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Influence of the Yellow Sea Warm Current on phytoplankton community in the central Yellow Sea

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ABSTRACT

In early spring, a hydrological front emerges in the central Yellow Sea, resulting from the intrusion of the high temperature and salinity Yellow Sea Warm Current (YSWC). The present study, applying phytoplankton pigments and flow cytometry measurements in March of 2007 and 2009, focuses on the biogeochemical effects of the YSWC. The nutrients fronts were coincident with the hydrological front, and a positive linear relationship between nitrate and salinity was found in the frontal area. This contrast with the common situation of coastal waters where high salinity values usually correlate with poor nutrients. We suggested nutrient concentrations of the YSWC waters might have been enhanced by mixing with the local nutrient-rich waters when it invaded the Yellow Sea from the north of the Changjiang estuary. In addition, our results indicate that the relative abundance of diatoms ranged from 26% to 90%, showing a higher value in the YSCC than in YSWC waters. Similar distributions were found between diatoms and dinoflagellates, however the cyanobacteria and prasinophytes showed an opposite distribution pattern. Good correlations were found between the pigments and flow cytometry observations on the picophytoplankton groups. Prasinophytes might be the major contributor to pico-eukaryotes in the central Yellow Sea as similar distributional patterns and significant correlations between them. It seems that the front separates the YSWC from the coastal water, and different phytoplankton groups are transported in these water masses and follow their movement. These results imply that the YSWC plays important roles in the distribution of nutrients, phytoplankton biomass and also in the community structure of the central Yellow Sea.

1. Introduction

Western boundary currents, such as the Kuroshio, are warm, swift, narrow oceanic currents found in the western side of the subtropical gyres. The branches of western boundary currents into marginal seas are important reasons for the ecosystem dynamics and complexity (Hu et al., 2015). It is clear that the Kuroshio branches are important drivers of the biogeochemical cycles in the East and South China Seas (Yang et al., 2012; Du et al., 2013).

The Yellow Sea is a semi-enclosed marginal sea with depths ranging from 20 to 90 m, bounded by China and Korean Peninsula and influenced by the East Asian Monsoon, the Kuroshio Current and riverine input. In winter and early spring, a hydrological front emerges in the central Yellow Sea where the warm Yellow Sea Warm Current (YSWC) meets the cold water of the Yellow Sea Coastal Current (YSCC) (Chen, 2009; Lie et al., 2009; Lin and Yang, 2011; Lin et al., 2011). The YSWC is an asymmetric upwind flow and will intrude into the central Yellow Sea along the western side of the Yellow Sea trough from winter to early spring (Lin et al., 2011). It originates from the northward Kuroshio branch current (Cheju Warm Current) and the Taiwan Warm Current in the northern part of the East China Sea (Lin et al., 2011). On the coastal side, the cold fresh YSCC is brought into the central Yellow Sea when the southward flowing current is influenced by winter monsoons (the northwestern monsoon) (Chen, 2009). Therefore, the front showing extreme contrasts between the warm saline

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YSWC and the cold fresh YSCC is developed from winter to early spring and provides a dynamic environment during this period.

Since the 1980s, several theories have been suggested concerning the origin and generation of the YSWC, mainly based on current measurements, historical hydrographic data and numerical models (Lie et al., 2001; Huang et al., 2005; Lin and Yang, 2011; Lin et al., 2011; Wang et al., 2012). To date, however, little is known concerning biogeochemical behaves of the YSWC (Liu et al., 2015). Chen (2009) reveals that the YSWC originates from the Kuroshio and Taiwan Warm Current and thus it is relatively warmer, saltier, and nutrient-poor. While, recent studies reveal that the nitrate concentrations in the YSWC reach up to 8 μM (Fu et al., 2009; He et al., 2013; Jin et al., 2013). It was suggested that nutrient concentrations in the YSWC have increased since the end of last century (He et al., 2013; Jin et al., 2013). However, the nutrients sources and their contributions are unclear (Liu et al., 2015). Despite high nutrient concentrations, quite low chlorophyll *a* (Chl *a*) concentrations dominated by picosize phytoplankton in the YSWC during winter were noted by the size-fraction Chl *a* results (Fu et al., 2009). Our previous study also reported low Chl *a* concentrations ($<0.6\ \mu g\ L^{-1}$) and abundant prasinophytes in the YSWC area in March (Liu et al., 2015). In the absence of direct evidence from flow cytometry observation on the spatial distributions of prokaryotic and eukaryotic picophytoplankton, the difference on phytoplankton community structure between the YSWC and the YSCC is still unclear.

During early spring the region of algal bloom coincides with that of the YSWC in the central Yellow Sea (Liu et al., 2015). High temperature and rich nutrients in the YSWC are hypothesized to be one of the explanations for the spring bloom and its succession patterns (Jin et al., 2013; Liu et al., 2015). During April 2007 and 2009, comprehensive observations were made in the China GLOBEC-IMBER Program (Tang et al., 2013). A special issue in the journal of Deep-Sea Research II (volume 97, 2013) provided a comprehensive picture of the spring bloom (Tang et al., 2013). Generally, the spring blooms are observed in the central Yellow Sea at the water depths >50 m (Hyun and Kim, 2003; Xuan et al., 2011; Liu et al., 2015). They typically last for about two months from April to May, and are composed of a series of sub-bloom events that show different dominant species compositions (Tang et al., 2013). Hu et al. (2004) demonstrated that the initiation of a spring phytoplankton bloom is critically related to the water column stability based on a 3-dimensional physical–biological coupled model. Further, Zhou et al. (2013) observed that the changes in stability of the hydrographic structure caused by oceanic and meteorological factors like horizontal advection, tides, wind and solar radiation affect the development of spring blooms in the central Yellow Sea. In addition, the trigger of the spring algal bloom is considered to be the imbalances in predator-prey relations rather than a reflection of rapid cell division (Behrenfeld and Boss, 2014). Sun et al. (2013) revealed that the grazing rates are generally lower than the growth rates during the pre-blooming phase in the central Yellow Sea, while the grazing rate reaches a balance with the growth rate during the blooming phase with the average net growth rates of the community being 0.207 and 0.005 d^{-1} at pre-blooming and blooming stations. This implies the net growth of phytoplankton during pre-blooming is the major cause of the bloom (Sun et al., 2013). Based on these results, the factors that influence community structure and growth of phytoplankton during the initial stage of the spring bloom are very important.

Previous studies in the special issue provide detailed evidence of the change in hydrological conditions (Zhou et al., 2013), nutrient concentrations (Jin et al., 2013) and temporal variation of picophytoplankton during the blooms (Zhao et al., 2013), but the total phytoplankton community structure. We analyzed results of hydrography, nutrients, phytoplankton biomass and composition, focusing on the biogeochemical characteristics, especially phytoplankton community of the YSWC and the YSCC during the pre-blooming phase in the central Yellow Sea. In the present study, phytoplankton pigments and flow cytometry measurements were firstly conducted simultaneously for this study area. Moreover, the nutrients sources of the YSWC and the factors controlling biomass and composition of phytoplankton community will be discussed.

2. Materials and methods

Two cruises were carried out on the R/V Beidou during 17–23 March 2007 and 20–30 March 2009 (Fig. 1), around 1–2 weeks before the satellites-derived Chl *a* maximum occurred (Fig. 3d) (Tang et al., 2013). In addition, two time series observations using surface Lagrangian drifters which lasted 102 h (from 3:00 am 4th April to 9:00 am 8th April) and 126 h (from 3:00 am 9th April to 9:00 am 14th April) respectively were carried out in 2009 at two stations (Stns. B23 and B20, Fig. 1). At Stn. B20, water in the euphotic zone was fundamentally driven by the YSCC and thus moved to the southwest, while tidal signal was relatively strong at Stn. B23 (the YSWC) as indicated by its orbit (Zhou et al., 2013). Hydrographic and nutrients data of the present study can be found

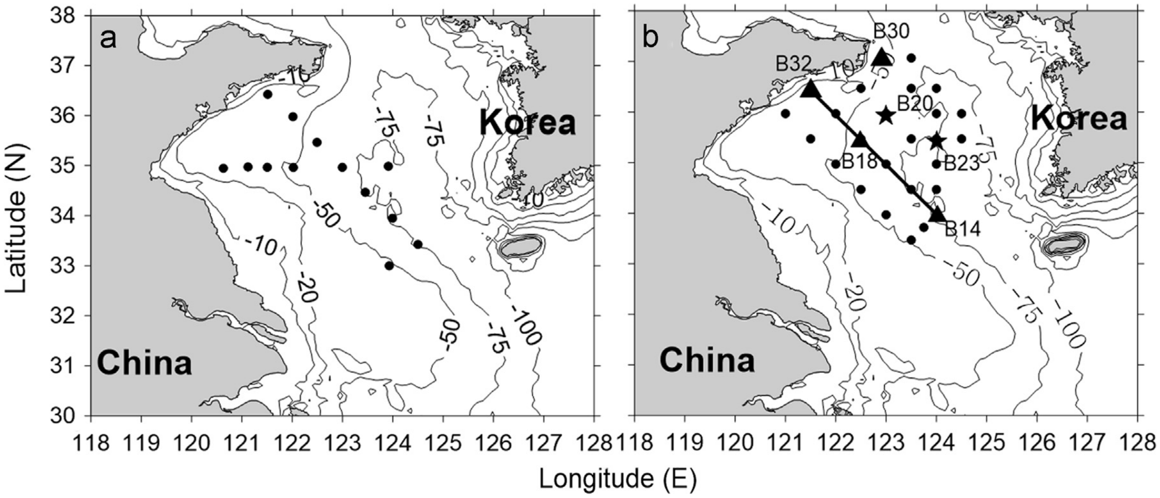

Fig. 1. Map of study area and sampling stations in the Yellow Sea during March 2007 (a) and 2009 (b). The black Triangles and stars indicate the location of Stns. B14, B18, B20, B23, B30 and B32.