

# Unusual distribution of floating seaweeds in the East China Sea in the early spring of 2012

Teruhisa Komatsu · Shizuha Mizuno · Alabsi Natheer · Attachai Kantachumpoo · Kiyoshi Tanaka · Akihiko Morimoto · Sheng-Tai Hsiao · Eva A. Rothäusler · Hirotoishi Shishidou · Masakazu Aoki · Tetsuro Ajisaka

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**Abstract** Floating seaweeds play important ecological roles in offshore waters. Recently, large amounts of rafting seaweed have been observed in the East China Sea. In early spring, juveniles of commercially important fish such as yellowtail accompany these seaweed rafts. Because the spatial distributions of seaweed rafts in the spring are poorly understood, research cruises were undertaken to investigate them in 2010, 2011, and 2012. Floating seaweed samples collected from the East China Sea during the three surveys contained only *Sargassum horneri*. In 2010 and 2011, seaweed rafts were distributed only in the continental shelf and the Kuroshio Front because they had become trapped in the convergence zone of the Kuroshio Front. However, in 2012, seaweed was also distributed in the Kuroshio Current and its outer waters,

and massive strandings of seaweed rafts were observed on the northern coast of Taiwan and on Tarama Island in the Ryukyu Archipelago. Environmental data (wind, currents, and sea surface height) were compared among the surveys of 2010, 2011, and 2012. Two factors are speculated to have caused the unusual distribution in 2012. First, a continuous strong north wind produced an Ekman drift current that transported seaweed southwestward to the continental shelf and eventually stranded seaweed rafts on the coast of Taiwan. Second, an anticyclonic eddy covering northeast Taiwan and the Kuroshio Current west of Taiwan generated a geostrophic current that crossed the Kuroshio Current and transported the rafts to the Kuroshio Current and its outer waters. Such unusual seaweed distributions may influence the distribution of fauna accompanying the rafts.

T. Komatsu (✉) · S. Mizuno · A. Natheer · A. Kantachumpoo · K. Tanaka · E. A. Rothäusler  
5-1-5, Kashiwanoha, Kashiwa 277-8564, Japan  
e-mail: komatsu@aori.u-tokyo.ac.jp

A. Morimoto  
Hydrospheric Atmospheric Research Center, Nagoya University,  
Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan

S.-T. Hsiao  
Marine Fisheries Division, Fisheries Research Institute of Taiwan,  
199, Hou-Ih Road, Keelung 20246, Taiwan

H. Shishidou  
Kagoshima Prefectural Fisheries Technology and Development  
Center, Ibusuki, Kagoshima 891-0315, Japan

M. Aoki  
Division of Applied Aquatic Bio-Science, Graduate School of  
Agricultural Science, Tohoku University, 1-1 Amamiya-machi,  
Tsutsumidori, Aoba-ku, Sendai, Miyagi 981-8555, Japan

T. Ajisaka  
Division of Applied Biosciences, Graduate School of Agriculture,  
Kyoto University, Kitashirakawa Oiwakecho, Sakyo-ku,  
Kyoto 606-8502, Japan

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## Introduction

*Sargassum* species grow on rocky coasts in the temperate zone of the northwestern Pacific coast, forming luxuriant forests in spring that become less dense by summer (Komatsu et al. 1982). Their stems extend for several meters in spring when most of these species mature. *Sargassum* forests have important influences on coastal marine environments. For example, seaweeds affect the spatial and temporal distribution of water temperature (Komatsu et al. 1982, 1994; Komatsu 1985), downward illumination via shading by their canopies (Komatsu 1989; Komatsu et al. 1990), pH (Komatsu and Kawai 1986), and dissolved oxygen content by their respiration and assimilation (Komatsu 1989). They can also slow water flow (Komatsu and Murakami 1994), and they

play vital ecological roles as spawning, nursery, and feeding grounds for marine animals (e.g., Thiel and Gutow 2005; Abé et al. 2012).

*Sargassum* species contain many vesicles that are filled with gas for buoyancy and keep plants facing upward from the bottom (Hurka 1971). In spring, the drag force of waves and currents may become greater than the fixation force of elongating seaweeds, detaching them from the bottom (Yoshida 1963). The buoyancy provided by the vesicles allows seaweeds to float after detachment, and seaweed rafts form in waters around Japan (Yoshida 1963) and in areas such as the Sargasso Sea. Although floating *Sargassum* species in the Sargasso Sea can complete their entire life through vegetative reproduction in a floating state (Parr 1939), floating *Sargassum* species in the East China Sea would have originally grown on rocky coastal bottoms (Yoshida 1963).

In offshore waters, floating seaweeds are an important habitat, providing a moving ecosystem for attaching or accompanying flora and fauna (e.g., Cho et al. 2001). Attached or accompanying organisms disperse with the floating seaweeds, which thus serve as means of dispersal for littoral animals such as intertidal organisms (e.g., Ingólfsson 1995). Seaweed sampling and aquarium experiments in a controlled environment demonstrated that the seaweed composition influences the macrofaunal species composition and abundance (Vandendriessche et al. 2006). For example, samples dominated by *Sargassum muticum* (Yendo) Fensholt displayed higher densities but lower diversities of macrofaunal species compared to samples dominated by *Ascophyllum nodosum* (L.) Le Jolis and *Fucus vesiculosus* L. Because floating algae may be dispersed over great distances (Hinojosa et al. 2011), they influence the biogeography and evolution of the fauna accompanying them (Thiel and Haye 2006). Floating seaweeds continue to grow while afloat (Vandendriessche et al. 2007; Rothäusler et al. 2009, 2012; Tala et al. 2013). Moreover, seaweeds also enlarge their own habitats by means of drifting rafts. For example, Hernández-Carmona et al. (2006) reported that sporophytes of drifting *Macrocystis pyrifera* (L.) C. Agardh remained fertile with a high germination success as long as sori were present (125 days). Rafting bull kelp (*Durvillaea antarctica* (Chamisso) Hariot) near north central Chile was also found to be fertile (Tala et al. 2013). *S. muticum* invaded France in the 1960s and has colonized the North Sea Coast through floating seaweeds which can grow and become fertile (Rueness 1989). Abiotic and biotic factors limit the floating persistence and dispersal potential of floating seaweeds (Rothäusler et al. 2011). The floating persistence of seaweeds is increased by lower water temperatures and decreased by high water temperatures with an accompanying increase in the activity of grazers (Rothäusler et al. 2009; Vandendriessche et al. 2007).

Yoshida (1963) reported that most Japanese floating seaweeds were found in nearshore coastal waters (within 20 km from the shore) in the vicinity of oceanic fronts west or north of Kyushu Island in the East China Sea (Fig. 1). Yoshida (1963) also noted that floating seaweeds were most abundant from March to May and that their abundance became significantly lower in waters south of the Osumi Peninsula and, especially, south of Tanegashima Island and Yakushima Island (Fig. 1). Senta (1965) reported that floating seaweeds were not present in the oceanic front between continental shelf waters and the Kuroshio Current. Thus, since the 1960s, floating seaweeds have been reported to be rare in the offshore waters of the East China Sea (Fig. 1).

Recently, however, floating seaweeds were found on the continental shelf along the East China Sea oceanic front (between Kuroshio and continental shelf waters) between March and May (Konishi 2000; Komatsu et al. 2007). While densities of seaweed rafts along transects increased southward in survey areas in both months, survey area in March was limited in the northern East China Sea (Komatsu et al. 2009). These floating seaweeds were composed of only one species, *Sargassum horneri* (Turner) C. Agardh. Although it is now accepted that floating seaweeds occur in this specific area, little is known about their abundance and distribution. The Kagoshima Prefectural Fisheries Technology and Development Center investigated floating seaweeds, mainly by a visual survey, to determine the open season for fisheries of yellowtail (*Seriola quinqueradiata*) juveniles (Kubo 2004, 2006) to be used as aquaculture seedlings because cannibalism behavior of yellowtail during the juvenile period (Anraku and Azeta 1965) prevents the industrial production of its seedlings and yellowtail aquaculture, of which the production is the most important among the finfish aquacultures in Japan, depending on wild juveniles accompanying seaweed rafts. However, efforts were concentrated in coastal waters, and the abundance of floating seaweeds in deeper waters has remained unstudied.

In February to March, yellowtail juveniles start to accompany floating seaweeds in the East China Sea (Yamamoto et al. 2007). It is necessary to characterize the spatial distribution of floating seaweeds in the area. Thus, using research vessels, three surveys of seaweed rafts in the East China Sea were conducted from February to March in 2010 to 2012. We found unusual distributions of seaweed rafts consisting of *S. horneri* in the Kuroshio Current and also in the outer region of the Kuroshio Current. Huge floating masses of seaweeds were stranded on the north coast of Taiwan and on Tarama Island in the Ryukyu Archipelago in 2012 (Fig. 1). Hydrographical and meteorological data were used to examine the unusual phenomenon whereby many rafts were distributed in the Kuroshio Current and its outer waters and also became stranded in Taiwan and Tarama Island in the early spring of 2012.

**Materials and methods**

Field observation and sampling

Visual censuses were conducted at sea during good conditions (i.e., wave height less than 1 m) from sunrise to sunset. Three surveys were undertaken: from 22 February to 6 March 2010 (R/V Tansei Maru, KT10-1), from 18 to 23 February 2011 (R/V Tansei, KT11-1), and from 9 to 16 March 2012 (R/V Tansei, KT12-3). Observations were taken from the vessel deck at a height of 11.5 m above the sea surface, with the vessel navigating along designed transects. The following elements were recorded at each location where floating seaweed was observed: time, position, perpendicular distance from the boat, and seaweed raft diameter. Distance and diameter were estimated by four trained researchers (two teams of two people), operating alternately. Some rafts were sampled randomly every day using an ORI ring net with a diameter of 1.6 m. Samples were identified and weighed (wet weight). Floating seaweed abundance was estimated with reference to the line transect method (Buckland et al. 2001) and calculated using the software Distance 6.0 Release 2 (<http://www.ruwpa.st-and.ac.uk/distance/distance60download.html>; Thomas et al. 2010). Following Thomas et al. (2010), we estimated the parameter  $\hat{\mu}$ , which is referred to as the effective strip half width (ESW) and defines the maximum limit for distinction:

$$\hat{D} = \frac{n}{2\hat{\mu}L} \tag{1}$$

where  $\hat{D}$ ,  $n$ , and  $L$  are the abundance of seaweed rafts, the total number of seaweed rafts along a transect, and the length of the transect, respectively.  $\hat{\mu}$  was estimated from several different models fitted to the frequency distribution of seaweed rafts per distance class. It was necessary to account for differences in the sea and meteorological conditions between transects when

selecting a model. The model with the lowest value of Akaike information criterion (AIC), as defined by Eq. (2), was adopted as the reference model (Buckland et al. 2001):

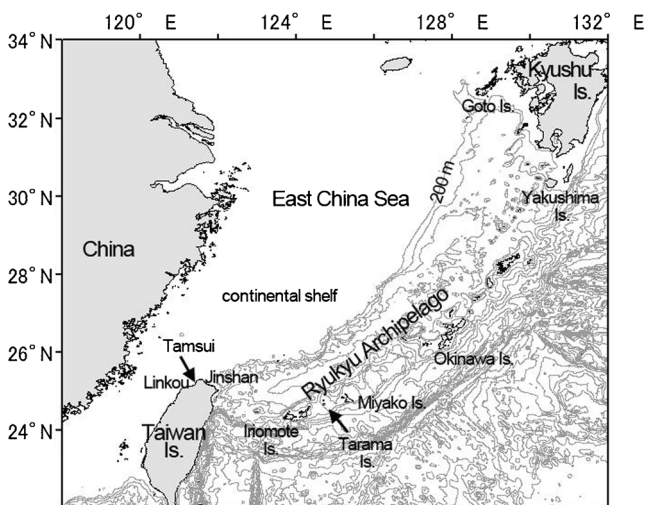
$$AIC = -2 \cdot \ln(\Lambda) + 2q \tag{2}$$

where  $\Lambda$  is the maximized likelihood, and  $q$  is the number of estimated parameters. The number of estimated parameters was the number of parameters based on a combination of key function and an adjustment term provided by the program Distance 6.0. The maximized likelihood was obtained from a maximum likelihood estimation (Buckland et al. 2001). Seaweed rafts were classified into classes (0–10, 10–20, 20–30, and 30–40 m) representing the perpendicular distance between the boat and the raft. We ignored rafts situated farther away than 40 m, at which point it became difficult to estimate the distance and to observe the seaweed. The number of rafts along each transect (number of rafts/area along a transect) was obtained based on observed number of rafts and ESW of each transect based on a model selected by the lowest AIC.

The stranding of seaweed rafts was observed by one of the coauthors (S.T. Hsiao) who confirmed the presence of stranded *S. horneri* in northern Taiwan and collected samples and information on a large stranding there. Another coauthor (T. Ajisaka) visited Tarama Island in the Ryukyu Archipelago and verified the presence of fresh *S. horneri* stranded on the beach.

Kuroshio Current axis, current, wind, and sea surface height anomaly

The Kuroshio Current is an important factor influencing the transport of seaweed rafts. The 11th Regional Coast Guard Headquarters in Japan estimates the main stream of the Kuroshio Current based on field observations and satellite remote sensing data every week. These published data were used to understand the oceanic front of the Kuroshio Current. Current is the main factor influencing the transport and distribution of floating seaweeds. We used the surface current determined from the Japanese Fishery Research Agency (FRA)–Japan Coastal Ocean Prediction Experiment (JCOPE) (FRA-JCOPE2) reanalysis data; these data were provided by the Ocean Downscaled Prediction Research Team (ODPRT) of the Japan Agency for Marine–Earth Science and Technology (<http://www.jamstec.go.jp/frcgc/jcope/vwp/>). By assimilating most of the available observation data into the JCOPE2 ocean forecast system, the ODPRT created the FRA-JCOPE2 reanalysis data set with a horizontal high resolution of 1/12°. These data have been used to describe the oceanic variability associated with the Kuroshio–Kuroshio Extension, the Oyashio Intrusion, and mesoscale eddies from January 1993 to the present (Miyazawa et al. 2009). Collaboration with the FRA has allowed the ODPRT to assimilate large amounts of in



**Fig. 1** Map of the East China Sea and key locations of this study

situ data for areas around Japan. Assimilations of these in situ data have successfully identified Kuroshio frontal waves, the Oyashio Intrusion, and mesoscale eddies. Thus, we used the data for the East China Sea and Pacific Ocean, relating to the study area in February to March of 2010, 2011, and 2012.

Wind also influences currents in the surface layer. Wind speed and direction are monitored by the Automated Meteorological Data Acquisition System (AMEDAS) operated by the Japan Meteorological Agency (JMA). Daily maximum wind speed and direction data from the JMA are available via the internet (<http://www.jma.go.jp/jma/menu/obsmenu.html>). We used maximum wind speed data (the maximum daily value among mean 10-min wind speeds); these data were measured by a wind sensor set at 10.1 m above sea level at the Iriomotejima Meteorological Station (24°25.6'N, 123°45.9'E) on Iriomote Island (Okinawa Prefecture, Japan). The US National Oceanographic and Atmospheric Administration (NOAA) National Operational Model Archive and Distribution System (NOMADS) is a web-based service that provides both real-time and historical climate and weather model data (Rutledge et al. 2006). NOMADS includes archives of daily and monthly global wind data through the Live Access Server (<http://nomads.ncdc.noaa.gov/las/getUI.do>). We obtained monthly mean wind vector data in March 2010 and February 2011, and daily data for the period when seaweed rafts were stranded in March 2012 from archives of NOAA Multiple-Satellite Blended Sea Surface Winds.

Sea surface height (SSH) can indicate the spatial distributions of eddies, which also influence the current and the transport of floating seaweed. These data are obtained by satellite altimeters and were provided by the Colorado Center for Astrodynamic Research ([http://eddy.colorado.edu/ccar/data\\_viewer/info](http://eddy.colorado.edu/ccar/data_viewer/info)). The SSH product is a multi-satellite-merged product that includes data from all of the available altimetry satellites on a particular day. We used a historical product during the survey periods. The product is based on the highest quality Geophysical Data Records (GDR) of the GEOSAT ERM, ERS-1, Topex/Poseidon, ERS-2, GEOSAT Follow-On (GFO), Envisat, Jason-1, and OSTM/Jason-2 missions. Historical along-track data were provided by the Radar Altimeter Database System maintained by the Delft Institute for Earth-Oriented Space Research.

## Results

### Spatial distributions of drifting seaweed rafts

In February to early March 2010, seaweed rafts were distributed on the continental shelf west of the Kuroshio Front that

passed along the 200-m isobath in the East China Sea (Fig. 2a). This type of distribution also appeared in February 2011 (Fig. 2b). However, in March 2012, seaweed rafts were distributed not only on the continental shelf but also in the Kuroshio Current and its outer waters in the East China Sea (Fig. 2c). Observations of seaweed rafts conducted south of Shikoku and Honshu Islands in March 2012 revealed that many rafts were distributed in the Kuroshio Current (Fig. 3). In all three surveys, seaweed rafts collected in waters south of 32°N and west of 129°E in the East China Sea consisted of only *S. horneri*.

The number of seaweed rafts increased in the southwestward direction during the 2010 and 2011 surveys (Fig. 2a, b). However, the maximum number was observed in waters south of Kyushu Island during the 2012 survey (Fig. 2c).

### Surface currents in the East China Sea during the field observations

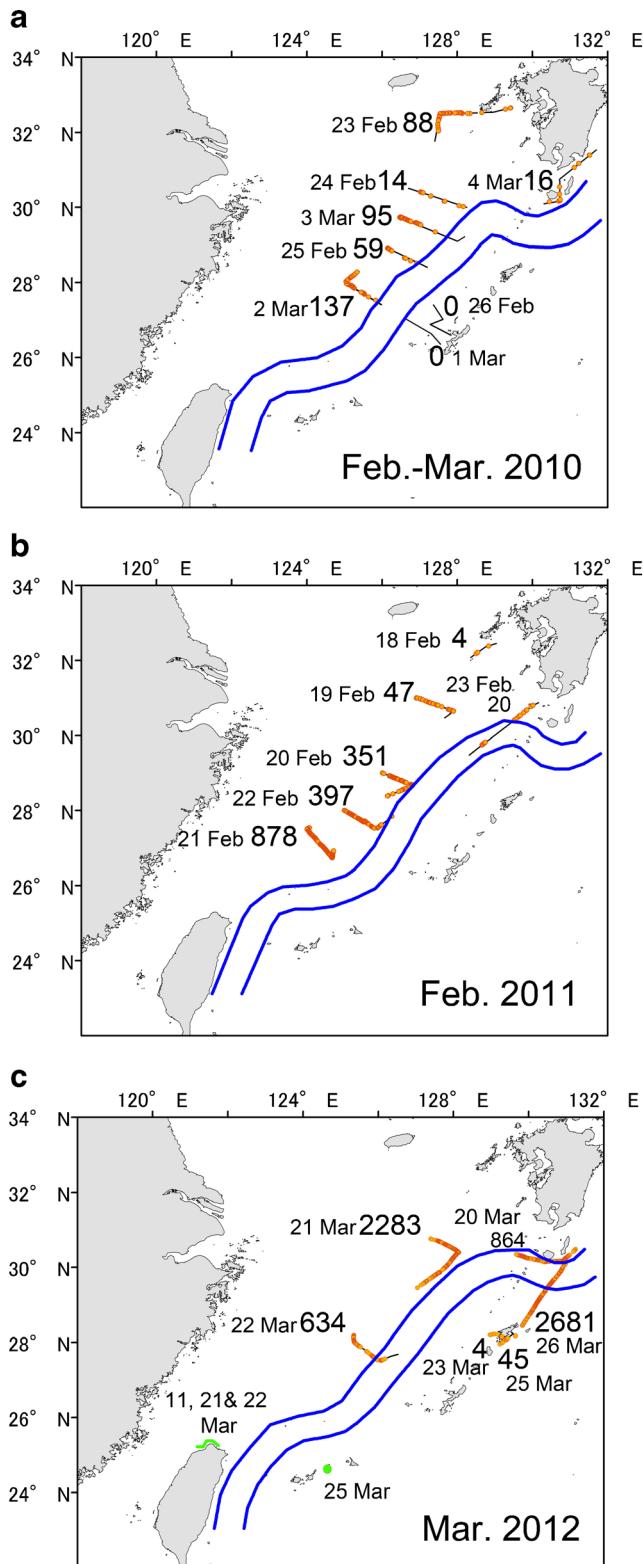
Surface current is the most important factor in the transport of seaweed rafts. On 1 March 2010, the current originating from southwest of Taiwan, referred to as the Taiwan Warm Current (TWC) (Zhu et al. 2004), passed near Taiwan and moved northeastward along the Kuroshio Current from 25°N to 27°N with a narrowing interval around 26°N (Fig. 4a). On 15 February 2011, the TWC originating from the southwest of Taiwan moved northeastward in the waters north of Taiwan and turned northward at 26°N and 122°E (Fig. 4b). The current heading southeast near the north coast of Taiwan was very weak on 1 March 2010 and 15 February 2011 (Fig. 4a, b). On 15 March 2012, a northeast current passing west of Taiwan turned southeastward to the north of Taiwan and merged into the Kuroshio Current (Fig. 4c). The rest of the TWC bifurcated north of Taiwan heading northeastward and slowed at 26°N and 122°E (Fig. 4c). A weak surface current was directed to Iriomote and Tarama Islands (Figs. 1 and 4c).

### Stranded *S. horneri* on coasts

A mass of *S. horneri* was reported to be stranded on the northern coast of Taiwan in Tamsui on 11 and 21 March (Huang 2012). From 21 to 22 March 2012, the stranding extended along a 70-km stretch of coastline from Jinshan to Linkou through Shimen, Sanchi, Tamsui, and Bali and from the estuary of Tamsui River at Tamsui to 7 km upstream of the river mouth (Anon 2012).

One of the coauthors (T. Ajisaka) found a mass of *S. horneri* stranded on the beach in Tarama Island between Ishigaki and Miyako Islands in the Ryukyu Archipelago on 26 March 2012 (Fig. 1). The freshness of the *S. horneri*





**Fig. 2** Observation transects (black narrow solid lines) in the East China Sea during the research cruises (KT10-1, KT11-1, and KT12-1), seaweed rafts (red closed circles), and stranded rafts (a green circle or a solid line). The water between the two blue solid lines is the main stream of the Kuroshio Current as estimated by the 11th Regional Coast Guard Headquarters (2010, 2011, 2012). Numbers on the maps are rafts within the effective stripe width. Dates on the maps indicate when the transect observations were undertaken. **a** 2010, **b** 2011, and **c** 2012

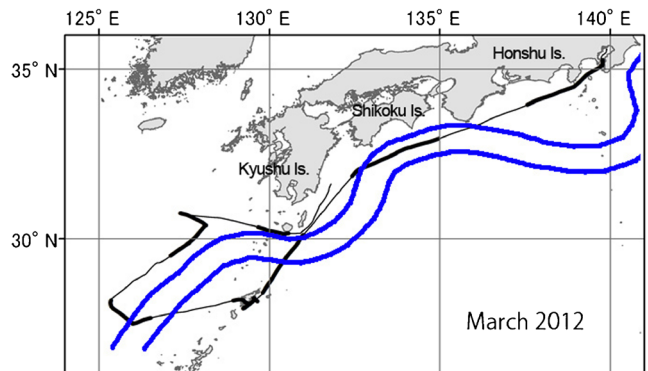
Wind at Iriomote Island and wind vector distributions in the East China Sea

Table 1 shows the wind directions and the mean maximum wind speeds at Iriomote Island (Fig. 1) near northern Taiwan and Tarama Island in March 2012, which corresponded to the stranding of drifting seaweed rafts on the coasts of northern Taiwan and Tarama Island. A predominantly north wind was recorded on 8–10, 20–21, and 23–24 March 2012, which corresponded with periods when drifting seaweed rafts were stranded on the coast at Tamsui on 11 March, the north coast of Taiwan on 21 March, and Tarama Island on 25 March 2012, respectively.

Monthly mean wind vector distributions, obtained from NOMADS, in March 2010 and February 2011 showed that northeast winds were predominant in the area of 25°–28°N, 122°–126°E (Fig. 5a, b). Daily mean wind vector distributions on 9 and 10 March 2012 showed strong north or north-northeast winds in this area (Fig. 5c, d). Records for 20 March 2012 also indicated strong north-northeast wind in the same area (Fig. 5e). On 24 March 2012, strong north or north-northeast winds were predominant in an area from 24°N to 26°N and from 122°E to 126°E (Fig. 5f) near Tarama Island (Fig. 1).

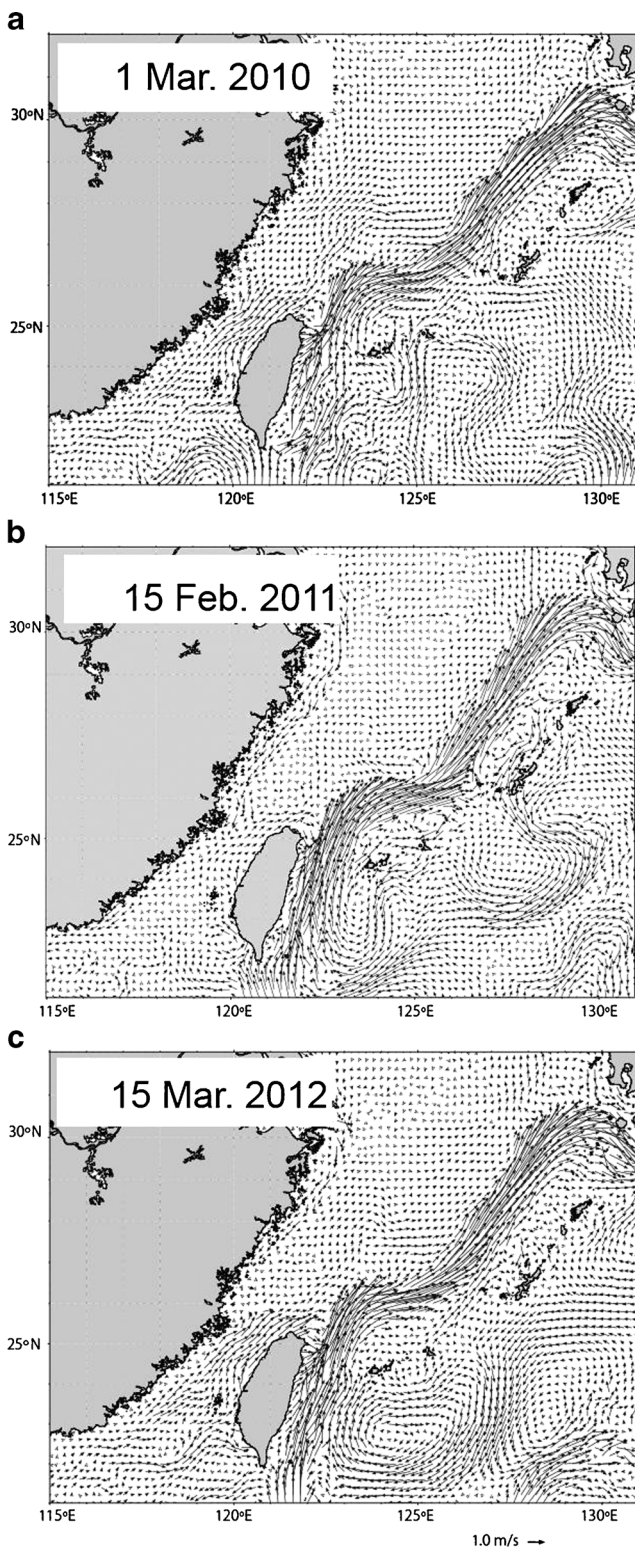
Sea surface height distribution in the East China Sea

Sea surface height indicates a spatial distribution of eddies. Anticyclonic and cyclonic eddies are characterized by high



**Fig. 3** Map showing ship tracks (black narrow solid lines) during KT-12-3 and drifting seaweed rafts (closed circles). The water between the two blue solid lines is the main stream of the Kuroshio Current as estimated by the Japan Coast Guard (2012)

indicated that the stranding likely occurred on the previous day.



**Fig. 4** Surface current distributions in the East China Sea on 1 March 2010 (a), 15 February 2011 (b), and 15 March 2012 (c), estimated by FRA-JCOPE2 data

SSH and low SSH, respectively. Anticyclonic eddies accompany a clockwise geostrophic current parallel to the

**Table 1** Daily maximum wind speed and wind direction observed in March 2012 at Iriomotejima Meteorological Station

Day	Maximum wind speed ( $\text{m s}^{-1}$ )	Wind direction	Day	Maximum wind speed ( $\text{m s}^{-1}$ )	Wind direction
1	4.6	SSE	17	8	S
2	6.9	NE	18	8.1	ENE
3	8.4	NE	19	7.4	ENE
4	6.8	SSE	20	8.8	N
5	8.4	SSW	21	7.3	NNE
6	7.1	ENE	22	5.7	SSE
7	8.3	SW	23	8.3	NNE
8	5.8	NNE	24	9.9	N
9	7.7	N	25	6.8	NE
10	6.3	N	26	5.9	ENE
11	7.3	NE	27	5.9	ENE
12	8.5	NE	28	6.6	ENE
13	5.9	ENE	29	5.3	SE
14	5.3	ENE	30	7.1	SSE
15	6.6	SSE	31	8.5	NNE
16	7.6	SSE			

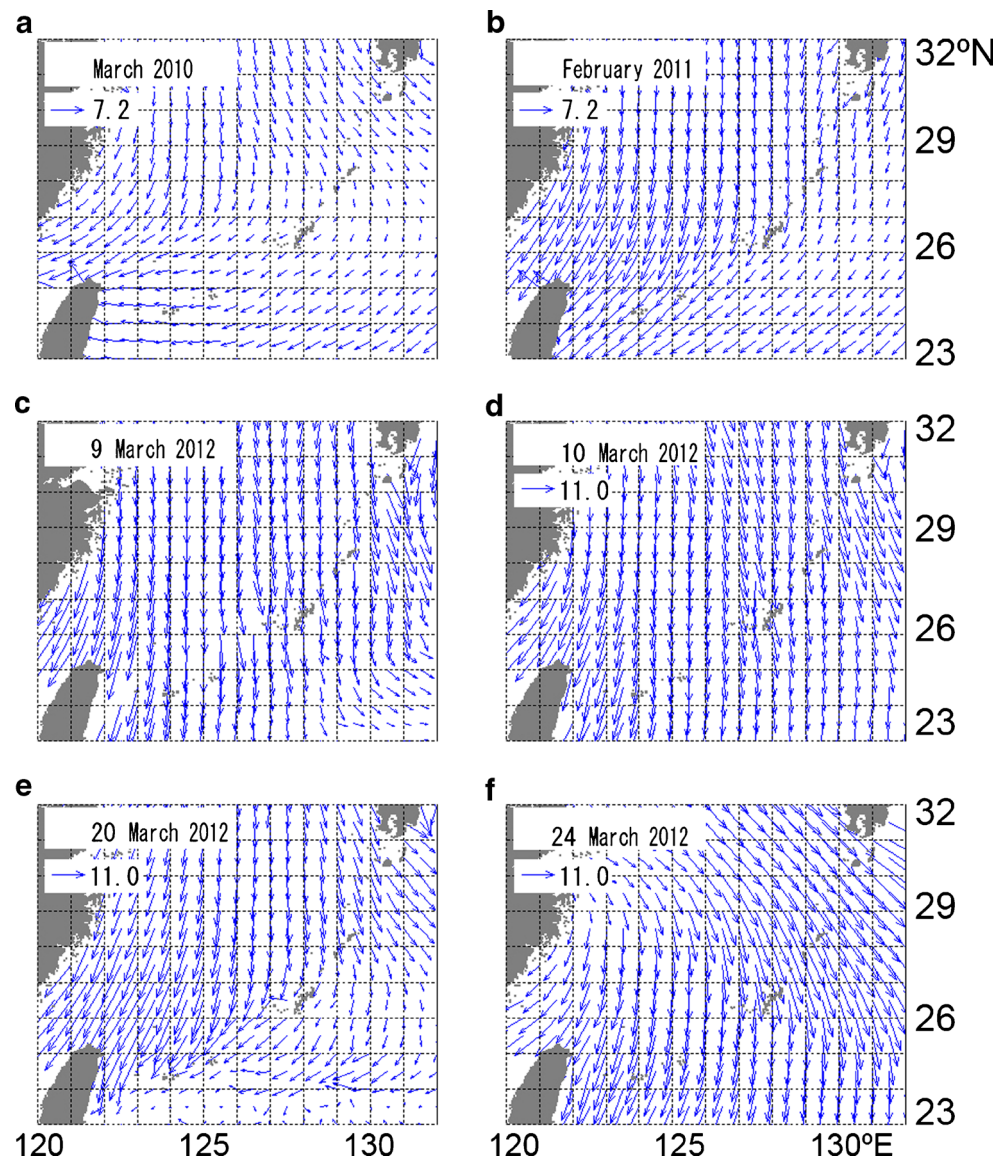
contours of SSH in the Northern Hemisphere due to the Coriolis force (Gill 1982).

From 15 February to 15 March 2010, a band of high SSH waters that were not higher than those in 2012 occupied the continental shelf area west of the Kuroshio Current in the East China Sea (Fig. 6). In 2011, a high SSH water mass was located northeast of Taiwan on 1 February and was linked to a band of high SSH from 15 February to 15 March on the continental shelf area west of the Kuroshio Front (Fig. 6c, d). However, the SSH was not as high as in 2012. In 2012, a high SSH water mass was located northeast of Taiwan and was also present at 23°N and 125°E on 1 February (Fig. 6e). This water mass was displaced to Taiwan on 15 February and remained east of Taiwan from 1 to 15 March 2012 (Fig. 6f). It extended southeastward crossing the Kuroshio Current. It was estimated that the difference in surface height between the high SSH and low SSH southeast of Taiwan in March 2012 was about 40 cm at a distance of 100 km (Fig. 6f).

## Discussion

Diverse floating seaweeds are found in temperate and subpolar regions of the world's oceans, where sea surface currents and winds determine their traveling velocities and directions (Rothäusler et al. 2012). In our survey of the East China Sea, floating seaweeds consisted of only one species, *S. horneri*. Because there have been no reports of asexual reproduction in this species during floating, it is likely that this species originates from coastal locations. Spatial distributions of fixed *S.*

**Fig. 5** Sea surface wind vector distributions in the East China Sea obtained from NOAA NOMADS. Monthly mean winds in March 2010 (**a**) and February 2011 (**b**) and daily mean winds on 9 (**c**), 10 (**d**), 20 (**e**), and 24 (**f**) March 2012



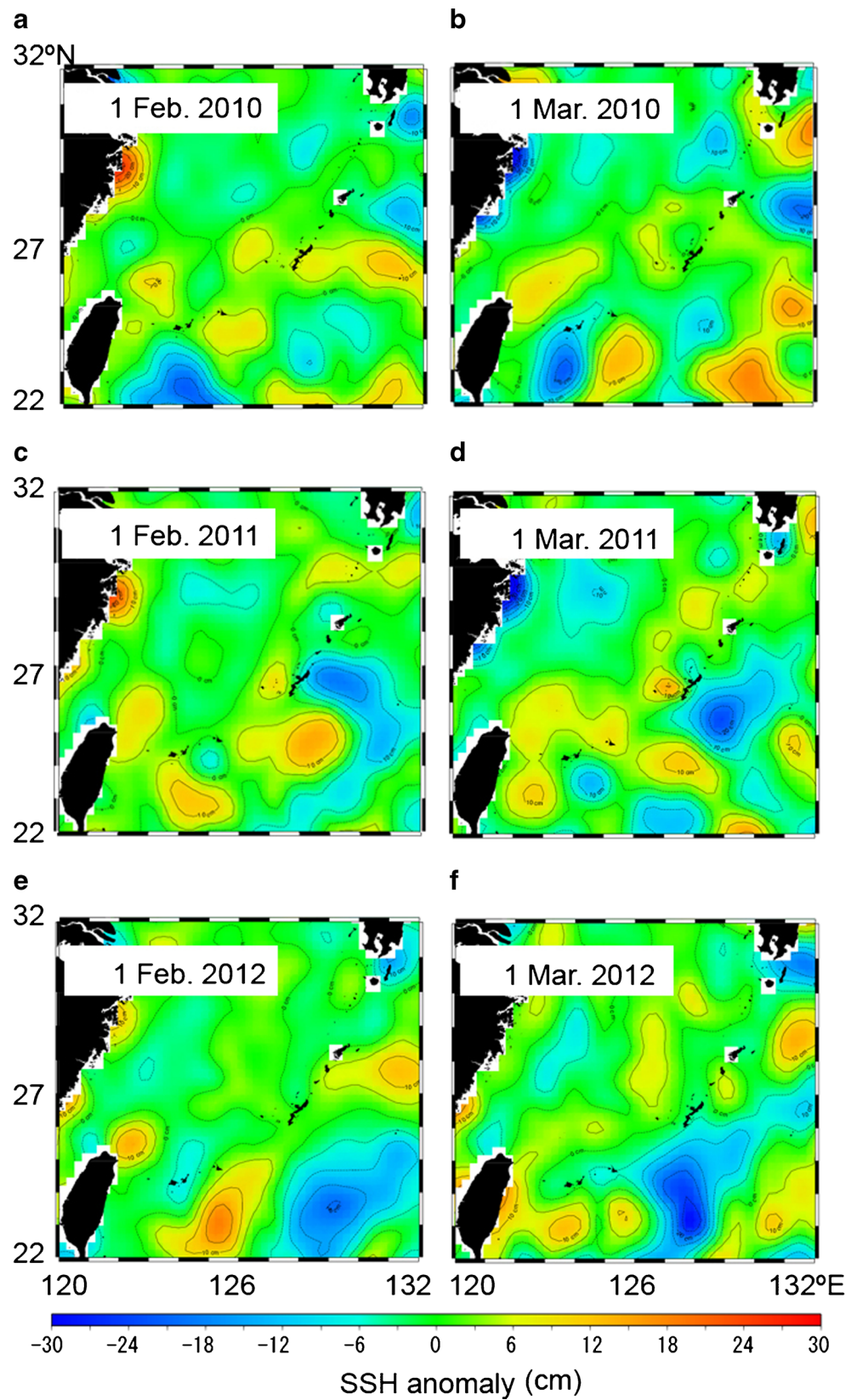
*horneri* in Japan are limited to the north of Kyushu Island. The passage of the Taiwan Warm Current through the Taiwan Strait and the flow of the Kuroshio Current would prohibit *S. horneri* from the north of Kyushu Island from being transported to the upstream of the Kuroshio Current in the East China Sea (e.g., Fig. 4). There are no records of *S. horneri* distributions in the Ryukyu Archipelago. Furthermore, although Chou and Chiang (1981) reported *S. horneri* in northern Taiwan, we could not locate this species during our field surveys in 2010. Rafts of *S. horneri* were stranded on the coast of northern Taiwan in spring 2012, suggesting that *S. horneri* grows in this region. Coral reefs were at the stranding sites during the field surveys. It is likely that coastal sites where coral reefs develop are not a good habitat for *S. horneri*. However, *S. horneri* is distributed along the Chinese coast from Dalian to Hainan Island (Tseng 2000; Hu et al. 2011). Komatsu et al. (2005) found

almost pure *S. horneri* beds in Gouqi Island off Zhejiang Province, China. Komatsu et al. (2007) deployed satellite tracking buoys attached to rafts of *S. horneri* off Zhejiang Province near the Chinese coast, and the rafts reached offshore waters in the East China Sea in early May. They concluded that the origins of floating *S. horneri* in the East China Sea were Chinese coastal sites based on the buoy results and the seaweed distribution. These findings are also supported by a numerical simulation using the Princeton Ocean Model of the East China Sea (Filippi et al. 2010). The modeled results also showed that particles of seaweed rafts, which were released from the Chinese coast, reached offshore waters in the East China Sea. Thus, it is expected that the seaweed rafts consisting solely of *S. horneri* observed in February and March in 2010, 2011, and 2012 originated from the Chinese coast.

Seaweed rafts have been found on the continental shelf and in limited areas where the Kuroshio front has strong



**Fig. 6** Sea surface height in the East China Sea on 1 February and 1 March in 2010 (**a**, **b**), in 2011 (**c**, **d**), and in 2012 (**e**, **f**) provided by the Colorado Center for Astrodynamics Research



horizontal shear due to the velocity of the Kuroshio Current (two to three knots;  $1\text{--}1.5\text{ m s}^{-1}$ ) (Kawai 1972); seaweeds

were found in this region in March 2004 (Komatsu et al. 2007), February and March 2010, and February 2011.



These floating seaweeds were likely trapped by the front in the convergence area of surface water, as in the study of Hinojosa et al. (2010) on the spatial and temporal distribution of floating kelp in southern Chile. However, seaweed rafts were distributed in the Kuroshio Current in the East China Sea and also south of the Osumi Peninsula in February 2012. This means that the seaweed rafts passed the Kuroshio Front in the upstream part of the Kuroshio Current in the East China Sea.

After the bifurcation of the TWC north of Taiwan in March 2012, no strong currents were present in the waters between the TWC flowing northeastward and the Kuroshio Current. Seaweed rafts can also be distributed in such stagnant waters. Thiel et al. (2011), in a ship-based visual survey, examined the abundance and composition of flotsam in the German Bight in the North Sea. They verified that the import of floating objects and retention times in the German Bight were influenced by wind force and direction; rapid transport of floating objects through the German Bight was driven by strong westerly winds. When wind blows continuously in the same direction for several days, an Ekman drift current is generated. According to Yanagi (1989), the direction of the surface current is 45° to the right-hand side of the direction of the wind heading. The speed of the surface current is 3.5 % of the wind speed under conditions where the boundary layer of the atmosphere is similar to that of the sea at the sea surface, and the resistance coefficient of the atmosphere is the same as that of the sea. Using this relation, we can estimate the Ekman drift current at the sea surface. From 8–10 to 20–21 March 2012, north or north-northeast wind blew continuously. If we assume that the wind speed was 10 m s<sup>-1</sup> (according to the data in Fig. 5), surface current flow southwestward was about 35 cm s<sup>-1</sup>. The distances of seaweed transport by this current from 8 to 10 March and from 20 to 21 March 2012 were estimated to be 90 and 60 km, respectively. The seaweed

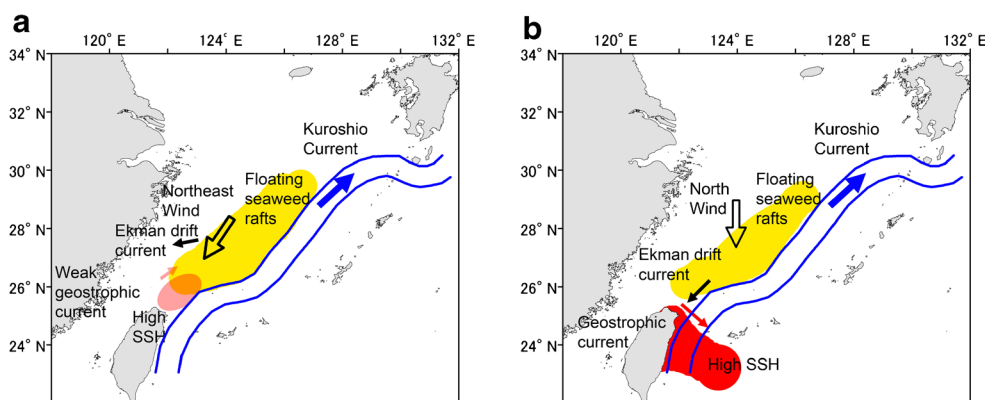
rafts present in the stagnant waters northeast of Taiwan could have reached the coast of northern Taiwan on 11 and 21 March 2012.

A water mass with high SSH accompanies the geostrophic current parallel to the contours of SSH. The current direction is clockwise in the Northern Hemisphere. A water mass with a high SSH was located around Taiwan or north of Taiwan and extended to the Kuroshio Current region in March 2012. The geostrophic current due to the high SSH moved southeastward crossing the Kuroshio Current. Therefore, the geostrophic current transported seaweed rafts southeastward. If we assume hydrostatic approximation is applicable to the Navier–Stokes equations, in which we can neglect viscosity, external forces, and nonlinear terms, the speed of the geostrophic current can be obtained from the distance and difference in SSH as follows:

$$v = g \frac{\Delta h}{f \Delta x} \tag{3}$$

where  $v$ ,  $g$ ,  $f$ ,  $\Delta h$ , and  $\Delta x$  are the geostrophic current speed, gravity, Coriolis parameter under the plane approximation, difference in SSH, and distance between high and low SSHs. It was estimated that the distance ( $\Delta x$ ) and the difference in surface height ( $\Delta h$ ) between the high SSH and low SSH southeast of Taiwan in March 2012 were 100 and 40 cm, respectively (Fig. 6f). Using Eq. (3), the speed was estimated to be 50 cm s<sup>-1</sup>. The surface current velocity off the northeast coast of Taiwan west of the Kuroshio Current is also about 50 cm s<sup>-1</sup> (Fig. 4c), which indicates that the estimated geostrophic current speed is realistic.

If we assume the width of the Kuroshio Current to be 100 km (Fig. 7), it would take 50 h for seaweed rafts to traverse the Kuroshio Current under the geostrophic current conditions due to the high SSH. Because the Kuroshio Current flows at



**Fig. 7** Schematic diagrams of the physical conditions during the usual (a) and unusual (b) distributions of seaweed rafts in the East China Sea. The two blue solid lines and the solid arrow represent the main stream of the Kuroshio Current and its current. The empty and solid black arrows

are the predominant wind direction and Ekman drift current in the surface layer, respectively. Red and pink areas indicate high SSH and relatively lower high SSH. The red and pink arrows are the geostrophic currents associated with the corresponding SSH

about  $1.5 \text{ m s}^{-1}$  (three knots) (Kawai 1972), seaweed rafts are transported for a distance of 270 km along the Kuroshio Current. The rafts are transported to waters southwest of Okinawa Island and northeast of Miyako Island (Fig. 1), where the surface current is stagnant. When the north wind blows continuously in this area, seaweed rafts are transported south-westward. If seaweed rafts entered the Kuroshio Current east of Taiwan on 20 March 2012 after a period of north wind, they might have exited northeast of Miyako Island on 23 March 2012. From 23 to 24 March 2012, a north wind was predominant at Iriomote Island. If we assume that the wind speed was about  $10 \text{ m s}^{-1}$  (from Fig. 5f), the Ekman drift current in the surface layer is estimated to be about  $35 \text{ cm s}^{-1}$ . This is sufficient to transport seaweed rafts 60 km from the northeast of Miyako Island to Tarama Island. The seaweed rafts could then reach Tarama Island on 25 March 2012. Because these processes are stochastic, the spatial distribution of seaweed rafts may show probability density distributions. Seaweed rafts remaining in the Kuroshio may be transported south of Yakushima Island (Fig. 2c).

The distribution of seaweed rafts in the East China Sea in February and/or March can be summarized in schematic diagrams based on the above discussions (Fig. 7). The diagrams for 2010 and 2011 indicate the usual distributions with floating seaweeds not being widely distributed in the Kuroshio Current. However, 2012 had an unusual distribution, with floating seaweeds observed in the Kuroshio Current and also in its outer waters. It is speculated that the physical conditions responsible for this unusual distribution were a continuous strong north wind and high SSH eddies near Taiwan Island, crossing the Kuroshio Current.

Such unusual distributions may influence marine organisms accompanying or attached to the seaweed rafts because they would also be transported to the Kuroshio Extension with the Kuroshio Current or to the outer regions of the Kuroshio Current. Because these waters are not coastal but offshore, fauna attached to or accompanying seaweed rafts may die after settling on seaweed rafts because of a loss of buoyancy. It would be interesting to examine yellowtail recruitment in 2012 along the Kyushu, Shikoku, and Honshu Islands because the unusual distribution of floating seaweed probably influenced the transport of yellowtail juveniles, which are caught by fishermen each spring.

This study has presented the first description of the unusual distribution of seaweed rafts in the East China Sea and the Kuroshio Current off Kyushu, Shikoku, and Honshu Islands. It is speculated that the unusual distribution of *S. horneri* rafts in the East China Sea was generated by both a continuous strong north wind and a high SSH water mass that covered northeast Taiwan and the neighboring Kuroshio Current in the early spring of 2012 (Fig. 7). Further examination of this hypothesis is necessary using case studies and monitoring of floating seaweed communities.

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