THE INFLUENCE OF HYDRODYNAMICS ON THE CHLOROPHYLL FIELD IN THE OPEN BALTIC

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INTRODUCTION

The concentration of chlorophyll a - more correctly, its in vivo fluorescence - is unique among the many biological parameters characterizing a pelagic ecosystem, because it is amenable to measurement by in situ and remote sensors. The chlorophyll a concentration is important as an index of the phytoplankton abundance. Moreover, it may be a useful indicator of hydrodynamic processes, as discussed in this paper.

The spatio-temporal dynamics of chlorophyll is much more complicated than that of the common hydrographic variables, e.g. salinity, due to its intense vertical fine structure and its essentially nonconservative nature. The time scales of the spatially heterogeneous nonconservative processes, the phytoplankton reproduction and the grazing by zooplankton, are of the order of 1 day. Hydrodynamics controls the chlorophyll field by 1) advection and diffusion, and 2) by changing the local rates, e.g., of reproduction and grazing. A delicate balance between these processes determines which one of them dominates on some particular space and time scales.

Skellam (1951), Kierstead and Slobodkin (1953), and a number of their followers (Okubo, 1978) have examined the balance between diffusion and reproduction. Their analysis leads to a critical patch size, below which a phytoplankton patch is erased by diffusion. However, the concept is only of limited cognitive value to a field ecologist because all the relevant processes are spatially heterogeneous.

The relative importance of advection versus reproduction may be assessed by the nondimensional number, S, introduced by O'Brien and Wroblewski (1973). For a geostrophic flow;

$$S = \frac{U}{r} \left(\frac{f}{A_H}\right)^{\frac{1}{2}} \qquad (1)$$

where U is the characteristic speed of the organized flow, r is the maximum growth rate of the plankton, f is the Coriolis parameter, and A_H is the eddy diffusivity for momentum. When S exceeds unity, advection becomes dominant over biological turnover in determining the horizontal chlorophyll distribution. For parameter values typical of the Baltic ($r = 2x10^{-5}$ s^{-1}; $f = 10^{-4}$ s^{-1}; $A_H = 10^6$ cm^2 s^{-1}) it appears that advection dominates if $U > 2$ cm s^{-1}. Despite the uncertainty in the estimate of A_H, the gross validity of this result will be demonstrated later.

METHODS

The chlorophyll field and its interaction with the hydrodynamic processes in the south-eastern Gotland Basin were studied by means of recurrent quasi-synoptic surveys at stations covering various rectangular grids, with a spacing of 5 nautical miles (9.3 km) between grid points. A typical grid area was 20x25 nautical miles. At each grid point, vertical profiles were obtained using a Variosens _in situ_ fluorometer, measuring chlorophyll _a_ fluorescence, and a Neil Brown Mark III CTD probe. The fluorometer calibration and other details may be found in Kahru (1981a) and Kahru _et al._ (1981). The duration of a survey was about 1 day. As the chlorophyll concentrations at fixed depths are readily contaminated by internal waves and the variable vertical fine structure (Kahru _et al._, 1981), only vertically integrated concentrations are considered in this paper. The CTD data of the same surveys are interpreted in detail by Aitsam and Elken (this volume).

OBSERVATIONS AND DISCUSSION

The ecology of the Baltic Sea has been recently reviewed by Jansson (1978). A characteristic feature of the Baltic Sea hydrography is the distinct layering of the water column into 3 layers in summer: the upper layer, which coincides approximately with the photic layer; the intermediate layer, or the winter convection layer; and the deep, saline layer (Fig. 1). The 2 peaks in the Brunt-Väisälä frequency, separating the layers, are associated with the seasonal thermocline (depth of 15 to 30 m) and the permanent halocline (50-70 m). After the spring phytoplankton bloom, lasting for a few weeks, the upper 2 layers are almost depleted of inorganic nitrogen, and the phytoplankton growth is limited by biological destruction and by the rate of upward mixing of nitrates from the deep layer (where the nitrate concentration remains about 100 times higher than in the higher layers). Consequently, the influence of the hydrodynamics on the phytoplankton growth is manifested mainly through the transfer of nutrients into the upper layer. A number of mixing patterns is revealed by the chlorophyll surveys.

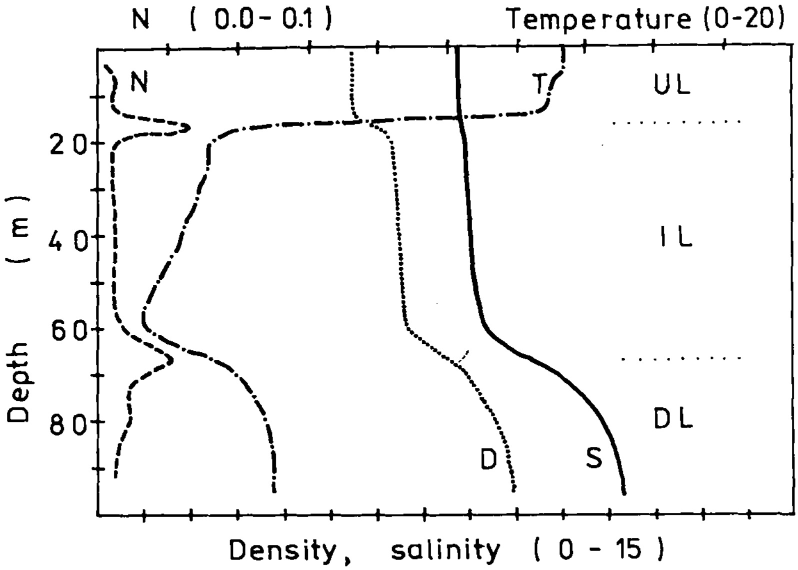

Fig. 1. Typical thermohaline layering of the Baltic Proper into 3 layers: upper (UL), intermediate (IL), and deep layer (DL), with plots of temperature (T, °C), salinity (S, °/oo), density (D, sigma-t), and the Brunt-Väisälä frequency (N, rad s^{-1}) (from Kahru et al., 1981).

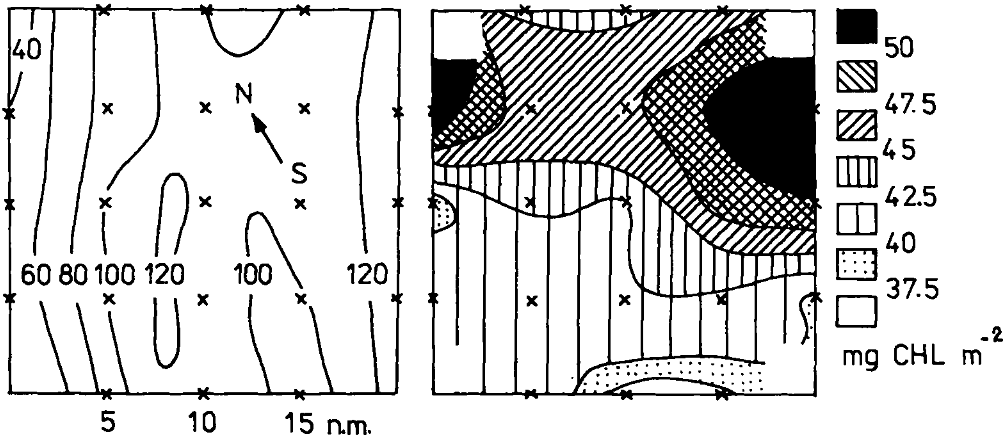

Fig. 2. Chlorophyll distribution (mg m^{-2}, integrated between 2.5 and 32.5 m) in relation to the bottom topography (m). July 15-16, 1979. The upper left patch was observed repeatedly and is ascribed to bottom mixing on the shallow bank. The upper right patch remains unexplained.

The bathymetry of the Baltic is very irregular so that the currents (Kielman et al., 1973) and, hence, the intensity of vertical mixing are subject to a strong topographical influence. When a stratified fluid flows over a shallow submarine bank, and if the flow is subcritical with respect to the internal Froude number, the isopycnals are compressed (Turner, 1973), and the bottom turbulence may cause an upward transport of nutrients. This can be recognized on some of the chlorophyll maps (Fig. 2). Although little is known about bottom mixing in the Baltic, this kind of boundary mixing can be important for the overall ecology due to the frequent occurrence of shallow banks.

Geostrophic currents, significantly guided by the topography, are associated with the sloping of isopycnals. The resulting vertical displacement of the thermocline and/or of the halocline modifies the thicknesses of the basic layers. We have established significant relationships between the water stratification and the chlorophyll level, suggesting intensified mixing under certain conditions. In particular, both the rising of the top of the deep layer (Fig. 3) and the narrowing of the intermediate layer (Fig. 4) are clearly associated with an increase in chlorophyll concentration in several surveys. I suggest that the rising of the halocline and the compression of

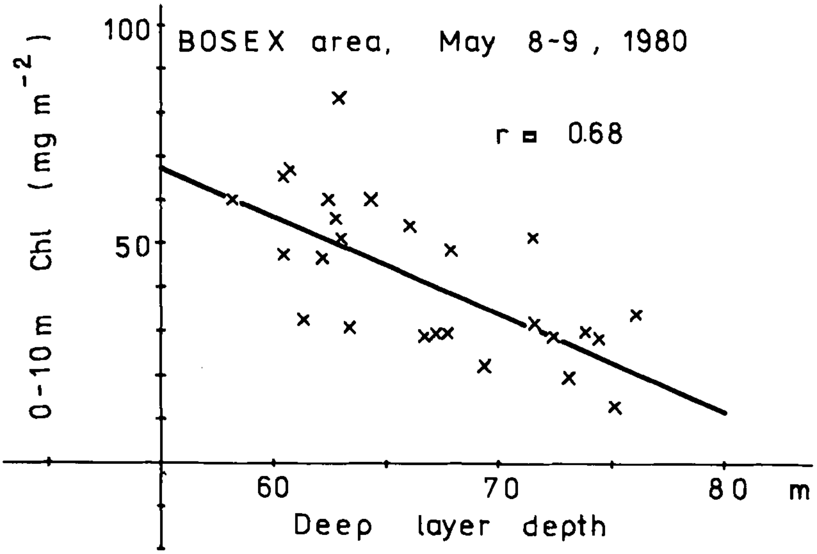

Fig. 3. Dependence of chlorophyll a in the upper 10-m layer (mg m^{-2}) on the halocline depth.

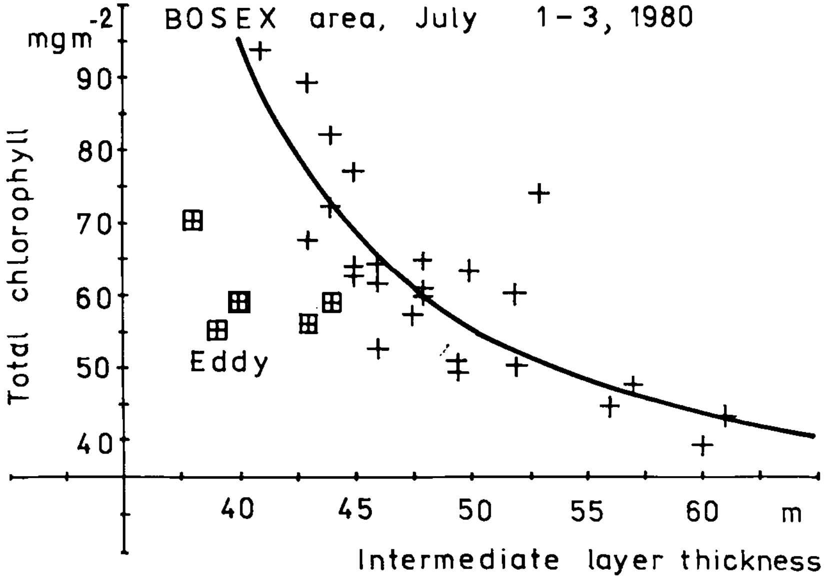

Fig. 4. Dependence of the total chlorophyll a in the upper 60 m layer on the intermediate layer thickness. The circled points, originating from a cyclonic eddy center, suggest suppressed mixing in the eddy center. They have been excluded when fitting the curve by least squares (from Kahru et al., 1981).

the intermediate layer, both favorable to the development of vertical shears, can give rise to instabilities, e.g. internal wave breaking, causing intense mixing and, hence, increased chlorophyll biomass. Figure 5 presents a typical section across a topographically guided baroclinic jet, showing the bottom contour and the corresponding integrated chlorophyll concentrations. Here, contrary to the case of bottom mixing, the chlorophyll concentration is inversely proportional to the depth: the shallowest area with the thickest intermediate layer supports the lowest chlorophyll level and vice versa.

The chlorophyll field shows striking mesoscale (≅ 10 km) patterns even if the concentration is integrated vertically over the upper 60 m layer. The correlations with the stratification suggest that most of the variability is caused by uneven nutrient fluxes from the deep layer rather than by lateral mixing of different water masses. It is tempting to try to estimate the vertical diffusivities that might be responsible for the generation of such heterogeneities. Using a ratio of nitrogen/chlorophyll = 16, appropri-

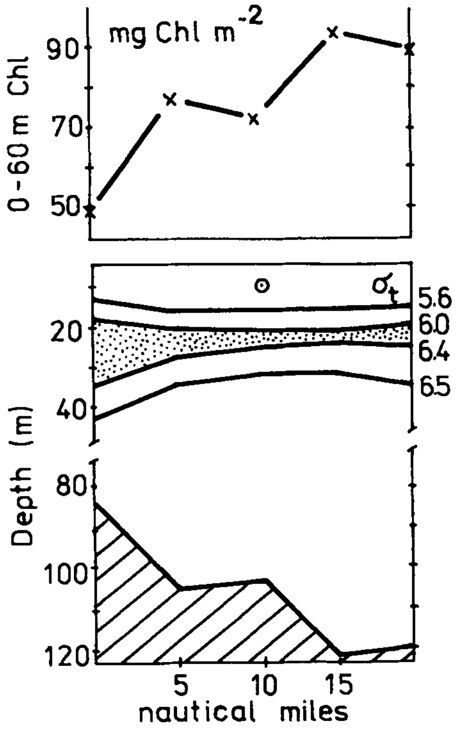

Fig. 5. Section across a baroclinic jet along the isobaths showing the bathymetry, the isopycnals in the intermediate layer, and the corresponding total chlorophyll levels. BOSEX area, July 1-3, 1980.

ate for nitrogen-deficient phytoplankton (Strickland, 1965), the chlorophyll concentrations may be crudely expressed in terms of nitrogen. For the surveys shown in Figures 3 and 4, the differences between maximum and minimum concentrations in the upper 60 m layer are 2220 and 875 mg N m^{-2}, respectively. These amounts correspond to about 18% and 8%, respectively, of the mean total nitrogen above the halocline. As a first approximation, the nitrate flux across the halocline may be estimated as

$$\Omega = - K_z \frac{\partial NO_3}{\partial z} \qquad (2)$$

where K_z is the vertical diffusivity and $\frac{\partial NO_3}{\partial z}$ is the vertical gradient of nitrate. The latter is approximately equal to 3 mg N m^{-3}/m for the 50-70 m layer. By means of dye diffusion experiments, Kullenberg (1977) obtained a value of $K_z = 2.2 \times 10^{-6}\ m^2\ s^{-1}$ for the mean vertical diffusivity in the halocline of the Bornholm Basin. Substituting these numerical values into equation (2), we obtain an upward nitrogen flux of 0.57 mg N m^{-2}/day. This flux is extremely small in view of the observed variability. Indeed, at this rate, more than 1000 days would be needed to accumulate an amount of nitrate similar to the typical observed variations (more than 500 mg N m^{-2}). As the time scale of the phytoplankton patches is probably of the order of 10 days, the observed chlorophyll variability cannot be explained with the above value of the vertical diffusivity. Consequently, processes with diffusivities higher by at least 2 orders of magnitude ($> 10^{-4}\ m^2\ s^{-1}$) should exist at least locally and temporarily. In the Baltic thermocline, vigorous short-term mixing caused by internal wave breaking in the intense shear zones, created by inertial waves, was shown by Krauss (1978). The possibility of nutrient transfer across the thermocline, e.g. during storms, is further substantiated by the very low nitrate values below the thermo- and above the halocline. The intermittency and dramatic variability of the vertical mixing in stratified waters has been stressed by Woods (1977). Hence, the vertical diffusivities $> 10^{-4}\ m^2\ s^{-1}$, required to explain my observations, are not necessarily in contradiction with the 2 orders of magnitude lower values measured by Kullenberg (1977) in quieter conditions. However, the evidence presented here for the existence of intense mixing events in the halocline of the open Baltic is indirect and no well-documented observations are available.

Satellite images (Ulbricht and Horstmann, 1979) as well as our CTD surveys (Aitsam and Elken, this volume) show a frequent occurrence of mesoscale eddies: on every survey eddylike disturbances of the relative dynamic topography can be discerned. The analysis of the interaction between energetic mesoscale eddies and the chlorophyll field is complicated by the advection and stirring action during the phytoplankton growth phase (1-3 days): taking into account the effect of advection, we have to relate the chlorophyll biomass to mixing conditions several days earlier. This has hardly been feasible in practice, and the apparent effect of advection is a reduction in the correlation between the stratification (i.e. mixing conditions) and the chlorophyll level.

Two surveys made 10 days apart during comparatively even phytoplankton growth showed that the chlorophyll field was distorted by a passing eddy as a passive scalar field (Kahru, 1981b).

Another survey (Fig. 4) seems to indicate that the mixing activity in a cyclonic eddy is remarkably suppressed. It seems that the hypothesis of a reduction of mixing energy in the eddy center is supported by observations suggesting a decrease in wave energy in the center of oceanic eddies (Frankignoul, 1974; Dykman et al., 1981).

Three surveys made during the decaying phase of a particularly energetic mesoscale eddy show unusually weak correlations between the stratification and the chlorophyll level. This is probably the result of the vigorous advection, stirring, and current shears, associated with the eddy. The observational evidence for this conclusion is as follows. The eddy has a translational velocity of about 2 cm s^{-1} and the rotational velocities are estimated at 20 cm s^{-1}. The isopycnal elevations in the center are 22 m at the top of the deep layer. Although the nutrient concentrations were not measured, a significant increase in the near-surface salinity provides evidence of intense vertical mixing and nutrient input. This evidence is based on a close relationship between the nutrients and salinity (Nehring, 1979) as both are mixed upwards from the deep, saline layer. The correlation between the upper and deep layer salinities is maximal during the most active phase of the eddy (Fig. 6A), also suggesting vertical mixing, and it decreases later to zero as a result of strong vertical shears. At the same time the near-surface salinity reaches its maximum. The occurrence of vigorous stirring is also substantiated by a decrease in the spatial scales of variability

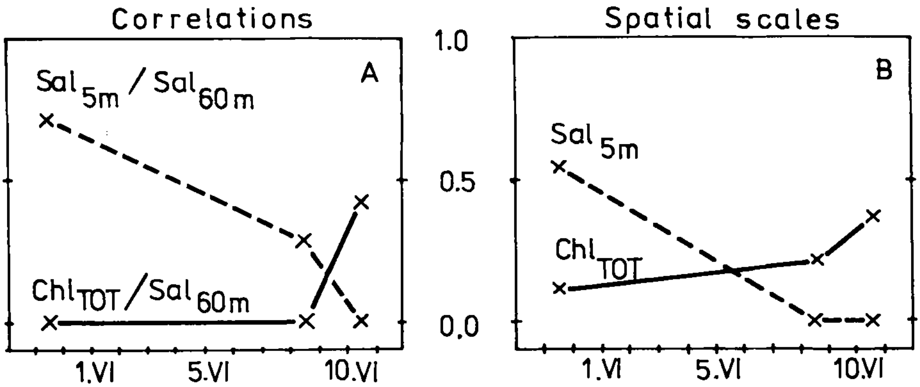

Fig. 6. Trends in several parameters on 3 consecutive surveys during the breakdown of an energetic mesoscale eddy: correlations between the total chlorophyll and the salinity at 60 m, and between the salinities at 5 m and 60 m (A); spatial autocorrelations over 5 nautical miles of the total chlorophyll and the salinity at 5 m (B).

of the near-surface salinity, i.e. by a shift from a coarse-grained to a fine-grained pattern (Fig. 6B). The chlorophyll field also shows an unusually fine-grained pattern. Although substantial amounts of nutrients were probably mixed into the upper layer by the cyclonic eddy, this is not apparent in the chlorophyll/salinity correlation due to the vigorous advection, stirring, and shears. The O'Brien-Wroblewski parameter, equation (1), calculated for the rotational velocity of the eddy, surely exceeds unity, which confirms the dominance of advection over the phytoplankton reproduction. In accordance with this concept, the weakening of the eddy coincides with a slight increase in both the chlorophyll/ salinity correlation and the spatial scales of the chlorophyll field (Fig. 6).

It should be stressed that our ability to interpret the biological dynamics and its complicated interaction with vigorous hydrodynamic processes is by no means unambiguous. More detailed synoptic surveys of several representative biological and hydrographic parameters are needed. A routine use of biological sensors mounted on a vertically undulating 'Batfish' (Denman and Herman, 1978) would represent a substantial progress.

CONCLUSIONS

The chlorophyll field in the open Baltic Sea is closely related to various hydrodynamic processes. The spatial and temporal scales considered in this paper are the so-called mesoscales (10-100 km and 1-10 days), where the biological turnover rate of the phytoplankton becomes comparable to the processes of advection and diffusion. An increase in chlorophyll biomass may be ascribed to the phytoplankton growth in response to a nutrient input from the deep layer as a result of vertical mixing. Several mixing regimes are discerned from the chlorophyll patterns: bottom mixing on shallow banks, shear induced mixing in a thin intermediate layer, and a suppression of mixing in the center of a cyclonic eddy. High vertical diffusivities in the halocline ($> 10^{-4}\ m^2\ s^{-1}$), at least locally and temporarily, are needed to explain the observed chlorophyll variability by uneven nutrient fluxes. This eddy diffusivity is 2 orders of magnitude higher than that measured by dye experiments in "quiet" conditions (Kullenberg, 1977). In accordance with the O'Brien-Wroblewski criterion, vigorous advection and stirring dominate over the biological turnover for some periods. For these periods the apparent correlations between the chlorophyll levels and the hydrography are decreased.

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