Satellite-measured seasonal variations in primary production in the scallop-farming region of the Okhotsk Sea

M. A. Mustapha, S. Sei-Ichi, and T. Lihan

Seasonal variation in primary production after a retreat of the sea ice in the scallop-farming region along the Hokkaido coast of the Okhotsk Sea (1998–2004) was determined using satellite images. Annual variability in primary production was caused by variability in the physical processes associated with retreat of the sea ice, advection of the Sōya Warm Current (SWC), and intrusion of the East Sakhalin Current (ESC). Variability in primary production resulted in variability in the Chl a concentration, which was also demonstrated with an empirical orthogonal function (EOF) analysis. Enhancement of Chl a concentration in the frontal area in late spring was demonstrated by the second EOF mode of Chl a concentration (14.2% of variance), in parallel with the generation of a well-developed frontal area resulting from the advection of warm waters of the SWC along the coast in late spring, as indicated by the second EOF mode of sea surface temperature (SST; 1.8% of variance). Elevated Chl a concentration and the presence of cold water of the ESC in late autumn were also highlighted by the third EOF mode of Chl a concentration (9.0% of variance) and SST (1.5% of variance). Prolonged high primary production within the scallop-farming region after spring is supported by the development of a frontal area in summer and strengthening of the ESC in autumn.

**Keywords:** EOF analysis, Hokkaido shelf, Okhotsk Sea, primary production, satellite images.

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**Introduction**

The Japanese scallop, *Mizuhopecten yessoensis* (Jay), the largest species of all the Pectinidae, is a Pacific-Asian boreal species of commercial value that is cultivated successfully along the shores of Hokkaido, Japan. Scallop landings from 1998 to 2004 were >140 000 t year⁻¹. The success of scallop farming can be partly attributed to the ideal habitat and environment provided by these waters for the growth of scallops (Bourne, 2000; Uki, 2006).

The sea in this area is enriched by a retreat of the sea ice in spring, a warm current in summer, and a cold nutrient-rich current in autumn, all of which produce and maintain an explosive growth of phytoplankton (Nakatsuka et al., 2004a; Mitník et al., 2005; Mustapha and Saitoh, 2008). This abundant supply of phytoplankton biomass is an important food source for the benthic community. In winter, this area experiences seasonal sea-ice events. Following the winter season, water properties in the area display a strong seasonal variability, because of the influence of two distinct water masses. The main features of the water dynamics are associated with the Sōya Warm Current (SWC), which transports warm and saline waters from the Japan Sea through the Sōya or La Pérouse Strait. This current flows along the coast of Hokkaido from March to November, as a coastal boundary current (Takizawa, 1982). The current is induced by the sea-level difference between the Japan Sea and the Okhotsk Sea. The SWC is characterized by higher temperature and salinity than the cold and less saline surface and intermediate waters of the Okhotsk Sea (Ohshima, 1987; Matsuyama et al., 2006). Meanwhile, the East Sakhalin Current (ESC), which contains less saline surface water originating in the Amur River in summer, arrives at the Hokkaido coast in November and is perceptible until March. The ESC transports cold freshwater and sea ice southwards (Wakatsuchi and Martin, 1991; Mizuta et al., 2003; Ebuchi, 2006). It is also important for the transport of dense shelf water (DSW), which forms in the northern shelf region of the Okhotsk Sea. The DSW is considered closely related to ventilation of the North Pacific Intermediate Water (Itoh et al., 2003).

Scallops feed continuously by filtering small particles of algae and organic matter from the water. Phytoplankton primary production supports the pelagic and benthic ecosystems and determines the rate of accumulation of organic material in the sediments. Depending on variability in environmental conditions, this food supply can also be prone to temporal variations (Grebmeier and Barry, 1991). The flux of organic matter to the bottom depends on primary productivity at the surface and on the water depth. Enhanced phytoplankton production in the upper water column results in greater deposition of organic matter in deeper waters. The transfer of these phytoplankton cells to the benthic organisms stimulates the growth and feeding activity of benthic organisms (Nodder et al., 2007).

Studies of food available to bivalves in coastal waters have revealed marked temporal variations in particulate matter and composition, which arise primarily from the seasonal cycle of...
primary production. Variation in food supply is a primary environmental factor that affects scallop growth in nature (Cranford et al., 1998). The unique characteristics of the study area are greatly influenced by global climate change (Hunt and Drinkwater, 2005). It is important to understand how climate change will affect the marine ecosystems and their sustainability. Without a better understanding of the effects of climate variability on processes that take place at the lower trophic levels, predictions made about their dynamics in relation to future climate-change scenarios will have limited value. Understanding the spatial and temporal distribution of primary production within the scallop-farming region is necessary to ensure sustainable production. The purpose of this paper is to describe seasonal variations in primary production within the scallop-farming region from 1998 to 2004, using satellite images.

Methods

Study area

The study was carried out within the scallop-farming region along the coastal region of the Okhotsk Sea, Hokkaido, Japan, where there is extensive culture of scallops on the seabed (Figure 1). Fishing grounds are partitioned into areas where 1-year-old juveniles are released each year, after clearing all megabenthos by dredging. The scallops are harvested when they are 4 years old (Goshima and Fujiwara, 1994; Uki, 2006).

Satellite images

All data analysed were based on monthly composite satellite images, which were divided into seasons (winter–spring, from January to May; summer, from June to October; and autumn, from November to December) to study seasonal events.

SeaWiFS–Chl a concentration

Sea-viewing Wide Field-of-view Sensor (SeaWiFS) measurements of Chl a concentration from 1998 to 2004 were obtained from the NASA GSFCs Distributed Active Archive Center (DAAC). Daily Level 1A data 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. The algorithms for optical data processing and calculation of plant-pigment concentrations are from O’Reilly et al. (2000). The individual remapped images were composite-averaged to provide monthly images of chlorophyll concentrations. The images were subsampled to the geographic extent of the study area.

NOAA/AVHRR–sea surface temperature

Sea surface temperature (SST) measurements from the AVHRR were collected by the satellite receiving station at Hokkaido University for the period 1998–2004. Daily SST images at 1.1 km spatial resolution were averaged to monthly composites by averaging all available images for each month on a pixel-by-pixel basis (excluding missing data and areas obscured by clouds) after geographical coordinate mapping of the images. The images were subsampled to the geographic extent of the study area.
Mean sea-level anomaly

The mean sea-level anomaly (MSLA) derived from TOPEX/ Poseidon merged data was obtained from the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO) scientific team of the Collecte Localisation Satellite (CLS)/Centre National d’Etudes Spatiales (CNES) data centre (www.aviso.oceansobs.com). Monthly composite images from 1998 to 2004 were derived from the weekly high-resolution MSLA with Mercator 1/3° grid data. Geostrophic current velocities were calculated as follows (Zainuddin et al., 2006):

\[ u = -\left(\frac{g}{f}\right) \frac{\partial \psi}{\partial y} \]  
\[ v = -\left(\frac{g}{f}\right) \frac{\partial \psi}{\partial x}, \]

where \( g = 980 \text{ cm s}^{-2} \), \( f = 2 \Omega \sin \Phi \), \( \Omega = 7229 \times 10^{-5} \text{ radians s}^{-1} \), \( \Phi \) is the latitude; \( \partial \psi / \partial y \) the north–south gradient of geostrophic current; and \( \partial \psi / \partial x \) the east–west gradient of geostrophic current.

Primary production

Primary production over monthly time-scales was estimated using the vertically generalized production model (VGPM; Behrenfeld and Falkowski, 1997). This model is suitable to study the spatial and temporal variability of primary productivity. The inputs to the VGPM are satellite-derived surface Chl \( a \) concentrations, SST, and photosynthetically active radiation (PAR) at the water surface. Monthly surface PAR level-3 data were obtained from the NASA GSFCs DAAC. The monthly SeaWiFS Chl \( a \) concentration images and SST data were remapped to a 9-km equal-angle grid using linear interpolation between grid points to match the SeaWiFS PAR data. Photoperiod (daylength) was calculated as a function of latitude and time of year. Total water-column Chl \( a \) concentration was estimated from the satellite Chl \( a \) concentration data and used to estimate the euphotic depth, using the equations of Morel and Berthon (1989). Estimation of the euphotic depth in the area is less affected by suspended particles, because the region has reasonably small rivers along the coast.

The VGPM calculates primary production, \( PP_{eu} \) (mg C m\(^{-2}\) d\(^{-1}\)) as follows:

\[ PP_{eu} = 0.66125 \cdot P_{opt}^{B} \cdot \left( \frac{E_{0}}{E_{0} + 4.1} \right) \cdot Z_{eu} \cdot C_{sat} \cdot D_{irr}, \]

where \( P_{opt}^{B} \) is the maximum C fixation rate within a water column, mg C (mg Chl\(^{-1}\)) h\(^{-1}\), \( E_{0} \) the sea surface daily PAR, mol quanta m\(^{-2}\) h\(^{-1}\), \( Z_{eu} \) the euphotic depth receiving 1% of \( E_{0} \), m, \( C_{sat} \) the surface Chl \( a \) concentration, mg Chl \( a \) m\(^{-3}\), and \( D_{irr} \) the photoperiod in decimal hours.

An empirical model with the VGPM for estimating \( P_{opt}^{B} \) was parameterized from the relationship between median \( P_{opt}^{B} \) and temperature (\( T \)). The SST data were used to estimate the local maximum rate of primary production (\( P_{opt}^{B} \)) in the model according to the \( P_{opt}^{B} \) vs. SST regression as follows:

\[ P_{opt}^{B} = -3.27 \cdot 10^{-8}T^7 + 3.4132 \cdot 10^{-6}T^6 - 1.348 \cdot 10^{-4}T^5 + 2.462 \cdot 10^{-3}T^4 - 0.02057T^3 + 0.06177T^2 + 0.27497T + 1.2956, \]

except the following conditions:

\[ P_{opt}^{B} = \begin{cases} 1.13 & \text{if } T < -1.0 \\ 4.0 & \text{if } T > 28.5 \end{cases}. \]

Surface windspeed data

Meteorological information on zonal and meridional windspeed values were obtained from the National Center for Environmental Prediction (NCEP) reanalysis provided by NOAA/OAR/ESRL PSD (Boulder, CO, USA) at their website http://www.cdc.noaa.gov/. The files contained regular grids of zonal and meridional windspeeds at 10 m above sea level, interpolated on equidistant cylindrical projection with 1° spatial resolution. These data were monthly averaged and recalculated to windstress \( \tau \) (kg m\(^{-1}\) s\(^{-2}\)) at 10 m height above sea level, using the equation of Nezlin and DiGiacomo (2005).

Sea-level data

Sea-level data were obtained from the Japan Oceanographic Data Center (JODC). The data supplied by the Meteorological Agency contained hourly values of sea level derived from tide gauge observations. Monthly sea level differences between Wakkanai (Japan Sea) and Abashiri (Okhotsk Sea) were used to determine interannual variations.

Empirical orthogonal function analysis

The method of empirical orthogonal function (EOF) analysis decomposes space- and time-distributed data into modes ranked by their temporal variance. This provides a compact description of their spatial–temporal variability with orthogonal functions. EOF analyses have been used frequently to study the temporal and spatial patterns in geophysical data and have become increasingly common in describing and quantifying oceanic variability (Brickley and Thomas, 2004; Otero and Siegel, 2004).

Temporal and spatial variations of Chl \( a \) concentration and SST were examined from the monthly composites. Low light levels and/or cloud cover during January–March prevented examination of winter patterns, so these data were excluded. To improve the spatial coverage before the EOF analysis, the data were interpolated using ordinary kriging, which weights the surrounding measured values to derive a prediction for an unmeasured location.

The time-series of Chl \( a \) concentration and SST 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):

\[ F(x, t) = \sum_{i=1}^{N} a_i(t)c_i(x), \]

where \( a_i(t) \) are the principal 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 \( R = F \cdot F^T \). This analysis results in \( N \) statistical modes, each with a vector of expansion coefficients related to the original data time-series by \( a_i = F c_i \) and a corresponding spatial component map \( c_i \).
accumulated primary production from April (44.9 g C m\(^{-2}\)) to May (123.3 g C m\(^{-2}\)), reaching 338 g C m\(^{-2}\) in October, and 353.4 g C m\(^{-2}\) year\(^{-1}\) by December 2004. Area 3 displayed a similar increase in accumulated primary production from April (38.6 g C m\(^{-2}\)) to May (145.8 g C m\(^{-2}\)), reaching 357.4 g C m\(^{-2}\) in October, and 376.5 g C m\(^{-2}\) year\(^{-1}\) by December.

In comparison, the highest winter values of accumulated primary production were encountered in Area 3 in 1999 (93.0 g C m\(^{-2}\) in March). Primary production increased to 127.3 g C m\(^{-2}\) in April, followed by a steady increase in primary production throughout the season, to reach 359.9 g C m\(^{-2}\) in October and a peak of 388.7 g C m\(^{-2}\) year\(^{-1}\) in December 1999. In 1999 in Area 6, accumulated primary production of 56.7 g C m\(^{-2}\) was measured during winter (March). A moderate increase in accumulated primary production was recorded after March, reaching 275.3 g C m\(^{-2}\) in October, and 301.3 g C m\(^{-2}\) year\(^{-1}\) in December.

Lower increases in accumulated primary production were recorded in 2001 than in any of the other years. Limited availability of data for 2001 limited the analysis to the period January–September. Even so, the accumulated primary production recorded within the scallop-farming region was still low from January to September compared with the other years. In Area 2, from April to May 2001, the accumulated primary production increase from 19.9 to 43.0 g C m\(^{-2}\) and in Area 3 from 17.6 to 58.7 g C m\(^{-2}\). In September 2001, the production was just 167.6 g C m\(^{-2}\) in Area 2 and 200.5 g C m\(^{-2}\) in Area 3. The same pattern was observed in Areas 1 and 2.

Variations in sea level

Sea level differences between Wakkanai and Abashiri were used as an index of the strength and transport of water masses in the SWC and the ESC (Takikawa and Yoon, 2005). The monthly sea level differences indicated seasonal exchanges of water masses in March/April and November. A positive difference is indicative of advection of the SWC from Wakkanai, and a negative difference indicates an intrusion of the ESC. Positive differences were observed earlier in March–April 1999, 2002, and 2004. However, in 2001, negative differences were observed in March–July, and it only increased slightly at the beginning of August. However, the observed increase was lower than in any other year (Figure 4).

Geostrophic current velocities and windstress

Geostrophic current velocities were calculated to determine the southward flow of the ESC. In December, the ESC was observed flowing eastwards off the Sakhalin shelf, moving southwards to the Hokkaido coast. The geostrophic current velocities extracted in an area where the ESC flows southwards demonstrated variations in current flow. Higher current flow (12.4 cm s\(^{-1}\)) was observed in December 1999 than in December 2003 (9.6 cm s\(^{-1}\); Figure 5).

Meanwhile, windstress extracted from the area where the ESC flows southwards indicated lower windstress in 1999 than in 2003. In 1999, mean windstress was <0.05 N m\(^{-2}\), with an occasional relaxation of wind events. However, in 2003, continuous high and fluctuating winds were observed; several wind events with mean stresses >0.10 N m\(^{-2}\) were encountered.

Results

Annual accumulated primary production

High total annual accumulated primary production was observed for each year within the scallop-farming regions (Figure 2a). Total accumulated primary production was 200 g C m\(^{-2}\) year\(^{-1}\) for 2001, and >225 g C m\(^{-2}\) year\(^{-1}\) for the other years. The highest values were observed in 1999 and 2004 (>275 g C m\(^{-2}\) year\(^{-1}\)). Interannual variability in accumulated primary production within the scallop-farming region was also evident in the primary production maps along the Hokkaido coast (Figure 2b).

The entire scallop-farming region experienced an increase in accumulated primary production after winter (Figure 3), with the highest totals again in 2004 and 1999. In 2004 in Area 2, an increase in accumulated primary production was observed between April (48.7 g C m\(^{-2}\)) and May (156.4 g C m\(^{-2}\)), and it continued to increase until October (358.4 g C m\(^{-2}\)). By December 2004, production had reached 380.8 g C m\(^{-2}\) year\(^{-1}\). This pattern was also apparent in Area 4, namely an increase in
Spatial and temporal variability in SST and Chl a concentration

Spatial and temporal variability in SST

Interannual variability in SST was evident in the scallop-farming regions and its surrounding waters, and this variability was summarized using an EOF analysis. The first mode of the EOF analysis of SST explained 94.6% of the total SST variance (Figure 6a). The spatial pattern of the first mode of the SST field described the seasonal cycle, exhibiting spreading of warm water southeastwards along the coast from Sōya Strait in summer. There was also some indication of a cooler belt of water parallel to the warmer water originating in Cape Krilion. In the shelf areas (inside the 50-m depth contour), the water was warmer than the cold belt, but cooler than the water along the coast.

The amplitude time-series of this mode indicated that this pattern was modulated by the seasonal cycle, namely a peak in summer to early autumn and a minimum signal during spring. The biggest signal was observed in 1999 and the smallest in 1998.

The second mode of the EOF analysis of SST accounted for 1.8% of the variance, and it emphasized the presence of warm water along the coast (Figure 6b). Its spatial pattern revealed a strong positive signal along the coast in the Sōya Strait and a lesser signal to the southeast. Cooler water was obvious on the shelf and offshore. The associated time-series of this mode indicated a positive signal in spring (May) for all years, except a negative signal in spring (April) 2000. The biggest positive signal was in 2004, followed by 1999. The rest of the years indicated a minimal positive signal in May. This mode related to the spring pattern of SST.
The third mode of the EOF analysis of SST, accounting for 1.5% of the variance, revealed a strong spatial pattern in the shelf area and a weak spatial pattern in the Soya Strait and offshore (Figure 6c). This pattern was indicative of the presence of warm water on the shelf and colder water offshore. The associated temporal amplitude revealed a positive signal in summer to early autumn and a negative signal in late autumn. The strongest positive signal was in August 2000, followed by 2004 and 1999. Meanwhile, the strongest negative signal was in December 1998, followed by December 2004. The other years had a minimal negative signal in December. This mode explained the summer to early and late-autumn conditions of SST.

Spatial and temporal variability of Chl a concentration
Interannual variability in Chl a concentration was also summarized using the EOF analysis. The spatial pattern of the first mode revealed the intensified Chl a concentration on the shelf and offshore in spring and a further peak of Chl a concentration in autumn, the latter describing the seasonal cycle. A large signal was identified offshore, in patches along the shelf and along the frontal area. Its amplitude function also revealed enhancement

Figure 4. Difference in sea level between Wakkanai and Abashiri from 1998 to 2004, presented as an index of the strength of the exchange in water masses of the SWC and the ESC. Positive differences were observed in March–April for all years except 2001.

Figure 5. Histogram of geostrophic current velocities (cm s$^{-1}$) in December, as calculated from the MSLA for all years extracted from the dashed box in Figure 1.
Seasonal variations in primary production in the Okhotsk Sea

Discussion

Environmental events contributing to high total primary production

The geographic location and the characteristics of the southwestern part of the Okhotsk Sea provide a suitable environment for scallop growth. The scallop-farming regions are sustained by the growth of phytoplankton throughout the year. The area is enriched by the retreat of sea ice in spring, the warm current-induced frontal system in summer to early autumn, and the cold nutrient-rich water in late autumn (Figure 8). Even during the weakening of one of the environmental processes, production in the area is sustained by reinforcement of the other processes. These processes are important in sustaining the productivity of the region. They produce and maintain the growth of phytoplankton and contribute to the total primary production in the scallop-farming region.
Seasonal variability in primary production was observed within the region. High total annual accumulated primary production within the region (>275 g C m\(^{-2}\) year\(^{-1}\)) was observed in 1999 and 2004. The other years had total values of >200 g C m\(^{-2}\) year\(^{-1}\) (Figure 2). Productivity in the region is considered high compared with the Bering Sea Green Belt, a known highly productive habitat along the continental shelf in the Bering Sea (Springer et al., 1996). Annual primary production values as high as 175–275 g C m\(^{-2}\) year\(^{-1}\) have been recorded for the Bering Sea Green Belt. The diversity in spatial and temporal patterns of primary production within the scallop-farming region in the Okhotsk Sea suggests that several mechanisms control phytoplankton dynamics and productivity in the area.

**Retreat of the sea ice in spring**

In the scallop-farming region of the Okhotsk Sea, accumulated primary production increases after winter. An earlier study (Mustapha and Saitoh, 2008) revealed high phytoplankton biomass within the scallop-farming region in early spring, at the onset of the retreat of the sea ice. Within the region, a longer persistence of sea-ice cover in 1999 resulted in ice-edge blooms, whereas a shorter persistence in 2004 was followed by the presence of open-water blooms. These two types of spring bloom have also been recorded in the Bering Sea, as described by Niebauer et al. (1995) and Hunt and Stabeno (2002). Wind events also affected the onset of the spring bloom in the scallop-farming region. Ice-edge blooms resulted in higher Chl \(a\) concentrations, and this probably explains the highest winter values of accumulated primary production, observed in 1999.

**Advection of the SWC**

We propose that the prolonged high primary production within the scallop-farming region after termination of the spring bloom is supported by the development of the frontal area of SWC in
The flow of the SWC depends on the seasonal variation in the difference in sea level between the Japan and Okhotsk Seas. Several studies have revealed a strong relationship between the surface current velocity and transport and sea-level differences in the region (Ohshima, 1994; Lyu and Kim, 2003; Takikawa and Yoon, 2005). Bigger positive sea-level differences indicate a greater inflow of SWC. The differences in the velocity and transport reflect the development of the frontal area and differences in the shape and sharpness of the front. The location and shape of the frontal area also depend on several other factors, such as current shear, tidal phase, windspeed, and direction (Ohshima and Wakatsuchi, 1990). According to Mitnik et al. (2005), the flow of SWC generates a wave-like frontal pattern. Offshore cold-water masses are often observed inside the SWC region, because of intrusion of offshore water caused by the wave-like motion.

High accumulated primary production correlated with the big sea-level differences (Figure 9). The variability in accumulated primary production within the scallop-farming region was related with the frontal features. Differences in the shape and sharpness of the front influenced the variability in accumulated primary production. A sharp increase in accumulated primary production after winter and a steady increase as the season progressed in the region in 2004 were related to the presence of a wider than usual and well-developed front along the coast on 16 June 2004 and 14 July 2004. High Chl \(a\) concentration in Areas 2–4 was apparent (Figure 10a). In 1999, high accumulated primary production was also related to the well-developed frontal area because of optimum advection of the SWC along the coast on 10 August and 28 September 1999. Optimum advection of the SWC was influenced by the presence of the biggest positive sea-level difference. The front was present throughout the scallop-farming region, and high Chl \(a\) concentration was observed in Areas 3 and 6 (Figure 10b).

The strong current shear and intense water dynamics play important roles in water mixing processes. The mixing of the opposite flow direction of the SWC and offshore waters of the Okhotsk Sea in early spring generates the frontal system and produces relatively cold, fresh, oxygen-rich water that allows enhanced phytoplankton growth in the frontal area (Mitnik et al., 2005). Fronts are often associated with increased primary productivity (Brandini et al., 2000; Bogazzi et al., 2005) and are sites of major phytoplankton concentration (Olson et al., 1994).

However, a smaller sea-level difference in 2001 did not generate the wave-like pattern. The front was only present for a short distance from the strait. When the sea level starts to rise after July, the wave-like pattern of the front develops and accumulated primary production increases. However, because the gradient was lower than in the other years, the front did not develop well along the coast. A lesser increase in accumulated primary production was measured in the entire region then, demonstrated by the Chl \(a\) satellite images of 28 May and 15 June 2001 (Figure 11a). The frontal area only developed later. However, the front was narrow (as revealed by the Chl \(a\) image of 14 August 2001; Figure 11b), and subsequently absent from the entire region (Chl \(a\) image of 4 September 2001).

Well-developed frontal areas forming along the coast from Cape Krilion towards Shiretoko contributed to the increase in accumulated primary production, resulting in an increase in Chl \(a\). The elevated Chl \(a\) concentration after the retreat of the sea ice was highlighted in the EOF analysis of Chl \(a\). The second EOF spatial mode of Chl \(a\) concentration indicated enhancement of Chl \(a\) concentration in the frontal area in spring 1999 and 2004. This happened in parallel with the generation of a well-developed frontal area, the latter resulting from the advection of warm water along coast with a bigger signal in the Sōya Strait than along the

Figure 8. Schematic representation of environmental processes that contribute to the high primary production within the scallop-farming region. In spring, a retreat of the sea ice results in an ice-edge bloom. In summer, advection of the SWC develops the frontal area, and in autumn, intrusion of the ESC and low wind events enhance nutrient supply. The dark area indicates high primary production.

Figure 9. Average sea level difference between Wakkanai and Abashiri, calculated from May to October (1998–2004), indicating a bigger sea-level difference in 1999 and 2004.
Figure 10. SeaWiFS Chl \(\alpha\) concentration images (mg Chl m\(^{-3}\)) indicating the shape and sharpness of the frontal area that apparently influences the Chl \(\alpha\) concentration. (a) A well-developed frontal area along the coast on 16 June and 14 July 2004, with associated high Chl \(\alpha\) concentration. (b) Additional well-developed fronts along the coast, one on 10 August and the other on 28 September 1999, also displaying high Chl \(\alpha\) concentration.

Figure 11. SeaWiFS Chl \(\alpha\) concentration images (mg Chl m\(^{-3}\)) indicating the shape and sharpness of the frontal area that supposedly influences the Chl \(\alpha\) concentration. (a) The frontal area was not well-developed, as indicated by the SeaWiFS Chl \(\alpha\) concentration images of 28 May and 15 June 2001, which displayed low Chl \(\alpha\) concentration. (b) The frontal area that developed later, as demonstrated on 14 August and 4 September 2001, displaying high Chl \(\alpha\) concentration.
Intrusion of the ESC

With the weakening of the advection of SWC from October to December, an intrusion of the ESC takes place into the scallop-farming area. The surface flow of the ESC is associated with less saline surface water, which results from the Amur River discharge. As the ESC moves south, the reduced-density low-salinity surface water creates stratification near the surface, which in turn allows an increase in temperature in the uppermost layer. The fresh surface water reportedly contains a very large amount of dissolved organic carbon, which probably comes from the Amur River. The natural environment in the Amur River basin contributes to the production of dissolved iron, which is one of the elements essential to Chl $a$ production and phytoplankton growth (Martin et al., 1994; Boyd, 2007). Iron from the Amur River is in the form of the fulvic–Fe (III) complex. In this form, it does not oxidize easily and can be transported over a long distance. Amur River water contains a large amount of nutrients, especially silicate, which increases the productivity of phytoplankton, such as diatoms, in the Okhotsk Sea (Nakatsuka et al., 2004a, b).

The intensity of the ESC changes seasonally, and intensification of the ESC in autumn also affects the marine ecosystem (Mizuta et al., 2003). An increase in the accumulated primary production during late autumn was evident in 1999 and 2004. The highest accumulated primary production was recorded in Areas 3 and 6 in 1999 and in Areas 2–4 in 2004. Images of 19 December 1999 and 9 November 2004 revealed elevated Chl $a$ concentration on the eastern Sakhalin shelf and along the coast of Hokkaido (Figure 12a).

Low accumulated primary production during late autumn in 1998 and 2003 was also demonstrated by the lower Chl $a$ concentration measured on 12 November 1998 and 13 December 2003 (Figure 12b). The intrusion of the ESC supports the phytoplankton bloom in the study area (Nakatsuka et al., 2004b). The geostrophic current indicated that the flow of the ESC was higher in 1999 than 2003, and the windstress lower in 1999 and 2004 than in 1998 and 2003. The relaxation of the winds in 1999 and 2004 happened a few days before the onset of elevated Chl $a$ concentration. Continuous high and fluctuating winds in 1998 and 2003 resulted in lower Chl $a$ concentration. High winds affect the water-column stability and prevent phytoplankton blooms (Findlay et al., 2006). This elevated Chl $a$ concentration in late autumn was highlighted by the third EOF mode of Chl $a$. The presence of Chl $a$ was apparent in the shelf area off Monbetsu, with the highest concentrations measured in late autumn 1999. This was also consistent with the presence of the cold waters of the ESC in the third EOF mode of SST, which revealed its biggest signal in late autumn 2004.

Conclusions

The southwestern part of the Okhotsk Sea displays high primary productivity because of (i) the retreat of sea ice in spring, (ii) the presence of a frontal area attributable to advection of the warm current in summer and early autumn, and (iii) the intrusion of cold nutrient-rich water into the scallop-farming area in late autumn. These events enhance the growth of phytoplankton. A longer persistence of the sea-ice cover results in ice-edge blooms,
thus contributing to high primary production. Confluence and mixing of the SWC and the offshore waters of Okhotsk Sea in summer generated in the frontal area is suggested to be responsible for the environmental conditions that increase primary production. Variability in the development of the frontal area depends on the flow of the SWC (Figure 8), which is influenced by differences in sea level between the Japan Sea and the Okhotsk Sea. Strong southward flow of the ESC to the south of Okhotsk Sea in autumn, which transports a rich supply of dissolved iron brought in by the Amur River, also contributes to the increase in the productivity of the coastal area. Variability in the primary production in this scallop-farming region results in variability in Chl a concentration; this was also demonstrated by the EOF analysis using monthly averaged images of Chl a. Interannual variability of primary production and Chl a concentration result from the variability in the physical processes. It is important to clarify the effects of these physical processes on primary production within the scallop-farming region, in order to understand the effect of future climate change. Such clarification would facilitate the formulation and implementation of rational management plans for sustainable scallop production in the Okhotsk Sea.

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