Boundaries in phytoplankton populations

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Abstract.

The transient nature of patterns in phytoplankton distribution (expressed as chlorophyll concentration) is emphasised by reference to work on Cockburn Sound, a shallow marine embayment on the coast of Western Australia. A point source provides most of the nitrogen and phosphorus to a system in which phytoplankton biomass is often limited by the level of inorganic nitrogen. Phosphate is present in excess, but phytoplankton distribution is correlated with phosphate in enriched water. Data, expressed as computer-generated maps, illustrate the dependence of patterns of phosphate and chlorophyll distribution on wind-driven water movement. In-situ fluorometry allows high-speed mapping, and discloses sharp boundaries between waters containing different chlorophyll levels. The importance of 'frontal processes' in maintaining discrete water masses is emphasised.

Introduction

The study of patterns in phytoplankton distribution poses special problems. In contrast to communities of terrestrial or attached aquatic plants, which can in most cases be visited repeatedly when more information is needed, patterns in phytoplankton distribution are transient. Water masses carrying these organisms move and mix in response to changes in wind, tide and radiation. The growth rate, biomass, and species composition of phytoplankton within a moving, mixing water mass are determined by the interplay of nutrient availability, the amount of light for photosynthesis, successional changes, grazing, dilution and sedimentation. The nutrient levels are in turn governed by recycling through organisms in the water column, release from the sediments, supply from sources external to the water body, and mixing processes. Nonetheless the fundamental questions remain: What factors are responsible for determining an observed pattern? Why is a boundary present at any particular time or place?

Because phytoplankton patterns are usually transient, it is important to gather as much relevant information as possible about the environment to explain the observed pattern. Two considerations follow. One is that a particular area might be revisited on a number of occasions to detect recurring patterns—patterns which might be characteristic of the water body. The other is that the rate at which information is gathered should relate to the rate at which patterns may change.

In this paper, these problems are addressed by reference to Cockburn Sound, a marine embayment on the coast of Western Australia.

General features of Cockburn Sound

Morphology

Cockburn Sound (Fig. 1) lies some 35 km south of Perth, Western Australia. It is a basin nearly 20 m deep, partly impounded on the west by Garden Island. In 1971-73 this island was linked to the mainland by a causeway built across a shallow bank (3-5 m deep), and spanned by two bridges. To the north lies another shallow region, Parmelia Bank (3-5 m deep), which also restricts exchange between the main water body and the open ocean. Within the Sound, there is on the eastern side a relatively level, shallow shelf 5-10 m deep, which slopes steeply into the deeper water of the main basin.

Use by man

Cockburn Sound is the only large, sheltered embayment near the metropolitan area of Perth, and this location has led to conflicting uses as a
Fig. 1—Cockburn Sound, Western Australia. The 10 m contour is shown; the depth of the basin reaches 20 m. The sites of outfalls from a sewage works and a fertiliser plant are indicated. The closed circles represent the sites at which water samples were taken during cruises.
resource. On the one hand, it is an ideal deepwater port, and consequently, beginning in 1954, the surrounding land has been industrialised. A large naval facility has been established on Garden Island; and on the mainland there are several industries including an oil refinery, blast furnace and steel rolling mill, superphosphate factory, and processing plants for alumina and nickel. On the other hand, the area is also very suitable for recreation: for swimming, boating, and fishing.

The data presented here were gathered in the course of an investigation of algal blooms in the Sound.

Phytoplankton biomass and nutrient levels

General levels

To determine general levels of biomass and nutrients, and to seek recurring patterns, water samples were collected at 20 sites in the Sound, at intervals of six weeks, and compared with a reference, offshore station in coastal waters to the south-west of Garden Island (Fig. 1). Each sampling cruise occupied two days. The data are summarised in Figure 2, where it can be seen that the Sound had very much higher levels of chlorophyll $a$ and phosphate than the coastal waters, whereas concentrations of inorganic nitrogen were usually comparable. The maximum chlorophyll $a$ concentration recorded was in excess of 110 $\mu g$ 1$^{-1}$, and in mid-summer values of 20-30 $\mu g$ 1$^{-1}$ were common; these levels are high for marine situations and agree with phytoplankton counts made by Chaney (1977), who found that the populations are usually dominated by diatoms or dinoflagellates.

Distribution at particular times

The distributions of various parameters measured during particular cruises were analysed by using the computer programme SYMAP (Dougenik and Sheehan 1977). This programme firstly requires the co-ordinates of points along the coastline, and then the co-ordinates of the sampling sites. Data collected at the sampling sites are then provided, and the programme uses them to calculate values at intervening points, assuming that the seven nearest data points have an effect which is inversely proportional to the square of their distance from the intervening point. The data set is divided into a number of specified class intervals. Contours of the class boundaries are then presented by different symbols and overtyping.

Figure 3 provides examples of the output of the
plot by using the SYMAP programme. It shows chlorophyll \(a\) concentrations divided into five class intervals, represented by different degrees of shading. It is clear that the distribution of chlorophyll \(a\) was not uniform during that cruise (October 1977), and that concentrations were higher on the eastern side than on the western side. As shall be emphasised later, the general distribution pattern of Figure 3 is observed regularly during summer.

**Relation between biomass and nutrients**

There is a marked relation between the distributions of phosphate and chlorophyll (Fig. 3), and this correlation is confirmed if all the cruise data for a year are pooled. The probability that an apparently linear relation between phosphate and chlorophyll is due to random chance is less than 0.001. There is no significant correlation of chlorophyll with inorganic nitrogen.

The ratio between inorganic nitrogen and phosphate in the water, expressed as gram atoms, is typically one or less (Chiffings 1979), so that one might expect inorganic nitrogen to 'limit' phytoplankton biomass (Goldman 1976) if temperature and light intensity are adequate. Assays of nutrient limitation add weight to this suggestion (Chiffings 1979). In these assays, samples of water from the Sound were incubated in the light, with or without additions of inorganic nitrogen, phosphorus, and other nutrients, and changes in chlorophyll levels measured. Typically, only inorganic nitrogen alone produced a marked increase in phytoplankton.

Thus it is the availability of nitrogen which is the primary limiting factor for growth, as indeed it is in marine systems in other parts of the world (e.g. Ryther and Dunstan 1971; Axelrad and Bulthuis 1977; Smith 1978). However, in winter, low light intensity and low temperature may largely determine the amount of chlorophyll present.
It may seem anomalous that there is such a good correlation of phytoplankton (as indicated by chlorophyll) with phosphate, as it is the availability of nitrogen which is limiting phytoplankton in the Sound. The correlation with inorganic nitrogen is poor because levels of this nutrient are generally limiting; levels are very low because most of the available nitrogen is incorporated in phytoplankton.

On the other hand, phosphorus is available in excess, but occurs in the same water masses as the high standing crops of phytoplankton. The phosphate level is so relatively high that the ion behaves conservatively, and can therefore be used as a ‘marker’ in studying the distribution of enriched water in the Sound.

The nutrient distribution

Sources of nutrients

Table 1 lists the significant external sources of nitrogen and phosphorus to the Sound. Industrial effluents and sewage contribute 79% of the nitrogen and 96% of the phosphorus to the system. The main source of both nitrogen (62%) and phosphorus (87%) is from CSBP/KNC—a superphosphate plant and an ammonium nitrate plant, which have a combined outfall (Table 2). The nitrogen from this outfall is 74% inorganic (mainly ammonia), and the phosphorus is 36% ortho-phosphate (Chiffings 1979). This outfall, which is located in the south-east of the Sound (Fig. 1), constitutes virtually a ‘point source’, and provides the bulk of the nutrients to the embayment. The sewage outfall contributed 29% of the nitrogen, and is located to the north-east (Fig. 1). The higher densities of chlorophyll and phosphorus are, in general, related to these two outfalls (Fig. 3, cf Fig. 1).

Water circulation and phytoplankton distribution

Wind-driven water movement

Although there is a recurring, general pattern of phytoplankton and phosphate distribution, there are exceptions. An example of one of the exceptions is given in Figure 4 where, although phosphate distribution again resembles that of chlorophyll, the two show a different pattern to that of Figure 3. The situation is not simple, and so attempts have been made to match the distribution patterns to water circulation in the Sound at the times of sampling.

Astronomic tides are of relatively small magnitude (some 0.6 m) on the coast, but wind-driven water movement is of great consequence. As part of the Cockburn Sound Study, a model for water movement was produced by consultants (Steedman and Associates; Steedman, 1979). The model is wind-driven. It has been partly validated in the field, and appears to describe water movement well at higher wind velocities, though it is less useful for low wind speeds (less than 5 m sec⁻¹).

An example of the model output is given in Figure 5. Arrows show the direction of water movement, and the distance between lines indicates rate of water movement; closely-spaced arrows indicate high rates, well-spaced arrows low rates. Figure 5 illustrates water movement under the prevailing summer weather pattern, with a strong afternoon sea-breeze. At such times water circulation is dominated by a large, anti-clockwise gyre which moves water to the north along the east

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**Table 1. Estimates of nutrient loads into Cockburn Sound waters from external sources.**

<table>
<thead>
<tr>
<th>Source</th>
<th>Nitrogen kg d⁻¹(%)</th>
<th>Phosphorus kg d⁻¹(%)</th>
</tr>
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<tbody>
<tr>
<td>Groundwater</td>
<td>447 (7)</td>
<td>1(&lt;1)</td>
</tr>
<tr>
<td>Coastal Waters and Sewage</td>
<td>218 (3)</td>
<td>145(4)</td>
</tr>
<tr>
<td>Air Emissions</td>
<td>667 (10)</td>
<td>3766(96)</td>
</tr>
<tr>
<td>Rainfall</td>
<td>2 (&lt;1)</td>
<td>0.5(&lt;1)</td>
</tr>
<tr>
<td>Total</td>
<td>6313</td>
<td>3914</td>
</tr>
</tbody>
</table>

1 Further information about all calculations is given by Chiffings (1979). Groundwater estimates were based on physical data for the water table and nutrient concentrations from a number of bore holes near the Sound (Layton Groundwater Consultants, 1979), and discharge estimates made by the Mines Department, Western Australia.
2 Based on estimates of volume exchange between the Sound and the open ocean (Steedman, 1979). Using these estimates, loads of inorganic N and P were calculated from the 1977 CSIRO data (unpublished) for the 50 m station, beyond Rott- nest Island, Western Australia.
3 From measurements made as part of the Cockburn Sound Study (Murphy, 1979).
4 Unpublished data from the Kwinana Air Modelling Study, W.A. Department of Conservation and Environment.
5 Data of O'Connell, CSIRO (pers. comm.) for a year's observations at Dwellingup, which has a similar rainfall to the Sound but is 30 km inland, were multiplied for the area of the Sound.
6 As NO₃ + NO₂⁻ N.
7 As NO₃⁻ N.
8 As PO₄⁻ P.
Table 2. Loads of nitrogen and phosphorus in industrial outfalls and sewage discharged to Cockburn Sound.¹

<table>
<thead>
<tr>
<th></th>
<th>Total Nitrogen kg d⁻¹ (%)</th>
<th>Total Phosphorus kg d⁻¹ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woodman Point Treatment Plant (Sewage effluent)</td>
<td>1422 (29)</td>
<td>261 (7)</td>
</tr>
<tr>
<td>State Energy Commission</td>
<td>110 (2)</td>
<td>220 (6)</td>
</tr>
<tr>
<td>AIS (Steel mill)</td>
<td>49 (1)</td>
<td>2 (&lt;1)</td>
</tr>
<tr>
<td>BHP (Steel mill)</td>
<td>0.9 (1)</td>
<td>&lt;1 (&lt;1)</td>
</tr>
<tr>
<td>BP (Oil refinery)</td>
<td>322 (6)</td>
<td>8 (&lt;1)</td>
</tr>
<tr>
<td>CSBP/KNC (Fertiliser Works)</td>
<td>3075 (62)</td>
<td>3275 (87)</td>
</tr>
<tr>
<td>Total</td>
<td>4979</td>
<td>3766</td>
</tr>
</tbody>
</table>

¹ Data from Murphy (1979).

Water movement and nutrient distribution

Using data from continuous wind records, the output of the model has been examined for days preceding and during each two-day period during which water samples were collected. It is instructive to examine the information from a particular cruise, which was interrupted for a day by a storm event, and then resumed.

Sampling commenced on 18 September in good weather under low energy conditions which are reflected in the output from the model (Fig. 6a); phosphate distribution (Fig. 6b) was consistent with the pattern of water movement suggested by the model. Sampling was disrupted on 19 September, when the passage of two strong fronts from the north-west brought winds which made sampling impossible. These winds produced...
Fig. 5—Output of the Steedman (1979) model for wind-driven water movement in Cockburn Sound (15 February, 1980). The pattern is typical of that produced by summer, sea-breeze dominated weather.

In general, we see how patterns of distribution of phosphate or chlorophyll are clearly related to the interplay between the input of nutrients and the mechanisms controlling water transport.

Chlorophyll a boundaries

Finer-scale distribution patterns

On many occasions marked discontinuities were observed in the concentration of chlorophyll a, over short distances. A programme was therefore begun in which these more detailed patterns were examined, by using *in situ* fluorometry to obtain rapid, quantitative measurements of surface chlorophyll a concentrations.

In this method, the boat was driven at full speed (25-27 knots), so that water was forced by the velocity of the boat into a tube at the stern, passed through a fluorometer (Turner Designs 10, Palo Alto, U.S.A.) in the boat, and was then discarded. Weather permitting, this allowed the Sound to be mapped in two h, and produced a large amount of data in the form of a chart trace. At the same time a number of discrete water samples was taken back to the laboratory for normal chlorophyll analysis, so that a calibration could be made between fluorometer readings and chlorophyll level. A programme was developed for digitising the chart records, correcting them to chlorophyll a, and placing the information straight into the SYMAP programme. Figure 7 shows a sequence of maps taken over a period of 42 days, usually at four-day intervals, which illustrates the changing patterns of chlorophyll distribution. At the beginning of the sequence, in late summer, the pattern was similar to that obtained during the summer cruises, and described above; there were high standing crops of chlorophyll on the eastern side of the Sound. This pattern was disrupted as the weeks passed, and the weather was less dominated by sea-breeze.

Another notable feature of these maps, in which chlorophyll concentrations were divided into ten ‘size classes’, is the very abrupt transitions between waters with high chlorophyll levels, and those with relatively low chlorophyll levels. In many of the maps the effect is especially marked on the eastern side of the Sound. When one of these boundaries was traversed during a fluorometry run, the chart record showed an abrupt discontinuity (Fig. 8), and the change in water colour was clearly visible to the unaided eye.

Boundary structure

Figure 9 shows chlorophyll a and inorganic nutrient concentrations, which were determined for samples collected at intervals across such a boundary. The pattern of plotted contours for phosphate, chlorophyll and nitrate are similar; that for ammonia is rather different. Clearly there is a marked difference in nutrient concentrations between the two distinct, adjacent water masses. The high nutrient, high chlorophyll a mass coincides with the predicted, northward-moving enriched water on the shallow, eastern side of the Sound.
Discussion

The oceanic and nearshore coastal waters near the southern Western Australian coast generally have very low levels of nutrients. The waters of Cockburn Sound, by comparison, are relatively nutrient-rich. This enrichment is a product of the loading of high concentrations of inorganic nitrogen and phosphorus at a point in the Sound, coupled with poor exchange between the water in the Sound and that in the open ocean. The net result is that high concentrations of phytoplankton occur within the Sound. Caperon et al. (1971), Hardy and Jubayli (1976) and Smith (1978) found similar increases in phytoplankton standing crops in marine coastal waters which had been enriched with sewage effluent.
Fig. 7—Changes in the distribution of chlorophyll in the surface waters of Cockburn Sound. Data were collected by in situ fluorometry over a period of 42 days, commencing 2 February, 1979, and divided into 10 size classes, from <0.5 to >15.5 at 1.5 µg l⁻¹ intervals. Output from the SYMAP programme was converted into different levels of shading and photographed.
Fig. 8—A boundary between two water masses in Cockburn Sound, containing different levels of phytoplankton. The vertical scale, of readings of in situ fluorescence units, corresponds with a change in concentration from 1.5 µg l⁻¹ to 0.5 µg l⁻¹ chlorophyll a. The horizontal scale is recorded as time, but represents in this case a traverse of 4,800 m.

Within the Sound, nutrients and phytoplankton are not evenly distributed, and the patterns most frequently observed are attributed to the location of the primary nutrient source in relation to the prevailing water circulation patterns. There are well-defined vertical and horizontal boundaries in the distribution of both chlorophyll a and nutrients, and so the physical processes which prevent the mixing of the water masses are of great importance. These 'frontal processes', which often persist during the summer period, lead to the containment of nutrient-rich waters along the eastern

Fig. 9—The distributions of nutrients and chlorophyll in the region of a 'front' in Cockburn Sound (14 March 1980). In each case, the dashed line suggests a boundary between two water masses. The surface 'boundary' (arrowed) was the position of a marked colour change observed during sampling.
edge and southern end of the Sound; such waters support high standing crops of phytoplankton.

In the sequence of surface chlorophyll maps which extend from late summer to early autumn there is a decline in the level of phytoplankton. This decline could be due to a reduction in primary production with a fall in light and temperature, or may result from a ‘weakening’ of the frontal processes leading to a more rapid dispersion of phytoplankton biomass. The possible role of transport processes in controlling levels of phytoplankton was also emphasized by Welch et al. (1972), who proposed that phytoplankton blooms occurred in the Duwarrish Estuary when minimum hydrological conditions led to a reduction in the dispersal of water masses in which phytoplankton populations could potentially build up.

The Cockburn Sound data add to a growing literature which demonstrates the importance of frontal processes, at a wide range of scales, to phytoplankton density. Density differences may be associated with major oceanic boundaries (Brandt and Wadley, this volume). Iverson et al. (1979) reported enhanced phytoplankton production associated with a shelf-break front in the southeastern Bering Sea. Savidge (1976) described differences in phytoplankton populations across a thermal front in the Celtic and Western Irish Seas; and differences in sea colour in the Irish Sea on either side of a front were attributed by Simpson and Hunter (1974) to differences in phytoplankton density. On a finer scale, Bowman and Essaies (1977) found that differences in phytoplankton density were associated with tidally-induced fronts in the shallow waters of Long Island Sound. The spectral analysis of patterns of phytoplankton distribution in lakes and marine systems suggests that physical transport systems are important in controlling phytoplankton abundance, especially at scales of less than about five km (Platt and Denman 1975).

These observations emphasize the importance of physical factors in controlling the exchange of nutrients between water masses, and thus in controlling standing crops of phytoplankton. The presence of such boundaries has important management implications for the siting of effluent discharges in shallow, marine ecosystems.

Acknowledgements

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References


