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Determination of Physical Processes Influencing Chl a Distribution using Remotely Sensed Images

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Abstract: In management of the Japanese scallop *Mizuhopecten yessoensis* culture, it is important to understand the phytoplankton bloom development in the coastal region of the Okhotsk Sea. Variations in food available to this benthic bivalve are a primary environmental factor affecting growth in nature. This paper determined the seasonal variability of Chlorophyll a (Chl a) at the scallop farming region in the Okhotsk Sea from 1998 to 2004 using satellite imageries. Satellite images were processed using default NASA coefficients and community-standard algorithms as implemented by Sea DAS. Spatial and temporal variation of Chl a was determined by EOF analysis. The Chl a concentration showed high seasonal and interannual variability. Peak of Chl a concentration occurred in spring followed by autumn and summer. This was evident in the Empirical Orthogonal Function (EOF) analysis. The spatial pattern of the first mode of EOF analysis of Chl a revealed intensified Chl a at the shelf and offshore areas in spring and autumn (51.8% of variance). The second mode explained 14.2% of the variance indicating enhancement of spring (April-May) Chl a pattern in the frontal area along the coast. Meanwhile, the third mode captured 9.0% of the variability demonstrating high Chl a extending seaward from the shelf area during late autumn. These seasonal variability of Chl a resulted from the variability in occurrences of physical processes associated with retreat of sea ice in spring, advection of Soya Warm Current in summer and intrusion of East Sakhalin Current in autumn.

Key words: Chl a, EOF, Okhotsk Sea, physical processes, satellite images, seasonal variability

INTRODUCTION

Aquaculture is rapidly developing in almost all regions of the world. Recently there has been an increase in demand for aquatic food from the global population, and aquaculture appears to have the potential to make a significant contribution to this growing demand. World aquaculture has grown tremendously during the last fifty years. Production of safe and quality products requires enhanced enforcement of regulations and better governance of the sector (FAO, 2006). In order to maintain aquaculture production, an understanding of resources productivity in its natural environment is therefore important. Satellite imageries, because of their broad scale coverage, cost effectiveness and high levels of precision are ideally appropriate to support environmental monitoring and assessment. Knowledge on status of its natural environment and estimates of production can be predicted and incorporated into management decisions for promoting sustainable use of the resources (Mumby *et al*., 1999; Dennison, 2008).

Aquaculture is an important sector of the Japanese coastal fishery production. The Japanese scallop, *Mizuhopecten yessoensis* (Jay), is being successfully cultivated along the shores of Hokkaido off Okhotsk Sea (Uki, 2006). This benthic community's abundance and biomass is influenced by food supply from the overlying water column. Depending on variability in environmental condition, this food supply can also be subjected to variations (Funaki *et al*., 2002).

The Okhotsk Sea experiences seasonal sea ice events. Sea ice plays an important role in the high production at the ice edge in the Okhotsk Sea in spring. Ice edge blooms contribute to the primary production over the shelf areas (Niebauer *et al*., 1995; Okunishi *et al*., 2005). Advection of Soya Warm Current (SWC) occurs in summer. The SWC carries warm and saline Japan Sea waters through the Soya Strait and flows along the Hokkaido coast as a coastal boundary current (Ebuchi *et al*., 2006). It creates a distinct front as it mixes with the cold offshore waters. Fronts are sites of major phytoplankton concentration (Bogazzi *et al*., 2005). High accumulations

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of phytoplankton have been reported to occur along frontal bands (Saraceno *et al*., 2005). Meanwhile intrusion of cold nutrient rich East Sakhalin Current (ESC) occurs in autumn. The fresh surface water is reported to carry very large amount of dissolved organic carbon which is suggested to have originated from the Amur River (Mizuta *et al*., 2003). This supports phytoplankton bloom (Ebuchi, 2006).

These abundant supplies in biomass are important as food source for the benthic community (Bourne, 2000). Studies on the spatial and temporal variability of phytoplankton in this area are important to evaluate location and magnitude of marine productivity. Variations in food supply are a primary environmental factor affecting growth in nature (Cranford *et al*., 1998). It is important to understand variations in food supply affected by these seasonal changes. The objective of this study is to clarify the seasonal variability of Chl a at the scallop farming area in the Okhotsk Sea from 1998 to 2004 using satellite imageries.

MATERIALS AND METHODS

Study area: The study was carried out within the scallop farming region along the coastal area of the Okhotsk Sea, Hokkaido, Japan where extensive culture of scallops on the sea bed is carried out (Fig. 1). One year old juveniles are released into the fishing grounds and are harvested when they are 4 years old (Uki, 2006).

SeaWiFS-Chl a concentration: The Chl a data analysed in this study were derived from the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) measurements. Daily Level 1A data from 1st January 1998 to 31st December 2004 were downloaded and processed to Level 2 geophysical products using default NASA coefficients and community-standard algorithms as implemented by SeaDAS (version 5.0) and remapped to a cylindrical projection at 1.1 km resolution. Seasonal variability of Chl a at the scallop farming region was analysed. The individual remapped images were combined to provide monthly composite images of Chl a concentrations and were subset to the geographic extent of the study area which includes the Okhotsk Sea (O'Reilly *et al*., 2000).

Empirical Orthogonal Function (EOF) analysis: The Empirical Orthogonal Function (EOF) method decomposes space and time distributed data into modes ranked by their temporal variance. This provides a compact description of their spatial-temporal variability in terms of orthogonal functions. EOF has been frequently used to study temporal and spatial patterns in geophysical data

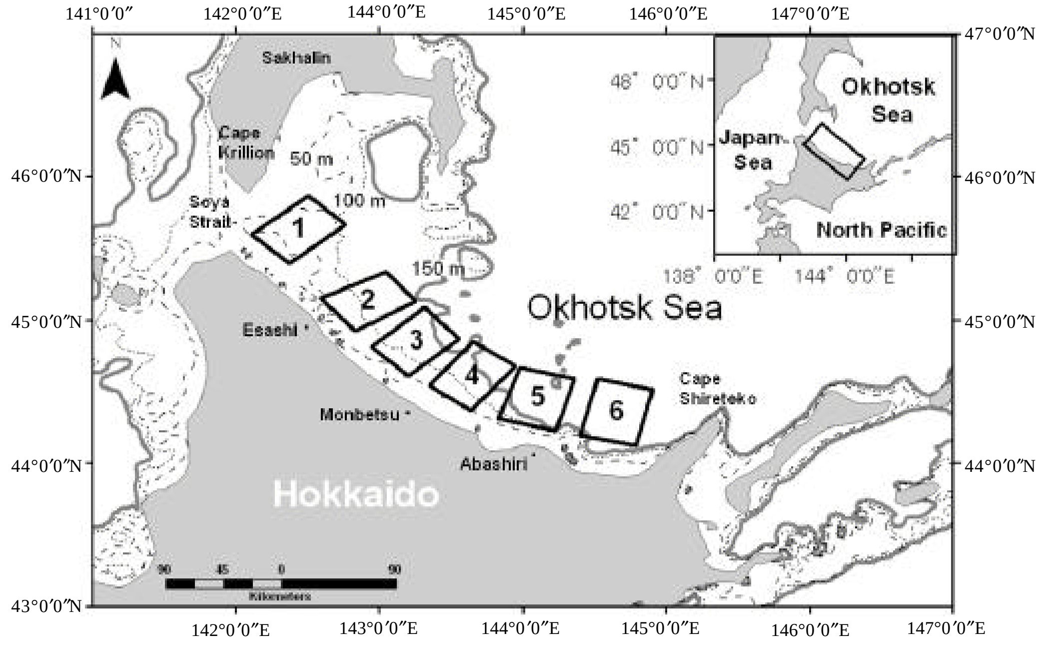

Fig. 1: The Japanese scallop farming area shown by the numbered box along the Hokkaido coast. Contours indicating depth in meters

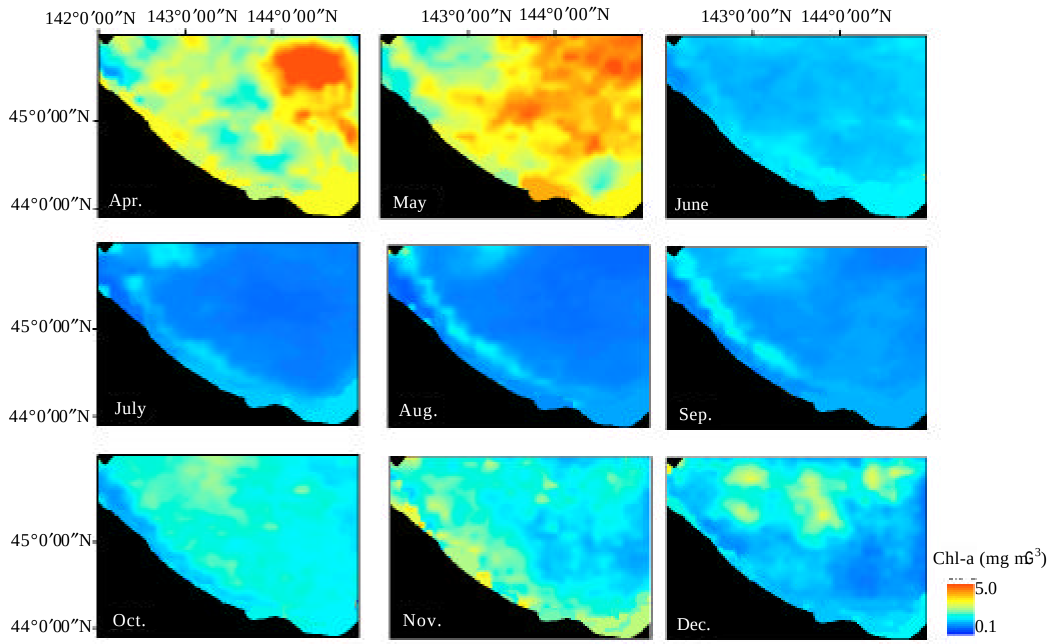

Fig. 2: Chl a mean annual cycle derived from the SeaWiFS monthly composite data

and it has been increasingly common in describing and quantifying oceanic variability (Brickley and Thomas, 2004; Otero and Siegal, 2004).

Sspatial and temporal variation of Chl a was examined from the monthly composites. Further monthly averaging over the study period produced a climatologically monthly seasonal cycle. Low light levels and/or cloud in January to March prevented examination of winter patterns and these data were excluded. To improve the spatial coverage prior to the EOF analysis, the data was interpolated using Ordinary Kriging technique. It weighs the surrounding measured values to derive a prediction for an unmeasured location.

The time series of Chl a monthly averaged images were detrended and standardized by removing the monthly mean from the time series and decomposed following the method of Polovina and Howell, (2005);

$$F(x,t)=\sum_{i=1}^{N}a(t)c_i(x) \qquad (1)$$

where, $a_i(t)$ are the principle component time series or the expansion coefficients of the spatial components $c_i(x)$. The temporal and spatial components are calculated from the eigenvectors and eigenfunctions of the covariance matrix R, where R = F'*F. This analysis results in N statistical modes, each with a vector of expansion coefficients related to the original data time series by a_i = Fc_i and a corresponding spatial component map c_i.

RESULTS AND DISCUSSION

Seasonal variability of Chl a was observed at the scallop farming area. Diversity in spatial and temporal patterns suggests that several mechanisms may control phytoplankton dynamics and productivity.

Observation of the Chl a climatology seasonal cycle indicated that the scallop farming region experiences a distinct spring bloom and a less distinct autumn bloom (Fig. 2). The seasonal variability of Chl a at the scallop farming area and its surrounding waters were evident. Interannual variability of Chl a concentration at the scallop farming region also indicated peak of Chl a in spring and autumn. In summer, Chl a was also high from 1998 to 2004, above 0.5 mg m^{-3} (Fig. 3). This variability was summarised by the EOF analysis. The first mode of the EOF analysis of Chl a explains 51.8% of the variance (Fig. 4a). The spatial pattern of the first mode reveals the intensified Chl a at the shelf and offshore areas in spring and another peak of Chl a evident in autumn. High signal occurred in the offshore areas, patches along the shelf and along the frontal area. Its amplitude function also revealed enhancement of Chl a concentration in spring

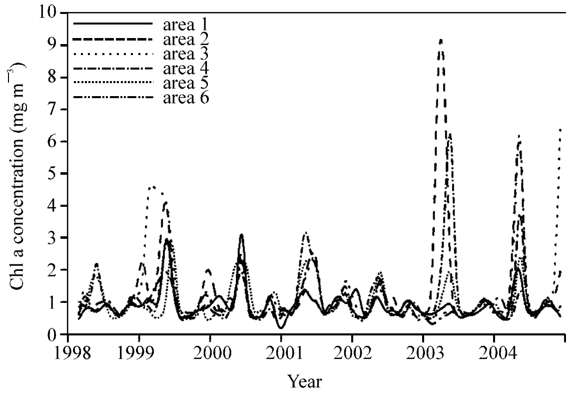

Fig. 3: Interannual variatiov of Chl a (mg m^{-3}) at the scallop farming region with highest peak in spring, a lesser in autumn followed by summer

and lesser in autumn. Strongest positive signal was observed in spring 2003 and spring 1999 and lower peak during autumn. Its associated amplitude function confirms that this mode indicates seasonal cycle of Chl a bloom (Fig. 4b). This elevated Chl a concentration in 1999 is evident in the SeaWiFS Chl a image on 1 March 1999 (Fig. 4c).

The second mode of EOF explained 14.2% of the variance (Fig. 5a). High Chl a was evident in the frontal area and lesser along the coast and offshore area. Its amplitude function is positive in spring of all years with the exception of negative signal in spring (April) 2003 (Fig. 5b). Highest positive signal was observed in April 1999 followed by May 2004, 2000 and 2002. The rest indicated minimal positive signal in May. This mode indicated enhancement of spring (April-May) Chl a pattern in the frontal area. A well developed frontal area is evident in 2004 and this contributed to increase of Chl a at the scallop farming area (Fig. 5c).

The Okhotsk Sea is among the most biologically productive regions in the world (Saitoh *et al*., 1996). According to Sorokin and Sorokin (1999), the process of ice melting in spring and rapid warming of the upper layer creates a shallow pycnocline that results in high vertical stability within the euphotic zone from the beginning of the bloom period and during all spring to summer. Availability of nutrient during this period leads directly to an increase in phytoplankton biomass.

The scallop farming region displays the highest Chl a in spring because of seasonal sea ice events in winter which plays an important role in the high production at the ice edge (Mustapha and Saitoh, 2008). High phytoplankton biomass in the scallop farming area occurs at the onset of retreat of sea ice in early spring. Phytoplankton bloom development is a common response to the spring overturn and mixing of nutrients to the surface. The vertically mixed upwelled waters bring high nutrients to the surface, as well as phytoplankton from the subthermocline to the surface (Behrenfeld and Falkowski, 1997; Yokouchi *et al*., 2000; Wang *et al*., 2005). These nutrients support phytoplankton bloom (Kasai *et al*., 1997; Tang *et al*., 2003; Findlay *et al*., 2006). This event was evident in the EOF analysis as depicted in Fig. 4.

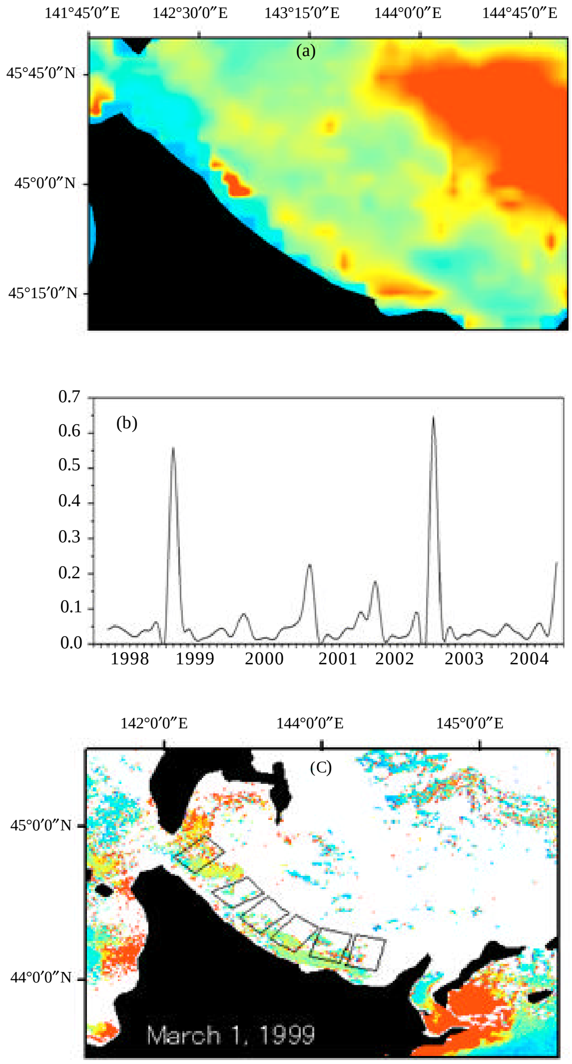

Fig. 4: (a) The spatial pattern, (b) the associated time series of Mode 1 of the EOF decomposition of the monthly image time series of Chl a (year indicates April to December with exclusion of winter, January to March) and (c) retreat of sea ice in spring (indicated by SeaWiFS chlorophyll a images on 1 March, 1999).

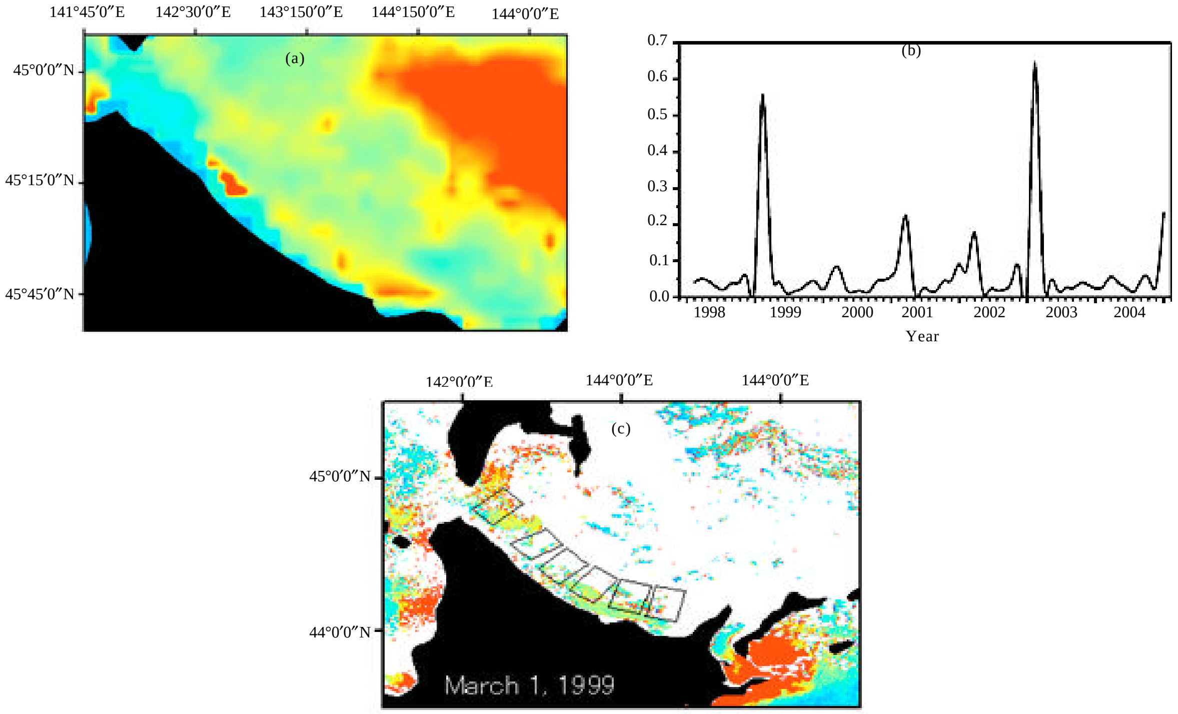

Fig. 5: (a) The spatial pattern, (b) the associated time series of Mode 2 of the EOF decomposition of the monthly image time series of Chl a (year indicates April to December with exclusion of winter, January to March) and (c) warm current in summer to early autumn (indicated by SeaWiFS chlorophyll a images on 14 May, 2004)

Meanwhile mixing between the SWC and the offshore waters of Okhotsk Sea in early spring produces relatively cold, fresh and oxygen rich water mass. Maximum advection of SWC through the Soya Straits occurs in summer. As the SWC enters the Soya Strait, a narrow belt of water mass occurs parallel to the current. This feature forms a boundary between waters with different properties, i.e between the warm Soya current and cold offshore waters. This water mass have characteristics that are different from the classes surrounding it.

This frontal system is suggested to be responsible for environmental conditions that allow enhanced phytoplankton growth in the area. The frontal area provides high biological productivity due to current shear and intense water dynamics that play important role in water mixing processes (Ohshima and Wakatsuchi, 1990). Flow of SWC is dependent on the seasonal variation of differences in sea level (Ohshima, 1994). The differences in the velocity and transport have been reported to reflect the development of the frontal area (Mustapha *et al.*, 2009). Higher positive sea level difference observed in 2004 indicates a higher inflow of SWC (Fig. 6). The well developed frontal area in 2004 (Fig. 7), resulted in the increase of Chl a as depicted in the EOF analysis (Fig. 5).

The third mode of EOF captures 9.0% of the variability. Intensified Chl a extending seaward from the shelf area off Monbetsu was evident (Fig. 6a). Negative pattern indicating lower Chl a was observed at the offshore area. Its temporal amplitude indicated high positive signal in December 1999, followed by November 2000 and November 2002. The rest indicated minimal positive signal (Fig. 6b). This mode explains late autumn condition (Fig. 6c).

The richness of the Okhotsk Sea is also partly supported by discharge from the Amur River which supplies sufficient dissolved iron to the sea. The natural environment in the Amur River basin contributes to the production of dissolved iron which is one of the elements that activates Chl a and is essential to its growth (Martin *et al.*, 1994). Strong southward intrusion of the less saline ESC which transports this rich supply of dissolved iron in autumn contributes to increase of Chl a at the coastal area. The fresh surface water is reported to have very large amount of dissolved organic carbon which supports the phytoplankton bloom during autumn

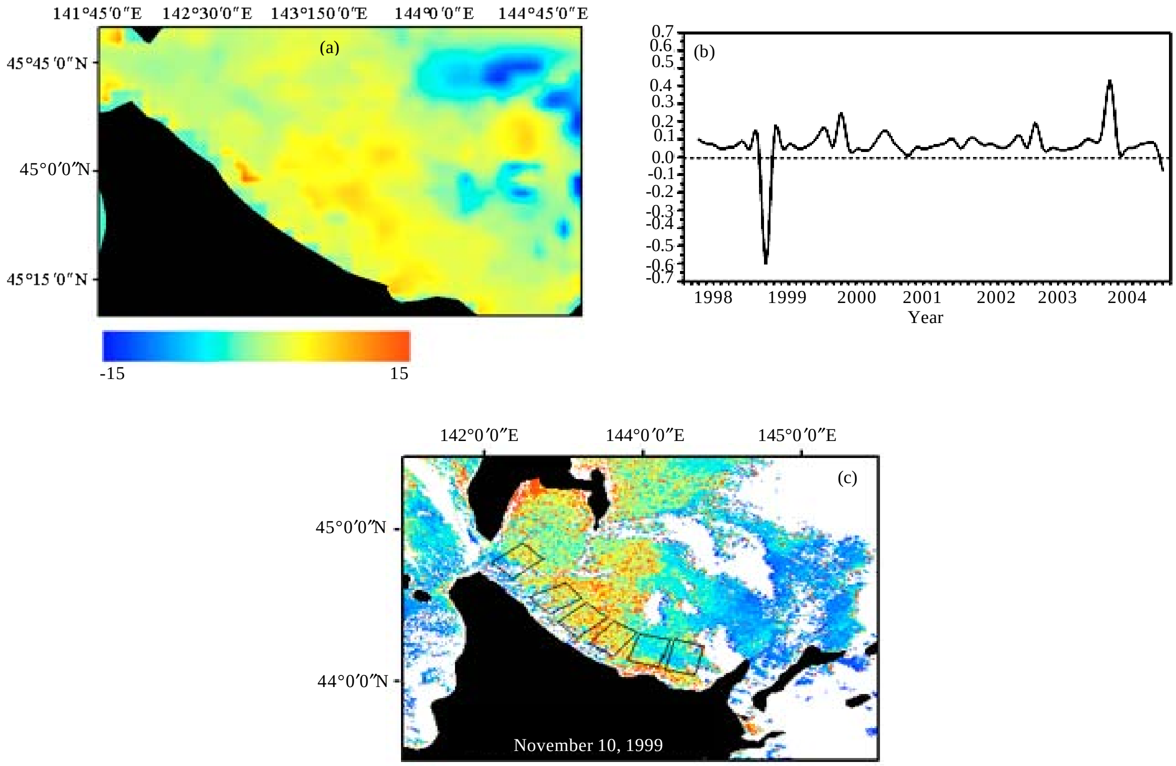

Fig. 6: (a) The spatial pattern, (b) the associated time series of Mode 3 of the EOF decomposition of the monthly image time series of Chl a (year indicates April to December with exclusion of winter, January to March) and (c) intrusion of cold, nutrient rich water in late autumn (indicated by SeaWiFS chlorophyll a images on 10 November, 1999)

of 1999 (Fig. 9) (Nakatsuka *et al.*, 2004). Intrusion of ESC occurs at the weakening of the advection of SWC from October to December. The intensity of the ESC changes seasonally (Mizuta *et al.*, 2003). Autumn intensification of the ESC affects the marine ecosystem. By December, ESC reaches the Hokkaido coast and it is accumulated and downwelled at the subsurface layers. Intensification of wind during autumn that brings nutrients from deeper water combined with downwelling of the low surface water temperature generates deep advection (Zhabin, 1999). High Chl *a* occurs in the coastal area during this season. This occurrence was evident in the EOF analysis (Fig. 8).

These events enhance the growth of phytoplankton. The geographic location and the characteristics of the south-western part of the Okhotsk Sea provide the scallop farming areas with a suitable environment for sustainable scallop production. This area is enriched by retreat of sea ice in spring, warm current in summer to early autumn and cold, nutrient rich water in late autumn.

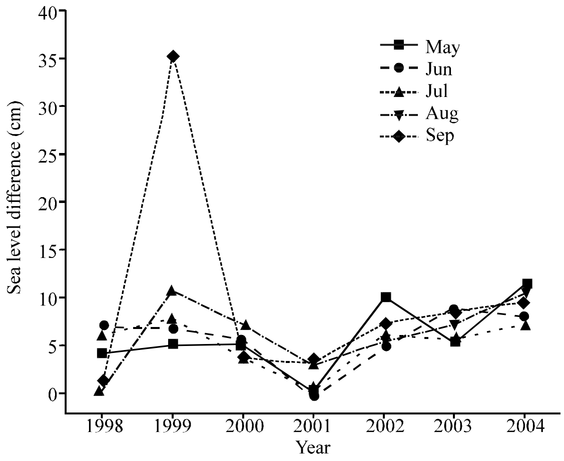

Fig. 7: Interannual sea level difference (cm) between wakkanai and abashiri from May to September indicating higher gradient in 2004

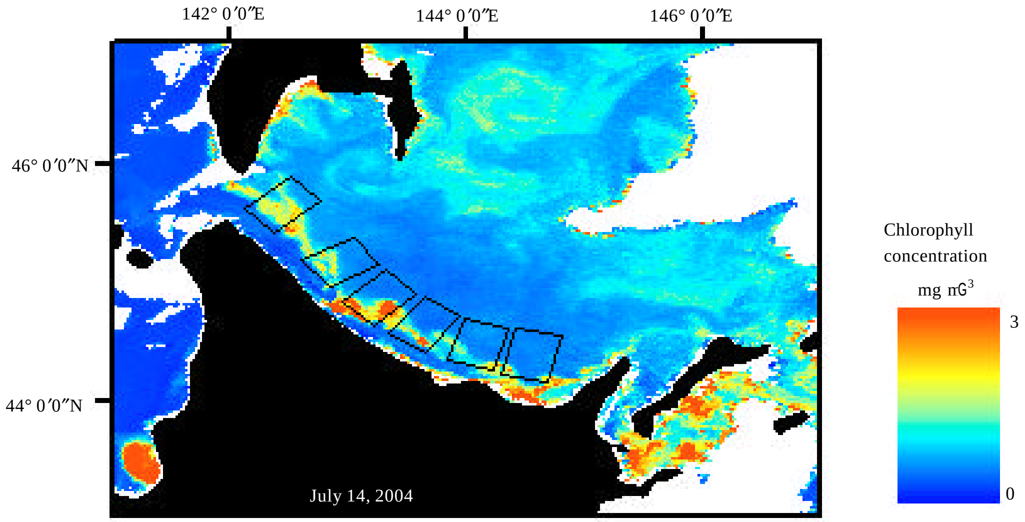

Fig. 8: SeaWiFS Chl a images indicating shape and sharpness of frontal area that is suggested to influence the Chl a concentration. Occurrence of a well developed frontal area along the coastal area on July 14, 2004 with high Chl a concentration

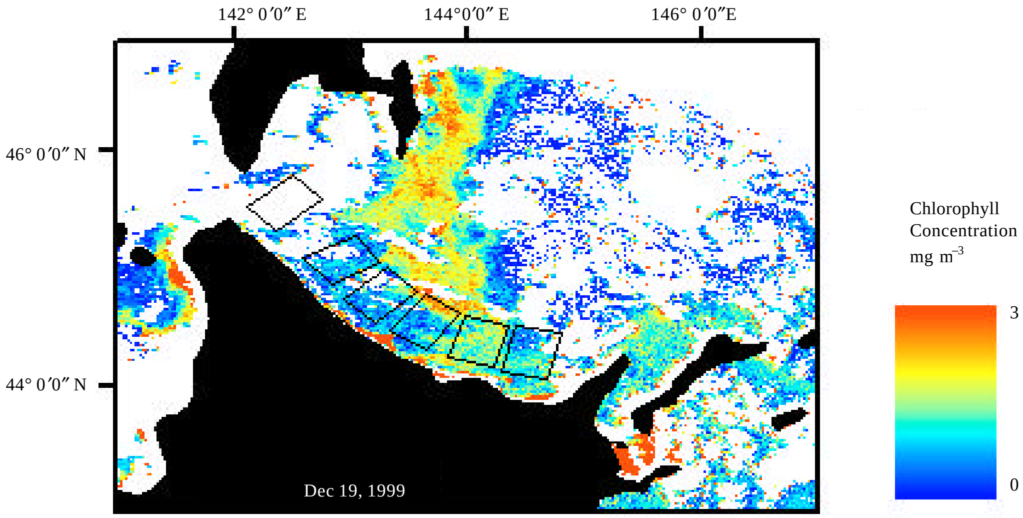

Fig. 9: SeaWiFS Chl a images indicating Chl a concentration in the east shelf of Sakhalin and coastal area of Hokkaido as a result of intrusion of ESC. High Chl a concentration on 19 December 1999

CONCLUSION

High variability of Chl a occurs at the scallop farming region with the highest peak of Chl a concentration in spring, a lesser extent in autumn followed by summer. This variability was explained by the EOF analysis. Mode 1 of EOF analysis explained the seasonal cycle of Chl a (51.8% of variance), mode 2 explained spring pattern (14.2% of variance) and mode 3 explained late autumn pattern (9.0% of variance). Variability of Chl a at the scallop farming region is related to spring bloom occurrences after sea ice retreat, advection of SWC in summer and enforcement of ESC in autumn.

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