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Temporal variation in water intrusion of a tidal frontal system and distribution of chlorophyll in the Seto Inland Sea, Japan

Tomohiro Komorita*, Xinyu Guo, Naoki Yoshie, Naoki Fujii[1], Hidetaka Takeoka

Center for Marine Environmental Studies, Ehime University, 2-5 Bunkyo-Cho, Matsuyama 790-8577, Japan

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ABSTRACT

Monthly field surveys conducted from April to November 2009 in a tidal front in the Seto Inland Sea, Japan provided a spatial and temporal dataset for investigating seasonal variations in nutrient supply and the formation of a chlorophyll *a* (Chl-*a*) maximum. The upward diffusive flux of nutrients is estimated from observational data but it accounted for less than 5% of the nutrients needed to support the primary production of phytoplankton in the front area of the stratification region when the density difference between the surface layer and bottom layer is greater than 0.5 kg m^{-3}. Instead of vertical diffusion, the lateral intrusion of water with high nutrient concentration from the mixed area represented the major nutrient supply in the front area. The depth of the lateral intrusion changed with the month: the surface layer in July became the middle layer in August. According to the calculation of numerical model, an anti-clockwise circulation is intensified by removing river runoff (i.e., low precipitation) in this study area, and the change of lateral intrusion is likely caused by the change of anti-clockwise circulation along with the temporal variation in river runoff. Consequently, the Chl-*a* peak appeared in the vicinity of the surface front (up to 3 μg L^{-1}) in July, but was in the subsurface (up to 9 μg L^{-1}) in August. Diatom species were a relatively minor taxa of the phytoplankton community up to July, although a relatively high $Si(OH)_4$-Si concentration (up to 20 μmol L^{-1}) was confirmed. In contrast, the subsurface Chl-*a* maximum (SCM) in August was mainly comprised of diatoms as evidenced by the reduction of both $Si(OH)_4$-Si and Si/N from the surface to subsurface layer (0–20 m depth). Therefore, the supply of both nutrients and the seed population necessary for the formation of the SCM results from the tidal frontal system and phytoplankton assemblages within the tidal front system should be varied on a monthly basis.

1. Introduction

Tidal fronts develop seasonally in many coastal waters (Simpson and Hunter, 1974), forming a transition zone between stratified regions developed as a result of solar heating and regions of weak tidal currents and mixed regions due to strong tidal currents. Traditionally, the stratified region has been considered to be a two-layered system in which the transfer of nutrients from the bottom layer to the surface layer is suppressed by strong thermal stratification, allowing phytoplankton to remain in the euphotic layer for extended periods of time causing the development of nutrient depletion. In the mixed region, phytoplankton remain in the euphotic layer for only a short period of time due to strong vertical mixing and growth is likely to be limited by light availability; consequently, depletion of inorganic nutrients does not occur. Optimal nutrient and light conditions are therefore achieved only in the frontal zone between the mixed and stratified regions (Le Fevre, 1986; Mann, 2000). As a result, an area of high chlorophyll concentration forms in the surface layer or in the subsurface layer of the frontal zone (Franks and Chen, 1996; Holligan, n.d.; Martínez and Ortega, 2007; O'Boyle and Silke, 2009).

Several researchers have proposed an alternate model to the two-layered system. In the proposed three-layered system of the stratified region at the tidal front, stratification is separated into surface, bottom, and middle layers, and nutrients from the bottom layer of the stratified region are carried to the subsurface layer through the adjacent mixed region by newly described mechanisms such as “nutrient bypass” (Takeoka et al., 1993), “tidally-fed pump” (Pedersen, 1994), and “tidal pumping” (Richardson et al., 2000). In such three-layered systems, a subsurface chlorophyll maximum (SCM) may develop in response to the horizontal

* Corresponding author. *Present address*: Faculty of Environmental and Symbiotic Sciences, Prefectural University of Kumamoto, 3-1-100, Tsukide, Kumamoto 862-8502, Japan.
E-mail address: komorita@pu-kumamoto.ac.jp (T. Komorita).
[1] Present address: Institute of Lowland and Marine Research, Saga University, 1, Honjyo-Cho, Saga 840-8502, Japan.

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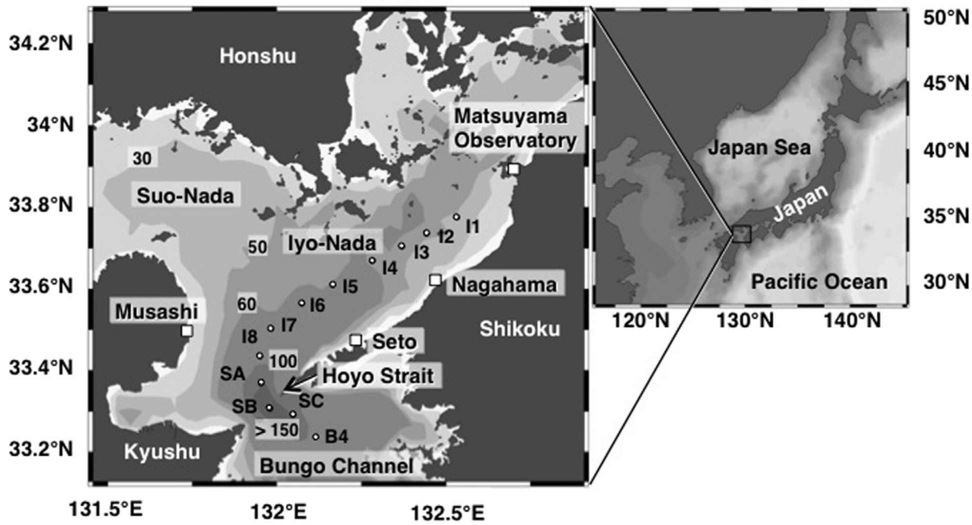

Fig. 1. Study area and sampling station locations. On the left panel, the open circles represent sampling stations and the numbers in the white boxes represent water depth in meters.

intrusion of nutrient-rich water into the photic zone (Richardson et al., 2000) and the introduction of a seed population of phytoplankton species by the horizontal intrusion from the mixed region (Kaas et al., 1991; Lund-Hansen and Vang, 2004; Nielsen et al., 1990).

Tidal fronts are generated in early spring and disappear in early autumn mainly because of seasonal variations in sea surface heat flux, wind forcing, and river discharge (Yanagi and Tamaru, 1990). However, most observations of tidal fronts are carried out only in the summer when the tidal front is fully developed (Gowen and Bloomfield, 1996; Holligan, n.d.; Townsend and Thomas, 2002). By making observations only on established tidal fronts, seasonal variations in biogeochemical dynamics and biogeochemical cycles related to the tidal fronts remain largely unknown.

The Seto Inland Sea is a large, shallow, semi-enclosed sea in western Japan with an area of 17,000 km^2 and mean water depth of 37 m (Fig. 1). This area has high biological productivity with annual primary production of 218 g C m^{-2} yr^{-1} in the water column (Tada et al., 1998). The annual fish catch in the sea is 3.2–28 times larger than that in other typical semi-enclosed seas such as the Chesapeake Bay, the Baltic Sea, the North Sea, and the Mediterranean Sea (Takeoka, 2002). The deep but narrow straits in the Seto Inland Sea produce strong tidal currents, leading to thorough vertical mixing of the water column in the straits, which remain mixed throughout the year (Takeoka, 2002). In contrast, the wide and shallow areas between the straits, known as *nada* in Japanese, have weak tidal currents and strong stratification develops in the summer. Consequently, several tidal fronts form between the *nadas* and straits (Takeoka, 2002). The strait-*nada* system, which is a tidal front system, along with the efficient transport of nutrients from the bottom layer of the *nada* (=stratified region) to the euphotic layer near tidal fronts is considered to be one of the most important mechanisms for sustaining the high biological productivity in the Seto Inland Sea.

In the eastern part of the Seto Inland Sea, tidal fronts develop in spring and are sustained until early autumn (Yanagi and Koike, 1987) between the Hoyo Strait and the Iyo-*Nada* (Fig. 1). In summer, intrusion of water carrying nutrients from the Hoyo Strait into the middle layer of Iyo-*Nada* (Takeoka et al., 1993) is suggested to stimulate the photosynthetic activity of phytoplankton assemblages (Yamamoto et al., 2000). In the central part of Iyo-*Nada* (i.e., stratified region), residual currents show an anti-clockwise circulation from spring to summer (Chang et al., 2009). The anti-clockwise circulation should be affected by several meteorological forcings such as solar heating, river discharge (i.e., rainfall), and wind forcing (Yu et al., in press). Thus, it is easily expected that the biogeochemical cycle related to the middle layer intrusion also varied with those seasonal meteorological forcings. However, field studies to examine seasonal variation in phytoplankton and nutrient distributions near the front have not been documented.

In this study, we conducted monthly field surveys from April to November 2009 to span the development and disruption of stratification in the Seto Inland Sea. We investigated spatio-temporal variation in physical (water stratification), chemical (nutrient), and biological (phytoplankton assemblages) processes. We used the vertical distribution patterns of water temperature, salinity, density, dissolved inorganic nutrients [NO_3+NO_2-N and $Si(OH)_4$-Si], and chlorophyll *a* (Chl-*a*) (both total and size-fractionated) in the tidal front system to examine the formation and disruption of the stratified region. Based on field data, we evaluated the horizontal intrusion of mixed region water into the middle layer of the stratified region, and we demonstrate the seasonal variation of horizontal intrusion, dominant phytoplankton taxa and nutrient composition in the tidal front system. Finally, we discuss the time series variation of the phytoplankton assemblages within a tidal frontal system based on the examination of the relationship between the Chl-*a* peak and the depth of the horizontal intrusion and the supply of seed species to the phytoplankton community.

2. Materials and methods

Ten field surveys were conducted from April to November 2009 (Table 1) in the three regions of Iyo-*Nada* with eight stations (Stns. I1–I8: approximately 50–80 m in depth), Hoyo Strait with three stations (Stns. SA–SC: over 150 m in depth) and Bungo Channel with one station (Stn. B4: approximately 80 m in depth) (Fig. 1). The daily tidal range recorded at the Matsuyama Observatory (Fig. 1) was obtained for survey days. The M_2 constituent was dominant over the entire Seto Inland Sea, and the amplitude of the M_2 tidal current constituent reached approximately 1.5 m s^{-1} in the Hoyo Strait (Takeoka, 2002).

At each station, a rosette sampling unit equipped with conductivity, temperature and depth probes, a chlorophyll fluorometer (JFE Advantech Co., Ltd.), and ten 3 l Niskin bottles (JFE