석사학위논문

Causes of Migration and Blooms of the Green Tide in the Western Yellow Sea in 2008

제주대학교 대학원

해양기상학 협동과정

이 준 호

2011년 2월

Causes of Migration and Blooms
of the Green Tide
in the Western Yellow Sea in 2008

지도교수 방 익 찬

이 준 호

이 논문을 이학 석사학위 논문으로 제출함.

2011년 2월

이준호의 이학 석사학위 논문을 인준함.

심사위원장 문일주 ㊞

위 원 강기룡 ㊞

위 원 방익찬 ㊞

제주대학교 대학원

2011년 2월

Causes of Migration and Blooms of the Green Tide in the Western Yellow Sea in 2008

Joon-Ho Lee
(Supervised by professor Ig-Chan Pang)

A thesis submitted in partial fulfillment of the requirement for the degree of Master of Science

2011. 2

Department of Marine Meteorology
GRADUATE SCHOOL
JEJU NATIONAL UNIVERSITY

Contents

List of Figures

Abstract

The green tide bloomed in the south coast of the Shandong Peninsula in 2008 was simulated with ROMS (Regional Ocean Modeling System) using a Lagrangian-particle-tracking experiment to investigate the physical process of green tide movement. The particles representing green tide seeds were launched in the coastal area along the Jiangsu province north of the Changjiang river mouth, which was suggested as a source of the green tide bloom in 2008. The simulated particle distributions are fairly consistent with the observed ones implying that the original source of green tide is very likely located along the coast of Jiangsu province. According to the analysis with the factors related to the migration and bloom of the green tide, the wind forcing seems to be the most responsible factor for the green tide appearance around Qingdao city in 2008. To check out whether this result can also be explained to the other year's green tide distribution, additional experiments were conducted using 2007 and 2009 wind forcing. The model results show a good agreement with the observed green tide indicating that the southerly wind is responsible for the offshore movement of green tide from the Jiangsu province and the easterly wind is responsible for its extension up to the coast of the Shandong peninsula. Through analyzing the pathway of particle trajectory, an upwelling region was found between the Jiangsu coast where the possible source of the green tide and western Yellow sea where the green tide massively bloomed. This area seems to provide a favorable condition for the recent green tide bloom as a possible nutrient supplier.

Keywords: green tide, Enteromorpha prolifera, particle-tracking experiment, wind forcing, Yellow sea, nutrient supply, upwelling

1. Introduction

A massive green tides (previously known as *Enteromorpha prolifera*, green macroalgae, Haden et al., 2003; Hu et al., 2010) were appeared just weeks before the opening of the Beijing Olympics around Qingdao coast in late June 2008. Green tides were piled up on Qingdao coast and over 10,000 people were accompanied to clean up and removed more than million tones of algae from the beach and coast of Qingdao (China Ocean News, 2008b) (Fig. 1). This is the largest green tide ever reported in the world, the most extensive translocation of a green-tide and the first case of expansive seaweed aquaculture leading to a green-tide (Liu., 2009; Hu et al., 2010). The initial causes were attributed to the coastal eutrophication and the action of tides and wind in bringing the algae ashore by the media and some scientists (China Ocean News, 2008b, c; Herald Sun, Daily Mail, 2008).

Recently, Liu et al. (2009) analyzed the translocation of these green tides using observed satellite image and modeled current data. The results suggested that the expansion of seaweed aquaculture along the Jiangsu province which is 250 km away from Qingdao coast is a possible origin of the massive algal bloom in 2008 around Shandong peninsula. They also pointed out that the coastal eutrophication can not be the primary cause of green tide. Ye et al. (2008) analyzed the observed data from oceanographic comprehensive surveys from the Subei bank to the center of Yellow Sea during the bloom and post-bloom periods in 2008. They also suggested that the massive green algal bloom occurred in Yellow sea in 2008 was not originated from the coastal area of Qingdao, but originated from between 33-34°N along the Jiangsu coast, then drifted to the coastal area of Qingdao by seasonal wind and currents. Recently, Hu et al. (2010) analyzed 10-year green tide distribution in the Chinese coast using high resolution satellite images, suggesting the green tide has been occurring not only in 2008 but almost every year from April to July.

Throughout reviewing previous studies, three fundamental questions are raised here. Firstly, is the Jiangsu coast really original source area of recent algal bloom? If so, what are their pathways and controlling processes? Secondly, is the massive algal bloom in Qingdao 2008 sporadic event or having a potential to occur again? Thirdly, during the migration of green tide from source region to the massively bloomed area, was (were) there any possible nutrient supplier(s)? To address these questions, three-dimensional numerical ocean model was introduced in this study with a special focus on exploring the physical process of the translocation of recent green tide using Largrangian particle tracking experiment. In order to simplify the model structure, the biological and ecological features of the green tide were neglected in this model.

The general features and conditions of numerical model are described in the next section. Results of the simulation in 2008 with Lagrangian particle-tracking experiment are presented in Section 3-1. They are compared with the satellite image from Moderate Resolution Imaging Spectroradiometer (henceforth, MODIS). The current patterns and migration process of green tide is shown in Section 3.2. Additional experiments for the green tide movement in 2007 and 2009 are presented and analyzed in the section 3.3. Explanation of upwelling region is made in 3.4. Possibility of reoccurrence of Qingdao event is addressed in 3.5. Finally, discussion and conclusions are given in Section 4.


Fig. 1. Massive green tide bloom in Qingdao, late June 2008

2. Numerical model and setup

2.1 The model

The numerical ocean model, ROMS (Regional Ocean Modeling Systems; Shchepetkin and McWilliams, 2005), is used for this study. The ROMS is a three dimensional, the free surface, primitive equation, finite-volume numerical model based on the nonlinear terrain-following coordinate (s-coordinate) of Song and Haidvogel (1994). The s-coordinate is an extension to the classical sigma-coordinate used in the Princeton Ocean Model (Blumberg and Mellor, 1987) and is able to provide enhanced resolution at either the sea surface or sea floor, which is a valuable feature for handling steep topography in coastal oceans. In ROMS, the hydrostatic primitive equations for momentum are solved using a split-explicit time-stepping scheme, in which the barotropic fast and baroclinic slow modes are separately advanced in time. The horizontal diffusion is calculated using the Smagorinsky diffusion parameterization. Details of the ROMS computational algorithms are described by Shchepetkin and McWilliams (2005).

2.2 Model domain and setup

The model region covers the entire Yellow Sea (YS) and the East China Sea with 1/20 degree (5km) horizontal resolution and 20 terrain-following coordinate levels (Fig. 2). The bottom topography is extracted from the recent bathymetry dataset made by Seo et al. (2008).

The model initialization for the spin-up is obtained from the northwestern Pacific model (henceforth, NWP model) with 1/8° horizontal resolution (Moon et al. 2009, personal communication). The NWP model is spun up for 17 years with climatological temperature and salinity obtained from World Ocean Atlas

(WOA2001, Stephens et al., 2002). Atmospheric forcing is extracted from the Comprehensive Ocean-Atmosphere Data Set (COADS) (Da Silva et al., 1994). The COADS data consists of surface heat and freshwater fluxes, and heat flux sensitivity to sea surface temperature. The total heat flux (Q) is applied to the surface grid level and formulated as in Barnier et al. (1995). A correction with respect to the surface temperature, dQ/dT derived from bulk formulas, is used to introduce thermal feedback (Marchesielloetal., 2001). A river source is included in the model to take into account the Changjiang river discharge using monthly discharge data at Datong station. Warner et al. (2005a) have incorporated a number of turbulence closure schemes into ROMS. In this study, we shall use Generic Length Scale (GLS) mixing scheme developed by Umlauf and Burchard (2003) as vertical mixing parameterization (this scheme is called gen scheme by Warner et al. (2005a) and the background diffusivity is chosen to be $10^{-5}m^2s^{-1}$. This vertical mixing scheme successfully replicated coastal and estuary area (Warner et al., 2005b; Banas et al., 2008; MacCready et al., 2008). The barotropic and baroclinic time steps are set to 80s and 10s respectively. At the bottom, the quadratic bottom friction law was applied.

Daily mean temperature, salinity and velocity of the NWP model based on Moon et al. (2009) are used for the lateral boundary conditions. At the boundaries, clamped conditions are introduced for the 3D velocity, temperature and salinity. Tidal harmonics extracted from a global tide simulation (Egbert et al., 1994; Egbert and Erofeeva, 2002) is applied as surface height and depth-averaged velocity boundary conditions using Chapman (1985) and Flather (1976) conditions respectively. The model was spun up with the climatology fields for 1 model year. After 1 year of spin-up, the model was run for additional 1 year with the Quik scatterometer (http://www.ifremer.fr/cersat/en/data/download/gridded/mwfqscat.htm) (hereafter, QuickSCAT) daily wind of 2008. In order to investigate yearly variability of algal bloom, additional experiments were conducted for 2007 and 2009 using

QuikSCAT daily wind of 2007 and 2009 after 1-year spin up.

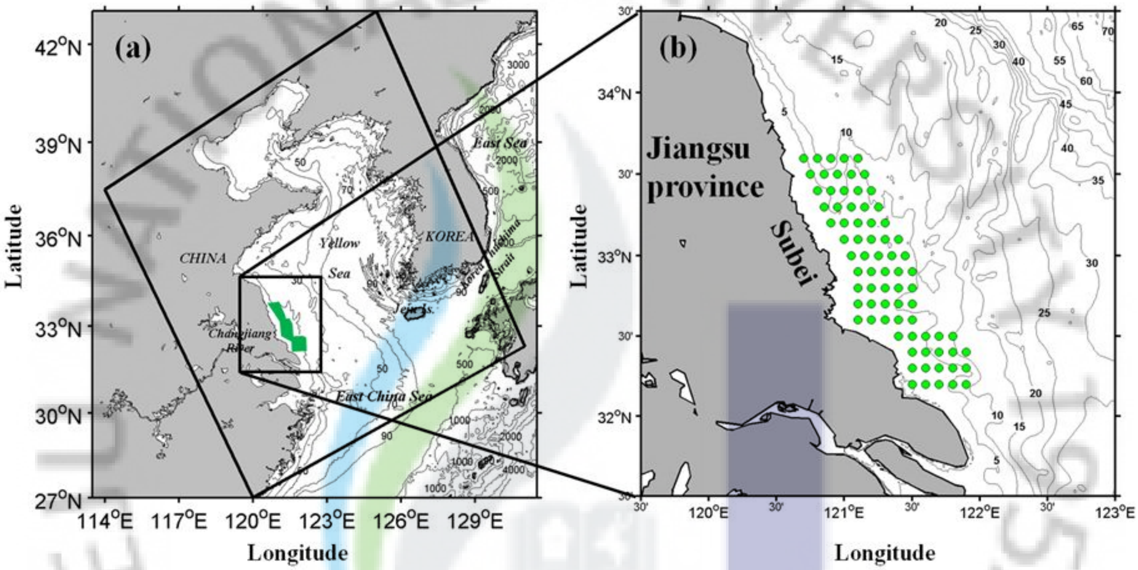

Fig. 2. Model domain and bottom topography (m). Rotated rectangular with single line denotes model domain (a) and green dots in the figure indicate the positions of the model particle in the areas of the northern Changjiang River (b).

2.3 Particle tracking experiments

The particles are tracked through the process that integrates 3D velocity fields calculated from ROMS. A fourth-order Runge-Kutta scheme is used for the integration with a model time step. As shown in Fig. 1, 75 particles per day were continuously released at the northern region of the Changjiang river as suggested by Liu et al. (2009), from April 20 to May 10, 2008. The released time is based on the harvesting period of seaweed aquaculture (Liu et al., 2009; Hu et al., 2010). All particles were released at the surface layer (top sigma level) and they were set to migrate along the surface layer (no vertical movement). Since the particles were set to translocate along the surface layer, they are not influenced by the turbulent mixing during the migration process.

3. Results

3.1 Comparison of the model results and satellite-observed data

Model results generally show a good agreement with the observed green tide distribution (Fig. 3). On 20th of May, the observed green tide was found at near 34.5° N as small green patches (Fig. 3a). Below them, the dark blue color represents the suspended sediment rich region. Both algae and sediments are suspended in water and show higher reflectance at NDVI (Normalized Difference Vegetation Index), which makes difficult in detecting green algae in this area (Hu and He, 2008).

Model results show that the particles are distributed along the Jiangsu coastline initially and then they started to move into the center of the YS. The distribution of the green patches at 35°N is quite well simulated in the model (Fig. 3e). Ten days later, the green patches moved into the center of the YS and widely spread in the YS (Fig. 3b). Actually, the patch of green tide was small on 20th of May. Ten days later however, it had grown rapidly covering about 1,200km^2 and impacting 40,000km^2 (Liu et al., 2009). This is the largest green patches ever reported based on satellite image analysis in 2008. Model simulation shows a similar behavior with satellite images. What are main processes controlling the generation of the massive bloom? Are these results because of the biological characteristics or the physical environmental factors? This answer will be addressed in section 3.3 and 3.4.

On 18th of June, these green patches are distributed along the coasts of the Shandong peninsula, spreading into the coast of Rizhao and Qingdao city (Fig.3c). These patches are well replicated by the model-tracked particles (Fig.3g). Sixteen days later, on 6th of July, these green tides moved northeastward along the Shandong peninsula. The modeled particles moved to the same direction as observed greentide (Figs. 3d and 3h).

From late June to early July, it is reported that a large amount of green tide moved into the coast of Qingdao (China Ocean News, 2008) and those distributions also are seen in satellite images. The simulated particles are not only capturing general pattern of the green tide movement but also replicating the location of green patches. This result clearly suggests that the northern parts of Changjiang river, near the Jiangsu province is a possible source of the green algae bloom in 2008 as reported in Ye et al., (2008), Liu et al., (2009) and Hu et al., (2010).

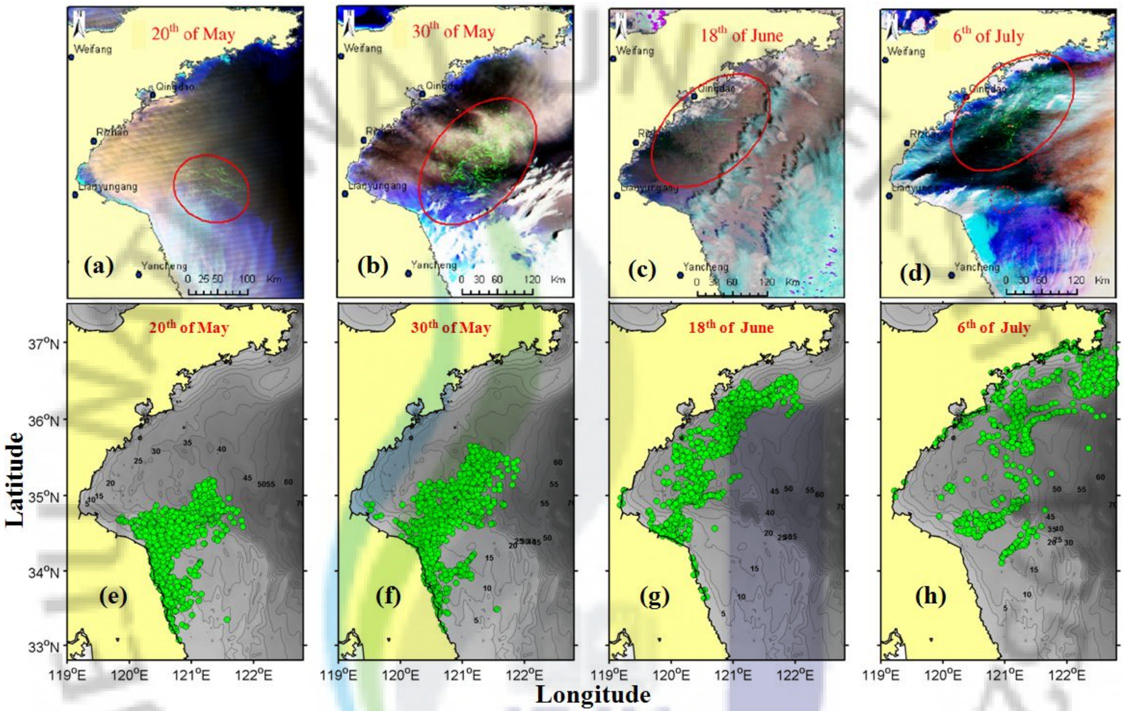

Fig. 3. Comparison of observed satellite image (a-d) (MODIS, NASA data distribution system, http://ocean-color.gsfc.nasa.gov; adopted from Liu et al., 2009) and simulated green tide distribution (e-h). Gray color (e-h) denotes depth (m). Note that simulated particles are accumulated particles released from 20th of April to 10th of May.

3.2 Spatial distribution of surface currents in the western YS.

Figs. 4a to 4e display the spatial distributions of the simulated 10-day mean surface currents from 1st of May to 30th of June in 2008. The calculated current pattern of the YS generally coincides with the previous result (Naimie et al., 2001). The most prominent feature is the northward flow from north of the Changjiang river to the northern YS although it varies with its speed and direction in region to region due to the topographic effect and local wind distribution. In northern regions of the Changjiang river mouth, along the coast of Jiangsu province, the current flows northwestward along the coastline until they meet the curved coastline near 34.5°N.

Then, these currents are diverged into three currents which are directed northwestward, northward and northeastward respectively. Firstly, the northwestward current flows along the coastline changing its direction clockwise near Lianyungang. Then it passes by the Qingdao coast and eventually moves to the northern part of the YS. Secondly, the northward current is directed almost straight forward until they encounter the Qingdao coast and then it flows to the northern part of the YS and finally merges with the first current. Lastly, northeastward current flows northward until it meets sloping bottom where the depth is deeper than 30 m and then turns anti-cyclonically. Sometimes this current becomes strong and flows eastward or southeastward even though the wind direction is almost opposite (Fig. 4b and 4c). This is because the tidal residual current flowing southeastward at the sloping bottom as discussed by Lee and Beardsely (1999) is strong enough to overcome the wind-induced current (Fig. 4f).

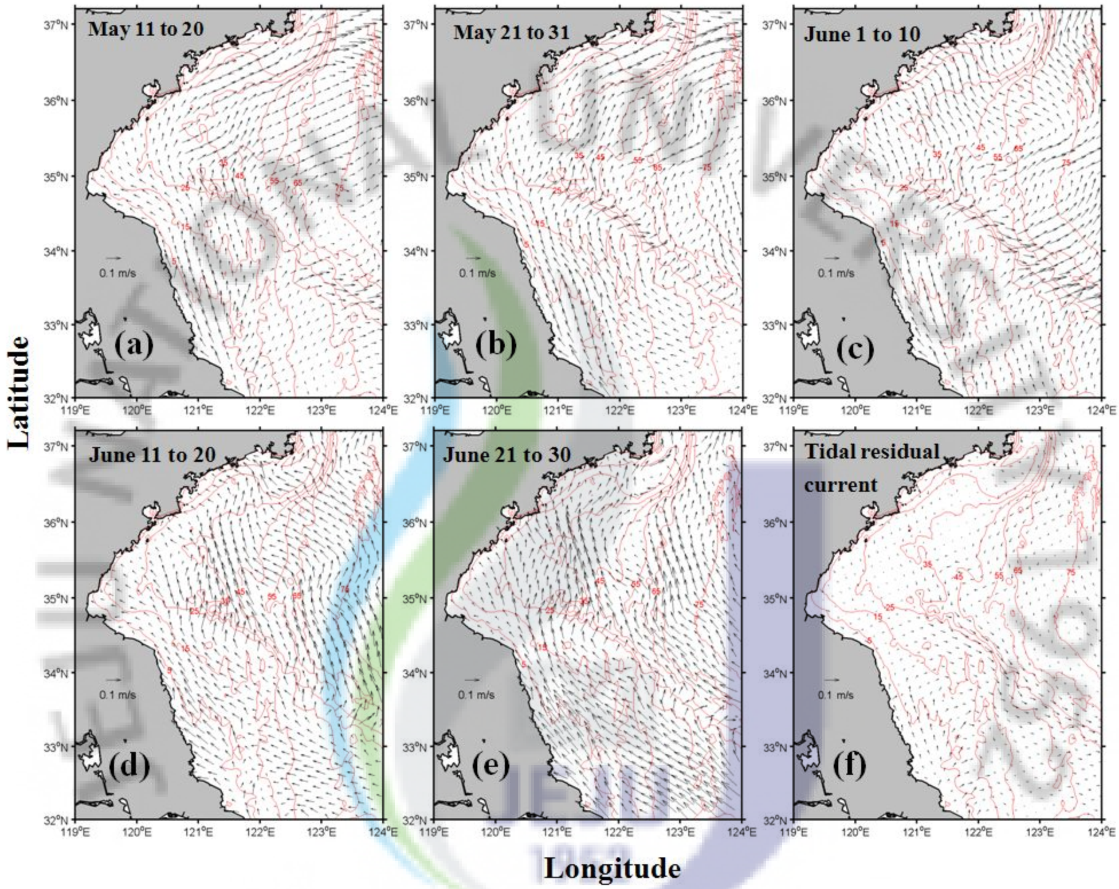

Fig. 4. Ten-day surface mean current from 11st of May to 30th of June in 2008 (a-e) and tidal residual current (f). Contour denotes depth (Contour interval is 5m).

3.3 Migration process of green tide

From 20th to 30th of May, the green patches expanded significantly (Fig. 3a and 3b). This suggests that the environmental conditions were favorable for their rapid growth. Previous researches on eight marine algal species associated with the green tide have been reported that ocean temperature plays a crucial role on controlling their growth. These species included *Enteromorpha* and *Ulva* which are closely related to *Enteromorpha prolifera*, dominant species of green tide bloom in 2008 (Liu et al., 2009). The optimal temperature ranges for the growth of the green tide are between 15°C and 20°C (Taylor et al., 2001; Largo et al., 2004). Monthly sea surface temperature (SST) from averaged daily microwave optimally interpolated data (http://www.ssmi.com/sst/microwave_oi_sst_browse.html) reveals that the temperature ranged from 13 to 16°C in May and from 16 to 20°C in June during the growth and movement period of green patches (Figs. 5c and 5g). This implies that the temperature in 2008 was optimum for their growth. Thus, the SST is thought to be responsible factor for the green tide bloom in 2008. However, the SST distributions in other years including the Advanced Very High Resolution Radiometer (hereafter, AVHRR) climatology (Casey and Cornillon, 1999) show that the temperature in 2008 was not the only optimal year for the green tide bloom (Figs. 5a, 5b, 5d, 5e, 5f and 5h). In other words, the SST between May and June is the suitable for the green tide bloom in every year. However, the SST distributions in other years including the Advanced Very High Resolution Radiometer (hereafter, AVHRR) climatology (Casey and Cornillon, 1999) show that the temperature in 2008 was not the only optimal year for the green tide bloom (Figs. 5a, 5b, 5d, 5e, 5f and 5h). In other words, the SST between May and June is the suitable for the green tide bloom in every year.

Fig. 6 compares every 10-day mean QuikSCAT wind field from 1st of May to 30th of June for 2007, 2008 and 2009. In May 2008, the wind direction around

Jiangsu province and Shandong peninsula exhibits almost same direction while its direction in 2007 and 2009 varies time to time (Figs. 6a, 6b and 6c). In June 2007 and 2008, the wind near Shandong peninsula in 2008 blew strongly westward while wind in 2009 was northward (Figs. 6d, 6e and 6f).

To investigate the effect of the different wind distribution on the migration of green tides, additional experiments for 2007 and 2009 were carried out using QuikSCAT wind field. Here, all conditions are the same as in 2008 except using 2007 and 2008 wind forcing. Figs. 7b and 7d as well as Figs. 7f and 7h compare the modeled particle distributions with satellite images, revealing that the model simulations are in good agreement with the observation. Here, since satellite images can be obtained at only cloud-free condition, the comparisons between model and satellite images are made at different time each year. However, the comparisons of particle distributions among 2007, 2008 and 2009 are made at the same time, 30th of May (Fig. 3f, Fig. 7a, Fig. 7e) and 6th of July (Fig. 3g, Fig. 7c, Fig. 7g).

From these figures, it is seen that the movements of particles were different each year. In 2007, although the particles were transported offshore from Jiangsu coast to the YS during 20th to 30th of May while in 2009 the particles stayed near the Jiangsu coast. These distributions can be explained with the wind pattern. From 11th to 20th of May in 2007, the wind direction is northeastward along the Jiangsu coast which makes the particles migrate same direction as the wind is, whereas the wind direction during the same period in 2009 is westward with fairly small magnitude leading to westward movement of particles. During the next ten days, the wind direction in 2007 is changed from northeastward to northwestward and the particles directed to the center of the YS.

The wind pattern during the same period in 2009, directed southward with a low speed and this prevents the particles from migrating northward. In June 2007, the wind direction is almost the same as in 2008 and this wind pattern possibly contributed for the particle migrating to the Shandong peninsula and eventually shows similar but less scattered distribution than those of 2008. These results also confirmed that there were blooms in Qingdao city in July 2007 (China Ocean News, 2007; Hu et al., 2010). On the other hand, both observed green patches and model tracked particles in 2009 were transported offshore to the center of the YS. This is because the wind direction in June 2009 is farther northward or northeastward than in 2008, which is enable to move the particles northeastward or eastward.

In 2007 and 2009, the observed green patches are distributed in the middle between coast of Jiangsu province and Qingdao, though the distributions in 2009 show wider than those of 2007. By contrast, the observed green patches in 2008 are much widely distributed and located closer to the coast of Qingdao (Fig. 3c). The calculated particles also show a similar pattern (Fig. 3g). Finally this distribution of green patches lead to a massive bloom in Qingdao coast after next ten days. Therefore these results demonstrate that the wind pattern plays a key role controlling the movement of green tide in each year.

In order to analyze the detailed process of particle movement, one particle which represents an average pathway of each year's total particle movement was chosen and tracked for the study period (Fig. 8). Among three years, all the selected particles move northward until they encounter the sloping side. And then both 2007 and 2008 show similar route migrating northward while the particle track in 2009 shows northeastward movement. With selected particles, zonal and meridional translocation distances were calculated during their migration and they were compared with the wind stress component at each of their translocation point (Figs. 9-11). In the inner shelf where the water depth is shallow and friction is large, the current responds almost instantaneously to local wind stress (Figs. 9-11, yellow shade boxes). As a result, particles move in the same direction as the wind until they reach the sloping bottom. When they reached the sloping bottom where the depth is deep enough to be affected by the Ekman flow (Figs. 9c, 10c and 11c), their translocation distances still do not proportionally increase/decrease with respect to the increasing/decreasing magnitude of the each wind component (Figs. 9-11, blue shade boxes). This is because the tidal residual current discussed in section 3.2 is dominant in this region. After the particles passed the sloping area (side) (Figs. 9-11, red shade boxes), their migration process is effected by wind (the Ekman flow).

Throughout analyzing the particle tracking information, one can see that the current in the study region is affected by various factors such as the Ekman flow, topographic effect and tidal rectification flow. Although there are various factors which are affecting the particles' migration process, the wind forcing plays a crucial role to determine each year's particle distribution. It is also noteworthy that the sea surface temperature is showing some variations during their migration. And it will be discussed in detail by following section.

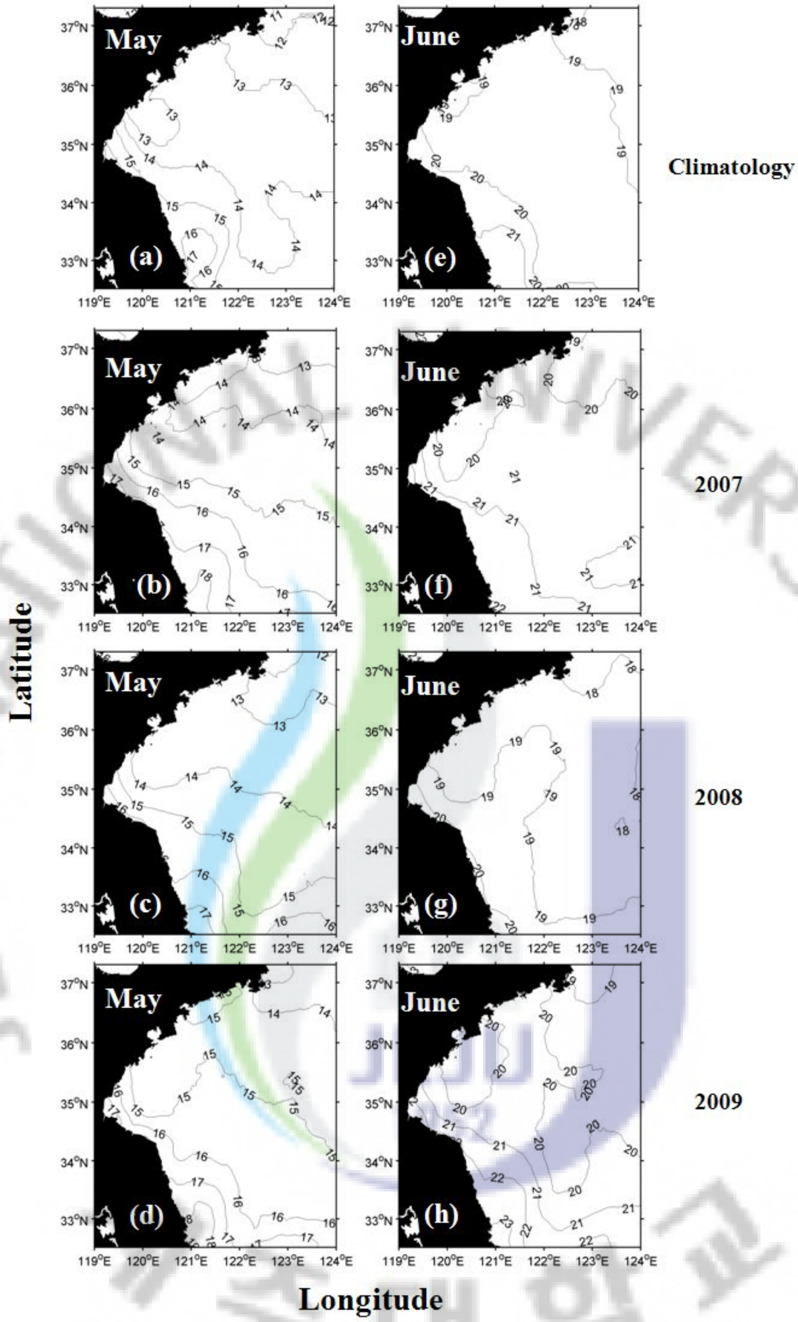

Fig. 5. Monthly SST(°C) averaged in May (a-d) and June (e-h) for climatology (a, e), 2007 (b, f), 2008 (c, g), 2009 (d, h). Climatology data from AVHRR 1985-1997, (Casey and Cornillon, 1999) and 2007-2009 data from microwave optimal interpolated data (http://www.ssmi.com/sst/microwave_oi_sst_browse.html).

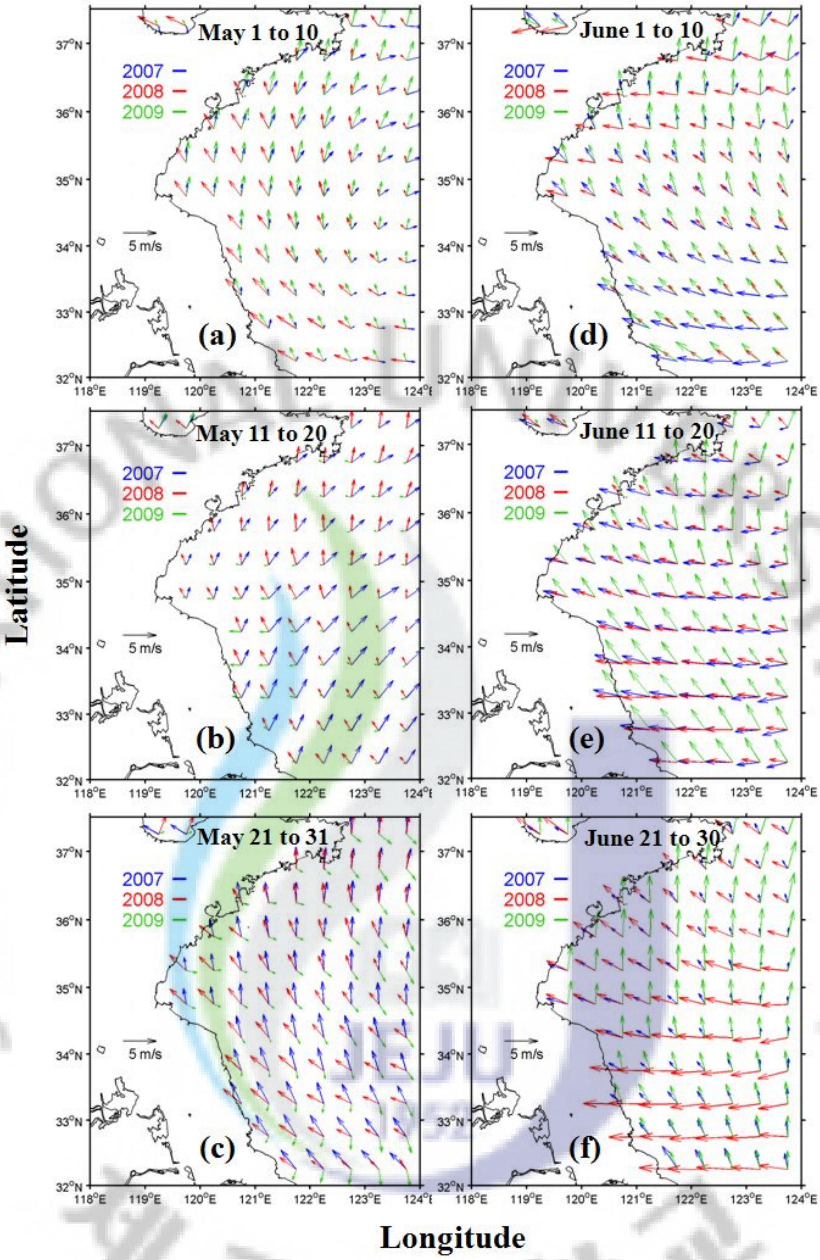

Fig. 6. Ten-day QuikSCAT mean wind speed vectors between 1st of May and 30th of June. Blue, red and black indicate 2007, 2008 and 2009 respectively (Data source : http://www.ifremer.fr/cersat/en/data/download/gridded/mwfqscat.htm)

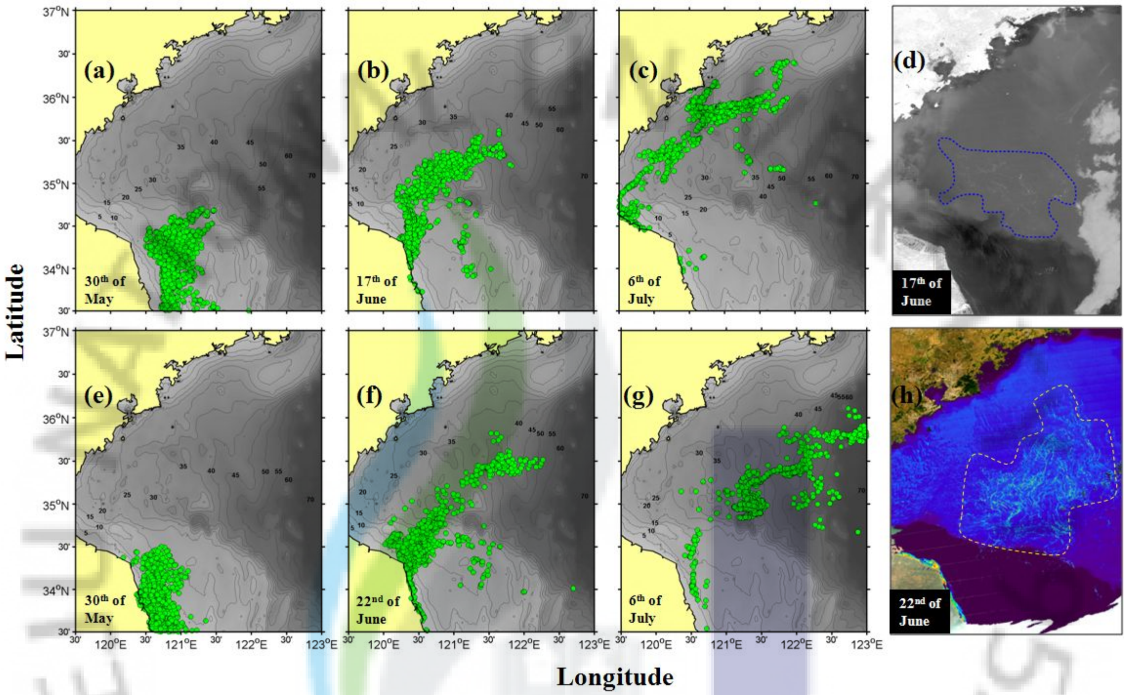

Fig. 7. Distributions of accumulated model particles during 20th of May to 6th of July in 2007 (a, b, c), 2009 (e, f, g). Gray color (a-c, e-g) denotes depth(m). Observed greenpatches also plotted in 2007 (d) and 2009 (h) for comparison.

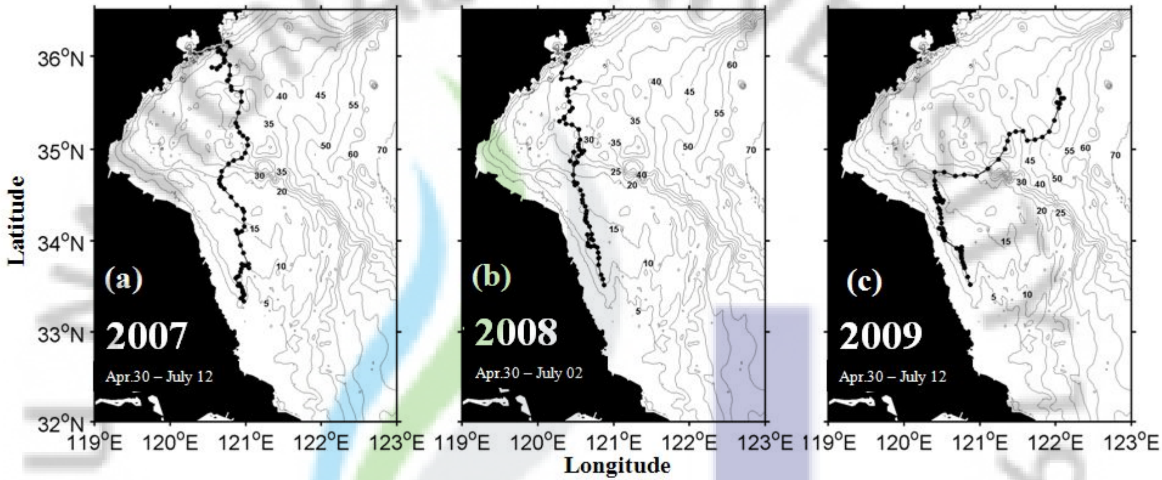

Fig. 8. Foot print of selected Lagrangian particle trajectories each year (color and contour denotes depth. Contour interval 5m)

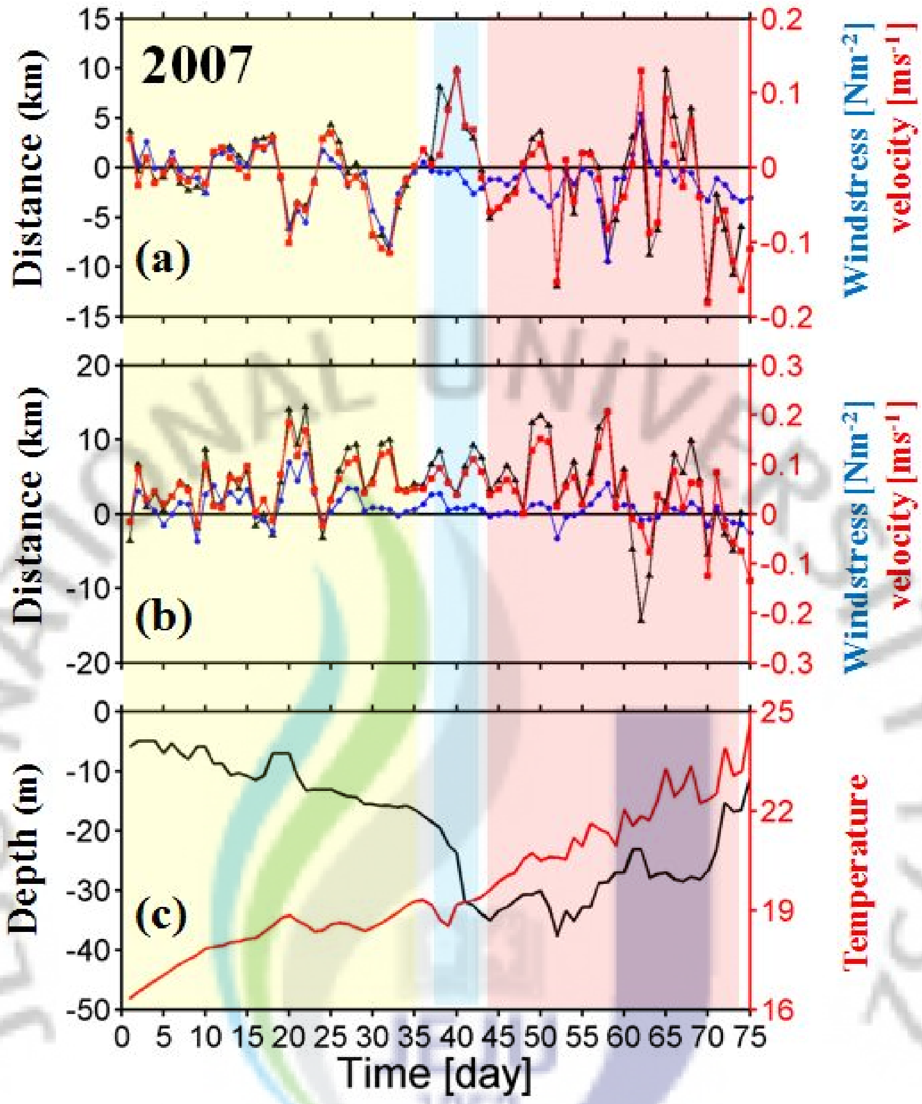

Fig. 9. Particle information along the track with zonal component (a) of distance (black), current (red) and wind stress (blue), meridional component (b) of distance (black), current (red) and wind stress (blue) and depth (black) with temperature (red) along the particle track (c) in 2007.

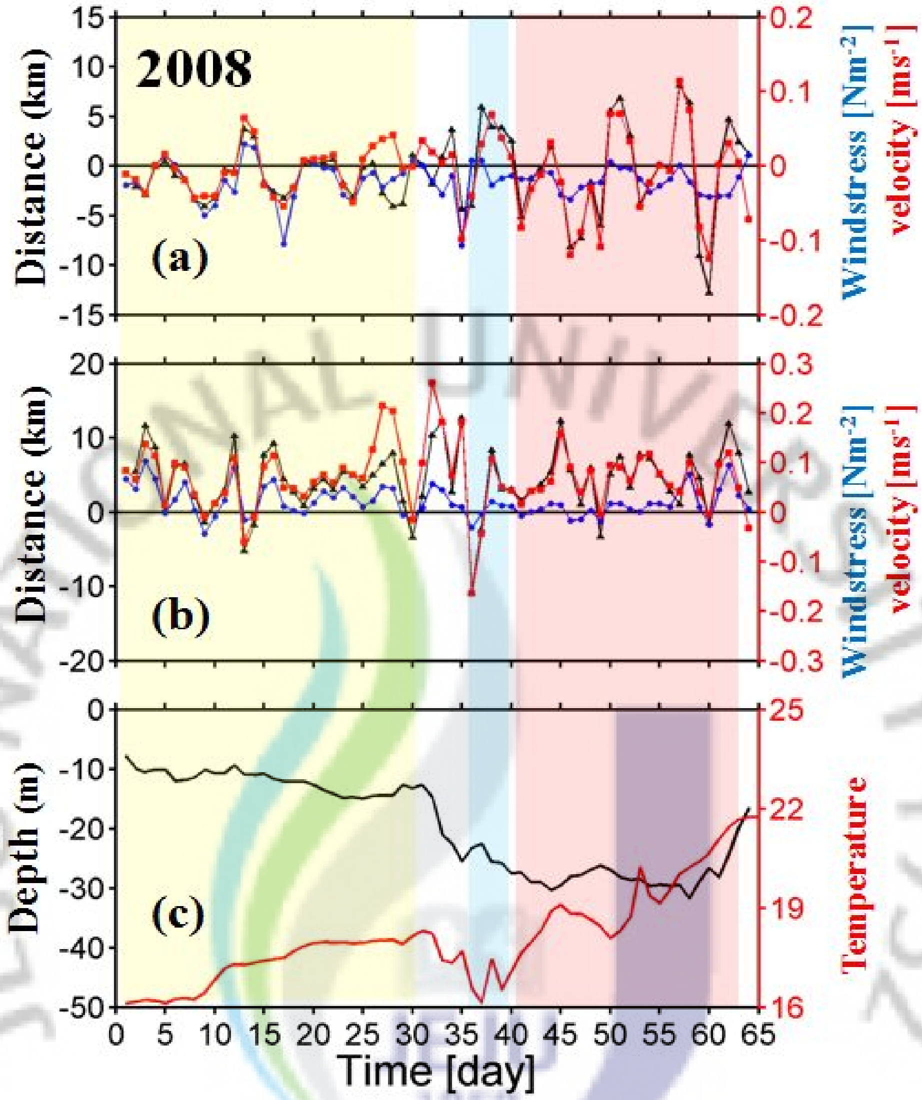

Fig. 10. Same as Fig. 9 except for 2008.

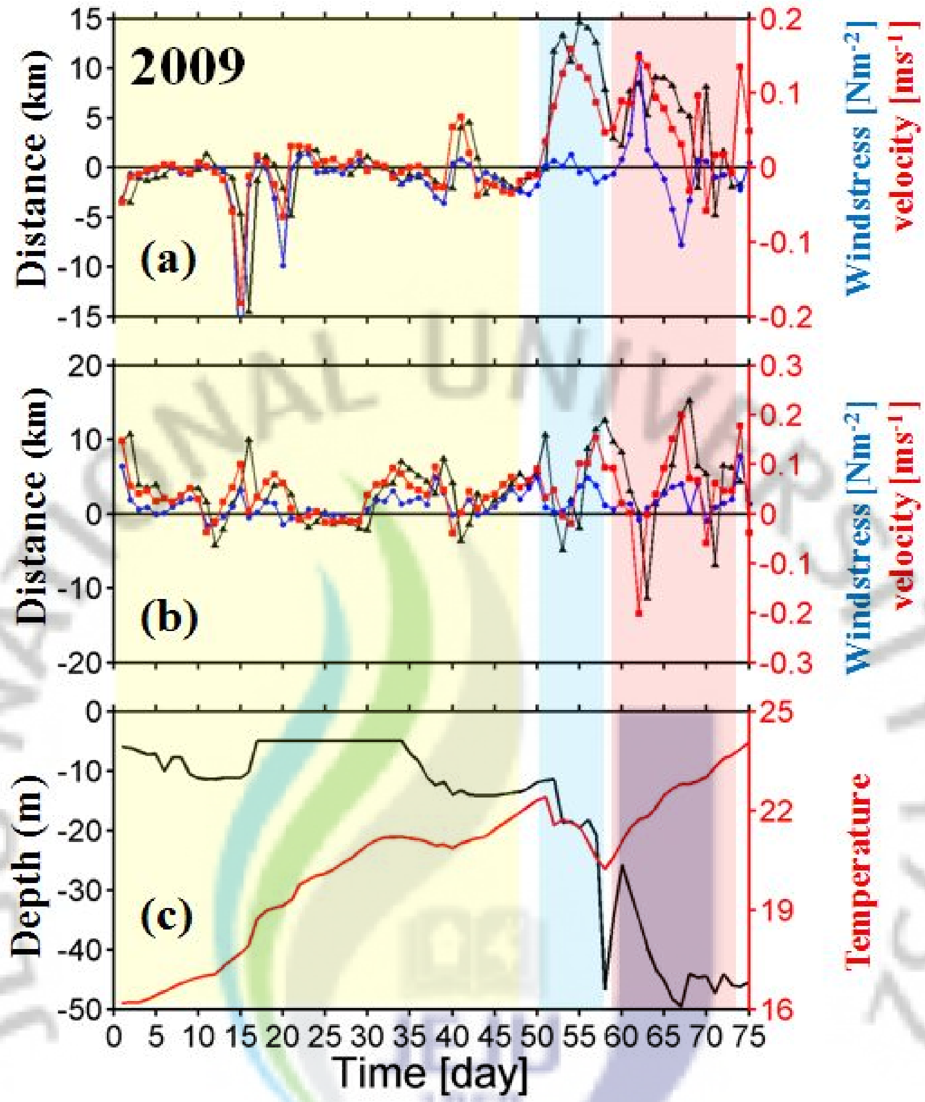

Fig. 11. Same as Fig. 9 except for 2009.

3.4 Nutrient supply by upwelling

The temperature along the particle track (Figs. 9c, 10c and 11c) tends to increase as time goes on mainly due to the increasing heat transfer from the atmosphere, satisfying which allows to reach the optimal temperature for growth and germination of the green tide. During the life span of each particle, an interesting feature was found when it migrated to the sloping bottom (Figs. 9c, 10c and 11c, blue shading boxes). The temperature suddenly dropped at the sloping bottom and increased again as it migrated farther. Considering the wind stress, it does not seem to relate with the wind induced mixing (Figs. 9-11).

A possible reason to produce this type of cooling is upwelling which seems to be caused by the tidal forcing. Lu et al. (2009) reported the upwelling mechanism in the YS. They suggested that there are two processes which generate surface cold patch. First, tidal mixing front induces the upwelling which supplies cold water from the deep layer to the surface. Second, tidal mixing itself can stir the bottom water upward and homogenize the water column vertically resulting in the surface cooling. In their numerical model, the upwelling region was located between the Jiangsu coast and the western YS (See Lu et al., 2009, Fig. 9a). In our model, we also found strong upward vertical velocity at the same place on 26^{th} of May in 2008 (Fig.12). Although this upwelling was not enough strong to destroy the thermocline, it implies that the upwelling works as a possible nutrient supplier for the green tide bloom. As we discussed in 3.3, the SST was not the crucial factor for the largest green tide expansion between 20^{th} and 30^{th} of May in 2008. Here, the nutrient supply by upwelling during the largest bloom period can explain the expansion of the green patches.

Zhu and Ivensen (1990) and Zhou et al. (2008) suggested that there is an anchovy rich region around 120-121°E longitude and 35°N latitude implying this area is a nutrient rich region (Fig. 13). Their researches also support our hypothesis that this upwelling is an important nutrient source for the green tide bloom. The generation of the cooling induced by upwelling occurs only when it is before/after the spring tide and there is a stratification in the ocean. Therefore, it is not easy to get a satellite image which satisfy both conditions with cloud free. A clear SST image which is taken from NOAA AVHRR on 23rd of July in 1997 supports that this area is an upwelling region (Fig.14). Note that this cooling seems to be caused by the spring tide (Moon's age 19 day). Here the tracked particles in each year were also plotted in the SST image. All the particles passed this region implying that the green tide from 2007 to 2009 passed this upwelling region and thus they were able to be massively bloomed.

Liu et al. (2009) insisted that the nutrient supply was not the primary cause of the green tide bloom in 2008. They explained it by comparing the nitrogen content in the green tide and the possible nitrogen amount of human produced sewage in the coastal area. Hu et al. (2010) also pointed out that the nutrients and other pollutants discharged from local rivers to the YS did not show any apparent increase in 2008 analyzing the several major pollutants from Sheyang river and annual statistics of pollution level index in the YS. The previous studies are more focused on the supply of pollutants from human sewage to the river or the entire YS. Our findings for the nutrient supplying region suggest that the local upwelling also need to be considered as a possible nutrient supplier which is likely to make the green tide expand.

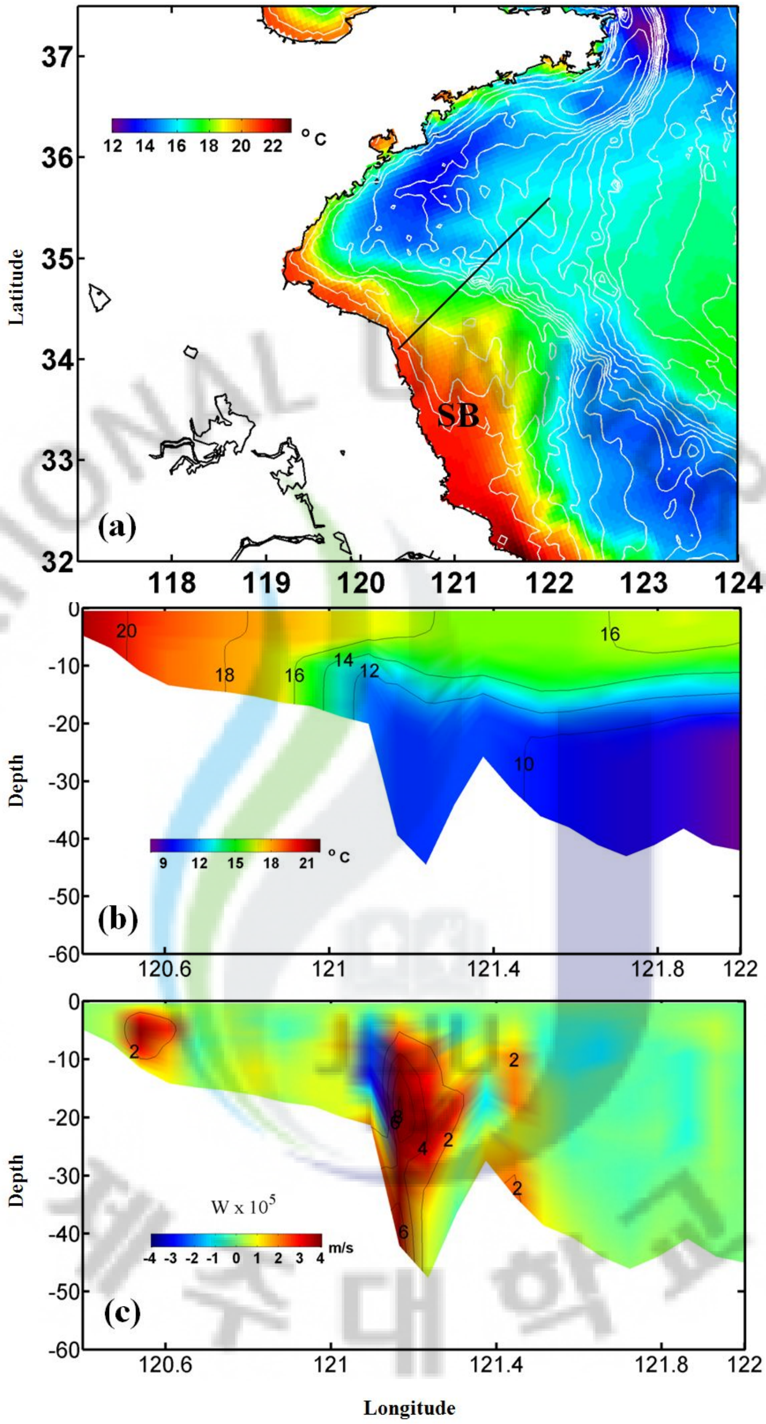

Fig. 12. Predicted SST distribution on 26th of May in 2008 from Model (white contour denotes depth) (a), vertical section of temperature at the front of Subei bank (SB) (b) and vertical section of vertical velocity at the front of SB (c).

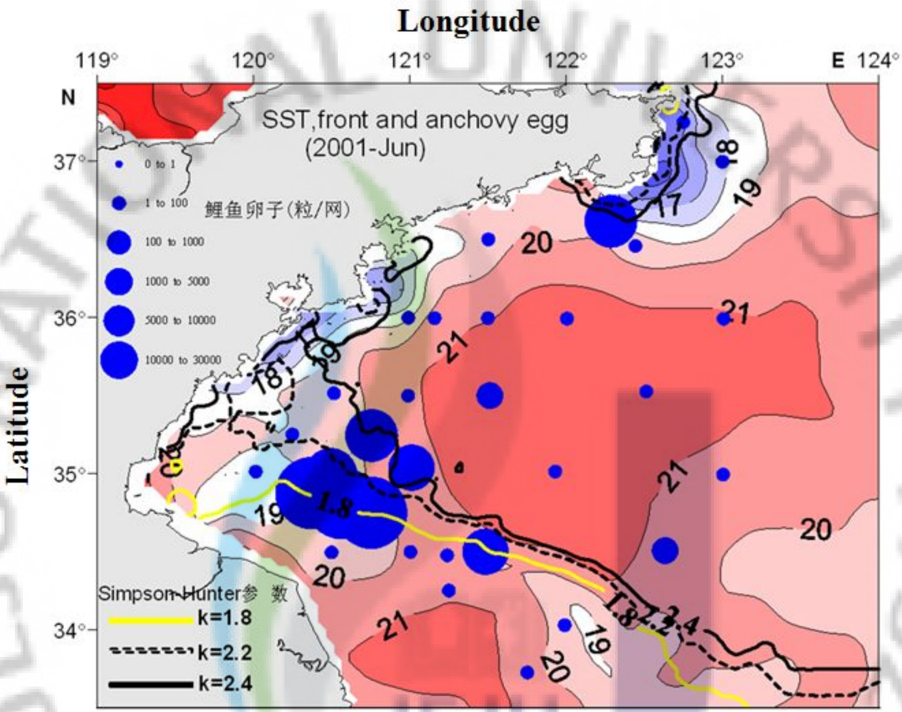

Fig. 13. Tidal front and its relation to the anchovy egg (adopted from Zhou et al, 2008).

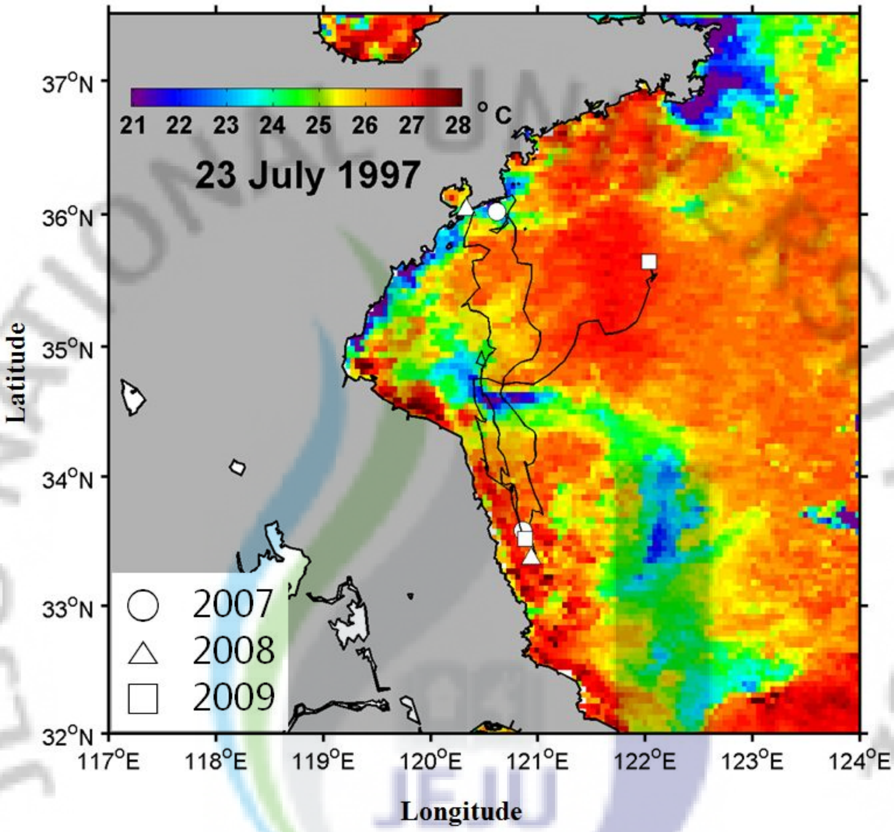

Fig. 14. SST distribution on 23th of July (Moon's age 19 day) from NOAA pathfinder AVHRR with model tracked particles each year.

3.5 Possibility of reoccurrence

The green tide had massively bloomed around Qingdao only in 2008 and it is thought to be one of the largest bloom in recorded history (Hu and He, 2008). Although the green tide was also observed in Qingdao 2007, it was negligibly small compare with 2008. As we discussed above, the wind is the most important factor for the distribution of the green tide. Then, how was the wind pattern in 2008 compare with other years? To address this question, we had made long term (from 1980 to 2009) wind vector analysis in the study region (Fig. 15).

In May 2008, the wind direction is northwestward with over 2 ms^{-1}. Since the southerly wind in May is responsible for the northward migration of the green tide, southerly wind with over 2 ms^{-1} were chosen for the last 30 years. There were about 6 more (1980, 1982, 1990, 1995, 2001, 2007) southerly winds which is larger than 2 ms^{-1}. In June 2008, the wind direction is westward with over 2 ms^{-1} and westward wind were 4 (1985, 1999, 2002, 2007) during the past 30 years. Only 2007 is the unique year that shows similar wind pattern satisfying both months as the wind in 2008. In other words, the wind in 2008 seems to be particular. Therefore, there is low potential that the Qingdao event will occur.

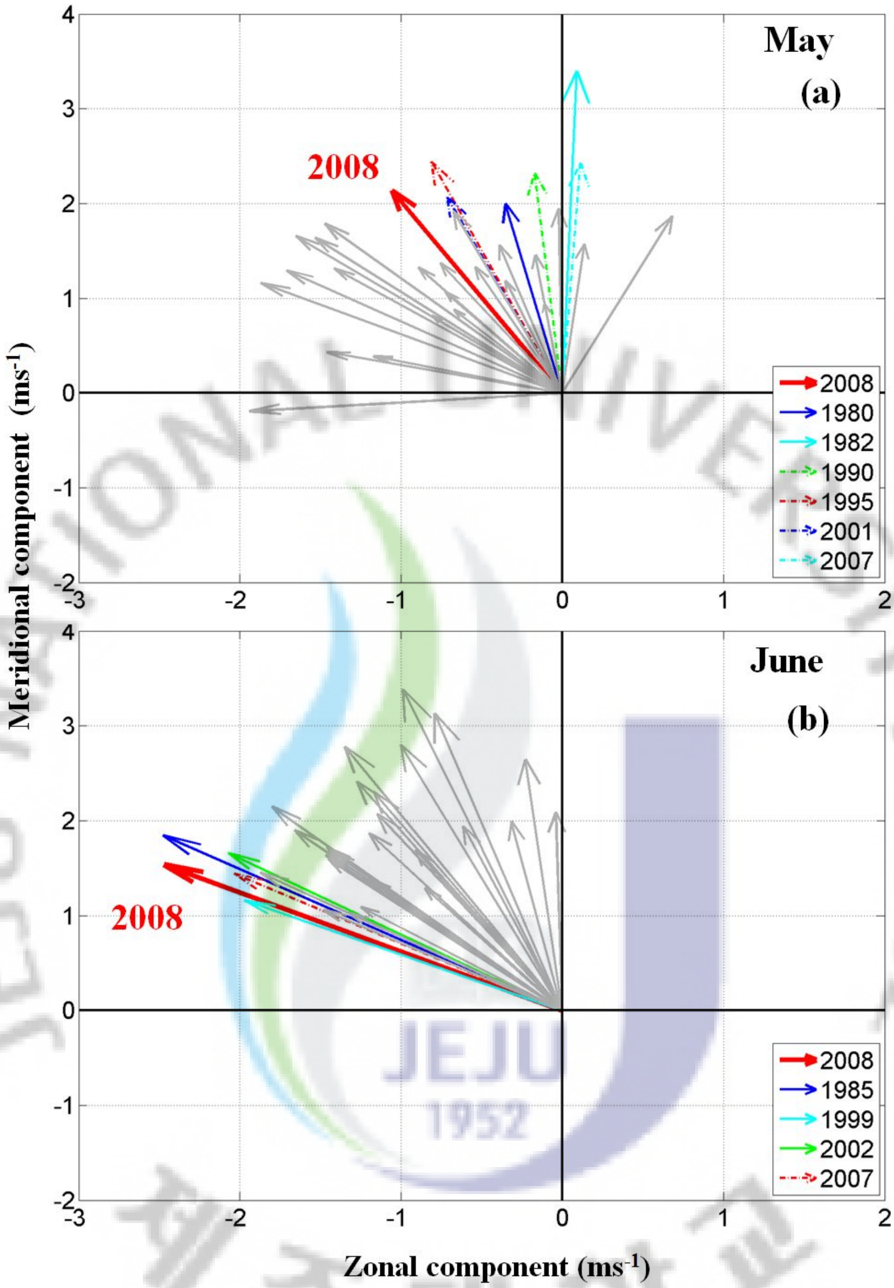

Fig. 15. Monthly averaged wind vector of research area (N 34-37 E 119-123) on May (a) and June (b) from 1980-2009. Northward vectors larger than 2 ms^{-1} in May and westward vectors larger than 2 ms^{-1} in June plotted with color and dotted line.

4. Discussion and conclusion

The present research was conducted to find out the migration process of green tide between 2007 and 2009 using a Lagrangian particle-tracking experiment. 75 particles per day were continuously released in the coast of Jiangsu province where the possible source of the green tide from 25th of April to 10th of May in 2008. Although the particles in the model were not considered the biological process such as germination, sinking and decaying, the model result was well simulated the observed green patches distribution suggesting some important features.

Simulated particle transporting in 2008 and other years represent that the Jiangsu coast is the strong possible source region. This region seems to be responsible for the recent green tide boom as suggested by Ye et al. (2008), Liu et al. (2009), and Hu et al. (2010).

Wind forcing plays a role in determining the spatial and temporal distributions of the green tide. In 2008 south-easterly wind in May is responsible for the offshore movement of the green tide and easterly wind in June plays a critical role for the green patches to migrate to the Qingdao coast. Throughout long term wind vector analysis, we found that the Qingdao event is caused by particular wind pattern. Therefore, there are low potentials for the Qingdao event occur again in the future.

Analysis of the horizontal monthly SST revealed that the temperature between May and June is in the optimum temperature range for the growth and germination of the green tide. Therefore the ocean temperature which was previously known to be the crucial factor for the green tide bloom is not a main cause of the recent green tide bloom.

An upwelling region between the Subei bank and the center of the YS seems to provide a favorable condition for the green tide bloom as a possible nutrient supplier. Tidally induced upwelling is bringing the nutrient to the sea surface and this process is well activated when it is near the spring tide. Therefore, if the green tide migrates up to this region near the spring tide, it is believed that the green tide may massively bloom.

In this paper, we elucidated the observed green patches using a 3D numerical model in order to find out the original source of the recent algal bloom, possible nutrient supplier and its migration process. The particle tracking analysis shows wind and tidal forcing are likely to be essential not only understanding and predicting the spatial and temporal variations in distribution of green patches but also finding a possible nutrient source area. The analysis also suggests that under favorable oceanographic conditions such as current, nutrient, SST and wind, these green-tides may transport again to the Shandong peninsula, near Qingdao city in future years.

Reference

Banas, N.S., MacCready, P., Hickey, B.M., 2008. The Columbia River plume as cross-shelf exporter and along - shelf barrier. *Continental Shelf Research*, this issue, doi:10.1016/j.csr.2008.03.011.

Barnier, B., L. Siefridt, and P. Marchesiello, 1995. Thermal forcing for a global ocean circulation model using a three-year climatology of ECMWF analyses. *J.Mar.Sys*.,6,363-380.

Blumberg, A.F., Mellor, G.L., 1987. A description of a three dimensional coastal ocean circulation model. In: Heaps, N. (Ed.), *Three-Dimensional Coastal Ocean Models*,Vol.4.American Geophysical Union, Washington, D.C.

Casey, K.S., Cornillon, P., 1999. A comparison of satellite and in situ based sea surface temperature climatologies. *JournalofClimate*12,1848-1863.

Chapman, D. C., 1985: Numerical treatment of cross-shelf open boundaries in a barotropic ocean model. *J.Phys.Oceanogr*.,15,1060-1075.

China Ocean News, 2007., <http://epaper.oceanol.com/zghyb/20070720/index.htm>.

China Ocean News, 2008., <http://epaper.oceanol.com/zghyb/20080822/index.htm>.

China daily, 2009., <http://www.chinadaily.com.cn/china/2009-06/13/content_8281573.htm.>

Flather, R. A., 1976: A tidal model of the northwest European continental shelf. *Mem.Soc.Roy, Sci.Liege*., 6, 141-164

Frederik Phycological Research 2009; 57:147-151

Haidvogel, D. B., A. Beckmann, and K. S. Hedstrom, 1991. Dynamical simulations of filament formation and evolution in the coastal transition zone. *J.Geophys.Res*., 96, 15017-15040.

Hu, C., and M.-X. He., 2008. Origin and offshore extent of floating algae in Olympic sailing area, Eos Trans. AGU, 89(33), 302-303.

Hu, C., D. Li, C. Chen, J. Ge, F. E. Muller-Karger, J. Liu, F. Yu, and M.-X. He (2010), On the recurrent Ulva prolifera blooms in the Yellow Sea and East China Sea, *J.Geophys.Res*., 115, C05017, doi:10.1029/2009JC005561

Egbert, G., Erofeeva, N., 2002. Efficient inverse modeling of barotropic ocean tides. *Journal of Atmospheric and Oceanic Technology* 19, N2

Egbert, G., Bennett, A., Foreman, M., 1994. TOPEX/Poseidon tides estimated using a global inverse model. *Journal of Geophysical Research*99, 24, 821-24, 852.

Largo, D.B., Sembrano, J., Hiraoka, M., Ohno, M., 2004. Taxonomic and ecological profile of green-tide species of Ulva (Ulvales, Chlorophyta) in central Philippines. Hydrobiologia 512, 247-253.

Liu, D., et al.(2009) World's largest macroalgal bloom caused by expandsion of seaweed aquaculture, *Marine pollution Bulletin.*

Lu, X., F. Qiao, C. Xia, et al. (2009), *Cont.ShlfRes.*,doi:10.1016/j.csr.2009.09.002.

MacCready, P., Banas, N.S., Hickey, B.M., Dever, E.P., Liu, Y., 2008. A model study of tide-and wind-induced mixing in the Columbia River estuary and plume. *Continental Shelf Research*, this issue, doi:10.1016/j.csr.2008.03.015

J.-H. Moon, I.-C. Pang, J.-Y. Yang, W.-D. Yoon, 2010. Behavior of the giant jellyfish Nemopilema nomurai in the East China Sea and East/Japan Sea during the summer of 2005: A numerical model approach using a particle-tracking experiment, *J.Mar.Syst.*, doi:10.1016/j.jmarsys.2009.10.015

Naimie, C.E., Blain, C.A., Lynch, D.R., 2001. Seasonal mean circulation in the Yellow Sea - a model generated climatology. *Continental Shelf Research* 21, 667-695.

Seo, S.-N., 2008. Digital 30sec Gridded Bathymetric Data of Korea Marginal Seas - KorBathy30s (in Korean with English abstract). *J.Korean Soc. of Coastal and Ocean Eng.*, 20(1), 110-120.

Stephens, C., J. I. Antonov, T. p. Boyer, M. E. Conkright, R. A. Locamini, T. D. O'Brien, H. E. Garcia, 2002: *World Ocean Atlas, Volume 1: Temperature.* S. Levitus, Ed., NOAA Atlas NESDIS 49, U.S. Government Printing Office, Wash., D. C., 167., CD-ROMS.

Taylor, R., Fletcher, R.L., Raven, J.A., 2001. Preliminary studies on the growth of selected green-tide algae in laboratory cultureL effects of irradiance, temperature, salinity and nutrients on growth rate. Botanica marina 44, 327-336.

Umlauf,. L., Burchard, H., 2003. A generic length-scale eqyation for geophysical turbulence models. Journal of Marine Research 61, 235-265

Warner, J. C., C. R. Sherwood, B. Butman, H. Arango, and R.P. Signell (2005a), Performance of four turbulence closure models implemented using a generic length scale method, *OceanModell.*, 8, 81-113

Warner, J.C., Geyer, W.R., Lerczak, J.A., (2005b). Numerical modeling of an estuary: a comprehensive skill assessment. *Journal of Geophysical Reserch* C5, 2004JC002666.

Ye N., Zhuang Z., Jin X., Wang X., Zhang X., Li D., Wang H., Mao H., Jiang Z., Li B., Xue Z., 2008. China is on the track tackling Enteromorpha spp forming green tide, *Nature Precedings*.Hdl:10101/npre.2008.2352.1

Zhou F., Huang D. J., Su J. L., Zhang T., Ding T., Zhou P. F., 2008. Observation and analysis of high tide of South northeast Yellow Sea in summer, *Ocean academic journal*.30:9-15.

Zhu, D., Iversen, S.A., 1990. Anchovy and other fish resources in the Yellow Sea and East China Sea November 1984-April 1988: fisheries investigations by R/V "Bei Dou". *Marine Fisheis Research*11,1-143 (In Chinese with English abstract)

Abstract (in Korean)

이 논문에서는 2008년 산둥반도의 남쪽에서 확장한 녹조류(가시파래)의 물리적인 이동과정을 연구하기 위하여 라그랑지안 입자 추적 실험을 사용한 3차원 수치모델(ROMS)을 수행하였다. 녹조류를 대신하는 입자의 최초 시작점은 2008년에 발생했던 녹조류 확장의 근원지로 지목되었던 양자강 북쪽에 위치한 장수성 연안으로 하였다. 모델 결과는 관측된 녹조류의 분포와 상당히 일치하는 모습을 보여주었으며 이것은 장수성 연안이 녹조류의 근원지가 될 가능성이 크다는 것을 시사한다.

녹조류의 번식 및 이동에 영향을 주는 요인을 분석한 결과, 녹조류가 2008년 산둥반도 연안의 칭다오에서 많이 발견된 이유는 바람의 영향을 많이 받았기 때문이며 녹조류의 이동에 결정적인 영향을 주는 준 요인이 바람이라는 것을 알 수 있었다. 이와 같은 결과가 다른 연도의 녹조류의 이동도 설명하는지를 확인해보기 위해 2007년과 2009년의 바람을 이용하여 추가적인 입자실험을 수행하였고 관측 결과와 유사한 모델 결과를 얻었다. 바람장 및 모델 결과 분석을 통하여 남풍 계열의 바람은 녹조류를 장수성 연안으로부터 외해로 이동시키며 동풍 계열의 바람은 녹조류를 산둥반도 연안으로 이동시킴을 알 수 있었다.

입자 궤적의 이동경로 분석을 통하여 녹조류의 근원지로 생각되는 장수성 연안과 녹조류의 확장이 일어난 산동반도 연안 사이에 용승이 잘 일어나는 지역이 발견되었다. 이 지역은 최근 들어 장수성 연안에서 산둥반도 주변으로 이동하는 녹조류에게 영양염 공급을 하는 역할을 하고 있는 것으로 보인다.

주요어 : 녹조류, 입자 추적 실험, 바람, 황해, 용승, 영양염 공급

Acknowledgement

First of all, I wish to express my gratitude to my advisor, Professor Ig-Chan Pang for his physical insight and wonderful encouragement during this study. I am also most grateful to his numerous guidances to my life as a mentor. I wish to record my appreciation to the Professor Il-Ju Moon for his valuable guidance of this study. Thanks are also due to Dr. Ki-Ryong Kang for his useful comments and corrections of this study. I am also indebted to Dr. Chan-Joo Jang, who gave me useful comments for this study and cheerful messages during the study period.

I am very grateful for the Dr. Jae-Hong Moon, who gave me lots of guidances when I first started the numerical ocean model. It is a pleasure to acknowledge the passion of taught and numerous instructions from Professor Dong-Kuk Paeng, who is a leader of the English Bible study group. I thank colleagues in marine meteorology laboratory, Eo-Su, Sang-Myung, Sung-Hun, Min-Young, Kwang-Suk, Chul-Min, Young-Yoon, Myung-Sun, Yu-Sun and Yu-Jung. Thanks are also due to Jae-In, Kyung-Hun, Kyoung-Hee, Chang-Soo and Sung-Jun who are alumni in our laboratory and Hyuk-Jun, Yong-Ho, Seung-Woo and Han-Sik, who are belong to the department of oceanography in Jeju National University. And a very special thanks to Mr. and Mrs. Hansen who always share their fruitful conversations and give me good advices. Especially, I want to give thanks to Louisa who always encourage me and listen to my ideas.

My gratitude goes to Ki-Hoon Kim and his wife for their cheerful messages and thoughtful treatments. I here express my more than grateful recognition to my friends, Jun-Ho, Seo-Ryong, Hyun-Ho, Young-Ju and Young-Sun, who have been encouraging me since high school. I also would like to record my gratitude to a number of individual who have given me help and encouragement over the period in which this dissertation was written.

I send my gratitude separately to my only brother who always assisted me in innumerable ways. Finally, my most sincere thanks go to my mom, who always trust and support her son for her patience, advice and love.