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Oxygen consumption in the Baltic proper[1]

Abstract—Total oxygen consumption rate, averaged over 1957–1982, and its variations with salinity in the deep water of the Baltic proper are calculated by a system of diagnostic advection-diffusion equations in a "natural" coordinate frame of reference. Although the data set used is not ideal for a more thorough investigation of the sensitivity of the model, an oxygen budget is formulated. A gross consumption rate of 3×10^{-9} mol m^{-3} s^{-1} is obtained. Further, a total consumption of about 0.14×10^{-6} mol m^{-2} s^{-1} is found, which is equivalent to an annual carbon input of 50 g C m^{-2} yr^{-1}.

Direct measurements of the rate of oxygen consumption and its distribution over depth are rare in the Baltic. These rates are, however, essential in ecosystem and eutrophication studies. Because of the high costs in carrying out such field programs, it is tempting to try to extract information from data gathered during routine surveys over many decades. This situation is not unique to the Baltic. Hence the approach suggested below may have more general interest.

Walin (1977) presented a method to extract such information for estuaries. He used conservation equations for various water properties in a "natural" coordinate frame of reference to derive basinwide average flux equations. Since isopycnal mixing is intense relative to diapycnal mixing, an approximate analysis in terms of isopycnically averaged properties may be justified. Given the inflow distribution of some substance, the corresponding advective and diffusive diapycnal fluxes are obtainable. Unfortunately, the practical and economic problems involved in determining these distributions with field measurements are considerable (Walin 1981; Stigebrandt 1987). By assuming that various water properties are mixed by the same turbulence field, however, Walin (1977) was able to formulate a similar model without having to prescribe the inflow distribution. Hence a turbulent diapycnal flux function can be determined by applying this diagnostic model to the observed distributions of parameters in question, both at the entrance region and within the semienclosed estuary. This approach was used by Rahm (1985) in a study of salt flux in the Baltic. Salinity was chosen as the independent variable because it dominates the density field of the deep water in this region. The deep water temperature was assumed to behave like a conservative tracer in the same region. Exchange coefficients were estimated from these calculations—their values are in accord with literature values for the Baltic Sea.

The present study is dedicated to the corresponding oxygen fluxes in the same basin, using, as before, hydrographic data from ICES. Oxygen consumption is estimated by combining oxygen and temperature distributions and fluxes with regard to salinity. The two dependent variables are averaged over 1957–1982 and hence represent the mean state of the system. Oxygen has, however, both a decreasing trend and strong variability during this period. Sometimes anoxic conditions occurred in the deeper parts (Matthäus 1984). These fluctuations are mainly due to infrequent inflows of deep water from the Kattegatt (Fig. 1).

Before performing the calculations, the equations are presented. Details and derivations are found in Walin (1977), whose nomenclature is followed throughout. The flux equation for a conservative tracer like temperature, in an idealized, semienclosed estuary (Fig. 2), becomes in steady state,

$$m(\gamma_T - T) + F\frac{\partial T}{\partial S^2} = 0 \qquad (1)$$

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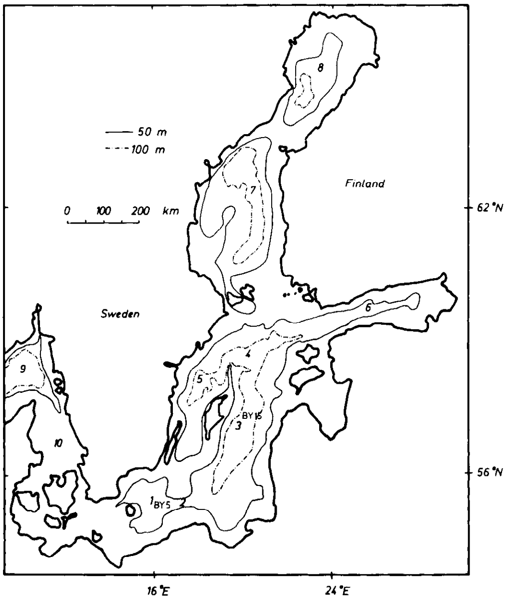

Fig. 1. The Baltic Sea and its basins: 1—Bornholm basin; 2—Stolpe Channel; 3—eastern Gotland and Fårö basins; 4—northern central basin; 5—Landsort and western Gotland basins; 6—Gulf of Finland; 7—Sea of Bothnia; 8—Bay of Bothnia; 9—Skagerrak; 10—Kattegatt.

where $\gamma_T(S)$ is the mean temperature distribution in the incoming water of volume flux $m(S)$ [representing inflow in the salinity range $(S, S + dS)$] and $T(S)$ is the weighted mean temperature within the basin. Further, $F(S)$ denotes the diffusive salt flux through the isohaline S. Since in steady state (Walin 1977)

$$m = \frac{\partial^2 F}{\partial S^2}, \tag{2}$$

Eq. 1 becomes

$$(\gamma_T - T)\frac{\partial^2 F}{\partial S^2} + F\frac{\partial^2 T}{\partial S^2} = 0. \tag{3}$$

$F(S)$ is determined (Rahm 1985) by specifying the distributions of both γ_T and T and applying relevant boundary conditions. The corresponding equation for a nonconservative tracer like oxygen is (cf. Walin 1977):

$$(\gamma_C - C)\frac{\partial^2 F}{\partial S^2} + F\frac{\partial^2 C}{\partial S^2} + q_C = 0 \tag{4}$$

where $q_C(S)$ represents the total oxygen pro-

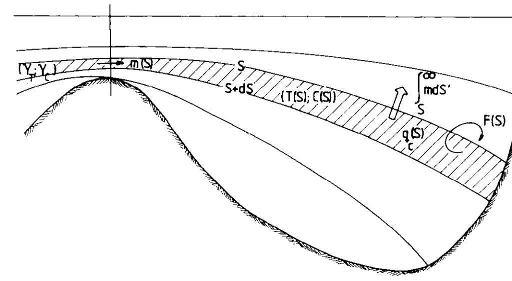

Fig. 2. Definition sketch showing the estuarine model. The inflow $m(S)$ of mean temperature and oxygen concentration $\gamma_T(S)$ and $\gamma_C(S)$ in the range $S, S + dS$ are shown as are the basinwide averages of temperature and oxygen $T(S)$ and $C(S)$. The total advective volume flux $\int_S^\infty m dS'$ and the total turbulent salt flux $F(S)$ through the isohaline S are also shown, as is the oxygen consumption $q_C(S)$.

duction or consumption in the range $(S, S + dS)$ and C is oxygen concentration. Oxygen distributions in the inflowing water and within the basin are defined by $\gamma_C(S)$ and $C(S)$ in an analogous way to $\gamma_T(S)$ and $T(S)$.

Combining Eq. 3 and 4 yields the consumption rate:

$$q_C = F\left[\frac{\gamma_c - C}{\gamma_T - T}\frac{\partial^2 T}{\partial S^2} - \frac{\partial^2 C}{\partial S^2}\right]. \tag{5}$$

Hence, to calculate $q_C(S)$, one must first determine $F(S)$ and then combine it with the corresponding oxygen distributions. Finally, the total consumption below the isohaline S becomes (Walin 1977)

$$Q_C(S) = -\int_S^\infty q_C(S)\, dS. \tag{6}$$

The applicability of Eq. 3 and 5 is limited to the stratified part of the basin because the T-S relations become non-unique in the well-mixed, brackish surface layer. Hence the equations are only applicable to a salinity interval ranging from the upper part of the halocline ($S = S_0$) to the salinity levels found at the deepest parts of the basin ($S = S_1$). If one assumes no turbulent flux of salt through the bottom,

$$F = 0 \text{ at } S = S_1. \tag{7}$$

Turbulent salt flux through the surface

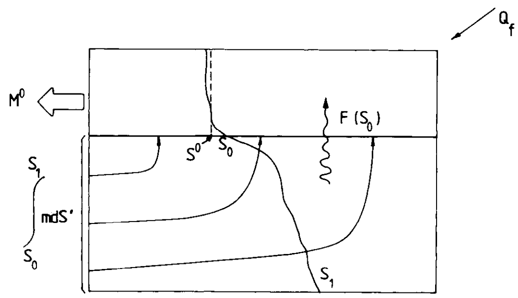

Fig. 3. Schematic figure showing the model used to determine the proper boundary conditions based on Knudsen relations. Total inflow and outflow from the estuary are denoted $\int_{S_0}^{S_1} mdS'$ and M°; the freshwater supply is called Q_f. The assumed salinity profile is indicated with its range in the deeper layer, as is the mean salinity S^0 of the upper layer. The total turbulent salt flux into the upper layer is represented by $F(S_0)$.

layer is determined by the Knudsen relations applied to the same layer (Fig. 3). The salt flux balance of the deep part becomes

$$\int_{S_0}^{S_1} mS\, dS = S_0 \int_{S_0}^{S_1} mdS + F(S_0), \quad (8a)$$

while the volume and salt continuity of the surface layer turns out to be

$$\int_{S_0}^{S_1} mdS + Q_f = M^{\circ} \quad (8b)$$

and

$$\int_{S_0}^{S_1} mS\, dS = S^{\circ}M^{\circ}. \quad (8c)$$

Here, M°, Q_f, and S° represent the total outflow from the estuary, the freshwater supply, and the mean salinity of the surface layer. Note that S° may, due to its definition, differ from S_0 to some degree. The boundary condition becomes

$$F(S_0) = S^{\circ}Q_f + (S^{\circ} - S_0) \int_{S_0}^{S_1} mdS \quad \text{at } S = S_0. \quad (9)$$

The Baltic proper (*see* Ehlin et al. 1974 for bathymetry and nomenclature) forms the physical counterpart to the idealized model basin above. Due to the high degree of isopycnal homogeneity, the hydrographic station BY15 (Gotland Deep) has been assumed to be representative for the Baltic proper. Because of lack of data, BY5 (Bornholm Deep) represents the source area, despite the fact that the Stolpe Channel is the proper inflow region (*see Fig. 1*). The errors induced are assumed to be small. Mean values of oxygen concentration and temperature are found for each 0.2‰ salinity interval in the range 8.0–12.6‰ (Figs. 4 and 5). (Note that the oxygen minimum at BY15 is probably due to the fact that when stagnation periods occur, oxygen concentration decreases at the same time as the bottom layer is mixed with overlying water, which is slightly richer in oxygen but of lesser salinity.) Only those observations where all parameters are unquestionable have been used. Observations separated by less than a month have also been omitted. During anoxic conditions hydrogen sulfide is produced. This sulfide is assumed completely

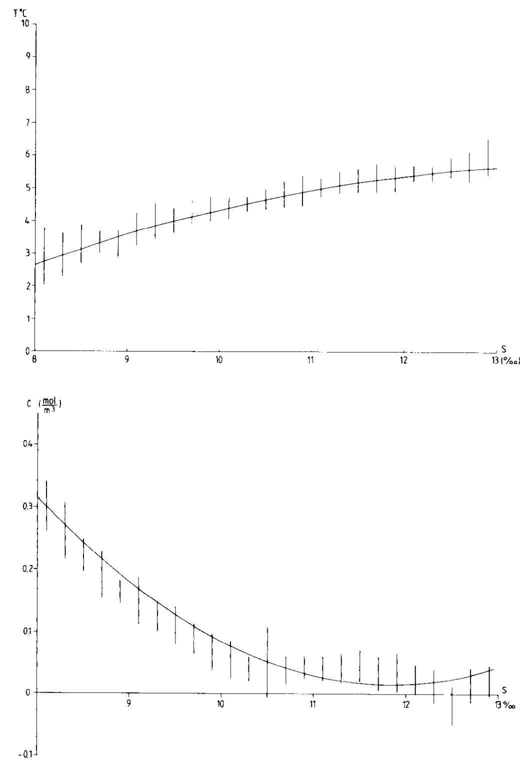

Fig. 4. Mean values of temperature and oxygen concentration vs. salinity from station BY15 together with the associated standard deviations. The solid line represents the corresponding polynomial.

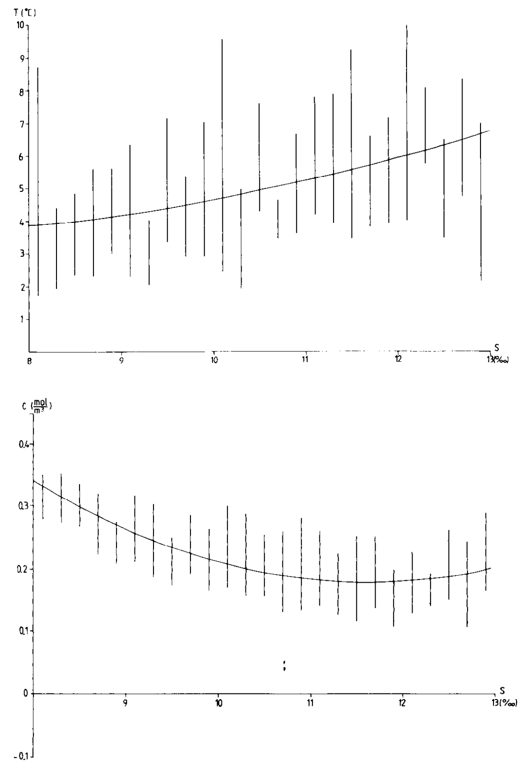

Fig. 5. As Fig. 4, but for station BY5.

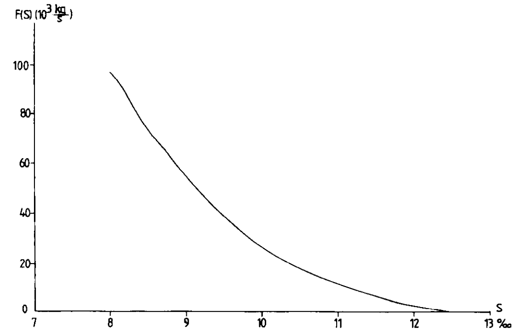

Fig. 6. Calculated turbulent salt flux vs. salinity for the Baltic proper.

oxidized to sulfate, thus representing oxygen consumption in the calculations.

Since the model equations are based on second-order derivatives, data are fitted to polynomials of low order by the method of least squares (Table 1). Equation 3 was reformulated as a parabolic differential equation, which was solved numerically by an explicit finite-difference scheme.

The boundary conditions, Eq. 7 and 9, are calculated for characteristic values of the Baltic proper (Pedersen 1977):

$S^0 = 7.7‰$, $Q_f = 14 \times 10^3 \text{ m}^3 \text{ s}^{-1}$, and $\int_{S_0}^{S_1} m dS = 34 \times 10^3 \text{ m}^3 \text{ s}^{-1}$. The boundary conditions become:

$$F = 98.8 \times 10^3 \text{ kg s}^{-1} \quad \text{at } S_0 = 8.0‰ \qquad (10a)$$

and

$$F = 0 \text{ kg s}^{-1} \quad \text{at } S_1 = 12.6‰. \qquad (10b)$$

The resulting $F(S)$ distribution (Fig. 6) agrees well with that of Rahm (1985). The value of $q_C(S)$ is then determined by Eq. 5 (Fig. 7). By assuming consumption to be insignificant for salinities above $S = S_1$ (due to the small volumes involved), $q_C(S)$ can be integrated to an arbitrary salinity level (Eq. 6). The resulting $Q_C(S)$ distribution is shown in Fig. 8.

The estimates obtained, and shown in Table 2, yield an overall consumption rate below the 8‰ isohaline of about 0.14×10^{-6} mol m^{-2} s^{-1} (12×10^{-3} mol m^{-2} d^{-1}). As a comparison, Shaffer and Rönner (1984) obtained a value of 20×10^{-3} mol m^{-2} d^{-1} for the same region. The consumption rates decrease with increasing salinity, indicating that the halocline is a level of intense mineralization.

The overall consumption rate shown above is equivalent to an annual carbon input of 50 g C m^{-2} yr^{-1} to the region of interest. It can be compared to the annual phytoplankton primary production in the same area, which is assumed to be 160 g C m^{-2} yr^{-1} (Ackefors and Lindahl 1979). With regard to the assumed recycling of carbon

Table 1. Coefficients for the second-order polynomials $\gamma_T(S)$, $T(S)$, $C(S)$, and $\gamma_C(S)$, based on data below the 8‰ isohaline. The polynomials are defined as $C_0 + C_1S + C_2S^2$.

	C_0	C_1	C_2
γ_T	5.793	−0.7488	0.06337
T	−10.889	2.360	−0.08368
γ_C	42.391	−6.314	0.2650
C	67.836	−11.296	0.4734

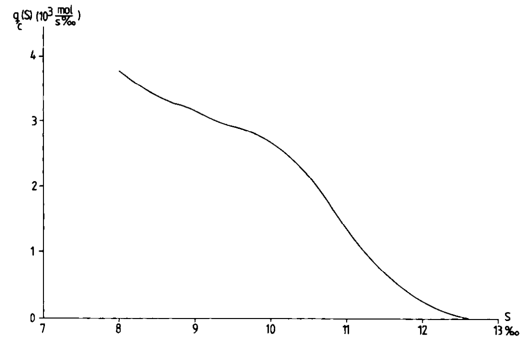

Fig. 7. Rate of oxygen consumption $q_C(S)$ vs. salinity.

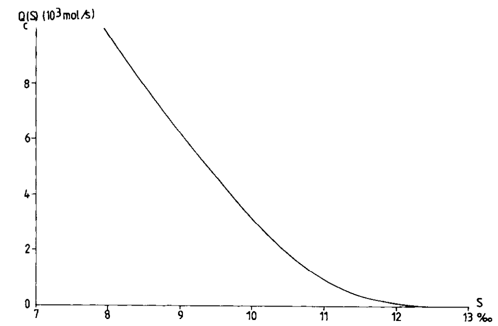

Fig. 8. Accumulated mean oxygen consumption $Q_C(S)$ above a salinity level S vs. salinity.

in the surface layer, the value seems reasonable. In fact, Elmgren (1984) gave an estimated energy input into the benthos of 48 g C m^{-2} yr^{-1}, while a value of 90 is given by Shaffer and Rönner (1984). Further, the present study yields a consumption rate of about 3×10^{-9} mol m^{-3} s^{-1}, which is comparable with the estimates of Rydberg (1978). He obtained roughly 4 mol m^{-3} s^{-1} below the 9‰ isohaline.

An oxygen budget is formulated as follows. Total inflow, $\int_{\tilde{S}}^{\infty} \gamma_C m dS$, to the basin below a certain isohaline $\tilde{S}$ is balanced by advective fluxes, $C(\tilde{S}) \int_{\tilde{S}}^{\infty} mdS$, diffusive fluxes, $F(\tilde{S})dC/\partial S$, and a source/sink, $Q_C(\tilde{S})$. Hence the total oxygen flux through the basin below $\tilde{S}$ becomes

$$\int_{\tilde{S}}^{\infty} m\gamma_C \, dS = C(\tilde{S}) \int_{\tilde{S}}^{\infty} mdS + F(\tilde{S})\frac{\partial C}{\partial S} + Q_C(\tilde{S}). \quad (11)$$

Note (Table 3) that the amount of oxygen transported into the Baltic proper from the Bornholm basin is almost balanced by consumption in the interior. A balance between the diffusive (downward) and advective (upward) fluxes is also found.

The aim of this work is to present a method and not an exhaustive study of oxygen dynamics in the Baltic proper, though the results obtained seem to agree with independent estimates. Investigations of the robustness of the model have not been carried out because the data set available is not ideal for this purpose, but one can assume that its dependence on second-derivative properties makes it rather sensitive to imperfect data. In fact, second-derivative properties demand high quality field data. Note that an increase in the salinity interval to 8.0–13.0‰, which has only minor effects on the "oxygen" polynomials, has drastic consequences for the second-order derivatives of T, resulting in an overall increase in $q_C(S)$ of about 30%. Another source of uncertainty lies in the derivation of boundary conditions. The Knudsen relations give only a crude estimate of the fluxes involved (Walin 1981). A further complication is due to the

Table 2. Calculated rates of oxygen consumption for the Baltic proper.

S (‰)	z (m)	A (10^3 km^2)	Q_C/A (10^{-9} mol m^{-2} s^{-1})	V (10^2 km^3)	Q_C/V (10^{-9} mol m^{-3} s^{-1})
8	62	70	140	35	2.9
9	73	61	100	27	2.3
10	85	51	60	20	1.6
11	106	37	30	12	0.8
12	140	15	10	5	0.2

Table 3. Estimated fluxes and consumption rates of oxygen in the Baltic proper below some isohalines. The fluxes are given in 10^3 mol s^{-1}.

$\tilde{S}$	$C\int_{\tilde{S}}^{\infty} mdS$	FdC/dS	$Q_C(\tilde{S})$	$\int_{\tilde{S}}^{\infty} m\gamma_C dS$
8	17.2	−16.4	9.8	10.6
9	7.5	−6.8	6.3	6.9
10	2.1	−3.2	3.2	2.2
11	0.4	−0.4	0.9	0.9
12	0.1	0	0.1	0.2

assumed mixing process where different properties are supposed to mix in the same way, disregarding such processes as double diffusion. Despite these problems, the model seems to yield a reasonable estimate of the oxygen budget of the Baltic proper. Hence the method appears to be useful for its purpose and it should be equally applicable to other estuaries such as the Black Sea.

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Temperature and velocity microstructure caused by swimming fish[1]

Abstract—Simultaneous acoustic and microstructure measurements obtained from a submarine showed a rapid increase in turbulent dissipation coincident with its passage through water vacated by a school of fish. The effect is attributed to the wake left by part of the school as it moved out of the submarine's path. Avoidance behavior of this type also occurs in the vicinity of free-fall microstructure probes; it is suggested that microstructure profiles may include such biological sources of turbulence when taken in waters having substantial aggregations of fish.

Temperature and velocity microstructure is an almost ubiquitous feature of the upper ocean and is normally interpreted as a manifestation of physical processes such as shear flow instability, convection, overturning, double diffusion, and related phenomena. However, it is also of interest to consider processes of biological origin that might contribute to microstructure in the ocean. Here we describe a set of observations which illustrates the possibility of swimming fish being a source of microstructure.

The observations were obtained aboard the submarine USS *Dolphin* in Monterey Bay, California. Temperate gradient and velocity shear measurements were obtained with special microstructure probes mounted on a mast near the submarine's bow (Osborn and Lueck 1985). In addition, observations were made with three high-frequency (119 kHz) 10° beam-width echo sounders aligned along the submarine axis and directed horizontally, vertically, and at an angle of 45° from a point on the bow, as shown in Fig. 1. The echo sounders were operated cyclically with a separation between each transmission of 0.1 s. If the range

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