Prediction of the Development of Red Tide by the Spectral Analysis - A New Approach.

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Abstract   Sequential observations were carried out in Atsumi Bay during the period from the beginning to the end of a bloom of the diatom *Eucampia zodiacus*. Spectral analysis was applied to the data sets of temperature, salinity and fluorescence, which were continuously monitored in the surface layer. From the unconcurrence of the peaks in the power spectral density of respective parameters, it appears that the behavior of phytoplankton patches was rather independent of the distribution of water masses. The red tide often extends to the whole area of the bay. Therefore, in a small-scale bay like Atsumi Bay, it would be difficult to discuss the developmental processes of red tide in the viewpoint of the so-called "critical size" at which the reproduction of phytoplankton and the physical dissipation of the eddies balance. However, the growth and deterioration of the phytoplankton patch in size were traced by the shift of density peaks in the power spectrum of fluorescence. The coherences among the parameters directly reflected the change in weather and the subsequent transition of the bloom. Spectral analysis could be employed for routine operation to clearly predict the development of red tides in a eutrophic bay.
Key Words: patch, phytoplankton, power spectrum, red tide, spectral analysis.

INTRODUCTION

Atsumi Bay is a part of the Ise Bay where the industrial waste is legally regulated; the industries draining more than $50 \, t \cdot d^{-1}$ are the target of the regulation by the local government. The regulation is actually carried out by the total amount of chemical oxygen demand (COD), and not for the concentration of nutrient salts such as dissolved nitrogen and phosphorus, that accelerate the eutrophication process in the bay. As an inevitable result, red tides frequently occur regardless of the seasons in the Atsumi Bay.

Nori culture is one of the successful fisheries in the bay. In recent years, the occurrence of red tides was observed in winter when a large amount of Nori is being cultivated. The formation of red tides results the depletion of nutrient salts in the culture ground that damages the growth of the Nori leaves. Considerable decrease in the Nori production due to red tides made the Fisheries Agency of Japan to finance a research project for the development of a model to predict the generation of red tide.

Computer simulation of coastal ecosystem could be one of the most superior methods to understand the ecosystem, and it has been applied as a practical method for the prediction of the formation of oxygen depleted water in the bottom layer of the bay (INOKAWA *et al.*,

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1989). However, for the routine running of the computer program, input of data such as organic nitrogen or phosphorus as the initial values are required, but the analyses of these parameters are time-consuming processes. On the other hand, temperature, salinity and fluorescence are easily measureable parameters *in situ* using submersible instruments, compare to the time-consuming chemical analyses of seawater. Advances in measuring technology enabled us to obtain continuously a large amount of data using the submersible instruments.

Spectral analysis has been applied to interprete these continuous records obtained in the aquatic environment (PLATT, 1972; DENMAN and PLATT, 1975; POWELL et al., 1975; DENMAN, 1976; FASHAM and PUGH, 1976). The theoretical background of the analysis is as follows (detail description will be made in the next section). Patterns of phytoplankton distribution in the aquatic environment are influenced fundamentally by both physical and biological processes. Turbulent process contributes to dissipate the phytoplankton patches, while reproduction of the cells acts to accelerate the development of phytoplankton patchness. Then we can imagine that there exists the critical phytoplankton patch size at which the growth and the physical dissipation balance. Moreover, we are able to know the spatial scale of the patch from the end product, power spectrum.

Although it would be difficult to discuss the development and cessation of phytoplankton patch from the critical size in a small bay when the size of the bay is equivallent to or smaller than the theoretical critical size, the byproduct of the spectral analysis, that is, coherence among parameters measured could be applied to see the relationship of spatial variation in these parameters. In the present study, discussions are made for the feasibility of the application of spectral analysis and the coherence to predict the development of red tide in a eutrophic bay.

THEORETICAL BACKGROUND

Spectral analysis is applied to various data showing random variations. The end product of the analysis, the power spectrum, is a plot of the distribution of variance for wavenumbers that generally show time- or space-scales. KOLMOGOROV (1941) deduced that the logarithmic plot of the power spectrum of velocity fluctuations shows a straight line with a slope -5/3 in the turbulent field of homogeneity and isotropy in three dimensions. And if a peak found in the plotted line, it means the predominance of variance at the wavenumber.

The first attempt to formulate an expression for the chlorophyll spectrum was made by DENMAN and PLATT (1976) who used the method of dimensional analysis. They explained, showing three regimes, that the relationship between the time-scale of turbulent eddy (τ; the time taken for an eddy of size d to transfer its kinetic energy to eddies of size d/2) and the time-scale of phytoplankton reproduction (μ). If $\tau < < \mu^{-1}$, the phytoplankton reproduction has a negligible effect, and the chlorophyll spectrum should not be different from those of conservative parameters such as temperature and salinity. On the other hand, if $\tau > > \mu^{-1}$, the reproduction cannot now be neglected, and the chlorophyll variance should have a gentle slope compared to those of conservative parameters. And $\tau \sim \mu^{-1}$ represents a transition regime.

In a turbulent flow field of isotropy in three dimensions, $E_v(k)$, the variance of velocity fluctuations, depends only on the wavenumber k and on the rate of transfer of kinetic energy from lower to higher wavenumbers. The transfer rate must be a constant equal to the rate of viscous dissipation, ε, at small scales. This leads to the well-known relationship of KOLMOGOROV (1941) mentioned earlier;

$$E_v(k) = A\varepsilon^{2/3}k^{-5/3}, \qquad (1)$$

where A is a dimensionless constant.

Consider next a coservative parameter, temperature, θ. Assume that its conductivity is small compared to the viscosity of the fluid, specify the variance spectrum, $E_\theta(k)$, using χ_θ which represents the destruction rate of the variance in θ at high wavenumbers. Here, χ_θ is a parameter completely analogous to ε. Since a dimensional analysis also predicts a $k^{-5/3}$ dependence for $E_\theta(k)$ (CORRSIN, 1951),

$$E_\theta(k) = A'\chi_\theta\varepsilon^{-1/3}k^{-5/3}, \qquad (2)$$

where A' is also a dimensionless constant.

On the other hand, the chlorophyll spectrum $E_\beta(k)$ will depend not only on parameters ε, k and χ_β but also on the reproduction rate μ, therefore the equation is expressed as below;

$$E_\beta(k) = A''\chi_\beta\mu^{-1}k^{-1}F(\varepsilon k^2/\mu^3). \qquad (3)$$

Here F is an unspecified function of the dimensionless group in the parentheses.

Considering the wavenumber at the critical patch size, k_c, which corresponds to the scale at which phytoplankton growth and turbulent energy dissipation are comparable, the regime of $\tau \sim \mu^{-1}$. Since the life span of turbulent eddies depends on ε, using ε and k by the concept of dimension analysis (OKUBO, 1979),
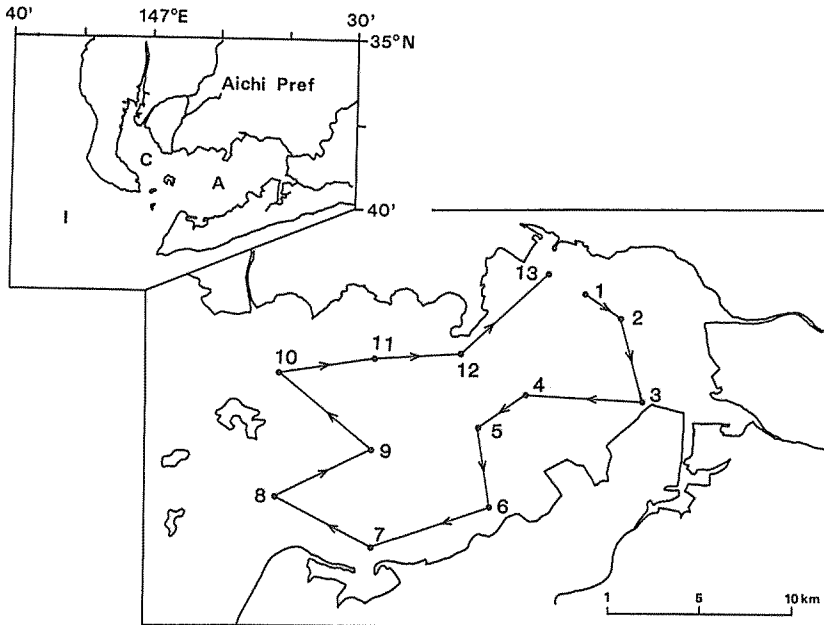
$$\tau \sim \varepsilon^{-1/3}k^{-2/3}. \qquad (4)$$

Fig. 1. Locations of 13 stations through which the continuous observations of temperature, salinity and fluorescence in the surface layer were carried out. A; Atsumi Bay, C; Chita Bay, I; Ise Bay.
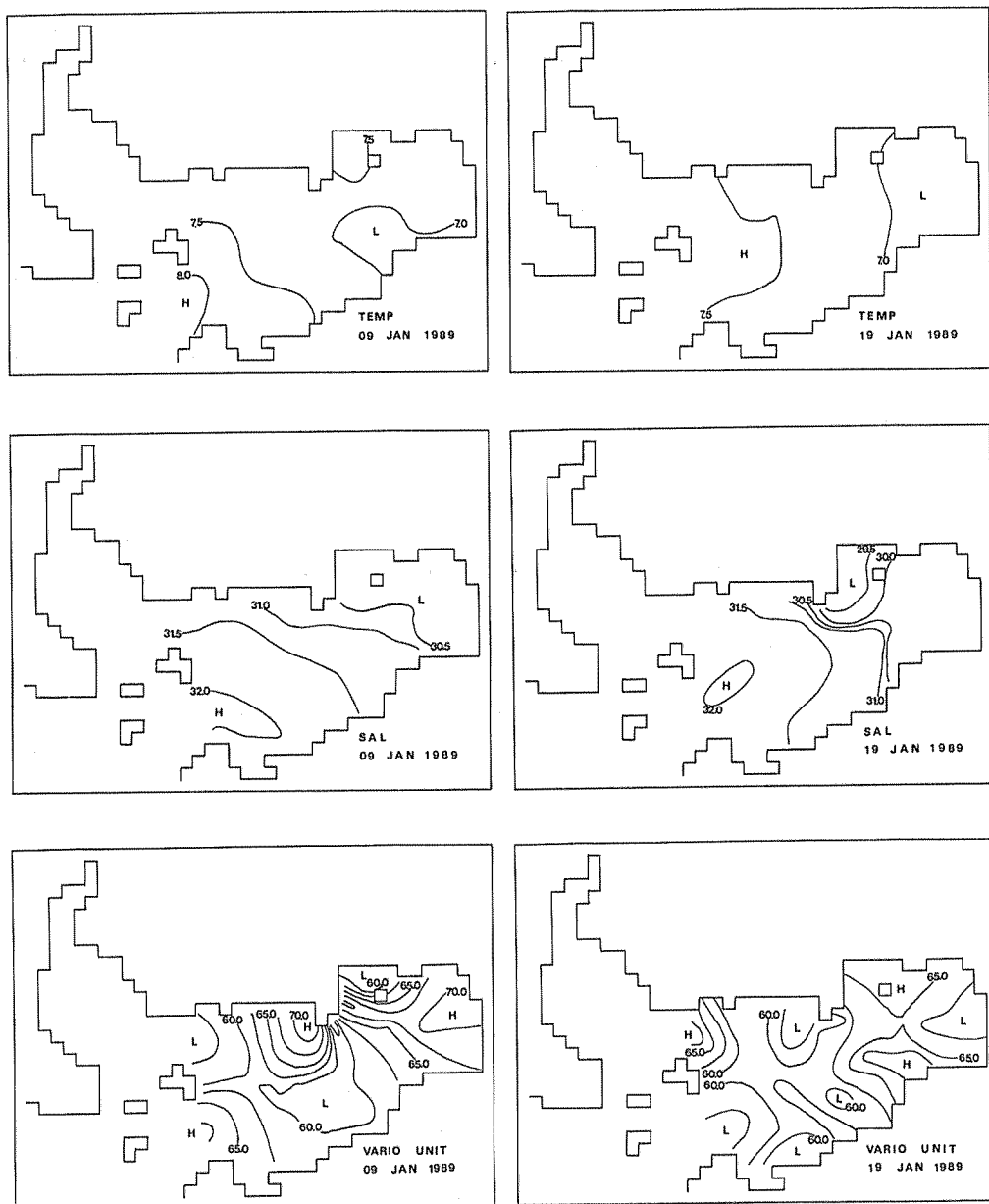
Fig. 2. Spatial distribution of temperature (°C), salinity and fluorescence (Vario unit; ×10 mV) of the surface layer.

Time taking for cell reproduction μ^{-1} is equal to τ at the critical patch size, therefore,

$$k_c \equiv (\mu^3/\varepsilon)^{1/2}. \tag{5}$$

Using this characteristic wavenumber, the equation (3) is rewritten as

$$E_\beta(k) = A''\chi_\beta\mu^{-1}k^{-1}F(k/k_c). \tag{6}$$

For the regime of $k \gg k_c$, namely the spatial scale less than the critical patch size, $E_\beta(k)$ should show a similar shape to $E_\theta(k)$. However, for the scale larger than the critical patch size, $k \ll k_c$, ε will be unimportant, then E_β will be written as follows,
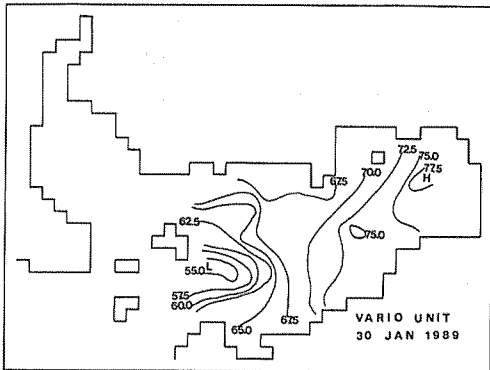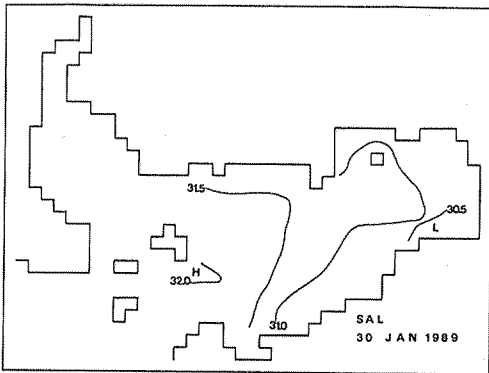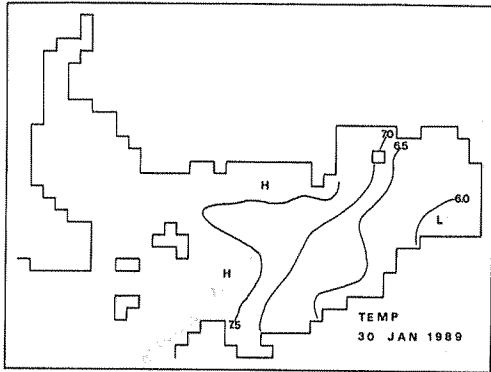
Fig. 2.   Continued.

$$E_\beta(k) = C\chi_\beta\mu^{-1}k^{-1}, \qquad (7)$$

where C is a dimensionless constant. We now recognized the chlorophyll spectrum has a gentle slope of −1 while the conservative paremeters have a slope of −5/3.

We must, however, consider the conditions that these deductions are rather intuitive and deserve attention on no consideration to the differences of growth and death rates among individual species (DENMAN and PLATT, 1976).

OBSERVATIONS AND ANALYTICAL METHODS

Temperature, salinity (CSTD, EMS-12, Electronic Measurement Systems Co., Ltd.) and *in vivo* fluorescence (Variosens II, Impulse Physics Co., Ltd.) of the surface layer were continuously measured cruising through 13 stations located in the Atsumi Bay (Fig. 1). The investigations were carried out on 9, 19 and 30 of January 1989. A filter having 77 % transmittancy in the range of 380–544 nm for excitation and another having 84 % transmittancy in 680±26 nm for receiver were respectively installed in the fluorometer. The CSTD and Variosens were set in a 55 l polyethylene container (water volume excluding the instruments is 38 l), and sea water was pumped up from the intake of the ship's bottom at 1.2 m depth. Data set was obtained at every 5 sec with a cruising speed of 32 km·h⁻¹, which corresponds to a spatial distance of 45 m per one sample. With flushing rate of the pump used, 50 l·min⁻¹, it is estimated to exchange 90 % of the water in the container in 2.7 min that corresponds to a spatial distance of 1.5 km. This leads to a consideration that the scale less than 1.5 km includes an error greater than 10 %. Therefore, the variation smaller than 1.5 km should be referred only as relative sense under an assumption that the water in the sampling container would be well mixed.

Power spectrum densities of temperature, salinity and fluorescence were calculated using a program containing a fast Fourier transformation (HINO, 1979) was modified for the
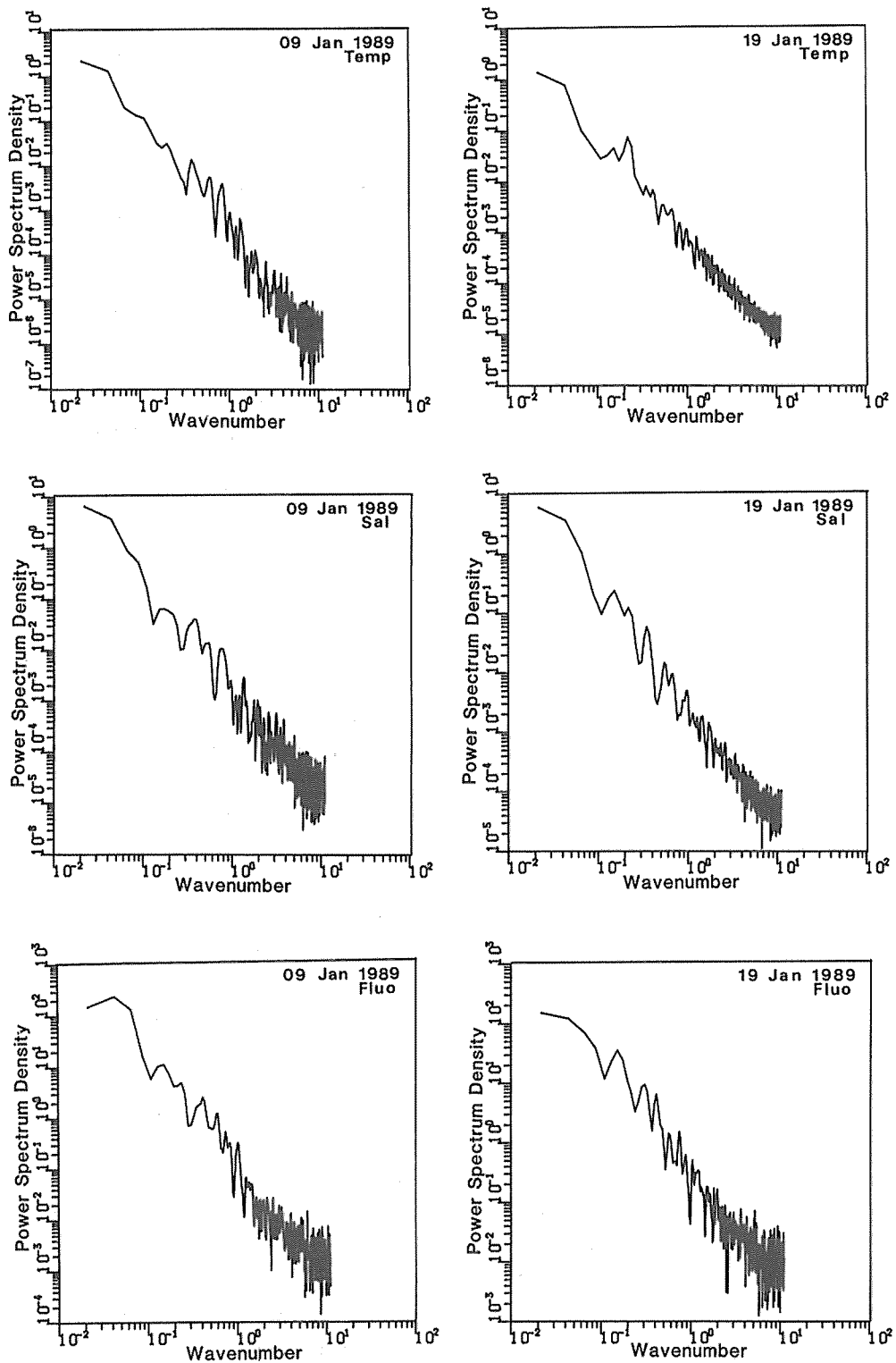
Fig. 3. Distribution of power spectral densities of temperature, salinity and fluorecence.
X-axis; km^{-1}, Y-axis; the second power of respective parameter·km^{-1}.
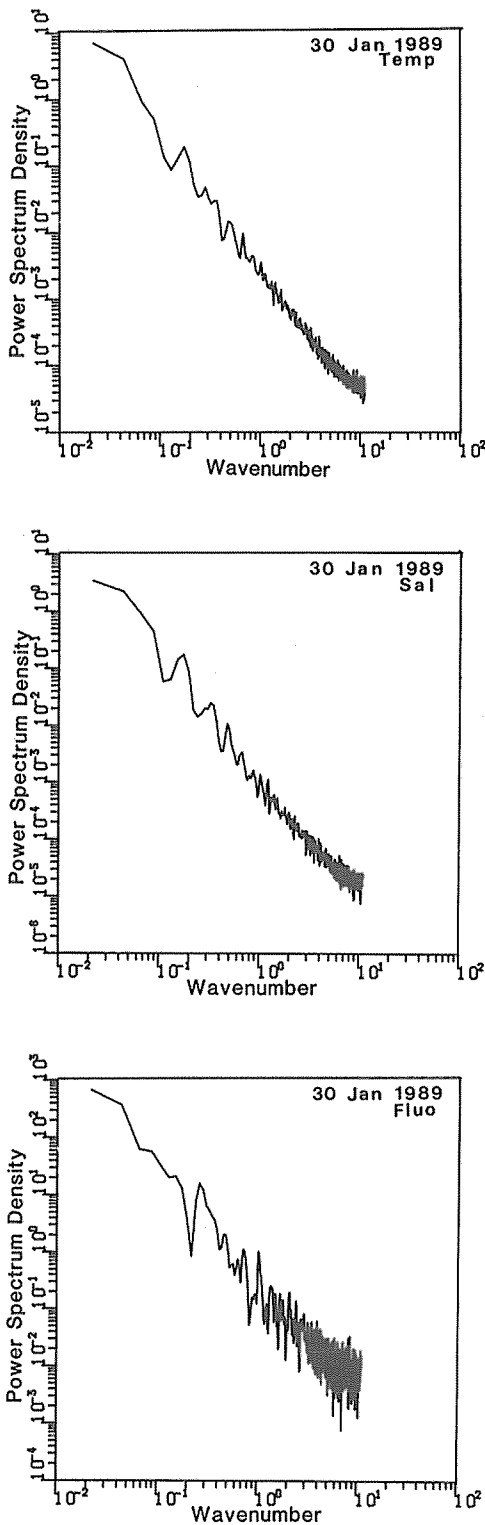
Fig. 3. Continued.

purpose of the present study. Coherence between the respective two parameters and the phase difference were also calculated.

RESULTS AND DISCUSSION

General sea conditions during the investigations

A bloom of the diatom *Eucampia zodiacus* was observed during the sequential field investigations. The cell number of the species averaged for the volume of the bay was increased from 240 on 9 January through 496 on 19 January to 731 cells·ml⁻¹ on 30 January. Average chlorophyll *a* also increased from 4.04 to 5.67 μg·l⁻¹ (YAMAMOTO *et al.,* 1992). The change in *in vivo* fluorescence in the surface layer, however, was not so remarkable because *E. zodiacus* has a property being concentrated on the sea floor (Fig. 2). Surface temperature and salinity were relatively constant with the values of *ca.* 7 ℃ and *ca.* 31–32 respectively, during the observation period (Fig. 2).

Three patterns in the relationship were found between the underwater fluorescence and the other two conservative parameters; high fluorescence in a low salinity water mass at the inner part of the bay (Stns. 1-2 and Stns. 12-13 on 9 January), high fluorescence in a warm saline water mass at the mouth of the bay (around Stn. 8 and Stns 9-10 on 9 January) and low fluorescence in a warm saline water mass (Stns. 8-9 on 30 January) (Fig. 2).

Power spectra and coherences

Slopes of power spectral density of temperature and salinity were sharper than −5/3 (Fig. 3), which means the destruction rate in the bay is greater compare to the surface layer of open ocean

where the turbulence is isotropic in three dimensions. This implies that isotropy is not almost true to the vertical direction because of the presence of sea floor.

At the first two observations, the power spectrum of fluorescence showed a breaking at the wavenumber of 10^{-1} (equivalent to 10 km converting to the spatial scale as a reciprocal of the wavenumber) accompanying a gentle negative slope in the lower wavenumber region, while the power spectral densities of the conservative parameters were distributed with a constant destruction rate even in the region of lower wavenumber (Fig. 3). In the original theory described in the previous section, this means that progress of phytoplankton bloom occurred in the spatial scales larger than 10 km overcoming the physical eddy dissipation. In the present case, however, the scale of phytoplankton patch must be considered as an imaginary sense, because the horizontal scale of the bay is *ca.* 10×25 km.

Density peak found in the power spectrum of fluorescence denotes predominance of phytoplankton patch having the diameter corresponding to the reciprocal of the wavenumber. Peaks were 2.42 and 1.65 km in the first observation, 6.58, 3.29 and 2.42 km in the second and 3.83 km in the third observation (Fig. 3). The patches totally appears to grow in size from the first (1.65 and 2.42 km) to the second observations (2.42, 3.29 and 6.58 km), and then cut into smaller ones (marked density peak was not found other than the scale of 3.83 km). Judging from the size sequence of phytoplankton patches, the first, second and third observations are considered to correspond to the periods of the beginning and prosperous and end of the bloom, respectively.

Density peaks of the three parameters did not concur with each other, if anything, the case of concurrence was rare (Table 1). About 100 peaks were counted out of the population that contained 512 data in each. The probability of concurrence was the highest between temperature and salinity (38-61 %, 53 % in average), and relatively lower between temperature and fluorescence (37-48 %, 42 % in average) and between salinity and fluorescence (32-48 %, 39 % in average). The probability of concurrence of all three parameters was much lower, 19-32 % with the average of 26 %. On the other hand, the density peaks of fluorescence being independent of the other two parameters were up to

Table 1. Number of peaks concurred at the same wavenmber in two or three paramenters (numerator) to the average number of density peak of the power spectral distribution of the parameters concerned (denominator), and their percentages (parentheses). T=S=F, for example, represents the results of the peak concurrence in temperature, salinity and fluorescence. The right end column shows the number of peaks in fluorescence which did not concur with the other conservative parameters. Total number of data processed by the spectral analysis were 512.

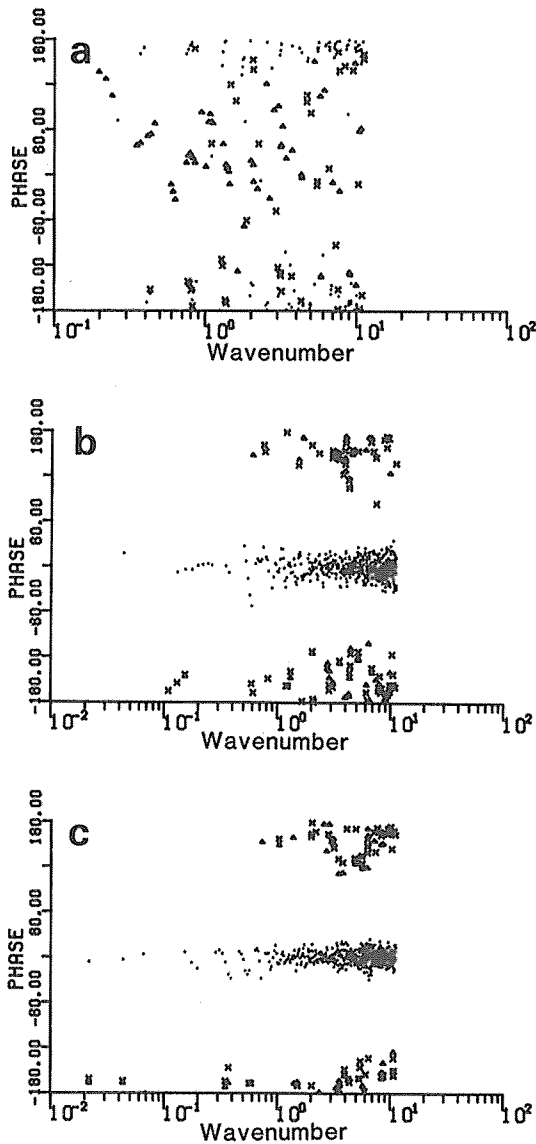|	T=S	T=F	S=F	T=S=F	F
09 Jan 1989	34/89	33/89	28/89	17/89	56/99
	(38%)	(37%)	(32%)	(19%)	(57%)
19 Jan 1989	60/101	48/101	38/101	27/101	42/102
	(59%)	(48%)	(38%)	(27%)	(41%)
30 Jan 1989	63/103	42/103	49/103	33/103	40/98
	(61%)	(41%)	(48%)	(32%)	(51%)
Average	(53%)	(42%)	(39%)	(26%)	(50%)

Fig. 4. Phase differences between respective two parameters among temperature, salinity and fluorescence. •; temperature and salinity, ▲; temperature and fluorescence, ×; salinity and fluorescence. X-axis; km⁻¹, Y-axis; degree. (a) 09 Jan 1989, (b) 19 Jan 1989, and (c) 30 Jan 1989.

41-57 % with the average of 50 %. Of the above described patches that showed obvious peaks in the power spectral density distribution, only the one of 6.58 km of the second observation concurred with peaks of both temperature and salinity. From these results, it appears that the behavior of phytoplankton patches was rather independent of the distribution of the eddies or physically determined water masses.

Plots of coherence between the respective two parameters would offer us many more informations. In Fig. 4, selecting data sets of the coherence greater than 0.8, and their phase differences were plotted to the respective wavenumbers. Except the outcome of the first observation, there found the phase difference nearly 180° between fluorescence and both temperature and salinity, while the latter two parameters fluctuated in the same manner. At the first observation, however, the two conservative parameters showed a phase difference nearly 180°, and the points concerning to fluorescence dispersed between +180° and -180° (Fig. 4a). The pattern of phase difference at the first observation is probably due to the previous unstable weather that should have necessarily been a cause of disturbance of sea conditions too. The dispersed pattern seems to denote that the bloom should have initiated in overall areas independent of low or high in temperature and salinity. In the second observation, the extention of the bloom is well documented being completed in low

temperature and low salinity water masses following the settling of sea conditions (Figs. 4a and 4b). Although the calm weather continued until the third observation was carried out, the reproduction of phytoplankton cells is assumed to have deteriorated judging from the phenomena as follows; the trend of the recovering of the negative slope in the power spectrum of fluorescence from lower to higher in the lower wavenumber region, and the size

reduction of the patchness as described above (*cf.* Fig. 3).

Routine operation of spectral analysis using a computer system is appearently easy and simple compared to the running of a simulation program in which we take into account the time-consuming chemical analyses. Although it would be difficult to discuss the transition processes of phytoplankton patch on the basis of the slope of fluorescence spectrum in the lower wavenumber region than the critical patch size, the byproduct, coherence would fundamentally be useful to apply the prediction of the development of red tides in such small-sized bays as investigated in the present study.

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スペクトル解析による赤潮の発達の予測——新しいアプローチ

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　渥美湾において珪藻 *Eucampia zodiacus* のブルームの始まりから終わりにかけて連続した観測を行った。表層から連続的に得られた水温，塩分および蛍光度のデータセットに対してスペクトル解析を行った。それぞれのパラメータのスペクトル密度のピークの不一致から，植物プランクトンのパッチは水塊の分布に対してかなり独立に振舞っていることがわかった。赤潮はしばしば湾全体に広がる。したがって，渥美湾のように小規模な湾においては，植物プランクトンの増殖と渦の物理的消散がバランスする，いわゆる植物プランクトンパッチの「臨界サイズ」の観点からは赤潮の発達過程を議論することは困難である。しかしながら，植物プランクトンパッチサイズの成長と衰退は蛍光度のパワースペクトルの密度のピークのズレで追うことができた。パラメータ間のコヒーレンスは気象の変化とそれに続くブルームの変遷を直接反映していた。スペクトル解析は富栄養化した湾における赤潮の発達を明確に予測するためのルーチン作業として採用できよう。

キーワード：赤潮，植物プランクトン，スペクトル解析，パッチ，パワースペクトル。