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Satellite Monitoring and Prediction for the Occurrence of the Red Tide in the Middle Coastal Area in the South Sea of Korea

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Abstract : It was studied the relationship between the red tide occurrence and the meteorological and oceanographic factors, the choice of potential area for red tide occurrence, and the satellite monitoring for red tide. From 1990 through 2001, the red tide continuously appeared and the number of red tide occurrence increased every year. Then, the red tide bloomed during the periods of July and August. An important meteorological factor governing the mechanisms of the increasing in number of red tide occurrence was heavy precipitation. Oceanographic factors of favorable marine environmental conditions for the red tide formation included warm water temperature, low salinity, high suspended solid, low phosphorus, low nitrogen. A common condition for the red tide occurrence was heavy precipitation 2~4 days earlier, and the favorable conditions for the red tide formation were high air temperature, proper sunshine and light winds for the day in red tide occurrence. From satellite images, it was possible to monitor the spatial distributions and concentrations of red tide. It was founded the potential areas for red tide occurrence in August 2000 by GIS conception: Yeosu~Dolsan coast, Gamak bay, Namhae coast, Marado coast, Goheung coast, Deukryang bay, respectively.

Key Words : Red Tide, Meteorological and Oceanographic Factors, Remote Sensing, Marine GIS.

1. Introduction

Red tide is a natural phenomenon in the coastal area that blue sea water becomes by the fertile breeding and growth/accumulation of phytoplankton(Han, 1998). Then, phytoplankton groups as standing corps related to red tide are generally divided into diatoms and flagellates(Yoon, 2001). Anytime diatom can be bred in large quantities under the favorable conditions. Flagellate was occurred at the same area and similar period every year, and under favorable environments its dormant spore rises from the sea bottom and become phytoplankton.

Actually the heavy industrial and human activities have contributed to bring various pollutants required for the increasing of red tide occurrence from land through river discharge. This red tide has destructed the marine ecology and environments, and has given the great damage of coast fisheries and caused national problems of socio-economics(NFRDI, 1996 and 1997). Especially it is considered as a serious matter that red tide appears frequently to the southern coastal area and extends

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gradually to the all coastal areas in the Korean peninsula. Thus, it is necessary to know beforehand the characteristics of the meteorological and oceanographic conditions, and the possibility of satellite monitoring and prediction for the prevention of disasters related to red tide in this study area(Yoon, 1999). Many studies for red tide have carried out at the limited fields as taxonomy, physiology, ecology and molecular biology(Iizuka and Mine, 1979; Wade and Quinn, 1980; Park, 1991, Kim, 1998), but they have not given a full and satisfying answers. Recently a few papers have studied for the mechanism related to red tide in the fields of physics, dynamics, remote sensing, and GIS(Tyler and Stumpt, 1989; Tester *et al.*, 1991; Keafer and Anderson, 1993; Ahn, 2000; Suh *et al.*, 2000).

Generally the important meteorological factors for red tide occurrence were known to be air temperature, precipitation, sunshine and winds(Yanagi *et al.*, 1992; Yamamoto and Okai, 1996; Yamamoto *et al.*, 1997), and the oceanographic factors for red tide formation were known to be water temperature, salinity, nutrients, chemical substances(Sharples, 1997; Choi, 2001). The main object of this study is to understand the mechanism and favorable conditions for red tide occurrence and formation on their related meteorological and oceanographic factors, and additionally find the potential area for red tide occurrence in the middle coastal area of the South Sea of Korea.

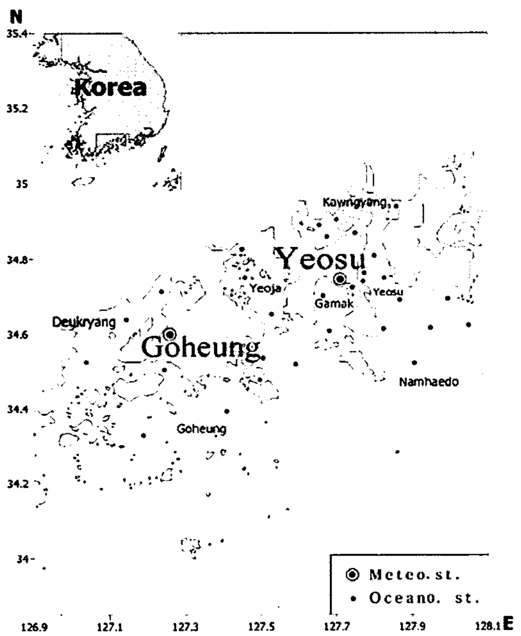

Fig. 1. Middle coastal area in the South Sea of Korea.

2. Field Observation Data

The study area is the middle coastal area in the South Sea of Korea(Yeosu and Goheung, Fig. 1). The reported monitoring data used are as follows: the meteorological factors are air temperature, precipitation, sunshine and winds for the periods of 1990 to 2001 and the observed intervals of 3hour; the oceanographic factors are water temperature, salinity, chlorophyll_a, suspended solids, phosphorus, nitrogen for the periods of 1996 to 2001 and the observed times of February, May, August, and November. The chloroohyll_a concentrations on August 22, 2000 was calculated from the ocean chlorophyll 2 algorithm(O'Reilly *et al.*, 1998). The red tide occurrence data is in-situ data for the periods of 1984 to 2001.

3. Results and Consideration

Fig. 2 shows the annual variations of red tide occurrence. The occurrence of red tide appeared each year except only 1989 and commonly increased each year(Fig. 2a). It was particularly prominent on 1995, 1996, 1997 and 1998 with the total number of days reaching up to 24, 25, 15 and 19 days, respectively. The duration of red tide tended to be shorter since 1990 and is only 1 day at present(Fig. 2b). The phytoplankton groups increased from 1994(Fig. 2c). Then, the standing crops are flagellates on 1995 and diatoms on 1985, 1986, 1996 and 1998, respectively. In the monthly

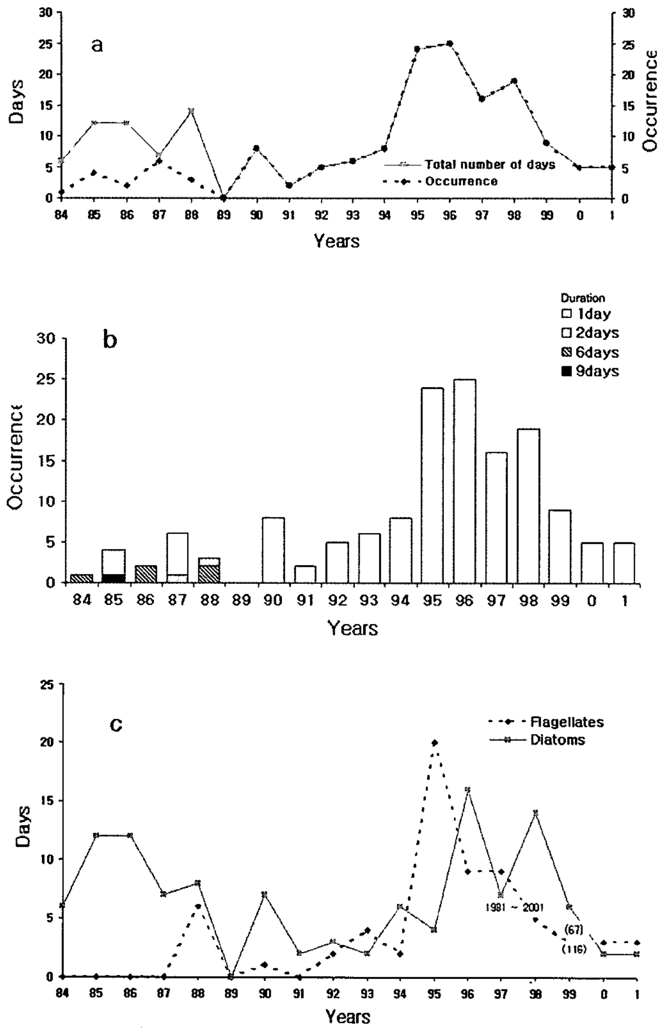

Fig. 2. Annual variations of red tide occurrence during 1984~2001. (a) Total number of days and the number of occurrence, (b) proportion of red tide forming duration, and (c) the proportion of two major phytoplankton taxonomic groups.

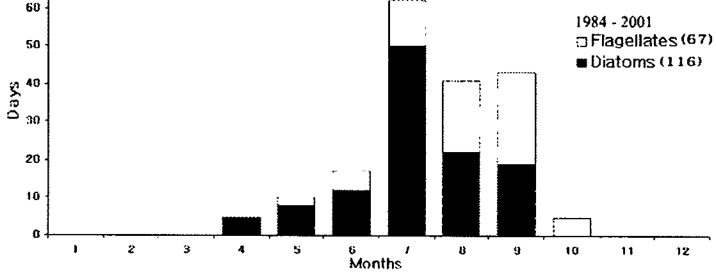

Fig. 3. Monthly variation of red tide occurrence during 1984~2001.

variation of red tide occurrence(Fig. 3), the occurrence of both diatom and flagellate red tide during last 18 years(1981~2001) appeared usually from April to October(significantly July, August and September). For the total number of days, diatoms showed 63.4% and flagellates showed 36.6%. For the standing crops, diatoms appeared from April to July and flagellates appeared from September to October. Table 1 shows the situations of the red tide occurrence during 1984~2001. Here, the numbers of appearance are as follows; Coclodinium polykrikoides is 33, heterosigma akashiwo is 14, Gymnodinium mikimotoi is 2 and Gymnodinium is sp. is zero, respectively. For the annual variation in areal distribution of red tide formation(here, the figure was not shown in this paper), It appeared mainly nearby Yeosu before 1993, and simultaneously Yeosu and Goheung after 1994.

Fig. 4 shows the annual variation of meteorological factors in Yeosu. The annual average value of air temperature presented 13.52°C in 1995, 13.50°C in 1996, 14.20°C in 1997 and 16.68°C in 1998(Fig. 4a). The annual accumulated value of precipitation presented 1902.5mm in 1995, 2341.4mm in 1996, 2879.9mmm in 1997 and 3470.2mm in 1998(Fig. 4b). The annual

Table 1. Situations of red tide occurrence during 1984~2001.

Mon. \ Yrs	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4													4/8 4/15 4/23					
5											5/23		5/28 ◆5/31	5/20	5/6 5/7 ◆5/13 5/27			
6				6/10 6/19				6/19			6/7	◆6/7 ◆6/13 ◆6/15	6/13 6/22		6/8 6/29 6/30	◆6/9	6/24	6/27
7		7/4 7/23	7/1~6	7/20 7/22	★7/8 ~13 7/19 ~20		7/5	7/19	7/27		7/5	7/23	◆7/1 7/3 7/8 ◆7/9 7/13 ◆7/24 7/27	7/15	7/2 ◆7/4 7/6	7/6	◆7/3 7/18	◆7/18 7/20
8				8/10 8/19 ~20			8/17		●8/6 ●8/10 8/24	8/16 8/25	8/4 ★8/13 ◆8/16	8/17 8/23 ★8/29 ★8/31	8/23	8/5 ★8/25 ★8/26 ★8/28 ★8/30	8/5 ◆8/6 ★8/31	8/10 ★8/11	★8/22 ★8/23	★8/14
9	9/20 ~25	9/3 ~11					★9/13					★9/4 ★9/5 ★9/11 ★9/13 ★9/15 ★9/17 ★9/19 ★9/30	★9/5 ★9/7 ★9/11	★9/3 ★9/6 ★9/7	★9/2 9/3	9/15		
10										★10/14 ★10/16 ★10/18 ★10/22	★10/13							

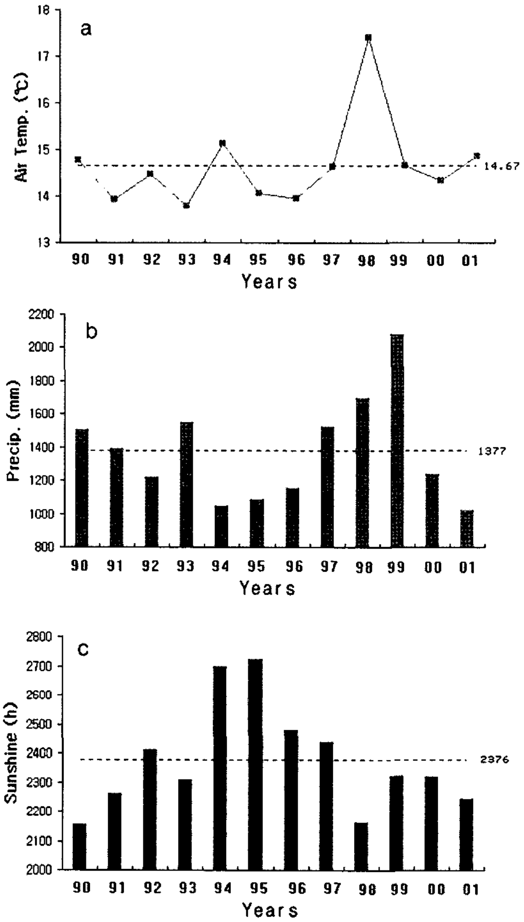

Fig. 4. Annual variations in (a) air temperature, (b) precipitation and (c) sunshine duration in Yeosu. The average value is indicated by a broken line.

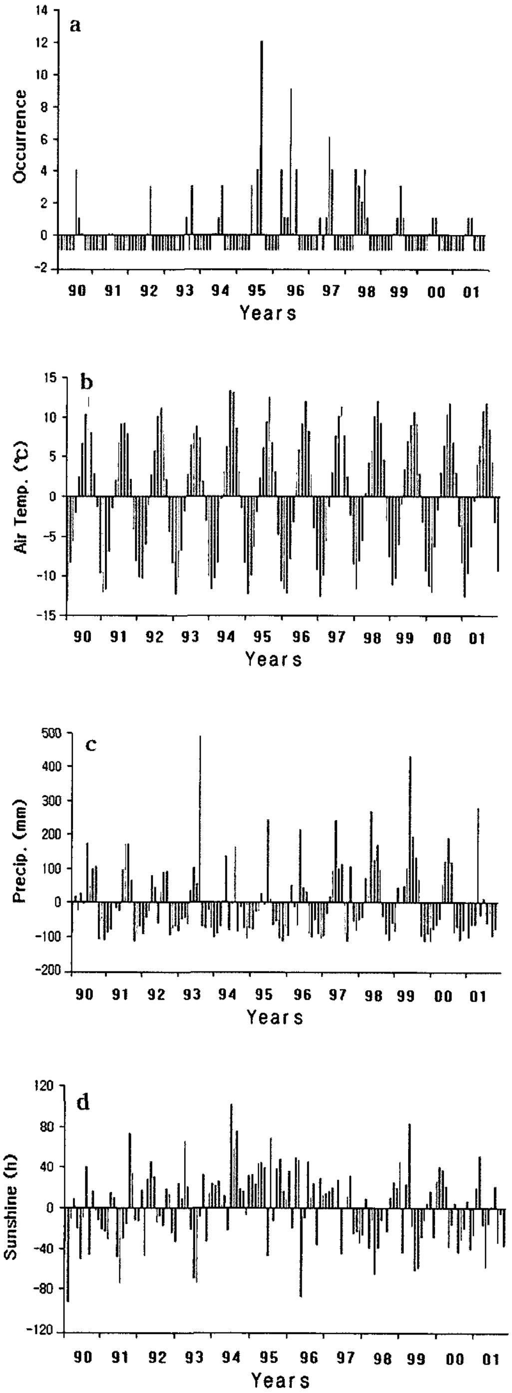

Fig. 5. Monthly variations of deviations to the average in (a) total number of days of red tide occurrence, (b) air temperature (c) precipitation and (d) sunshine duration in Yeosu.

accumulated value of sunshine duration presented 5090.1h in 1995, 4693.9h in 1996, 4719.6h in 1997 and 4199.4h in 1998(Fig. 4c). Here, the figure for Goheung was not shown in this paper because the meteorological factors presented almost the same values in the annual and monthly variations.

For the red tide occurrence, the monthly variations of meteorological factors presented the predominant seasons on July, August and September in 1995, 1996, 1997 and 1998(Fig. 5). Here, '+' value of the anomaly means favorable meteorological condition for the red tide occurrence. In this predominant seasons, air

Table 2. Monthly average values(July, August and September) of meteorological factors(air temperature, precipitation, sunshine duration and wind) and red tide occurrence in Yeosu during 1990~2001, respectively

Years \ Months (Metro. factors / Station)		Air Temp.(℃)	Precip.(mm)	Sunshine(h)	Wind(m/s)	Occurrence
		Yeosu	Yeosu	Yeosu	Yeosu	Yeosu
90	7	24.83	160	184.7	2.68	5
	8	26.95	214	235.2	2.73	2
	9	22.47	219.6	148.9	4.74	1
91	7	23.60	287.1	120.4	3.20	1
	8	23.68	287.1	165.5	4.58	0
	9	22.33	177	179.4	4.15	0
92	7	24.60	146.1	180.9	3.03	1
	8	25.58	304.2	187.5	3.94	4
	9	22.62	305.7	177.8	4.53	0
93	7	22.31	168	126.1	3.49	0
	8	23.32	603	120.3	3.49	2
	9	21.86	42.7	186.1	3.14	0
94	7	27.81	111.9	296.2	3.20	2
	8	27.49	277.4	252.2	3.98	3
	9	23.04	28.3	270.3	3.85	0
95	7	23.91	354.2	147.6	3.00	1
	8	26.96	134.2	263.7	2.80	5
	9	21.22	46.2	181.8	3.54	8
96	7	23.62	159.7	185.4	3.22	10
	8	26.48	145.8	240.5	3.51	1
	9	22.65	21.9	205	3.39	4
97	7	24.50	213.2	149.8	3.90	2
	8	25.75	225	195	4.31	5
	9	22.11	22.3	205.4	4.76	2
98	7	24.57	239.2	155	4.46	3
	8	26.46	283.2	182.5	3.66	4
	9	23.68	308.5	195.2	4.01	2
99	7	23.49	546.2	133.6	4.46	2
	8	25.03	302.1	135.5	3.66	3
	9	23.63	246.2	166.5	4.01	0
00	7	24.86	234.6	178.5	4.18	2
	8	26.17	305.7	199.7	3.15	1
	9	21.31	230.1	151.7	6.23	0
01	7	25.25	76.2	179	3.30	2
	8	26.20	123.1	196	4.11	1
	9	22.97	51.9	215.8	5.27	0

temperature, precipitation and sunshine duration of the '+' anomaly presented in Fig. 5, and the numbers of the red tide occurrence appeared in Table 2.

Fig. 6 shows the daily variations of meteorological factors in monthly data. This is the case studies for the days in the red tide occurrence from June to August, 2000. The first case is the Gamak bay. In July 1, 2000 before the red tide occurrence, the daily accumulated precipitation was 23.4mm. In July 3, 2000 in red tide occurrence, the daily average air temperature was

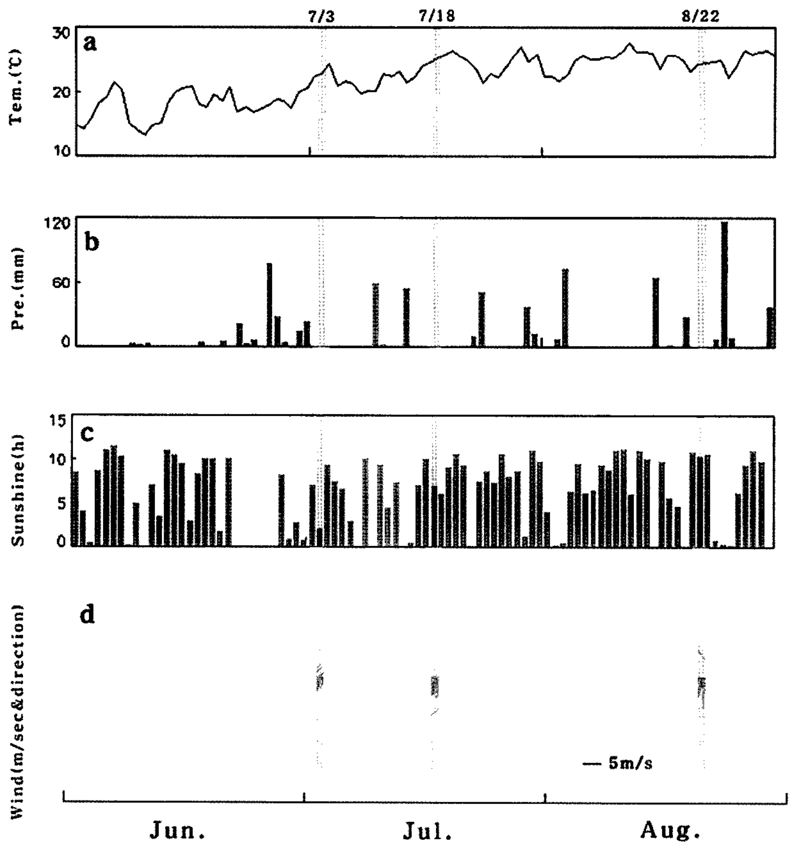

Fig. 6. Daily variations in Yeosu during June~July 2000. Shadow regions denote the time when the red tide was occurred.

24.66°C(max.: 27.3°C), the daily accumulated precipitation was 0mm, the daily accumulated sunshine was 2h, and the main wind speed was 0.25m/s in southwest direction(max.: 5.5m/s and 200° from the north). The second case is the Yosu~Dolsan coast. In July 14, 2000 before the red tide occurrence, the daily accumulated precipitation was 54.4mm. In July 18, 2000 in red tide occurrence, the daily average air temperature was 26.48°C(max.: 29.4°C), the daily accumulated precipitation was 0mm, the daily accumulated sunshine was 6.9h, and the main wind speed was 0.25m/s in southwest direction (max.: 5.1m/s and 200° from the north). Finally, the third case is the Dolsan coast. In August 20, 2000 before the red tide occurrence, the daily accumulated precipitation was 27.5mm. In August 22, 2000 in red tide occurrence, the daily average air temperature was 25.85°C(max.: 28.7°C), the daily accumulated precipitation was 0mm, the daily accumulated sunshine was 10.3h and the main winds was 0.46m/s in the southwest direction(max.: 7.7m/s and 180° from the north), respectively.

Chlorophyll_a in August 22, 2000 was obtained from SeaWiFS image by using the ocean chlorophyll 2 algorithm(OC2)(Fig. 7). Fig. 8 shows the comparison between satellite data and in-situ data. Here, in the case of the Dolsan coast, the satellite values presented 2.509 ~ 41.879 mg/m^3(average: 7.699 mg/m^3) and the in-situ values presented 80~910 cells/l(average: 495

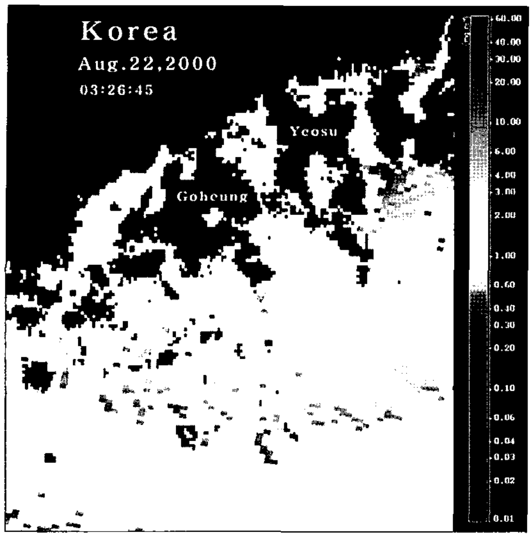

Fig. 7. Areal distributions of Chlorophyll_a from SeaWiFS image on August 22, 2000.

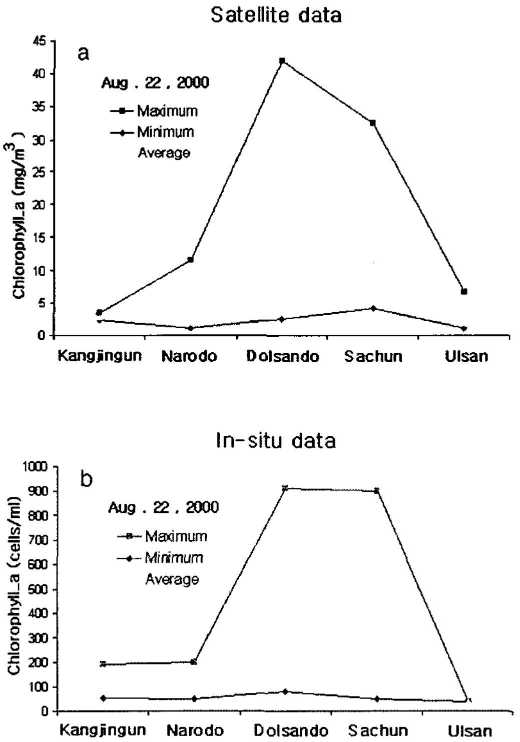

Fig. 8. Comparisons of (a) satellite data and (b) in-situ data in Kangjin, Naroda, Dolsando, Sachun and Ulsan on August 22, 2000.

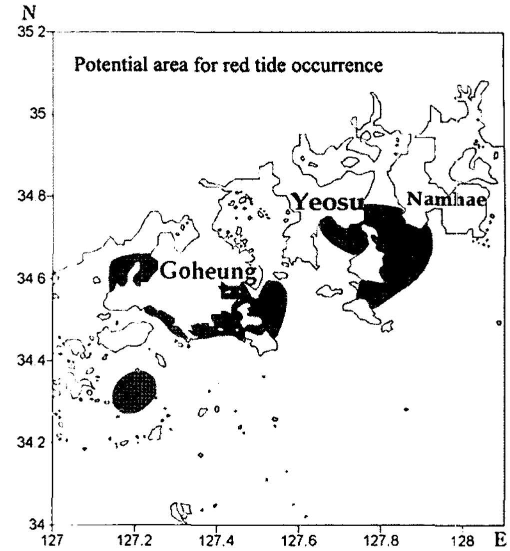

Fig. 9. Areal distributions of potential area for red tide occurrence on August 2000.

cells/l), respectively.

In the distributions of oceanographic factors(here, the figures were not shown in this paper), the favorable oceanic conditions for the red tide formation in August, 2000 are considered as follows; the calm weather (25.93°C & 199.7h) increases sea water temperature (23~28°C), the heavy precipitation(305.7mm) brings some riverine water, nutrients and other chemical substances to ocean: low salinity(22~32‰), high suspended solid(10~35mg/l), low phosphorus(0.025~0.070mg/l) and high nitrogen(0.04~0.18mg/l), respectively.

We decided the potential areas in the coastal zones vulnerable to the red tide occurrence based on the limited factors controlling the growth of phytoplankton. Then, the representative criteria are nutrients(phosphorus and nitrogen) and suspended solids(chemical substances; Fe, Mn, Vitamins, etc.) in the ocean. By using GIS through the overlap for three subject figures(phosphorus, nitrogen and suspended solids), potential area for red tide occurrence on August 2000 was obtained(Fig. 9). It was founded that the potential areas are the Yeosu~Dolsan coast, the Gamak bay, the Namhae coast, the Narodo coast, the Goheung and Deukryang bay. This result is very well coincided to the results of the satellite and in-situ data.

5. Conclusions

In the middle coastal area of the South Sea, the occurrence of red tide appeared and increased every year, enlarged from Yeosu to Goheung after 1994, and concentrated in July, August, and September. The duration of red tide tended particularly to be shorter as 1 day after 1992. In the total number of days, diatoms and flagellates presented 63.4% and 36.6%, respectively. For the analysis of meteorological factors, the annual variation showed no clear trend, the monthly variations presented in seasonal scale followed characteristic of meteorological conditions in each year and showed favorable meteorological condition as + value of anomaly, and the daily variations showed the clear trend and can apply to find the mechanism and favorable conditions for red tide formation. The analysis of oceanographic factors showed favorable marine environmental conditions for the red tide formation as follows; warm water temperature (23~28°C), low salinity (22~32‰), high suspended solid (10~35mg/l), low phosphorus (0.025~0.070mg/l), and low nitrogen (0.04~0.18 mg/l).

The important meteorological factor governing the mechanism of the increasing number of red tide occurrence is heavy precipitation. This appeared to bring nutrients and other chemical substances required for growth of phytoplankton from land through river discharge(eg: Sumjin river near Yeosu~Dolsan coast). The common condition for the red tide occurrence is heavy precipitation(23.4~54.5mm) 2~4 days earlier. The commonly favorable conditions for the red tide formation was as follows; high air temperature(24.64~25.85°C), proper sunshine(2~10.3h) and light winds(2~4.6m/s & SW) in the day in red tide occurrence. The calm weather with warm temperature and low wind velocity resukts in less dispersion of the vegetative cells of red tide organisms. Finally, It was possible to choose for the potential area related the red tide occurrence by the overlap of three subject figures (phosphorus, nitrogen and suspended solids) as the limited factors.

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References

Ahn, Y. H., 2000. Development of remote sensing reflectance and water leaving radiance models for ocean remote sensing technique, *J. of the Korean Soc. of Remote Sensing*, 16(3): 243-260.

Choi, H. Y., 2001. Oceanographic condition of the coastal area between Narodo Is. and Sorido Is. in the Southern Sea of Korea and its relation to the disappearance of red-tide observed in Summer 1998, <the Sea>, *J. of the Korean Soc. of Oceanography*, 6(2): 49-62.

Hahn, S. D., 1998. History of algal records in Korean coastal waters, In Harmful algal blooms in Korea and China(ed. Kim, H. G., S. G. Lee and C. K. Lee), NFRDI, Korea: 34-43.

Iizuka, S. and K. Mine, 1979. Maximum growth rate of Gymnodinium sp.(Type-'65), a red tide dinoflagellate, expected under culture condition, *Bull. Plankton Soc. of Japan*, 30: 139-146.

Keafer, B. A. and D. M. Anderson, 1993. Use of remotely-sensed sea surface temperature in studies of *Alexandrium tamarense* bloom dynamics, *Toxic Marine Phytoplankton* (ed. Smayda T. M. and Y. Shimizu), Elsevier, pp. 23-26.

Kim, H. G., 1998. Harmful algal blooms in Korean coastal waters focused on three fish-killing dinoflagellates(ed. Kim, H. G., S. G. Lee and C. K. Lee), NFRDI, Korea, pp. 1-20.

NFRDI(National Fisheries Research and Development Institute), 1996. *Marine pollutions and red tide*, 191p.

NFRDI, 1997. Red tide in the Korean coastal Waters: 280p.

O'Reilly J. E., S. Maritorena, B. G. Mitchell, D. A. Siegel, K. L. Carder, S. A. Graver, M. Kahu, and C. McClain, 1998. Ocean color chlorophyll chlorophyll algorithms SeaWiFS, *J. of Geophys. Res.*, 103-C11(24): 937-24, 953.

Park, J. S., 1991. Red tide occurrence and countermeasure in Korea, *Recent approacher on red tides*(ed. Park, J. S. and H. G. Kim), NFRDI, Korea, pp. 1-24.

Sharples, J., 1997. Cross-shelf intrusion of subtropical water into the coastal zone of northeast New Zealand, *Cont. Shelf Res.*, 17(7): 835-857.

Suh, Y. S., J. H. Kim, and H. G. Kim, 2000. Relationship between sea surface temperature derived from NOAA satellites and *Coclodinium polykrikoides* red tide occurrence in Korean coastal waters, *J. Korean Environ. Sci. Soc*, 9: 215-221.

Tester, P. A., R. P. Stumpf, F. M. Vukovich, P. K. Flower, and J. T. Turner, 1991. An expatriate red tide bloom: transport, distribution, and persistence, *Limnol. Oceanogr.*, 36: 1053-1061.

Tyler, M. A. and R. P. Stumpf, 1989. Feasibility of using satellite for detection of kinetics of small phytoplankton blooms in estuaries: tidal and migrational effects, *Remote Sens. Environ.*, 27: 233-250.

Wade, T. L. and J. G. Quinn, 1980. Incorporation distribution and fate of saturated hydrocarbones in sediments from a controlled marine ecosystem, *Mar. Environ. Res.*, 3: 15-33.

Yanagi, T., Y. Asai and Y. Koizumi, 1992. Physical conditions for red tide outbreak of *Gymnodinium mikimotoi, Fisheries and Marine Research*, 56(2): 107-112.

Yamamoto, T. and M. Okai, 1996. Statistical analyses on the relationships between red tide formation and meteorological factors in Mikawa bay, Japan, *Fisheries and Marine Research*, 60(4): 348-355.

Yamamoto, T., M. Okai, K. Takeshita, and T. Hashimoto, 1997. Characteristics of meteorological conditions in the years of intensive red tide occurrence in Mikawa bay, Japan. *Fisheries and Marine Research*, 61(2): 114-122.

Yoon, Y. H., 2001. A summary on the red tide mechanisms of the harmful dinoflagellate, *Cochlodinium polykrikoides* in Korean coastal waterts, *Bull. Plankton Soc. Japan*, 48(2): 113-120.

Yoon, H. J., 1999. Satellite Remote Sensing and Earth Science-Satellite Oceanography, *J. of the Korean Soc. of Remote Sensing*, 15(1): 51-60.