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An Unusual Coastal Environment and *Cochlodinium polykrikoides* Blooms in 1995 in the South Sea of Korea

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Cochlodinium polykrikoides bloom in 1995 was studied with a focus on an unusual coastal environment in the South Sea of Korea. Data on temperature, salinity, and zooplankton biomass during 1965-1998 and nutrients during 1990-1998 and chlorophyll-*a* during 1995-1998 were used in this study. These data were obtained from the serial oceanographic observations in Korean waters carried out by the National Fisheries Research and Development Institute. In 1995 the *C. polykrikoides* bloom began in the coastal area around Narodo Island in August and consequently occurred to the whole coastal area of the South and East Seas of Korea. During June-October 1995, the coastal environment was unusual compared with the long-term means during 1965-1998. In June 1995, sea surface temperature was 1-2°C warmer than in other years in all coastal areas, while salinity was high only to the east of Jeju Island. In August 1995, a strong coastal front appeared inshore of a line between Jeju and Tsushima Islands. In particular, a strong coastal front which showed the characteristics of upwelling front occurred in the coastal area around Narodo and Sorido Islands, not only because of a strong intrusion of the Tsushima Warm Current but also because of the upwelling of cold bottom water. Salinity was low in the neighboring waters of western side of Jeju Island. Nutrients and chlorophyll-*a* were high in the inshore area between Narodo and Sorido Islands in 1995 in contrast with the other years and areas. Zooplankton showed an unusually high abundance in the coastal area in October 1995. We conclude that the Tsushima Warm Current strongly influenced the South Sea of Korea in 1995 and created strong upwelling front bordering cold upwelled water in the coastal area around Narodo and Sorido Islands. It leads us that these physical structures introduce the favorable environment for the development of *C. polykrikoides* blooms. We suggest that *C. polykrikoides* has a bio-physical tolerance of high shear and stress and prefers frontal and upwelling relaxed areas as its habitat. We also find that nutrients were not supplied to the coastal area from the offshore where a low salinity water mass with high nutrients appeared around Jeju Island. Because the strong upwelling front protect the reach of offshore low saline water mass. The main source of nutrients was the upwelled water mass in the coastal area of Wando-Narodo-Sorido.

Keywords: Harmful algal blooms, *Cochlodinium polykrikoides,* Environment, Narodo Island, South Sea of Korea

INTRODUCTION

Harmful algal blooms are a serious environmental problem in eutrophic coastal areas, and sometimes cause severe economic damage to aquaculture. Harmful dinoflagellate blooms were generally restricted to enclosed or semi-enclosed Bays, such as Jinhae and Kosung Bays in the South Sea of Korea until the early 1990's. However, since the large *Cochlodinium polykrikoides* blooms in 1995, the *C. polykrikoides* blooms have taken place to the West and East Seas and continue to cause large economic losses.

Kim (1998) reported that *C. polykrikoides* blooms were first observed at the Nakdong River estuary and the eastern side of Gaduckdo Island in 1982 and occurred less than 10 times prior to 1995 in Korean waters. But in 1995, *C. polykrikoides* blooms appeared widely and lasted for 8 weeks in Korean coastal

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waters. The blooms started in the coastal area around Narodo Island, located in the western offshore area of the South Sea of Korea. Since 1995, *C. polykrikoides* blooms have usually started in the coastal area around Narodo Island. This differs from the usual appearance of red tides in eutrophic inshore coastal area. So, many questions were raised about the initiation of *C. polykrikoides* blooms in the coastal area around Narodo Island in 1995. Why do *C. polykrikoides* blooms usually start in the coastal area around Narodo Island? Why have large blooms of this species occurred since 1995?

After the outbreak of *C. polykrikoides* in 1995, many studies were focused on the initiating mechanisms of *C. polykrikoides* blooms and the relationship between environmental conditions and outbreaks. Kim *et al.* (1999) suggested that blooms are initiated when the Kuroshio Warm Current is mixed with eutrophic waters in the coastal area around Narodo Island. Environmental conditions, which included warm and slightly eutrophic water in the coastal area around Narodo Island, were favorable to enhanced growth of vegetative cells and excystment of *C. polykrikoides*. Yang *et al.* (2000) suggested that the outbreak of red tides in the coastal waters of Goheung was associated with the intrusion of new water mass transported from offshore in 1997. Additionally, Choi (2001) emphasized that the influx of low salinity water from offshore and the breakdown of stratification were important to red tide formation in the coastal area between Narodo and Sorido Islands in 1998. On the other hand, biological interactions between red tides and phytoplankton or zooplankton were studied in the coastal area around Narodo Island Goheung (Jung *et al.,* 1999; Jeong *et al.*, 2000a, 2000b). It was concluded that zooplankton, such as salps and cladocera, and heterotrophic dinoflagellates were very important in controlling outbreaks of red tides in the initial stages. Smayda and Renolds (2001) classified the cross-shore habitat preferences of dinoflagellate bloom species into 9 types. They stated that *Gymnodinium catenatum* and similar species prefer the frontal zones and upwelling relaxed regions, and those species are closely associated with two critical attributes: biophysical tolerance to elevated shear/stress and an ability to achieve growth rates which exceed the ratio of upwelling velocity to depth of the stratified water layer (Figueiras *et al.*, 1994).

Although there are many studies on *C. polykrikoides* blooms in the coastal area around Narodo Island, it is not enough to resolve the question of why the large bloom occurred in 1995 and began in the coastal area around Narodo Island. Knowledge of environmental characteristics in the coastal area around Narodo Island is essential to understand the initiating mechanisms of *C. polykrikoides* blooms. In this study, the environmental characteristics of coastal waters in 1995 were examined, focusing on *C. polykrikoides* blooms in the South Sea of Korea. The causes of the *C. polykrikoides* blooms in 1995 are discussed with reference to the difference between 1995 and the long-term trend in oceanographic conditions.

DATA AND METHODS

The National Fisheries Research and Development Institute (NFRDI) has conducted regular bimonthly oceanographic surveys (February, April, June, August, October and December) in Korean waters since 1965 (Fig. 1). In these surveys, seawater temperature,

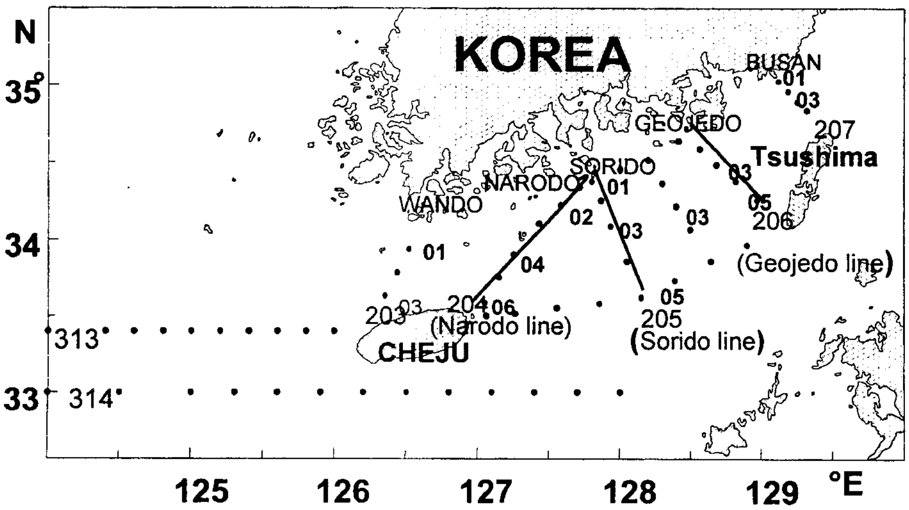

Fig. 1. Map showing the sampling stations and study area.

salinity and dissolved oxygen were estimated at standard depths. Zooplankton was collected to calculate biomass and count four major zooplankton groups, copepods, amphipods, chaetognaths and euphausiids. Dissolved nutrients (nitrate, nitrite, silicate and phosphate) and chlorophyll-*a* have been estimated since 1995. Of these data, seawater temperature, salinity, and zooplankton biomass from 1965-1998, dissolved nitrogen (NO_2+NO_3) from 1990-1998 and chlorophyll-a concentrations from 1995-1998 were used in this study. The data for June, August and October were analyzed, as these months encompass the duration of the *C. polykrikoides* bloom.

Seawater temperature and salinity were estimated using a thermometer and CTD (Seabird 19) at 0 m, 10 m, 20 m, 50 m, 75 m, 100 m depths and the bottom in the South Sea of Korea. Dissolved nitrogen (NO_2+NO_3) and chlorophyll-*a* concentrations were analyzed with a spectrophotometer (Varian Co. DMA 80, optical cell length: 1 cm or 10 cm), following the method of Strickland and Parsons (1968). Zooplankton was vertically collected with a Norpac net (mouth: 0.45 m and mesh size: 0.33 mm) and biomass was estimated as wet weight.

RESULTS

Cochlodinium polykrikoides blooms in Korean coastal waters

In Korean waters, *Cochlodinium polykrikoides* blooms first occurred in Nakdong River estuary and the eastern side of Gaduckdo Island in the South Sea in September 1982 (Kim, 1998), and then reoccurred in Dangdong Bay (inner Jinhae Bay) and Namhaedo Island in the South Sea in September 1984. However, densities did not exceed 3,000 cells/ml, and blooms were

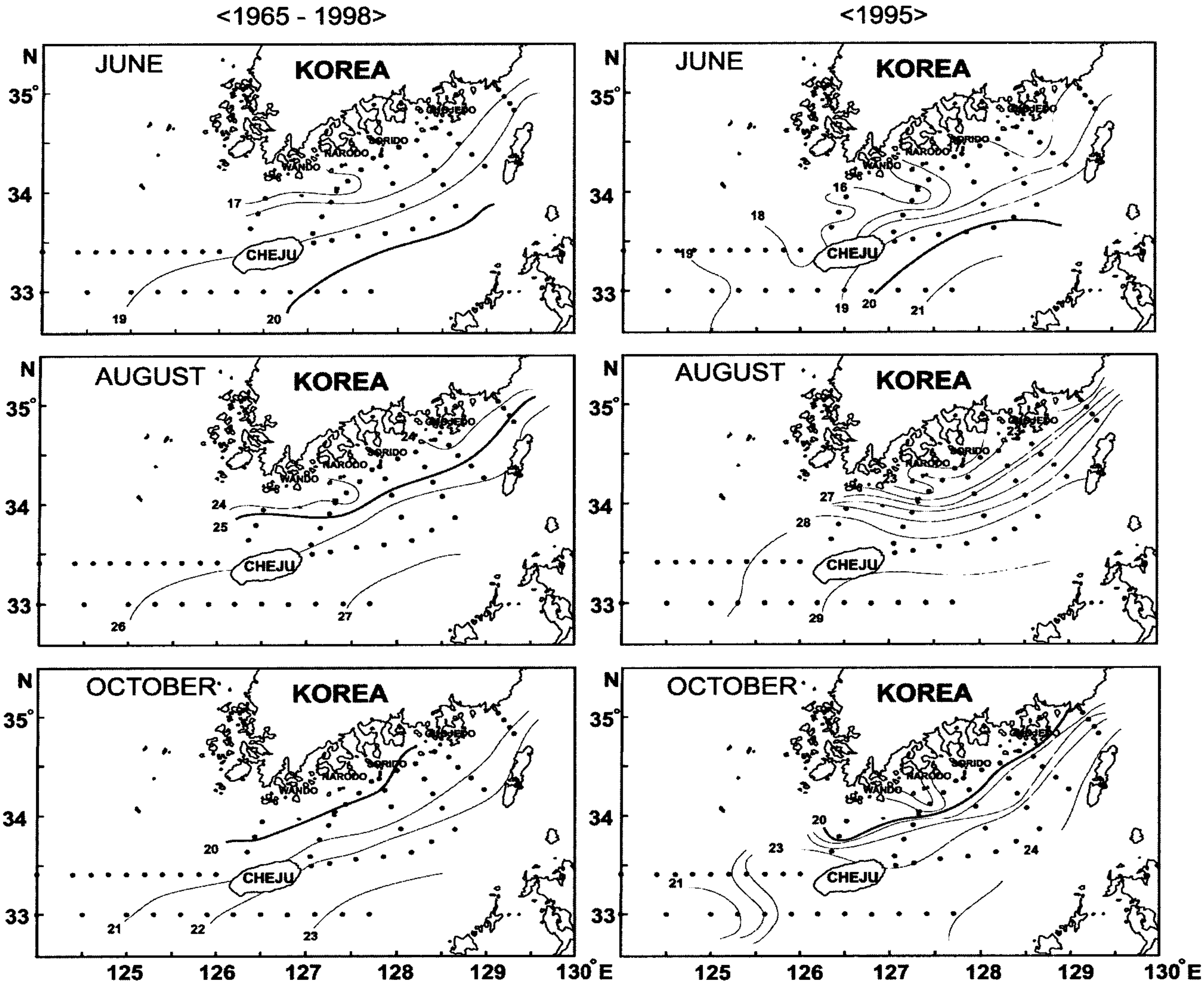

Fig. 2. Horizontal distributions of sea surface temperature (°C) in June, August and October, 1995 and the mean of 1965-1998.

limited to a small area in the South Sea of Korea until 1994. But in 1995, *C. polykrikoides* blooms started in the coastal area around Narodo Island in August and occurred continuously to the whole coastal area of the South and East Seas in October, will cell numbers over 20,000-30,000 cells/ml in August 1995 (Kim *et al.*, 1999). After 1995, outbreaks of *C. polykrikoides* showed similar patterns, usually beginning in the coastal area around Narodo or Sorido Islands, and then occurred continuously to the coastal areas of the South and East Seas. However, the *C. polykrikoides* bloom in 1995 was the biggest one in its extent and number of outbreaks (Kim *et al.*, 1998, 1999 and 2000).

ENVIRONMENTAL CONDITIONS

Temperature

The horizontal distributions of sea surface temperature (SST) are shown in Fig. 2. In June, SST gradually decreased from offshore to inshore with ranges of 16–21°C in 1995 and 17–20°C for the mean of 1965–1998. Isothermal lines ran parallel to the coastline. In August 1995, a strong front appeared inshore of a line between Tsushima and Jeju Islands, with a temperature range 23–27°C. This front is not apparent in the mean of 1965-1998. A cold water mass, less than 23°C, was found in the coastal areas around Wando-Narodo, Sorido-Geojedo and Geojedo-Busan. Warmer water, greater than 25°C, was widely distributed in the South Sea of Korea except in these coastal areas. Additionally, the thermocline was found at 10–20 m depths, and upwelling appeared near the inshore area of the Narodo Island (Fig. 3). However, the strong thermocline and upwelling were not found in the mean of 1965-1998. In October 1995, the dis-

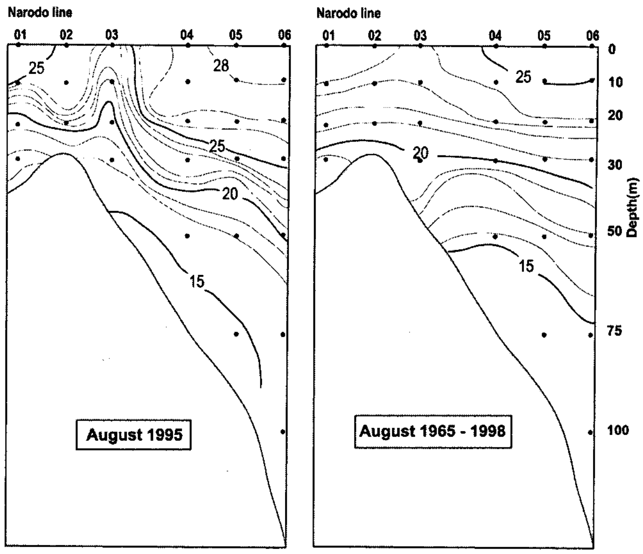

Fig. 3. Vertical distributions of temperature (°C) along the Narodo line in August 1995 and the mean of 1965-1998.

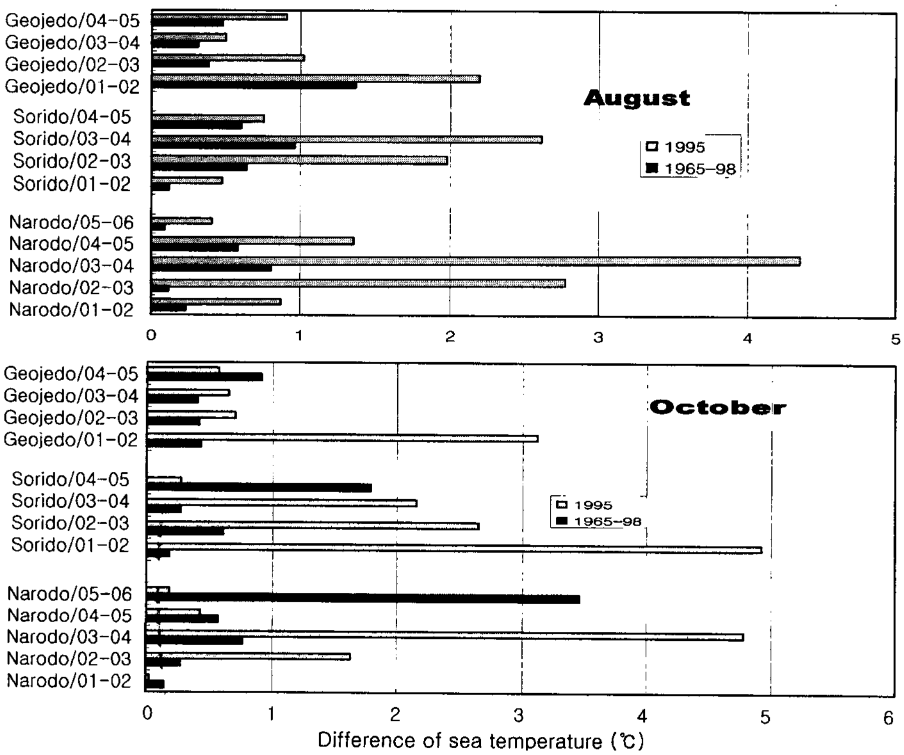

Fig. 4. Differences in sea surface temperature (°C) between adjacent stations on the Narodo, Sorido and Geojedo lines in August and October 1995 and the mean of 1965-1998.

tribution of SST was similar to that in August. The upwelling and the strong front were sustained in the coastal around Wando-Narodo from August to October.

SST differences between adjacent stations on the Geojedo, Sorido and Narodo lines in 1995 were contrasted with the means of 1965-1998 (Fig. 4). The differences were computed by subtracting the SST at one station from that at the next station. The SST differences were usually higher in 1995 than in the mean of 1965-1998. In 1995, high SST differences exceeding 3–4°C appeared inshore on the Narodo line in August and extended eastward to the inshore areas of the Sorido and Geojedo lines in October. However, SST differences exceeding 3–4°C did not appear in the mean of 1965-1998 with the exception of the offshore end of the Narodo line in October.

Salinity

To minimize the effects of rain, the horizontal distributions of salinity at 10 m depth were analyzed (Fig. 5). In June, salinity was *ca* 0.5 psu higher in 1995 than the mean of 1965-1998. In particular, the area east of Sorido Island showed high salinity exceeding 34 psu. In August 1995, a water mass with salinity less than 30 appeared in the area south of Jeju Island. However, this low salinity water mass not found in the mean of 1965-1998. On the other hand, the salinity of the inshore area in 1995 was high contrasted with that of the offshore area and the mean of 1965-1998. In October 1995, the distribution of salinity was similar to that of the mean of 1965-1998 with the exception of low salinity water

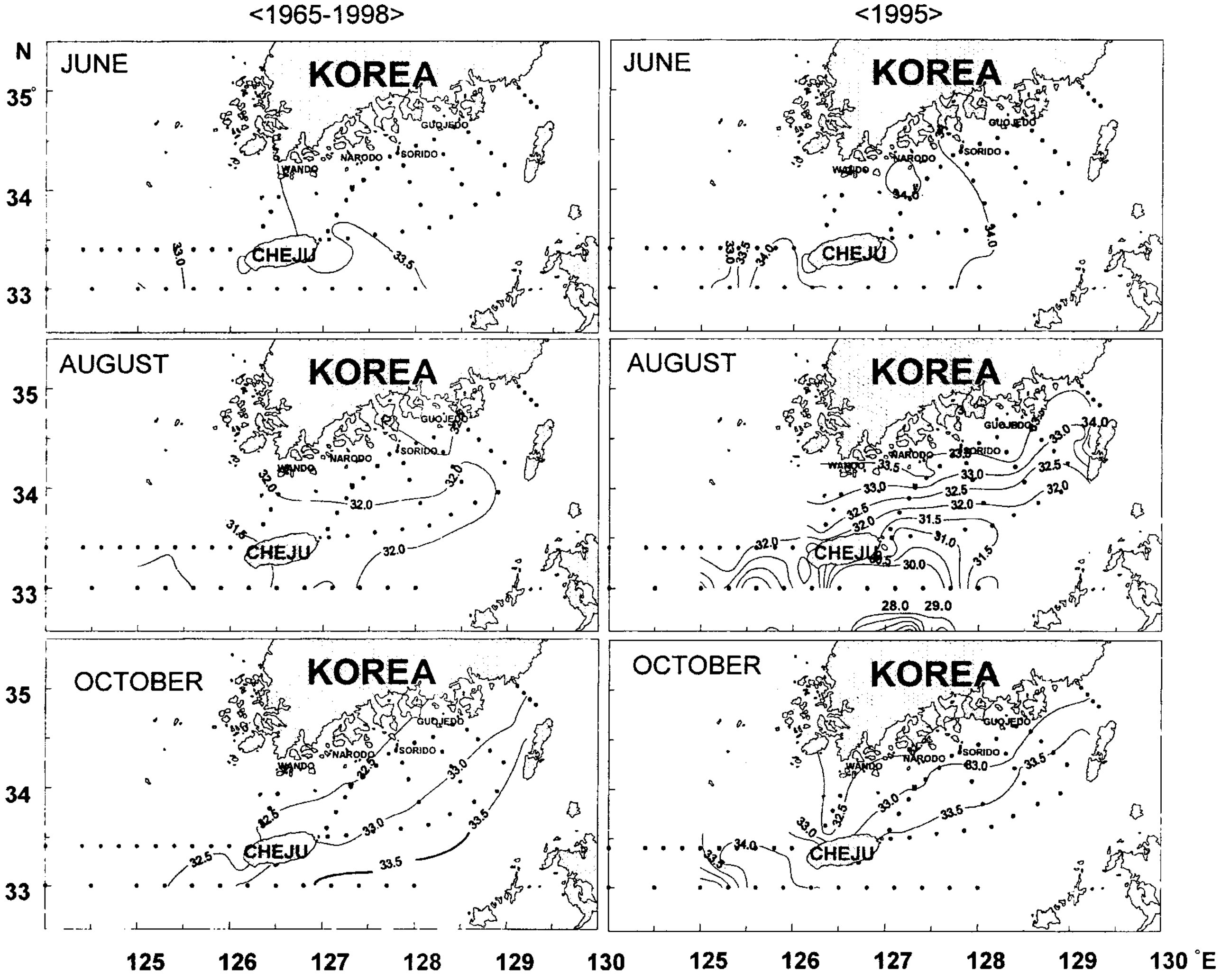

Fig. 5. Horizontal distributions of salinity (psu) at 10 m depth in June, August and October 1995 and the mean of 1965-1998.

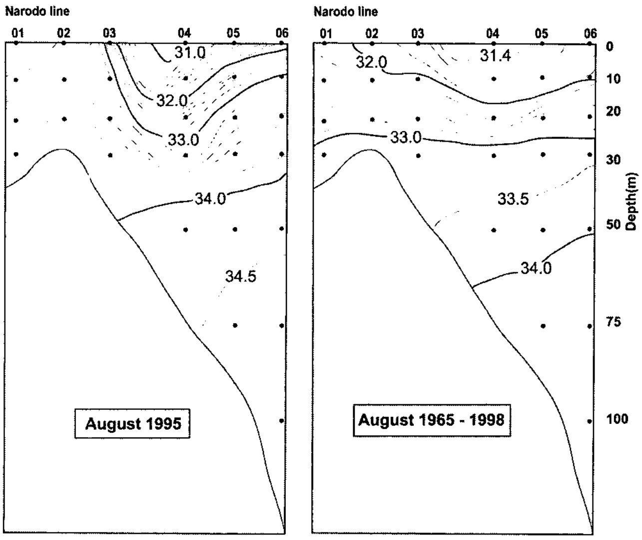

Fig. 6. Vertical distributions of salinity (psu) along the Narodo line in August 1995 and the mean of 1965-1998.

to the west of Jeju Island.

The vertical distribution of salinity along the Narodo line in August 1995 was also compared with the mean of 1965-1998 (Fig. 6). Salinity was usually higher inshore and lowers above 20 m offshore in August 1995. A strong halocline at salinity values of 31–32 psu was found at 10–20 m offshore in 1995, while there was no halocline in the mean of 1965-1998.

Nutrients, Chlorophyll-a and zooplankton

The horizontal distributions of dissolved inorganic nitrogen (DIN: NO_2+NO_3) are shown in Fig. 7. In June, the DIN concentration was *ca.* 2–3 μg-at/L higher in 1995 than the mean of 1990-1998. In particular, high concentrations exceeding 3.5 μg-at/L were found to the west of Sorido in 1995. In August, the DIN concentration was also higher in 1995 than in the other years especially to the south of Jeju Island. In October, the DIN concentration increased gradually from offshore to inshore. High DIN concentrations greater than 2.5 μg-at/L were found in the coastal area around Wando-Narodo and Geojedo in the mean of 1990-1998 and in the coastal area around Sorido Island in 1995.

Stations Narodo-02 and Sorido-01 were selected as representative of the coastal area around Narodo and Sorido Islands to examine nutrient conditions. The anomalies of DIN and PO_4 were calculated as the difference between the value of 1995 and the mean of 1990-1998 in June, August and October (Fig. 8). The concentrations of DIN in June and August 1995 were high contrasted with the mean of 1990-1998 at both stations. The anomalies of PO_4 concentration were continuously positive in June, August and October 1995. The PO_4 anomaly of Narodo-02 was always higher than that of Sorido-01.

Horizontal distributions of chlorophyll-*a* concentration in 1995 and the mean of 1995-1998 are shown in Fig. 9. Chlorophyll-*a* concentration gradually increased from offshore to inshore with running parallel to coastal line. In June, chlorophyll-*a* concentrations greater than 0.5 μg/L were found in the coastal area of Geojedo-Busan in 1995 and the mean of 1995-1998. In August 1995, the chlorophyll-*a* concentration was higher than average, especially in the coastal areas of Sorido and Narodo. In October, chlorophyll-*a* concentrations were usually high in the coastal area of Geojedo-Busan in both 1995 and the mean of 1995-1998. The vertical distribution of chlorophyll-*a* along the Narodo line from Narodo to Jeju Island is shown in Fig. 10. In Agust 1995, the chlorophyll-a concentration was higher than the mean of 1995-1998. In particular chlorophyll-*a* was abundant at 10–20 m in the inshore area in August 1995.

Zooplankton biomass was usually high in 1995 contrasted with the mean of 1965-1998 in the inshore area (Fig. 11). In 1995 zooplankton biomass greater than 150 mg/m^3 appeared in the coastal area near Geojedo in June and shifted to the coastal area around Narodo and Sorido Islands in August. In October 1995, zooplankton biomass greater ca. 300 mg/m^3 occurred in all the coastal areas, while the mean of 1965-1998 was less than 100 mg/m^3.

DISCUSSION

In August 1995, a strong upwelling front contiguous with the thermocline was found in the coastal area around Narodo Island where *C. polykrikoides* blooms started. Horizontal and vertical distributions of sea water temperature and salinity show that the Tsushima Warm Current's effect in the South Sea of Korea was stronger in 1995 than in the other years. It is known that the Tsushima Warm Current shows high temperature and salinity and is the branch of the Kuroshio Warm Current (Kim, 1982; Hong and Cho, 1983). In August, upwelling occurred strongly in the coastal area around Narodo Island and cold water mass appeared the coastal area around Wando and Sorido Islands. Jeong (2001) also stated the appearance of cold water mass in these areas. These

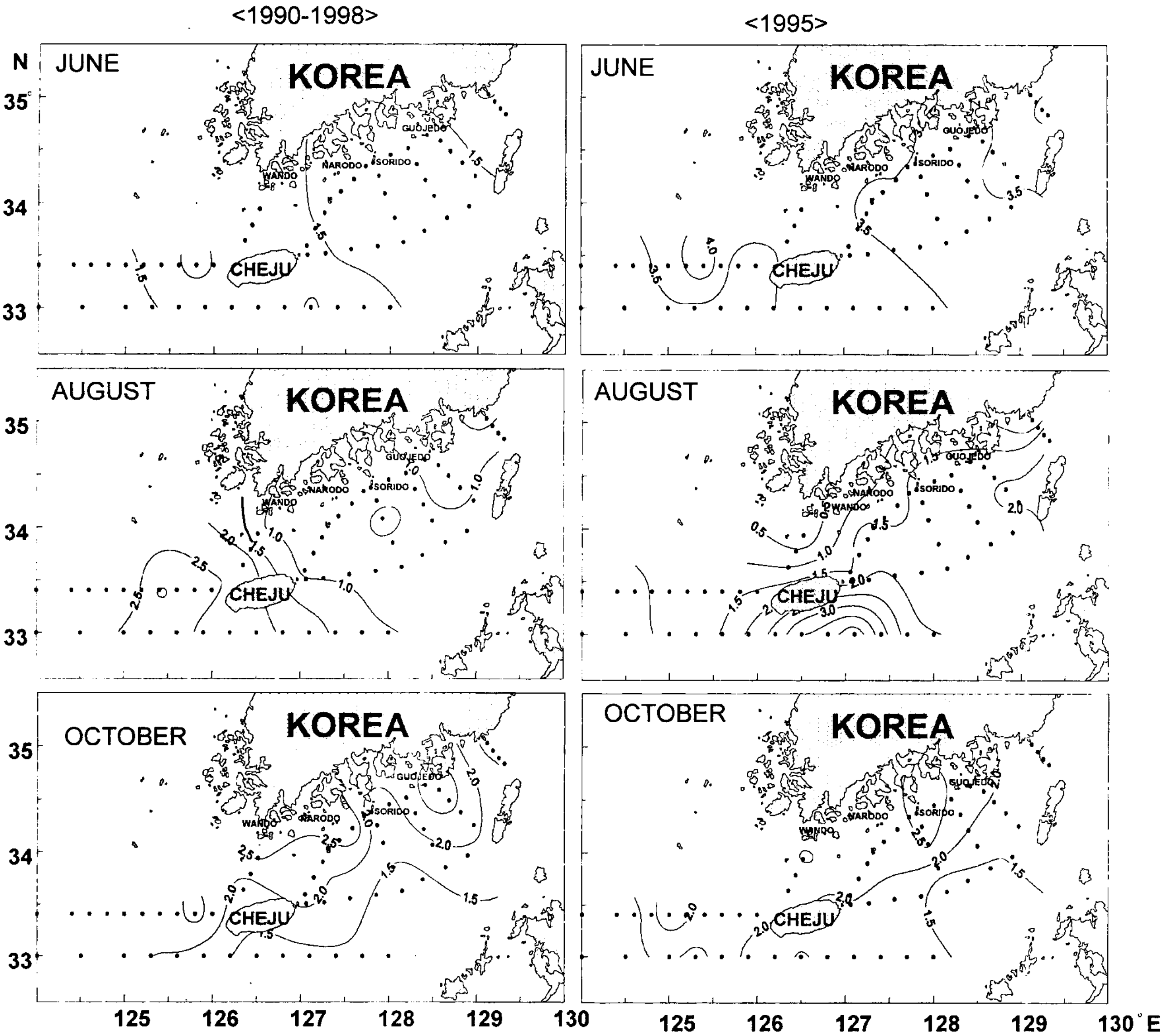

Fig. 7. Horizontal distributions of NO_2+NO_3 (μg-at/L) at the surface in June, August and October 1995 and the mean of 1990-1998.

cold water masses and upwelling made strong coastal fronts including upwelling front faced with the Tsushima Warm Current in the coastal area around Wando-Sorido-Narodo Islands in August 1995. Pingree *et al.* (1975) and Le Fevre (1986) emphasized that the coastal fronts containing shelf-sea front and upwelling front are important in enhancing phytoplankton and zooplankton production and found dense aggregations of phytoplankton along fronts in the English Channel. Pingree *et al.* (1975) stated that in the frontal region with a weak thermocline, water column production was 6.5 times greater than in the tidally mixed area. They also reported that there was high phytoplankton biomass along the front, and that the most abundant organism in the phytoplankton was *Gymnodinium aureloum*, a species also noted for red tide formation. In particular, *G. aureloum* was abundant around the thermocline in summer. Armstrong *et al.* (1987) studied an upwelling front across the southern Benguela system north of Cape Town. They found that the greatest biomass and productivity of the phytoplankton, when integrated over the euphotic layer, was in the frontal region.

We also found that *C. polykrikoides* blooms were closely associated with a strong upwelling front bordering the thermocline. The concentration of chlorophyll-*a* was very high around the thermocline in this study. Our results agree well with previous stud-

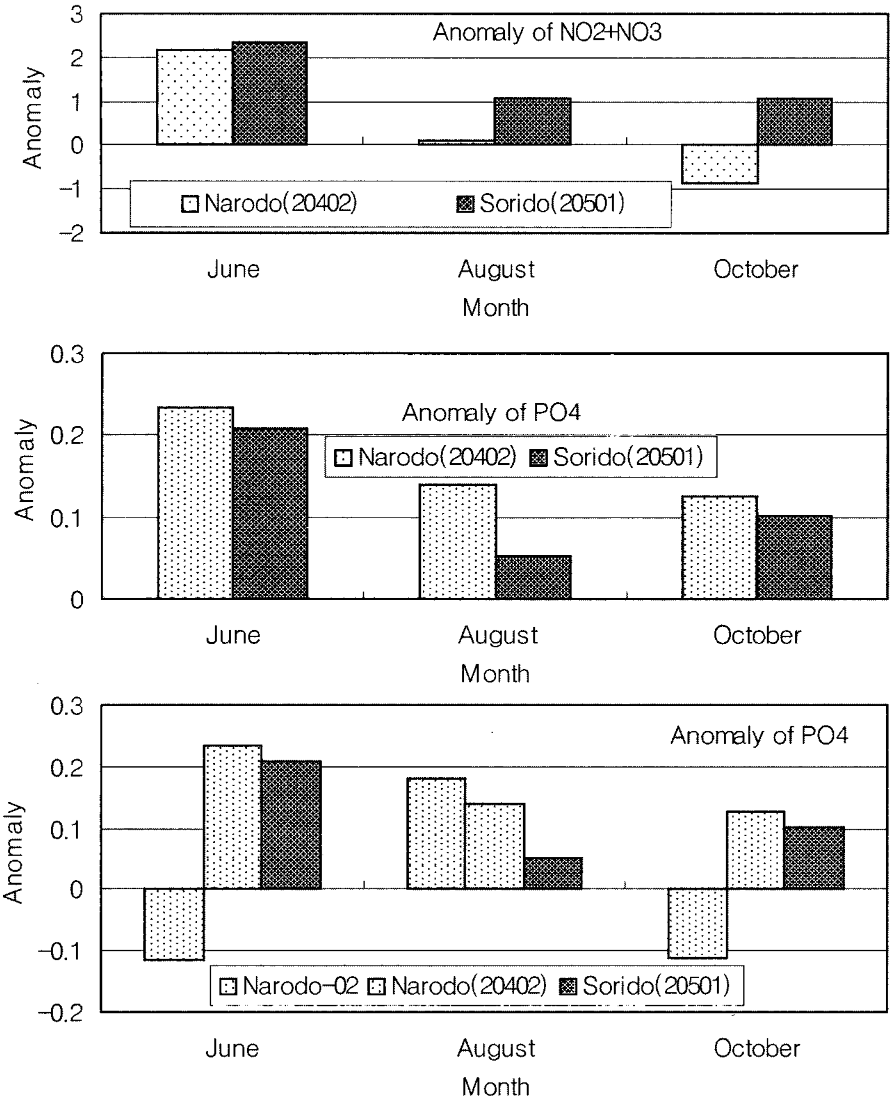

Fig. 8. Anomalies of nutrients and chlorophyll-*a* in the coastal areas of Narodo and Sorido in 1995. Nutrient anomalies are differences between 1995 and the mean of 1990-1998. Chlorophyll-*a* anomalies are differences between 1995 and the mean of 1995-1998.

ies (Pingree *et al.*, 1975; Le Fevre, 1986; Armstrong *et al.*, 1987; Frank and Chen, 1996) that demonstrated high phytoplankton production in fronts, especially shelf-sea and upwelling fronts, in summer. There is other evidence of the importance of fronts in the occurrence of red tides. In 1995, a strong upwelling front occurred in the coastal area around Narodo Island in August and then occurred continuously to the coastal area around Sorido and Geojedo Islands in October. Its occurring pattern was very similar to that of the *C. polykrikoides* bloom. In 1995, the *C. polykrikoides* bloom began in the coastal area around Narodo Island in August and then expanded along the coastal front in the coastal area around Sorido and Geojedo Islands in October (Kim *et al.*, 1998; Kim *et al.,* 2001).

Smayda and Reynolds (2001) described 9 types of dinoflagllate bloom found along an onshore-offshore gradient of decreasing nutrients, reduced mixing, and deepening euphotic zone. Of these types, type IV is closely associated with frontal zones, and type V with upwelling relaxation. The representative species of types IV and V are *Gymnodinium* species such as *Gymnodinium catenatum* and *G. mikimotoi*. *G. mikimotoi* prefers frontal zones because of associated high nutrient recycling activity (Blasco *et al.*, 1996). It is also highly adapted to entrainment within coastal currents, leading to regional dispersion (Lindahl, 1986). It has spread rapidly and has achieved great abundance throughout the North Sea and contiguous water, where it is a frequent cause of mortality, since first recorded in the 1960s (Smayda, 1989; Dahl and Tangen, 1993). Considering the environmental conditions in the coastal area around Narodo in August 1995, *C. polykrikoides*

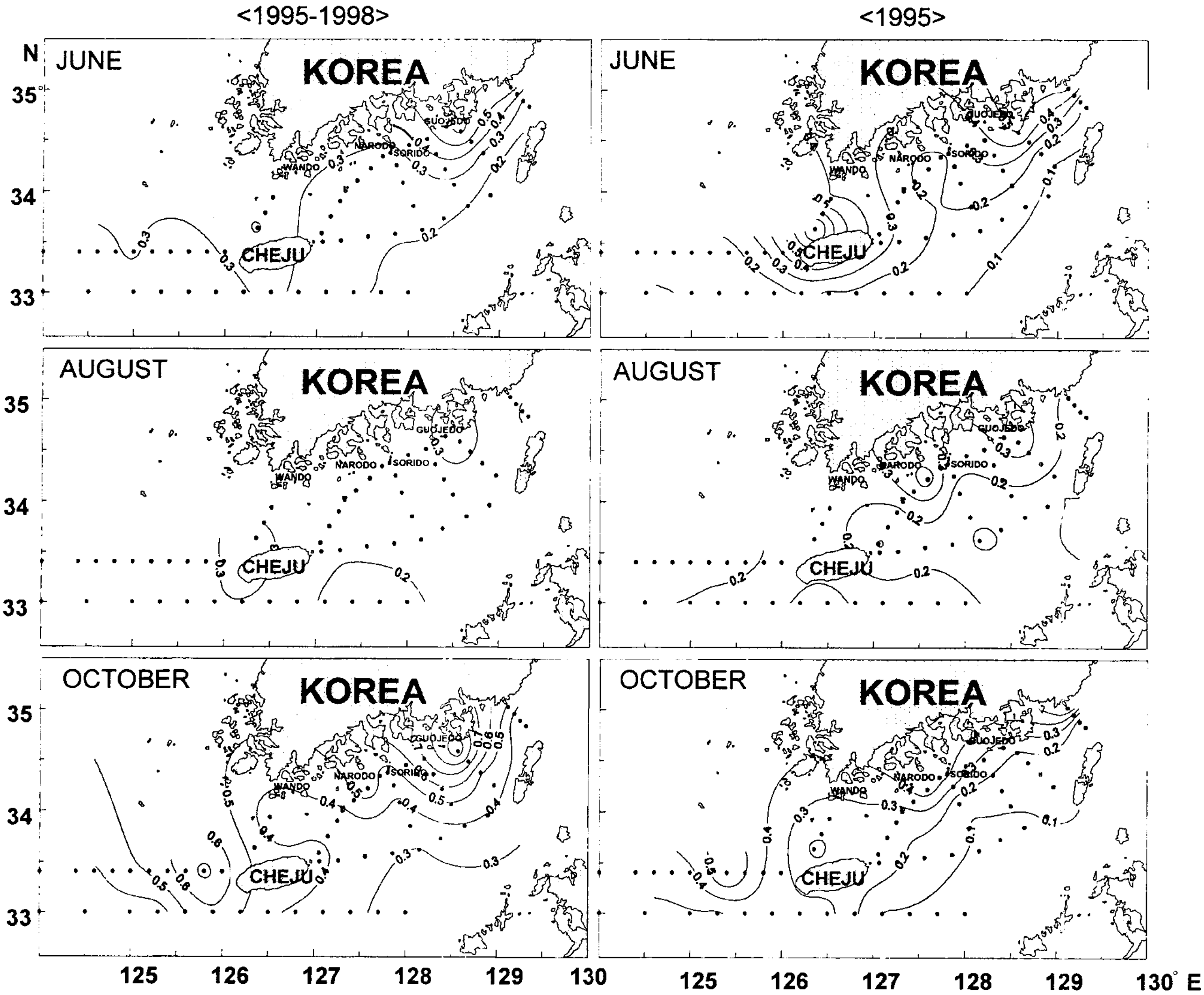

Fig. 9. Horizontal distributions of chlorophyll-*a* (μg/L) at the surface in June, August and October 1995 and the mean of 1995-1998.

should be included dinoflagellate species tolerated high shear and stress. Knowledge of the physiological characteristics of *C. polykrikoides* is essential to understanding its reaction and tolerance of turbulence, such as fronts and upwelling. However there is very limited knowledge of the physiology of *C. polykrikoides*. Kim *et al.* (2001) stated that ammonium is more important to the growth of *C. polykrikoides* than other inorganic nutrients. Lee *et al.* (2001) reported on the effects of temperature, salinity, irradiance and nutrients on the growth of *C. polykrikoides*. But there was no study on the physiological reaction to turbulence or high-shear environments. Kim *et al.* (1999) also referred to the importance of fronts in the outbreak of *C. polykrikoides* but didn't mention the physiological response. Thus, more studies are needed on physiological reactions to turbulence to understand the mechanism of *C. polykrikoides* blooms in relation to fronts.

Narodo Island is opened to offshore waters and is affected partly by the eutrophic coastal waters and partly by offshore waters. This raises the question, what is the source of nutrients supplied to Narodo Island to initiate *C. polykrikoides* blooms. Nutrient enrichment has most often been suggested as a cause of harmful algal blooms (Paerl, 1988). Thus, we tried to identify the source of nutrients supplied the coastal area around Narodo Island. We found an intrusion of extremely low salinity water with high nutrients around Jeju Island in August 1995. However, this water mass didn't reach the coastal area around Narodo and Sorido Islands. On the contrary, the coastal

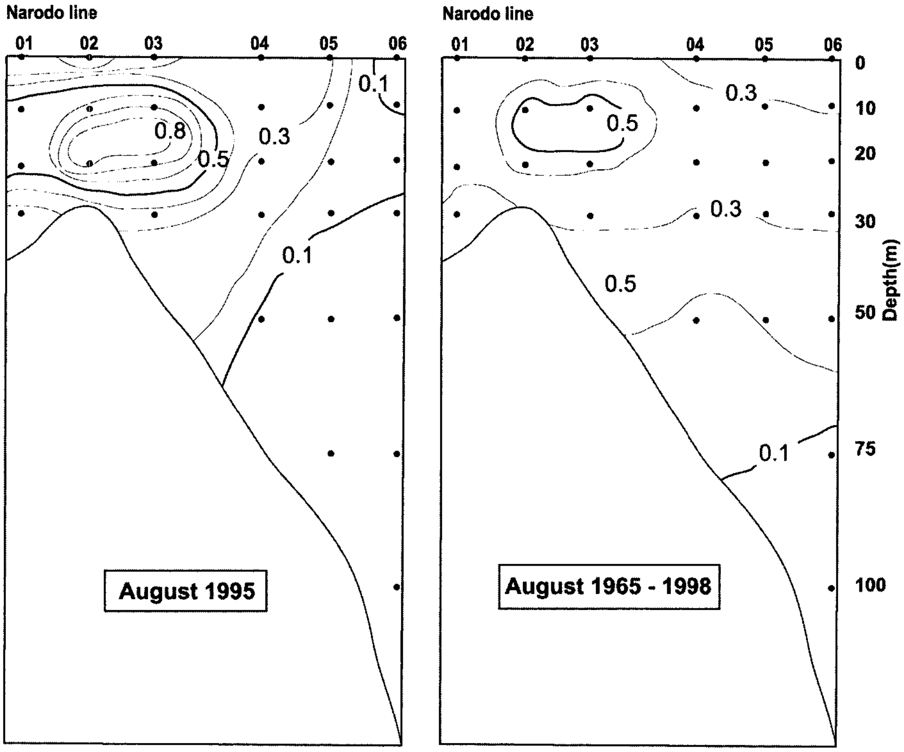

Fig. 10. Vertical distributions of chlorophyll-*a* (μg/L) along the Narodo line in August 1995 and the mean of 1995-1998.

area of Narodo and Sorido Islands showed high salinity compared to the offshore area around Jeju Island. However, Yang *et al.* (2000) found extreme environmental variations in seawater during the red tide in the coastal waters of Narodo Island in 1997. They suggested the possibility that offshore water mass influenced by the Yangtze River provided a high nitrate content, high seawater temperature and low salinity to the waters around Narodo Island. Choi (2001) also noted that variation in salinity was closely associated with the appearance and disappearance of red tides in the coastal area between Narodo and Sorido Islands. He also reported an influx of low salinity water from the offshore area, and emphasized the need for more study of the general circulation of the South Sea of Korea in order to better understand red tides. In this study, we found that in August 1995, the Tsushima Warm Current mixed with Yangtze River water strongly influenced the South Sea of Korea, but it did not approach the coastal area around Narodo Island. However, the water mass contributed to the strong upwelling front in the coastal area around Narodo Island. It was evident that a narrow gradient of salinity existed at the offshore area around Narodo Island in August 1995, with a high salinity water mass in the coastal area and a low salinity water mass in the offshore area. Thus, the low salinity water in the offshore area was one good source of nutrients in the South Sea of Korea in August 1995. But it did not directly contributed to the *C. polykrikoides* bloom in the coastal area around Narodo Island.

We suggest the nutrient source was the upwelling of cold bottom water around Wando-Narodo Islands. Upwelling brings nutrients from the bottom into the surface waters and stimulates primary productivity (Mann and Lazier, 1991; Huntsman and Barber, 1977). This upwelled water mass formed a upwelling front with offshore waters. The upwelling front is normally marked by a sharp temperature transition from the cold, nutrient-rich upwelled water inshore to the warmer, nutrient-poor stratified water offshore (Mann and Lazier, 1991). But clearly, any mechanism causing a mixing these waters is likely to stimulate primary productivity. In this study, the upwelling front formed at the interface between the inner coastal water mass and upwelled water mass. The inshore area showed the strong stratification at 10-20 m. These physical characteristics have a high possibility of enhancing phytoplankton growth. It is evident that the inner areas of Narodo and Sorido Islands showed high concentrations of nutrients and chlorophyll-*a* in August 1995 compared to the other years in spite of a high salinity water mass. Ryther (1967) found large con-

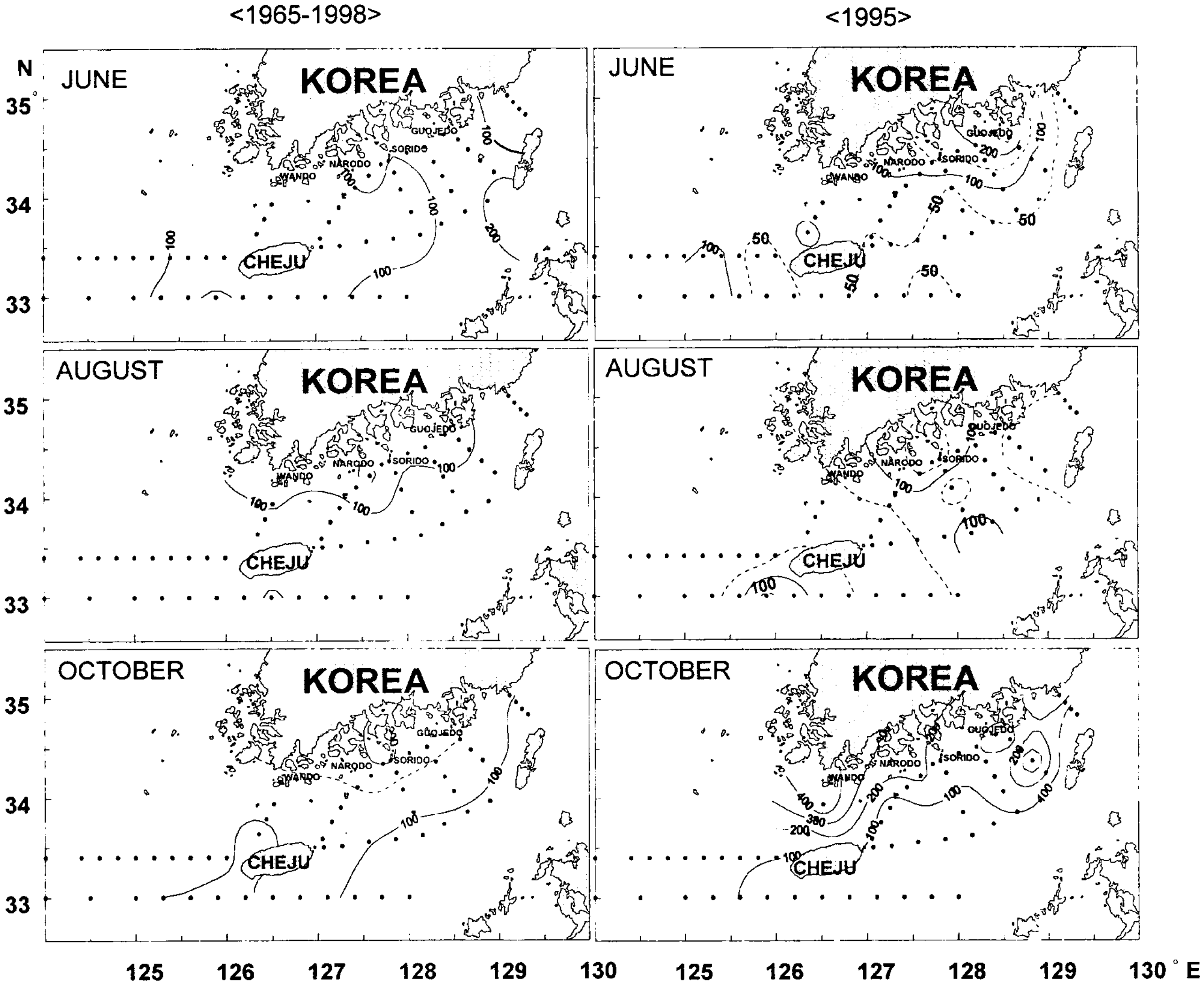

Fig. 11. Horizontal distributions of zooplankton biomass (mg/m^3) in June, August and October 1995 and the mean of 1965-1998.

centrations of a ciliate, which colored the water red, on the inshore edge of the upwelling front off Peru. Packare *et al.* (1978) also reported that large concentrations of phytoplankton formed on the inshore edges of upwelling fronts.

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