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The Role of Axially Varying Vertical Mixing along the Path of a Current in Generating Phytoplankton Production

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The role of axially varying vertical mixing along the path of a current in generating phytoplankton production

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In temperate continental shelf seas, high phytoplankton growth rates are normally restricted to two to three weeks in spring coinciding with the onset of stabilization of the water column and a large supply of nutrients. Thereafter production is slowed down because available nutrients are depleted and increased stability restricts the rate of recycling of nutrients. High levels of production can persist for a longer period wherever nutrients can be made readily available at or near the surface, most notably in upwelling areas and mixed coastal regions, and, to a lesser extent, adjacent to fronts. This paper demonstrates another mechanism whereby a stratified shelf current passes through a small area of intense tidal mixing, entraining nutrient-rich bottom water before becoming restratified. This results in a relatively large area where 'spring' conditions persist throughout the summer, injecting many growing phytoplankton into a sea that is otherwise less productive.

Introduction

There are a number of practical reasons for conducting physical oceanographic research near the continental-shelf. All are related, directly or indirectly, to man's activities and include coastal and offshore engineering, waste dispersal and fisheries. Currently physical oceanographic research in the North Sea has applications in these three activities with fisheries being responsible for the initiation of considerable research since *ca.* 1886.

This work has led Cushing (1966) to believe that the effects of climatic change on the hydrography of the North Sea influence fluctuations in fish stocks significantly. He shows that climatic change affects the stocks in various ways, and suggests that an important factor is the variation in the timing of the spring outburst of phytoplankton relative to the times of spawning of fish. This interpretation does not necessarily explain many of the year-to-year fluctuations in recruitment, however, (Daan 1978) thus drawing attention to the dangers inherent in attempting correlations between the vast meteorological and oceanographic data sets that are readily available.

There have been other attempts to relate fisheries and environmental fluctuations including a 'successful' correlation by Carruthers (1938) relating wind velocity to haddock brood strength. This correlation was based on an understanding of the circulation and wind effects in the North Sea interpreted from drift-bottle information (Tait 1937), an interpretation that differs significantly from that obtained from recording current meters (Dooley 1974; Reipma 1980). Not surprisingly, Carruthers correlation did not stand the test of time (Saville 1959). In the long term the indication is that trends in a fishery can be of climatic origin and recently Cushing (1980) has discussed the possibility as the cause of an increase in gadoid (e.g. haddock, whiting, cod) in the sixties. Year-to-year, however, it is still not possible to venture beyond the progress made by Carruthers (1938) particularly for the northern North Sea. For example, it is not possible to demonstrate either by using 'fishery' or 'environmental' data the cause of the fluctuations of year class strength in haddock (figure 1), the number of which can vary by almost two orders of magnitude from year to year (R. Jones 1977, unpublished manuscript I.C.E.S. CM 1977/F36).

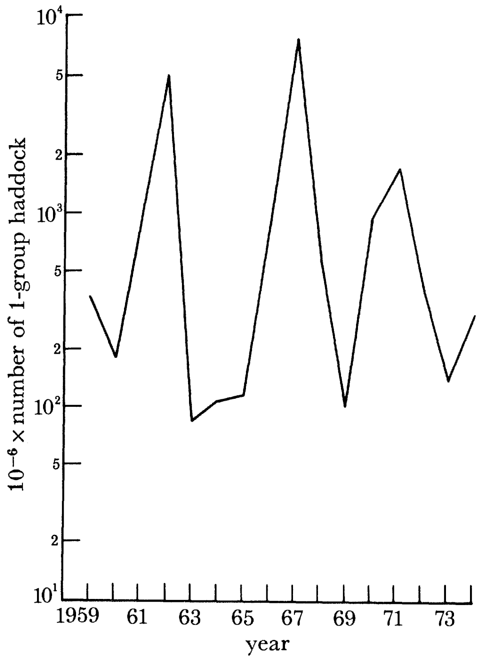

Figure 1. Year class strengths of haddock in the northern North Sea from 1959–1974.

The object of this paper is not to attempt to relate the fluctuations to environmental change but to demonstrate the need for a more detailed understanding of underlying physical and biological processes before one attempts to establish statistical links between environmental change and fish recruitment. It will be demonstrated that relatively minor but significant changes in the hydrographic régime of the North Sea can have significant effects on the phytoplankton composition and produce considerable year-to-year variations in the total phytoplankton production of the North Sea, consistent with the observed fluctuations in fish recruitment. This paper is particularly relevant to this symposium as it discusses a mechanism for summer production of phytoplankton, a process normally associated with fronts or upwelling.

Observations

The observations on which this paper is based were collected conventionally. Current measurements were obtained by using Aanderaa and Plessey current meters suspended from sub-surface buoys deployed at a depth of at least 30 m to avoid degradation of the current-meter performance due to wave action. Station sampling was undertaken by using Knudsen water bottles. Samples were analysed for salinity by using an Autolab salinometer and nutrients and chlorophyll *a* were analysed by the methods of Strickland and Parsons (1968).

Predicted and observed distributions of fronts

Apart from the spring bloom of phytoplankton, the productivity of the continental shelf seas is significantly dependent on the production that persists throughout the summer as a consequence of physical mixing processes (Steele 1958). Steele was able to show that in the North Sea variations in summer production rates were primarily responsible for the variation in yearly totals of production, the rates being maximized at intermediate levels of vertical mixing. Since vertical mixing is a function of stratification, this would appear to be in agreement with Pingree (1978) who presented observational evidence demonstrating that maximum production rates were related to the frontal boundary between stratified and unstratified waters.

Hansen (1950) was the first to demonstrate that the distribution of stratification in the continental shelf seas was related to the distribution of tidal currents. Hansen's ideas were further refined by Dietrich (1954) who developed a method to determine the depth of the thermocline, and hence the point at which it outcrops to the sea surface, by comparing the vertical density gradient caused by diurnal heat insolation with the critical vertical density gradient that suppresses tidal current tubulence. Dietrich's approach was basic and relied on three simple assumptions of fairly general validity.

(*a*) The vertical distribution of maximum tidal currents can be described by

$$v = v_0(z/H)^{\frac{1}{7}},$$

where v is velocity at depth z, v_0 is velocity at the surface and H is the depth of water. This relation is closely satisfied over much of the northern North Sea.

(*b*) Active vertical mixing takes place if the Richardson number is less than a critical value (0.5), i.e.

$$Ri = \frac{g}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}z}\Big/\left(\frac{\mathrm{d}u}{\mathrm{d}z}\right)^2 < 0.5.$$

(*c*) The diurnal fluctuations in sea-surface temperature penetrate downwards by the processes of heat conduction and produce a vertical temperature gradient derivable from the heat conduction equation

$$\mathrm{d}T/\mathrm{d}z = 2^{\frac{1}{2}}BT_0\,\mathrm{e}^{-Bz},$$

where T is the temperature, $B = (\pi/Kzt)^{\frac{1}{2}}$, T_0 is the amplitude of temperature changes, K_z is the vertical diffusion coefficient and t = 1 day.

From the three relations it is possible to determine the depth of the thermocline if we define it as the depth where the vertical density gradient created by the diurnal fluctuations in sea-surface temperature prevents vertical mixing due to the shear in the tidal current.

Thus for any depth of water and diurnal temperature cycle, the depth of the thermocline is predicted by the amplitude of the tidal stream, the depth of water, and the coefficient of vertical mixing. These quantities are normally very nearly constant from year-to-year and thus the depth of the thermocline in the summer, and therefore the location of fronts, where the thermocline outcrops to the sea surface, will change little, an observation already made by Pingree and others. If this is so, then physical/biological investigations on shallow sea thermoclines and fronts may not be expected to show much variability except possibly in areas of weak tidal stream gradients and very shallow thermoclines where wind-mixing can be particularly effective (Holligan 1978). Such observations may not be expected to contribute to our understanding of possible links between environmental variability and fisheries. The above simple relations evidently do not take into account all the factors, as illustrated in figure 2. Presented here are density sections across a frontal region east of Orkney off northern Scotland (at latitude 59°17′ N). These can be compared with the theoretical thermocline depth derived from the above relations (figure 2*a*) which is relatively constant at 36 m in the east and gradually

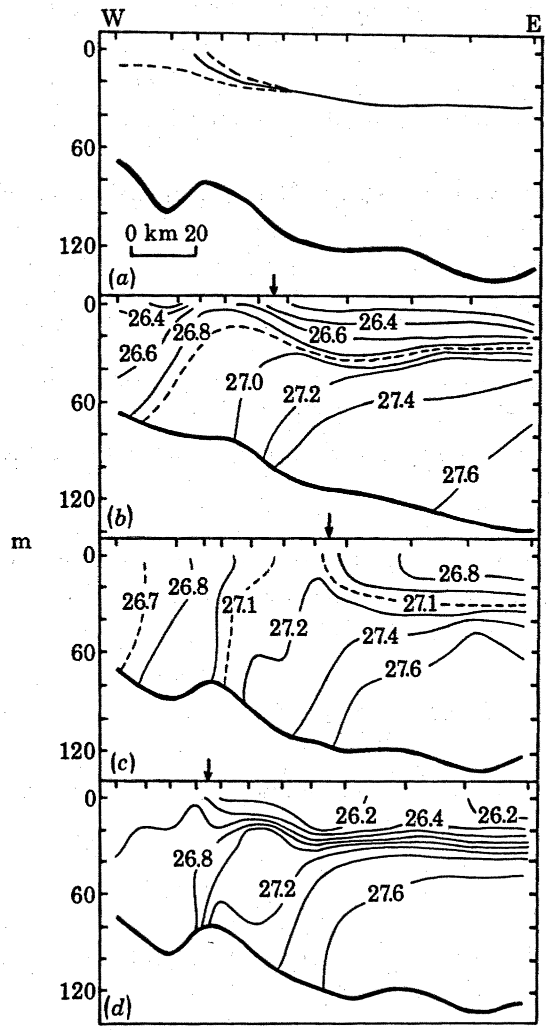

Figure 2. (a) Predicted thermocline depth east of Orkney (——, average tides; ---, spring and neap tides) and density distribution (——) east of Orkney along 59° 17′ N for (*a*) predictions, (*b*) 11 August 1977, (*c*) 14 July 1979 and (*d*) 9 August 1980.

shoals in response to decreasing water depth and increasing tidal current amplitudes towards the west. Theoretically the thermocline outcrops to the surface at the third station from the west end of the section under average tidal conditions, but during spring tides the front should be a very small distance further east while during neap tides the thermocline should extend to the west end of the section eliminating any surface frontal features. Although these thermocline movements are slight it should be noted that they represent an extreme case, as such movements will normally be reduced or eliminated by stored buoyancy owing to the reduction of the vertical eddy diffusion by stratification (James 1977).

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The predicted front at the third station agrees only with observations made on 9 August 1980 (figure 2*d*). In figures 2*b* and *c*, which are sections worked on 11 August 1977 and 14 July 1979 respectively, the observed fronts are some 20 and 30 km respectively to the east of the predicted location. Although figure 2 presents only one section in the summer of each of the given years, each is typical of other sections during the same summer which implies that the observed frontal fluctuations are a consequence of long-period changes in the hydrography of the area. From records collected since regular observation began in this area in 1973, figure 2*c* for 14 July 1977 is found to show the most frequently observed distribution of density, and figures 2*b* and *d* can therefore be regarded as atypical even though the latter agrees with theoretical expectations. Indeed the normal year shows a considerable departure from theory, as the observed front (figure 2*c*) is some 30 km east of the position theoretically expected (figure 2*a*). At the predicted location, the expected and observed (figure 2*d*) thermocline depths are both 32 m, which reduces the possibility of variation in wind-mixing as being a

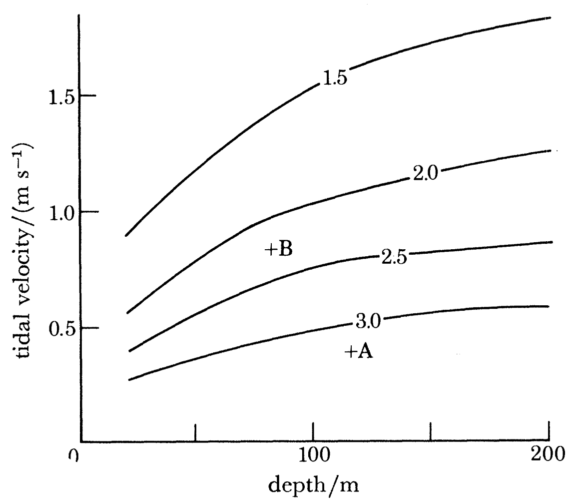

FIGURE 3. Contours of tidal power density parameter (lg v^3/H) against tidal velocity and depth. Points A and B mark position of front on 14 July 1979 and 9 August 1980 respectively.

causative factor in producing the fluctuations in the position of the front (Pingree 1978). Figure 2*b* for 11 August 1977 shows an even greater departure from theory in that the area of least stratification coincides with the predicted frontal position. Inshore and offshore of this position water is stratified, which suggests a serious violation of the established theory. A similar departure from prediction also appears in the distribution of the tidal power density parameter of Simpson & Hunter (1974) who demonstrated that the positions of fronts around the British Isles are determined by fixed values of a parameter similar to the tidal power density V^3/H, assuming that the bouyant energy input is constant over the ocean. Defining $k = \lg(V^3/H)$, Simpson & Hunter (1974) found typical values of k at the location of fronts of 1.7–2. This is roughly in agreement with the frontal position on 9 August 1980 as indicated by point B in figure 3 which is a contour plot of the parameter k against tidal velocity and depth. On 14 July 1979 (figure 2*c*), however, the frontal position coincided with a value of $k > 3$ (point A in figure 3). Similar values of k (> 3) have already been reported for the eastern Bering Sea by Schumacher *et al.* (1979) who explained the high value as being due to an additional input of buoyant energy from melt water. This additional input does not occur on the British continental shelf and another explanation has to be sought for the apparently anomalous position of the front in figure 2*b*. It will now be shown that the observed anomalies can arise from fluctuations in the strength of the Fair Isle current which enters the North Sea between the Orkney and Shetland Islands.

Residual currents around Orkney

Since the end of the last century the existence of a flow of water entering the North Sea between Orkney and Shetland has been recognized as a major factor influencing the hydrographic and biological characteristics of the northwestern North Sea (Dooley 1974). Much of the early evidence for this flow was based on deductions made from the distribution of plankton. Later, studies made by using bottom drift markers supported these conclusions, and more recently indirect evidence has emerged from analyses of the distribution of the radioactive tracer Caesium 137 (Mauchline 1980).

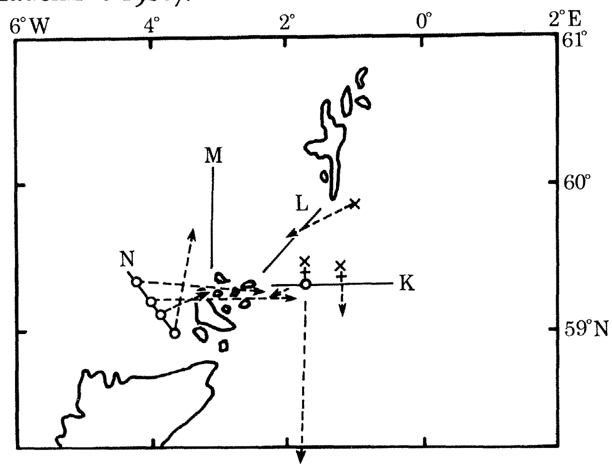

Figure 4. Chart showing position of sections N, M, L, K worked in August 1974. Current vectors indicate mean currents measured in, ×, May 1972; +, May 1973; and, o, August 1974.

An attempt to investigate the intensity and path of the flow more directly was made in August 1974 when five current meter moorings were deployed to the west of Orkney and two to the east (figure 4). The density distribution east of Orkney was then very similar to that of figure 2*c*. The current meters to the east of Orkney were deployed close to the fourth and ninth stations from the west end of this section, i.e. on either side of the front. A strong (*ca.* 15 cm s^{-1}) southwards residual flow was apparent in the well mixed inshore water only (figure 4). To the west of Orkney the moorings were deployed in water stratified in temperature and salinity, and they too showed a strong residual flow but directed towards the east and confined to the upper part of the water column. No attempt was made to establish the continuity of flow through the area because of the difficulties in deploying current meters between Orkney and Shetland due to the very strong tidal streams and intense fishing activity in this area. Residual currents were, however, in approximate geostrophic balance especially in the stratified water to the west and this enabled the estimation of geostrophic volume transport across the four sections K, L, M, N (figure 4) which were worked on five occasions while the moorings were deployed. These sections consistently demonstrated a geostrophic flow of water into the North Sea whose transport increased by a factor of 1.5 from west to east (figure 5). The flow of water was typically 0.2×10^6 m^3 s^{-1} to the west and 0.3×10^6 m^3 s^{-1} to the east of Orkney which represents a considerable volume influx of water to the North Sea, especially to the area east of Orkney. Clearly not all of the influx east of Orkney was originating from the west but the steady increase in flux through sections M and L suggests a slow entrainment of water into the flow as it passes through the tidally active area between Orkney and Shetland. This interpretation is supported by the observation of a steady but relatively weak southwesterly flow of water which was made to the southeast of Shetland in May 1972 (figure 4).

The assumed path of the current is shown schematically in figure 6 and is similar to that deduced by Dooley (1974) and supported by many subsequent measurements. Also shown is the other major current feature of the northern North Sea: the continental slope current that crosses its northern entrance. This flow has a considerably higher volume transport (by a factor of five) than the current entering the North Sea through the Orkney–Shetland (or Fair Isle) Channel and persists throughout the year, whereas the Fair Isle current is much less clearly defined in winter (Reipma 1980). Also shown in figure 6 are the location of the east Orkney section (figure 2) and the contours of tidal current speeds (0.5 and 1 m s^{-1} (dotted lines). This clearly shows how the Fair Isle current must pass through an area of strong tidal

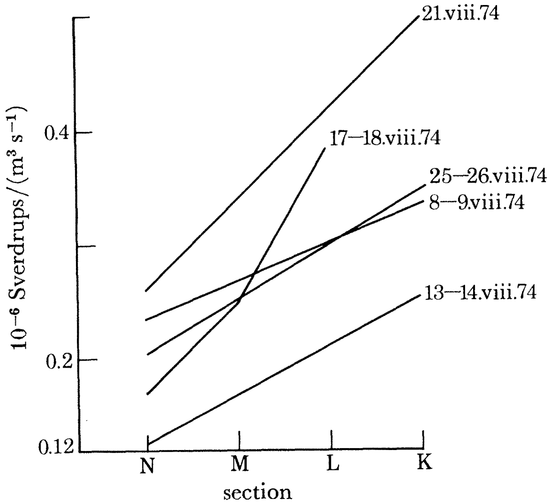

FIGURE 5. Volume transport in Sverdrups (10^6 m^3 s^{-1}) through sections N, M, L, and K.

streams (in excess of 1 m s^{-1}) as it enters the North Sea. The resultant strong vertical mixing in the Fair Isle channel explains why the stratified current to the west of Orkney becomes a flow of vertically well mixed water to the east of Orkney where the downstream weakening of the tides will enable a restratification of the current.

The anomalous distribution of density and, especially, the occasional large departure from theoretical expectations of the frontal position east of Orkney can now be explained. The typical transit time of the water from the well mixed Fair Isle channel waters to the section east of Orkney is only two to three days when the Fair Isle current is at its strongest. Clearly this is insufficient time for equilibrium stratification conditions to be reestablished which violates the above theoretical assumptions. Thus at times of weak or no flow the distribution of stratification can be expected to be as predicted but there will be a gradual offshore migration of the front with increasing flows. Comparison of table 1 with figure 2 supports this contention. Table 1 provides statistics of the five occasions since 1972 when currents have been measured during spring/summer east of Orkney at a position closely coinciding with the fourth station on the east Orkney section (59° 17′ N, 1° 41′ W). In 1972, 1973, 1974 and 1979 the southward flow of the Fair Isle current was uniformly strong (greater than 10 cm s^{-1} near surface) with directional stabilities always in excess of 90 % and standard deviations only about 30 % of the mean. On these occasions density distributions showed the front located near to the seventh station (figure 2*c*). In 1977, however, currents were considerably weaker than hitherto measured with the mean near surface speed only one half of that measured previously. Close to the bottom, residual currents were negligible. Thus the inshore (westward) migration of the front and the atypical density distribution in figure 2 (*b*) can be interpreted as a consequence of the weaker Fair Isle current observed during August 1977. It is unfortunate that there were no

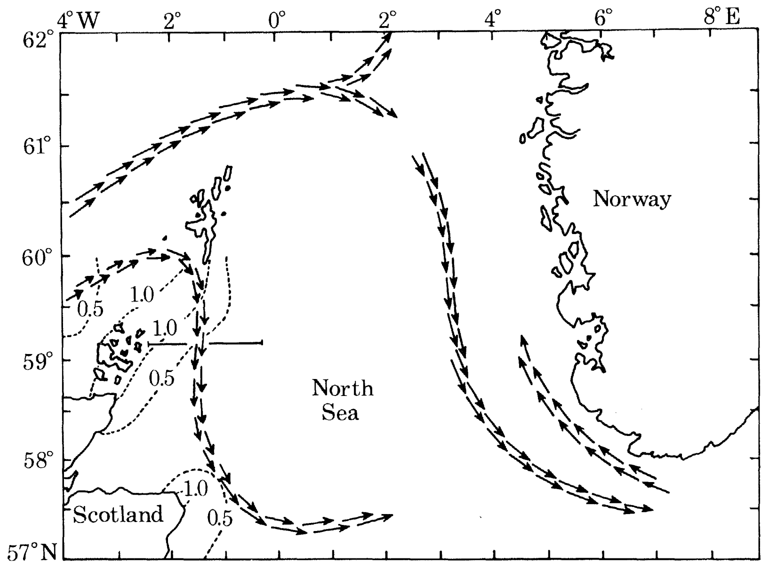

FIGURE 6. Chart showing principal residual currents in the northern North Sea. Contours of tidal current of amplitude 0.5 and $1\,\mathrm{m\,s^{-1}}$, and the east Orkney section along 59° 17′ N are also indicated

TABLE 1. STATISTICS OF MEAN CURRENTS DURING SPRING/SUMMER AT 59° 17′ N, 1° 41′ W

record number	deploy	recover	measurement depth/m	$\frac{\bar{u}}{\mathrm{cm/s}}$	$\frac{\sigma_u}{\mathrm{cm/s}}$	$\frac{\bar{v}}{\mathrm{cm/s}}$	$\frac{\sigma_v}{\mathrm{cm/s}}$	stability (%)
75	10. v. 72	30. v. 72	22	0.3	2.2	−10.3	5.8	96
			47	−1.1	2.2	−8.7	5.6	92
95	19. iv. 73	30. v. 73	61	−1.1	1.7	−7.7	6.5	89
130	8. viii. 74	25. viii. 74	30	−4.1	2.5	−14.2	5.0	98
			70	1.5	2.7	−7.5	4.6	94
165	11. viii. 77	26. viii. 77	26	1.2	2.2	−5.7	4.9	79
			65	1.0	3.1	−0.9	2.4	35
189	4. vii. 79	16. vii. 79	29	2.2	2.1	−11.6	1.6	99
			65	0.6	2.1	−7.8	2.2	96

current measurements coincident with the section worked in 1980 and it can only be surmised that the observed additional westward movement of the front in that year was due to an even weaker flow than observed in 1977.

Thus there is strong evidence to suggest that the cause of the variable density distribution east of Orkney is a direct consequence of the fluctuations in the strength of the Fair Isle current. These fluctuations also influence nutrient and biological conditions east of Orkney and these will be described in the following sections, comparisons being made between the years 1977, 1979 and 1980.

Nutrient distribution east of Orkney

Figure 7 compares the distributions of nitrate east of Orkney for (*a*) August 1977, (*b*) July 1979 and (*c*) August 1980. All the sections show that, in the well stratified summer water in the east, surface nitrate concentrations are very low (often below detection level) and nitrate concentrations in the bottom layers are high (10–12 μmol l^{-1}). At the western end of the section levels are variable from year to year. In 1977 and 1980 nutrient concentrations in this area were generally very low, especially in 1977. In 1979, however, there was a broad band of nutrient-rich water (*ca.* 2 μmol l^{-1}) occupying the area of the Fair Isle current. This indicates that the current can be a supplier of nutrients to the western end of the section. The waters of

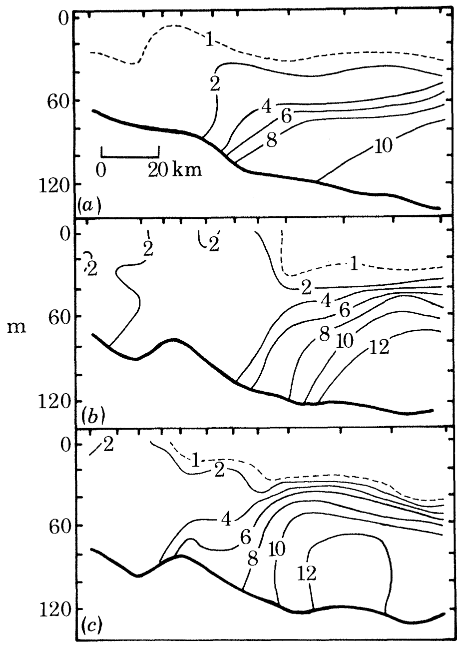

Figure 7. Nitrate distribution (μmol l^{-1} of NO_3) east of Orkney on (*a*) 11 August 1977, (*b*) 14 July 1979 and (*c*) 9 August 1980.

the current to the west of Orkney are nutrient-poor and flow over a large pool of high density nutrient-rich water. Presumably the increased vertical mixing that the current experiences as it approaches the tidally active Fair Isle channel releases some of the nutrient before the current enters the North Sea with higher nutrient levels. As in any coastal upwelling area the injection of nutrients into the surface layers will provoke the onset of primary production of phytoplankton.

Primary production and phytoplankton east of Orkney

The first observations to demonstrate the impact of the Fair Isle current on biological conditions east of Orkney were made on 5 July 1975 (figure 8). The position of the offshore front suggested that the Fair Isle current was of moderate strength, somewhere between the values obtained in 1977 and 1979. The waters associated with the current were again nutrient rich, and the chlorophyll *a* distribution, which in a general sense can be taken as a measure of phytoplankton production, shows that the presence of nutrients was promoting growth. The chlorophyll-rich region was some 40 km wide but its eastward extent was sharply cut off at the surface by the presence of the warm, oligotrophic surface waters beyond the seventh station. The chlorophyll-rich water extends even further eastward at thermocline depth. Here it is mostly in water of the same temperature and salinity as that at the eastern edge of the Fair Isle current, which suggests that its presence there is a consequence of mixing along isopycnal surfaces rather than local production within the thermocline. Similar distributions of chlorophyll-rich water have been observed throughout the summer whenever the Fair Isle current was interpreted as being strong (front far offshore), but at times of weaker flow in 1977 and 1980 radically different distributions were observed (figure 9*a* and *c*). In August 1977 when the weaker flow resulted in low values of nutrients in the Fair Isle current and slight stratification close inshore, the more usual chlorophyll distributions were not apparent. Instead very high levels of chlorophyll were observed only in the weakly stratified inshore water where values as great as 150 mg m^{-3} resulted in a distinct brown discolouration to the water. This discolouration was due to high

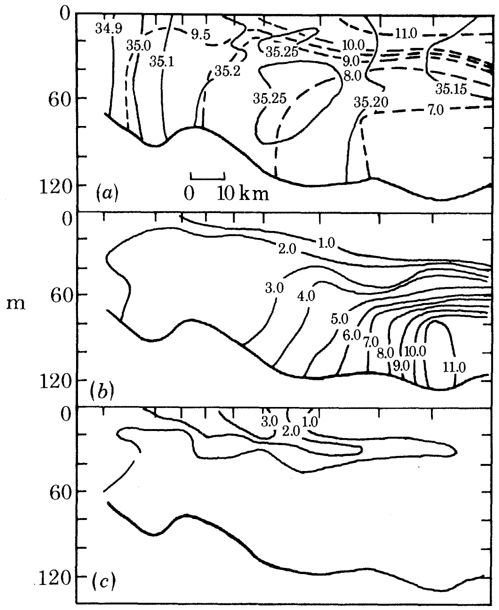

FIGURE 8. Distributions of (*a*) temperature (°C) (- - -) and salinity ($S/10^{-3}$) (——), (*b*) nitrate (μmol l^{-1} of NO_3), and (*c*) chlorophyll (mg m^{-3}) east of Orkney on 3 July 1975.

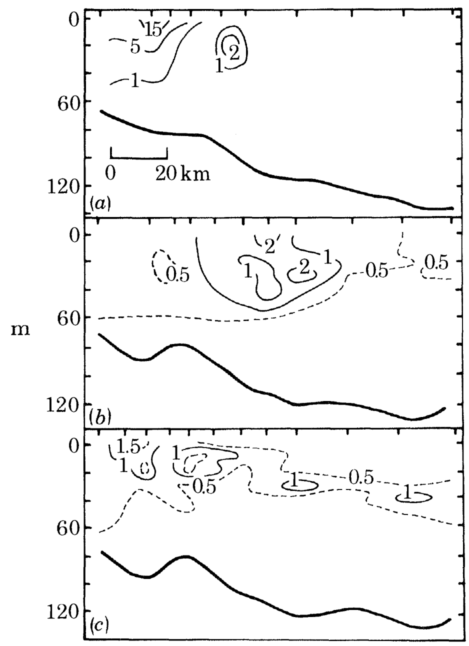

FIGURE 9. Chlorophyll distribution (mg m^{-3}) east of Orkney on (*a*) 11 August, 1977 (*b*) 14 July 1979 and (*c*) 9 August 1980.

concentrations of various dinoflagellate species including *Ceratium*, *Peridinium*, *Dinophysis* and *Prorocentrum*. The dinoflagellates were associated with high numbers of calanoid copepods, the high chlorophyll values therefore suggesting high division rates in spite of the very low nutrient concentrations. This supports the conclusions of Weiler (1980) that dinoflagellates (specifically *Ceratium*) can maintain high division rates in such environments. Weiler considered that physiological adaptation and phagotrophy were important in maintaining this growth rate and might also reflect the dinoflagellate's ability to position themselves at an optimal depth in terms of light or nutrient, giving them an advantage over non-motile phytoplankters.

In August 1980 at the time of very weak flow of the Fair Isle current, chlorophyll levels were low except, once again, very close inshore where slightly enhanced levels were apparent (figure 9). These levels were much lower than in 1977 in spite of the higher nutrient levels

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(*ca.* 2 μmol l^{-1}). This would suggest that the dominant phytoplankton species were diatoms but no samples were collected and this statement cannot be confirmed. Samples were collected during July 1979 when the chlorophyll distribution was similar to that encountered during the periods of strong current flow (figure 9*b*). Diatoms dominated the phytoplankton but the distribution of species was complex with only one species predominating in any one sample. The concentration of any one species often exceeded several million cells per litre and included the diatoms *Pseudonitszchia delicatissima*, *Pseudonitszchia senata*, and *Chaetoceros debile*, and the small green algae Chlorophyceans. There were also many signs of active primary and secondary production with the condition of the diatoms similar to that encountered during spring, i.e. many cells were in the process of division. The presence of the filter-feeding zooplankter *Fritillaria* and copepod nauplii also demonstrated that the diatom population was being grazed upon.

Discussion

Phytoplankton production east of Orkney responds very subtly to changes in the hydrography resulting from the varying strength of the Fair Isle current. The transport of the Fair Isle current east of Orkney is normally about 0.3×10^6 m^3 s^{-1} and, from the very limited evidence presented here, this influences nutrient and stratification conditions in such a way as to favour the primary production of diatoms (figure 9*b*). At times of weaker flow the lower levels of nutrients appears to favour dinoflagellate production in the slightly stratified water inshore of the main current axis where stratification is weaker (figure 9*a*). Whenever the current is absent the coastal zone east of Orkney is not different from any other coastal zone, and levels of production are relatively low. This indicates that the varying strength of the Fair Isle current has an impact on the year-to-year fluctuations in the level of primary production in the northern North Sea. To appreciate the potential level of this impact, consider a 200 km × 200 km area of the northern North Sea that represents the bulk of the sea between Shetland, Orkney and Norway. If the spring phytoplankton bloom utilizes 10 μmol l^{-1} of N in the upper 30 m of water then the total of nitrogen utilized is 10^{10} mol N. Further, if the level of nitrogen in the Fair Isle current is taken as 3 μmol l^{-1} of N then the total input of nitrogen that could potentially be utilized in primary production during a 100-day summer period is also 10^{10} mol N. Thus the Fair Isle current is capable in 100 days of adding to the total primary production of the northern North Sea an amount equivalent to that produced in the spring bloom. The increase in production during the dinoflagellate year 1977 may have been even greater.

Modelling studies (Jones 1973) have suggested that fluctuations in annual primary production by this sort of magnitude could produce a change of at least an order of magnitude in fish larval survival. Thus the calculated changes in primary production are consistent with the observed magnitude of the year-to-year fluctuations in year class strengths (figure 1). It is of course much too early to assess the affect of these fluctuations may have on the fishery of the northern North Sea as the data set is still too short. Furthermore direct effects of changes in the environment are normally masked by other factors, including those directly related to biological factors, and the present paper can be regarded as a small but probably important part of a complex jigsaw. These findings, do, however, seem to support Professor Hempel's comments (Hempel 1978, p. 448) regarding the future of fisheries oceanography which I quote in full: 'Apart from long-term averaging observations on changes in sea surface temperature, detailed information on local currents, vertical stability and bottom temperature during critical periods, is necessary for the understanding of year-to-year changes in primary and secondary production, as well as of egg drift and larval survival. It seem necessary for ICES to develop new approaches to fisheries oceanography, both in long-term observations at crucial places in the North Sea and in complex case studies.'

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