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Living coccolithophore assemblages in the Yellow and East China Seas in response to physical processes during fall 2013

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ABSTRACT

Living coccolithophore assemblages collected at discrete depths (0–490 m) from eleven stations across the shelf and slope regions of the Yellow and East China Seas (YECS) during fall 2013 were analyzed using a scanning electron microscope. A total of 32 taxa were recorded, and the predominant taxa were *Emiliania huxleyi*, *Gephyrocapsa* spp., *Syracosphaera* spp. and *Algirosphaera robusta*. The body coccoliths of *A. robusta* exhibited an unusual morphology with incomplete hoods, which were recorded in nearly half of the samples and may represent a new variety. In addition, an agglutination relationship was observed between *Gephyrocapsa* coccoliths and the tintinnid *Dictyocysta lepida* in oligotrophic waters. Total coccolithophores reached a maximum cell abundance of 252×10^3 cells/l (on average 27.8×10^3 cells/l), with the contribution of *Gephyrocapsa ericsonii*, *E. huxleyi* and *Gephyrocapsa oceanica* accounting for 36.4%, 29.6% and 15.3%, respectively, of the total abundance. Coccolithophore assemblages in the YECS were a mixture of coastal, shelf and subtropical taxa, with the diversity decreasing in a radial direction from the Okinawa Trough to the inner shelves. Distinct deep-water flora existed in the Kuroshio slope waters (100–490 m), which was precisely reflected by the cluster analysis, illustrating very low percent similarity (48.1%) with the other groups. The occurrence of subtropical taxa in the coccolithophore assemblages can be used as benign warmer water signals. In the bottom turbid layers, the coccolithophore assemblages were largely composed of free coccoliths (84.3%), implying complex processes, such as cell death, resuspension and lateral advection, in the sandy and detrital waters. To clarify the relationship between the species distribution and ambient environments, a redundancy analysis (RDA) was applied to distinguish how much the variation in the taxon composition could be attributed to changes in the environmental conditions. Conclusively, salinity and temperature, which to some extent could reflect the physical properties of water stability and stratification, were key factors in driving the distribution patterns of living coccolithophores in the study areas.

1. Introduction

In general, living coccolithophores are a group of marine calcifying unicellular phytoplankton that are usually small in size (~20 μm). They are recognized as playing a crucial role in the global carbon cycle through the production and export of organic carbon and calcite (Rost and Riebesell, 2004). As primary producers, the contribution of coccolithophores to the total primary production was assessed at ~20% (~7 PgC y^{-1}) on a global scale (Rousseaux and Gregg, 2014). As calcifiers, they make a great contribution to the global budget of biogenic carbonate. Using time-series sediment trap samples, the coccolith contribution to the total carbonate flux was quantified as ranging from 20% to 80% in different marine settings, with an average of 60% (Honjo et al., 2008). Due to their biogeochemical significance, coccolithophores have attracted considerable interdisciplinary interest in extensive studies of taxonomy, biogeography, ecology and paleoceanography (Jordan and Winter, 2000; Andruleit and Rogalla, 2002; Young et al., 2003; Balch et al., 2011).

Research on coccolithophores in the China Seas increased greatly from the beginning of this century, covering the East China Sea (ECS, Yang et al., 2001, 2004; Tanaka, 2003), the South China Sea (SCS, Chen et al., 2007; Fernando et al., 2007) and the Yellow Sea (YS, Wang et al., 2012; Luan et al., 2013). These researches provided valuable information on the biogeographic distribution of this calcifying phytoplankton group based on the samples collected in seawaters, mooring traps and surface sediments. Although the qualitative and quantitative studies of coccolithophores from the China Seas were extensively carried out,

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there is still a lack of understanding of the link between the species distribution and ambient environment.

As *k*-strategists, coccolithophores possess a high affinity for nutrients and commonly inhabit well-stratified waters (Iglesias-Rodríguez et al., 2002). A model organism, *Emiliania huxleyi*, can reach high densities both in laboratory and in situ environments, irrespective of nutrient concentrations and nitrate to phosphate ratios (Egge and Aksnes, 1992; Fernández et al., 1993; van der Wal et al., 1994). Yang et al. (2004) suggested that the presence of malformed coccolithophores in the ECS was mainly caused by the nitrate deficiency in ambient waters. Chen et al. (2007) considered that the coccolithophore abundance was closely related to surface nitrate availability and monsoons in the northern SCS. Luan et al. (2013) noted that the increasing seawater temperature, in combination with the water column stability, determined the high cell abundance and habitat preferential distribution of coccolithophores in the southern YS.

Based on a *973-program* supported cruise investigation in fall 2013, we studied the biogeographic distribution of coccolithophores across the shelf and slope regions of the Yellow and East China Seas (YECS). Sampling was conducted in offshore waters, and the deepest samples were taken from the shelf edge/break area with water depths >300 m. We described an interesting morphology of *Algirosphaera robusta* (with incomplete hoods, different from Probert et al., 2007), which was consistently present in the samples and may be a new variety. Additionally, we observed an agglutination relationship between coccoliths and the tintinnid *Dictyocysta lepida*. To clarify the species-specific demands of coccolithophores for environments, a multivariate ordination method of redundancy analysis (RDA) was applied to this work, which provided meaningful explanations with respect to environmental controls on the species distribution of these calcifying organisms.

2. Regional setting

The Yellow and East China Seas are located on the broad continental shelf of China's coast, in conjunction with the rim of the northwestern Pacific Ocean through the Okinawa Trough and Ryukyu Archipelago (Fig. 1A). The Kuroshio, originating from the oligotrophic equatorial waters, carries heat and salt. It flows to the northeast of Taiwan Island and passes the shelf break regions of the ECS before changing its direction to the east at Tokara Strait (Su, 1998; Hsueh, 2000; Zhou et al., 2015). The Taiwan Warm Current (TWC) maintains its path northeastward from the Taiwan Strait and intrudes into the bottom water of the inner ECS shelf before rising and uniting with the Changjiang Diluted Water (Katoh et al., 2000). The Yellow Sea Warm Current (YSWC), which carries anomalously warm and saline water into the trough during the cold months (Guan, 1994; Yuan and Hsueh, 2010), is generally thought to be a branch of the Tsushima Warm Current (TSWC, originates from Kuroshio, west of Kyushu). In addition, a permanent upwelling also exists off northeast Taiwan as a result of the impingement of the Kuroshio onto the ECS continental shelf (Chern et al., 1990).

Biological processes in the YECS were subjected to circulation dynamics and the associated nutrient behaviors. Higher phytoplankton abundances were found in the Changjiang plume and coastal upwelling regions, followed by intermediate and lower values in the mid-shelf and shelf break areas (Ning et al., 1988). Seasonal and inter-annual variations of satellite-derived sea surface chlorophyll-*a* (Chl-*a*) also revealed the close link between phytoplankton biomass and Changjiang discharge (Yamaguchi et al., 2012). Due to the existence of 'excess nitrate' in surface waters (Wong et al., 1998), primary production in a significant portion of the ECS may be phosphate-limiting rather than nitrogen-limiting, in contrast to the open ocean in general. However, the excessive phosphorus from upwelling can stimulate phytoplankton growth and, consequently, consume the excessive nitrogen from river discharges (Chen et al., 2004).

MODIS/AQUA monthly average datasets of sea surface temperature and chlorophyll-*a* during the current work (Oct. 2013) were in accordance with the distribution patterns of the bathymetry of the YECS (Fig. 1B, C). The coastal waters (<50 m) were characterized by low temperatures (19–25 °C) and high Chl-*a* concentrations (2–5 μg/l), while the offshore waters (>50 m) had high temperatures (25–28 °C) and low Chl-*a* concentrations (0–2 μg/l).

3. Material and methods

3.1. Cruise track and sampling

An interdisciplinary cruise investigation was carried out in the Yellow and East China Seas in fall 2013 (from 13th Oct. to 6th Nov.). During this cruise, we were able to sample the deep shelf waters and the slope area adjoining the Okinawa Trough (Fig. 1A). A total of 57 filter samples from 11 stations (9 over the shelf, 2 over the slope) were taken at discrete depths, with the deepest sample at 490 m (Table 1).

For coccolithophore sampling, seawater samples were collected using a Sea-Bird 25 CTD sampler equipped with a rosette of twelve 5-liter Go-Flo bottles. Immediately onboard, 1 l subsamples were filtered

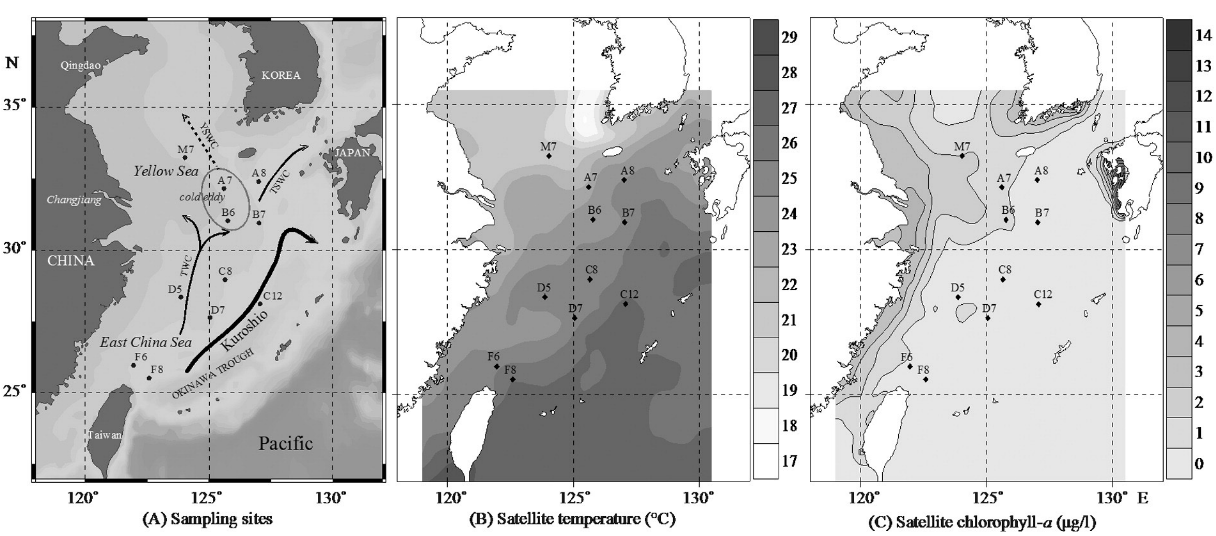

Fig. 1. Sampling locations and regional backgrounds in the Yellow and East China Seas during the cruise. (A) Sampling sites superimposed on the topographical map; current sketch after Yuan and Hsueh, 2010; TWC, the Taiwan Warm Current; TSWC, the Tsushima Warm Current; YSWC, the Yellow Sea Warm Current, cold months. (B) Satellite-derived sea surface temperature in Oct. 2013, MODIS/AQUA monthly average datasets from the NASA ocean color server http://oceancolor.gsfc.nasa.gov/. (C) Satellite chlorophyll-*a* in Oct. 2013.