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Biological productivity of meso-scale eddies caused by frontal disturbances in the Kuroshio

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Temporal and spatial changes in nutrient and chlorophyll distributions caused by frontal disturbances of the Kuroshio, which is well known as a western boundary current in the Pacific Ocean, were observed. The region of high nitrate and phosphate concentrations is characterized by an eddy with positive vorticity. Although the eddy detaches from the Kuroshio front within a few days of generation, the nutrients supplied to the euphotic layer by the upwelling in the cyclonic eddy accelerate primary production in the frontal region. A specific growth rate is calculated from temporal changes in chlorophyll and nitrate concentrations. The rate, 0.8 d^{-1}, is considerably larger than that estimated for the surrounding water. Since the frontal disturbances occur in association with short-term fluctuations in the Kuroshio frontal meander, which has a period of a few weeks, the biological production enhancement by the eddy is expected to occur with high frequency. According to our rough estimations, the total annual nitrogen input to the region by the eddies could result in a carbon production rate of 40gC $m^{-2}y^{-1}$. This production rate is equal to the regenerated production rate and would create good feeding conditions for larval sardine and anchovy, which are spawned in and around the Kuroshio front. In fact, high densities of copepod nauplius seem to correspond with high chlorophyll concentration around the eddy. Therefore, the eddy caused by frontal disturbances plays a significant role in determining larval survival processes in the Kuroshio region.

(ei Sardine)

(ei Engraulis ec)

1.Introduction

Cyclonic circulations in frontal eddies associated with the wave-like meander of the western boundary current have been well described by satellite imagery and hydrographic observations, particularly in the Gulf Stream front between the Florida Straits and Cape Hatteras. In this region, meanders of wavelength of several hundred kilometres and amplitudes of a few tens of kilometres propagate to the northwest. The southward movements of the tongue-like extrusions of the Gulf Stream, derived from the wave crest, generate a cold upwelled core in the wave trough about every two weeks (Lee et al., 1981). The phase velocity of the wave is estimated to be 40-50 cm s^{-1} (Legeckis, 1979; Lee et al., 1981), although the horizontal scales are dependent on bottom topography (Legeckis, 1979; Bane and Brooks, 1979). The eddies travel northward with the same phase velocity as the wave and contribute to rapid shelf-Gulf Stream water exchange. Cross stream horizontal scales of the eddy are in the order of a few tens of kilometres and the along stream scales extend larger than the cross stream scales. In the cyclonic eddy, nutrients are supplied to the euphotic layer by upwelling and accelerate primary production in this frontal region (Lee et al., 1981; Yoder et al., 1981). Since eddies are frequently generated in the region, the enhancement of biological productivity in the coastal water is large. According to a calculation by Lee et al.(1981), the annual carbon production by phytoplankton in the Gulf Stream front is about 32-64 gC $m^{-2}y^{-1}$.

Similar frontal disturbances in the Gulf Stream front are also recognized in the Kuroshio region which is well known as a counterpart of the Gulf Stream in the Pacific Ocean. In the Kuroshio region, wave-like meanders with wavelengths of 100, 200, 400 km occur with periods of 5-8, 10-12 and 17-19 days respectively, west of Cape Shionomisaki in the Enshu-nada Sea (Kimura and Sugimoto, 1993) and generate frontal cyclonic eddies. Considering the results in the Gulf Stream, these eddies seem to enhance the biological productivity in the sea. In fact, coastal regions of the sea are well known as nursery grounds of the Japanese sardine and anchovy larvae. However, adequate explanation to understand the high biological productivity has never been given despite many studies on coastal upwelling by wind and topography. Thus, in this paper, we describe the biological production in the Kuroshio front focusing on upwelling in the cyclonic eddy and point out its importance to the understanding of the production in the coastal area.

2.Observations

Hydrographic observations with conductivity-temperature-depth profiler (CTD), water sampling and net sampling were carried out at 39 stations in the Enshu-nada Sea along six sections during 18-23 May, 1994 as shown in Figure 1. Water samples were taken at selected depths with Niskin bottles mounted on a rosette sampler coupled to the CTD. Concentrations of phosphate, nitrate and chlorophyll were obtained at depths of 0, 30, 50, 100, 200, 300, 500 and 1000m on Line 2 and 4, and 0m on other lines. Copepod nauplii were filtered from surface waters at all stations. An ORI net of 1.6m diameter with 0.33mm mesh was used to collect larvae of Japanese sardine and anchovy and zooplankton at the sea surface of Line 2 and 4.

3.Results

3.1 Hydrographic structure

During the observational period, the Kuroshio took a non-large meander path, termed N-type by the Japanese scientists. AVHRR satellite image on May 17 shown in Figure 2 shows the path of the Kuroshio located close to the Japanese coast with small scale meandering. A frontal disturbance of the north wall of the Kuroshio, accompanied with a cyclonic cold eddy and westward movement of a tongue like streamer, is recognized off Cape Daiozaki at 137E. The horizontal wavelength scale of the frontal meander is 150 km, and an eddy, with 80 km diameter, is located in the trough of the meander. According to the successive imagery, the crest and trough of the meander move downstream with phase velocity of 60 cm s^{-1}, which is almost the same as the current speed around the eddy measured with ship mounted ADCP (Acoustic Doppler Current Profiler) (unshown). Therefore, suggesting that the eddy moves downstream with the wave trough and the property of the water mass in the trough is conserved.

Figure 3 shows the surface temperature and salinity distribution during the observational period. Temperature and salinity minimums along the Kuroshio front suggest the existence of upwelling water in the surface. The vertical structure is shown in Figure 4. Although large gradients of temperature and salinity associated with the Kuroshio show a peak at K12 deeper than 150 m depth, another peak is also significant at K11 shallower than 150 m depth. Since the location of the peak corresponds to the location of the cyclonic eddy observed by the satellite, it seems likely that the water mass at K11 shallower than 150 m depth is upwelling water associated with the eddy. This result indicates that the vertical scale of the upwelled water mass is their order of 50-100m.

Since the observations spared 6 days, the horizontal distributions do not certainly represent the instantaneous hydrographic structure around the front. The cold temperature region below 19°c, generated by the cyclonic eddy, therefore, is described by a long belt with a temperature associated with its eastward movement. Assuming the eddy is moving at 60 cm s^{-1}, the eddy shown in Figure 2 moves on Line 1 in May 18 and distance of displacement of the eddy in one day corresponds to the distance between Line 1 and Line 2. Since each line observation had been completed in one day, the center of the eddy is always located on each line with a daily time lapse.

3.2 Primary production

As a result of the upwelling associated with the eddy, nutrient input to the surface and continuous primary production are expected. Figure 5 shows horizontal surface distributions of nitrate, phosphate and chlorophyll concentrations in the area. Regions of high nutrient and chlorophyll concentrations are evident along the Kuroshio front. For convenience of further analyses, we put numerals on high concentrated cores of nitrate distribution, as shown in Figure 5(a). The highest concentration of phosphate is in Core 1, slightly north of the high concentration of chlorophyll. Since the location of Core 1 corresponds to the location of the eddy, which has travelled half to one day from the eddy seen in Figure 2, it suggests that the high nutrients are supplied by upwelling within the eddy. According to the hydrographic observations, the water mass at Line 1 reaches Line 3 in two days. Temperature and salinity profiles at the centre of Core 1 (K4) correspond well to that at Core2 (K17), particularly at depths less than 200 m, although those at the other stations on Line 1 and 3 spread over a wider range (Figure 6). Therefore, the results indicate that Core 2 water was in the same as Core 1 two days previously. In the two days, the concentration of nitrate decreases from 6 to 3 μ M and phosphate from 0.15 to 0.05 μM, with chlorophyll concentration increasing from 1.5 to 2.5 $\mu g l^{-1}$ at the sea surface. This result suggests that phytoplankton growth has resulted in the consumption of 3 μM of nitrite and 0.1 μM phosphate. The nitrogen to phosphate ratio taken by the phytoplankton, 30:1, is slightly larger than the Redfield number.

Figure 7 shows vertical sections of nutrients and chlorophyll along Lines 2 and 4. Nutrient structure along Line 2 is very similar to the hydrographic structure. Although peaks of both nutrients are recognized at K12 deeper than 200 m, those shallower than 200 m depth are seen at K11, thus indicating that regional upwelling occurs onshore of the Kuroshio front. The location of high chlorophyll concentrations does not correspond to that of the nutrients. However, considering the contour of 1.0 $\mu g l^{-1}$ spread over neighbouring stations and the time lag between the nutrient supply and consumption, the high concentrations could be treated as the same one. The vertical scale of the high concentration of chlorophyll is about 50 m with a maximum at a depth of 30 m.

On Line 4, high concentrations of nutrients corresponding to the edge of Core 2 are recognized at K22 and K23. A highly chlorophyll concentrated region is also located at K25, coinciding with that of Core 3. Although it is very difficult to identify the origin of Core3, the nutrients in Core 3 could be used for the high phytoplankton production. However, high concentration of nitrate is limited to depths shallower than 50 m and does not show the dome structure observed on Line2.

3.3 Distributions of fish larvae and zooplankton

The nursery ground for larvae of Japanese sardine and anchovy are distributed widely in coastal regions of the Enshu-nada Sea. Large amounts of larvae were caught in coastal area from K8 to K11 on Line 2 (unpublished data by Nakata). The highest density was found at K10, between the coast and the upwelling region. The water mass in the area moves to the Kuroshio region associated with the cyclonic circulation around the edge of the eddy. As a result, a large abundance of the larvae in the Kuroshio frontal region, on Line 4, has been transported by the process. Since K23 is located in the edge of the eddy, larvae in the eddy are re-transported to the coastal region. However, the larvae distributed on Line 4 other than K23 would not contribute to reproduction. The highest density of copepod nauplii is observed at K23 (unpublished data by Nakata). This means that the eddy is a good environment for growth of zooplankton because of the high productivity of the phytoplankton.

4. Discussion

In the cyclonic eddy, 3μM of nitrate was consumed for production of phytoplankton which is equivalent to 1.0$\mu g l^{-1}$ chlorophyll during two days. The apparent specific growth rate of phytoplankton in terms of chlorophyll were calculated assuming an exponential change

$\mu' = 1/(t_2-t_1) \ln c_2/c_1$,

where c_1 and c_2 are the concentrations of chlorophyll at times of t_1 and t_2 respectively. Time is measured from 0 on Line 1. The apparent specific growth rate is estimated to be 0.26 d^{-1}. Supposing the nitrogen : chlorophyll ratio equals 0.7 (Ishizaka et al., 1986), 3μM decrease of nitrate indicates 4.3 $\mu g l^{-1}$ chlorophyll production by phytoplankton. Since the concentration of chlorophyll increased by only 1.0$\mu g l^{-1}$, 3.3 $\mu g l^{-1}$ chlorophyll was lost by sinking and zooplankton grazing during the two days.

Eddy vorticities on each observational line estimated from current velocity measured with ADCP decrease with time lapse; Line1 $2.0*10^{-5}$ s^{-1}, Line 2 $1.5*10^{-5}$ s^{-1}, Line 3 $1.0*10^{-5}$ s^{-1}. Since the eddy diameter is 80 km and the velocity difference between the center of eddy and the Kuroshio front is about 150 cm s^{-1}, the initial vorticity of the eddy is estimated to be $3.5*10^{-5}$ s^{-1}. According to this estimation, the eddy is generated two days before Core 1. Supposing that the initial concentration of surface nitrate is 8 μM, because the vertical scale of the upwelling is 50-100 m, fluctuation of nitrate is able to be explained by the following equation.

$y = 12 - 6*\exp(0.2*t)$

According to the equation, the nutrient will be consumed within 3-4 days from the Core 1. This daily loss of the nutrients contributes towards the total primary production. Since this primary production calculated by the equation includes an increase in the apparent primary production detected by the observation, the balance accounts for losses of primary production by grazing and sinking. For instance, although apparent concentration of chlorophyll at time 0 increases by 0.45 $\mu g l^{-1}$ to 1.95 $\mu g l^{-1}$ at time 1, actual total primary production is estimated to be 3.40 $\mu g l^{-1}$ and the balance, 1.45$\mu g l^{-1}$, is lost by grazing and sinking in one day. Considering the loss, the averaged growth rate is 0.8 d^{-1}, which is considerably larger than that estimated in the surrounding water. These aspects are explained in Figure 8.

The Nutrient-enriched eddy detached from the Kuroshio front intrudes into the coastal area of the Enshu-nada Sea. According to our calculations, the life span of the eddy is estimated to be 7 days from vorticity changes and 6 days from nutrient consumption. Therefore, new production by the upwelling in the eddy spreads over the Enshu-nada Sea and contributes to the coastal primary production within a week. The concentration of the eddy reaches 3.7 μgl^{-1} when the nutrient is exhausted and the vorticity of the eddy becomes less than $1*10^{-5}$ s^{-1}. The net primary production including losses by grazing and sinking at the center of the eddy is estimated to be 12.3 μg^{-1}, based on the initial surface nitrate concentration. Assuming the eddy has 80 km diameter and 50 m depth and the concentration becomes lower at the edge of the eddy with the same ratio, the input of nitrogen to the coast by one eddy would be $1.4*10^{9}$gN. Using a value of chlorophyll:nitrogen ratio, 30 (parsons et al., 1984), the value is the same as $4.2*10^{10}$gC.

From satellite imagery, the frontal disturbance has about 150 km wavelength. In the Kuroshio region east of Cape Shionomisaki, the disturbance with the wavelength occurs every 10 days (Kimura and Sugimoto, 1993). The impact of the net onshore flux of nitrate on phytoplankton production can be estimated knowing the area influenced by the disturbance and its frequency. According to the period, 36 eddies would be generated in a year. However, since vertical mixing in winter enhances the nutrient supply to the euphotic layer, 18 eddies in summer, when stratification is developed, should be considered for significance. Assuming 18 eddies intrude into the Enshu-nada Sea which has an area of 100 km * 200 km, this perturbation could result in a carbon production of $40gCm^{-2}y^{-1}$ (Figure 9).

Since no precise estimation of usual primary production in the Enshu-nada Sea has ever been made, it is very difficult to evaluate this estimated production. However, according to a rough estimation by Ichimura (1965), primary productions in the coastal area and an area between the coastal area and the Kuroshio front are 110-180 and $40\text{-}70gCm^{-2}$ y^{-1} respectively. The primary production by the frontal disturbance, therefore, accounts for a large part of coastal primary production. In fact, high densities of copepod nauplius seem to correspond with high chlorophyll concentration in the eddy, suggesting it is important to understand survival processes of the higher food web. In addition, this estimation well corresponds well with a similar estimation in the Gulf Stream front; $32\text{-}64gCm^{-2}y^{-1}$. Although this is the first time a comparison between the Kuroshio and the Gulf Stream has been made about primary production caused by the frontal disturbance, this study shows very interesting results for further analyses in future.

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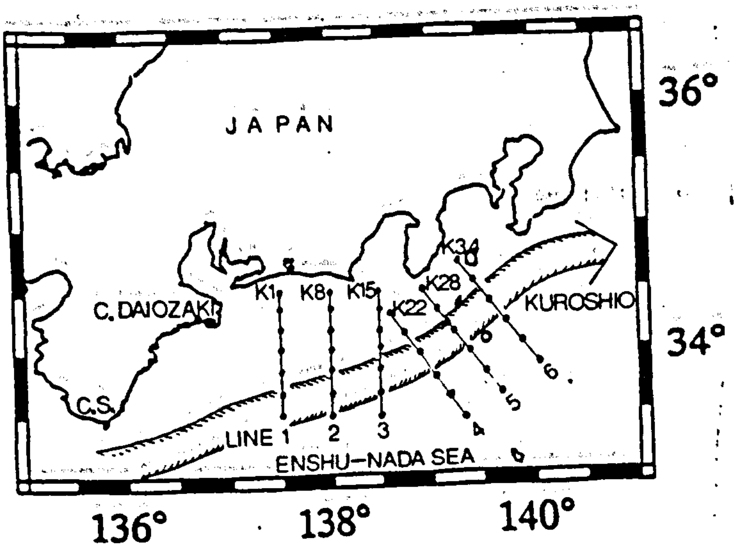

Figure 1 Observational locations

Figure 2 Satellite image of the Kuroshio on May 17

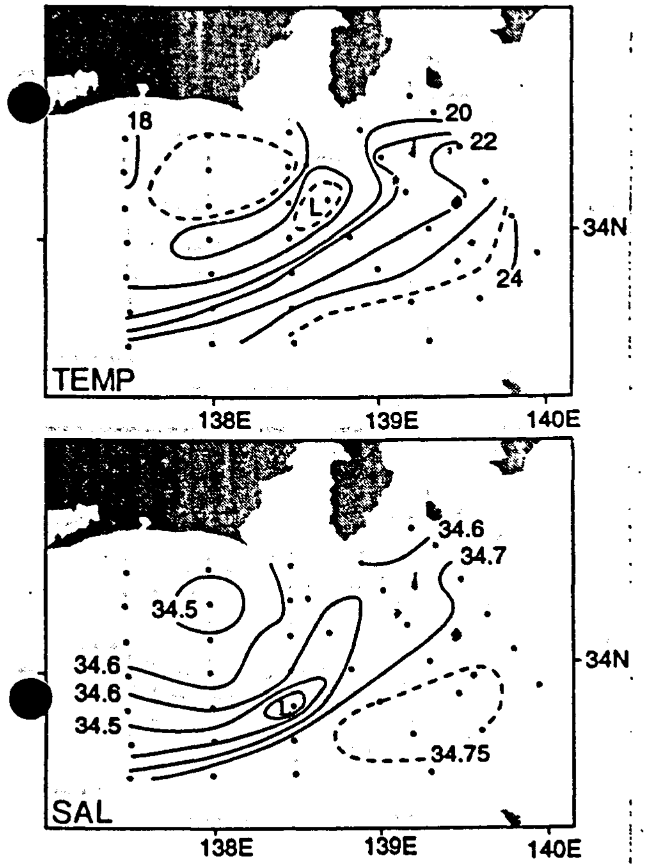

Figure 3 Surface temperature and salinity distributions

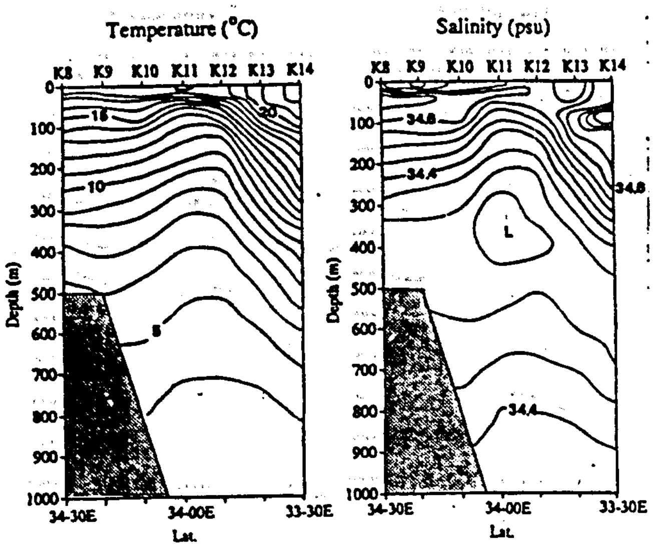

Figure 4 Vertical temperature and salinity sections

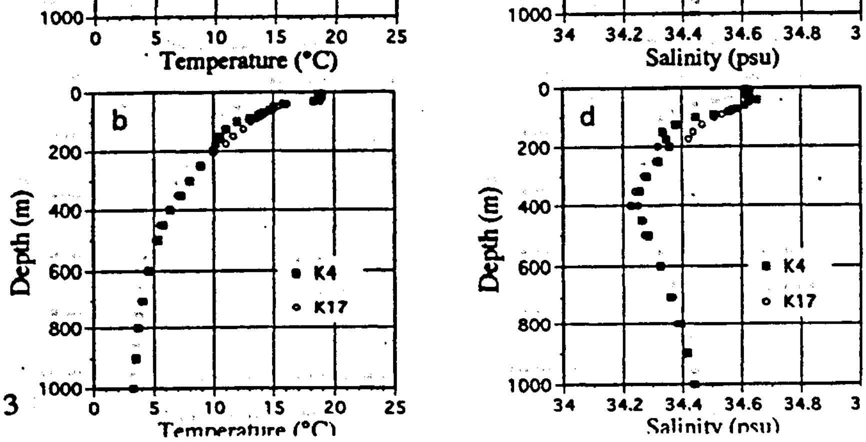

Figure 6 Temperature and salinity vertical profiles along Line 1 and 3

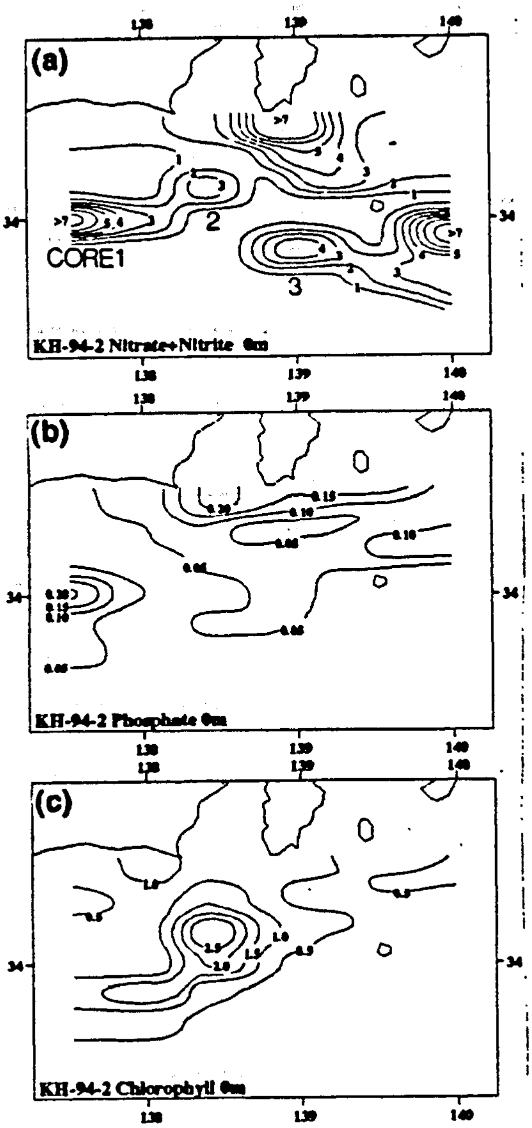

Figure 5 Surface distributions of nutrients and chlorophyll concentrations

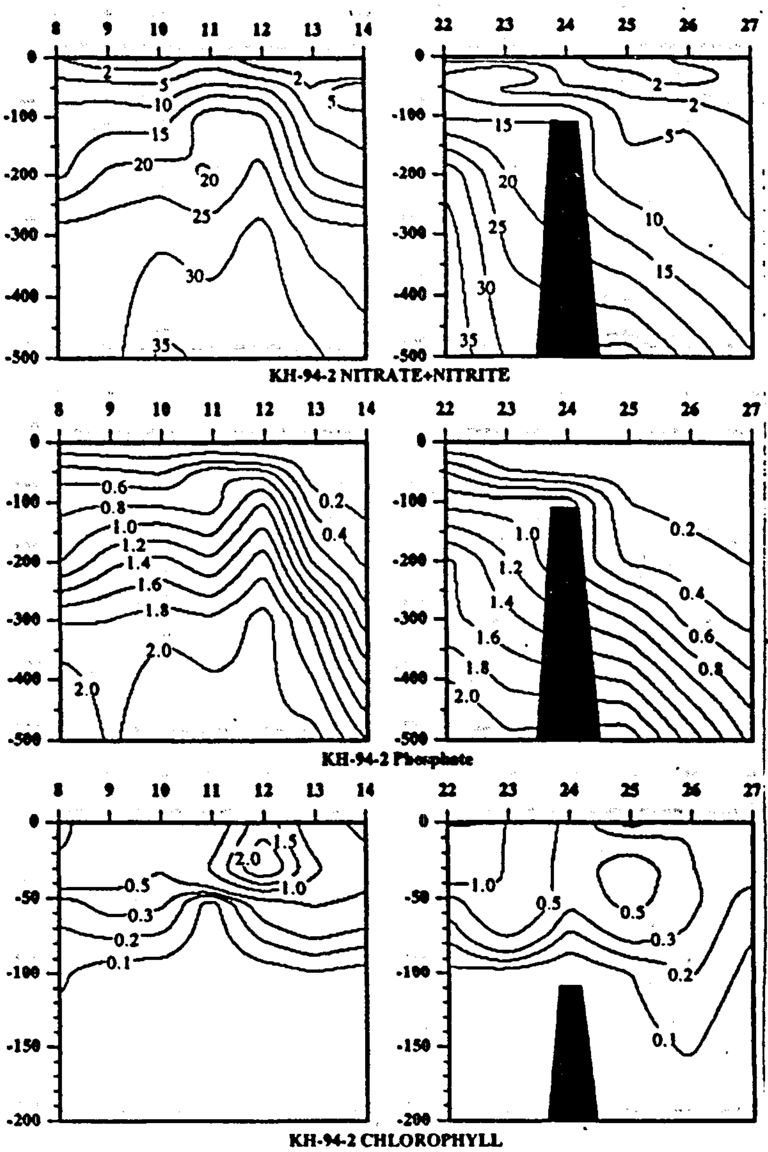

Figure 7 Vertical nutrients and chlorophyll concentrations

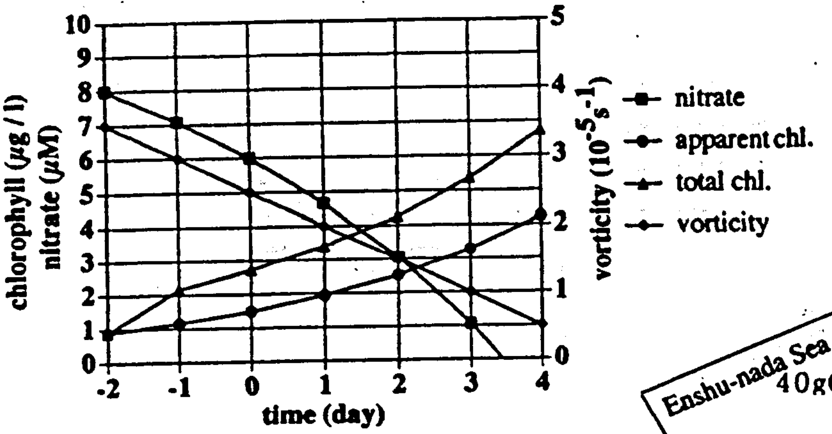

Figure 8 Variations of Estimated physical and biological factors in cyclonic eddy

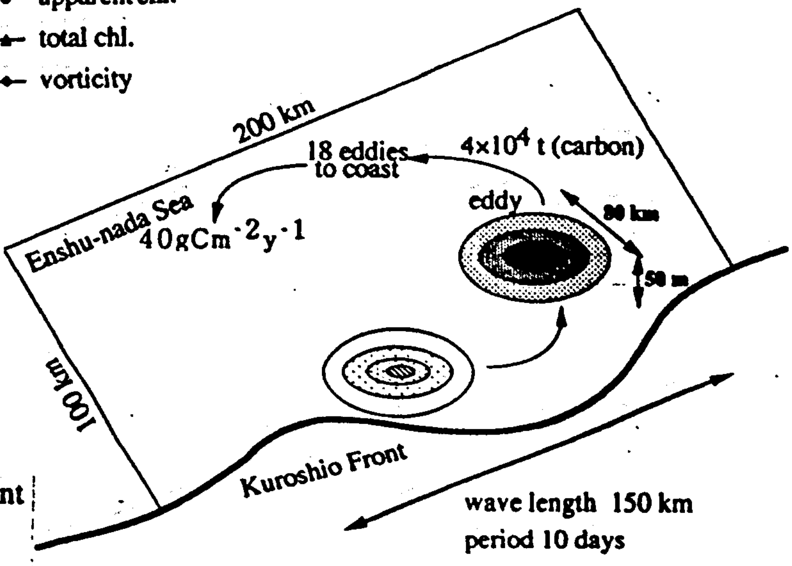

Figure 9 Schematic view of the Kuroshio front with diagrams of primary production