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Large-scale transport of *Cochlodinium polykrikoides* blooms by the Tsushima Warm Current in the southwest Sea of Japan

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ABSTRACT

Since 2002, blooms of the harmful dinoflagellate *Cochlodinium polykrikoides* Margalef have occurred in the eastern San-in area, the Japanese coastal area fronting the southwest Sea of Japan. To investigate the occurrence mechanisms of the blooms, numerical experiments were conducted using a Lagrangian particle-tracking model, under different hydrographic conditions in 2002–2008. The results of Lagrangian simulations revealed that the source region of the blooms was located in the southeast Korean coastal area, >500 km away from the eastern San-in area. They were transported by the Tsushima Warm Current over about two weeks to one month. The blooms in the eastern San-in area were thought to occur only when a series of sequential conditions were met, which included preceding outbreaks in Korean waters, southwesterly winds in the Tsushima Strait, and the nearshore position of the Tsushima Warm Current off the San-in coast, veering eastward from the Korean peninsula.

1. Introduction

The red tide forming dinoflagellate genus *Cochlodinium* appears to be expanding globally, as well as blooming and/or causing more economic losses within its previously reported geographic distribution (Kudela et al., 2008). In particular, *Cochlodinium polykrikoides* Margalef has been one of the most harmful species for fish aquaculture in western Japan and southern Korea over the last two decades, where it has caused serious economic damage to the aquaculture industry (e.g., Yoon, 2001; Kim et al., 2004; Matsuoka and Iwataki, 2004; Kim et al., 2007a; Han et al., 2008; Matsuoka et al., 2008). Blooms of this species often occur extensively, owing to oceanographic and meteorological conditions such as ocean currents and sea surface winds (e.g., Matsuoka and Iwataki, 2004; Ahn et al., 2006; Azanza et al., 2008; Lee, 2008). In southeast Asia, a transboundary *C. polykrikoides* bloom, extending from the western coast of Sabah, Malaysia, to Palawan, Philippines, has been revealed by satellite ocean color images (Azanza et al., 2008).

Since 2002, *C. polykrikoides* blooms have occurred in the eastern San-in coast and the Oki Islands (Fig. 1), the Japanese coastal area fronting the southwest Sea of Japan. The species bloomed for the first time in the Tottori area in 2002 and on a larger scale in 2003, causing great damage to coastal fisheries (Miyahara et al., 2005). The area is sparsely populated, relatively non-industrialized, and does not have large rivers, where few crucial harmful algal blooms had been recorded. Oceanographic conditions off the San-in coast are affected by the Tsushima Warm Current, which flows northeast from the East China Sea, transporting temperate and nutrient-poor water to the Sea of Japan through the Tsushima Strait. Following the sudden and almost simultaneous occurrence of large-scale bloom in 2003, Miyahara et al. (2005) suggested that there was a high possibility that the bloom was transported from upstream regions, including Korean coasts, by the Tsushima Warm Current, but they could not identify the exact origin.

Nagai et al. (2009) analyzed the genetic structure of *C. polykrikoides* using 13 samples isolated from 11 different localities

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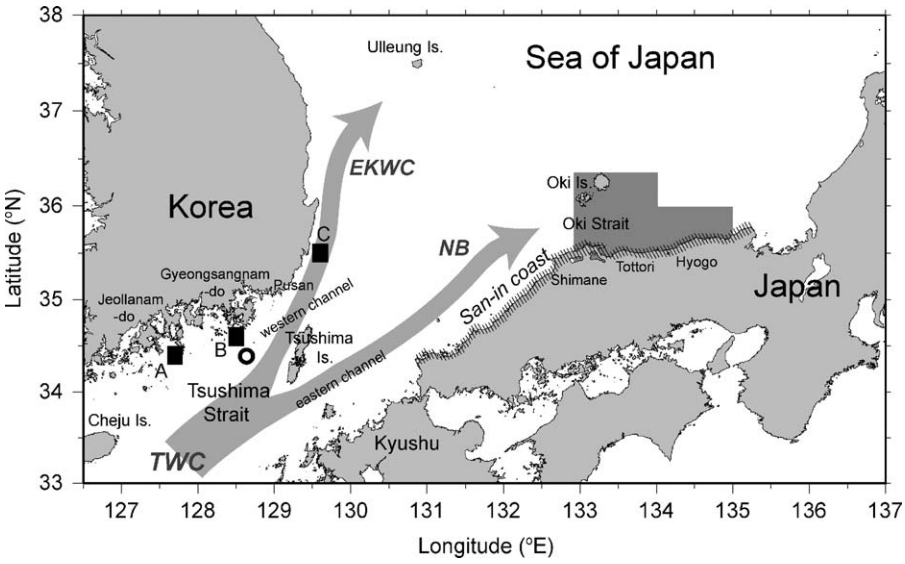

Fig. 1. Map of the study area in the southwest Sea of Japan. Open circle shows the observation station of wind vectors obtained by QuikSCAT/SeaWinds. Closed squares of A, B, and C indicate the release locations of particles in Lagrangian simulations. Diagonal lines along the Japanese coast indicate the San-in coast. Gray arrows represent the Tsushima Warm Current (TWC) and its branches the East Korean Warm Current (EKWC) and the Nearshore Branch (NB). See Fig. 4 for the shaded area of the eastern San-in coast.

in Japanese and Korean coasts with 10 polymorphic microsatellites. The proportion of shared alleles shown by pairwise individuals analyses between the Sea of Japan (Korea, Tsushima and Tottori) and the other (Japanese coastal areas) samples suggested that a large genetic barrier has occurred between the populations. There were no significant differences among the Sea of Japan samples, although there is a maximal geographic distance of >600 km between these samples. They suggested that the geographical origin of *C. polykrikoides* red tide, seen in the Sea of Japan, is the Korean coast and not western Kyushu, and that this large-scale transport from west to east has occurred via the Tsushima Warm Current.

In Korea, the northeastward propagation of the bloom area from the southern coast has been reported in previous studies (e.g., Yoon, 2001; Lee, 2008). Lee (2008) suggested a relationship between the eastward propagation of *C. polykrikoides* blooms and the Ekman transport induced by along-shore winds in the South Sea of Korea. He suggested that blooms are transported offshore when weak southwesterly winds blow along the coast of the South Sea of Korea following *C. polykrikoides* bloom formation, and they propagate to the east driven by northeastward along-shore currents. The mechanisms suggested by Lee (2008) explain the transport of *C. polykrikoides* blooms in Korean waters, but there have been no studies focusing on their transport in the offshore area of the southwest Sea of Japan.

In the present study, the large-scale transport of *C. polykrikoides* blooms in the southwest Sea of Japan, as suggested by Miyahara et al. (2005) and Nagai et al. (2009), was examined by numerical simulations using a Lagrangian particle-tracking model. First, we investigated the occurrence patterns of *C. polykrikoides* blooms in the eastern San-in coast and the Oki Islands (hereafter the eastern San-in area), and Korean coastal waters during 2002–2008. On the assumption that *C. polykrikoides* blooms were transported from Korean coastal areas, we then conducted Lagrangian simulations to elucidate the transport mechanisms of *C. polykrikoides* blooms from the upstream Korean coast to the downstream eastern San-in area.

2. Materials and methods

2.1. Field and satellite data

The Marine Ecology Research Team of the National Fisheries Research and Development Institute (NFRDI), Korea, releases daily data on bloom location and cell density for every harmful algal bloom (HAB) species through its website (http://www.nfrdi.re.kr/redtideInfo). In the present study, we used the daily maximum cell density during 2002–2008 in the provinces of Jeollanam-do, Gyeongsangnam-do, and from Pusan to the northeast. The fishery research institutes of Shimane, Tottori and Hyogo prefectures recorded the occurrence of *C. polykrikoides* blooms and the cell density in the eastern San-in area during 2002–2008. In 2007, water samples from the offshore areas were collected by Japanese research vessels to investigate dominant HAB species and cell density.

Ocean surface wind vectors were remotely measured by the SeaWinds scatterometer on board the satellite QuikSCAT. The level 3 gridded data with a horizontal resolution of 0.25° were processed by the Physical Oceanography Distributed Active Archive Center (PO-DAAC) at the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL). Temporal variations in daily southwesterly winds in the Tsushima Strait were used for interpreting the wind-driven transport of *C. polykrikoides* blooms along the Korean coast. Images of chlorophyll *a* were derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the satellite Aqua. Snapshots of chlorophyll *a* images with a pixel resolution of approximately 1 km were processed by the Earth Observation Center (EOC) of the Japan Aerospace Exploration Agency (JAXA).

2.2. Hydrodynamic model

The current velocity field was obtained by reproducing the spatial and temporal variations of hydrographic conditions using the Sea of Japan version of the Research Institute for Applied Mechanics (RIAM), Kyushu University, ocean model. This model is a free-surface primitive ocean general circulation model (Lee et al., 2003). It assumes a hydrostatic balance using the Boussinesq approximation and solves the three-dimensional, nonlinear, primitive external and internal mode equations on an Arakawa B-grid. The horizontal grid size is 1/12° in the zonal and meridional directions. There are 36 levels with thicknesses ranging from 5 to 600 m in the vertical direction. The model has been shown to successfully simulate realistic oceanographic conditions using daily forcing and assimilating satellite measurements (Hirose et al., 2007). The daily mean current velocity during July–October in