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Relationship between Temperature Distributions and Outbreaks of Harmful Algal Blooms in Korean Waters

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Harmful algal blooms (HABs) of *Cochlodinium polykrikoides* frequently occur around the South Sea of Korea, causing economic losses in coastal breeding grounds. HAB outbreak scale usually changes each year depending on physical, biological and environmental conditions. Relatively large-scale HABs occurred in 1995, 1997, 1999, 2001, 2002 and 2003 with respect to spatial scale, duration and maximum density. Considering HAB scale and temperature distributions around the South Sea, we found that low coastal temperatures in August correspond to enormous HAB outbreaks. Cold waters created by coastal upwellings around the southeastern coast of Korea also corresponded to these outbreaks. Serial oceanographic investigations in August in the South Sea revealed that sea surface temperature anomalies had distinctively negative values when large-scale HAB outbreaks appeared. With regard to temperature differences between the surface and the 30-m layer, there was a tendency for large-scale outbreaks when temperature gradients around the seasonal thermocline weakened.

Key words: Harmful algal bloom, Temperature structure, Physical condition

Introduction

Red tide is defined as a red discoloration of marine waters caused by the presence of enormous numbers of certain microscopic algae (Halstead, 1965). Outbreaks of red tides have clearly increased during the last 20 years and threaten human health and fisheries resources. The algae that occur in red tides include approximately 300 species of diatoms, dinoflagellates, silicoflagellates, prymnesiophytes and raphidophytes. Among these species, 60-80 species are considered Harmful Algal Bloom (HAB) species because of biotoxins, physical stresses, hypoxia, decreases of luminous intensity and states incongruent with nutrients. Most (90%) of these HAB species are dinoflagellates (Smayda, 1997).

Studies regarding HAB threats to human health and damages to fisheries have been conducted throughout the world (Watras et al., 1982; Yasumoto et al., 1993; Lefebvre et al., 2002). In Korea, HABs frequently occurred in some coastal areas in the 1980s, although they occurred only intermittently in the 1970s. HABs have not only occurred within inner bays and coastal areas; since the 1990s they have also been observed in the open ocean (Kim et al., 2001). HAB species around the Korean peninsula have mainly included *Cochlodinium polykrikoides* during the last few years. Blooms of *C. polykrikoides* frequently occurred around the South Sea and the East Sea of Korea in 1995, causing considerable damage to fisheries. These natural phenomena have frequently occurred year after year in the summer, causing enormous economic loss and waste in oceanic ecosystems since 1995 (NFRDI, 1997a; b; 1999; 2000; 2002; 2004). Studies of HABs dominated by *C. polykrikoides* were initiated in 1996 and have increased our understanding of the outbreak mecha-nism, physiology and ecology of algae and mecha-nisms of fish mortality (Kim et al., 2000a; b; Kim and Cho, 2000).

The cause of HAB outbreaks is not yet clear, although several hypotheses have been proposed. Comparing integrated and accumulated oceano-graphic data to the scale of HAB outbreaks since 1995, we quantitatively and qualitatively examined oceanic conditions when HABs occurred in Korean waters. As a matter of course, this biological phenol-menon could not be explained simply by physical variation. However, by examining the physical con-

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ditions of HAB outbreaks, this study helps to clarify the causes of HAB outbreaks in Korean waters.

Materials and Methods

The data on HAB outbreaks were derived from a spatial map created by the Marine Ecology Research Team of NFRDI and the East, South and West Sea Fisheries Research Institute of the NFRDI from 1995 to 2005. To compare HAB outbreaks to temperature, three types of temperature data were used. The first temperature dataset involved serial oceanographic investigations with a bi-monthly time scale for examinations of onshore and offshore temperature distributions and temperature differences between the surface and sub-surface layers (Fig. 1; data were collected by the Ocean Research Team and the South Sea Fisheries Research Institute of the NFRDI). The second dataset comprised coastal oceanographic data collected once a day in a fixed area along the Korean coast. We used data from two stations to compare temperature variation with outbreaks in Yeosu and Sorido and four stations to compare HABs to occurrences of cold-water masses due to coastal upwellings in Ulgi, Gampo, Busan and Wando. The final dataset was the Multi-Channel Sea Surface

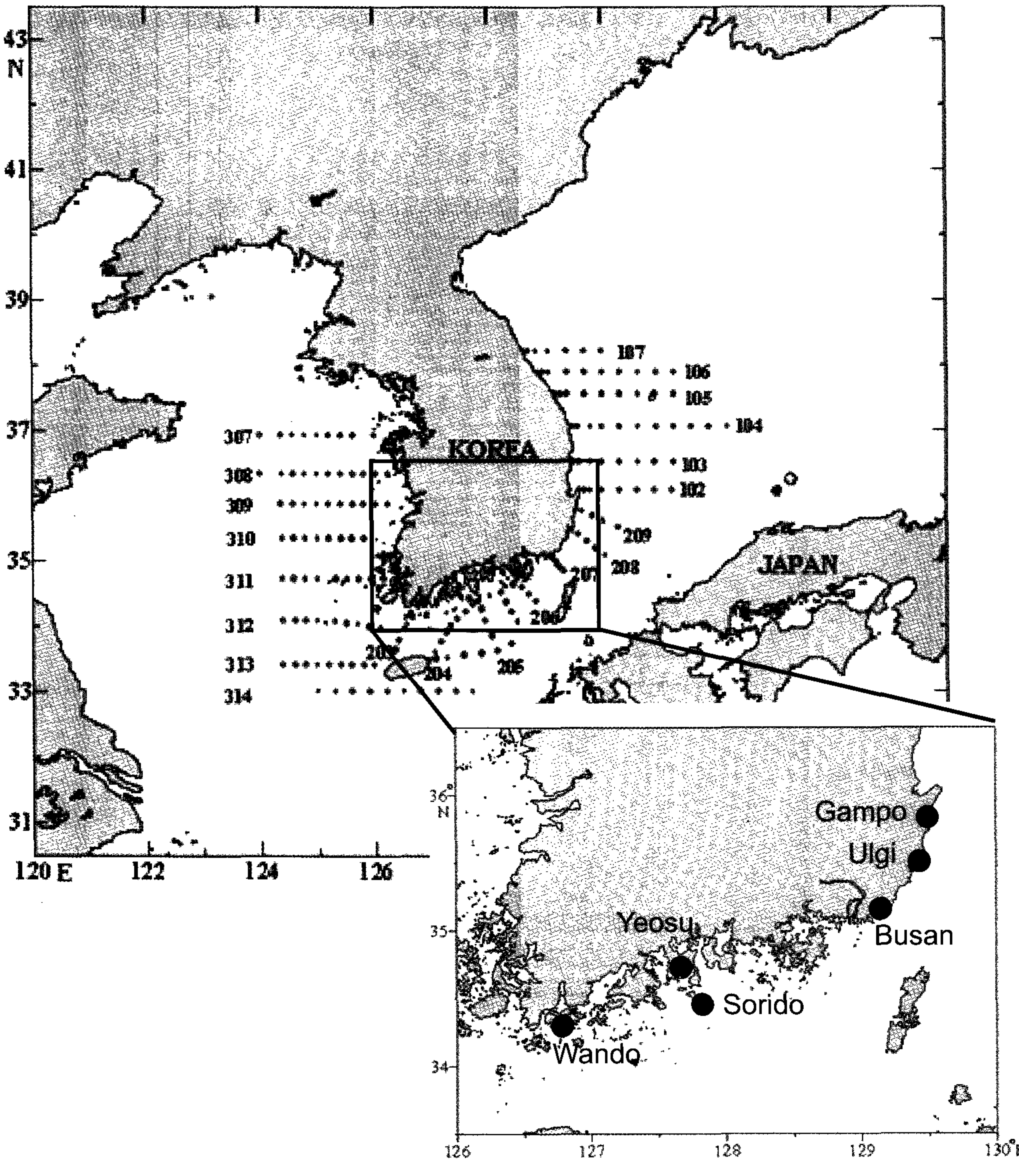

Fig. 1. Location maps for serial oceanographic investigation and coastal temperature measurement.

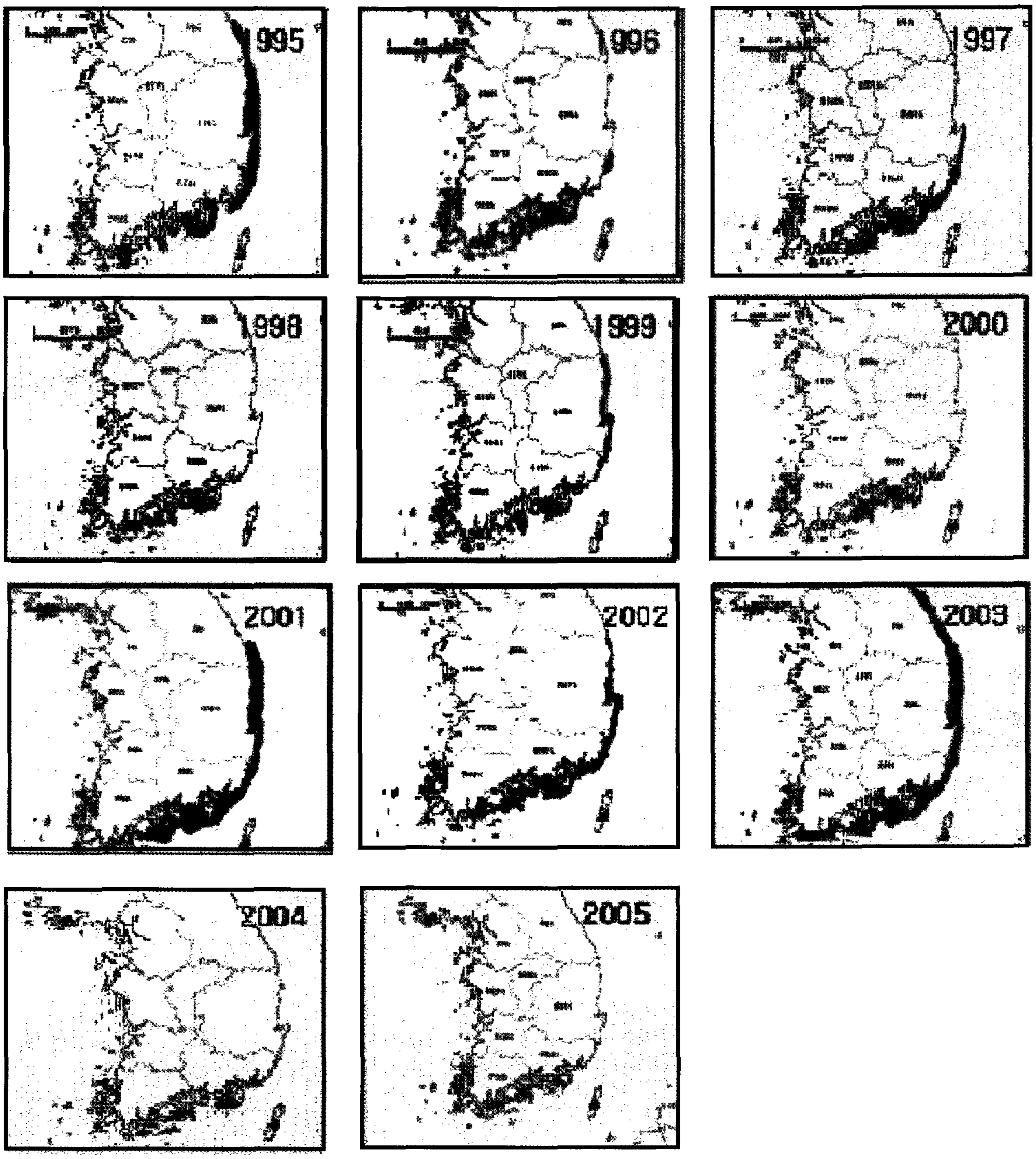

Fig. 2. The spatial map of HAB outbreaks (red area) along the Korean coast from 1995 to 2005.

Temperature (MCSST) dataset collected by the Naval Research Laboratory (NRL), which we used to examine temperature variation over a wide area. From these datasets, snapshots of MCSST anomalies were used for comparisons to HAB outbreaks around the Korean Peninsula.

Results

Outbreaks of HABs in Korean Waters

The NFRDI, Marine Ecology Research Team monitors outbreak states of HABs twice a month around the coastal area using research vessels and helicopters from May to October each year. These monitoring efforts produce spatial maps of HAB outbreaks (Fig. 2). Extensive HABs, which extended to the eastern coast of Korea, occurred in 1995, 1997, 1999, 2001, 2002 and 2003. Especially large-scale HABs appeared in 1995, 2001 and 2003. The HAB outbreaks in 1996, 1998, 2000, 2004 and 2005 were smaller, although they occurred locally around the

Table 1. Summary the HAB outbreaks by *C. polykrikoides* during the last 11 years

Items	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
First outbreak date	8. 29	9. 4	8. 24	8.30	8. 11	8. 22	8. 14	8. 2	8. 13	8. 5	7. 19
Disappearance date	10.23	10. 2	9. 20	10. 2	10. 3	9. 19	9. 24	9. 27	10.13	9. 3	9. 14
Duration (days)	55	28	27	34	54	29	41	57	62	30	58
First outbreak area (on Fig.3)	A	A	A	A	A	B	B	C	C	D	C
Maximum density (10^3×cells/mL)	30	23	20	22	44	15	32	30	48	5.8	25
Amount of damage (hundred million KRW)	764	21	15	1.6	3.2	2.6	84	49	215	1.2	10

South Sea coast of Korea. The trend for outbreaks during the last 11 years is summarized in Table 1. HABs generally begin in early or mid August, although one occurred in mid July in 2005, and usually end between late September and mid October. The duration of HABs around the Korean Peninsula is approximately 27-62 days, with the longest event lasting 62 days in 2003. The first outbreak area for HABs that occurred between 1995 and 1999 was generally around Naro-do (A on Fig.3). In 2000 and 2001, HABs started around Dolsan (B on Fig. 3), located a few tens of kilometers east of Naro-do. In 2002, 2003 and 2005, HABs also began around the Bodol Sea and around Geoje in 2004 (C and D, respectively, on Fig. 3). Maximum densities of *C. polykrikoides* are about 5,800-48,000 cells/mL; highly concentrated HABs, with densities > 30,000 cells/mL, appeared in 1995, 1999, 2001, 2002 and 2003.

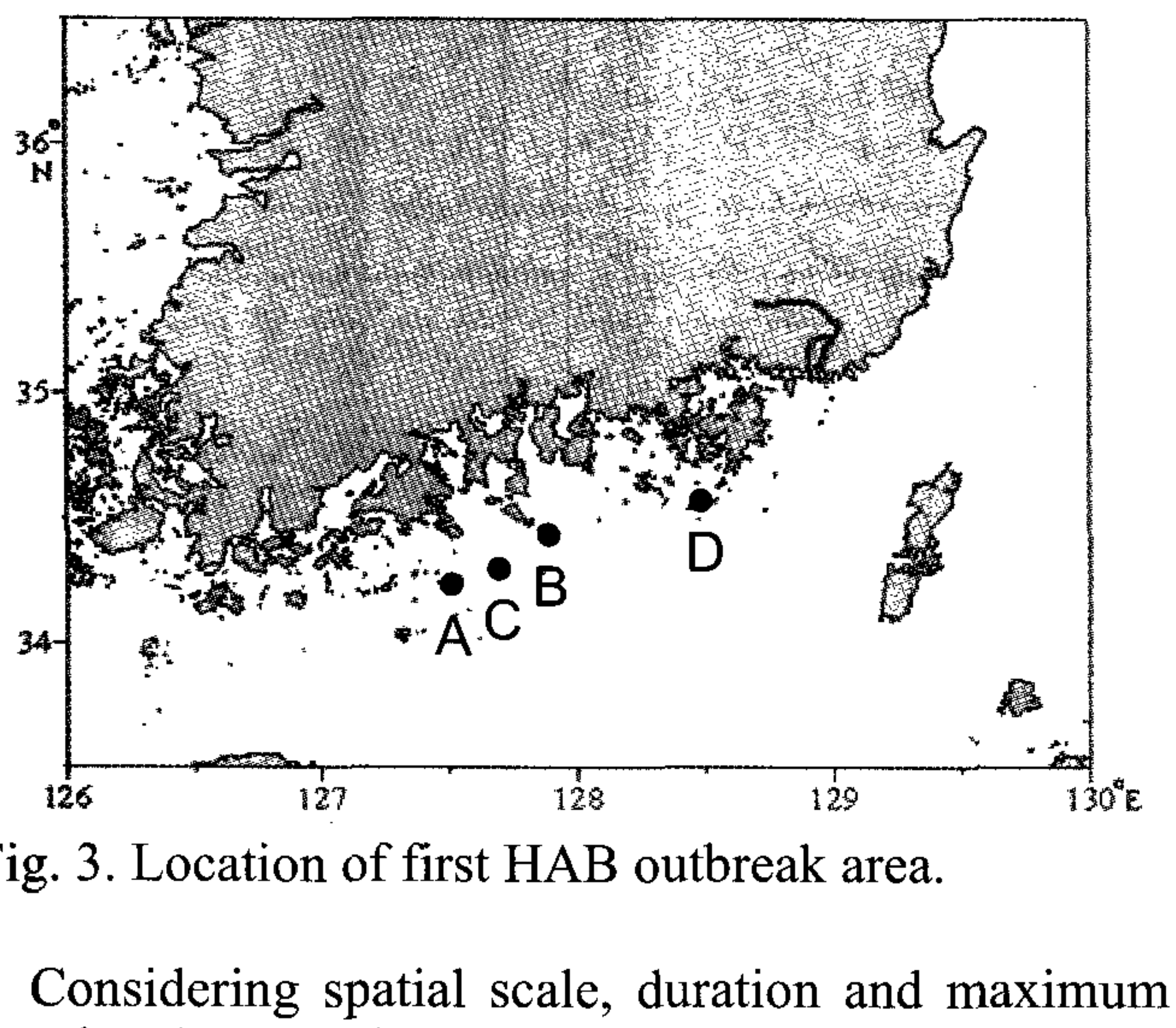

Fig. 3. Location of first HAB outbreak area.

Considering spatial scale, duration and maximum density, large-scale HABs occurred in 1995, 1997, 1999, 2001, 2002 and 2003, while smaller-scale events appeared in 1996, 1998, 2000, 2004 and 2005. The larger- and smaller-scale HABs generally occurred with year-to-year variation before 2001, although this pattern has deteriorated since 2002.

Coastal temperature variation with HABs

To examine the relationship between HAB outbreaks and coastal temperature, the data for which were obtained through coastal oceanographic investigations by the NFRDI, Fig. 4 shows temporal variations of monthly mean temperature in Yeosu and Sorido (locations indicated on Fig. 1) in June, July and August during the last 11 years. In June, significant variation in monthly mean temperature was not found, although monthly mean temperature was slightly lower in 2000. In July, relatively high temperatures in Yeosu and Sori-do were recorded in 1995, 1997, 1998, 1999, 2001, 2002 and 2004, while relatively low temperatures were noted in 1996, 2000

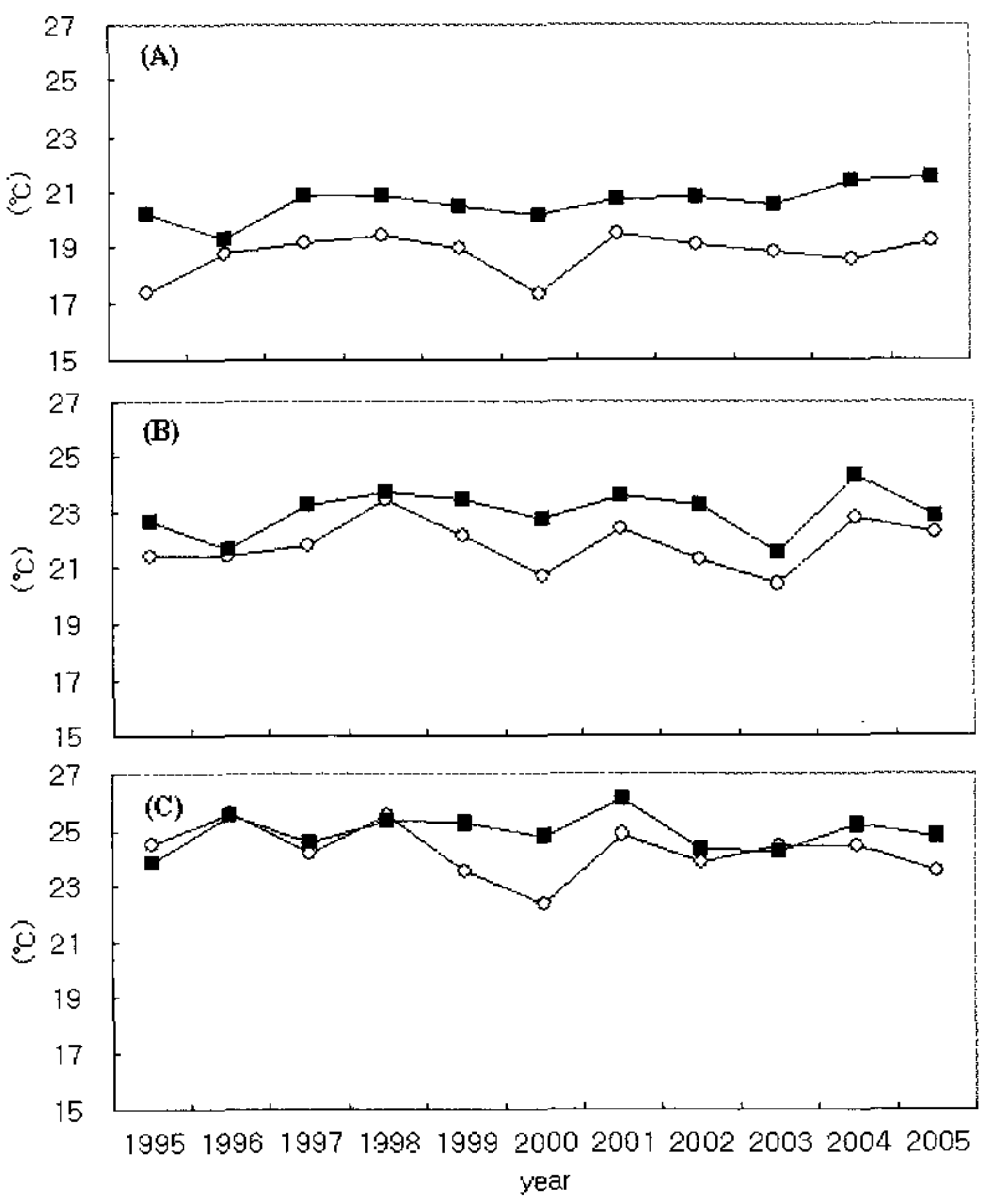

Fig. 4. Temporal variation of monthly mean of coastal temperature at Yeosu (closed square) and Sorido (open circle) in June (A), July (B) and August (C) from 1995 to 2005.

and 2003. In August, relatively high temperatures were recorded in 1996, 1998 and 2004, small-scale HAB years, whereas the highest temperature was recorded in 2001, during a large-scale HAB year. From these results, temperature variation around the first outbreak area did not produce a significant relationship with HABs in June and July. However, monthly mean temperatures in August were lower during large-scale HAB years.

In summer, coastal upwellings frequently occur because of sustained northward winds around the southeastern coast of Korea (Lee 1983; Lee and Na, 1985). These coastal upwellings generate cold-water masses in the surface layer and can be considered a barrier to northward HAB extension. Fig. 5 shows temporal variation in daily temperature in August during the last 11 years at Ulgi, Gampo, Busan and Wando, where coastal upwelling frequently occurred. Lower temperatures (<20°C) at Ulgi and Gampo were frequently recorded in 1995, 1997, 1999, 2001, 2002 and 2003. These years clearly corresponded to vast HAB outbreaks that extended to the eastern coast of Korea. Therefore, we hypothesize that the coastal

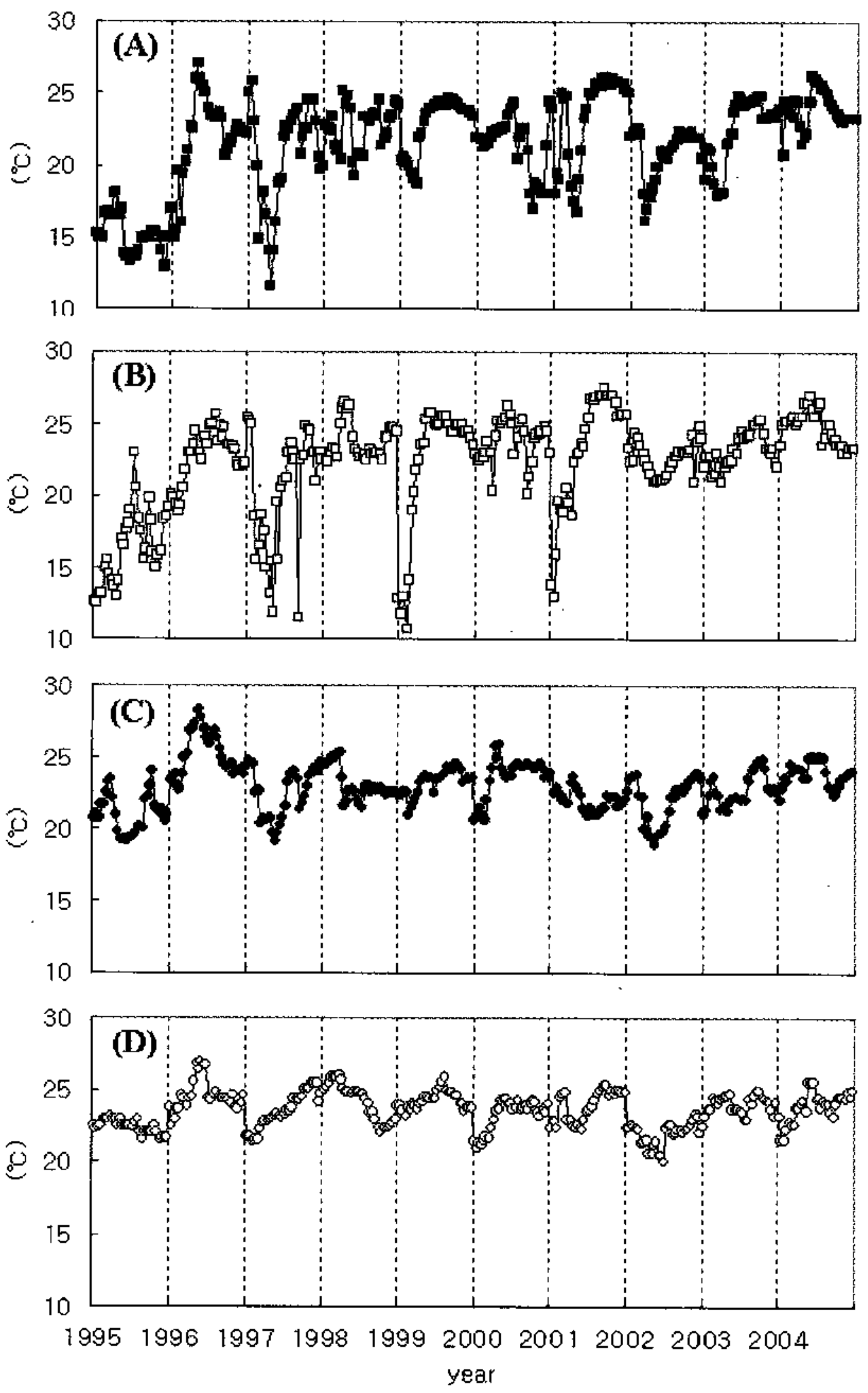

Fig. 5. Temporal variations of daily temperature in August at Ulgi (A), Gampo (B), Busan (C) and Wando (D) from 1995 to 2004.

upwellings provide nutrients from lower layer and promote northward extension, although the extension is briefly delayed.

Surface temperature distribution and vertical temperature differences with HABs

Using the data obtained from serial oceanographic investigations in August during the last 11 years, distributions of temperatures and temperature anomalies in the surface layer are shown in Figs. 6 and 7. In the South Sea of Korea, the current pattern is complex, with Korean coastal water flowing along the coast of the South Sea, the Jeju Current flowing through the Jeju Strait, and the Tsushima Warm current flowing into the Korea/Tsushima Strait. The serial oceanographic investigations were usually conducted in early or mid August, when HABs were generally starting in the coastal region of the South Sea. When extensive HABs occurred, as in 1995, 1997, 1999, 2001, 2002 and 2003, a distinct thermal front was recorded between the coastal and offshore waters (the front was noticeably weaker in 1997); the front ran parallel to the coastal line, extending to the Korea/Tsushima Strait. The distributions of surface temperature anomalies in August were well expressed within the HAB outbreaks. Negative temperature anomalies appeared around the southeastern coast of the Korean Peninsula in 1995, 1997, 1999, 2001, 2002 and 2003. These anomalies clearly corresponded to large-scale HAB outbreaks, although negative temperature anomalies also occurred in 2000, when the HAB was smaller. These results explain the relatively lower surface temperatures related to large-scale HABs. The lower temperatures may result from weakened seasonal thermoclines and deep surface mixed layers, increasing the supply of nutrients from lower layers and generating ideal conditions for *C. polykrikoides* (Lim et al., 2003). Moreover, these results correspond well with those of Lee et al. (2001), who showed that *C. polykrikoides* blooms occur when the temperature difference between the surface and bottom layers decreases.

Additionally, we examined whether weakened thermoclines formed during large HABs. Fig. 8 shows the spatial distribution of temperature differences between the surface and the 30-m layer in the South Sea of Korea during the last 11 years. When large-scale outbreaks occurred in 1995, 1997, 1999, 2001, 2002 and 2003, temperature differences were about 3-7°C around the coastal area. During small HAB years, the differences were about 4-10°C around the coastal area. With the exception of 1998, large temperature differences between the surface and

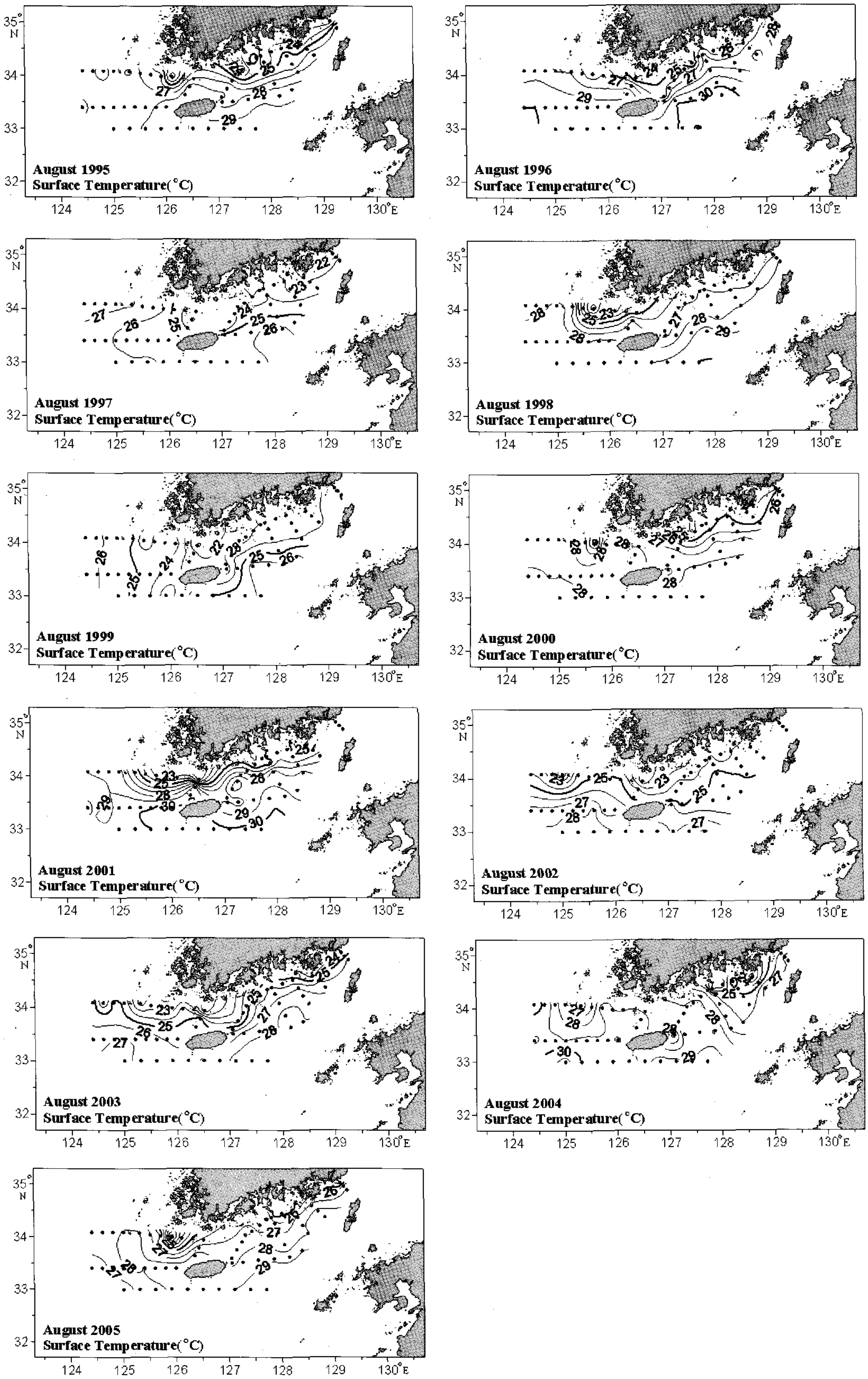

Fig. 6. Distributions of sea surface temperature in the South Sea of Korea in August from 1995 to 2005.

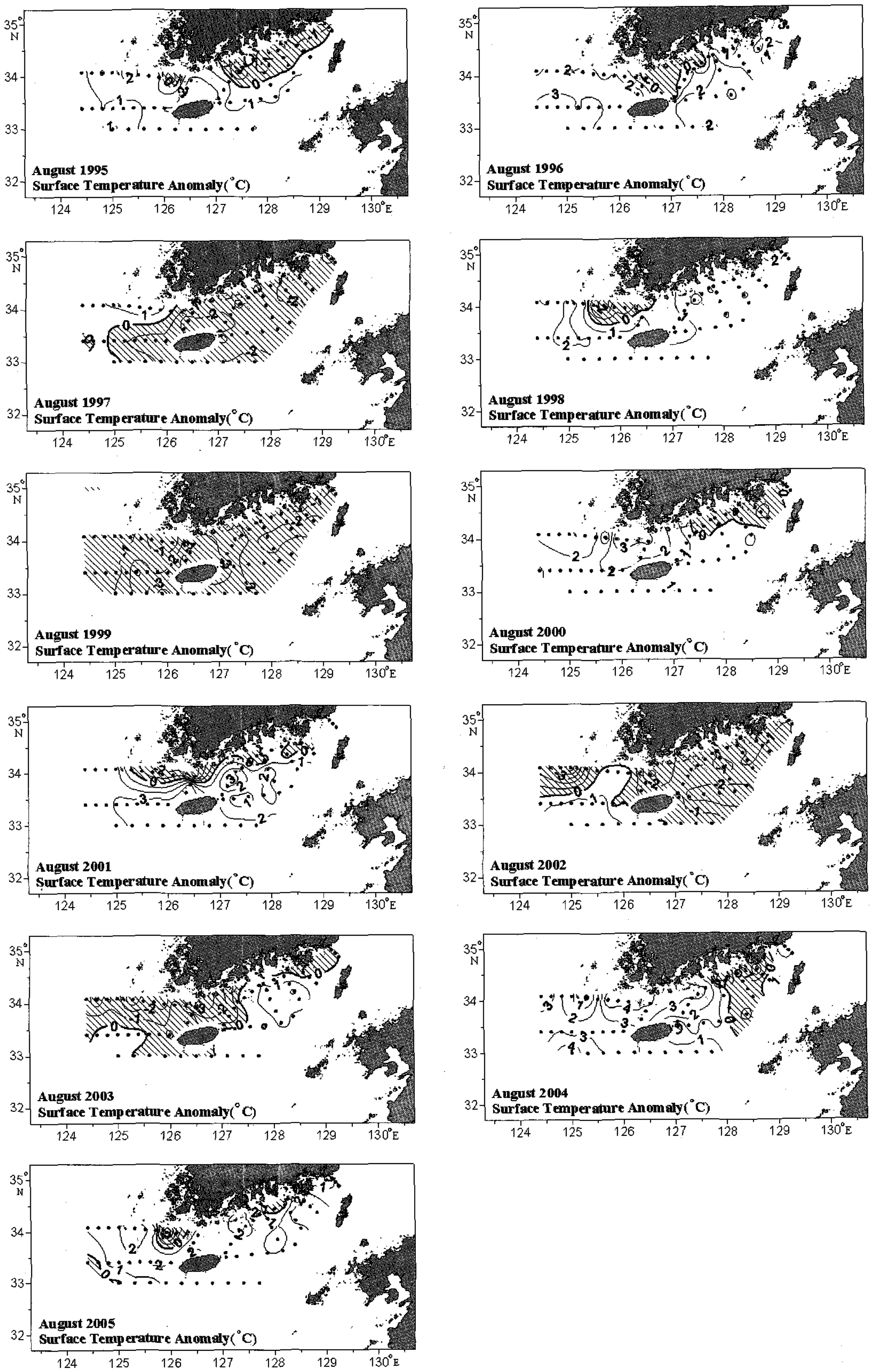

Fig. 7. Distributions of sea surface temperature anomaly in the South Sea of Korea in August from 1995 to 2005. Shaded marks indicate negative value.

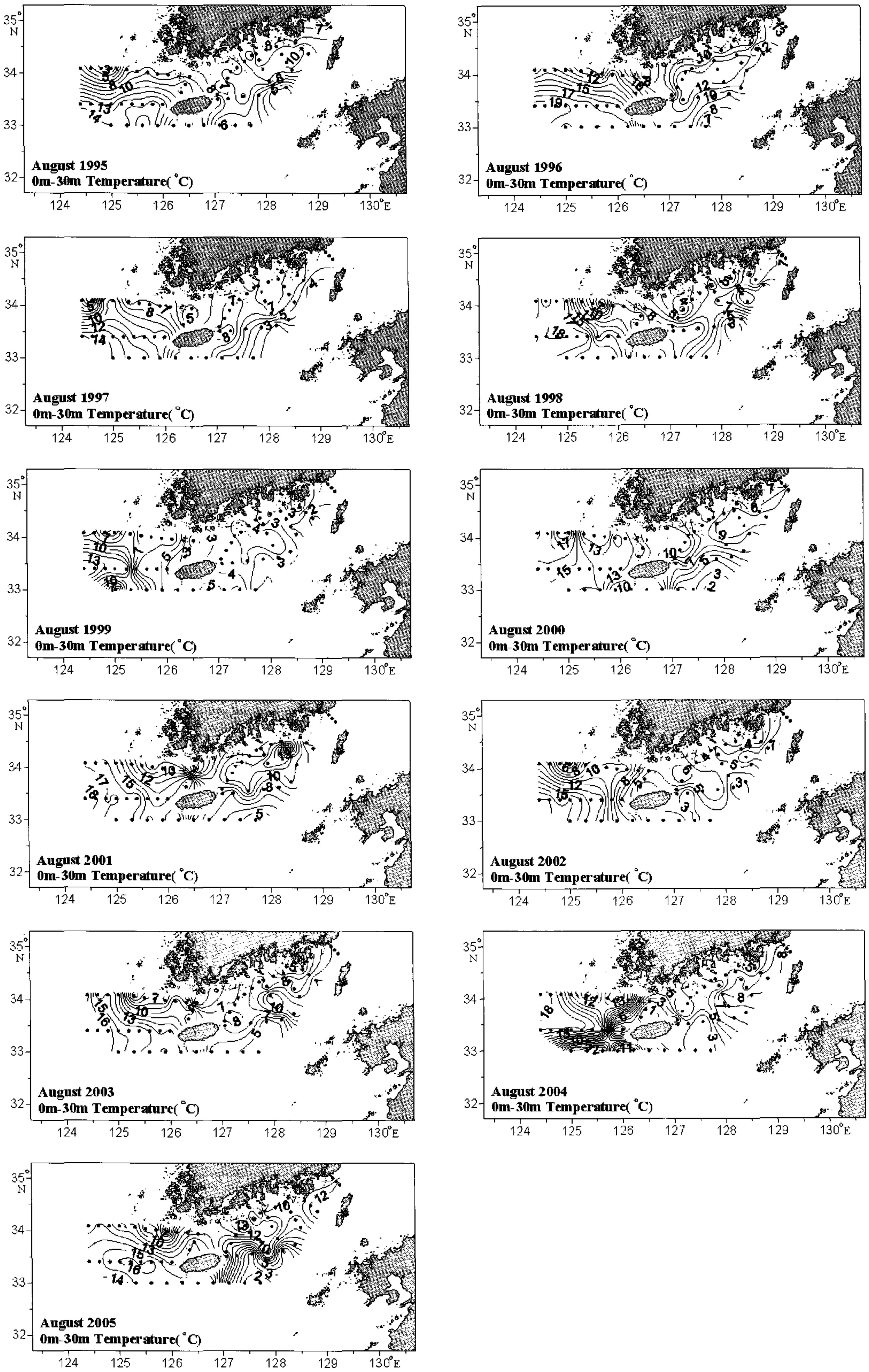

Fig. 8. Distributions of temperature differences between the surface and 30-m layer in the South Sea of Korea in August from 1995 to 2005.

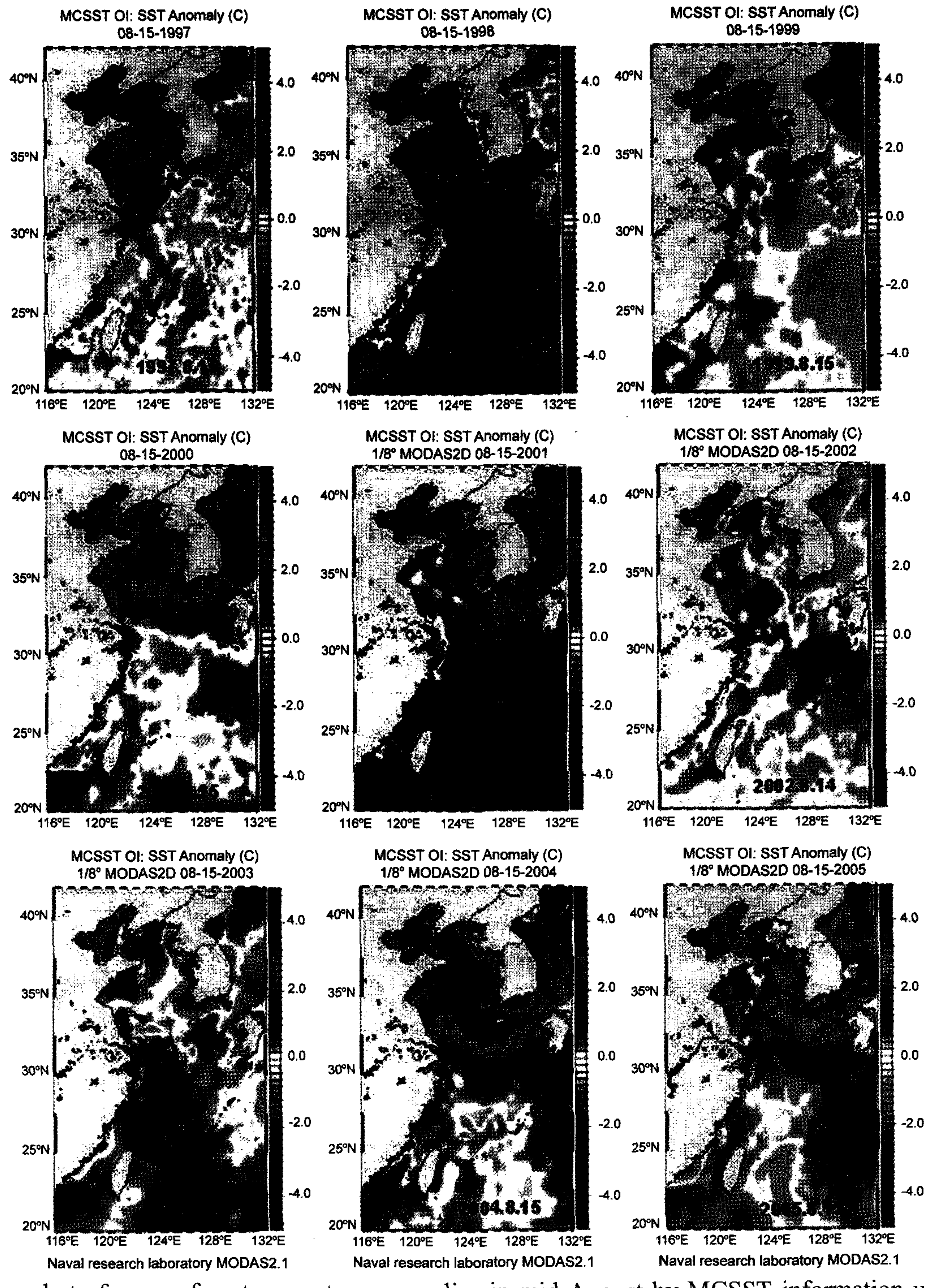

Fig. 9. Snapshot of sea surface temperature anomalies in mid August by MCSST information using MODAS with OI around the East China Sea and Yellow Sea from NRL achieved data set (http://www7320.nrlssc.navy.mil/altimetry/regions/reg_ecs.html).

the 30-m layer clearly corresponded to small-scale HABs.

To examine the relationship between HAB outbreaks and wide area temperature information, snapshots of sea surface temperature anomalies (SSTAs) around mid August during the last 9 years were obtained from the NRL. SSTAs are calculated by subtracting a climatological field from the temperature field produced by the Modular Ocean Data Set (MODAS) with Optical Interpolation (OI). The climatological sea surface temperature field is interpolated from University of Wisconsin-Milwaukee/Comprehensive Ocean-Atmosphere Data Set (UWM/COADS) 1-degree monthly sea surface temperature climatology. From these SSTA snapshots, we found that negative SSTAs around the South Sea of the Korean Peninsula appeared in 1997, 1999, 2002 and 2003. On the other hand, significantly positive SSTAs appeared in 1998, 2000, 2004 and 2005, although the positive SSTA in 2001 was dominant except around the coastal area of the South Sea. When large-scale HAB outbreaks occurred in the Korean waters, SSTAs were clearly negative over a wide area.

Discussion

HABs may occur through complex mechanisms including physical, biological and environmental factors. Specifically, studies of the generation, propagation and disappearance of HABs from a physical viewpoint have been insufficient, although some research has been conducted. Frank and Anderson (1992) examined *Alexandrium tamarense* blooms in relation to wind stresses in the Gulf of Maine. Shaples (1997) discussed that intrusions of offshore currents by surface wind stresses were closely related to dinoflagellate blooms off New Zealand. Steidinger et al. (1998) showed that physical processes such as winds and currents were closely related to *Gymnodium breve* blooms in the Gulf of Mexico. Around the Korean Peninsula, Suh et al. (2000; 2003) reported relationships between sea surface temperatures by NOAA satellite information and *C. polykrikoides* blooms, and the spatio-temporal variation of *C. polykrikoides* blooms with oceanographic environmental conditions. Lee and Kang (2003) explained that physical environments of *C. Polykrikoides* blooms involved onshore transport due to wind stresses around Naro-Do. In spite of these studies, the physical mechanisms that affect HABs in Korean Waters are not yet clear. Moreover, additional research is needed to clarify the relationships between oceanographic conditions and large-scale HABs to enable early stage prediction of HAB scale.

In this study, we examined multiple comparisons between HAB outbreaks and physical factors such as coastal temperature, offshore temperature and temperature differences between surface and intermediate layers. Initially, lower coastal temperatures in August around the South Sea corresponded to large-scale outbreaks. The appearance of cold bottom waters due to coastal upwellings around the southeastern coast of Korean Peninsula was distinct in 1995, 1997, 1999, 2001, 2002 and 2003. These upwellings clearly corresponded to large-scale HABs. Thus, this strong cold water, which originates from the bottom layer, likely plays an important role in HAB extension by providing a sufficient supply of nutrients, although it should also create a local obstruction. Serial oceanographic investigations in August in the South Sea revealed that SSTAs around the South Sea were negative when large-scale HABs occurred. Moreover, SSTAs over a wide area including the East China Sea, which were examined by OI of MODAS data from NRL, were also negative during large-scale HABs. From the results of the temperature differences between the surface and the 30-m layers, large-scale HABs usually occurred when the temperature gradient around the seasonal thermocline was weakened.

In conclusion, HABs tends to occur with the following physical conditions: 1) lower sea surface temperature around the coastal area, 2) occurrence of a cold water mass in the surface layer due to coastal upwellings, 3) negative SSTAs in the offshore and wider area, 4) weakened temperature gradients around the seasonal thermocline in the coastal area of the South Sea. In this study, we found correlations between physical oceanographic conditions, especially temperature, and HAB outbreaks. Exceptions were noted, however, and quantitative descriptions were insufficient. In a future study, we plan to clarify the relationships between HAB outbreaks and physical conditions such as spatio-temporal variations in temperature and salinity structure, current patterns, wind stresses, coastal upwellings, precipitation and typhoons in detail through concentrated surveys around the South Sea of Korea.

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