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Variability of factors driving spatial and temporal dispersion in river plume and *Chattonella antiqua* bloom in the Yatsushiro Sea, Japan

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ABSTRACT

The dynamics of river plume in relation to harmful blooms of the raphidophycean flagellate, *Chattonella antiqua* in summer 2008–2010 in the Yatsushiro Sea, Japan were studied using a hydrodynamic model and monitoring data. In the southern area, the bloom formed in the waters stratified by a halocline caused by the southward expansion of riverine water from the Kuma River after the bloom initially forming in the northern area. The timing of the southward riverine water advection can be explained by the balance between the wind stress term and the pressure gradient term calculated from the horizontal density difference between the northern and southern areas. The wind stress and pressure gradient terms were evaluated using the sea surface temperature, salinity, wind speed and direction at two stations. Real time monitoring or continuous observations in these areas will enable nowcasts of bloom expansion when a bloom develops in the northern area.

1. Introduction

The dynamics of a river plume in coastal waters are generally complex, as tidal currents and winds impact its behavior (Kourafalou et al., 1996; Garvine, 1999; Fong and Geyer, 2001; Fujiwara et al., 2002; Isobe, 2005; MacCready et al., 2009). In Japan, river plumes vary in physical phenomena and affect the ocean states of coastal waters during the rainy season in summer. The freshwater loads of the river supplies enriched nutrients to the coastal waters (Justić et al., 1995; Howarth et al., 1996), creates the favorable oceanic condition for the growth and transports the bloom to the downstream (Harper and Guillen, 1989; Aoki et al., 2012). The plankton community responses changes in the ocean condition due to the river discharge variation, and the specific plankton species forms the bloom in consequence (Lampert et al., 2002; Lunven et al., 2005; Guillaud et al., 2008).

Blooms due to harmful algae are a recurrent phenomenon, severely damaging aquatic organisms in coastal waters and human activities. In the last decade, blooms of the raphidophytes flagellate *Chattonella* spp. have appeared in Japanese coastal waters and resulted in huge economic losses to aquaculture industries (Honjo, 1994; Okaichi, 1997; Imai et al., 1998; Imai and Yamaguchi, 2012; Katano et al., 2012). In the Yatsushiro Sea (Fig. 1), *Chattonella antiqua* blooms occurred in 2009 and 2010, causing mortality of cultured fishes (e.g. *Seriola quinqueradiata* and *Seriola dumerili*) with an approximate value of ¥7,000,000,000 (US$70,000,000; at an exchange rate of ¥100 = $1) (Fisheries Agency, 2010, 2011). Therefore, various researches to determine the effective mitigation and/or prediction strategies are required.

According to Onitsuka et al. (2011), the 2010 *C. antiqua* bloom in the southern area of the Yatsushiro Sea was triggered by the formation of the haline stratification (halocline). The increase in the cell density of *C. antiqua* was synchronized with the sea surface salinity decrease. Aoki et al. (2012) studied the spatio-temporal distribution of the 2009 *C. antiqua* bloom using a three-dimensional hydrodynamic model coupled to a Lagrangian particle-tracking model. The simulation results indicated that the northeastern area was the source region of the widespread bloom, and the southwestward evolution of the bloom was primarily controlled by the passive transport due to the surface residual current driven by the fresh water discharge from the Kuma River,

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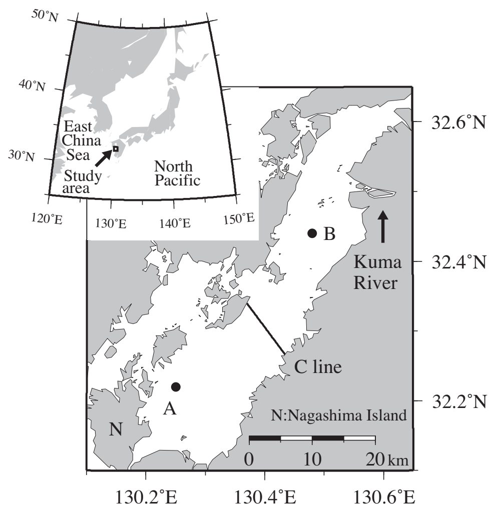

Fig. 1. Map of the study area (Yatsushiro Sea). Solid circles indicate locations of stations A and B.

the largest river located in the northern area of the Yatsushiro Sea, and northeasterly winds. They suggested that the discharge from the Kuma River was likely to affect not only the spatio-temporal variation of the bloom by providing buoyancy flux but also the bloom formation in the northeastern area due to nutrient supply.

The previous studies have indicated that the dynamics of the river plume play an important role for the bloom of *C. antiqua* in the Yatsushiro Sea. Limitations in time and space of the observations restrict understanding of the short term dynamics of the river plume. The aim of this study is to clarify the physical processes affecting *C. antiqua* blooms in the Yatsushiro Sea using a numerical model. In particular, we focus on the dynamics of the river plume and stratification related to both the expansion and subsequent breakdown of the bloom from 2008 to 2010. Driving force of river plume and bloom advection are quantitatively evaluated in order to aid in constructing forecasts for *C. antiqua* blooms.

2. Materials and methods

2.1. Study area

Yatsushiro Sea is a eutrophic and semi-enclosed sea located in the coastal region of the western Japan (Fig. 1). The bay is about 70 km long and 15 km wide with mean depth 30 m. The tidal range is about 4 m in the spring tide (Takikawa et al., 2004). In the inner part, the annual cycle of a sea surface temperature with a maximum in August of 27 °C and a minimum in February of 10 °C is shown by monthly field survey (Tai et al., 2011). The Kuma River is the largest river running into the study area and located in the northern area of the Yatsushiro Sea. The annual mean discharge is about 100 $m^3 s^{-1}$ and discharge increases from May to August. The enriched nutrient water frequently distributes and the plankton bloom frequently occurred in the northern area around the mouth of Kuma River in this period (Takikawa et al., 2004). The Yatsushiro Sea connects to the East China Sea through two narrow straits located in the southern area. Flows through the straits are main contributors to the exchange of salt and nutrient between the open ocean.

2.2. Description of field observations

We used cell density data of *C. antiqua* to compare the spatio-temporal distributions of the simulated river plume with the bloom. Water sampling was conducted at stations A and B (Fig. 1 for their locations) by the Kumamoto Prefectural Fisheries Research Center, the Kagoshima Prefectural Fisheries Technology and Development Center and the Azuma-cho Fishery Cooperative Association during the summer from 2008 to 2010. Water samples were collected with a Van-Dorn sampler or Kitahara water sampler at depths of 0, 5, 10 m (additionally also 2 m at station B). Samples were not fixed on the ship, and cell number of *C. antiqua* was counted within a day using microscopes.

2.3. Description of hydrodynamic model

The hydrodynamic model adopted in this study is identical to the model used by Aoki et al. (2012), which demonstrates the behavior of *C. antiqua* bloom that occurred in the summer of 2009 in the Yatsushiro Sea. Modeled short term fluctuations of salinity and temperature in the Yatsushiro Sea showed good agreement with the mooring buoy data (Fig. 5 of Aoki et al. (2012)). Since a detail description of the model is given in Aoki et al. (2012), only the essential parts are presented here.

The numerical model is based on the Regional Ocean Modeling System (ROMS: Shchepetkin and McWilliams, 2005). The grid spacing is 1/350° in both the zonal and meridional directions. The model is divided into 20 layers vertically using S-coordinates. The vertical resolution near the sea surface is enhanced to reproduce the behavior of the river plume. The model was forced by the daily atmospheric data of mesoscale atmospheric model (Saito et al., 2006) and freshwater discharge from 60 rivers. Lateral boundary conditions included 4 tidal constituents (M_2, S_2, K_1 and O_1), and the climatological monthly mean temperature and salinity was processed from the data of the Japan Oceanographic Data Center (JODC). Temporal integration was carried out from 1 January 2008 to 30 September 2010.

2.4. Stratification parameter and fresh water flux

The formation, maintenance and breakdown processes of the stratification in the related to the bloom are discussed using stratification parameters. The stratification parameters (Φ and Φ_S) were calculated by using daily mean modeled vertical profiles of the density, temperature and salinity.

$$\Phi = 1/h \int_{-h}^{0} (\bar{\rho} - \rho) gz\, dz,$$

$$\bar{\rho} = 1/h \int_{-h}^{0} \rho\, dz,$$

$$\Phi_S = 1/h \int_{-h}^{0} [\bar{\rho}(S, \overline{T}) - \rho] gz\, dz,$$

$$\overline{T} = 1/h \int_{-h}^{0} T\, dz,$$

where Φ, Φ_S, T, $\overline{T}$, S, h, ρ and $\overline{\rho}$ indicates the potential energy per cubic meter of the water column, potential energy per cubic meter of the water column due to the halocline, temperature, vertically averaged temperature, salinity, depth, density and vertical averaged density.

We use the fresh-water flux to estimate the southward expansion of the river plume. The freshwater flux (V_f) is given by

$$V_f = \int (S_0 - S)/S_0\, v\, dA,$$

where S and S_0 are modeled salinity and reference salinity, chosen to be 33.5 so as comparable to climatological bottom salinity in the sea. The v and A are modeled velocity of each grid and the area of vertical section, respectively.