Estuarine, Coastal and Shelf Science 153 (2015) 74–85

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Assessing depth-integrated phytoplankton biomass in the East China Sea using a unique empirical protocol to estimate euphotic depth

Hiroshi Koshikawa [a, *], Hironori Higashi [a], Toru Hasegawa [b], Kou Nishiuchi [c], Hiroaki Sasaki [b], Masanobu Kawachi [a], Yoko Kiyomoto [b], Kazufumi Takayanagi [d], Kunio Kohata [e], Shogo Murakami [a]

[a] National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Japan
[b] Seikai National Fisheries Research Institute, Fisheries Research Agency, Taira-machi, Nagasaki 851-2213, Japan
[c] Fisheries Research Agency, 2-3-3 Minatomirai, Nishi-ku, Yokohama, Kanagawa 220-6115, Japan
[d] Sanyo Techno Marine Inc., 1-3-17 Nihonbashi-horidome-cho, Chuo-ku, Tokyo 103-0012, Japan
[e] Center for Environmental Science in Saitama, 914 Kamitanadare, Kazo, Saitama 347-0115, Japan

ARTICLE INFO

Article history:
Received 21 April 2014
Accepted 15 November 2014
Available online 8 December 2014

Keywords:
East China Sea
Changjiang (Yangtze) river
river plumes
euphotic zone
phytoplankton
biomass

ABSTRACT

The Changjiang (Yangtze) River plume has a direct impact on phytoplankton biomass in the East China Sea (ECS). The present study aimed to analyze the spatial distribution of depth-integrated chlorophyll *a* (Chl-*a*) concentrations from the surface to the euphotic depth (Z_e; $\sum Chl_{Z_e}$) using samples collected at 50 stations in the ECS during a cruise in June 2007. However, spatial coverage was limited because the Z_e, obtained from radiometric measurement of the vertical diffuse attenuation of solar irradiance, was only available at the 20 daytime stations. To address this limitation, it was determined that Z_e could be expressed empirically using the vertical means of Chl-*a* concentration, turbidity, and salinity in the euphotic zone. Using this relationship, the potential value of Z_e at night-time or low-light stations was calculated, and a dataset of ($\sum Chl_{Z_e}$) for the entire research area was obtained. A low salinity surface water mass (LSSW) was identified on the eastern continental shelf (125.0°–126.5°E, 30.0°–31.0°N), probably part of the Yellow Sea Mixed Water, but clearly influenced by Changjiang Diluted Water (CDW) extending from the west. The Taiwan Current Warm Water mass (TCWW) was located to the south of the LSSW. Other oceanic water masses, including Kuroshio Surface Water, were located to the east of the LSSW. The means of the Z_e and $\sum Chl_{Z_e}$ in the LSSW were significantly shallower and higher, respectively, compared with the TCWW and other oceanic water masses ($p < 0.01$). The present study suggests that the extension of the Changjiang River plume beyond the CDW affects the phytoplankton biomass on the eastern continental shelf of the ECS, more than 300 km from the river mouth.

1. Introduction

Large river plumes have important impacts on marine ecosystems, not only in estuaries, but also on adjacent continental shelves. The Amazon River plume enhances primary production for hundreds of km along the neighboring continental shelf (e.g., Dagg et al., 2004). For some large rivers with highly populated watersheds, additional anthropogenic influences on marine ecosystems occur through the extended plume. For example, the extended plume of the Mississippi River has both natural and anthropogenic impacts on the ecosystem in the Gulf of Mexico (Lohrenz et al., 1997).

The Changjiang (Yangtze) River is ranked fifth in the world in terms of discharge volume and is one of the large rivers thought to have considerable anthropogenic impacts on the marine ecosystem on the continental shelf of the East China Sea (ECS). Since the 1980s, algal bloom events have become more frequent and the chlorophyll *a* (Chl-*a*) concentration has increased in the Changjiang estuary and in the adjacent western shelf area of the ECS (122°–123.5°E, 30.5°–32°N) where surface shading by suspended particulate matter is less marked (e.g., Chen, 2003; Chai et al., 2006). During the summer wet season, the waters at the leading edge of the plume, referred to as Changjiang Diluted Water (CDW) and with a salinity of less than 31, often extends east or northeast beyond the

* Corresponding author.
E-mail address: koshikaw@nies.go.jp (H. Koshikawa).

http://dx.doi.org/10.1016/j.ecss.2014.11.017
0272-7714/

adjacent western shelf and reaches the eastern shelf around 124°–125°E, 30°–33°N, more than 300 km from the river mouth (Hu, 1994; Su and Weng, 1994). Siswanto et al. (2008) identified an increase in dissolved inorganic nitrogen on the central and eastern shelf (123.5°–125.5°E, 31°–32°N) in conjunction with an increase in nitrogen fertilizer use in China during the last few decades, suggesting that anthropogenic river-borne nutrients are transported in the plume. A recent analysis of satellite images showed that an eastward shift of areas of high surface Chl-*a* coincided with the movement of CDW from the river mouth to the east of Jeju Island during summer (e.g., Yamaguchi et al., 2012). Therefore, the extension of the plume might affect the surface phytoplankton biomass on the eastern shelf beyond the estuary and on the adjacent western shelf, especially in summer.

The distribution of surface Chl-*a* as an index of phytoplankton biomass can be estimated from satellite data. However, in eastern shelf waters in summer, phytoplankton aggregates in subsurface waters rather than in surface waters (Zhao and Guo, 2011), forming a subsurface chlorophyll maximum (SCM) (Kim et al., 2009; Wang et al., 2014). The SCM cannot be clearly determined from satellite data but is a substantial component of the phytoplankton biomass in the water column (Kim et al., 2009). The SCM in eastern shelf waters of the ECS could be maintained by the supply of nutrients from deep waters (Kim et al., 2009; Zhao and Guo, 2011), implying that the plume extension could have less influence on the SCM than on surface Chl-*a*. To date, however, it is not clear whether the plume extension towards the eastern shelf and beyond the CDW is directly associated with the SCM and/or phytoplankton biomass on the shelf. One way to investigate this uncertainty is to determine whether the phytoplankton biomass in the water column differs between waters inside and outside the plume, using depth-integrated Chl-*a* ($\sum Chl$) measured with an *in situ* optical chlorophyll sensor.

Many previous studies have investigated the spatial distribution of Chl-*a* in the ECS (e.g., Ning et al., 1988; Gong et al., 2003; Chai et al., 2006). However, most of these studies have reported the Chl-*a* as concentrations at specified depths or at the SCM, and the results have not provided detailed information on the spatial distribution of $\sum Chl$.

There have been few studies of the spatial distribution of $\sum Chl$ in the ECS (e.g., Gong et al., 1996; Kim et al., 2009), possibly as a result of the practical difficulties involved in defining the vertical integral interval. From an ecological viewpoint, the $\sum Chl$ should be integrated within the euphotic zone ($\sum Chl_{Z_e}$). The euphotic zone is defined as the depth interval from the surface to the euphotic depth (Z_e), at which the downward irradiance of photosynthetic active radiation (PAR) is 1% of the surface value. However, the widely used radiometric measurement of Z_e can only be carried out during daytime. Research cruises generally operate on 24-h schedules and Z_e data cannot be collected at night-time stations, resulting in poor spatial coverage of the Z_e dataset. Although some of the missing Z_e data can be interpolated geo-statistically using data from other stations, the accuracy of such interpolation tends to be poor, first, because the geometrical relationship between the actual and interpolated Z_e data is not ideal, and second, because there can be a large variation in Z_e between neighboring stations associated with changes in water masses.

Gong et al. (1996) investigated $\sum Chl$ in the upper 50 m of the water column, and found a very high phytoplankton biomass in the region of the CDW. Kim et al. (2009) investigated $\sum Chl$ from the surface to the sea floor, or to 100 m if the depth was more than 100 m ($\sum Chl_{Total}$), and found that $\sum Chl$ varied little among different water masses, including CDW.

Both of the depth-integration methods described above have some inherent problems. First, $\sum Chl_{Total}$ may include Chl-*a* present below the Z_e, which may not be actively involved in primary production. Second, especially when the depth from the surface to the sea floor is used as the integral interval, high concentrations of suspended non-algal particles near the sea floor may lead to significant errors in the *in situ* optical measurements of Chl-*a* (Omand et al., 2009). Suspended non-algal particles are present as a result of strong tidal flows and turbulence on the shallow continental shelf of the ECS (Matsuno et al., 2006). This problem may be addressed by using a specified water depth instead of the sea floor as one edge of the integral interval, but there is still uncertainty in estimating living phytoplankton biomass if the actual Z_e varies widely across the specified depth.

If the waters of the ECS are classified as Case I water, in which internal optical properties are well parameterized by the concentration of Chl-*a* as an optically active compound (OAC), some existing empirical or theoretical models for the diffuse attenuation coefficient of PAR (K_d; m^{-1}) (Morel, 1988; Platt and Sathyendranath, 1988; Morel and Maritorena, 2001) could be used to predict the mean K_d within the euphotic zone ($K_{d,(0\to Z_e)}$) in the ECS. Consequently, the Z_e (m) could be calculated based on the assumption of a natural logarithmic relationship between Z_e and $K_{d,(0\to Z_e)}$ (Eq. (1); (Kirk, 1994)

$$K_{d,\ (0\to Z_e)} = -\frac{1}{Z_e}\ln 0.01 \tag{1}$$

However, the surface waters of the ECS have been categorized as Case II water, with high levels of river-borne colored dissolved organic matter (CDOM) and sometimes suspended silt particles (Gong, 2004; Siswanto et al., 2011). Unlike the K_d estimation model for Case I water, the model for Case II water is still under development because of its optical complexity (Morel et al., 2006; Odermatt et al., 2012). However, Devlin et al. (2009) successfully explained the variation in K_d from coastal to offshore waters around the United Kingdom (probably Case II water) using a simple linear equation.

$$K_d = k_w^* + k_{CD}^*\cdot \mathrm{CDOM} + k_{PH}^*\cdot \mathrm{chloro} + k_{SP}^*\cdot \mathrm{SPM} \tag{2}$$

where CDOM, chloro, and SPM are concentrations of CDOM, phytoplankton, and suspended particulate matter, respectively, as representative OACs, the parameter k_w^* is the partial attenuation coefficient of water, and k_{CD}^*, k_{PH}^*, and k_{SP}^* are specific attenuation coefficients per unit concentrations of CDOM, chloro, and SPM, respectively. Regression analysis between K_d and concentrations of these OACs generated fitting parameters that provided a good empirical explanation of the variation in K_d in that study (Devlin et al., 2009). It should be noted that Eq. (2) may only have physical meaning when the four attenuation effects are independent and additive, and this is unlikely, even in Case I water. Therefore, the fitting parameters used by Devlin et al. (2009) to estimate K_d may only work empirically and for water masses similar to where the survey data were obtained. Nevertheless, the application of a similar protocol was expected to produce practical fitting parameters to explain the variation in K_d in the ECS. Appropriate fitting parameters could be used to estimate $K_{d,(0\to Z_e)}$ and Z_e for night-time stations based on vertical measurements of OACs and Eq. (1). It is important to note that the Z_e calculated for night-time stations should be considered as a potential value based on the assumption that the same water column is exposed to the mean incident light conditions during daytime observation.

The primary objective of the present study was to determine whether the Changjiang River plume, extending towards the east of the ECS shelf, influences phytoplankton biomass in the euphotic zone. Data were collected in June 2007 during a research cruise