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Key Points:
- An unprecedented massive floating algae bloom in the East China Sea is discovered, which appears to be Sargassum horneri
- The bloom is thought to be a result of increased water temperature, light, and expanded seaweed aquaculture along the ECS coast
- Bloom origin is traced back to coastal waters off Zhejiang coast, with a "hot spot" identified, yet other origins cannot be ruled out

Supporting Information:
- Supporting Information S1

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Floating Algae Blooms in the East China Sea

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Abstract A floating algae bloom in the East China Sea was observed in Moderate Resolution Imaging Spectroradiometer (MODIS) imagery in May 2017. Using satellite imagery from MODIS, Visible Infrared Imaging Radiometer Suite, Geostationary Ocean Color Imager, and Ocean Land Imager, and combined with numerical particle tracing experiments and laboratory experiments, we examined the history of this bloom as well as similar blooms in previous years and attempted to trace the bloom source and identify the algae type. Results suggest that one bloom origin is offshore Zhejiang coast where algae slicks have appeared in satellite imagery almost every February–March since 2012. Following the Kuroshio Current and Taiwan Warm Current, these "initial" algae slicks are first transported to the northeast to reach South Korea (Jeju Island) and Japan coastal waters (up to 135°E) by early April 2017, and then transported to the northwest to enter the Yellow Sea by the end of April. The transport pathway covers an area known to be rich in *Sargassum horneri*, and spectral analysis suggests that most of the algae slicks may contain large amount of *S. horneri*. The bloom covers a water area of ~160,000 km^2 with pure algae coverage of ~530 km^2, which exceeds the size of most *Ulva* blooms that occur every May–July in the Yellow Sea. While blooms of smaller size also occurred in previous years and especially in 2015, the 2017 bloom is hypothesized to be a result of record-high water temperature, increased light availability, and continuous expansion of *Porphyra* aquaculture along the East China Sea coast.

Plain Language Summary A massive floating algae bloom in the East China Sea was first captured in Moderate Resolution Imaging Spectroradiometer satellite imagery in mid-May 2017. Both its size and location are unprecedented. Several means have been used to identify the algae type and bloom origin, including the use of multisource satellite imagery, numerical particle tracing experiments, and laboratory experiments. While multiple origins are possible, the bloom could be tracked to Zhejiang coastal waters where the "initial" algae slicks back in February were transported to the northeast following the Kuroshio Current and Taiwan Warm Current to reach South Korea (Jeju Island) and Japan coastal waters by early April 2017, and then transported to the northwest to enter the Yellow Sea by end of April. Spectral analysis and historical field surveys suggested that the bloom may be dominated by *Sargassum horneri*, while expanded seaweed aquaculture and record-high water temperature and increased surface light may have contributed to the unprecedented bloom, which covered a water area of ~160,000 km^2 with pure algae coverage of ~530 km^2, both exceeding the maximum size of most Ulva blooms in the Yellow Sea.

1. Introduction

Since 2008, blooms of the green macroalgae *Ulva prolifera* (often called green tides) have occurred every May–August in the western Yellow Sea (YS) off the Shandong Peninsula, China. These blooms have been studied extensively using remote sensing, field and laboratory measurements, and numerical models (Bao et al., 2015; Hu et al., 2010; Keesing et al., 2011; Lee et al., 2011; Shi & Wang, 2009; Son et al., 2015; Wang et al., 2015; Xing et al., 2015; many others). The blooms have been attributed to *Porphyra yezoensis* (a species of *Porphyra*) seaweed aquaculture in Subei Shoal (Figure 1) where 90% of China's *P. yezoensis* aquaculture is located. *Ulva* usually grows on the *P. yezoensis* aquaculture rafts. During harvest, *Ulva* is released from the rafts, and then advected to the western YS where rapid growth occurs under favorable temperature, light, and nutrient availability, leading to massive blooms (maximum daily coverage ≥ 500 km^2 since 2013; Qi et al., 2016). Although the exact reasons for the annual fluctuations in bloom sizes have not been fully explained, the bloom origin and ecological factors affecting algae growth have been well studied and understood (Hu et al., 2010; Keesing et al., 2011; Liu et al., 2010; Wang et al., 2015; Zhang et al., 2014, others).

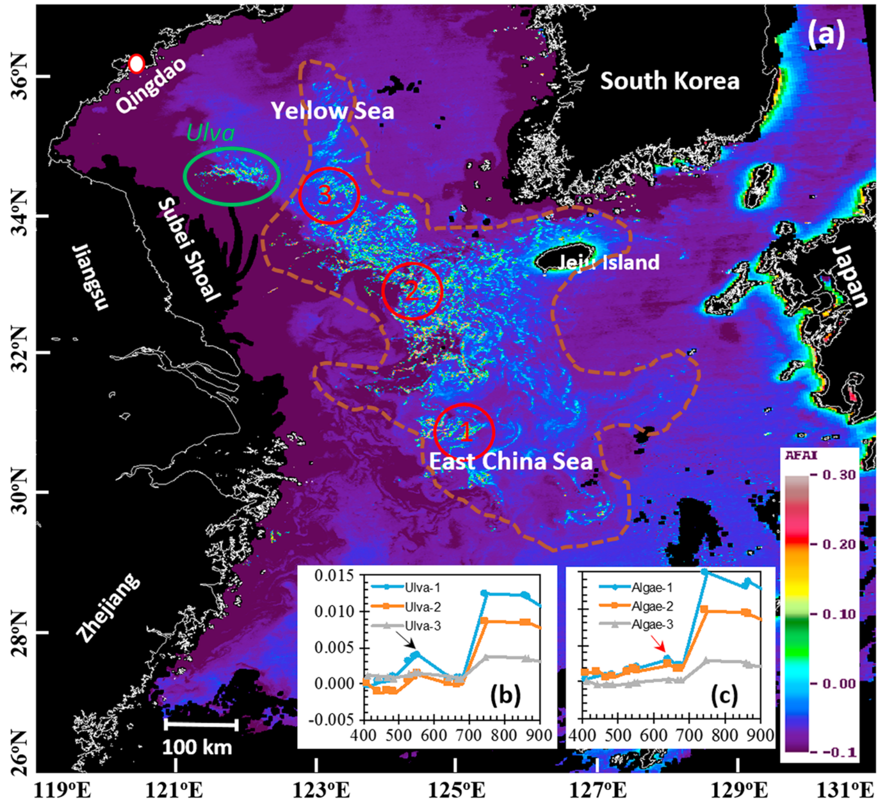

Figure 1. (a) MODIS AFAI image on 18 May 2017 covering the East China Sea and Yellow Sea. Two floating algae blooms are identified and outlined in the figure: one in the western YS (green outline) and the other in the ECS and southern YS (brown outline, ~160,000 km^2). The former is the *Ulva* bloom that recurs every year, while the latter is of unknown type (termed as EFA bloom in this study). (b) Reflectance spectra from three random pixels of the *Ulva* bloom. (c) Reflectance spectra from three random pixels of the EFA bloom. Note the reflectance peak around 555 nm in all three spectra in Figure 1b (black arrow) and the absence of the same 555 nm peak in Figure 1c. The *x* axis of the inset graphs is wavelength in nanometer, and the *y* axis is R_{rc} difference between the algae pixel and nearby algae-free pixel.

In mid-May 2017, satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) showed an extensive floating algae bloom extending from the southern YS to the East China Sea (ECS), including waters near Jeju Island (Figure 1a). For convenience, this bloom is referred to as the ECS floating algae bloom (EFA bloom). Although a separate, smaller bloom near Subei Shoal was also observed, that bloom is the well-known *Ulva* bloom that has occurred in the same place, at the same time of year, since 2008. In contrast, the EFA bloom has not been previously reported.

The primary objective of this study is to determine the bloom origin and algae type using remote sensing data and numerical particle tracking experiments as well as laboratory measurements. A secondary objective is to establish time series of bloom events in the ECS.

2. Data and Method

2.1. Satellite Data and Processing

Satellite sensors used in this study include MODIS (on both Terra and Aqua), VIIRS (Visible Infrared Imaging Radiometer Suite), GOCI (Geostationary Ocean Color Imager), and Landsat-8 OLI (Ocean Land Imager), each having its unique spectral bands, swath width, revisit frequency, signal-to-noise ratio, and spatial resolution. The nominal resolutions are 1 km, 0.75 km, 0.5 km, and 30 m for these sensors, respectively. All satellite data were obtained from the NASA Goddard Space Flight Center (http://oceancolor.gsfc. 63 nasa.gov) and processed to generate Rayleigh-corrected reflectance ($R_{rc}(\lambda)$, dimensionless). Then, AFAI (alternative floating algae index) images were generated to examine the red-edge reflectance of vegetation (Qi et al., 2016; Wang & Hu, 2016).

$$\begin{aligned} \mathrm{AFAI} &= R_{\mathrm{rc},\,\lambda 2} - R_{\mathrm{rc}}{}'_{,\,\lambda 2}, \\ R_{\mathrm{rc}}{}'_{,\,\lambda 2} &= R_{\mathrm{rc},\,\lambda 1} + \left(R_{\mathrm{rc},\,\lambda 3} - R_{\mathrm{rc},\,\lambda 1}\right)(\lambda_2 - \lambda_1)/(\lambda_3 - \lambda_1), \end{aligned} \tag{1}$$

where λ_1, λ_2, and λ_3 are 667, 748, and 869 nm for MODIS but adjusted for VIIRS, GOCI, and OLI using their corresponding bands.

The algae coverage was estimated through unmixing of mixed algae-water pixels using lower bound (0% algae coverage) and upper bound (100% algae coverage) threshold values (Qi et al., 2016; Wang & Hu, 2016). If a 1 km^2 pixel contains 10% algae coverage, its pure algae area is 0.1 km^2. The algae-containing water area was estimated through manual delineation of the algae bloom borders (outlined in Figure 1a).

2.2. Numerical Particle Tracking Experiments

The experiments are based on surface currents from the Hybrid Coordinate Ocean Model (HYCOM) (Chassignet et al., 2009) made available by the National Ocean Partnership Program (http://hycom.org). HYCOM currents used in this study have a spatial resolution of 1/12° with daily updates. Particles were released at various locations where algae slicks were detected from satellite AFAI imagery, and then followed for a month (both forward and backward) using HYCOM mean daily surface currents, with particle locations and densities recorded.

2.3. Laboratory Measurements

Reflectance spectral shapes of *Ulva* and *Sargassum horneri* are found in the literature (He et al., 2011; Hu et al., 2017; Jin et al., 2016). Reflectance spectral shapes of *P. haitanensis* (dominant *Porphyra* seaweed in Zhejiang) were determined using a hand-held GER1500 spectrometer from laboratory measurements with *P. haitanensis* in a blackened tank (about 0.5 m in diameter and 0.7 m in depth) filled with tap water.

2.4. Environmental Data

Monthly temperature anomaly imageries were obtained from the Goddard Institute for Space Studies (GISS) Surface Temperature Analysis (GISTEMP) data products (GISTEMP Team, 2016; Hansen et al., 2010). Daily mean Multi-scale Ultra-high Resolution Sea Surface Temperature (MUR SST) data were obtained from the NASA Jet Propulsion Laboratory (https://mur.jpl.nasa.gov) and then used to compute monthly sea surface temperature (SST) anomaly for the study region. Both products have been regarded as some of the most reliable temperature products for studying climate variability. Monthly photosynthetically active radiation (PAR) data derived from MODIS/Aqua were obtained from NASA Goddard Space Flight Center.

2.5. Seaweed Aquaculture Data

Data of annual aquaculture production of the *Porphyra* seaweed (primarily *P. haitanensis* but also *P. yezoensis*) in Zhejiang province and *P. yezoensis* seaweed in Jiangsu province were obtained from the China Fishery Statistical Yearbook (China Fishery Statistical Yearbook (CFSY), 2009–2017). These represent the best data source even though there might be some uncertainties associated with these data due to discrepancies between the methods used to calculate aquaculture area (Nan et al., 2015).

3. Results

3.1. Bloom Origin and Transport Pathways

For the entire study region bounded by 26–37°N and 119–131°E (Figure 1a), image sequences from MODIS, VIIRS, and GOCI in 2017 show that algae slicks first appear in waters off the Zhejiang coast between late February and early March (Figure 2).

The origin of the algae slicks off Zhejiang (Figure 2) on 1 March is difficult to determine from satellite imagery because of their coarse spatial resolution and frequent cloud cover (Figure S2 in the supporting information). For example, MODIS 1 km pixels cannot detect algae slicks of <2 m × 2 km in size (Wang & Hu, 2016). Particles released at algae locations on 1 March were tracked backward for 1 month revealing locations ~100 km

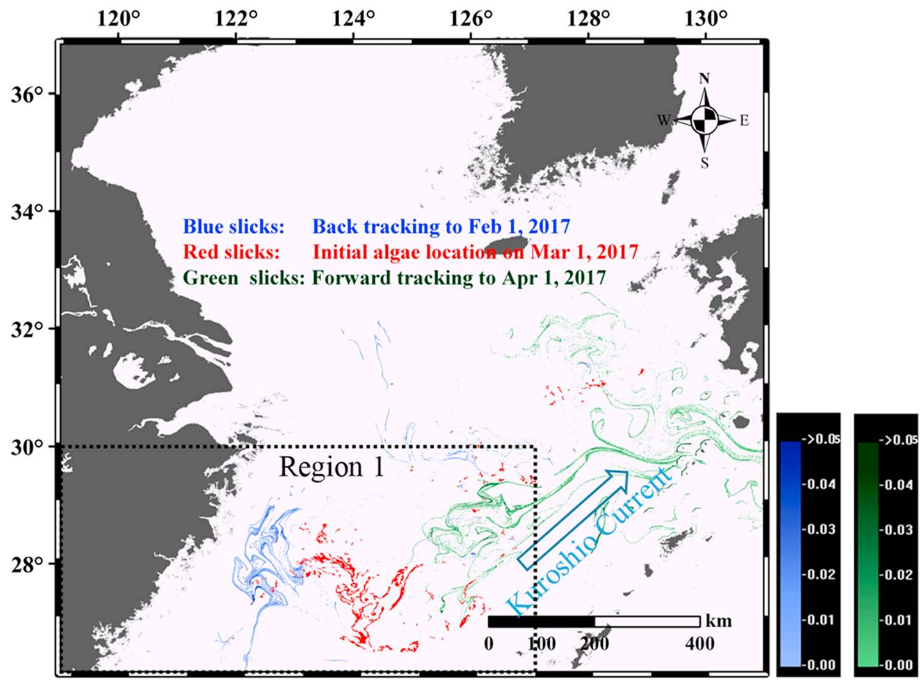

Figure 2. Results from the numerical particle tracking experiments using HYCOM daily surface currents. The particles were released on 1 March 2017 according to algae locations detected from the MODIS AFAI imagery (red slicks). The blue slicks show the algae location on 1 February 2017 after backward tracking for 1 month, while the green slicks show the algae location on 1 April 2017 after forward tracking for 1 month. The dominant direction of the Kuroshio Current is annotated. The color shades indicate relative algae density. MODIS-detected algae slicks on 4 April 2017 are shown in Figure 4f, which are, in general, in agreement with the forward modeling. A local region (Region 1) off the Zhejiang coast is outlined for further analysis.

closer to the Zhejiang coast than the 1 March start location, thus suggesting that these algae slicks originated from Zhejiang coastal waters. Inspection of the OLI image series shows small algae-like slicks in these coastal waters, confirming the particle tracking results (Figure 3). The forward tracking experiment indicates that these algae slicks were transported to the northeast following the dominant Kuroshio Current and Taiwan Warm Current (Zhu et al., 2004), reaching South Korea and Japan by early April. MODIS AFAI imagery in early April indicates that algae slicks reached waters off southwest Japan at 135°E (Figure S1). The image sequences after early April show north and northwest movements of the algae slicks, reaching the southern YS by mid-May (Figure 1a). Note that the physical transport experiments cannot rule out the possibility that some of the algae slicks originate locally where they were observed in satellite imagery, for example, from Jiangsu Shoal or coastal waters off Japan or South Korea.

The last day algae slicks were observed is 14 June 2017, after which persistent cloud cover for a month made further observations impossible. The bloom size (in terms of pure algae coverage after pixel unmixing) increased significantly from ~30 km^2 on 1 March (Figure 2) to ~530 km^2 on 18 May (Figure 1a). The algae-containing water area also increased from 33,000 km^2 to ~160,000 km^2 (Figure 1a, brown outlined area).

3.2. Algae Type

The MODIS R_{rc} spectra in Figures 1b and 1c display a clear difference between the *Ulva* bloom and the EFA bloom. *Ulva*-containing pixels always show a local reflectance peak around 555 nm (thus making it appear greenish to a human eye) regardless of the reflectance magnitude in the near-infrared (an indication of algae density). However, the 555 nm peak does not appear in any of the three random locations of the EFA bloom although a 645 nm peak is found (Figure 1c). Similar to the coarse-resolution MODIS spectra, the high-resolution OLI pixels (30 m) also reveal the same discrepancy in their R_{rc} spectra, with a 561 nm reflectance peak in the *Ulva* bloom (Figures 3d and 3d) but not in the EFA bloom (Figures 3b and 3c) regardless of the

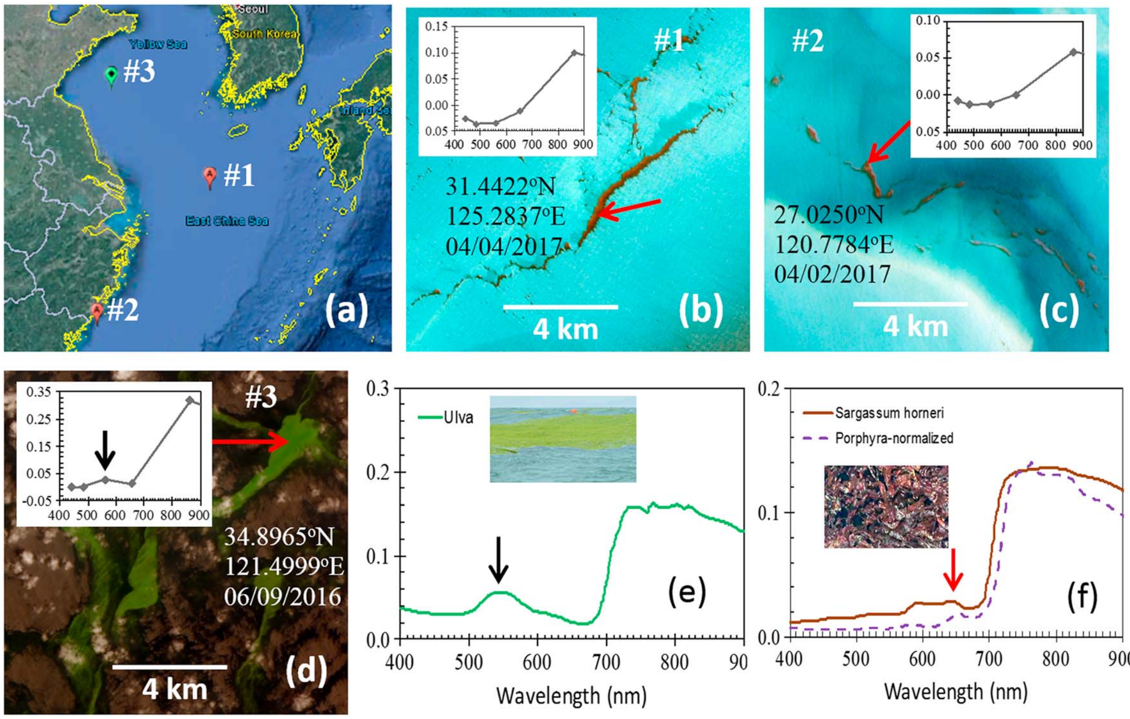

Figure 3. Reflectance spectra from satellite and laboratory measurements. (a) Three locations (#1, #2, and #3) in the ECS, Zhejiang coast, and YS, respectively, where (b–d) sample OLI spectra from typical algae pixels and the RGB images are shown, respectively. (e) Reflectance spectra from field measurements of *Ulva* (Hu et al., 2015). (f) Reflectance spectrum from laboratory measurements of *Porphyra* (inset photo), together with the *S. horneri* spectrum from Jin et al. (2016).

imaging times and locations. The algae slicks also show difference in their morphology, with *Ulva* slicks being wider (Figure 3d versus Figures 3b and 3c). Clearly, most of the algae in the EFA bloom are not *Ulva*. The *S. horneri* reflectance spectrum reported earlier (Jin et al., 2016) shows relatively high reflectance between 590 and 650 nm, and *Porphyra* reflectance spectra measured in the lab (Figure 3f) also show high reflectance around 650 nm. Therefore, the algae in the EFA bloom could be either *S. horneri* or *Porphyra* from a pure spectroscopy perspective. Scattered *S. horneri* mats have been observed in February and March of 2010–2012 (Komatsu, Mizuno, et al., 2014; Komatsu et al., 2007; Mizuno et al., 2014) along the algae transport pathway derived from the numerical modeling here. In contrast, there has been no report that *Porphyra* could survive in the ocean for a prolonged time. Therefore, without concurrent field confirmation, one may infer that the EFA bloom is most likely dominated by *S. horneri*.

3.3. Historical Blooms

An analysis of MODIS and VIIRS AFAI imageries since 2002 and 2012, respectively, shows that the first massive EFA bloom occurred in 2015 with nearly the same temporal evolution and transport pathway as the 2017 bloom but was considerably smaller in extent. Figure 4 shows several sample images for the two bloom events. They both initiated from waters off the Zhejiang coast in late February–early March and evolved into EFA blooms by mid-May. The image sequence also shows that the 2015 EFA bloom ended in the southern YS by the end of June. The algae coverage of the EFA bloom on 18 May 2017 (~530 km^2) exceeds the daily maximum size of *Ulva* blooms in the YS in all years except 2014 and 2015 (Qi et al., 2016). The algae-containing water area of the 2017 EFA bloom (~160,000 km^2) also exceeds the 2015 *Ulva* bloom (~44,000 km^2 in 2015), suggesting that the mean EFA bloom algae density (530/160,000 = 0.3%) is 8 times less than the mean *Ulva* density (1,160/44,000 = 2.6% on 21 June 2015) during maximum bloom days.

Algae slicks have appeared in the same location off Zhejiang coast by late February–early March every year since 2012 (Figures 4i and S3), yet only in 2015 and 2017 did large blooms develop in later months in the central ECS.

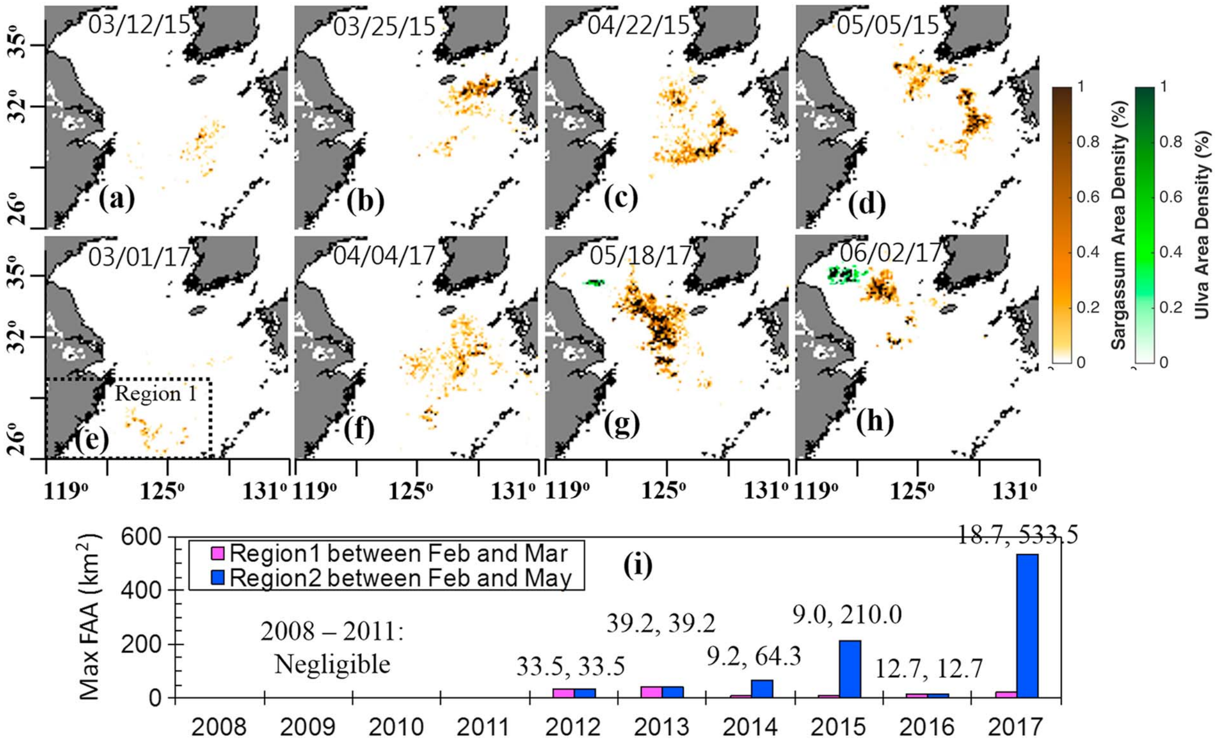

Figure 4. (a–h) MODIS and VIIRS image sequences show EFA bloom progression in 2015 and 2017. All but the 5 May 2015 (Figure 4d) and 4 April 2017 (Figure 4f) images are from MODIS. The color scale represents floating algae area density. These images represent the best "cloud-free" conditions between February and early June. (i) Daily maximum floating algae area (FAA) for two regions between 2008 and 2017. Region 1 is off Zhejiang coast (see Figures 2 and 4e for coverage), and Region 2 covers the entire study region, which also covers Region 1. *Ulva* coverage was excluded in these calculations. The FAA numbers (in km^2) for the two regions are annotated for each year. If the two numbers are identical in a year, then they are from the same image. More images for Region 1 are provided in Figure S3.

4. Discussion: Causes of the EFA Blooms and Their Interannual Variability

Sargassum horneri wet biomass from field surveys ranges between a few kilogram to tens of kg km^{-2} (occasionally exceeding 100 kg km^{-2}) along the algae transport pathways following the Kuroshio Current (Figure 4 of Mizuno et al., 2014, and Figure 2 of Komatsu, Mizuno, et al., 2014). Based on MODIS observations on 18 May 2017 (Figure 1a), the mean area density of floating algae is about 0.3% (=530/160,000), or 3,000 m^2 km^{-2}. This is significantly higher than the *Sargassum* density found in the western Central Atlantic (Wang & Hu, 2016), which rarely exceeds 0.1%. Assuming a wet weight of 2 kg m^{-2} (Hu et al., 2017; Mizuno et al., 2014), this density is equivalent to 6,000 kg km^{-2}, far exceeding those reported from field sampling in 2010–2012. The spatial extent of the 2017 bloom also represents a historical record (~160,000 km^2), with a total integrated wet biomass of $>10^9$ kg (=1 million metric tons). Because MODIS 1 km pixels cannot capture algae slicks of <2 m × 2 km (Wang & Hu, 2016), the satellite-based estimates are likely biased low. Indeed, along the pathway of field surveys in February and March of 2010–2012 (Komatsu, Mizuno, et al., 2014; Komatsu et al., 2007; Mizuno et al., 2014), MODIS and VIIRS imageries show almost no algae slicks. Furthermore, *S. horneri* sampling in the field is primarily restricted to the southeast ECS (Mizuno et al., 2014), while most of the bloom shown in Figure 1a has never been sampled. So what causes the recurrent EFA blooms and their annual variations?

Sargassum horneri initially grow on the bottom along the ECS coast but can be detached from the bottom due to wind or current perturbations and then became pelagic (Tseng, 1983). Additionally, *Porphyra* aquaculture along the Zhejiang coast has expanded significantly in recent years (CFSY, 2009–2017) (Figure 5a), possibly leading to enriched nutrient environment due to increased fertilization. Therefore, we speculate that the initial *S. horneri* bloom off the Zhejiang coast (Figure 2) could be a result of aquaculture-induced nutrient enrichment in recent years, which stimulated initial *S. horneri* growth. Likewise, fertilizers used in aquaculture

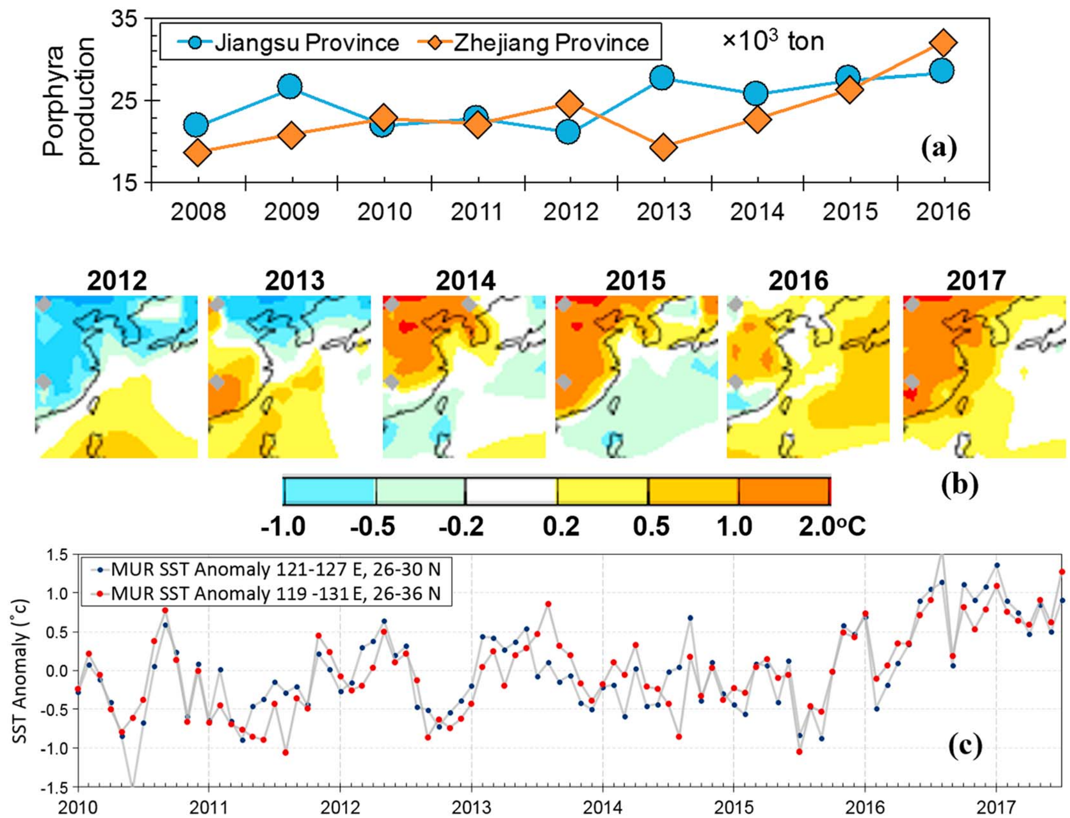

Figure 5. (a) Seaweed aquaculture annual production in two provinces along the ECS coast (source: CFSY 2009–2017). Note the increasing trend in Zhejiang Province after 2012. (b) GISS temperature anomaly of January–March of 2012–2017 for the region of 11–42°N 111–137°E, in reference against a 20 year monthly climatology between 1992 and 2011. (c) MUR SST anomaly of January 2010 to July 2017 for two regions of the ECS, in reference against a monthly climatology between 2010 and 2017. Note the positive anomaly of 0.7–1.3°C during winter 2017 for Region 1. Surface light anomaly is provided in Figure S4.

in Subei Shoal may have also contributed to nutrient enrichment in the ECS. Adding to this trend is the record-high temperature in the winter months of 2017 (Figures 5b and 5c), providing more favorable conditions for *S. horneri* growth than in previous years. Laboratory studies suggest that *S. horneri* could initially grow in waters of 9.2–11.6°C (Umezaki, 1984). The average MODIS SST in February is ~10°C along the Zhejiang Coast, and a slight increase of SST by 0.5–1°C in 2017 could stimulate initial *S. horneri* growth. Likewise, following the transport pathways, a higher temperature in 2017 can also stimulate faster growth than in previous years, leading to the unprecedented 2017 EFA bloom. This argument is in line with the scenarios described in Komatsu, Fukuda, et al. (2014), where *S. horneri* blooms were predicted to move northward under global warming. However, the temperature argument could not explain why a moderate-sized bloom also occurred in 2015 as temperature in winter 2015 had a slight negative anomaly. We speculate that this could be due to changes in surface light availability, as surface PAR between April and May in 2015 was much lower than in 2017 (Figure S4) for most of the ECS and in 2016 surface PAR was the lowest. Therefore, we hypothesize that continuous nutrient enrichment may have resulted in a "tipping point" in 2015 causing a moderate-sized bloom, after which both temperature and light availability may have played major roles in affecting bloom sizes. If this is true, we speculate that in future years when temperature and/or PAR show similar positive anomalies as in 2017, another major bloom should occur. In any case, such a hypothesis needs to be tested with more observations, especially through comprehensive and multidisciplinary field studies to understand *S. horneri* physiology and ecology in the ocean environment. Meanwhile, the image sequence presented here may provide a general guide for planning future field surveys, as the timing and location of the bloom can be inferred from historical data (e.g., Figure S3) and from near-real-time online imagery specifically designed to track floating algae (http://optics.marine.usf.edu/cgi-bin/optics_data?roi=YS_ECS&current=1; Hu et al., 2014).

5. Conclusion

After the limited field surveys in reporting scattered *S. horneri* mats by other researchers, this letter represents a first effort to document massive ECS floating algae blooms, including diagnosing their origin and transport pathways as well as documenting historical bloom events. Image analysis and numerical experiments suggest a bloom origin of waters off the Zhejiang coast although other origins cannot be ruled out. The spectral signature of the massive bloom suggests that it is likely dominated by *S. horneri*. We hypothesize that the record-high ocean temperature, together with favorable light availability and potential nutrient enrichment from continued expansion of seaweed aquaculture, led to the unprecedented EFA bloom in 2017, yet more in-depth studies are required to understand bloom characteristic, their origins, and their environmental impacts.

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