KMI International Journal of Maritime Affairs and Fisheries • Volume 12 Issue 2 December 2020 pp. 021-035 •

An Analysis on the Distribution of Floating Seaweed in the East China Sea and Southern Yellow Sea in 2015 − the Case of Sargassum observed by the Geostationary Ocean Color Imager

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ABSTRACT

In early 2015, a large amount of brown seaweed, known as Sargassum horneri macroalgae, was piled up along the shore of Jeju Island and the southwest islands of the Korean Peninsula. This event was associated with a huge bloom of floating Sargassum in the East China Sea (ECS) and southern Yellow Sea (SYS). Ship surveys or aerial surveys can only cover a limited space and are time consuming and expensive. This study aims to capture temporal variation in the geographical distribution of floating S. *horneri* using satellite imagery obtained from the Geostationary Ocean Color Imager (GOCI). The GOCI acquires eight images a day with a 500-m spatial resolution, a high signal-to-noise ratio and a constant viewing angle, providing imagery suitable for monitoring a large-scale floating algae event and its temporal evolution. Semi-monthly aggregated images were generated to determine fractional coverage area per pixel or density of the floating algae from January to June, 2015. The results are consistent with previous field-survey-based studies, but also reveal a number of new findings. Unexpectedly, S. *horneri* patches were detected as early as January over a broad area of the ECS continental shelf. The floating algae were detected not only near the outer continental shelf area along the Kuroshio front and Eastern Kuroshio Branch current as previously reported in literature but also along the western inner continental shelf. The floating seaweed patches along the eastern outer shelf proliferated during the second half of March, then moved north, entering the Korea-Tsushima Straits in the west of Kyushu to the north. The algae patches in the western shelf moved north in April and May and separated, one entering the Jeju Strait and the Korea-Tsushima Straits, and the other entering the SYS. Overall, S. horneri density peaked in late April, then decreased in May and June before disappearing from the ECS in July.

Keywords: floating Sargassum, satellite, imagery, GOCI, remote sensing, distribution, East China Sea

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Received 12 Nov. 2020; Received in revised form 21 Nov. 2020; Accepted 20 Dec. 2020

1. Introduction

In early 2015, a large amount of floating brown seaweed accumulated on the southwest islands of the Korean Peninsula and along the coast of Jeju Island, located in the northern East China Sea (ECS) (Hwang et al. 2016). The unprecedented scale of this event resulted in significant economic loss to local aquaculture sites for *Porphyra* and *Saccharina* and abalone and to fishers by preventing them from getting into the sea. In addition, approximately $800,000 USD were spent to clear over 10,000 tons of seaweed washed ashore Jeju Island (unpublished data; Hwang et al. 2016). The seaweed was identified as *Sargassum horneri* (Turner) C. Agardh, a species of brown algae that had been previously observed as drifting patches offshore in the ECS but not in local benthic colonies from south of Kyushu Island to Taiwan through the Ryukyu Archipelago (Komatsu et al. 2007; Mizuno et al. 2014). *S. horneri* originally grows while attached to shallow rocks, but can become detached during rough weather and floats due to its gas-filled vesicles. Floating *S. horneri* in the ECS serves as important habitat for various marine lives including several species of commercially valuable fish (Safran and Omori 1990; Cho et al. 2001; Abé et al. 2013; Mizuno et al. 2014). Despite its ecological importance in offshore waters, the brown algae become problematic when it washes ashore on a large scale.

Traditionally, most studies of floating *Sargassum* patches in the ECS have been based on visual surveys and *in situ* sampling onboard a research vessel (Komatsu et al. 2007; Komatsu et al. 2014; Mizuno et al. 2014). Such field surveys have provided valuable information on the species composition, morphology, size, shape, and the weight of individual rafts. However, ship-based surveys only cover small portion of bloom area, so it is impossible to understand synoptic distribution of *Sargassum* throughout the ECS without satellite images.

Satellite remote sensing techniques allow us to observe wide areas of the ocean surface at once, and are complementary to conventional ship-based observations. Satellite ocean color (OC) observation, primarily designed to estimate oceanic phytoplankton biomass, has been used to detect extensive floating *Sargassum* in the western Gulf of Mexico in 2005 (Gower et al. 2006). In fact, all OC sensors (including the Geostationary Ocean Color Imager [GOCI] onboard the COMS satellite [http://kosc.kiost.ac.kr], the Moderate Resolution Imaging Spectroradiometer [MODIS] onboard the Terra and Aqua satellites [https://oceancolor.gsfc.nasa.gov/], the Visible Infrared Imaging Radiometer Suite [VIIRS] onboard the Suomi NPP satellite [https://oceancolor.gsfc.nasa.gov/], and the Ocean and Land Color Instrument [OLCI] onboard the Sentinel-3 satellite [https://sentinel.esa.int/web/sentinel/missions/sentinel-3/instrument-payload/olci]), have visible and infrared channels, which allows to discriminate floating seaweed from sea water. Recently, satellite OC data have been widely used to study the distribution of floating *Sargassum* blooms in the Gulf of

Mexico, Caribbean Sea, Sargasso Sea, and central Atlantic Ocean (Gower and King 2008; Hu 2009; Gower and King 2011; Smetacek and Zingone 2013).

Previously, several studies have used satellite remote sensing to detect green algae, *Ulva prolifera*, blooms in the Yellow Sea (YS) and ECS (e.g., Hu and He 2008; Hu et al. 2010), these blooms are typically more intense and create a signal stronger, i.e. easier to detect, than *Sargassum* blooms. This study used the GOCI multi-spectral data to investigate the geographic extent and temporal variability of the 2015 *Sargassum* bloom event in the ECS. GOCI operates on geostationary orbit, thus providing the unique capability to capture eight images a day over the Northeast Asian seas (including the ECS) with a 500-m spatial resolution, a constant viewing angle, and importantly, negligible sun-glint interference. The frequent observations allow for the estimation of algae coverage within a relatively short period, thus providing seasonal geographic variability. This study aims to capture temporal variation of the Sargassum bloom distribution with semi-monthly composite data derived by GOCI imagery. The satellite-based spatio-temporal information will be discussed in relation to the known ocean currents or monsoonal wind in the region.

2. Study Area, Methods and Data

A map of the ECS and southern YS is displayed in Figure 1. The ECS is a marginal sea in northeast Asia, located between China, Japan, and Korea. It connects the Taiwan Strait in the southwest, the Pacific Ocean to the south and to the east, the YS in the northwest, and the Korea-Tsushima Straits in the northeast. The YS is a semi-enclosed marginal sea between China and Korea with depths of less than 100 m. The ECS consists of a broad continental shelf with steep slope and deep trough. Most of the ECS is less than 200 m in depth, with a shallower inner continental shelf to the west and a deeper outer continental shelf to the east. The deep trough area (over 1000 m in depth) extends from the northeast of Taiwan up to latitude 29.5 °N along the edge of the continental shelf. The Kuroshio Current, the major open ocean current in this region, enters the ECS along the east of Taiwan, flows along the continental slope, and exits the ECS through the Tokara Strait. The East Asian monsoon affects this area. North and northwest winds are predominant in winter, and southern and southeastern winds are predominant in summer. The seasonal wind pattern strongly influences surface currents along the ECS continental shelf. Other weaker currents in this area, such as the Taiwan Warm Current (TAWC), Eastern and Western Kuroshio Branch currents (EKB & WKB), Cheju Warm Current (CWC), Yellow Sea Warm Current (YSWC), and Chinese Coastal Current (CC), are indicated in Figure 1. For more information on the circulations in the ECS and YS, please refer to Lie and Cho (2016) and references therein. Satellite imagery is presented for the area enclosed by the dotted rectangle (between latitudes 27 °N and 35 °N and longitudes 120 ° E and 130.5° E) in Figure 1.

GOCI images acquired from January to June of 2015 were analyzed to detect the drifting *Sargassum* patches. Details of the data processing algorithm are presented elsewhere (Park et al., 2020), but basic principle is described here. Floating algae have a distinct spectral characteristic, which allows us to easily detect with red and near infrared (NIR) spectral bands. These bands are common in OC sensors and high resolution optical sensors. The distinct spectral trait of the floating algae comes from the pigment chlorophyll *a*, which exhibits low reflectance at red wavelength due to strong absorption and much higher reflectance at NIR wavelength. Seawater displays low reflectance at red wavelength and even lower reflectance at NIR wavelength (Gower et al. 2006). Therefore, the difference in reflectance between the red and NIR bands, called red-edge reflectance difference, is a sensitive metric for detecting floating algae and allows one to easily discriminate between the floating *Sargassum* and seawater. However, the reflectance of background seawater can vary across the field-of-view of a sensor, depending on seawater turbidity and illumination angles (Garcia et al. 2013; Hu 2009). The spatial variability of the seawater signal was accounted for in this study by removing seawater background signal before estimating the floating algae. Following removal of the seawater variability background, the red-edge reflectance difference depends primarily on the fractional area occupied by the floating algae, or algae-covered fractional area (AFA). The AFA is a number that falls between 0 (free of floating algae) and 1 (fully occupied by floating algae). For example, an AFA of 0.01 indicates that 1% of a pixel is occupied by floating algae.

Figure 2 displays an example of an individual scene, including a true color composite and processed AFA image. Floating algae patches are not apparent in the true color image because reflectance change due to the presence of floating algae is small compared to other color variabilities in the visible bands.

The AFA data are averaged in space to enhance visibility. Most of the individual images from space showed fragmented ocean surface area due to irregular cloud cover. To synthesize a complete picture, a semimonthly composite of the AFA images was generated. Furthermore, small isolated algal patches can hardly be visible after resampling for size reduction of the AFA images for display. For example, the original image size of Fig. 2 (b) was approximately 2K by 2K in resolution. We performed spatial averaging for a box size of 6 by 6 pixels to enhance the visibility of algal patch distribution. The data are, then aggregated to produce semi-monthly distribution, which are compared with previous work and interpreted with ocean currents and monsoonal wind. The study flow is shown in figure 3.

Figure 1. A map of the East China Sea and southern Yellow Sea. Isobath lines for 50 m, 200 m, and 1000 m are indicated as black, dark grey, and light grey, respectively. The area enclosed by the dotted rectangle is the area for which GOCI images were analyzed in this study. Ocean currents for winter are adopted from Lie & Cho (2016). TAWC, Taiwan Warm Current; WKB, Western Kuroshio Branch Current; EKB, Eastern Kuroshio Branch Current; WKC, Western Kyushu Current; CWC, Cheju Warm Current; YSWC, Yellow Sea Warm Current; CC, Chinese Coast Current.

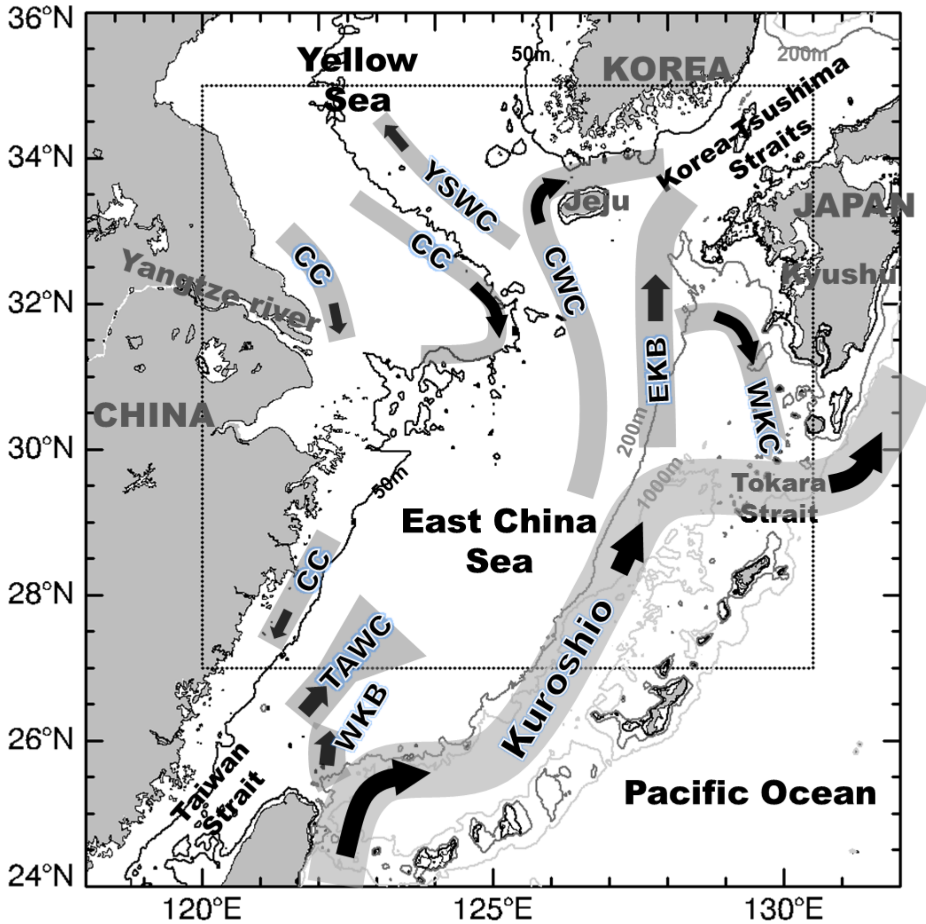


Figure 2. GOCI image taken on May 5, 2015: (a) True color composite (Red: 660 nm, Green: 555 nm, Blue: 443 nm), (b) Algae-covered fractional area per pixel, AFA. Color pixels indicate pixels of floating algae present; grey indicates land, cloud, or highly turbid water; black indicates algae-free water pixels.

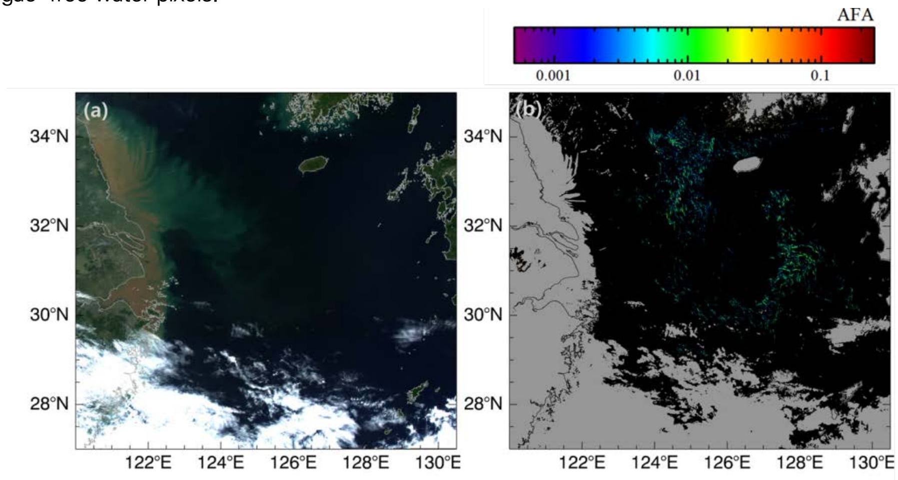
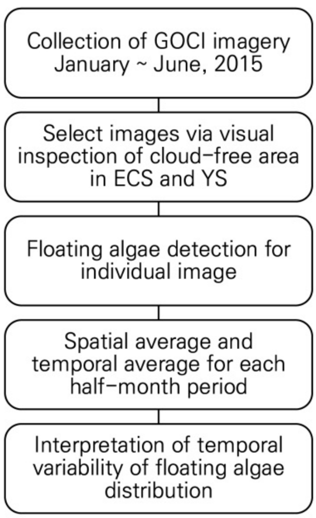


Figure 3. Study flow diagram



3. Results: Distribution of Floating *Sargassum* from January to June, 2015

Figures 4 and 5 show semimonthly AFA composite images of *Sargassum patches* in the YS and ECS between January and March and from April to June, 2015, respectively.

During the first half of January 2015, *S. horneri* patches were detected in limited areas of the inner continental shelf with low density (AFA =~ 0.0003), and small patches were also detected near Zhoushan Island of Zhejiang Province, China. During the second half of January, low-density patches were observed over a broader area inclusive of the northern Kuroshio front, from latitude 28.5 to 32 °N and longitude 122.5 to 127 °E. Floating algal patches were also identified near the west coast and south of Jeju Island, which is consistent with local media reports of massive *Sargassum* rafts stranding on the coast of Jeju Island at the end of January.

In February, the algal patches spread to the south (to latitude 28 °N) and east, crossing the 200-m isobath line and eventually reaching the Kuroshio and EKB currents. Cloud coverage was persistent along the continental slope during the second half of February. Cautiously, we speculate that a strong northerly wind in January and February combined with the residual tidal current (Lie and Cho, 2016) produced a southward flow along the western inner continental shelf and a southeastward flow along the eastern outer continental shelf.

During the first half of March, the patches in the south moved even further south to 27°N, and the patches along the eastern outer shelf accumulated along the Kuroshio front. A small patch entered the Kuroshio main stream at approximately 128°E and 29°N. Eastern outer shelf patches aligned with the Kuroshio and EKB currents. During the second half of March, the eastern patches intensified more than the patches to the west and moved north towards the Korea-Tsushima straits. According to MODIS-Aqua data, the sea surface temperature was between 13 and 17°C for the eastern outer shelf area in the second half of March (https://oceandata.sci.gsfc.nasa.gov/MODIS-Aqua/Mapped/8Day/4km/sst/). The direction of floating patch movement changed from southeastward in January and February to northward during the latter half of March. The northward movement could be attributed to weakened winter monsoonal (northerly) winds. It is worth noting that circulation along the ECS continental shelf varies depending on monsoonal winds (Lie and Cho 2016).

A portion of the eastern patches turned southeastward to follow the WKC just west of Kyushu, and eventually flowed into the Pacific Ocean south of Kyushu, where algal patches were once identified by ship observation in March, 2004 (Komatsu et al. 2007).

During the first half of April, the intensity of algal patches detected along the eastern outer shelf weakened significantly, which may have been related to low irradiation due to persistent cloud or rain in the ECS throughout this period. In April, the algal patches along both the inner and outer shelves moved northward with a southern limit of approximately 29°N, and peak intensity was detected over a wide area of the central northern ECS in the second half of April. Sea surface temperature from MODIS-Aqua data was between 13 and 17°C for the central northern ECS during this period. The presence of the algal patches in the Korea-Tsushima Straits also intensified. A part of the patches to the west of Jeju Island turned east and entered the Jeju Strait, also called the CWC (Lie et al. 2000).

In May, the algal patches continued to move into the YS and Korea-Tsushima straits via the Jeju Strait. The intensity of the algal patches along the east outer continental shelf began to weaken in May. This was likely due to increased sea surface temperatures (over 18°C) along the Eastern Kuroshio Branch towards the end of May.

As sea-surface temperature rose above 20°C in June across most of the ECS, *S. horneri* patches in the northern ECS (south of Jeju Island) disappeared. Sparse *S. horneri* patches continued to move to the YS along the western inner shelf.

Floating *Sargassum* patches disappeared almost completely from the ECS in July, although these data are not shown here. It was noted that stronger floating algae patches, consisting of the green algae *Ulva prolifera*, appeared on the north side of the Subei Bank in the southern YS in the second half of May (as depicted by the dotted circle in Figure 5). This *U. prolifera* bloom has occurred every year since 2008, and many studies have described this annual green algae event in the YS (e.g. Hu et al. 2010; Garcia et al. 2013).

Figure 4. Semi-monthly composite images of AFA in the ECS from January to March, 2015: (a) January 04–15; (b) January 18–24; (c) February 01–14; (d) February 17–24; (e) March 02–13; (f) March 15–29. The 200-m isobath is depicted as a thick line.

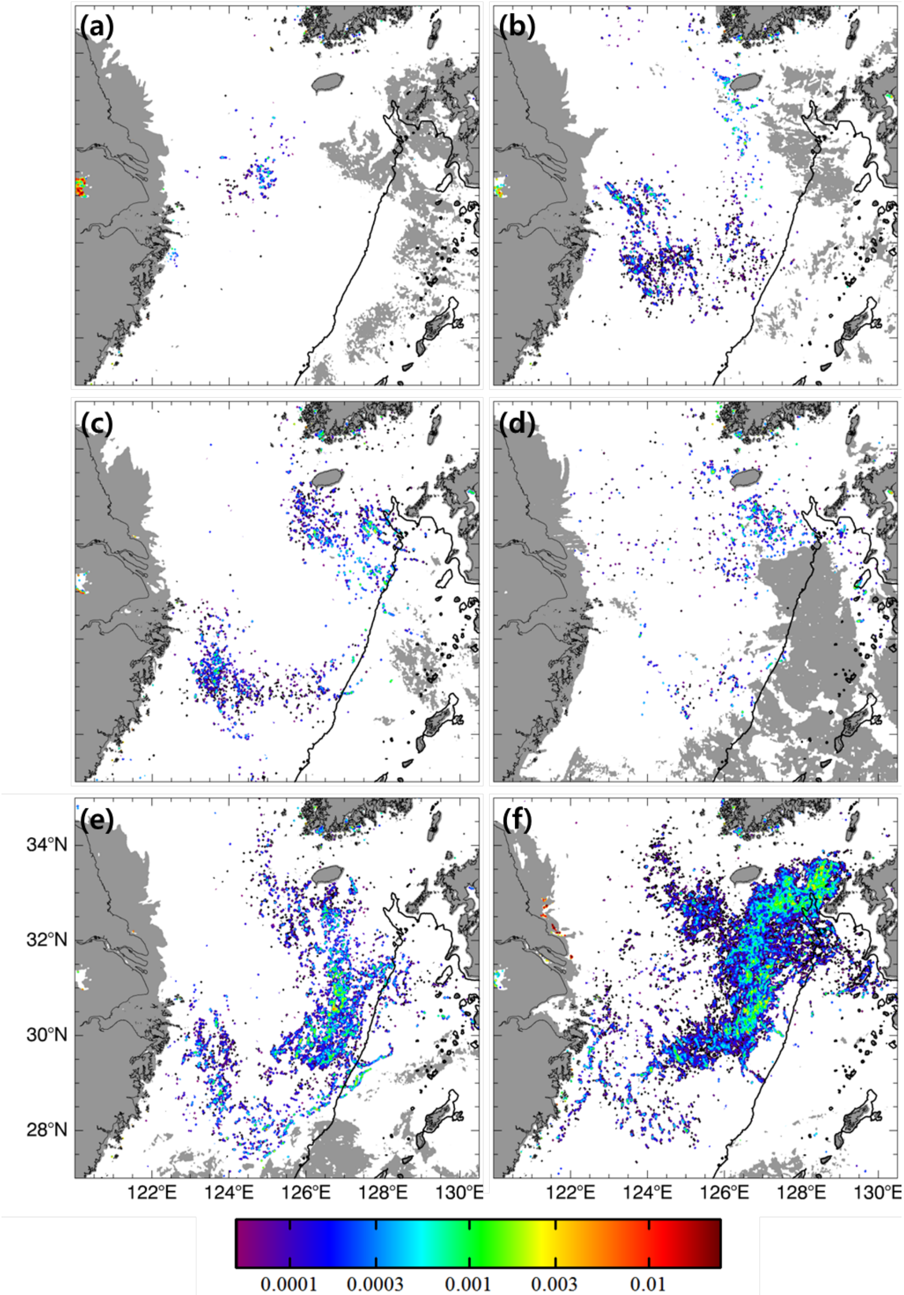
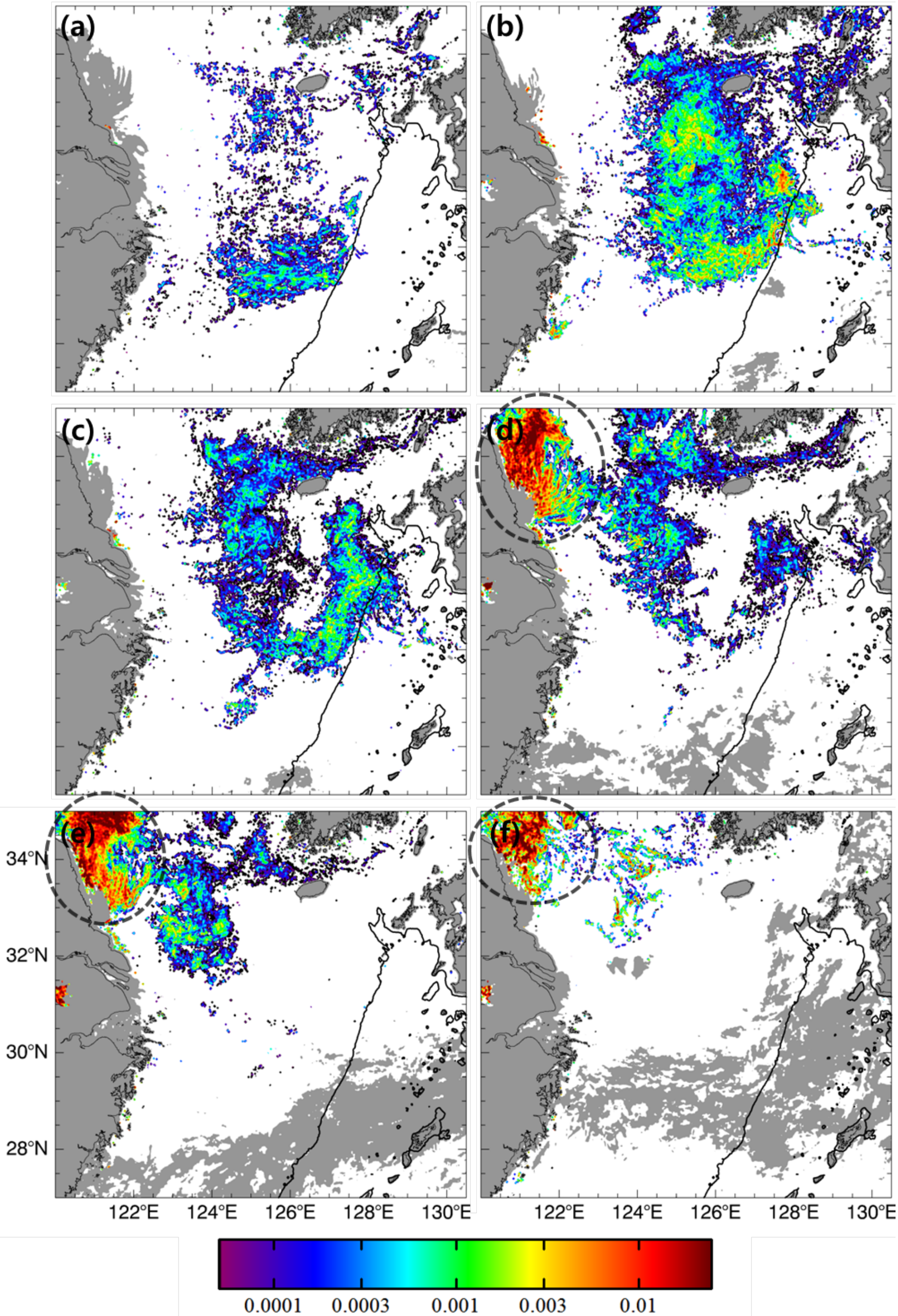


Figure 5. Semi-monthly composite images of AFA in the ECS from April to June, 2015: (a) April 09–17; (b) April 21–30; (c) May 01–13; (d) May 20–31; (e) June 01–12; (f) June 16–28. The 200-m isobath is depicted as a thick line.



4. Discussion

As mentioned above, there have been several previous reports of the geospatial distribution of *Sargassum* in the northeast ECS based on visual observations and sampling work using research vessels (Komatsu et al. 2007; Komatsu et al. 2014; Mizuno et al. 2014). Field surveys have provided detailed information on individual patches but have been limited geographically to the Japanese economic exclusive zone, which includes the eastern ECS; therefore, we sought to compare satellite data to data from field surveys.

Field surveys conducted in May 2002 and March 2004 identified drifting seaweed on the continental shelf along the Kuroshio front (Komatsu et al. 2007; Komatsu et al. 2008), and those observations are consistent with satellite data presented in this study. Previous studies reported significantly higher biomass (in wet weight/km^2) in May than in March, reflecting seasonal growth of *S. horneri*. However, here we show that density (AFA) increased from March to April before decreasing in May along the eastern continental shelf. The difference may be explained by conditions such as sea water temperature, which may vary by year and warrants further analysis.

Additional ship-based surveys were conducted from late February to March, 2010 and in February, 2011, both of which confirmed previous findings of seaweed rafts distributed primarily along the continental shelf west of the Kuroshio (Mizuno et al. 2014). However, unusual distributions were observed and reported in the Kuroshio Current proper and its outer waters in the Pacific Ocean in March of 2012 (Komatsu et al. 2014). Satellite-based observation in 2015 did not indicate such unusual distributions.

According to previous field surveys, seaweed samples collected in the offshore ECS consisted of a single species, *Sargassum horneri* C. Agardh. There have been no reports of *S. horneri* as a benthic species from south of Kyushu Island to Taiwan through the Ryukyu Archipelago, but benthic distribution of *S. horneri* has been reported along the Chinese coast. Considering the surface currents of the ECS, it has been reasonably assumed that the floating seaweed in the ECS originated from the Chinese coast. Tracking experiments using buoys attached to drifting seaweed demonstrated that seaweed detaches from the coast of Zhejiang Province, China, and takes two months to travel to the offshore continental shelf waters near the Kuroshio front (Komatsu et al. 2007). This pattern explains the origin of floating seaweed observed along the eastern offshore ECS from March to May. A simulation study has shown that particles released off the Chinese coast in the southern YS and southern ECS on February 15, 2002 were transported to the eastern ECS continental shelf waters, where floating *Sargassum* was observed in May (Filippi et al. 2010). This study shows that floating seaweed is distributed over a much broader area in the ECS, including along the inner continental shelf and waters near Jeju Island, as well as in the Kuroshio front as early as January. Therefore, further studies are required to elucidate the geographic distributions and to clarify the origin and time of detachment of floating algae observed along the ECS continental shelf.

5. Conclusion

In this study, we used GOCI satellite imagery to describe the geographic distribution of floating algae, *S. horneri* bloom in the ECS and southern YS occurred in 2015.

The spatial coverage of floating seaweed was much broader than previously reported from research-vessel based field surveys. Algae patches were detected along the inner continental shelf in the western ECS, as well as along peripheral shelf areas in the Kuroshio front and Eastern Kuroshio Branch current. Though low in density, broad distributions of algal patches were observed as early as January.

The distribution and movement of floating algae over time was generally consistent with known surface water circulations in the ECS and southern YS. From January to early March, algal patches spread southward and eastward to outer shelf areas. During the second half of March, algal patches along the eastern peripheral shelf moved north, following the Eastern Kuroshio Branch current; this coincided with weakened northerly wind strength. One section of the patch between China and Jeju Island followed the Cheju Warm Current, while the other moved north and entered the YS in April and May. In June, the *Sargassum* patches had nearly retreated from the ECS, and weakened patches proceeded to the YS.

This study improves upon our understanding of the geographic distribution and temporal variations in *Sargassum*. Further studies are necessary to identify the origins of the floating algae that spread over wide areas of the continental shelf as early as January and February.

Floating patches of *S. horneri* play an important ecological role in offshore waters. However, their mass stranding in coastal waters may cause significant problems within local coastal communities. The 2015 floating *Sargassum* event was unprecedented in scale; since, every year floating *Sargassum* blooms are observed in the ECS and another bloom of scale similar to that in 2015 occurred in 2017. The cause of these events deserves further investigation so that we may improve understanding of these events and inform better information for decision making.

In addition, satellite-based information can be used to estimate a likely pathway of the bloom when used in conjunction with ocean current forecast data, which will help plan for preventive measures such as strengthening monitoring activities, minimizing damage by early notifying the ports and fishing villages and clearing operation at sea or on land. In this regards, the Korean government uses the GOCI imagery as an important source for drifting Sargassum monitoring. Sargassum bloom is one of the annual marine environmental issues in the East China Sea and the Yellow Sea. This study confirms that as an environmental issue, *Sargassum* bloom event, originating from one country affect neighboring countries through shared seas. International cooperation will be required to understand the causes of this marine environmental problem and to find solutions.

Acknowledgements

This study was supported by the Korea Ministry of Oceans and Fisheries (MOF) through the research projects, "Technology development for Practical Applications of Multi-Satellite data to maritime issues" and "Development of the integrated data processing system for GOCI-II". The author is grateful to Dr. Gi-Hoon Hong for his encouragement and guidance for this research and to other KIOST colleagues for providing GOCI data.

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