Chapter 2. Seasonal and Interannual Variability of Sea Surface Chlorophyll *a* Concentration in the Japan Sea

2.1. Introduction

With the development of satellite remote sensing, it has been possible to know the phytoplankton distribution by spectra of radiance from the sea surface. The Coastal Zone Color Scanner (CZCS) first supplied experimental phytoplankton pigment (chlorophyll *a* + pheopigments) data from 1978 to 1986 although observations were sporadic (Feldman, Kuring, Ng, Esaias, McClain, Elrod et al., 1989). Kim et al. (2000) analyzed the seasonal variability of phytoplankton pigment concentration in the Japan Sea using average CZCS data using empirical orthogonal function (EOF) analysis. They showed that the phytoplankton bloom occurred in spring and fall in the Japan Sea. They argued that spring blooms began in the northwestern region and moved to southern area, and then to northern area. They also argued that fall blooms appeared in the order of the southwest, southeast and northeast and then northwest. However, CZCS took only sporadic data in the Japan Sea, and they are not enough to describe the seasonal cycle or interannual variability of chlorophyll *a* concentration in the Japan Sea.

The Ocean Color and Temperature Scanner (OCTS) provided a larger amount of chlorophyll *a* data for 8 months from November 1996 to June 1997 (Kawamura and the OCTS team, 1998), and the Sea-Viewing Wide Field of View Sensor (SeaWiFS) has continued the time series of ocean color observations until the present, after OCTS with only a two months gap. The objective of this study is to describe the variability of surface chlorophyll *a* concentration in the Japan Sea (34 to 50°N, 127 to 143°E, Fig.

2-1) by using two improved ocean color sensors, OCTS and SeaWiFS. Furthermore, the physical factors such as sea surface temperature, wind speed and sea ice were also shown by satellite remote sensing data, because they were expected to give some effects to the stratification of the surface layer that controls the bloom condition. Then, we discuss relationship between interannual variability of seasonal bloom and its implication to primary production in the Japan Sea. The possibility that the spring bloom in the Japan Sea is affected by the global climate system such as ENSO events is discussed.

2.2. Data and Methods

2.2.1. Satellite Chlorophyll *a* Data

OCTS Version 4 (Kawamura and OCTS-team, 1998) and SeaWiFS Version 4 chlorophyll *a* data were used in the present study. OCTS was the sensor on satellite 'ADEOS' operated by National Space Development Agency of Japan (NASDA). It provided chlorophyll *a* data from November 1996 to June 1997. Weekly (7 days) and monthly Level 3 Binned Maps during the period were used in this study. SeaWiFS is the sensor on the satellite 'OrbView-2' of National Aeronautics and Space Administration (NASA). It has been operating from September 1997 to the present. Eight-day and monthly Standard Mapped Image (SMI) Products from September 1997 to August 2002 provided from NASA Goddard Space Flight Center (GSFC) Distributed Active Archive Center (DAAC) were used. Spatial resolutions of both data sets are 9 km.

Monthly average chlorophyll *a* concentration images for the study period

(1997–2002) were generated from the monthly data set. Average chlorophyll *a* concentration from 1997 to 2002 were also calculated by eight-day data and showed seasonal variability of four typical locations. A phase diagram along a section at 136°E was also shown to describe the interannual variability of chlorophyll *a* by weekly and eight-day composite data from November 1996 to August 2002. In order to understand the spatial and interannual variability of the timing of the bloom, images obtained during the first week of spring and fall blooms were shown. Bloom conditions were defined as chlorophyll *a* concentrations exceeding 0.8 $\mu g\ l^{-1}$ in both spring and fall. The average chlorophyll *a* concentration during seasons without blooms (summer and winter) was 0.4 $\mu g\ l^{-1}$.

2.2.2. Satellite Sea Surface Temperature Data

Best Sea Surface Temperature Data of Advanced Very-High Resolution Radiometer (AVHRR) Ocean Pathfinder from the 39th week in 1996 to the 24th week in 2002 were used. This data set was obtained from the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) at the Jet Propulsion Laboratory (JPL), California Institute of Technology. The spatial resolution of this data set is 9 km. We generated the monthly average of SST from 1997 – 2002 to show the seasonal variability over the Japan Sea.

2.2.3. Satellite Sea Wind Data

Special Sensor Microwave / Imager (SSM/I) data operated by Defense Meteorological Satellite Program (DMSP) was used for sea surface wind (Wentz, 1997;

Wentz and Spencer, 1998). The spatial resolution of this dataset was 0.25 degrees, and the value was the wind speed at 10m height from the sea surface. Monthly data from January to April and September to December during 1997 to 2002 were used to calculate average wind stress during spring and fall, respectively. Average wind speed at four locations in the Japan Sea (shown in Fig. 2-1) was compared with Northeast Asian Monsoon Index (MOI) that is difference of sea surface pressure between Ulan Ude in Russia (51.80°N, 107.42°E) and Nemuro, Japan (43.03°N, 145.75°E) to derive relationship between the wind speed in the Japan Sea and winter westerly monsoon. These sea surface pressure data were obtained by JMA, and MOI was calculated as average from January to April.

2.2.4. Satellite Sea Ice Concentration Data

DMSP SSM/I Daily Polar Gridded data from 1997 to 2002 were obtained from National Snow & Ice Data Center (NSIDC) for the sea ice concentration in Mamiya Strait. NASA Team algorithm data set was used. This algorithm is functionally same with the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) algorithm (Cavalieri, Gloersen and Campbell, 1984; Gloersen and Cavalieri, 1986). Sea ice concentration is the percentage of ice coverage in a certain area, and the area where the sea ice concentration exceeds 10% was defined as sea ice area. The spatial resolution of this data is 25 km. Eight-day composite data were made from this daily data from March to April for each year. The integrated sea ice area from 46.5 to 52°N was calculated for each year to derive the change of sea ice area in Mamiya Strait.

2.3. Results

2.3.1. Seasonal Variability of Chlorophyll *a* Distribution in the Japan Sea

Monthly averaged satellite chlorophyll *a* from 1997 to 2002 clearly showed large seasonal variability (Fig. 2-2). High chlorophyll *a* was observed in spring (March to June) and fall (October to December), and low chlorophyll *a* was observed in winter (January and February) and summer (July to September), respectively. Chlorophyll *a* concentration varied from 0.1 to more than 3.5 $\mu g\ l^{-1}$. Large north-south differences in SST were observed. The subpolar front is formed between the northern area and the warm southern area around 38-40°N (Fig. 2-3). The seasonal change of SST was also seen in both northern and southern area, and lowest (-1.5°C) and highest (28°C) SST was observed in March and August, respectively.

In January and February, chlorophyll *a* concentration was high around the subpolar front (0.6 $\mu g\ l^{-1}$), and low north of the subpolar front (~ 0.3 $\mu g\ l^{-1}$). The concentration in the south was slightly lower but increased with time to the level in the subpolar front. A region of high chlorophyll *a* was also found to the north of 48°N along the Primorye coast and the East Korean Bay. SST at north and south of the subpolar front was about 1 and 10°C, respectively.

Chlorophyll *a* concentration was highest from March to June. In March, chlorophyll *a* concentration around the subpolar front increased to more than 0.8 $\mu g\ l^{-1}$ and became bloom condition in this study. High chlorophyll *a* area along the Primorye coast and East Korean Bay extended southward and eastward, respectively. In April, chlorophyll *a* concentration increased and exceeded 0.8 $\mu g\ l^{-1}$ in most areas except the middle of the Japan Basin (41-44°N, 134-140°E). Chlorophyll *a* concentration started to decrease south of the subpolar front and off Vladivostok in May (0.4 μg l^{-1}) and decreased further in June (0.2 μg l^{-1}). The bloom in the Japan Basin occurred later and reached more than 1.0 μg l^{-1} as SST exceeded 8°C in May, and started to decrease in June. The bloom along the Primorye coast east of 133°E continued until May, and decreased in June as in other parts of the Japan Basin.

From July to September, chlorophyll *a* concentration was low, around 0.2 - 0.3 μg l^{-1}, in most of the Japan Sea and SST was high both south (~27°C) and north (~20°C) of the subpolar front. However, higher chlorophyll *a* concentration was observed continuously along the eastern and southern coasts of the Korean peninsula. Chlorophyll *a* concentration in the area was 0.4 μg l^{-1} in July and August, and increased in September (~1.3 μg l^{-1}). Higher chlorophyll *a* concentration (~0.4 μg l^{-1}) was also observed in the Mamiya Strait in summer.

From October to December, chlorophyll *a* concentration increased while SST decreased. Chlorophyll *a* concentration throughout the Japan Sea increased during this period; however, the spatial pattern was not as distinctive as in spring. The fall bloom appeared in the east of the Korean Peninsula and north of 45°N in October, and extended to the middle of the basin in November. In addition, chlorophyll *a* concentration was generally higher in the western area than in the eastern area south of 43°N. SST decreased during the period in the north and south from 15° to 6°C and 21° to 14°C, respectively.

From the average monthly satellite images, it is clear that seasonal variability of chlorophyll *a* was large spatially and temporally, including both spring and fall blooms. It seems that areas north and south of the subpolar front showed different patterns of variability. However, even within the northern area, the Primorye coast showed quite different behavior compared to the middle of the Japan Basin. Western and eastern areas also differed within the southern area (Fig. 2-4).

In the southern area, the spring bloom occurred approximately six weeks earlier than the northern area in the middle of the Japan Basin (cf. Fig. 2-5-a). However, the bloom along the Primorye coast, started at almost the same time as the southern area, and the magnitude was even higher than the southern area and nearly twice the concentration of the middle of the Japan Basin. The magnitude of the spring bloom in the southwestern area was about 1.5 times higher than one in the southeastern area.

On the other hand, the difference in the timing of fall bloom was not clear as the spring bloom; however, the fall bloom in the middle of the Japan basin tended to be later than other areas (cf. Fig. 2-6-a). The chlorophyll *a* concentration in the southeastern area was about a factor of half lower than southwestern area. The tendency for chlorophyll *a* concentrations to be lower in the southeastern area persists throughout most of the year, except winter.

2.3.2. Interannual Variability of Chlorophyll *a*

As described in the previous section, monthly satellite chlorophyll *a* data indicates that there were distinctive spring and fall blooms in the Japan Sea and the timing and magnitude were different among the areas (Figs. 2-2 and 2-4). The data for seven years showed similar seasonal changes of chlorophyll *a* concentration, including spring and fall blooms. However, there were differences in the timing and magnitude of blooms year by year.

Spring blooms along 136°E started around April 1 every year, and the bloom occurred earlier south of the subpolar front (south of 40°N) and along the Primorye coast (north of 42°N) than the middle (Fig. 2-7). Because of the difference in timing, the bloom in the south and in the Primorye coast seemed to propagate north and south, respectively. The bloom the southern area in 1998 appeared in late February and almost ended before April 1, about three weeks earlier than other years. On the other hand, the spring bloom started in early April in 2000. The bloom along the Primorye coast to the middle of the Japan Basin appeared in early March in 1997 and 1998, mid-March in 2000 and 2002, in late March in 1999 and 2001.

Similar interannual variability was seen in a wide area of the Japan Sea except the western area near Korea (Fig. 2-5). The features of blooms of each year from Fig. 2-5 were summarized in Table 2-1. Spring bloom was generally earlier in 1998 and 2002 (Figs. 2-5-c, f). Spring bloom in 1998 appeared in late February in most of the southern area except near Tsushima Strait, and spring bloom in 2002 also occurred earlier in late February particularly in the southwestern area. Blooms of both of years were occurred in late March and in early May along the Primorye and middle of the Japan Basin, respectively. On the other hand, bloom in 2000 at the southern area and near the Primorye coast appeared in April (Fig. 2-5-e) later than other years. The bloom in 1999 and 2001 started later than other years in middle of the Japan Basin and the Primorye coast. The start timing was different and complex in the southern area. The bloom in 1997 and 1999 started earlier around subpolar front than in the Tsushima Current region, and the bloom in 2001 showed opposite. However, the general pattern of transition in the southern area was not obvious.

Fall bloom along 136°E occurred around December 1 every year, and there was no typical temporal difference (Fig. 2-7). Chlorophyll *a* concentration during the fall bloom was higher north of the subpolar front than south of subpolar front from 1997 to 2001. Chlorophyll *a* concentration during the fall bloom was high and continued longer in 1999 than in other years, lasting for more than six weeks north of 39°N.

The beginnings of fall blooms from 1997 to 2001 are shown in Fig. 2-6. The timing of the fall bloom was generally earlier along coast than the middle part of the Japan Sea. In the northwest region, the fall bloom started earlier in 1999 and later in 1998 than in other years. It can also be noticed that the area where the chlorophyll *a* concentration did not reach 0.8 $\mu g\ l^{-1}$ changed year by year. The fall bloom was widest in 1999, and the area without a bloom was observed only in the southeastern area (Fig. 2-6-d). Blooms were mainly found in the northern area in 1997 and 2001, in the western area and north of 43°N in 2000. The trend was unclear, but it was obvious that there was large interannual variability in the magnitude of fall bloom.

2.3.3. Interannual Variability of the Wind

In the previous section, the start of the spring bloom was shown to have interannual variability. As winds are known to affect water column stability, a condition required for the onset of the spring bloom, average wind speeds from January to April were examined (Fig. 2-8). Wind speed was generally stronger along the Japanese coast, and relatively weaker in the northwestern area every year. It is clear that average wind speeds were weak in 1998 and 2002 and stronger in 2000 in most of area. Wind was also strong in the northern area and along the Primorye in 1999 and 2001. This corresponds to the interannual difference in the start time of spring blooms shown in Table 2-1; spring bloom tended to start earlier when wind was weak, and later when wind was strong. Probably weak and strong wind induced early and late development of the thermocline and spring bloom, respectively.

Wind speed in fall (average from September to December) also showed interannual variability (Fig. 2-9). The wind was weak in 1997 in the whole Japan Sea, and wind was strong in 2000 except the western area. However, the interannual variability of the wind seems to be unrelated to the magnitude of the fall bloom directly (Table 2-1).

2.4. Discussion

As described in results section, the seasonal blooms in the Japan Sea had great variability spatially and interannually. Here, the spring bloom, the bloom in the Primorye coast, the fall bloom and their implications for higher trophic production are discussed.

2.4.1. Spring bloom in the Japan Sea

The spring bloom took about three months from late February to mid-May to start in the Japan Sea, although it persisted for only about one month in each location. The evolution of the spring bloom in the Japan Sea had been detected by CZCS (Kim et al., 2000) and OCTS images (Yanagi et al., 2001). Kim et al. (2000) concluded from sporadic CZCS data that the spring bloom began in the northwestern region and moved to the southern area, and moved to the northern area. However, this propagation was not confirmed during 1997 to 2002 in this study. Yanagi et al. (2001) simulated the northward movement of the bloom based on what is found in OCTS image of spring 1997 (Tameishi, Nakasono, Saitoh and Takahashi, 1998) using an ecosystem model coupled with a hydrodynamic model. Our analysis showed that the spring bloom also started early along the Primorye coast and west of Hokkaido and sometimes from polar frontal area.

In the southern area, the spring bloom in 1998 and 2002 started about four weeks earlier than in other years. Chiba and Saino (2002) suggested the "early summer hypothesis" that the timing of the spring-summer transition of the composition of the diatom community along the PM line occurred relatively early during the 1980s than in other years and was accompanied by early nutrient depletion in the surface layer. Our analysis of satellite data collected from 1997 to 2000 indicated that the timing of spring bloom changed drastically year by year and it seems to be related to atmospheric factors that are known to vary on multiple temporal scales. Therefore, the result of this result may support the possibility of existence of large shift of spring bloom timing by decadal scale, and persistent period of years of early or late spring blooms such as occurred during the 1980s could be the result of persistent climate regimes.

Average spring wind speeds were weaker in 1998 and 2002 and stronger in 2000 than the other four years (Fig. 2-8). This seems to correspond to the annual start of the spring bloom (Fig. 2-10). There were positive correlations, specifically, the correlation was stronger in middle of the Japan Basin and Primorye; the bloom in 1998 and 2002 started earlier in weaker wind, and the one in 2000 started later in stronger winds. Onitsuka and Yanagi (2004) investigated the seasonal variation of lower trophic level ecosystem dynamics in the Japan Sea using an ecosystem model that included mixed layer depth and euphotic layer depth, and showed that the variation in timing of the bloom depends on the variation in mixed layer depth. It is expected that the weak wind stress could restrain the mixing and facilitate the formation of thermocline, and lead to an early spring bloom.

Correlations between the start of spring bloom and wind speed were weaker in the southern area (Fig. 2-10, Table 2-1). It may be affected by other factors than wind condition. Yoo and Kim (2004) showed that the weak Tsushima Current spread over the Ulleung Basin in the southwestern area forming a thick layer (up to 150m) of nutrient-poor water. Chiba and Saino (2002) analyzed PM line data in the southeastern of the Japan Sea from 1972 to 1999, and hypothesized that lower spring phytoplankton biomass during 1980s was related to the decrease of the Tsushima Current in upper layer. The Tsushima Current may be one of the factors of the interannual variability of spring bloom in the southern area.

Spring blooms appeared earlier and winds were weaker during the ENSO years of 1998 and 2002. Hanawa, Yoshikawa and Watanabe (1989) reported that mid-latitude westerly wind field shifts northward in winter during ENSO events. ENSO events involve an eastward shift of warm surface water in the equatorial Pacific, and a corresponding eastward shift in the equatorial the low pressure region. It may lead to a change the winter air pressure distribution of the globe (Horel and Wallace, 1981). The Aleutian Low shifts eastward compared with usual winters and the pressure gradient between the Aleutian Low and the Siberian High decreases. It means that the path of the westerly monsoon that supplies cold air from Siberia shifts northward. The variation of wind speed anomaly at four locations (Fig. 2-1 and 2-4) and MOI that indicates average strength of westerly monsoon from January to April were shown (Fig. 2-11). The MOI was weak in ENSO years of 1998 and 2002 and strong in 2000. The wind speed anomaly at four locations in the Japan Sea corresponded to MOI. Therefore, weak winter winds are expected in the mid-latitudes of the western North Pacific during ENSO events and the reduced winds may explain why early spring blooms have occurred in the Japan Sea during ENSO years. .

Analyzing shipboard observations taken offshore of the Tsushima Current region, Chiba and Saino (2003) revealed that increases in water column stability caused nutrient depletion in spring during the two ENSO years of the 1990s (1992 and 1998). They discussed the possibility that the weak wind associated with ENSO caused the enhancement of water stratification and shifted spring bloom timing although their study was based on a very limited data set taken four times a year at three stations. This study observed the timing shift of the spring bloom, and demonstrated that the ENSO-related, wind-driven mechanism was quite applicable to explain interannual variation of start timing of the spring bloom in wide area of the Japan Sea.

Sasaoka, Saitoh, Asanuma, Imai, Honda, Nojiri et al. (2002) observed interannual variability of chlorophyll *a* by satellite and ship observation from 1997 to 1999 in the subarctic northwestern Pacific and they also observed sea surface winds of the North Pacific using satellite data. They did not describe the timing of the spring bloom, however their data along 155°E showed that winds north of 40°N were weak during 1998 and an area of high chlorophyll *a* was found in 1998 in the north of 40°N earlier than 1997 and 1999. This corresponds with our observation about the change in start timing of spring bloom in the Japan Sea. Similar biological response to the ENSO events with that in the Japan Sea may be observed in larger scale in the western North Pacific.

2.4.2. Bloom in the Primorye Coast

Spring blooms along the Primorye coast were detected every year from 1997 to 2002 by satellite remote sensing. A similar spring bloom had been described by Komaki (1972). The spring blooms in this area started from mid-March to late May (Fig. 2-7). The bloom in this area started earlier than the one in the middle of the Japan Basin. It seemed that the spring blooms along the Primorye coast started inshore and moved offshore as time passed. SST was high and low in the south and the north respectively (Fig. 2-3), and formation of the seasonal thermocline was expected to proceed from south to north. However, the blooms started earlier along the Primorye coast where the temperature was even lower than in Japan Basin. It is suspected that blooms along the Primorye coast are not controlled by the development of thermocline.

Yoshimori, Ishizaka, Kono, Kasai, Saito, Kishi et al. (1995) investigated the spring bloom in the Western Subarctic Pacific (off Japan). Early spring blooms were also observed by CZCS data at inshore (northern) station than offshore (southern) station in their study. They pointed out that the earlier inshore bloom was caused by low salinity subarctic water along the Japanese coast. Due to low salinity water in the sea surface layer, water column stability increased earlier and the bloom also started earlier.

The Primorye coast is supplied with low salinity water by the Liman Current. Martin and Kawase (1998) suggested that source of the Liman Current that flows along the Primorye coast is low salinity water from melting of the sea ice in the Mamiya (Tartarskiy) Strait from January to March. The fresh water does not come from the Amur River because the north part of the Mamiya Strait is covered with thick ice, and the discharge from the Amur is almost zero in this period. It seems that the halocline is formed off the Primorye coast by melting of sea ice in the Mamiya Strait. In fact, Zakharkov, Lobanov, Mitchell, Sovetnikova and Talley (2000) described that a halocline existed in the northern coastal area (around 46^{O}N, 138^{O}E), and high chlorophyll *a* concentration was observed in the spring 2000.

Hunt and Stabeno (2002) described that two kinds of spring blooms are occurred in the Bering Sea: one is associated sea ice melting, and the other is associated by water column stratification when winds weaken and solar energy increase. They indicated that the former occurs late March or April, and the latter occurs in May or June. In this study, spring bloom started earlier in the Primorye coast than in the middle of the Japan Basin. Earlier spring bloom associated by sea ice melting in April was expected in the Primorye coast. On the other hand, spring bloom associated by water column stratification was expected in the middle of the Japan Basin and started in May later than the Primorye coast.

The blooms in the Primorye coast started three weeks later in 1999 and 2001 than other four years (Fig. 2-7). As mentioned above, the halocline formed by low salinity water from melting sea ice in the Mamiya Strait may be also important factor for the development of stratification in this area. We calculated the width of sea ice area through time in the Mamiya Strait (Fig. 2-12) and found that there was significant interannual variation in the sea ice area. In 1999, a year when the bloom was delayed, sea ice maintained its coverage until April later than other years. On the other hand, the ice had melted by March in other years, including 2001 when the bloom started later (Fig. 2-9). Since wind speed was strong in 2001, halocline made by sea ice melting in March was broken by strong wind and spring bloom in 2001 might occur later. Timing of melting of the sea ice and strength of wind speed play important rolls synergistically for the spring bloom in the Primorye coast.

2.4.3. Fall Bloom in the Japan Sea

The fall bloom in the Japan Sea starts from early October to early December in the most of the Japan Sea (Fig. 2-6). These blooms did not show a remarkable temporal transition as the spring bloom did, although fall blooms started a little earlier off the east coast of Korean Peninsula and the northern Primorye coast. Chlorophyll *a* concentrations of the fall bloom were higher in the western area than the eastern area, especially south of subpolar front. The chlorophyll *a* concentration in the eastern area was low, though it also increased compared with summer levels. On the other hand, the bloom in the western area was large and chlorophyll *a* concentrations were kept high throughout the year (Fig. 2-2). The difference between east and west was remarkable from summer to fall.

Nagata (1994) showed that there was a significant inverse relationship between chlorophyll *a* and transparency. Nagata et al. (1996) also showed that the transparency in October was higher in eastern area than in western area that might indicate that chlorophyll *a* concentration in the eastern area was lower than in the western area in fall. Baba et al. (1985) calculated the mean value of phosphate concentration in the Japan Sea from 1965 to 1983 based on the ship observations. From their result, it was shown that phosphate concentration was higher in western area than eastern area from surface to 100m depths. The western area is expected to have higher nutrients because it has a complex water structure through interaction of the North Korean Cold Current (Uda, 1934) and the East Korean Warm Current that is separated from the Tsushima Current (Kim and Legeckis, 1986). Shim and Lee (1983) also indicated that mixing by these two currents led high biomass of phytoplankton in this area in September 1981.

The area of the Japan Sea with fall blooms was different between years if a threshold chlorophyll *a* concentration was defined. The area of the Japan Sea with low chlorophyll *a* concentrations (white areas in Fig. 2-6) was smallest in the southeastern area in 1999 and this was the only year with this pattern. Low chlorophyll *a* areas in 1997 and 2001 were observed throughout the southern area, while in 2000, this area was observed in the eastern area in the south of 43°N. Although the timing of the fall bloom was not so variable as the spring bloom, the fall bloom in the northern region in 1999 occurred much earlier than other years (Fig. 2-6). While the average seasonal wind speed data in Fig. 2-9 does not reveal temporal distribution, the daily wind stress data showed that the wind stress in 1999 increased in September while the wind stress in 1998 increased in late November (not shown). It shows that the peaks of wind stress were followed by increases in the chlorophyll *a* concentration. Ishizaka et al. (1997) described that the critical depth theory (Sverdrup, 1953) explains the timing of the peak of fall bloom. When the mixed layer depth deepens after the stratification in summer, nutrients are carried up from the subsurface and phytoplankton in the surface layer start to increase. When the mixed layer depth equal to the critical depth, chlorophyll *a* concentration should reach to the peak and start to decrease. Shallow mixing leads to supply of nutrient from subsurface layer, but deep mixing causes the lack of light condition and dissipation of the bloom. However the effect of wind stress for the magnitude of fall bloom is still unknown, wind stress may have a large effect for the initiation of the fall bloom in terms of breaking down the seasonal stratification that developed in summer.

2.4.4. Influences for the Higher Trophic Level in the Japan Sea

Large interannual variability in the timing and magnitude of the bloom in the Japan Sea was shown by this study. Such differences may affect the amount of productivity of higher trophic levels. Chiba and Saino (2003) showed that diatom and zooplankton species composition in the Japan Sea changed during ENSO years during the 1990s. In this study, it was shown that the start of the spring bloom varied with ENSO events in a wide area of the Japan Sea. The variability may affect species composition and the abundance of zooplankton and further to the fish larvae that graze on phytoplankton and zooplankton.

Recently, Platt, Fuentes-Yaco and Frank (2003) showed the relationship between the timing of spring bloom and the survival of haddock off the eastern Nova Scotia, Canada. They found that an early spring bloom gave an advantage by extending the spawning period and providing improved foraging opportunities to the fish larvae. Early blooms in 1981 and 1999 in the area increased the survival of haddock larvae. In this study, spring blooms in the Japan Sea were about four weeks earlier in 1998 and 2002 than other years. It is expected that fish larvae in the Japan Sea that graze on the spring bloom phytoplankton are affected by the shift of the timing.

Zhang, Lee, Kim and Oh (2000) showed that chlorophyll *a* concentrations during the fall bloom, estimated by monthly transparency data (Park, 1996) increased after the regime shift in 1976 as did the sardine (*Sardinops melanosticus*) stock in the Korean waters. Sardines are resident in the Japan Sea from June to November, and they feed on phytoplankton that increased during fall blooms. They suggested that variability in the magnitude of fall blooms might have large effects for the recruitment and growth of fish species that spend fall seasons in this area. As was shown in this study, phytoplankton in the Japan Sea varies spatially and temporally. If much longer time series of ocean color satellite data were accumulated, it is expected that the consequences of regime shift to the bloom and higher trophic level will be able to be understood more clearly.

2.5. Summary

The start of spring blooms had large spatial variability in the Japan Sea; it started subpolar front and southward in March, northward of subpolar front, west of Hokkaido and the Primorye coast in April, and in the middle of the Japan Basin in May. The timing also showed large interannual variability, which was correlated to average wind speed. Weak winds were observed in the springs of 1998 and 2002 when the start of the spring bloom was about four weeks earlier than in other years. This weak wind condition seemed to correspond to the global climate system caused by ENSO events. Weak wind conditions are expected to promote early stabilization of upper water column and establish conditions for an early timing of spring blooms in the Japan Sea. Chlorophyll *a* concentrations during fall blooms were higher in the western area than eastern area every year, especially in the southern part of the Japan Sea. The magnitude of fall bloom differed among years, although its relation to average wind was not clear. The global climate system may give large effects to the timing and magnitude of spring and fall blooms in the Japan Sea, and therefore it must give large effects to the primary production and higher trophic level production in the Japan Sea.

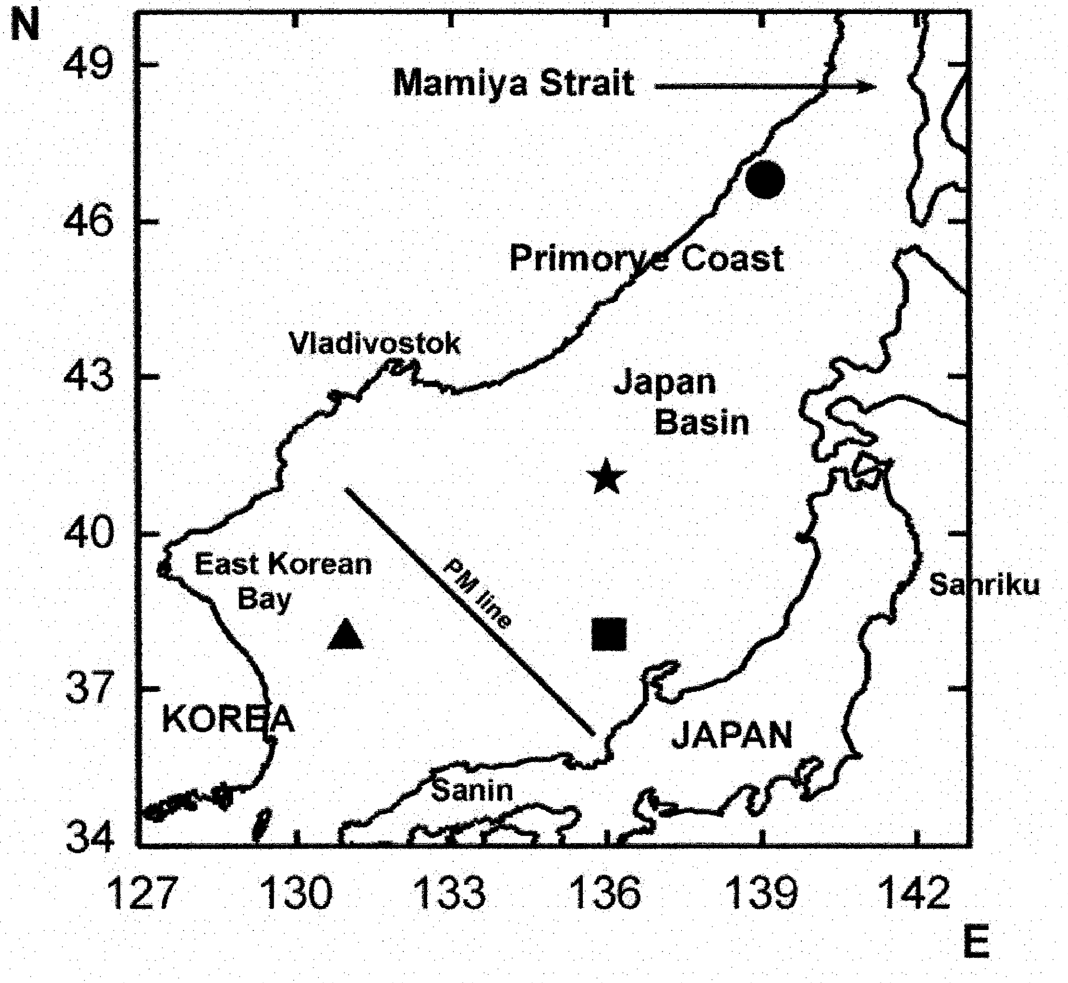

Fig. 2-1. Location map of four stations selected for satellite and ocean factors based on the formation of water masses and thermal front in the JES (34 - 50°N, 127 - 143°N). Primorye coast, middle of the Japan Basin, southeastern area and southwestern area in the Figs. 2-4 and 2-10 are shown by circle, star, square and triangle, respectively.

Monthly Average Chlorophyll *a* Image

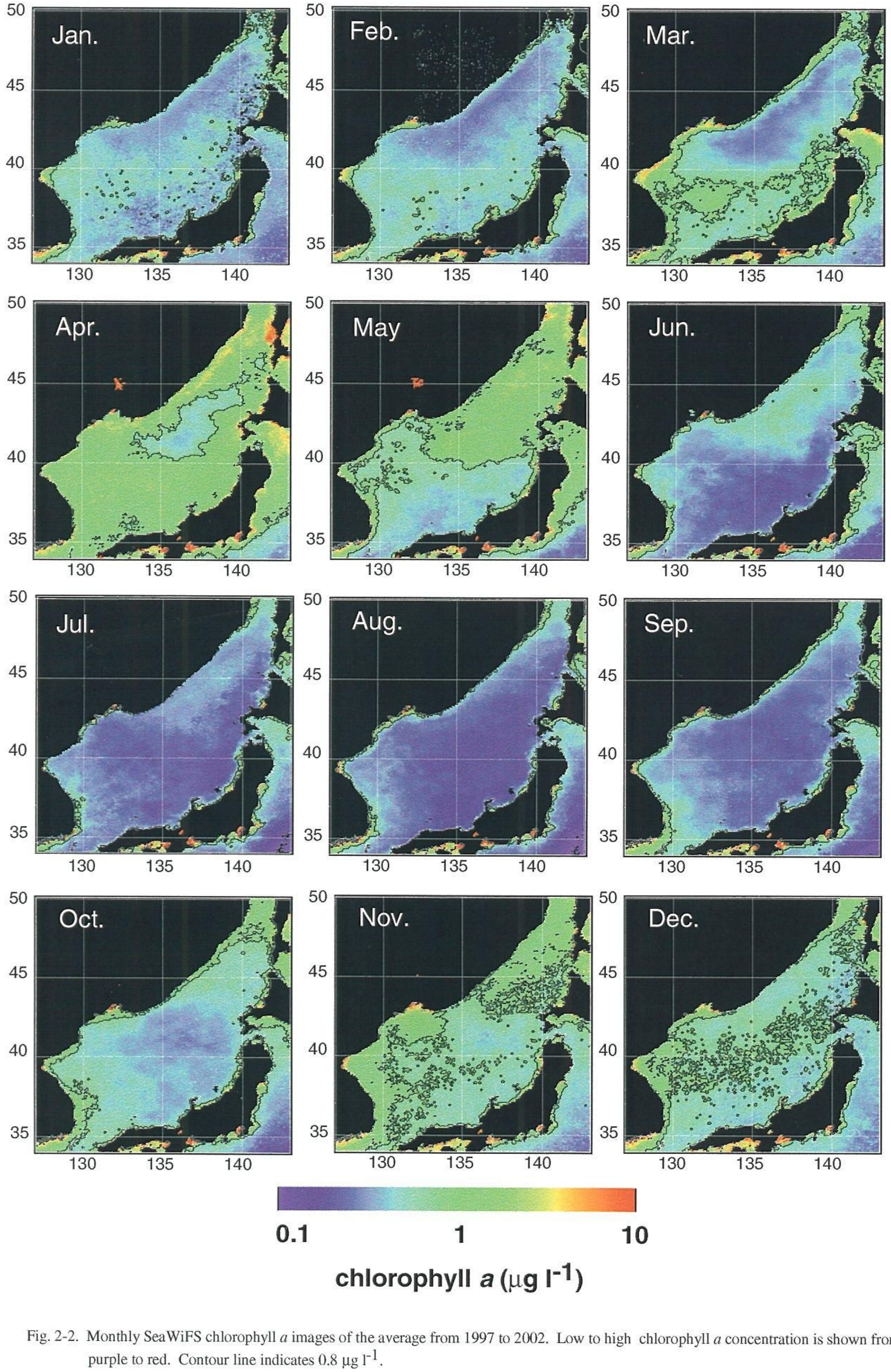

Fig. 2-2. Monthly SeaWiFS chlorophyll *a* images of the average from 1997 to 2002. Low to high chlorophyll *a* concentration is shown from purple to red. Contour line indicates 0.8 μg l^{-1}.

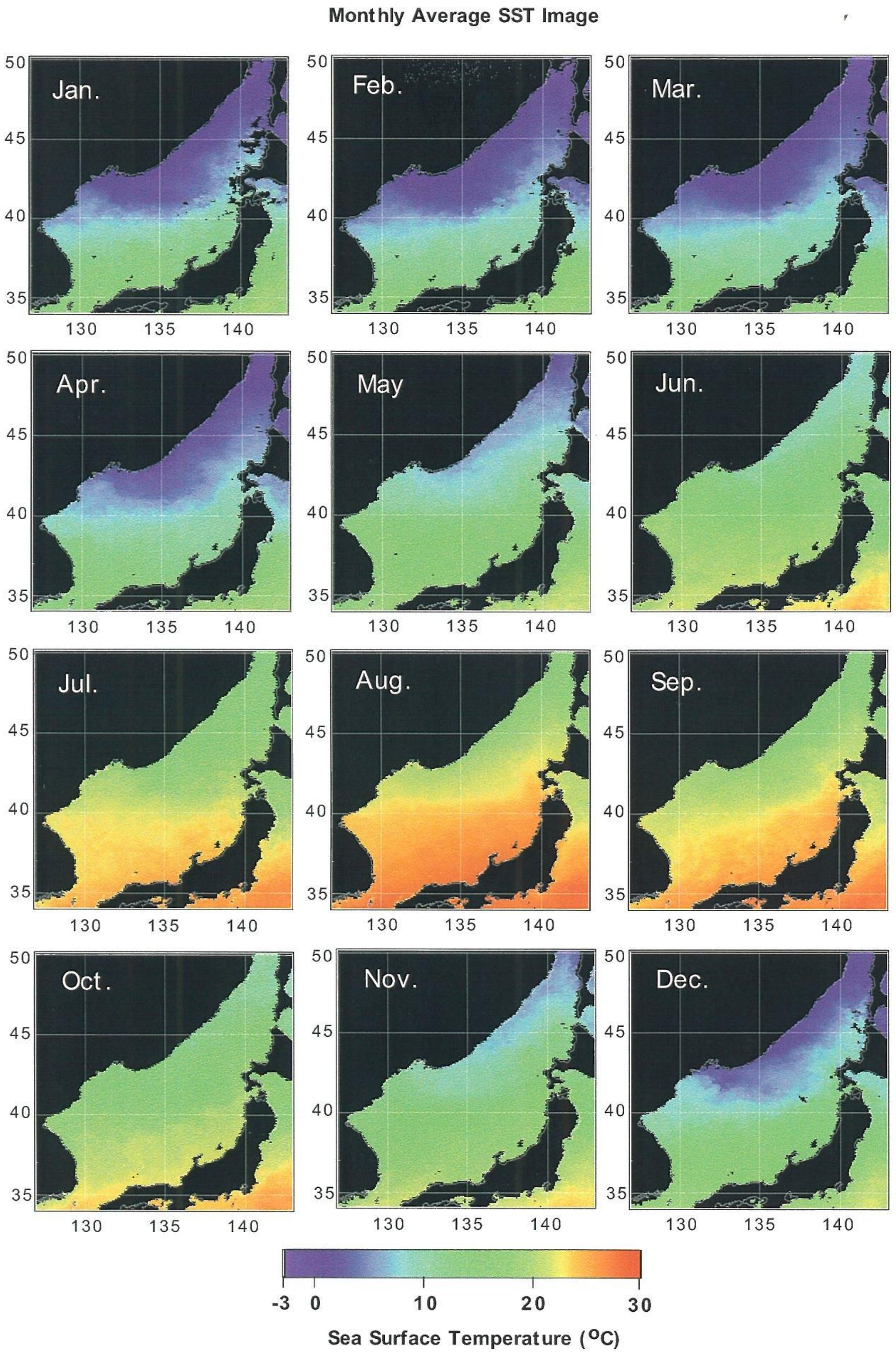

Fig. 2-3. Monthly average SST images from 1996 to 2002. Low to high SST is shown from purple to red.

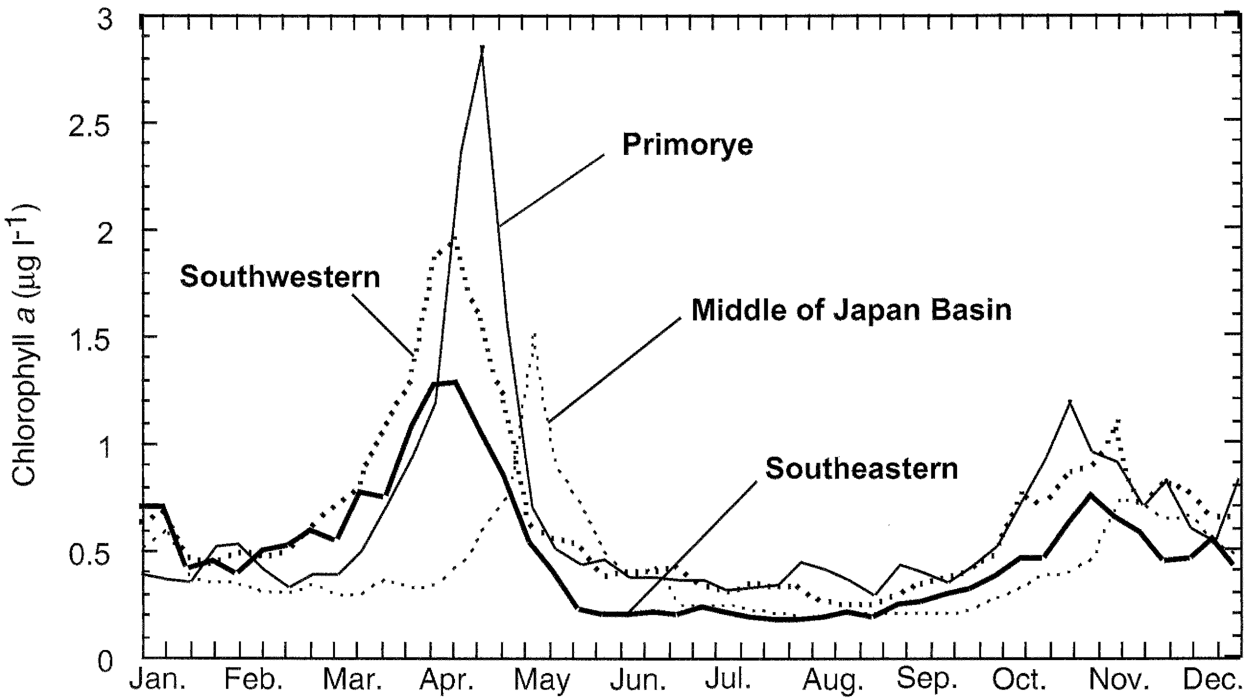

Fig. 2-4. Monthly variation of mean chlorophyll *a* concentration by area in the JES during 1997 to 2002: 46.5°N, 139°E (thin solid line), 41°N, 136°E (thin dotted line), 38°N, 136°E (thick solid line) and 38°N, 131°E (thick dotted line), as examples of the Primorye coast, middle of the Japan Basin, the southeastern area, and the southwestern area, respectively (cf. Fig. 2-1).

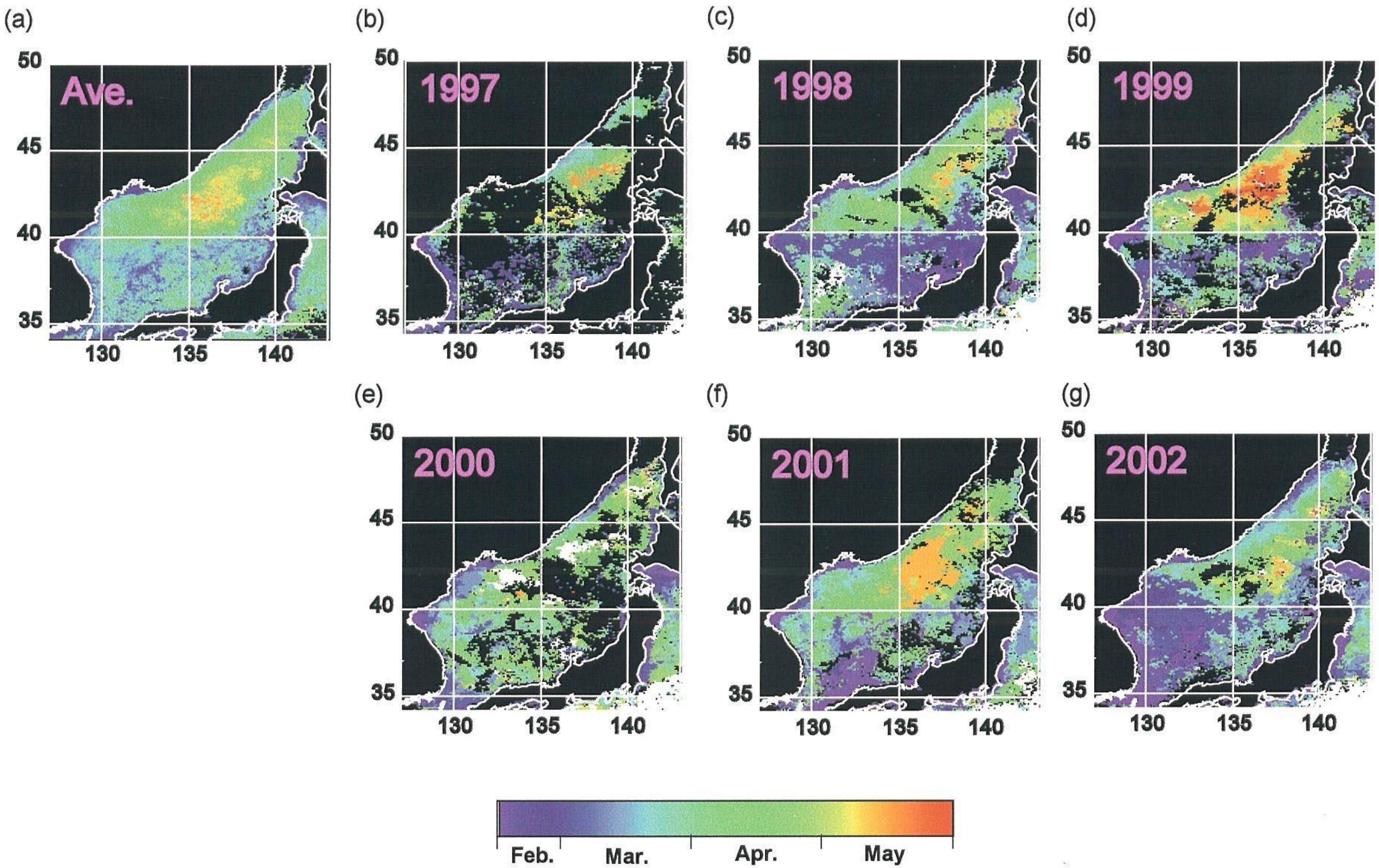

Fig. 2-5. Start of the spring bloom derived from OCTS and SeaWiFS data. Spring bloom was defined as the chlorophyll *a* concentrations >0.8 μg l^{-1}. White area is non-blooming area with chlorophyll *a* concentration <0.8 μg l^{-1} throughout mid-February to May. Earliest bloom is shown by purple and latest bloom is shown by red. When two continuous data were missed before chlorophyll *a* concentration reached to 0.8 μg l^{-1}, we excluded these data (shown by black pixels in the sea area). (a) Average from 1997 to 2002, (b) 1997, (c) 1998, (d) 1999, (e) 2000, (f) 2001 and (g) 2002.

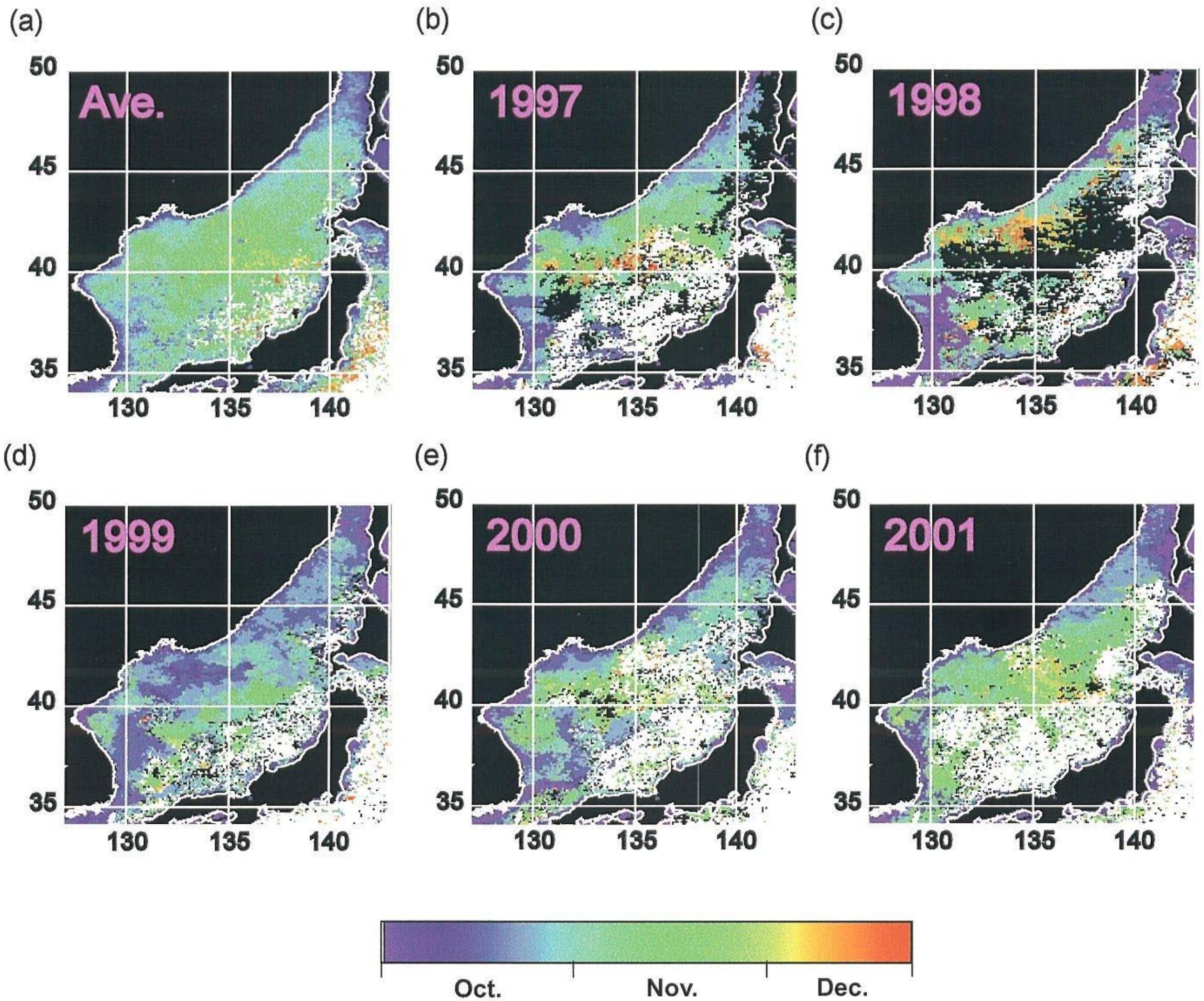

Fig. 2-6. Start timing of the fall bloom. Fall bloom was defined as the chlorophyll *a* concentration >0.8 μg l^{-1}. White area is area that chlorophyll *a* concentration <0.8 μg l^{-1} throughout October to December. (a) Average from 1997 to 2001, (b) 1997, (c) 1998, (d) 1999, (e) 2000, and (f) 2001. SeaWiFS weekly composite data was used.

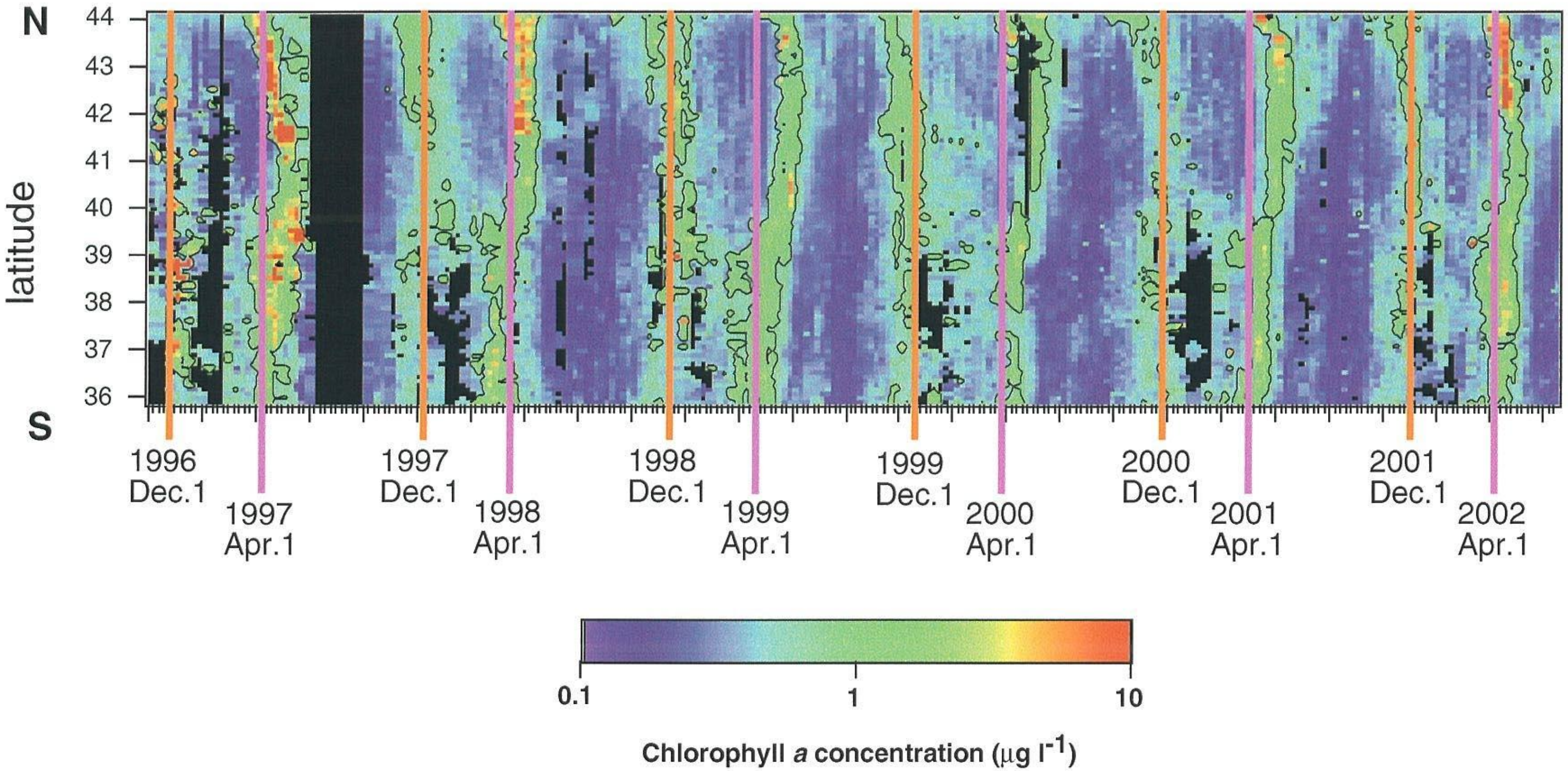

Fig. 2-7. Phase diagram of chlorophyll *a* concentration at 136^{O}E in the JES. Weekly composite data of OCTS and SeaWiFS were used from November 1996 to June 1997 and from September 1997 to August 2002, respectively. Contour line indicates 0.8 μg l^{-1}. Vertical and horizontal axis shows latitude and time, respectively. Missing data pixels were interpolated from four surrounding pixels except when all four neighboring pixels did not have any data , in which case they were regarded as 'no data'. Pink and orange lines show April 1 and December 1, respectively.

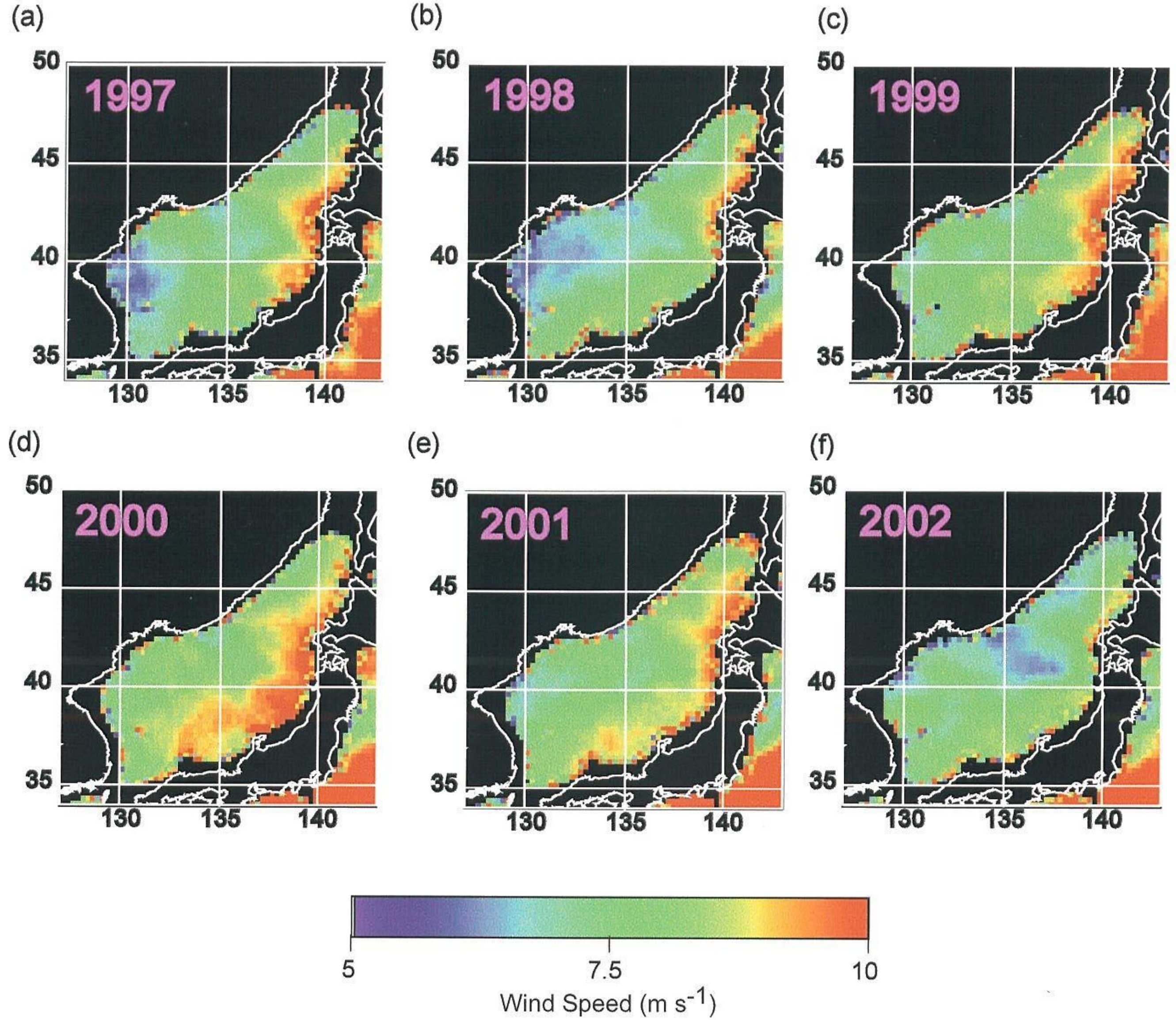

Fig. 2-8. Average wind speed during January to April. (a) 1997, (b) 1998, (c) 1999, (d) 2000, (e) 2001 and (f) 2002.

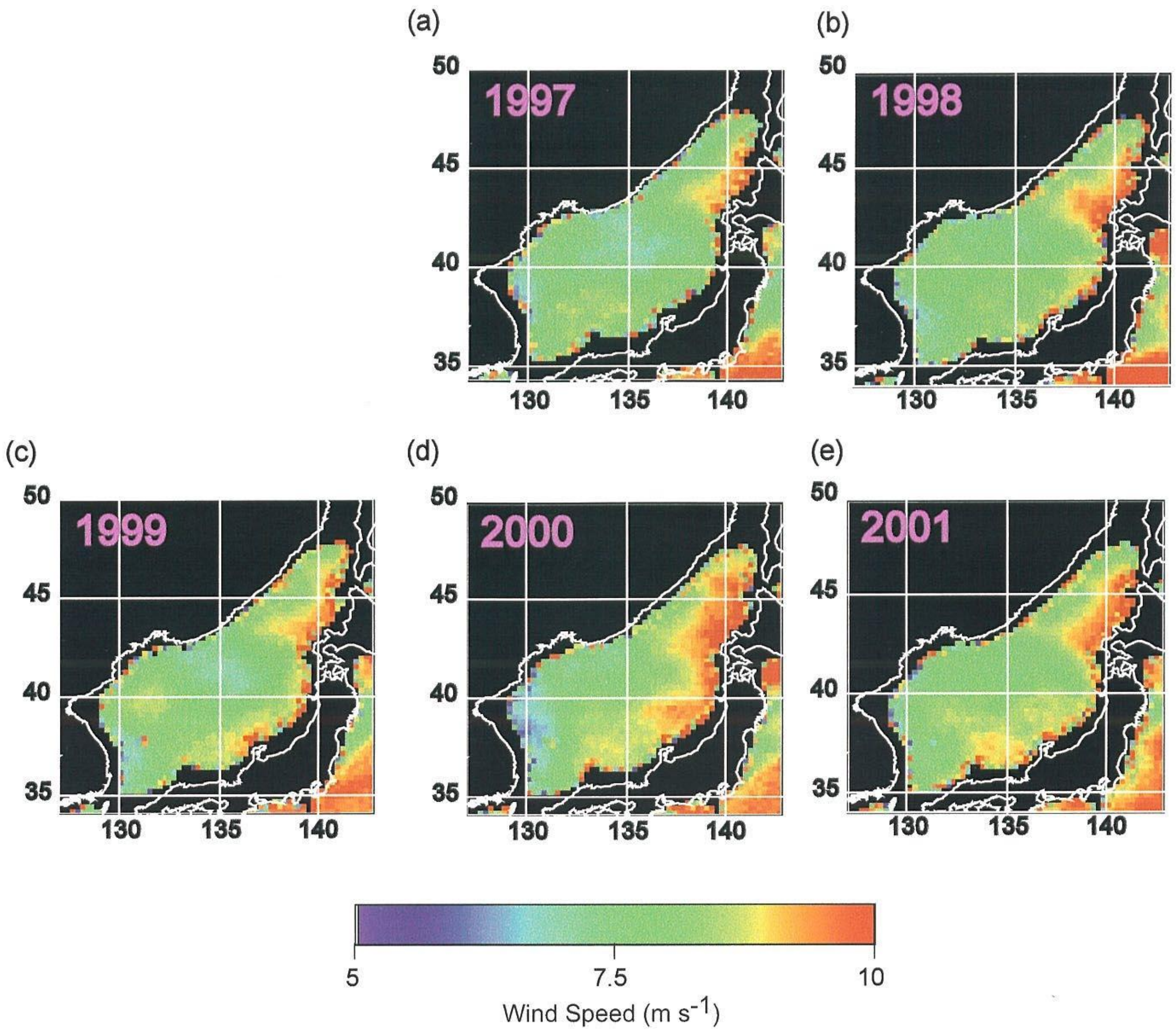

Fig. 2-9. Average wind speed during September to December. (a) 1997, (b) 1998, (c) 1999, (d) 2000 and (e) 2001.

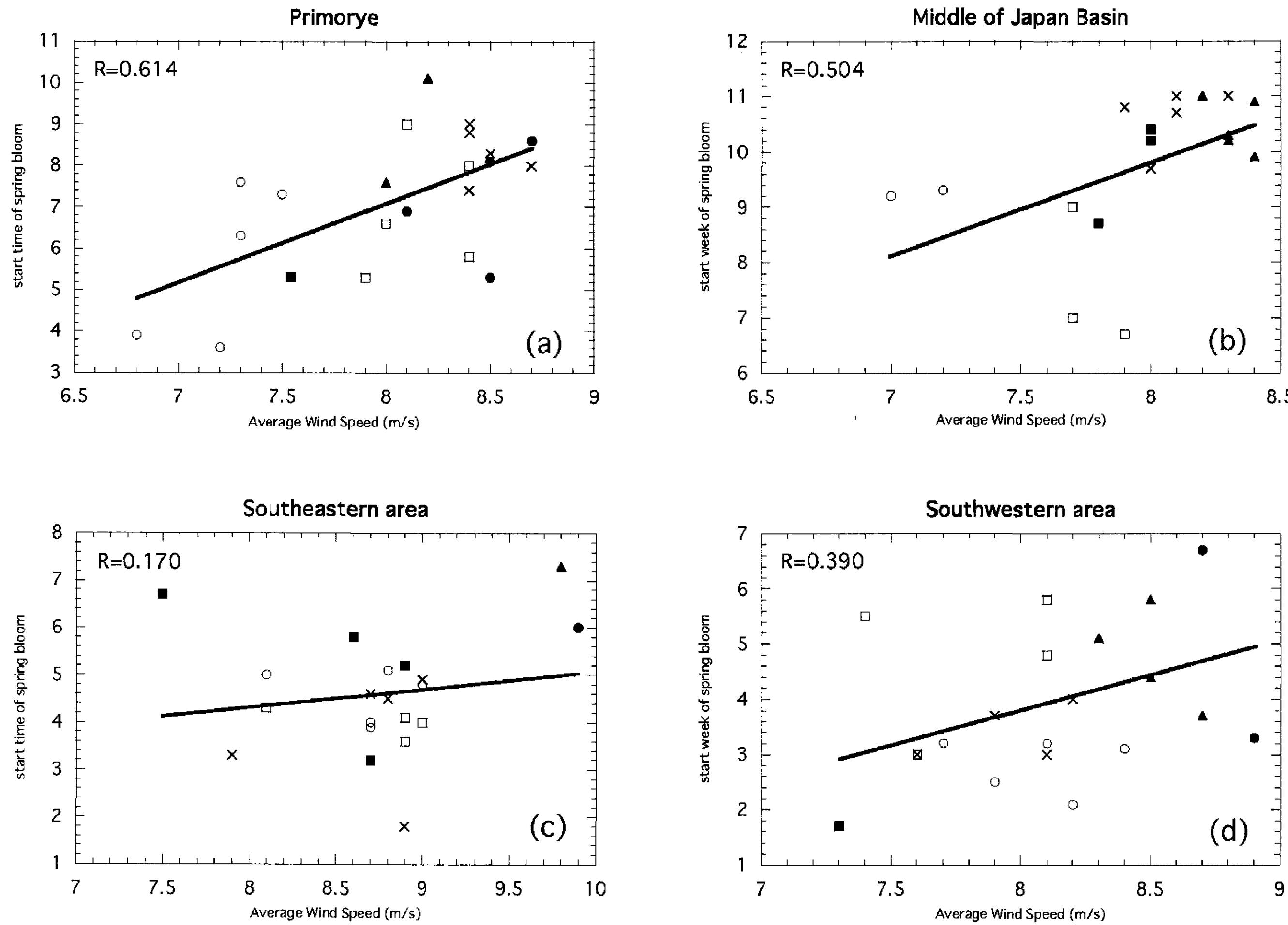

Fig. 2-10. Correlation between start timing of spring bloom and average wind speed during January to April at the Primorye (a), middle of the Japan Basin (b), the southeastern area (c) and the southwestern area (d). Black square, opened square, cross, black circle, black triangle and opened circle indicate 1997, 1998, 1999, 2000, 2001 and 2002, respectively.

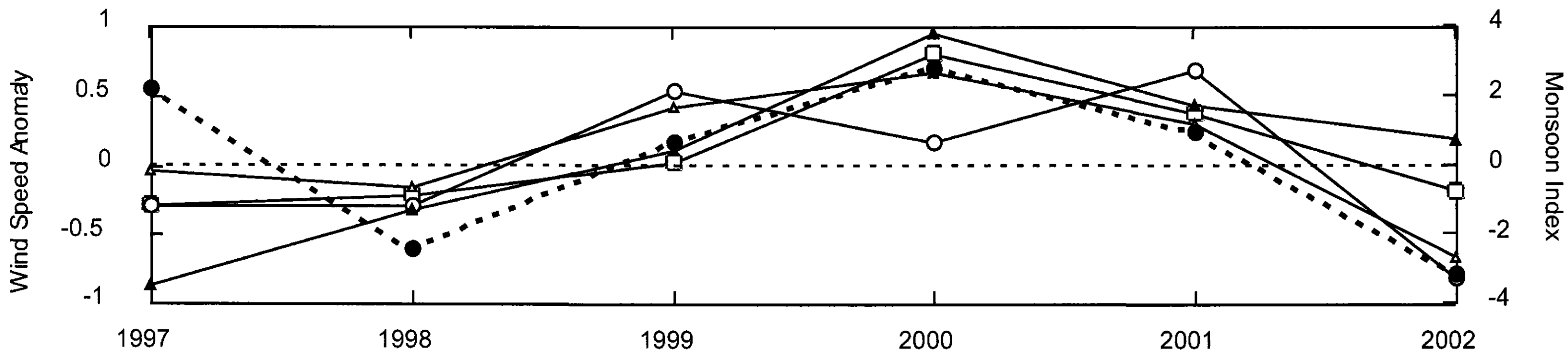

Fig. 2-11. Variation of average wind speed anomaly from January to April at four locations in the JES and MOI. Open circle, open triangle, open square and black triangle indicate wind speed anomaly at the Primorye, middle of the Japan Basin the southeastern area and the southwestern area respectively. MOI was difference of sea surface pressure between Ulan Ude Russia (51.80^{O}N, 107.42^{O}E) and Nemuro, Japan (43.03^{O}N, 145.75^{O}E).

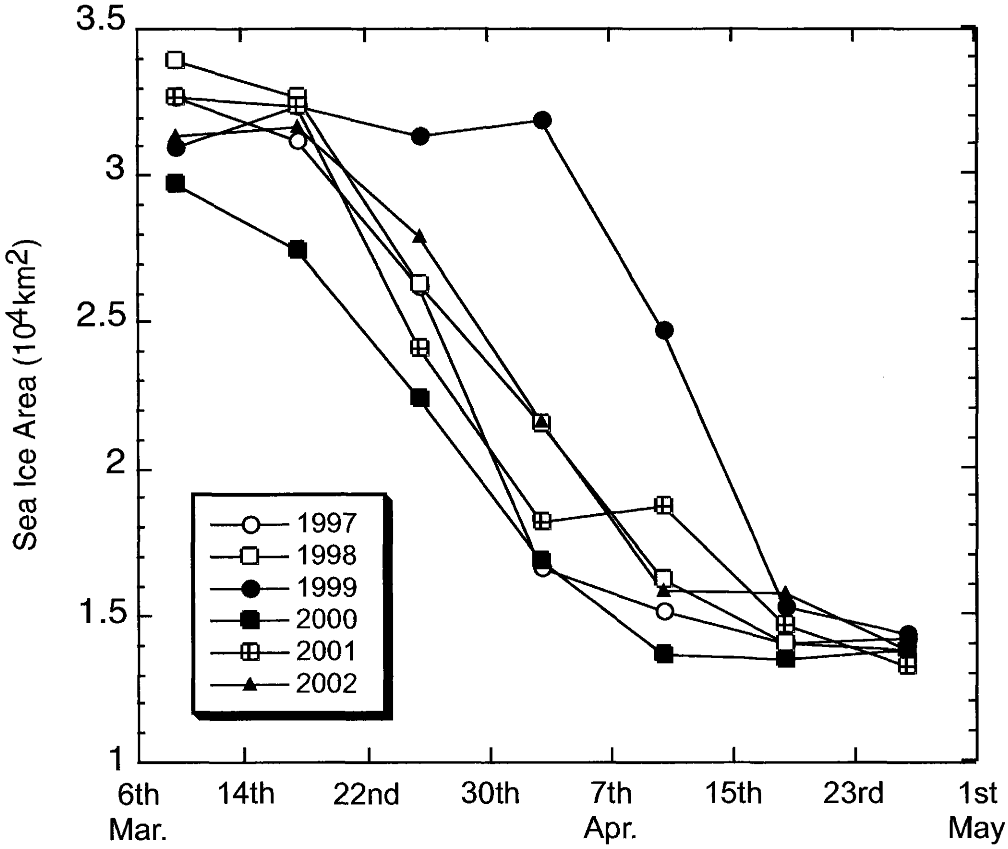

Fig. 2-12. Temporal change of area covered by sea ice in Mamiya Strait in March and April from 1997 to 2002.

Table 2-1

Features of spring and fall blooms of each year

	Southwestern area	Southeastern area	Northern area	Near Primorye
Spring				
1997	- (weak)	Middle (middle)	- (middle)	Early (middle)
1998	Middle (weak)	Early (weak) *	Early (weak) *	Early (weak) *
1999	Middle (middle)	Middle (middle)	Late (strong) +	Late (strong) +
2000	Late (strong) +	Late (strong) +	- (strong)	Late (strong) +
2001	Early (strong)	Late (strong)	Late (strong) +	Late (strong) +
2002	Early (middle)	Middle (weak)	Early (weak) *	Early (weak) *

	Bloom area	
Fall		
1996	-	(weak except north of 43°N)
1997	Only in the northern area	(weak)
1998	-	(middle)
1999	Widely distributed except southwest area	(middle)
2000	Only in the western area and north of 43°N	(strong except in the western area)
2001	Only in the northern area	(strong)

"-"indicates that there were not enough data to describe the features. "*" and "+" indicate that when spring bloom started early in the weak wind, and started late in the strong wind, respectively. Features of wind were shown in the ( ).