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Eddy- and wind-sustained moderate primary productivity in the temperate East Sea (Sea of Japan)

G.-H. Hong¹, D.-K. Lee², D.-B. Yang¹, Y. I. Kim¹, J.-H. Park¹, and C.-H. Park¹

¹Korea Institute of Ocean Science and Technology, Ansan 426-744, Republic of Korea

²Department of Oceanography, Pusan National University, Busan 609-735, Republic of Korea

Received: 10 May 2013 – Accepted: 6 June 2013 – Published: 27 June 2013

Correspondence to: D.-K. Lee (lee@makaha.ucsd.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Eddy- and
wind-sustained
moderate primary
productivity

G.-H. Hong et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Abstract

As part of the Dokdo East Sea Time Series Studies (DETS) in the East/Japan Sea, a DETS buoy system was moored on the 130 m deep continental shelf off the Dok Islets in the central part of the East Sea. Chlorophyll *a* concentrations in the surface water observed by the DETS buoy system exhibited low-frequency bimodal variations in the annual chlorophyll *a* concentration due to a spring phytoplankton bloom and a smaller fall bloom. In addition, between late spring and early fall when the water column is stratified, frequent low-concentration maxima occurred, which appear to have been triggered by the injection of nutrient-rich subsurface water to the sunlit surface water. The primary productivity in the nutrient-depleted surface ocean was found to be enhanced by subsurface water upwelling where the wind and water move in the same direction as the mesoscale eddy. New observations in the East/Japan Sea based on time-series measurements of chlorophyll *a*, wind, and other oceanographic variables at fixed sites in the center of the sea and using satellite measurements reveal that the vertical movement of water caused by wind-eddy interactions depends on the relative angle between the wind and the water current. The wind-eddy interaction appears to contribute to the unusually high primary productivity in the region where it was often sustained by the long-lived warm and cold eddies.

1 Introduction

Oceanic circulation is characterized not only by large-scale currents, but also by mesoscale eddies. Now, with the advent of ocean remote sensing, we can observe the mesoscale processes that dominate ocean energetics throughout most of the ocean (reviewed by Yoder et al., 2010). The infrared, microwave and visible imagery from various satellites have been used to estimate sea surface temperature (SST), chlorophyll *a* concentration, and sea surface height (SSH). Moored buoys or towers equipped with optical and electrical sensors (time-series stations) attached to mooring arrays at

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.1 Water temperature

The surface water temperature increased gradually from 10.6°C to 14.4°C during 1–11 April 2009, and then decreased until it reached 12.0°C on 28 April (Fig. 1). From the 11 April to 17 May 2009, relatively low temperatures were measured at all depths.

5 The surface temperature was > 23°C from 8 August to 30 September and decreased thereafter. Seasonal temperature variations were not apparent at or below depths of 40 m. The time-series evolution of the pycnocline structure can also be seen in Fig. 1 as density is largely determined by temperature in the East/Japan Sea (Lim et al., 2012).
10 Above the pycnocline, centered at 80 m, a mixed layer developed with an average depth of 60 m. Temperatures measured at 40, 60, 80, 100, and 120 m exhibited distinct semi-diurnal variations (data not shown).

3.2 Salinity

Salinity varied along with water temperature at 40, 60, and 80 m depths, with low salinity always related to low temperature (Fig. 2). From 11 to 30 April, salinity decreased
15 gradually from 34.436 psu to 34.211 psu. Salinity increased thereafter until it reached 34.382 psu on 16 May. A similar salinity decrease was also observed between 16 and 31 August 2009. Seasonal salinity variations were not apparent at or below depths of 40 m, although they were somewhat lower in summer than in winter.

3.3 Chlorophyll *a*

20 The daily mean chlorophyll *a* concentration varied seasonally with two maxima in spring (March–April) and fall (October–December) and with two minima in summer and winter (Fig. 3), as observed previously by satellite measurements (Yamada et al., 2004) and in other temperate seas (Parsons et al., 1984). The instantaneous chlorophyll *a* concentration varied from less than 0.01 to 8.9 mg m⁻³ (data not shown).

**Eddy- and
wind-sustained
moderate primary
productivity**

G.-H. Hong et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Aside from seasonal variability, small-scale variations in chlorophyll *a* concentrations were seen in the DETS buoy data. During 10–13 May 2009, chlorophyll *a* concentrations in the surface waters were $> 1.5 \text{ mg m}^{-3}$. Prior to this period, the temperature gradually decreased from 28 April to 6 May at depths of 40, 60, and 80 m. Similarly, a decrease in temperature at depths of 40, 60, and 80 m during 27–31 May preceded relatively high chlorophyll *a* concentrations observed on 3–7 June. The temperature at 40 m was $< 16^\circ\text{C}$ during 13–15 October. After this temperature decrease at 40 m, a small peak in the chlorophyll *a* concentration ($> 0.5 \text{ mg m}^{-3}$) was observed during 17–20 October 2009.

3.4 Diurnal variation of chlorophyll *a*

A persistent diel rhythm in the chlorophyll *a* concentration was measured using in vivo fluorescence, with daytime values about 2–6-fold lower than nighttime values in April 2009 (Fig. 4), and this diel feature was apparent year-round at the DETS buoy. A diel fluorescence cycle arises mainly from inhibition by light because fluorescence begins to decrease at dawn and increases again after dark. However, the subsurface chlorophyll *a* maximum was present at 35–45 m all day long at the buoy site (Fig. 5).

3.5 Daily mean wind speed and daily mean wave height at DETS buoy site

The daily mean sea surface wind speed was highly variable throughout the year with relatively strong winds in winter and weaker winds in summer. It varied from 1.4 to 14.3 m s^{-1} with a mean of 3.9 m s^{-1} (Fig. 6).

Daily mean wave height was also low in summer and high in winter with large variations. It varied from 0.2 to 4.0 m with a mean of 1.1 m (Fig. 7).

4 Discussion

4.1 Primary productivity in the East/Japan Sea

The East/Japan Sea is moderately productive, with carbon fixation of as much as 161–240 g C m⁻² yr⁻¹ based on in situ carbon-uptake measurements and satellite measurements from the Coastal Zone Color Scanner (CZCS) and Sea-viewing Wide Field-of-view Sensor (SeaWiFS) (Yoo and Park, 2009). Therefore, the sea as a whole draws down 0.16 to 0.22 GtC yr⁻¹ through photosynthesis. Even if community respiration is more than half of the gross production (Waku and Furuya, 1998), this amount of gross primary productivity is an order of magnitude greater than the net annual CO₂ flux at the air-sea interface (0.032 ± 0.012 GtC) based on the fugacity of CO₂ in the surface water and air, and based on the pH and alkalinity of the surface water (Oh et al., 1999). The settling flux of organic carbon in the southwestern part of the Japan Basin at a depth of 2.8 km was 2.9 g C m⁻² yr⁻¹, which falls in the upper range of the world ocean (Hong et al., 1977). This preliminary comparison indicates that the biological pathway for the drawing down of atmospheric CO₂ in the East/Japan Sea is very significant. Moreover, organic matter produced through phytoplankton photosynthesis sinks to the bottom of the sea to enhance the accumulation of CO₂ in the deep sea. One of the current estimates of the accumulation of anthropogenic CO₂ in the East/Japan Sea (80 mol C m⁻² as of 1999) is much greater than that in the North Pacific and comparable to that of the North Atlantic (Park et al., 2006). Consequently, a proper understanding of the environmental factors controlling phytoplankton primary productivity is of great importance in terms of quantifying the carbon dioxide budget in the East/Japan Sea.

In the sea, mesoscale eddies occur where major currents and oceanic fronts are present. The mesoscale eddies separate from the respective current or front and meander into water masses with different physical, chemical, and biological characteristics. The East/Japan Sea is one of the most eddy-rich fields in the world ocean (Ichiye and Takano, 1988; Isoda, 1996). The warm and cold eddies appear periodically in the southern part of the UB with lifetimes of about 1 month or longer (Morimoto et al.,

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



**Eddy- and
wind-sustained
moderate primary
productivity**

G.-H. Hong et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

2000). However, using lag correlation analysis, Morimoto et al. (2000) determined an eastward propagation of about 1.8 cm s^{-1} , suggesting eastward advection by the Off-shore Branch of the Tsushima Warm Current, a branch of the Kuroshio Current. There have been many descriptions of meandering currents in the UB (Naganuma, 1985; Kato, 1994; Morimoto and Yanagi, 2001), and they include both warm- and cold-water intrusions (Ichiye and Takano, 1988) and warm and cold eddies (Ichiye and Takano, 1988; An et al., 1994; Isoda, 1996; Lee and Niiler, 2010b).

Five eddy circulation patterns have been identified in the UB based on acoustic travel time from an array of inverted echo sounders (Mitchell et al., 2005). An anticyclonic eddy called the Ulleung Warm Eddy (UWE) is a major hydrographic feature of the UB. One very significant cold cyclonic eddy was located south of the Dok Islets throughout much of the year and was named the Dok Cold Eddy (DCE) by Mitchell et al. (2005). Previously, there were not enough systematic hydrographic observations in the eastern UB to detect the DCE, as the weak SST signal of the cold eddy precluded its detection based on an analysis of water mass properties. The DCE is typically $\sim 60 \text{ km}$ in diameter and originates from the pinching off of a Subarctic Front meander between Ulleung Island and Dok Islets (Mitchell et al., 2005). After its formation, the DCE remains southwest of the Dok Islets for 1–6 months before propagating westward toward Korea, where it deflects the path of the East Korean Warm Current (EKWC).

It has been observed that eddies displace isopycnals, which are uplifted at the center of cyclonic eddies. Up-sloping of the isopycnals due to eddy pumping is known to enrich oligotrophic surface layers (Falkowski et al., 1991; Olaisala et al., 1993; McGillicuddy et al., 1998; Seki et al., 2001). Phytoplankton biomass is determined by the availability of light and nutrients. These growth-limiting factors are in turn regulated by the physical processes of ocean circulation, mixed-layer dynamics, atmospheric-dust deposition, and the solar cycle.

The East/Japan Sea experiences bimodal phytoplankton blooms in spring and fall, as do other temperate zones in the global oceans (Nagata, 1994; Ishizaka et al., 1997; Nagata and Ogawa, 1997; Kim et al., 2000; Yamada et al., 2004, 2005). Satellite-derived

**Eddy- and
wind-sustained
moderate primary
productivity**G.-H. Hong et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

ocean color imagery has allowed large-spatial-scale observations of the seasonal development of phytoplankton biomass. Kim et al. (2000) demonstrated that phytoplankton biomass observed in CZCS images exhibited a bimodal seasonal pattern of spring and fall blooms in the East/Japan Sea. They attributed the seasonal patterns in phytoplankton populations to seasonal density stratification. In the East/Japan Sea, the depth of the seasonal thermocline increases to 100–150 m in winter and decreases to 10–20 m in summer. During the summer, the water is stratified and the upper layer is nutrient limited. The surface chlorophyll *a* concentration falls below 0.3 mg m^{-3} at this time, which is the lowest value of the year. In winter, deep mixing over the permanent thermocline replenishes nutrients in the upper mixed layer, while preventing phytoplankton from absorbing enough light for growth. Stratification in spring briefly satisfies the light-nutrient requirements for phytoplankton growth, inducing a temporary increase in phytoplankton abundance in the upper layer. In summer, stratification inhibits nutrient input from below, suppressing phytoplankton growth in the surface mixed layer. A second seasonal bloom occurs in the fall as weakening of the stratification allows nutrient input into the upper mixed layer.

Phytoplankton blooms also occur periodically when physical phenomena of various scales raise the concentrations of growth-limiting nutrients in the euphotic layer of the East/Japan Sea waters between late spring (after spring bloom) and early fall (before fall bloom). Examples of such events include mixing and decay of stratification due to passage of warm and cold currents and the formation of mesoscale eddy features (Falkowski et al., 1991). These phenomena are likely to be significant transport mechanisms of large quantities of nutrients to the euphotic zone, resulting in the enhanced phytoplankton populations seen in satellite ocean color observations in the East/Japan Sea (Ahn et al., 2005). Other than a few preliminary investigations (e.g., Kim et al., 2012), the relationship between these physical mechanisms and phytoplankton blooms in the region is not been yet clearly understood.

4.2 Cross-correlation analysis

Interpretation of time-series observations at fixed locations in the ocean is often complicated by spatial heterogeneity, which varies over time. Thus, it is important to differentiate spatial heterogeneity from temporal variation (McGillicuddy et al., 1999). In order to understand the variability of the surface chlorophyll *a* concentration in terms of the physical environment, a cross-correlation analysis was performed. As discussed above, relatively high chlorophyll *a* concentrations were observed in spring and fall. Apart from this bimodal feature of phytoplankton blooms, small-scale variations in chlorophyll *a* concentrations were observed during the year. Increases in chlorophyll *a* concentrations were often related to decreases in subsurface temperatures with a short lag time of a few days.

In the UB, subsurface chlorophyll *a* concentration maxima usually occurred at around 30–40 m owing to the diffusion of nutrients across the seasonal thermocline (Hong et al., 1997). However, this type of nutrient diffusion cannot support phytoplankton growth in surface waters. In most cases, small amounts of nutrients that diffuse through the strong thermocline are readily absorbed by phytoplankton living in subsurface layers, thus producing subsurface chlorophyll maxima (Fig. 5). An active mechanism is needed to transport nutrients upward to enhance phytoplankton growth in surface waters. Synchronous water temperature oscillations have been observed at 40–80 m, which seem to be coupled with the barotropic tide or internal waves (Park and Watts, 2006) as they travel relatively rapidly (Sangrà et al., 2005). Enhancement of biological productivity in shelf-break regions has also been attributed to internal tidal mixing, which induces upward transport of nutrient-rich cold water (Pingree et al., 1986; Mann and Lazier, 1991).

We postulated that mesoscale physical processes occurring in subsurface layers increases nutrients and influences chlorophyll *a* concentrations in the surface waters near the Dok Islets. In this context, we statistically analyzed the relationships between surface chlorophyll *a* concentrations and the subsurface temperature. The period for

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10, 10429–10458, 2013

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



the cross-correlation analysis was chosen to be from 1 May to 30 June when significant correlations were found between the chlorophyll *a* concentration and subsurface temperature. Daily mean values were exclusively used in this cross-correlation analysis. This highly correlated period occurred when the DETS buoy was located near the boundary of the DCE after the spring bloom (Fig. 8). When chlorophyll *a* concentration at the surface and the temperature at a depth of 40 m were cross-correlated, the highest correlation coefficient was found for a 6 day lag (Fig. 9a; $r = -0.47$, significant at the 95 % confidence level). This indicated that the highest chlorophyll *a* concentration typically occurred 6 days after a decrease in temperature at 40 m, which was an indication of upwelling, and thus, of transport of nutrients from the deep layer to the surface layer.

In October, the cross-correlation values for the temperature at a depth of 40 m versus the chlorophyll concentration reached their most significant (negative) value for a maximum lag time of 5 days ($r = -0.418$), implying that 5 days were required for the chlorophyll *a* values to change following a decrease in temperature at 40 m.

The mean surface chlorophyll *a* concentration was not correlated with the subsurface temperature from July to September. During the summer, the phytoplankton biomass in the upper layer is suppressed by low nutrient concentrations (typically $< 1 \mu\text{M}$ of nitrate) caused by the stratification of the water column (Rho et al., 2010; Kim et al., 2010). The nitrate concentration increased sharply at depths below 30 m and was $> 10 \mu\text{M}$ below 50 m (Fig. 5). Wind-induced upwelling of subsurface waters with surface water is considered to be one of the primary driving forces of the phytoplankton growth in late spring and early fall. The daily mean surface chlorophyll *a* concentration was not significantly correlated with wind speed or wave height.

4.3 Eddy and wind interactions

The DCE was observed near to the DETS mooring site year-round in 2009 (Fig. 8) using the eddy detection method of Lee and Niiler (2010b) and satellite measurements of the sea level anomaly. The five-day mean wind (red arrows) measured from

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



DETS and the geostrophic current (blue arrows) from the sea-level anomaly (Fig. 10a) clearly show two unusually high phytoplankton blooms (shaded periods) related to the upwelling events (Fig. 10b). The maximum chlorophyll *a* concentration was found in the area near the eddy rim, similar to the chlorophyll *a* concentration distribution reported by Yoder et al. (2010), and the mooring site was located in the eddy rim area (Fig. 8a and b) where the wind and current had the same direction over several weeks (Fig. 10a). These observations are the first direct observations that the upwelling induced by wind-eddy interactions (Lee and Niiler, 1998) is related to nutrient input to the euphotic zone in the cyclonic eddy. During the summer months, a strong and shallow thermocline with weak wind may hinder nutrient supply through upwelling driven by the wind-eddy interaction.

These variations in subsurface temperature, particularly at a depth of 20 m (Fig. 10b), appear to be indicative of deep-water upwelling or turbulent mixing due to eddy pumping in May, June, and October 2009. Episodic nutrient inputs into the euphotic zone associated with mesoscale eddies have previously been proposed to explain variations in chlorophyll *a* concentrations at the sea surface. We conclude that the nutrient supply from upsloping of the isopycnals due to eddy pumping may result in mesoscale changes in phytoplankton in the UB of the southwestern East/Japan Sea. We further suggest that the nutrients supplied through eddy pumping during seasonal bloom periods enhance phytoplankton bloom further (Fig. 10b). MODIS chlorophyll *a* images showed that cyclonic eddies often occurred and appeared to be responsible for scattered patches of phytoplankton in the East/Japan Sea (Lee and Niiler, 2010a).

5 Conclusions

Significant energy is introduced into the East/Japan Sea by inflow conditions through the Korea Strait, in particular to the Ulleung Basin in the southwestern part of the sea, and the intrusion of the Tsushima Warm Current into the sea and the bottom geomorphology of the sea favor eddy formation. Moreover, the sea is subject to winds that

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



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Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)

[⏪](#)

[⏩](#)

[◀](#)

[▶](#)

[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

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**Eddy- and
wind-sustained
moderate primary
productivity**

G.-H. Hong et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

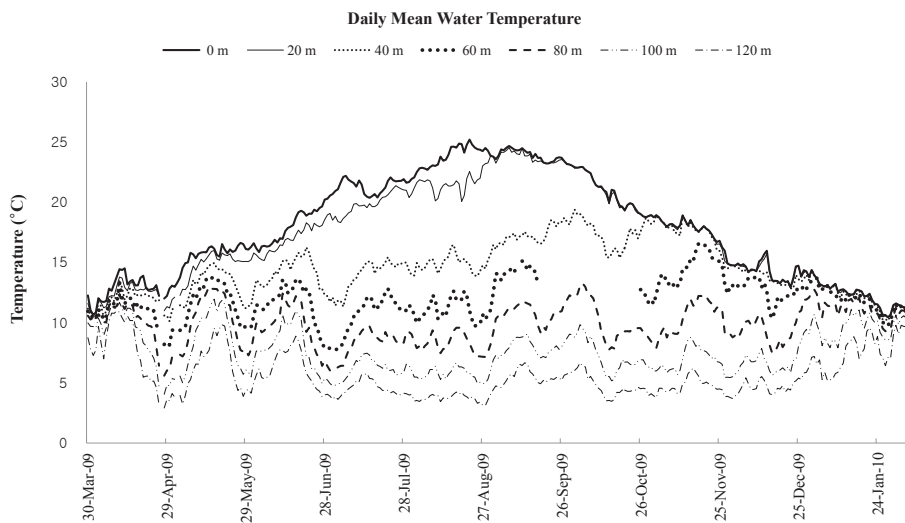
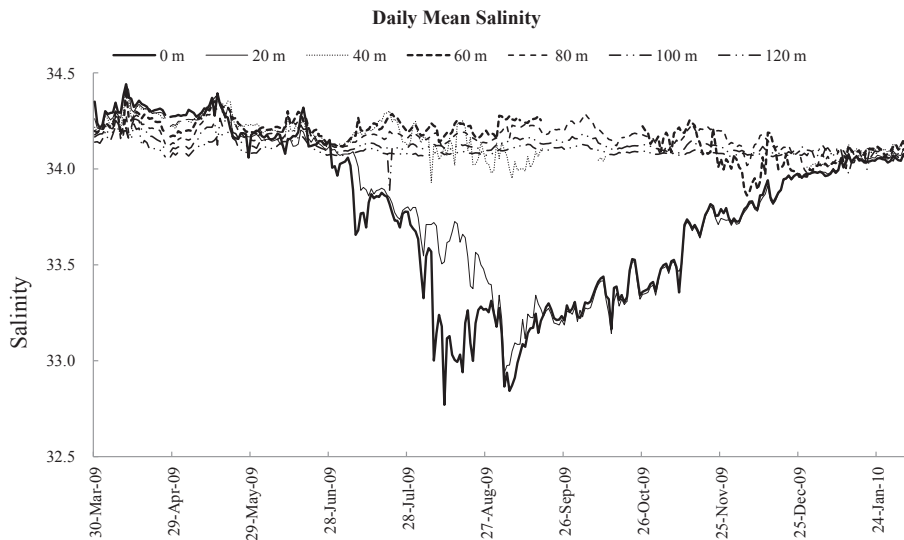


Fig. 1. Daily mean temperature during April 2009–February 2010 at the DETS buoy.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Eddy- and
wind-sustained
moderate primary
productivity**

G.-H. Hong et al.

**Fig. 2.** Daily mean surface salinity during April 2009–February 2010 at the DETS buoy.[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

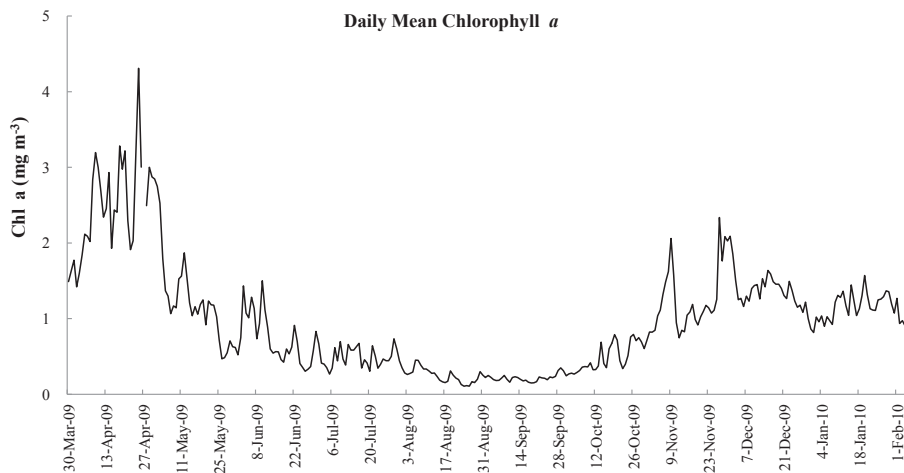


Fig. 3. Variation of daily mean chlorophyll *a* concentrations in the surface waters during April 2009–February 2010.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

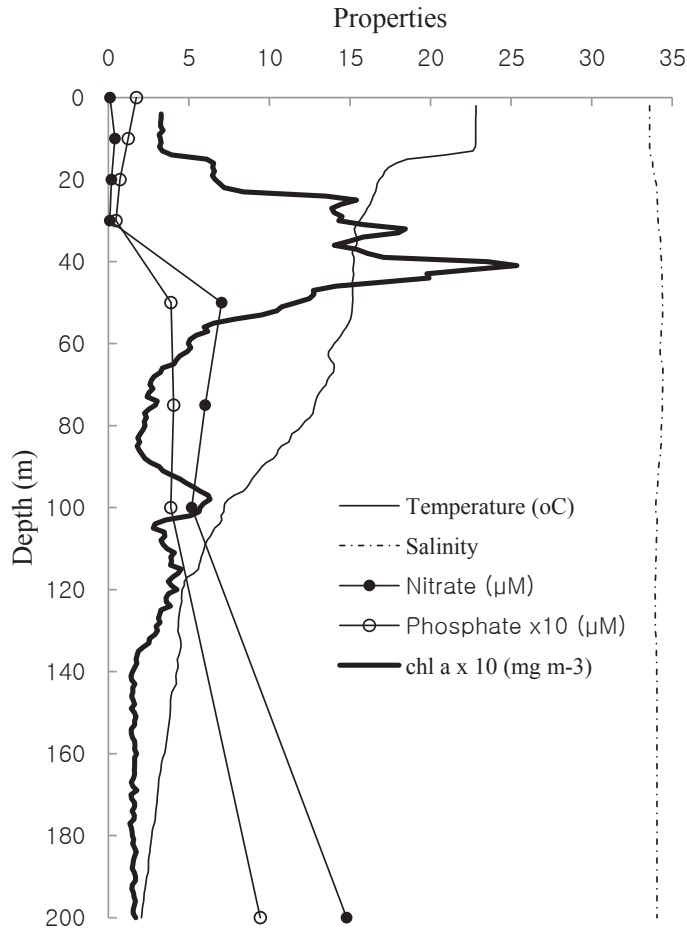


Fig. 5. Vertical distribution of chlorophyll *a* concentration derived from in vivo fluorescence and environmental variables near the DETS buoy (EC1, July 2010, Kim et al., 2010).

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

[Title Page](#)

[Abstract](#) | [Introduction](#)

[Conclusions](#) | [References](#)

[Tables](#) | [Figures](#)

[◀](#) | [▶](#)

[◀](#) | [▶](#)

[Back](#) | [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Eddy- and
wind-sustained
moderate primary
productivity**

G.-H. Hong et al.

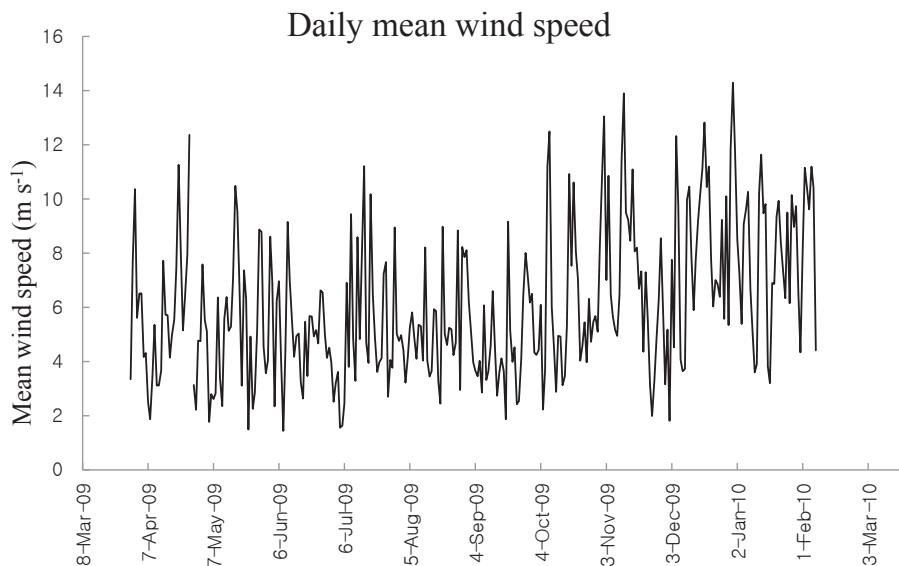


Fig. 6. Daily mean wind speed at the sea surface in the middle of the East/Japan Sea at the DETS buoy.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

**Eddy- and
wind-sustained
moderate primary
productivity**

G.-H. Hong et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

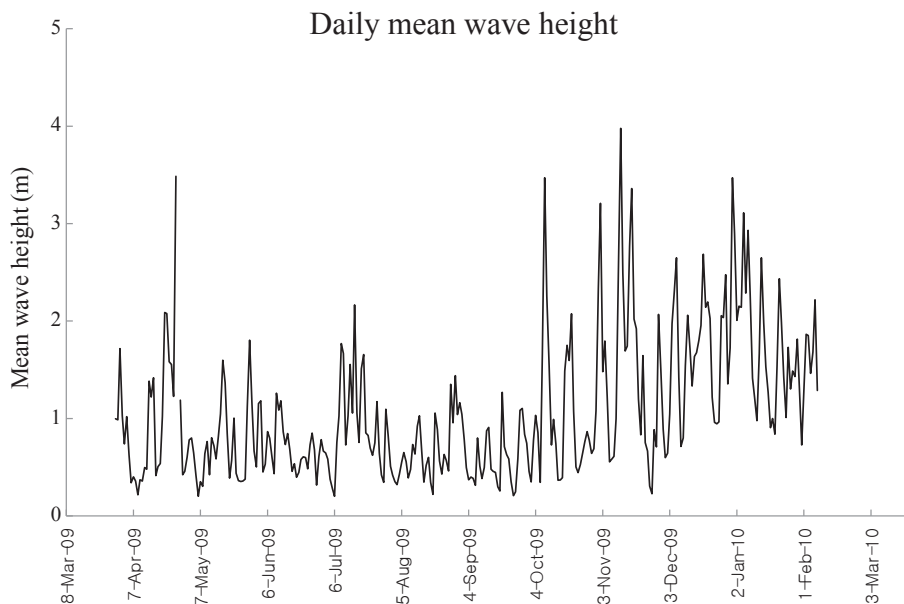


Fig. 7. Daily mean wave height at the sea surface in the middle of the East/Japan Sea at the DETS buoy.

Eddy- and wind-sustained moderate primary productivity

G.-H. Hong et al.

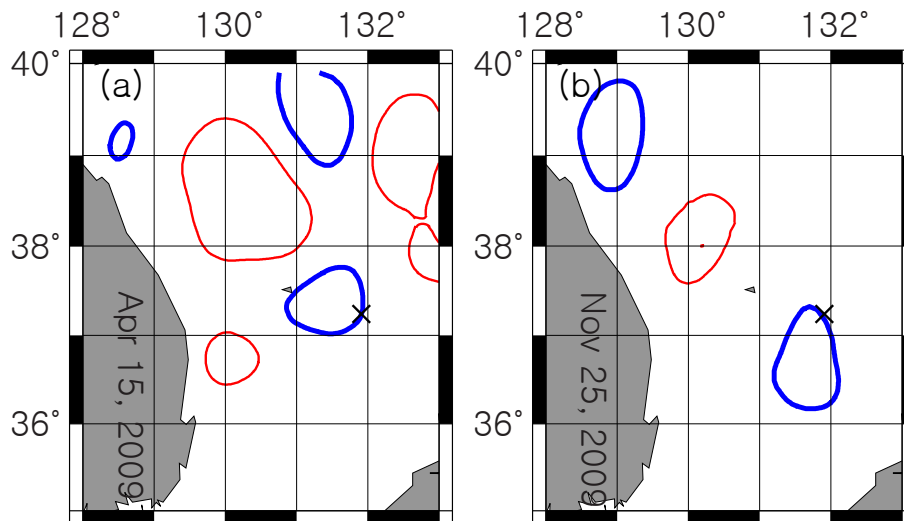


Fig. 8. Observed eddies from the sea-level anomaly using the eddy detection method of Lee and Niiler (2010b). Cyclonic eddies (cold eddies) are colored blue and anticyclonic eddies (warm eddies) red. The X denotes the location of the DETS buoy.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[⏪](#)[⏩](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Eddy- and
wind-sustained
moderate primary
productivity

G.-H. Hong et al.

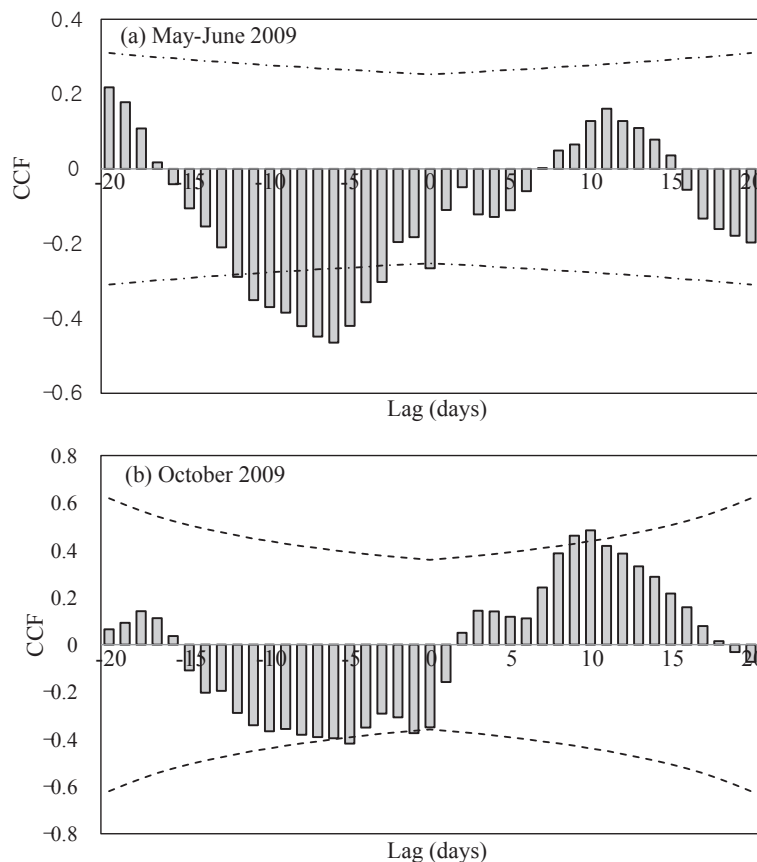


Fig. 9. Cross-correlation between chlorophyll *a* and temperature at 40 m depth: **(a)** 6 days ($r = -0.465$) in May and June and **(b)** 5 days ($r = -0.418$) in October 2009. 95 % confidence level of the Cross-correlation Coefficient (CCF) values (dashed lines) were calculated at 2σ standard deviation.

Eddy- and
wind-sustained
moderate primary
productivity

G.-H. Hong et al.

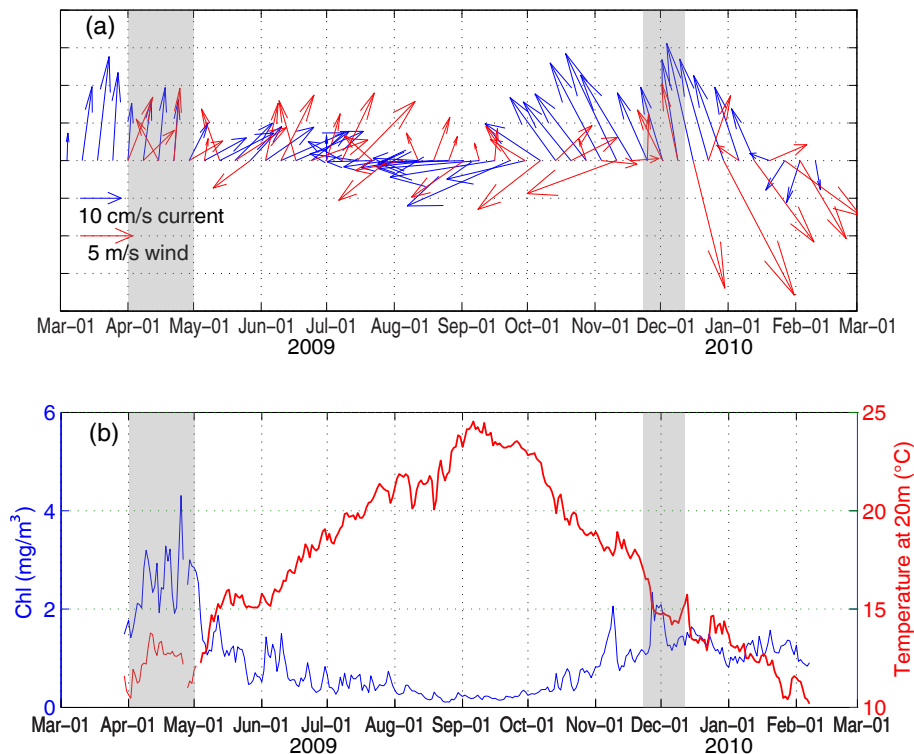


Fig. 10. (a) Wind (red arrows) measured by DETS and the geostrophic current (blue arrows) from the sea-level anomaly at the mooring site. (b) Chlorophyll *a* concentration (blue line) and temperature (red line) at a 20 m depth. Gray shaded areas represent blooms resulting from the wind-eddy interaction induced upwelling.