygen, and nutrient concentrations at Læsø Rende in \( \mu \text{mol/l} \). Surface water \( S < 30 \text{ PSU} \).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Winter</th>
<th>Summer</th>
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<tbody>
<tr>
<td>Salinity</td>
<td>26.19</td>
<td>24.12</td>
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<tr>
<td>Oxygen</td>
<td>7.02</td>
<td>6.81</td>
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<tr>
<td>DIP</td>
<td>0.61</td>
<td>0.22</td>
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<td>TOTP</td>
<td>1.09</td>
<td>0.87</td>
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<tr>
<td>DIN</td>
<td>5.16</td>
<td>1.26</td>
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<tr>
<td>TOTN</td>
<td>22.56</td>
<td>18.08</td>
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### References


