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Drifting trajectories of green algae in the western Yellow Sea during the spring and summer of 2012

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ABSTRACT

The northward drift of green algae (*Ulva prolifera*) from Subei Shoal in the western Yellow Sea, China, during the spring and summer of 2012, was investigated using satellite data and numerical modeling. Past studies have suggested that the green algae, documented offshore of Shandong province since 2007, originate in Subei Shoal region of the Yellow Sea. To test this hypothesis, drift bottles and satellite-tracked surface drifters were released from Subei Shoal and used to investigate the trajectories of green algae. Subei Shoal is characterized by complex bathymetry such as broad tidal flats and radial sand ridges. To identify processes that drive drift of the green algae around the shoal, a coastal ocean model based on the Finite Volume Coastal Ocean Model (FVCOM) was used. This model is forced by tides and surface winds, and has sufficient resolution to include tidal flats and sand ridges during both wetting and drying. The results of numerical experiments indicated that sand ridges limit the trajectory of particles. Without wind, particles scattered from their initial positions displayed a tendency to move northward, but were unable to move out of Subei Shoal. When a southerly wind was introduced to the model, particles traveled further north, out of the shallow waters. After leaving Subei Shoal, drifters remained limited by tide and topography until reaching 34°30.0′N. North of 34°30.0′N, 33% of the trajectory vectors can be explained by Ekman theory, and the remainder are probably controlled by the strong baroclinic processes in this area. For the six surface-following drifters deployed, the mean drift speed was 11.1 cm s^{-1} (288.8 km $month^{-1}$), close to the speed observed for patches of *U. prolifera*. Numerical models and the results from drifter bottles demonstrated that green algae could leave Subei Shoal, but only when aided by a southerly wind. Satellite-tracked drifters provided strong evidence that if floating particles do leave Subei Shoal, they could be transported to the Qingdao coast or even further north.

1. Introduction

Until recently, studies of the western Yellow Sea, China, especially those focused on Subei Shoal, were limited. Beginning in 2007, several outbreaks of green algal blooms (termed “green tides”) in this region have drawn considerable research interest. These green algae have been identified as *Ulva prolifera* (Lin et al., 2011a,b), a free-floating macroalgae. Model simulations, employing both forward and inverse algorithms (Lü and Qiao, 2008; Sun et al., 2008; Qiao et al., 2009; Lee et al., 2011; Lin et al., 2011a,b; Wang et al., 2011), have suggested that the green algae originate from Subei Shoal, a region located offshore of the northern Jiangsu province. In this region, prevailing currents flow southward throughout the year (Zhao et al., 1991; Guan, 1994; Hu, 1994; Su, 1998). In particular, during the summer months, the western Yellow Sea currents generally flow southward along the 40–50 m isobaths (Hu, 1994). In contrast, the green algae drift northward, as supported by satellite image data that show green algal patches moving from south to north (Liu et al., 2013). Recently, several studies have argued that the Subei coastal current may actually flow northward during the summer as a result of the southwesterly monsoon (e.g., Hu and He, 2008; Liu and Hu, 2009). To confirm this theory, in situ data are needed to detail the drifting path of green algae in this region.

In addition to the complex regional currents, Subei Shoal is characterized by complicated topography, including broad tidal flats and radial sand ridges (Fig. 1a). Two fundamental questions are examined in this study. (1) Could floating particles from the radial

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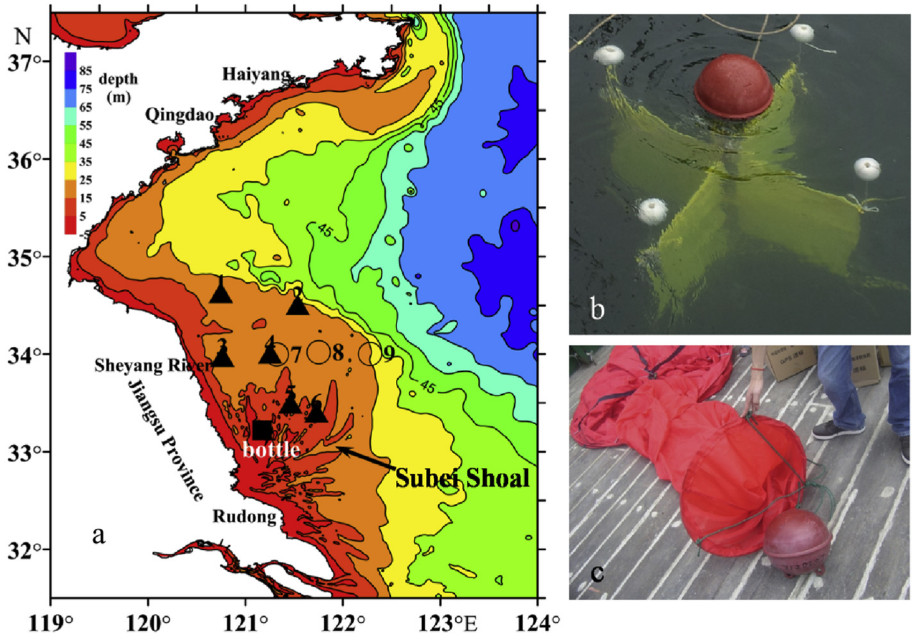

Fig. 1. (a) Topography of the southwestern Yellow Sea with release locations of drift bottles (■), satellite-tracked surface following Argos drifters (▲), and subsurface-following (○) Argos drifters. (b) A satellite-tracked surface drifter. (c) A satellite-tracked subsurface drifter.

sand ridges be transported out of Subei Shoal? (2) If floating particles do leave Subei Shoal, are they subsequently transported northward to the Qingdao coast or even further? Many studies have shown a northward current for deeper waters during the spring and summer (Hu and He, 2008; Hu et al., 2010; Wang et al., 2011), but this current only appears in numerical ocean models. There are no in situ data to confirm the existence of this northward current especially in the near-shore shallow zone. In this study, data from numerical experiments, drift bottles, and satellite-tracked drifters were used to test for the existence of this current and to answer the questions posed above.

2. Methods

2.1. Drift bottles and satellite-tracked Argos drifters

Drift bottles were deployed to observe floating particle transport paths in the waters of Subei Shoal. This region is very shallow, and is therefore unsuitable for the release of Argos drifters. In total, 80 bottles were released at 121°10.2′E, 33°13.3′N (Fig. 1a). Half of the bottles were deployed empty to ensure that they floated on the surface. To mimic the green algae more closely, the other half were filled with enough sand to ensure that they were almost completely immersed. Bottles were retrieved through a reward program whereby a small monetary reward was offered for reporting both the bottle location and the unique ID inside.

In total, nine satellite-tracked Argos drifters were deployed to study drift trajectories in the deep waters beyond Subei Shoal (Table 1). Depending on the floating center of gravity when settled in the water, two kinds of satellite-tracked Argos drifters were used: (1) six surface-following drifters (Fig. 1b) and (2) three subsurface-following drifters (Fig. 1c). Position data from the Argos drifters were recorded hourly and transmitted to the research team via satellite.

The surface-following drifters were constructed using four rectangular sails (40 cm in width by 70 cm in height) connected to a

Table 1
Details of the satellite-tracked drifters.

Drifter type	Drifter number	Release Date	Release location	End Date	End location
Surface-following	1	2012-06-03 08:15	120°44.8′E 34°37.8′N	2012-08-20 13:14	121°06.1′ E 35°51.3′ N
	2	2012-06-03 08:27	121°32.2′E 34°30.5′N	2012-08-20 12:45	123°44.0′ E 38°44.9′ N
	3	2012-06-03 18:39	120°45.8′E 33°58.5′N	2012-06-11 08:12	120°24.3′ E 33°58.7′ N
	4	2012-06-03 15:22	121°15.2′E 34°00.6′N	2012-07-19 11:11	120°26.6′ E 36°07.6′ N
	5	2012-06-04 12:31	121°27.7′E 33°29.8′N	2012-07-04 11:07	121°28.4′ E 35°24.7′ N
	6	2012-06-05 10:54	121°43.7′E 33°24.4′N	2012-08-10 23:51	121°31.7′ E 36°46.1′ N
Subsurface-following	7	2012-06-03 14:30	121°19.3′E 33°59.8′N	2012-06-05 17:35	121°11.3′ E 34°04.4′ N
	8	2012-06-03 12:34	121°45.1′E 34°01.2′N	2012-07-01 04:30	121°53.8′ E 34°44.2′ N
	9	2012-06-03 09:12	122°16.7′E 34°00.1′N	2012-06-22 01:14:30	122°30.4′ E 34°06.9′ N