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Key Points:
- Decadal primary production in the UB was analyzed
- A recent decline in the annual primary production was observed in the UB
- The current warming SST and a negative phase PDO were suggested for the decline

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Long-term annual primary production in the Ulleung Basin as a biological hot spot in the East/Japan Sea

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Abstract Although the Ulleung Basin is an important biological "hot spot" in East/Japan Sea (hereafter the East Sea), very limited knowledge for seasonal and annual variations in the primary productivity exists. In this study, a recent decadal trend of primary production in the Ulleung Basin was analyzed based on MODIS-derived monthly primary production for a better annual production budget. Based on the MODIS-derived primary production, the mean daily primary productivity was 766.8 mg C m^{-2} d^{-1} (SD = ±196.7 mg C m^{-2} d^{-1}) and the annual primary productivity was 280.2 g C m^{-2} yr^{-1} (SD = ±14.9 g C m^{-2} yr^{-1}) in the Ulleung Basin during the study period. The monthly contributions of primary production were not largely variable among different months, and a relatively small interannual production variability was also observed in the Ulleung Basin, which indicates that the Ulleung Basin is a sustaining biologically productive region called as "hot spot" in the East Sea. However, a significant recent decline in the annual primary production was observed in the Ulleung Basin after 2006. Although no strong possibilities were found in this study, the current warming sea surface temperature and a negative phase PDO index were suggested for the recent declining primary production. For a better understanding of subsequent effects on marine ecosystems, more intensive interdisciplinary field studies will be required in the Ulleung Basin.

1. Introduction

During the last several decades, dramatic changes in physical structure and vertical distribution of chemical properties were reported in the East/Japan Sea (hereafter the East Sea) [*Kim et al*., 1999, 2001; *Kang et al*., 2003; *Chiba et al*., 2008]. In detail, *Kim et al*. [2001] suggested that the East Sea has experienced a warming trend for more than the last 40 years. Especially, *Kang et al*. [2003] reported that the sea surface temperature of winter and spring in the southern region of the East Sea have steadily increased after the 1980s. Moreover, *Chiba et al*. [2008] reported that a dramatic change in vertical distribution of chemical properties occurred in the East Sea during the last 50–60 years, indicating a shift in the ventilation system.

The Ulleung Basin, located in the southwest of the East Sea, has been considered as a highly productive region compared with adjacent regions such as the Russian coast and the Japan Basin [*Yamada et al*., 2005; *Hyun et al*., 2009; *Yoo and Park*, 2009; *Lee et al*., 2009]. Based on monthly measurements, *Kwak et al*. [2013a] found that the primary productivity in the Ulleung Basin for a deep basin is markedly higher than those in offshore waters, and thus, they proposed that the Ulleung Basin is a biological "hot spot" in the East Sea and needs careful resource management and conservation efforts [*Kwak et al*., 2013a]. However, since their productivity measurements were executed during only 1 year from May 2010 to June 2011, seasonal and interannual variations in the primary productivity under a variety of environmental conditions should be considered for a better estimation of annual primary production in the Ulleung Basin as an important biologically productive region in the East Sea.

Generally, primary productivity can be estimated from ship-board measurement in collected water samples, which leads to a temporal and spatial underestimation of overall primary productivity (S. H. Lee et al., unpublished data, 2014). Recently, several different methodical approaches have been applied to obtain an improved high resolution of primary production and to separate between different regions worldwide

[*Longhurst et al*., 1995; *Gregg et al*., 2003; *Behrenfeld et al*., 2006]. Global time series of satellite-derived data allow monitoring intraannual, interannual, multiannual, and long-term changes in primary productivity.

In this study, we analyzed a recent decadal trend of rates of primary production in the Ulleung Basin estimated by the size-fractionated primary production estimation algorithm based on ocean color data derived from Moderate Resolution Imaging Spectroradiometer (MODIS-aqua) [*Kameda*, 2003; *Kameda and Ishizaka*, 2005; *Yamada et al*., 2005]. The main objectives of this study are to understand seasonal and interannual variations in primary production and to characterize an interannual pattern of primary production for a better annual production budget in the Ulleung Basin in the East Sea.

2. Materials and Methods

2.1. Satellite Data

Ocean color data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the satellite Aqua platform have been provided by the ocean biology processing group (OBPG) at the National Aeronautics and Space Administration (NASA) since July 2002 until present. The daily MODIS-aqua Level-2 products including chlorophyll-a, diffuse attenuation coefficient at 490 nm (K_d(490)), photosynthetically available radiation (PAR), and sea surface temperature (SST) from July 2002 to December 2012 covering the East Sea were directly obtained from the NASA OBPG website (http://oceancolor.gsfc.nasa.gov/). The Level-2 data were remapped to a standard projection at 1 km spatial resolution and then processed to generate composite images of various products. Mean values of primary production data were calculated for seasonal and interannual time series.

2.2. Primary Production Model for the East Sea

A regional primary production model for the satellite ocean color data in the East Sea was developed using in situ primary production data [*Yamada et al*., 2005]. The primary production model is based on the Vertically Generalized Production Model (VGPM) formulation [*Behrenfeld and Falkowski*, 1997] described as:

$$PP_{\mathrm{eu}} = 0.66125 \times P^B_{opt} \times [E_0/E_0 + 4.1] \times Z_{eu} \times Chl\text{-}a \times DL \quad (1)$$

where PP_{eu} is daily integrated primary production in the euphotic zone (mg C m^{-2} d^{-1}), P^B_{opt} is the optimal carbon fixation rate (mg C (mg Chl)$^{-1}$ h^{-1}), E_0 is daily *PAR* at the sea surface (E m^{-2} d^{-1}), Z_{eu} is the euphotic depth (m), *Chl-a* is chlorophyll-a concentration (mg m^{-3}), and *DL* is day length (photoperiod) in hour.

While, in the original VGPM [*Behrenfeld and Falkowski*, 1997], P^B_{opt} is derived from the seventh polynomial regression fit with SST, both SST and Chl-a are used to estimate P^B_{opt} for the regional primary production model in the East Sea [*Yamada et al*., 2005] as follows:

$$P^B_{opt} = \frac{0.071 \times T - 3.2 \times 10^{-3} \times T^2 + 3.0 \times 10^{-5} \times T^3}{Chl_{total}} + \left[1.0 + 0.17 \times T - 2.5 \times 10^{-3} \times T^2 - 8.0 \times 10^{-5} \times T^3\right] \quad (2)$$

where T is SST (°C) and $\mathrm{Chl_{total}}$ is sum of chlorophyll-a concentration of small and large sizes.

In this study, the regional primary production model for the East Sea by *Yamada et al*. [2005] is used to investigate a long-term variation of primary production in the Ulleung Basin. MODIS-measured Chl-a data are used for $\mathrm{Chl_{total}}$ and Kd(490) data are used for converting to euphotic depth as $Z_{\mathrm{eu}} = 4.6/K_{\mathrm{d}}(490)$.

2.3. Observed In Situ Data

The in situ data of temperature, salinity, nitrate, silicate, and phosphate were taken from the Korea Oceanographic Data Center (KODC) in the Korea National Fisheries Research and Development Institute (NFRDI, at http://kodc.nfrdi.re.kr/page?id=obs_04_01) and processed to investigate any change in the physical and chemical environmental conditions in the study region. The measurement surveys were routinely conducted every 2 months (February, April, June, August, October, and December) from 2003 to 2013. The temperature and salinity data were averaged from nine measurement stations for surface, 20 and 50 m water depths in the Ulleung Basin. Nutrient data were integrated from surface to 50 m depth and averaged from the nine stations (Figure 1).

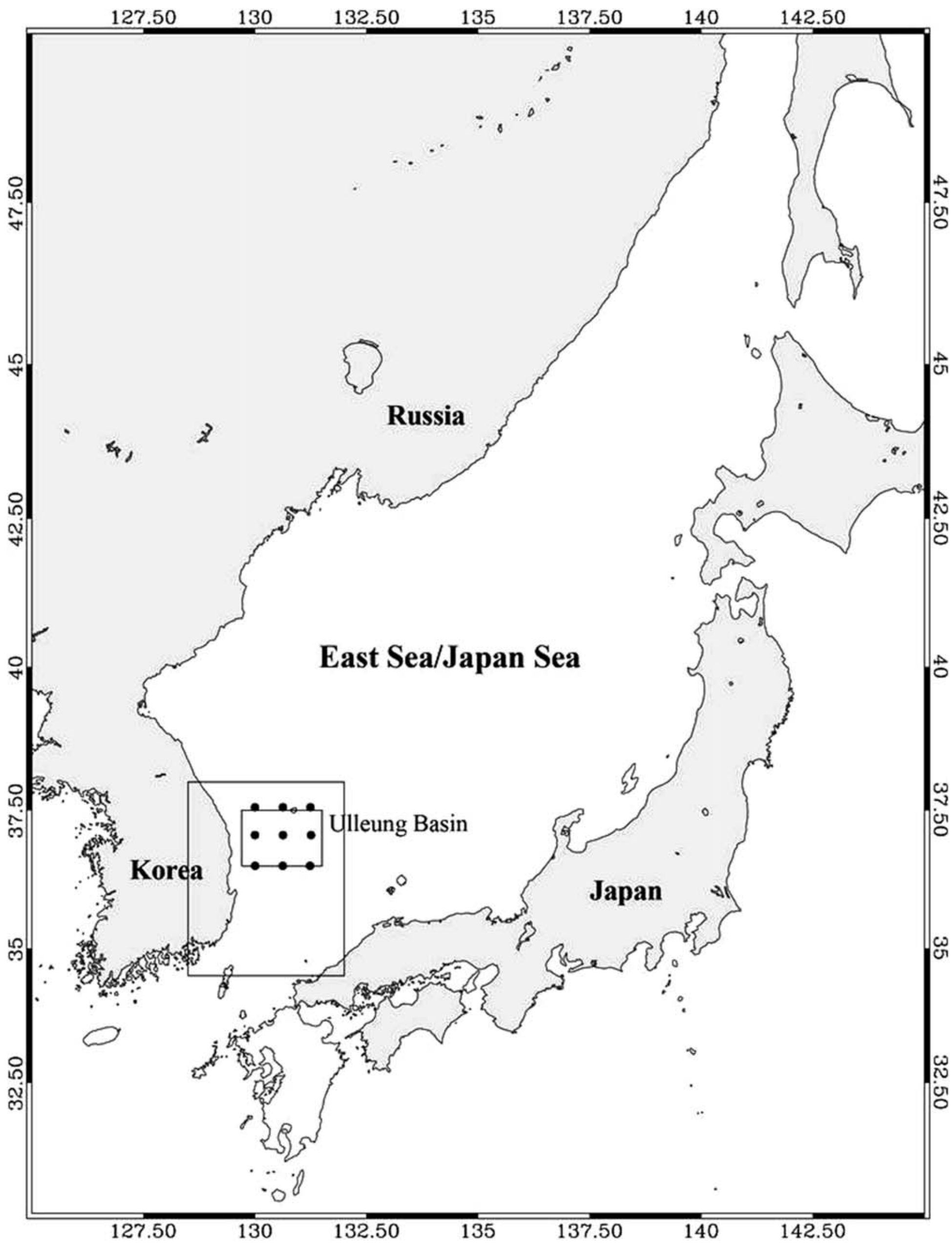

Figure 1. Areas of investigation in the East Sea. Dots are field measurement stations for physical and chemical parameters regularly conducted by the Korea National Fisheries Research and Development Institute (NFRDI, at http://kodc.nfrdi.re.kr/page?id=obs_04_01). The Ulleung Basin is marked with a small rectangular box and the southwest region of the East Sea is indicated by a large rectangular box.

3. Results

3.1. In Situ Environmental Field Data

The mean surface temperature ranging from 8.0 to 26.3°C was low in winter and high in summer, and the temperature at 50 m ranging from 9.2 to 18.3°C had a similar seasonal pattern to the surface temperature in the Ulleung Basin (Figure 2). In comparison, salinity had an inverse pattern with the temperature, low in summer and high in winter. Surface salinity ranged from 33.3 to 34.4 and the salinity at 50 m ranged from 33.6 to 34.4 (Figure 2). Generally, there was no apparent trend in water temperature and salinity in Ulleung Basin from 2003 to 2012. The major inorganic nutrient concentrations showed typical seasonal variations, low in summer and high in winter (Figure 2). Integrated phosphate concentrations ranged from 3.2 to

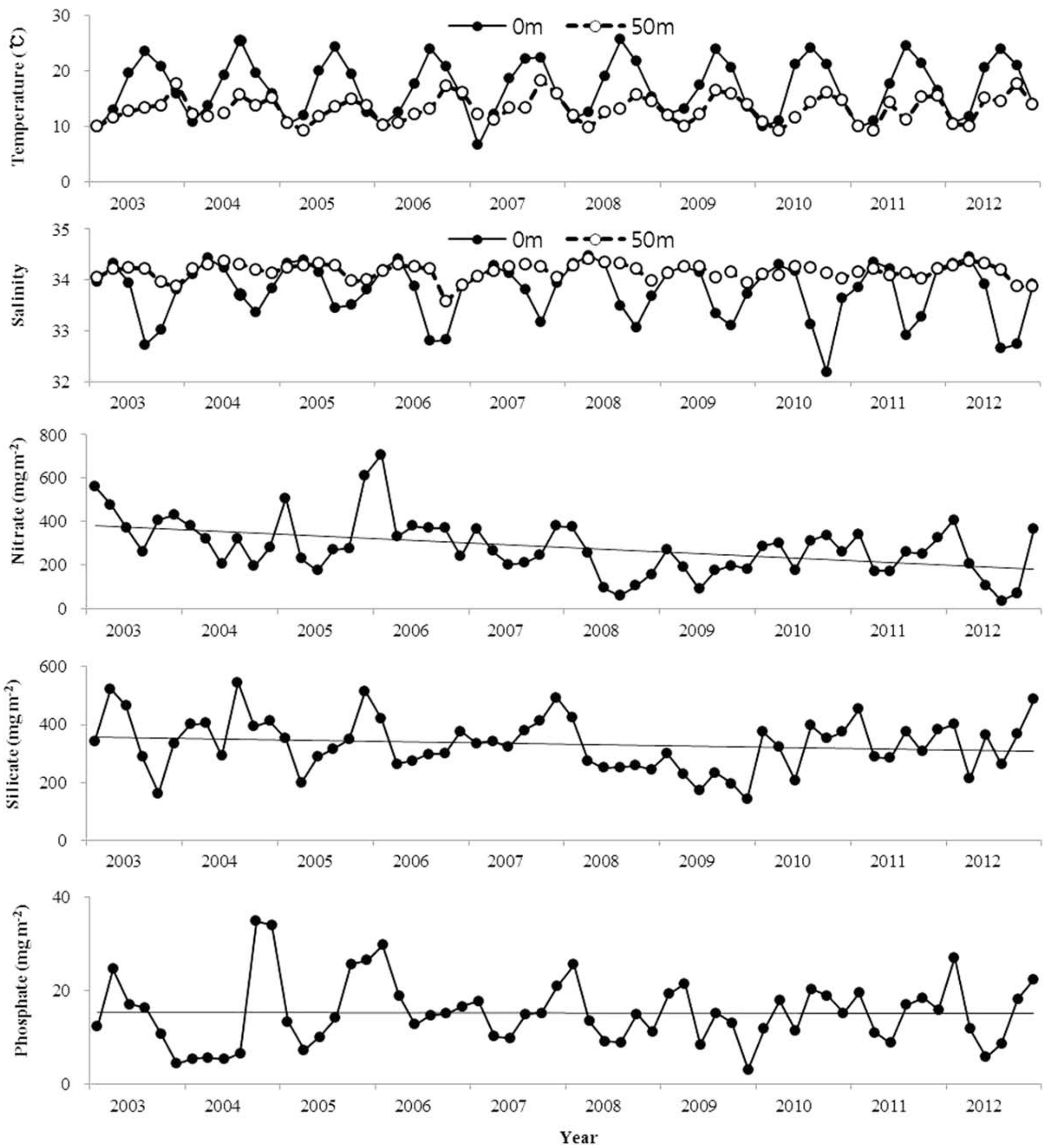

Figure 2. Monthly climatology of physical and chemical parameters in the Ulleung Basin from 2003 to 2012. Concentrations of nitrate, silicate, and phosphate are integrated from surface to 50 m water depth.

34.8 mg m^{-2} in the euphotic zone in the Ulleung Basin. Nitrate concentrations were from 35.5 to 707.7 mg m^{-2} and silicate concentrations ranged from 142.9 to 545.6 mg m^{-2}. Phosphate concentration did not show any marked overall trend, whereas the concentrations of nitrate and silicate showed weak decrease trends during the observation period from 2003 to 2012.

3.2. Seasonal Variation of Chlorophyll-a Concentration

Monthly mean surface chlorophyll-a concentrations from 2003 to 2012 in the Ulleung Basin largely varied among years (Figure 3). The highest peaks were found in spring seasons and second peaks occurred in fall seasons, whereas the lowest chlorophyll-a concentrations were observed in summer and winter. Generally, spring blooms started in March and disappeared at the beginning of summer (June). The chlorophyll-a concentration

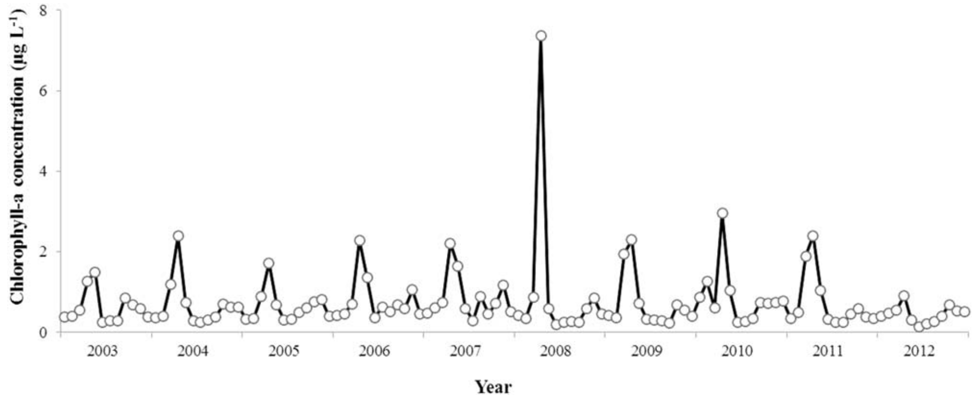

Figure 3. Monthly surface chlorophyll-a concentration in the Ulleung Basin derived from MODIS from 2003 to 2012.

during spring blooms had the highest value over 1.5 μg L^{-1}. Fall blooms in September to November had slightly larger chlorophyll-a concentrations of about 0.6 μg L^{-1}. Nonbloom seasons such as summer and winter showed low chlorophyll-a concentrations (<0.5 μg L^{-1}). During the study period, the highest chlorophyll-a concentration (7.4 μg L^{-1}) was observed in April 2008 and the lowest value (0.1 μg L^{-1}) was in June 2012.

3.3. Spatial and Seasonal Variability of MODIS-Derived Primary Production

The MODIS-derived primary production using the regional primary production algorithm [*Yamada et al.*, 2005] for the East Sea was strongly correlated with in situ measured primary production from *Kwak et al.* [2013a] in same locations (Figure 4). Based on this, monthly climatology images in the southwest region of the East Sea for July 2002 to December 2012 were generated (Figure 5). In general, primary production values were lowest in winter (January to February) over the southwestern East Sea. Primary productivity was relatively higher near the Korean coast than offshore regions including the Ulleung Basin. The highest primary productivity appears in spring (April to May) in the southwestern East Sea. In April, primary production values were higher near the Korean coast, while the production was higher in northern area (Ulleung Basin) of the southwestern East Sea in May. In summer, primary productivities decreased (from June to August) likely due to the nutrient limitation. However, higher productivity patches appeared along the southeastern Korean coast. In fall (September to October), as incident solar energy and water stratification were weaken, vertical mixing of the surface water allowed nutrients moving upward which resulted in primary production increase over all of the study area. The patch of higher primary production was observed along the Korean coast. Primary production values decreased again in November to December likely due to the reduced light availability (Figure 6). Similar to the seasonal variation of phytoplankton biomass (chlorophyll-a), there were two peaks in primary production, a higher one spring (May) and smaller peak in fall (September to October) in the Ulleung Basin (Figure 5), although timing of the peaks were slightly different from those of chlorophyll-a (Figure 4). Primary production values in Ulleung Basin were lowest in winter (December to January) and highest in May.

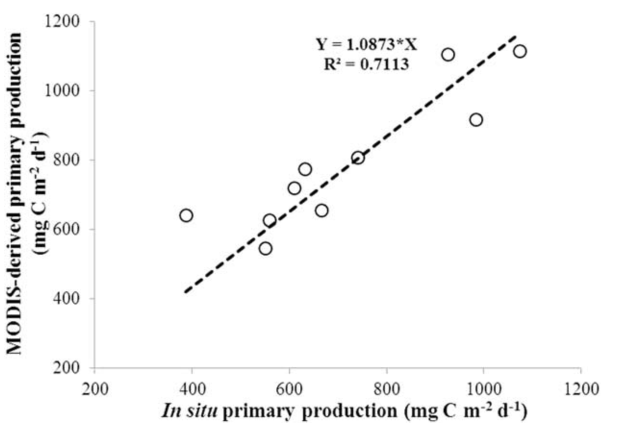

Figure 4. Correlation between in situ primary production and MODIS-derived primary production in the Ulleung Basin.

Daily primary productivity based on monthly climatology images of the MODIS-derived primary production (Figure 5) in the Ulleung Basin ranged from 446.9 (December 2011) to 1262.8 mg C m^{-2} d^{-1} (May 2013) with an average of 766.8 mg C m^{-2} d^{-1} (SD = ±196.7 mg C m^{-2} d^{-1};

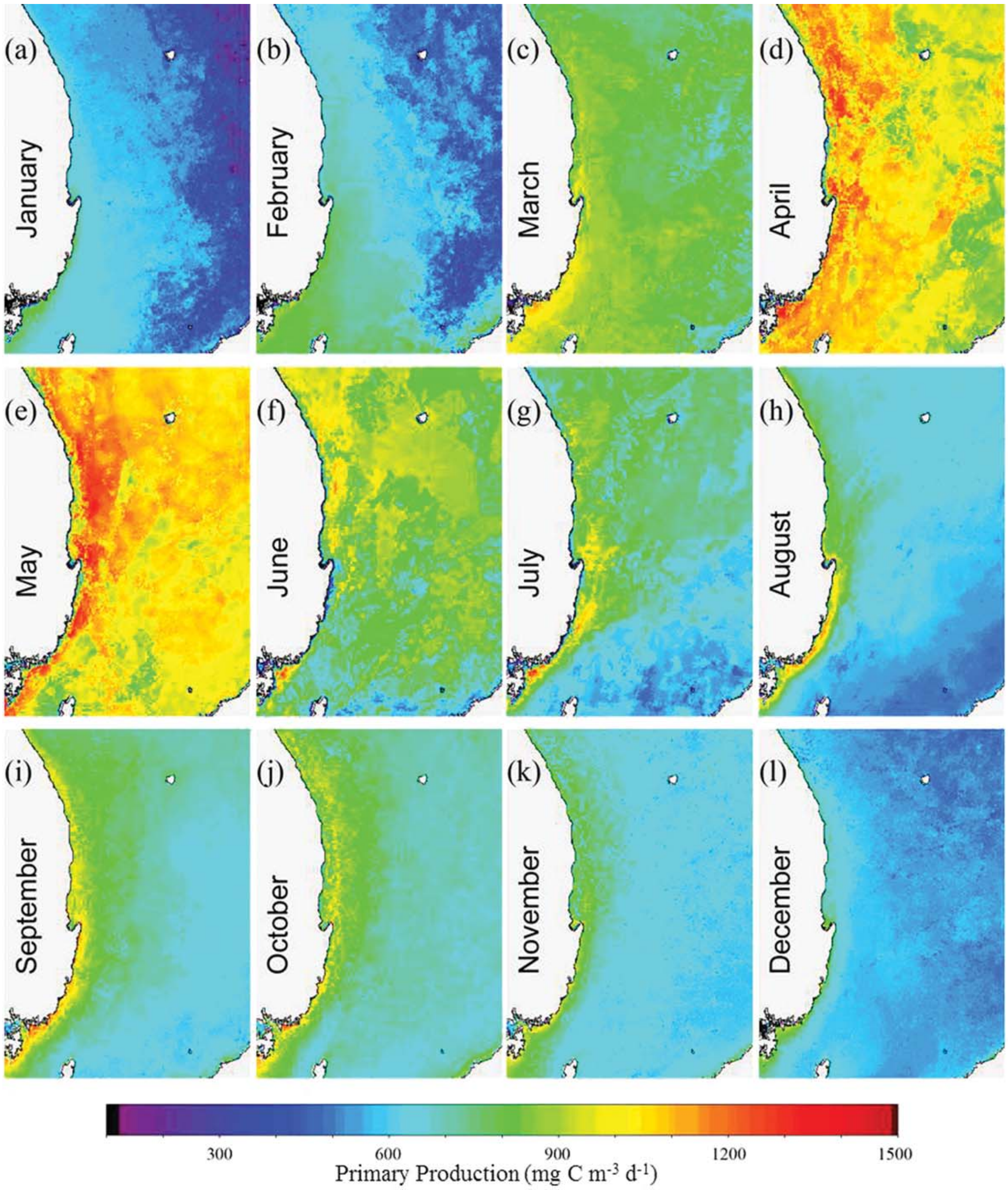

Figure 5. Monthly climatology images of MODIS-derived primary production for the months of January to December (July 2002 to December 2012) in the southwestern East Sea.

Figure 7). Based on the daily primary productivity, the annual primary productivity ranged from 248.8 g C m^{-2} yr^{-1} in 2012 to 298.9 g C m^{-2} yr^{-1} in 2006 with an average of 280.2 g C m^{-2} yr^{-1} (SD = ±14.9 g C m^{-2} yr^{-1}) in the Ulleung Basin during the study period (Figure 8). The monthly contributions of primary production averaged from 2003 and 2012 to the annual production in the Ulleung Basin were shown in Table 1. The monthly contribution ranged from 5.9% (SD = ±0.5%) in December to 12.1% (SD = ±1.1%) in May. The contributions of April and May during the spring bloom were 12.0 and 12.1%, respectively, which were not substantially higher than other months. In comparison, the contribution of September and October as a fall bloom was approximately 16%.

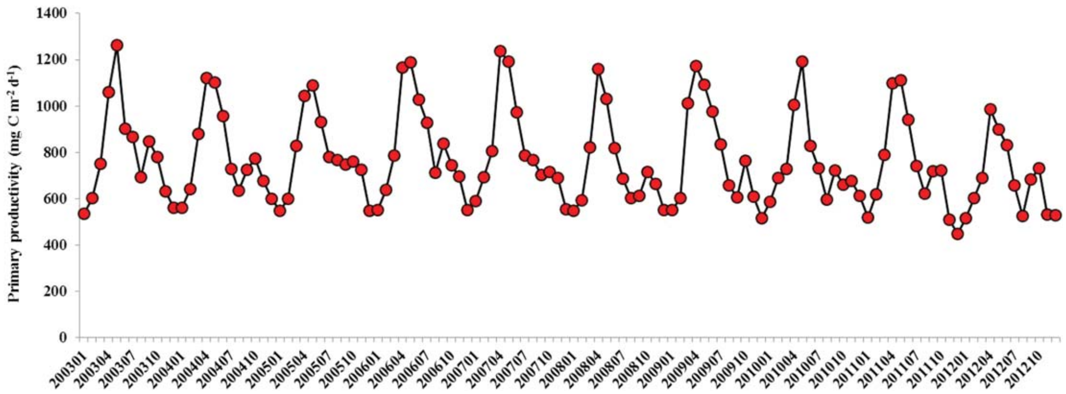

Figure 6. Monthly value of daily primary productivity in the Ulleung Basin from January 2003 to December 2012.

3.4. Relationships Between Primary Production and Environmental Factors

Pearson's correlation matrix was used to find relationships between primary production and environmental factors (Table 2). The primary production was negatively correlated with integrated silicate concentration (*r* value $= -0.301$, n $= 60$, $p < 0.05$) and water temperature at 50 m (*r* value $= -0.481$, n $= 60$, $p < 0.05$), whereas positively correlated with salinities at surface (*r* value $= 0.423$, n $= 60$, $p < 0.05$) and 50 m (*r* value $= 0.420$, n $= 60$, $p < 0.05$), Pacific Decadal Oscillation (PDO) index (*r* value $= 0.224$, n $= 120$, $p < 0.05$), and chlorophyll-a concentration (*r* value $= 0.536$, n $= 60$, $p < 0.05$).

4. Discussion and Conclusions

4.1. Primary Productions in the Ulleung Basin

The daily primary productivity pattern (Figure 6) was similar to the chlorophyll-a pattern (Figure 3) in the Ulleung Basin. The highest productivities were observed in April or May, were higher than 1000 mg C m^{-2} d^{-1} during the spring bloom followed by second bloom in September. The lowest productivities were found in winter seasons, December or January (Figure 7), which was rather different from the result in *Kwak et al.* [2013a] who reported that the maximal productivity was measured in May and the minimum productivity was observed in November between May 2010 and June 2011. The mean daily primary productivity (766.8 mg C m^{-2} d^{-1}) in this study was almost identical to that measured by *Kwak et al.* [2013a] (747.9 mg C m^{-2} d^{-1}). The mean daily of primary production in this study was substantially higher than the previous estimate (approximately 400 mg C m^{-2} d^{-1}) in the Ulleung Basin estimated by *Yamada et al.* [2005] using SeaWiFs (NASA Sea-viewing Wide Field-of-view Sensor) ocean color satellite data. This might be related to lower chlorophyll-a concentration in 1998–2002 period than recent period reported by *S.H. Lee et al.* (unpublished data). They found that 4 year average chlorophyll-a concentration was higher (about 40%) in the 2008–2011 period than in 1998–2001 period in the East Sea. In this study, the primary production was found to be strongly correlated with chlorophyll-a concentration (Table 1; *r* value $= 0.536$, n $= 60$, $p < 0.05$).

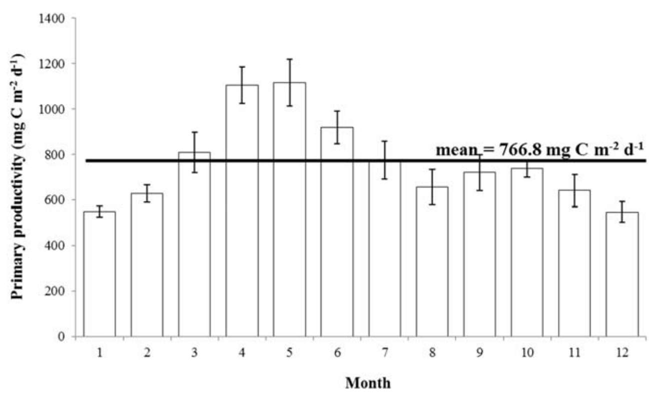

Figure 7. Monthly mean rates of primary production in the Ulleung Basin over 10 years from January 2003 to December 2012. The solid line represents a mean for the annual value.

Based on the daily primary production, our estimated annual

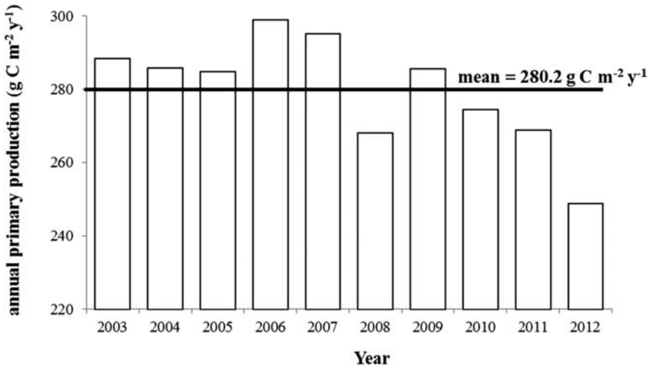

Figure 8. Annual mean rates of primary production in the Ulleung Basin from January 2003 to December 2012. The solid line represents a mean value.

Table 1. Monthly Mean Contribution (%) of Primary Production Averaged From 2003 to 2012 in the Ulleung Basin

	% ± SD
Jan	6.0 ± 0.3
Feb	6.8 ± 0.4
Mar	8.8 ± 1.0
Apr	12.0 ± 0.9
May	12.1 ± 1.1
Jun	10.0 ± 0.8
Jul	8.4 ± 0.9
Aug	7.1 ± 0.8
Sep	7.8 ± 0.9
Oct	8.0 ± 0.4
Nov	7.0 ± 0.8
Dec	5.9 ± 0.5

primary production ranged from 249.4 to 299.1 g C m^{-2} yr^{-1} (mean ± SD = 280.2 ± 14.9 g C m^{-2} yr^{-1}) in the Ulleung Basin for the recent decade from 2003 to 2012 (Figure 8). This result is consistent with the annual production (273.0 g C m^{-2} yr^{-1}) from *Kwak et al.* [2013a] based on the monthly measured primary production, even though they obtained the field productivity data for only one year from May 2010 to July 2011. In fact, this study found a relatively small interannual variation in the annual primary production among years in the Ulleung Basin (Figure 8). The annual primary production in the Ulleung Basin as a deep basin (>2000 m water depth) was substantially higher than that in oceanic regions deeper than 200 m (Figure 9). Generally, annul rates of primary productions in oceanic regions were low ranging from 55 to 102 g C m^{-2} yr^{-1}, whereas annual rates of primary production in upwelling waters were substantially high ranging from 300 to 398 g C m^{-2} yr^{-1} (Figure 9). For a specific comparison, the annual primary production in the Eastern and Western Basin of the Mediterranean Sea which has similar environmental conditions as the East Sea ranged from 109 to 158 g C m^{-2} yr^{-1}, based on Costal Zone Color Scanner data, respectively [*Estrada*, 1996]. Among other regions in the East Sea, the annual primary production in the Ulleung Basin was highest [*Yamada et al.*, 2005; *Lee et al.*, 2009; *Kwak et al.*, 2013a]. *Yamada et al.* [2005] reported that mean annual rates of primary productions from 1998 to 2002 estimated by a satellite-based primary production model were 170 and 161 g C m^{-2} yr^{-1} with the Russian coast and the Japan Basin, respectively, which were somewhat lower than those

Table 2. Pearson's Correlation Matrix of Primary Production and Various Environmental Parameters[a]

	Tem0	Tem50	sal0	sal50	IntNIt	IntSil	IntPho	PDO	Chla	PP
Tem0	1									
Tem50	0.588	1								
sal0	−0.697	−0.632	1							
sal50	*	−0.481	0.378	1						
IntNIt	−0.386	*	*	−0.277	1					
IntSil	*	*	*	*	0.523	1				
IntPho	*	*	*	*	0.345	0.468	1			
PDO	−0.267	−0.271	0.27	*	0.471	*	*	1		
Chla	−0.329	−0.407	0.327	*	*	*	*	*	1	
PP	*	−0.481	0.423	0.42	*	−0.287	*	0.224	0.536	1

[a]The *r*-values shown in this table indicate statistical significance when *p*-values are < 0.05. Asterisks indicate that *r*-values are not significant. Tem0: surface temperature, Tem50: 50 m temperature, sal0: surface salinity, sal50: 50 m temperature, intNit: integrated nitrate, IntSil: integrated silicate, IntPho: integrated phosphate, PDO: Pacific decadal oscillation index, Chla: chlorophyll a, PP: daily primary production.

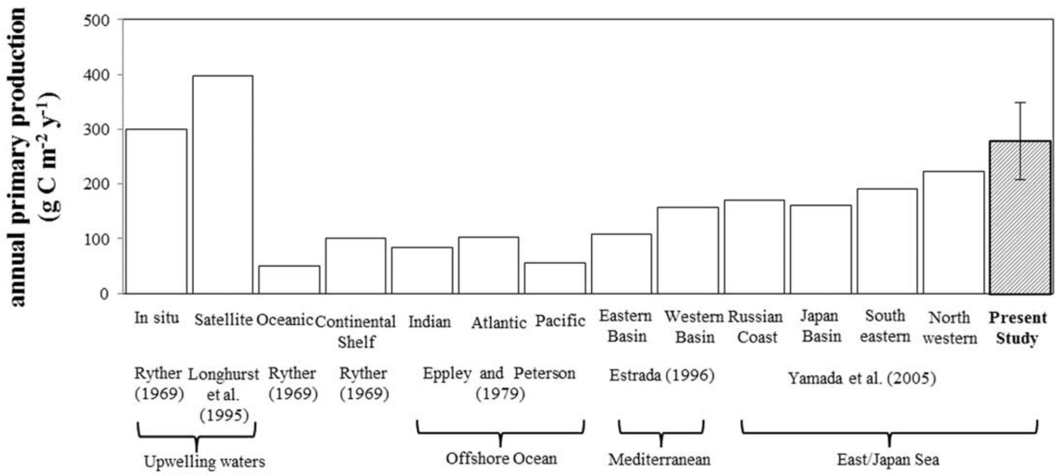

Figure 9. Comparison of annual primary production among various regions.

(191–222 g C m^{-2} yr^{-1}) in the southern East Sea. But, these values were still considerably lower than those of the Ulleung Basin in this study.

Surprisingly, an interannual variation in the annual rates of primary productions was not largely variable among years except 2012 in the Ulleung Basin (Figure 8). The sustaining high production over the study periods with the small variation indicates that the Ulleung Basin is a prominent biologically productive region called as "hot spot" in the East Sea [*Kwak et al*., 2013a]. Several potential mechanisms such as different types of subpolar fronts [*Chiba et al*., 2008], frequent eddies [*Hyun et al*., 2009; *Kim et al*., 2012; *Lim et al*., 2012], and coastal upwelling [*Yoo and Park*, 2009] were thought to have caused the high productivity in the Ulleung Basin. In addition, *Kwak et al*. [2013b] suggested that a strong upward flux of nitrate through a shallower pycnocline depth and euphotic depth that are caused by hydrographic conditions sustains the high phytoplankton productivity in the Ulleung Basin. In fact, the monthly contributions of primary production to the annual production in the Ulleung Basin were not variable among different months, although the contribution of primary production in April and May as a spring bloom was relatively higher than others (Table 1). Especially, the contributions of summer time from June to August ranging from 7.1 to 10.0% were not lower than others.

Based on their measurements of NO_3 and NH_4 uptake rates, *Kwak et al*. [2013a] estimated the *f*-ratio value (0.59) in the Ulleung Basin. This *f*-ratio originally is equivalent to the fraction of organic matter exported from the total production (new production) in the euphotic zone [*Eppley and Peterson*, 1979]. Therefore, our new production can be estimated based on their *f*-ratio. The new production ranges from 147.2 to 176.5 g C m^{-2} yr^{-1} (mean $\pm$ SD $=$ 165.3 $\pm$ 8.8 g C m^{-2} yr^{-1}) in the Ulleung Basin from 2003 to 2012 which are somewhat higher than that (145.6 g C m^{-2} yr^{-1}) of *Kwak et al*. [2013a] based on their average assimilated C/N uptake ratio (3.4) and annual nitrate uptake rate (62.6 g N m^{-2} yr^{-1}). This high new production in the upper water column estimated in the Ulleung Basin matches well with the high organic carbon flux estimation at 1020 m water depth and high organic carbon content observed in the uppermost sediment [*Lee et al*., 2008].

4.2. Recent Trend of Annual Primary Production in the Ulleung Basin

Since 2006, the annual primary production in the Ulleung Basin has significantly declined each year (Figure 8; $y = -7.0222x + 14385$, $R^2 = 0.7528$). Presently, we do not have any specific reason for the declining rates of primary production. A possible reason is the increase of SST in the East Sea which has experienced a warming trend over recent decades according to *Kim et al*. [2001] and *Kang et al*. [2003]. The warming SST could lead to increase stratification of the surface mixed layer and consequently decrease the entrainment of major nutrients into the upper layer [*Sarmiento et al*., 1998]. In addition, the warming SST in winter time could lead to different mixing conditions in the East Sea. However, no substantial changes in sea surface temperature and salinity were observed in the study region over the investigation period (Figure 2) probably because the observation period was too short to detect any small change. However, the primary production in the Ulleung Basin is significantly related with PDO index (Table 2). *Chiba et al*. [2008] reported that the reduced warm surface Tsushima current combined with the shoaling of the cold subsurface water originating from the northern East Sea consequently resulted in reduction of lower-trophic level productivity caused by nutrient depletion during strong spring stratification in the cold phase of PDO in the East Sea. In fact, a strong correlation (Table 2) was found between PDO and the nitrate concentration integrated from surface to 50 m water depth. In addition, a decreasing trend in the nitrate concentration especially for winter season was observed in the study region from 2003 to 2012 (Figure 2), although the nitrate concentration were not strongly correlated with the rates of primary production (Table 2). To date, the basis for the current status and structure of the pelagic ecosystem has not been resolved for the Ulleung Basin. More intensive interdisciplinary field studies are needed for a better understanding of the declining trend of annual production and subsequent effects on the marine ecosystems in the Ulleung Basin as a biological hot spot in the East Sea under ongoing climate and environmental changes.

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