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Article

The Physical Environments and *Cochlodinium polykrikoides* Bloom in the Sea near Naro-Do

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Abstract : The initiation of *Cochlodinium polykrikoides* blooming in the South Sea of Korea occurs in the sea near Naro-Do in late August. In this paper, the relationships of this annual occurrence with the environmental conditions are presented. In early summer, the winds in the sea near Naro-Do are southwesterly and the upwelling occurs in the near-shore area. The favorable winds to the upwelling are relaxed in August and the downwelling favorable northeasterly winds set in around late August. The change of wind direction causes the onshore transport of warm-and-fresh off-shore water into the sea near Naro-Do and a front between near-shore water and off-shore water is formed. Along the front, downwelling occurs and the environmental conditions for the diatom become unfavorable. When the typhoon and storm bring well-mixed East China Sea water into the sea near Naro-Do in September, the conditions for the dinoflagellates become unfavorable and blooming of *C. polykrikoides* disappears.

Key words : red-tide, wind, downwelling, front

1. Introduction

The last two decades have been marked by recognition of the serious impacts of the marine phenomena called Harmful Algal Blooms (HABs) worldwide. HABs have increased in frequency, intensity and geographic distribution in the past two decades. These blooms caused the economic losses and the negative impacts on various things that include risks to human health, losses of natural or cultured seafood resources, and the impairment of tourism and recreational activities (Zingone and Enevoldsen 2000).

The major causative organisms of these blooms are dinoflagellates. *Cochlodinium polykrikoides* is one of the most harmful dinoflagellates causing red tides and of the highly toxic to fish (Onoue and Nozawa 1989; Yuki and Yoshimatsu 1989; Kim *et al.* 2000; Kim *et al.* 2002). Red tides due to this dinoflagellate have been reported in Japan, Korea, and other countries (Onoue and Nozawa 1989; Yuki and Yoshimatsu 1989). In recent years, blooming of *C. polykrikoides* was observed on the west coast of Vancouver Island from August to October 1999 and the economic loss to salmon growers was reported to be about $1.5 million (Whyte *et al.* 2001).

The *C. polykrikoides* blooms in the South Sea of Korea (Nam-Hae) have been reported since 1995. The bloom caused losses to the fishery industry amounting to $95.5 million in the fall of 1995. Although economic loss caused by this particular dinoflagellate species for aquaculture industry is significant, the outbreak mechanisms related to the environmental conditions and the eco-physiological aspects of the outbreak have not been well understood. Kim *et al.* (1999) and Lee *et al.* (2001) reported that the abundant supply of nutrients and increase of water column temperature initiated *C. polykrikoides* bloom. Yang *et al.* (2000) and Choi (2001) related intermittent intrusion of the low salinity water formed by the Yangtze River runoff to the outbreak and disappearance of *C. polykrikoides* in the sea near Naro-Do. The red tide bloomed along the front between the coastal water and the off-shore water (Lim *et al.* 2002) in 2000 and the downwelling (upwelling relaxed) area in 1995 (Kang *et al.* 2002). Jeong *et al.* (2000a, 2000b) explained that the

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distribution of *C. polykrikoides* in the coastal area off Kohung-Bando depended upon the horizontal movement of water (convergent and divergent zone) and the competition between diatoms and dinoflagellates.

The physical factors relating to the formation and transport of the dinoflagellate bloom have been studied in other countries. Franks and Anderson (1992a, 1992b) emphasized the role of wind stress on *Alexandrium tamarense* blooms using the plume-advection hypothesis in the Gulf of Maine. Tester and Steidinger (1997) and Steidinger *et al.* (1998) documented *Gymnodinium breve* blooms which began in the offshore area and moved onshore. The blooms were closely coupled with physical processes such as wind and currents in the Gulf of Mexico. Sharples (1997) showed that surface wind stress caused intrusion of offshore water and a dinoflagellate bloom in the coastal area off New Zealand.

Several outbreak patterns have emerged from previous studies on *C. polykrikoides* blooms which occurred during the past decade in Korea. The *C. polykrikoides* bloom usually starts (initiates) in the coastal area off Kohung-Bando, especially near Naro-Do in late August. In this paper, we will focus on the physical environmental conditions for a *C. polykrikoides* outbreak and try to explain the causes of those environmental setups which make favorable conditions for sudden *C. polykrikoides* growth. In Section 2, the physical reasons for *C. polykrikoides* outbreak in the area near Naro-Do is explained using remote sensing data and mean water characteristics from routine hydrographic observations by National Fisheries Research and Development Institute (NFRDI). The physical conditions for the outbreak of the *C. polykrikoides* bloom in late August are described in Section 3. The outbreak mechanisms deduced from *C. polykrikoides* outbreaks between 1995 and 2000 are presented in Section 4 and summaries and discussions follow in Section 5.

2. Why the first *C. polykrikoides* bloom in Korea begins in the area near Naro-Do

The bottom topography of the southern coast of Korea (Fig. 1) reveals that Sori-Do, which is the southern tip of

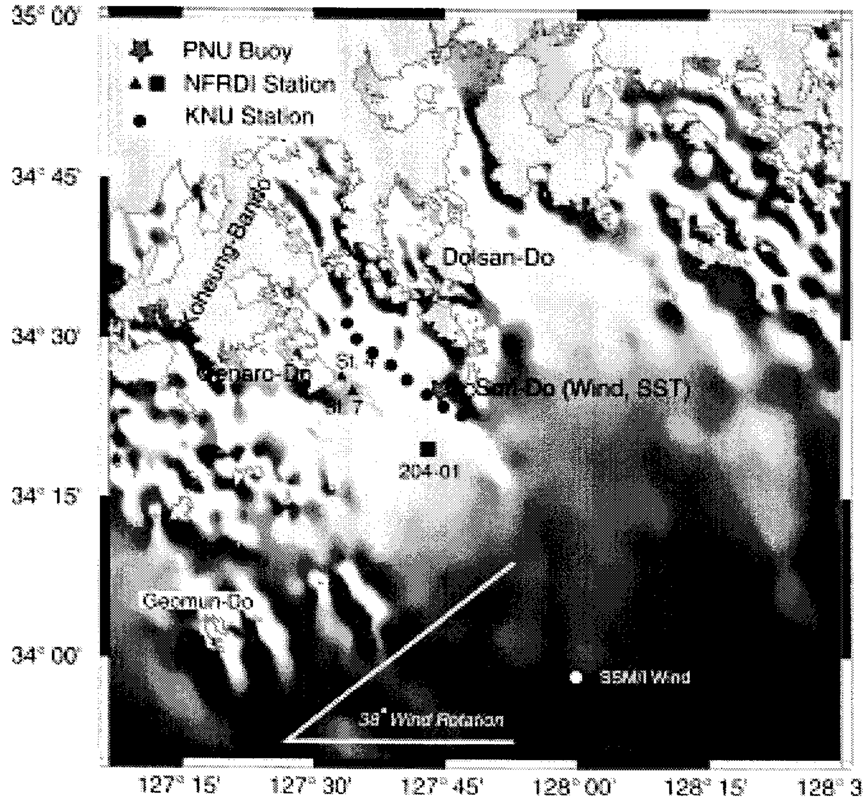

Fig. 1. Topographic map showing locations of the observations used in this paper. The winds are rotated 38° counter-clockwise for aligning the winds parallel to the coast.

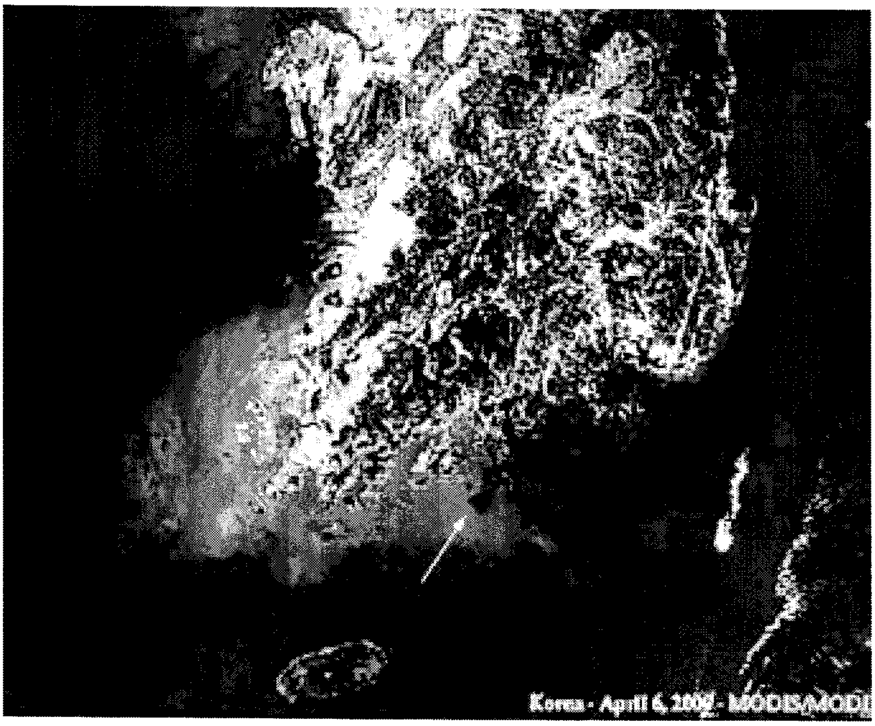

Fig. 2. True color image of the South Sea of Korea on April 6, 2000 from the NASA MODIS Terra satellite. The intrusion of off-shore water west of Sori-Do is marked by the white arrow.

the Kohung-Bando, is located at the middle of the submarine canyon opening to the open ocean. Through the submarine canyon, deep off-shore water enters the near-shore area and mixes with near-shore water. The range of daily salinity variation is near 2 psu at the head of the submarine canyon and it is controlled by the tide (see Fig. 5 in Lee and Niiler 2003). The submarine canyon and island chain from Dolsan-Do to Sori-Do can act as a topographic feature blocking the eastward near-shore current. The alignment of the submarine canyon is such that the Ekman current caused by south-westerly wind, which is favorable upwelling wind in July, easily transports open ocean deep water toward the area near Naro-Do.

According to Pang and Hyun (1998), the mean current in August is eastward along the southern coast of Korea. As Lim *et al.* (2002) points out, the front formed in the area off Naro-Do is the boundary between the clear offshore water and turbid near-shore water of the western south coast of Korea. The intrusion of clear offshore water into the area south of Naro-Do is clearly shown in true color photograph taken on April 6, 2000 (Fig. 2). The most plausible cause of the front between offshore water and near-shore water in the area south of Naro-Do is the topographic features, i.e. the submarine canyon and islands in the middle of it that divide the shallower western Nam-Hae and the deeper eastern Nam-Hae.

3. Why the first outbreak of *C. polykrikoides* bloom occurs in late August

The daily air temperature averaged over the last 30 years at Sori-Do reaches its annual highest value on August 7th and the annual highest water temperature occurs on the 17th of August (Hahn *et al.* 1997). Between 1995 and 1999, *C. polykrikoides* bloom started at 10-15 days after the date of the annual maximum temperature of water (Fig. 3). But in 1997, the annual highest water temperature occurred 15 days later than that of previous years and it occurred after the *C. polykrikoides* bloom started. The highest annual water temperature in 1999 occurred in late July before the air temperature reached its highest value and the *C. polykrikoides* bloom started 15 days earlier than other years. The earlier date of the highest annual water temperature in 1999 compared to the average highest annual air temperature implies that the sea water at Sori-Do was not locally warmed but was affected by the horizontal advection of sea water. Lee *et al.* (2002)

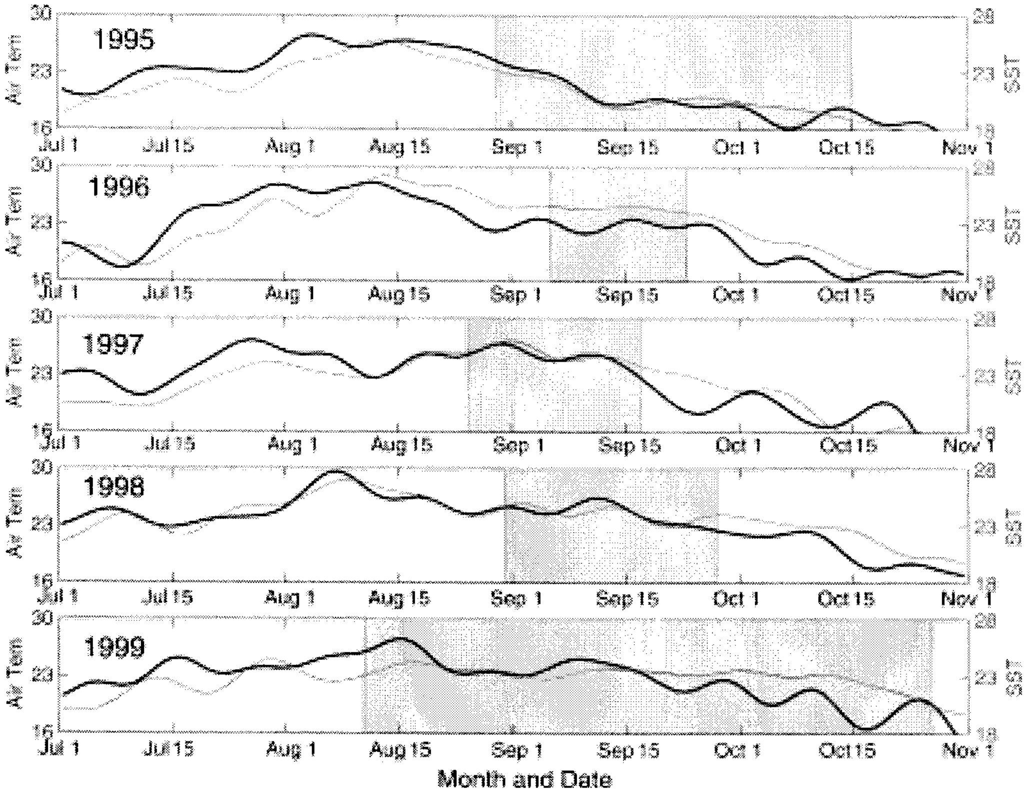

Fig. 3. Time series of daily sea surface temperature (thin lines) and air temperature (thick lines) at Sori-Do. Periods of *C. polykrikoides* bloom are indicated by gray boxes.

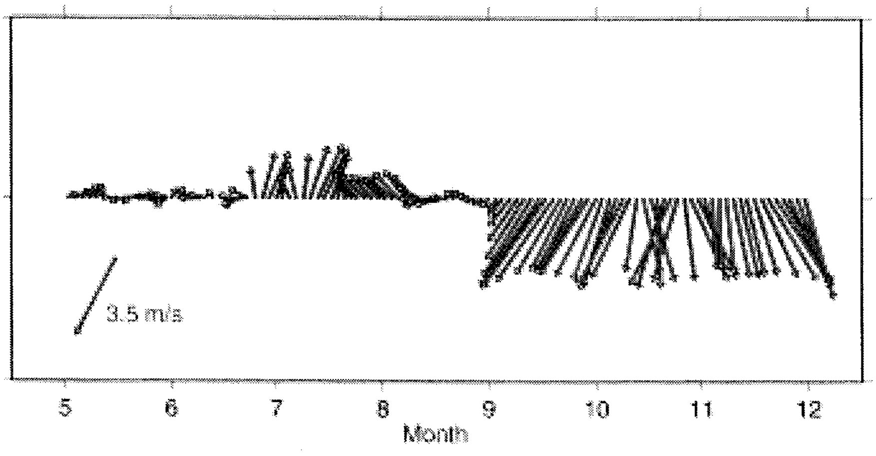

Fig. 4. Daily SSM/I wind vectors from May to November at 34°N, 128°E. The winds are averaged over 13 years from 1988 to 2000.

achieved the maximum growth rate of *C. polykrikoides* in 25°C water but the variation of growth rate between 20°C and 27°C was very small. The water temperature may affect growth of *C. polykrikoides* but it is not a critical environmental condition for initiating red tide.

The daily mean off-shore winds, estimated from the Special Sensor Microwave Imager (SSM/I), averaged over 13 years between 1988 and 2000 show dramatic wind pattern changes in late August (Fig. 4). From May to June, winds are weak and are mostly south-westerly.

South-westerly winds become stronger in July up to early August and they are upwelling favorable winds. From the middle to late August, upwelling favorable south-westerlies are relaxed and winds become easterlies. In early September, winds become strong north-easterlies which can transport off-shore water to the area near Naro-Do. Can these downwelling favorable winds followed by the weakening of upwelling favorable winds in late August be the cause of sudden growth of *C. polykrikoides*? The possible mechanism of *C. polykrikoides* bloom related with wind in the area near Naro-Do is presented in the next section using various observational data.

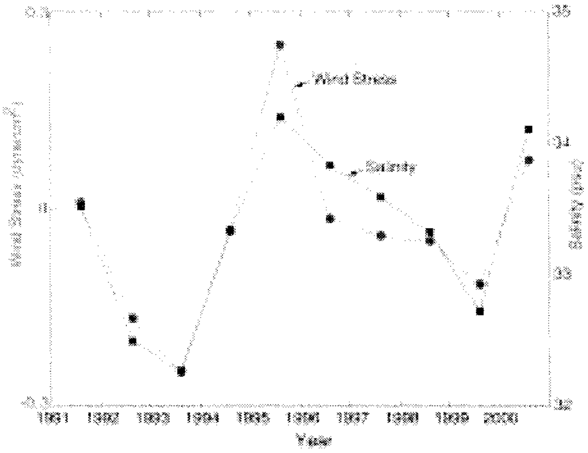

Fig. 6. Yearly variations of bottom salinity (right axis and dashed line) and mean wind stress (left axis and solid line) during 15 days prior to salinity observation at NFRDI Station 204-01 in August. Station location is indicated in Fig. 1.

4. How the *C. polykrikoides* bloom starts and ends

When bottom water near Naro-Do warmed up and the thermal stratification collapsed in August, the *C. polykrikoides* bloom in the area near Naro-Do started (Fig. 5). In 1999, the collapse of stratification happened in August 9th (15-20 days earlier than the normal year) and coincided with the early outbreak of *C. polykrikoides* bloom. The collapse of stratification at Station 7 was not clear in 2000

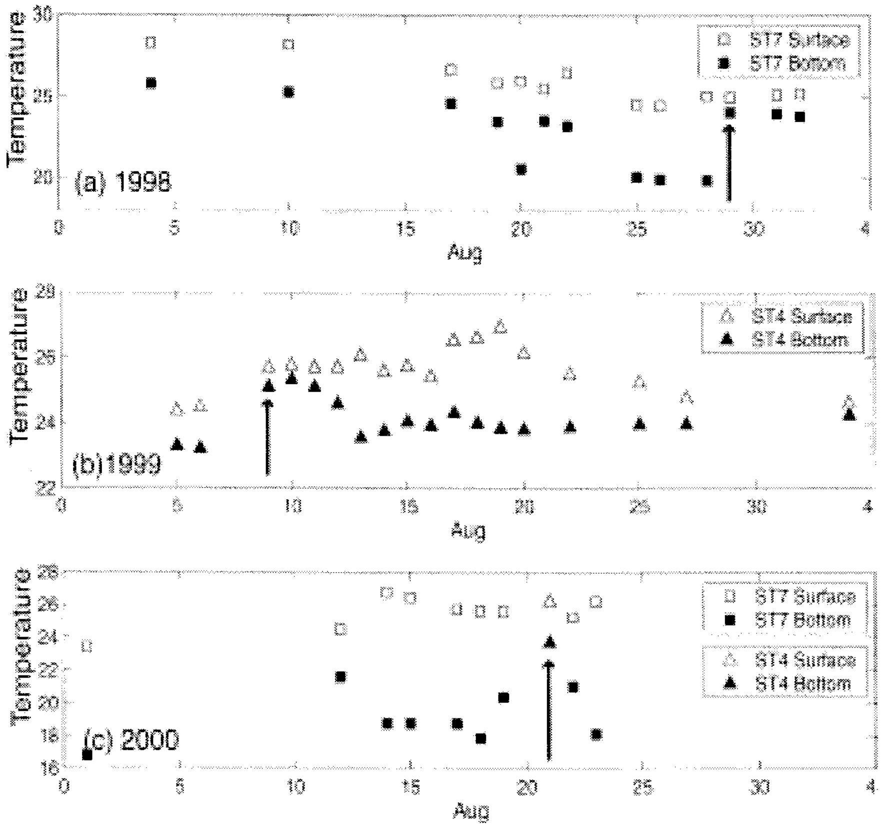

Fig. 5. Time series of daily surface and bottom temperature at stations 4 and 7 (redrawn from Lee *et al.* 2001). Locations of stations are indicated in Fig. 1.

because of the lack of daily temperature observations on the day when *C. polykrikoides* first appeared, but the *C. polykrikoides* bloom started on the day when bottom water temperature increased to 24°C at Station 4. Since the temperature at the surface did not change, the collapse of stratification was not caused by the vertical mixing of the water column. The warming of the bottom water may have been caused either by the intrusion of warm bottom water or the downwelling of the surface water. Observation using the moored buoy equipped with a thermister chain is needed to determine the exact dynamic nature of stratification collapse and to verify the relationship between the stratification and the *C. polykrikoides* bloom.

One of the physical conditions for the downwelling in the near-shore area is the onshore wind-driven transport by along-shore wind. In the area off Sori-Do, the winds are southwesterly from late June to July and they induce upwelling. But those upwelling favorable winds are relaxed in August and change to strong downwelling favorable northeasterly winds in September (Fig. 4). To show the relationship between onshore water transports and along-shore wind in August, the bottom salinity and the wind stress at the NFRDI station off Sori-Do are presented in Fig. 6. The NFRDI station 204-01 is located in the area where offshore water intrusion occurs through the submarine canyon (Fig. 2). The bottom salinity reached 34.2 psu in 1995 and 2000 when the wind was upwelling favorable southwesterly but it was lower than 33 psu when the wind was downwelling favorable northeasterly in 1993 and 1999. The salinity fluctuations clearly demonstrate the wind influences on onshore transport of deep offshore water which has a low temperature and high salinity. The yearly observations of salinity and temperature at NFRDI station 204-01 demonstrate the inverse relationship between temperature and salinity; i.e. the bottom water was warm when salinity was low (Fig. 7) with the exception of 1998. The warm-and-fresh water at the bottom was found after the *C. polykrikoides* bloom started (Fig. 8a), but the cold-and-saline water and strong stratification below 10 m were observed before the red tide outbreak (Fig. 8b). The yearly observations of bottom temperature and salinity at the boundaries between near-shore water and off-shore water suggest that *C. polykrikoides* bloom starts when cold-and-saline bottom water is replaced by warm-and-fresh water as a result of downwelling favorable northeasterly wind.

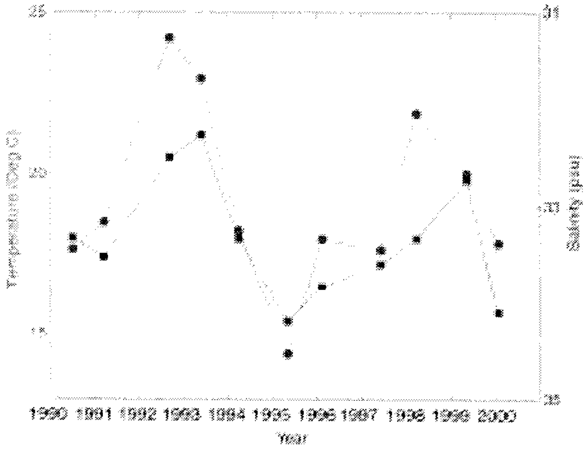

Fig. 7. Yearly variations of bottom salinity (inverted right axis and solid line) and bottom temperature (left axis and dotted line) at NFRDI station 204-01 in August.

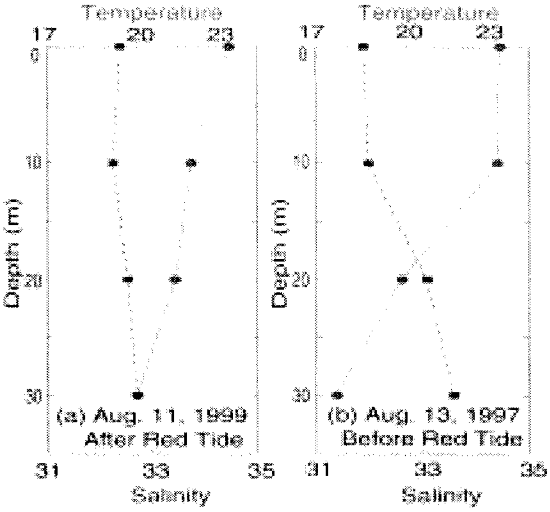

Fig. 8. Vertical profiles of temperature (top axis and solid line) and salinity (bottom axis and dotted line) (a) one day after red tide outbreak and (b) ten days before red tide outbreak at NFRDI Station 204-01.

The wind and sea surface temperature at 10 A.M. have been observed everyday at Sori-Do since 1966 (Hahn *et al.* 1999). To verify the winds measured at Sori-Do, they are compared with SSM/I winds (Fig. 9). Since we are only interested in the trend of directional change of the along-shore wind component, both winds were rotated 38° counterclockwise to align with the shoreline and were filtered using a low-pass filter with a cut-off frequency of 0.12 cycles per day. The off-shore winds observed by SSM/I were somewhat stronger than the winds observed at Sori-Do but the changes of wind direction measured at Sori-Do closely followed the SSM/I winds. The daily along-shore wind stresses observed at Sori-Do from 1995

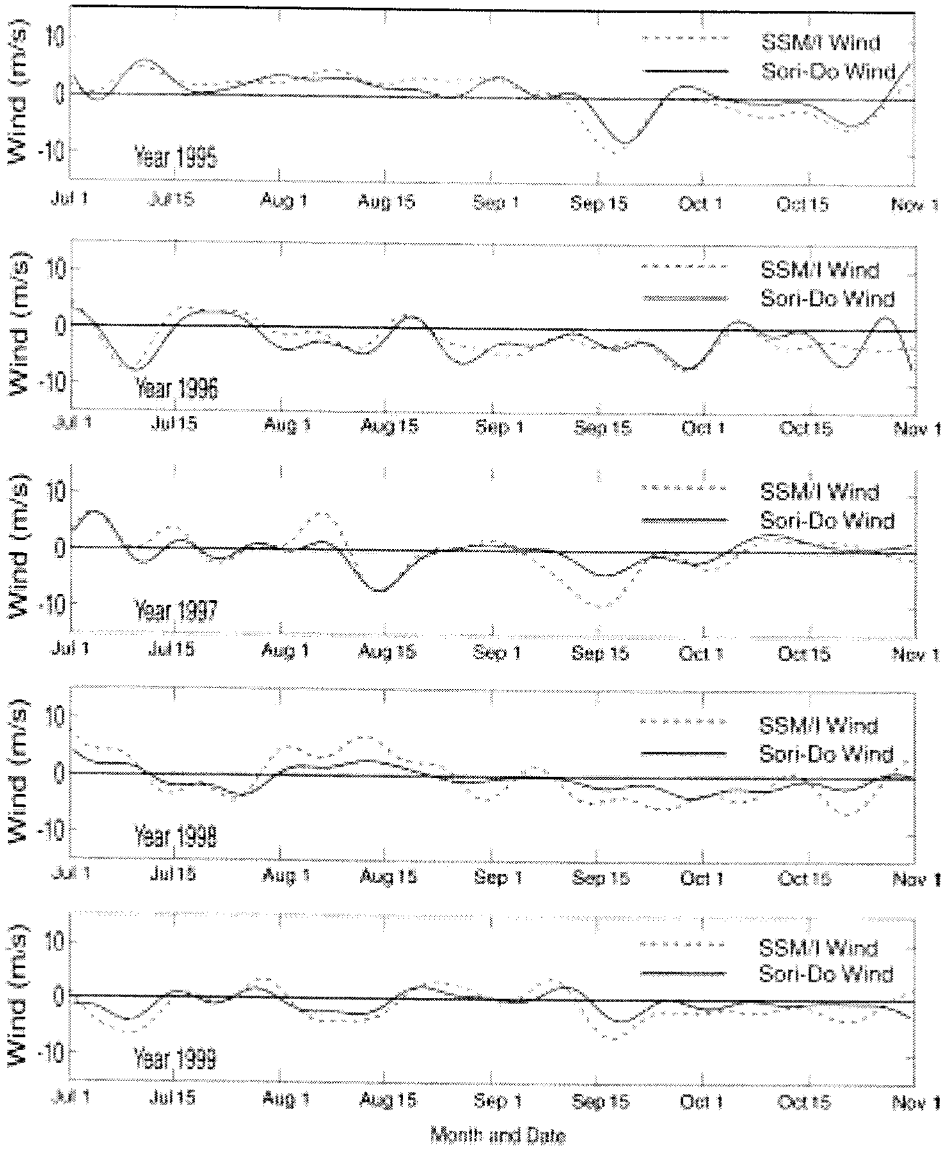

Fig. 9. Comparison of winds measured at Sori-Do (blue lines) and by SSM/I (red lines). Descriptions of data are in the text.

to 1999 are presented in Fig. 10 with the periods of *C. polykrikoides* bloom which occurred in the area near Naro-Do. After September 1, 1999, the wind measured at Sori-Do did not match with the SSM/I wind (Fig. 9), so only SSM/I winds were used in 2000. Negative wind stresses in Fig. 10 are the northeasterly wind stresses that are downwelling favorable. Patterns of outbreak and disappearance of the red tide can be deduced from *C. polykrikoides* blooms and wind data between 1995 and 1999. (1) *C. polykrikoides* blooms started after the typhoon incursion (1995 and 1999) or after the period of northeasterly wind (1996, 1997 and 1998). Although filtered wind was weak southwesterly before bloom in 1995, winds at Sori-Do were mostly northeasterly during the week before *C. polykrikoides* bloom. The filtered winds became southwesterly just by one day of typhoon force wind. There was one exceptional year (2000) when *C. polykrikoides* blooms started during weak southwesterly winds. (2) *C. polykrikoides* blooms were ended by the strong northeasterly wind events (1995 and 1996) or by typhoon incursions (1997-2000). Several days before the typhoon reached the southern coast of Korea, offshore

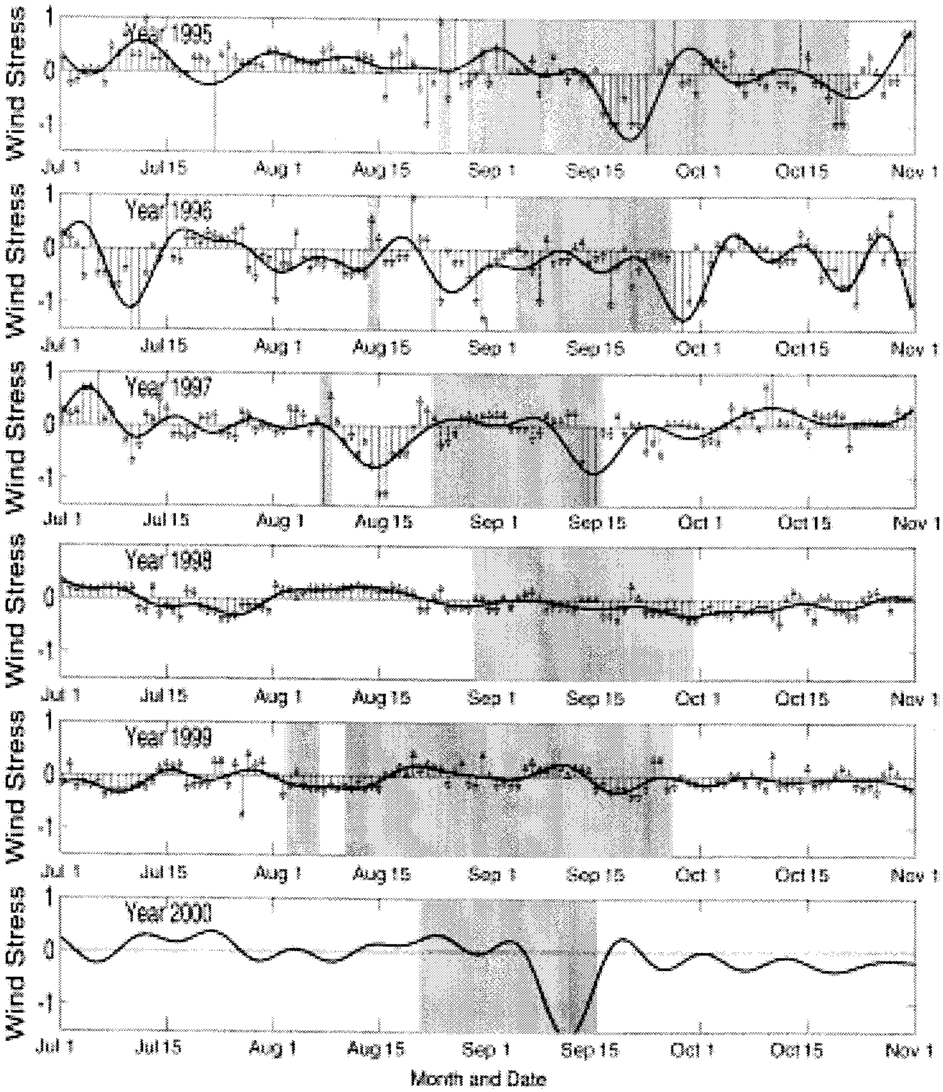

Fig. 10. Time plots of daily wind stress (arrows) and filtered wind stress (solid lines) at Sori-Do, typhoon periods (gray boxes), and periods of *C. polykrikoides* bloom (red boxes). SSM/I wind stress are used for 2000.

water was transported to the near-shore area by easterly or north-easterly winds (Lee and Niiler 2003). In 1995, strong northeasterly wind events in September did not stop *C. polykrikoides* bloom and the bloom lasted until the middle of October. If the fact that the governing physicochemical environments for *C. polykrikoides* bloom are complicated is considered, the simple relationships between *C. polykrikoides* bloom and wind event presented here are quite surprising. Continuous wind, temperature and salinity near Naro-Do should be observed in August and September for better understanding of these relationships.

Depending upon the season, the onshore transports by northeasterly wind made the environment either favorable or unfavorable to *C. polykrikoides* growth. Lee *et al.* (2002) related the disappearance of *C. polykrikoides* by a typhoon to the temperature drop in the area. But there were many different cases, especially in 1995 in which the *C. polykrikoides* bloom continued below 22°C. Besides temperature drop, the offshore water transported by a typhoon had different physicochemical characteristics than that of offshore water which intruded in late August. In early August, the surface layer in the East China Sea is covered by the low salinity water which is a mixture of the East China Sea water with the Yangtze River discharge. The runoff from the Yangtze River comes into the East China Sea during the East Asian monsoon between May

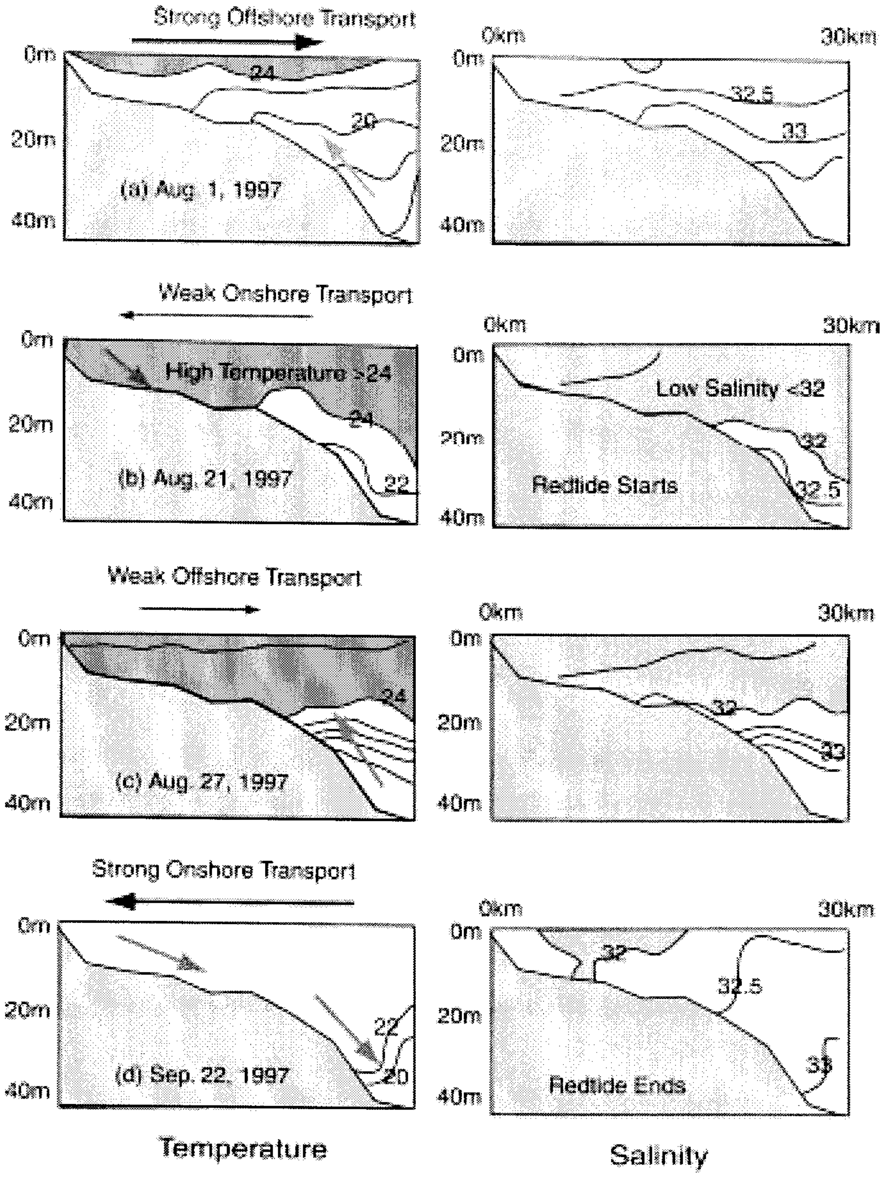

Fig. 11. Vertical profiles of temperature and salinity in the sea near Naro-Do (a) before the red tide outbreak, (b) on the day of red tide outbreak, (c) during the red tide and (d) on the day of the red tide disappearance (redrawn from Yang *et al.* 2000).

to July and most of the nutrients carried off by the runoff are depleted by the time the water reaches the southern coast of Korea. The hydrographic observations conducted by NFRDI show the low nutrient level in the South Sea of Korea in August. But the water transported by a typhoon in late September is rich in nutrients because of strong vertical mixing of surface water with nutrient rich deeper water which may trigger a diatom bloom (Lee and Niiler 2003).

The expansion of *C. polykrikoides* bloom to the eastern South Sea of Korea is related to the direction of along-shore current. In 1998, *C. polykrikoides* bloom did not expand eastwards and the winds were very weak northeasterly. The result of numerical model by Lee (1999) showed that the eastward along-shore current developed when southwesterly winds were applied. The expansion pattern of phytoplankton growth in the case of eastward along-shore current was very similar to the red tide propagation pattern. The relation of the red tide to the along-shore current is a very complicated issue and the difficulties of measuring coastal current hinder the finding of the relationship between the *C. polykrikoides* bloom and the coastal current.

Although there are many physicochemical factors controlling the population growth of *C. polykrikoides*, the best scenario for the outbreak and disappearance of *C. polykrikoides* is constructed here using a two layer model: the surface layer consists of the cold-and-fresh near-shore water and the warm-and-fresh offshore water, and the cold-and-saline off-shore water constitutes the bottom layer. Yang *et al.* (2000) demonstrated the relationship between growth of the *C. polykrikoides* and onshore-offshore water transport and their observations are redrawn in Fig. 11. Before August 1st 1997, there were periods of upwelling favorable wind events (Fig. 10). Starting from August 7th the winds had directions favorable to the onshore transport. When near-shore water became homogeneous with warm and fresh water on August 24th, the *C. polykrikoides* bloom started. Weak but upwelling favorable winds and the *C. polykrikoides* bloom continued until the incursion of the Typhoon Oliwa on September 17th. Resulting from massive onshore transport by the Typhoon Oliwa, the near-shore area became flooded with nutrient rich water and the *C. polykrikoides* disappeared (Lee *et al.* 2001).

5. Discussions

The scenario of the *C. polykrikoides* outbreak and disappearance is deduced mostly from a physical point of view. When warm and low-salinity water from the off-shore area meets with near-shore water near Naro-Do, a

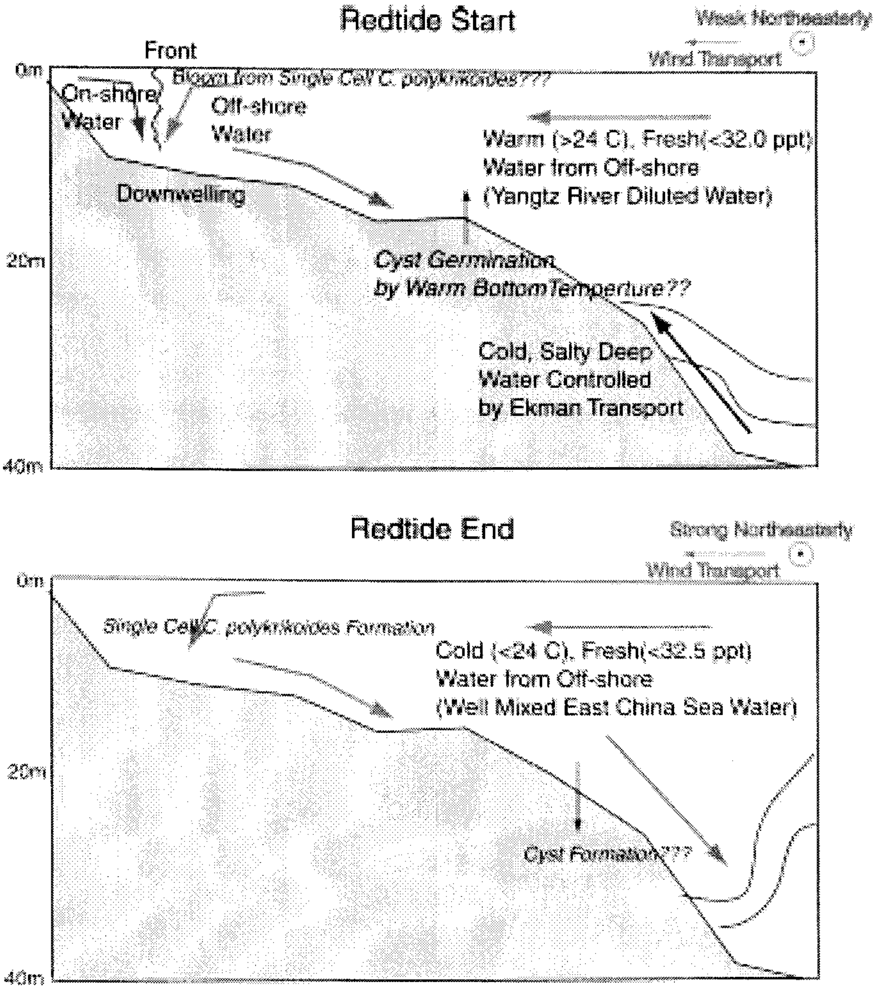

Fig. 12. Schematics of the relationship of the red tide with the physical environmental changes (a) for the outbreak and (b) for the disappearance.

front is formed along the shore of Naro-Do (Fig. 12). Along the front, downwelling occurs and it makes diatom growth more difficult because of diatom's limited floating adjustment. But the downwelling creates favorable physical conditions for *C. polykrikoides* which can move vertically in a water column. The *C. polykrikoides* cysts may germinate in warm bottom water or single cell *C. polykrikoides* may have been transported from the offshore area. When nutrient rich offshore water is transported into the red tide infected area by typhoon or storm in September, diatoms can compete successfully with *C. polykrikoides* and the *C. polykrikoides* bloom disappears from the South Sea of Korea.

The above scenario is based on the observations made between 1995 and 2000. The *C. polykrikoides* bloom did not always follow the scenario presented here during the last 8 years. More observational studies are needed to construct the relationship between physical environment changes and the *C. polykrikoides* bloom, including the continuous monitoring of subsurface temperature and salinity, wind, and currents in the red tide outbreak area. But we are confident that the scenario presented here can be used to explain most aspects of the outbreak and disappearance of *C. polykrikoides* between 1995 and 1999.

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