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Relationship between chlorophyll and temperature fields in the St. Lawrence estuary.

by

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Summary

Power spectral analysis has been applied to series of chlorophyll *a* and temperature obtained from multiple-depth tows. Coherence between temperature and chlorophyll at the same depth was usually significant at most wavelengths greater than 100 m. Signals from sensors separated 4-5 m in the vertical showed no significant coherence. In several runs with high chlorophyll variance and low coherence between chlorophyll and temperature, the observed variance in chlorophyll was more than 10 times that which could be accounted for by the effects of internal waves and vertical mixing. Such runs are believed to have taken place in regions of greater biological activity as characterized by higher growth rates.

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Introduction

The importance of spatial heterogeneity as a stabilizing factor in ecosystems has been demonstrated theoretically (May, 1973; Steele, 1974). The pelagic ecosystem of the sea is particularly interesting because passive dispersal of the primary producers (phytoplankton) by

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the physical dynamics of the medium should be a controlling force on the spatial structure. However, the sea itself presents a formidable obstacle to anyone attempting to obtain samples sufficiently dense yet sufficiently synoptic to resolve the spatial structure on scales that it is important. Only for phytoplankton biomass, which can be sampled in a continuous automatic manner through the utilization of chlorophyll *a* fluorescence properties (Lorenzen, 1966), are we able to obtain data which satisfy the above criteria. With the use of powerful statistical techniques such as spectra analysis, these data allow us to separate out the existing spatial and temporal structure from the background error variance associated with inadequate sampling.

Previous work concerned with time or space series of chlorophyll *a* obtained from submerged pumps, either anchored or towed at a constant depth, suggest that turbulent dispersion may be controlling the variability but that at least part of the variability of chlorophyll observed on constant-depth contours can be explained by vertical displacements (Platt, 1972; Denman and Platt, 1975; Powell *et al.*, in press).

In this paper, a series of experiments are presented where chlorophyll *a* and temperature fluctuations were measured along horizontal transects, simultaneously at two depths 4 or 5 m apart. Two main questions are addressed: how much does the observed horizontal variability depend on vertical structure?; and to what extent does the horizontal structure depend on biological processes?

Experimental Results

During the period 22-26 June, 1973, ten data runs of chlorophyll *a* and temperature along horizontal transects were obtained in the maritime estuary of the St. Lawrence River. The first four runs contain data obtained simultaneously at two depths, the rest contain data at one depth only. The signals were sampled at a rate of 1 Hz and stored on magnetic tape. The time series have been converted to space series along horizontal transects under the assumption that the horizontal pattern changed little in the time taken to complete a transect ($\sim$ 2 h). For a ship speed of about 3 m s^{-1}, the one-second sampling interval in time corresponds then to a 3 m sampling interval in space.

The space series for two runs with information at a single depth shown in Fig. 1 represent the two extreme cases for the data set. Run 24-1 (Fig. 1a) represents the case of least correlation between chlorophyll and temperature at the same depth, and Run 25-1 represents the case of greatest correlation. The negative correlations are a general characteristic of the observations; only for one run did the signals show positive correlation.

The sign of the correlations can be explained by the sign of the vertical gradients of temperature and chlorophyll. Suppose that most of the observed horizontal variance is due either to vertical displacements by the internal wave field or to non-uniform vertical mixing, the intensity of which depends on the vertical gradients. Then, if the signs of the gradients of both chlorophyll and temperature are the same, fluctuations from these processes will be positively correlated; but, if the gradients are of the opposite sign, such fluctuations will be negatively correlated. Information on the vertical gradients, obtained from the two-depth runs and from vertical profiles taken between runs, is entirely consistent with this hypothesis, indicating that nonuniform vertical displacements, caused primarily by internal waves, are responsible for a significant fraction of the observed chlorophyll variance.

Coherence and phase spectra have been calculated between the series so that the degree of correlation, the wavelengths at which the correlation occurs, and the phase of the correlation can all be quantified. In Fig. 2 are shown coherence and phase spectra for the series plotted in Fig. 1. The dashed lines on the coherence plots represent the 95% significance for coherence greater than that expected between two random series (Benignus, 1969). In Run 24-1 there is little or no significant coherence between temperature and chlorophyll; in Run 25-1 they are highly coherent at all inverse wavelengths (reciprocal of the wavelength) up to 2×10^{-2} m^{-1} (a wavelength of 50 m). The phase spectra are consistent: in Run 24-1 the phase is random at all scales, but in Run 25-1 the phase is near 180° (negative correlations) at inverse wavelengths up to 2×10^{-2} m^{-1} then becomes random, corresponding to the regions of significant and insignificant coherence.

The runs with signals from two depths separated by 4 to 5 m in the vertical, of which Fig. 3 is representative, provide additional information on vertical layering. Although chlorophyll and temperature at the same depth were usually coherent over some range of inverse wavelengths (as shown in the two left-hand panels of Fig. 3), neither parameter was coherent over a vertical separation of 4 m (two right-hand panels of Fig. 3).

We can, from these runs, estimate the contribution by effects of the vertical gradients to the observed variance in chlorophyll along a horizontal transect. Consider the temperature variance s_T^2 (the second moment of the original series) to be due entirely to displacements of the vertical gradients by internal waves and/or turbulent mixing across the gradients. Then s_T^2 should be proportional to the square of the mean vertical gradient along the tow, which we estimate from the difference between the mean temperatures at the two depths, $\Delta\langle T\rangle$. If chlorophyll variations were also caused by vertical displacements, then chlorophyll variance should be proportional to the square of the mean chlorophyll gradient, and the two ratios, $R(C) = s_C/\Delta\langle \text{Chl } a\rangle$ and $R(T) = s_T/\Delta\langle T\rangle$ should be equal:

$$R(C)^2/R(T)^2 \simeq 1.$$

However, if fluctuations of biological origin should dominate the observed chlorophyll variance, then

$$R(C)^2/R(T)^2 >> 1.$$

These ratios for all the two-depth runs are presented in Table 1. While $R(C)^2/R(T)^2$ is roughly 1 in several cases, in other cases, notably 22-4 (5 m), 23-1 (8 m) and 23-2 (8 m), the chlorophyll series contain more than 10 times the variance accounted for by vertical gradient effects.

Discussion

The data runs with coherence between chlorophyll and temperature indicate that a significant portion of the observed chlorophyll variance along horizontal transects is of physical origin. Furthermore, the data from some of the multiple-depth tows suggest that physical processes which scale according to vertical gradients, such as internal waves and vertical mixing, are responsible for much of the observed variance.

However, runs with low temperature-chlorophyll coherence and runs which have variance well in excess of that attributed to vertical gradients suggest that often most of the chlorophyll fluctuations are of biological origin. From the entire data set, Spearman rank-correlation analyses indicate significant associations (at a 95% level): first, between low coherence (between chlorophyll and temperature) and high chlorophyll variance, and second, between $R(C)^2/R(T)^2$ from Table 1 and corresponding values of an index of relative chlorophyll variability.

In such cases of excess chlorophyll variability, it is likely that the phytoplankton were growing fast enough to create horizontal fluctuations on the kilometre scale which were relatively long-lived in the face of the dispersive effects of the non-steady fluid motions. In the other cases of low variance and high coherence, the phytoplankton may have been in a slowly growing or senescent phase.

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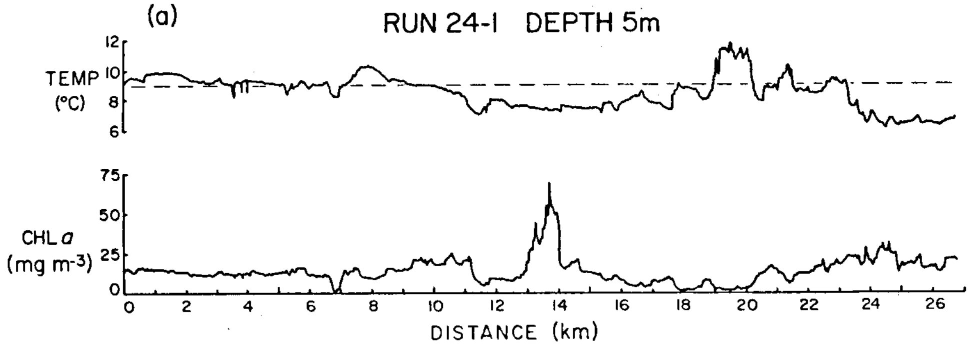
Table 1: Ratios of the root-mean-square signal variation along a transect, s, to the difference between the mean signals from two depths, Δ<T>.

Run	Depth (m)	R(Temp) (= $s_T/\Delta\langle T\rangle$)	R(Chl a) (= $s_C/\Delta\langle \text{Chl } a\rangle$)	$\frac{R(C)^2}{R(T)^2}$
22-4	5.0	0.16	0.85	28
	9.0	0.44	0.54	1.5
22-5	6.0	0.43	1.14	7.0
	9.4	0.23	0.62	7.3
22-6*	3.8	0.10	-0.06	0.4
23-1	4.2	0.13	-0.17	1.7
	8.0	0.38	-1.31	12
23-2	4.4	0.12	-0.11	0.8
	8.4	0.18	-0.78	19

*Chlorophyll a signal was off scale about 12% of the time on the deeper signal so only the mean value of that signal was used.

Figure 1: Series of chlorophyll *a* and temperature for Runs 24-1 (Panel a) and 25-1 (Panel b).


(a)
RUN 24-1 DEPTH 5m
TEMP (°C)
12
10
8
6
CHL a (mg m-3)
75
50
25
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
DISTANCE (km)

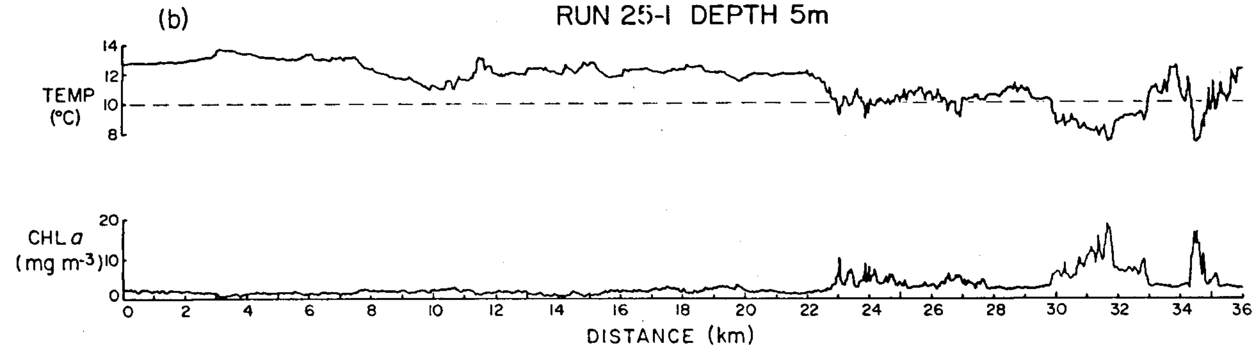

(b)
RUN 25-1 DEPTH 5m
TEMP (°C)
14
12
10
8
CHL a (mg m-3)
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
DISTANCE (km)

Figure 2: Coherence and phase estimates plotted against inverse wavelength for Runs 24-1 and 25-1.

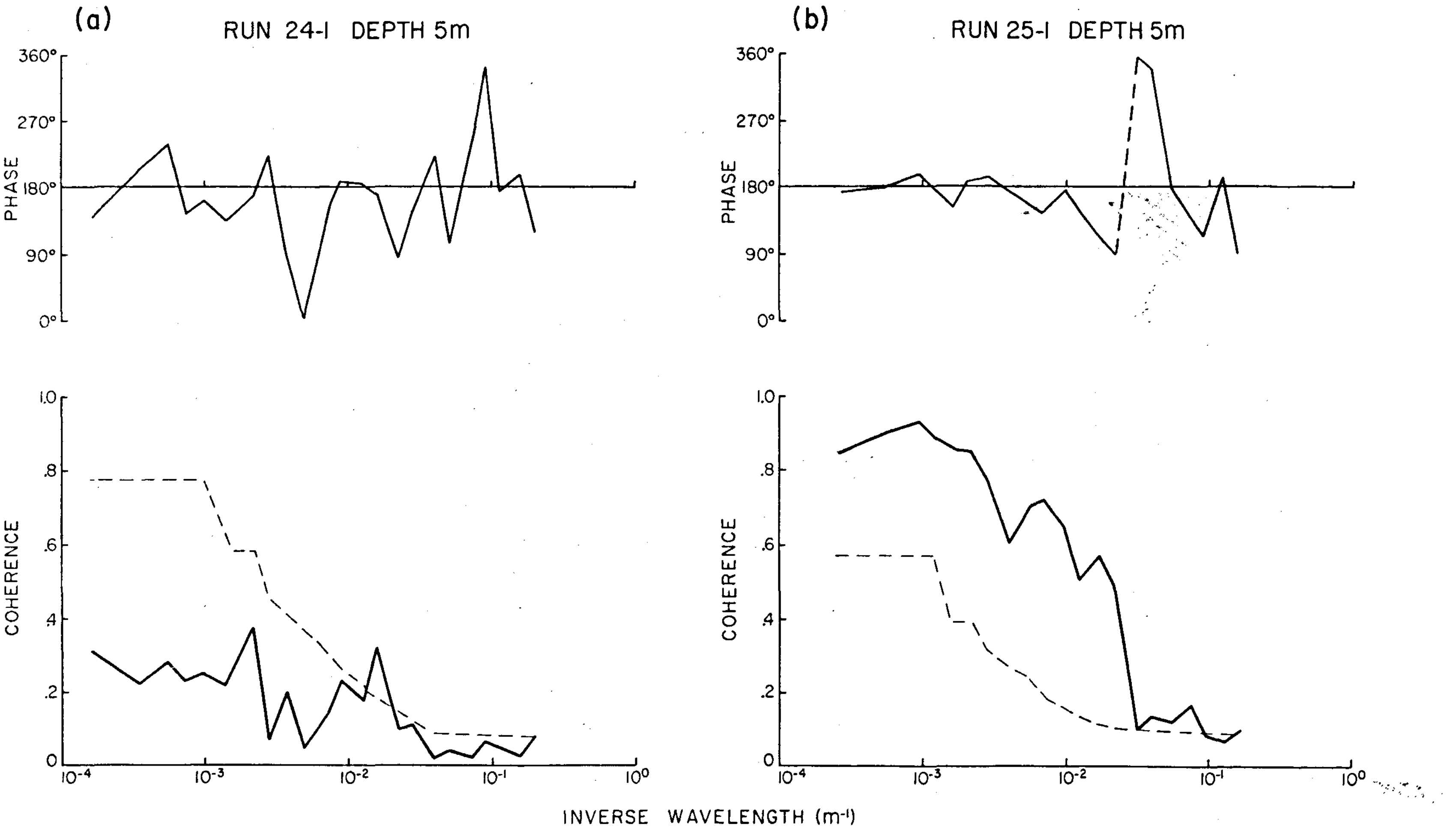
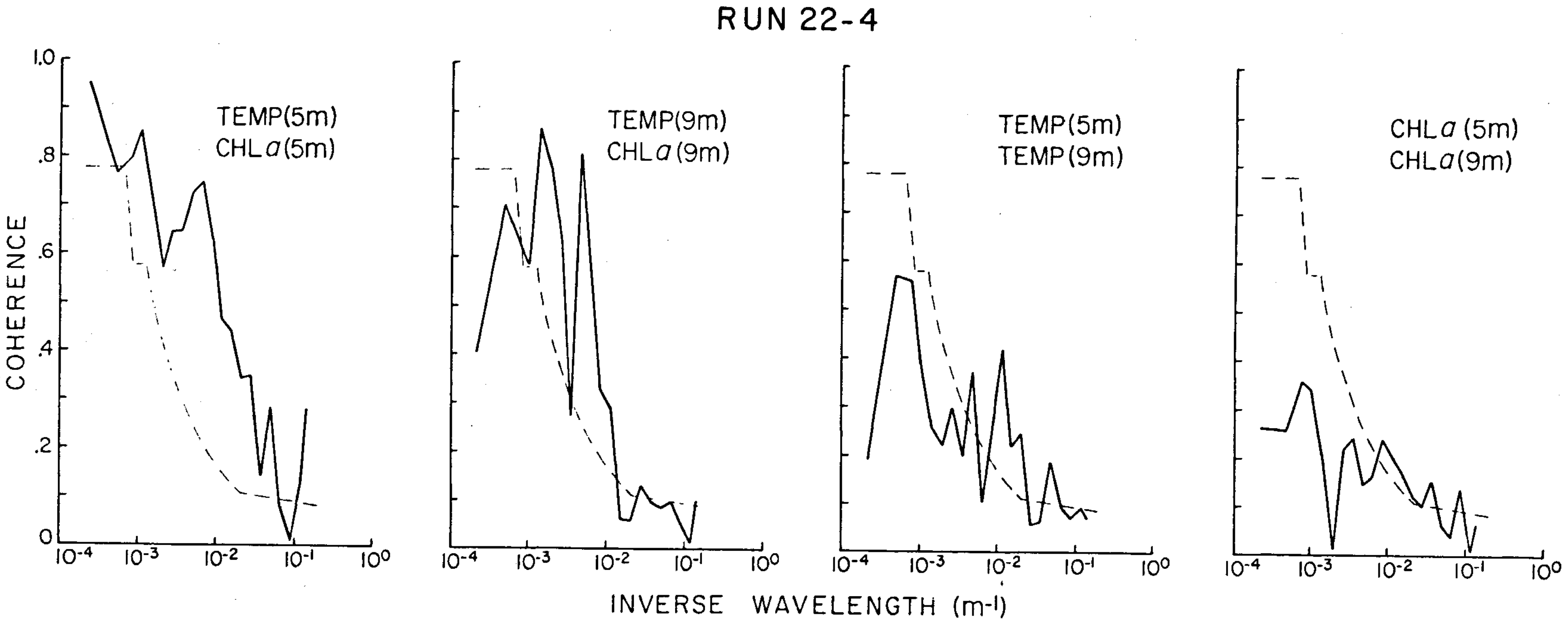

(a)
RUN 24-1 DEPTH 5m
(b)
RUN 25-1 DEPTH 5m
PHASE
360°
270°
180°
90°
0°
COHERENCE
1.0
.8
.6
.4
.2
0
10^-4
10^-3
10^-2
10^-1
10^0
INVERSE WAVELENGTH (m^-1)

Figure 3: Coherence estimates for four combinations of the series at two depths in Run 22-4.


RUN 22-4
COHERENCE
1.0
.8
.6
.4
.2
0
TEMP(5m)
CHL a(5m)
TEMP(9m)
CHL a(9m)
TEMP(5m)
TEMP(9m)
CHL a (5m)
CHL a(9m)
10-4
10-3
10-2
10-1
100
INVERSE WAVELENGTH (m-1)