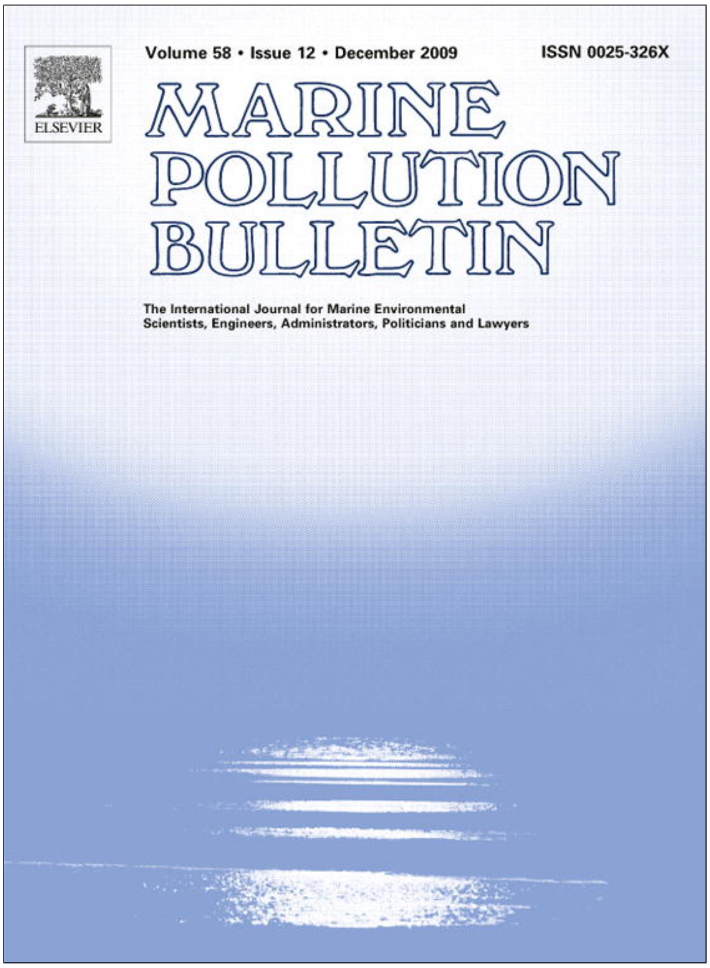
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# Banded structure of drifting macroalgae

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ABSTRACT

A massive bloom of macroalgae occurred in the western Yellow Sea at the end of May, 2008, and lasted for nearly 2 months. The surface-drifting macroalgae was observed to accumulate in a pattern dominated by linear bands. The maximum length of individual algal bands exceeded 10 km and the distance between neighboring bands ranged from hundreds of meters to 6 km. Seven satellite images were analyzed to determine the distances between neighboring bands. Proportions of about 24%, 38%, and 22% are responsible for the separation distances smaller than 1 km, between 1 and 2 km, and between 2 and 3 km, respectively. The separation of about five percent of the bands exceeds 4 km. The probability distribution of the separation distance is quite close to log-normal which is that found in Langmuir circulation. However, the observed algal band separation greatly exceeds the distances between convergence lines reported in Langmuir circulation.



## 1. A macroalgae bloom in the western Yellow Sea

The Olympic sailing games were held in Qingdao, China, in August 2008. However at the end of May, about 3 months before they were due to begin, a massive bloom of macroalgae occurred Fig. 1. The macroalgae, reported to be of the genus *Enteromorpha* and known as sea lettuce, is a non-toxic marine species of green algae that floats and is often found attached to rocks exposed at low tide. The bloom was first found by monitoring aircraft about 140 km to the southeast of Qingdao on May 30, 2008, was carried to the shore area from the southern Yellow Sea by the mean currents. Its origin is still unclear. Satellite data (Hu, 2008) and ship observation show the macroalgae occupied about 13,000 km$^2$ with the estimated coverage of 1%. Large amounts of the algae accumulated in the coastal water, close to shore and even on the beaches, putting in jeopardy the internationally important Olympic sailing competition.

A massive clean-up operation was set in motion; more than 20,000 people and 1800 boats per day were involved in the clean-up efforts for about 40 days. Some 750 million kilograms of wet macroalgae were removed and buried on land, and floating barriers with a perimeter of 29 km were deployed to block the macroalgae from floating into the Olympic sailing area. The coastal waters of Qingdao were eventually clear of the algae by July 15, 2008.

Numerical simulations, chemical and biological studies have been undertaken since the macroalgae bloom occurred (e.g., Lü and Qiao, 2008). We focus here on the spatial structure of floating macroalgae.

## 2. The banded structure of drifting macroalgae at the sea surface

Nearly all the floating macroalgae were found in linear bands. The lengths of individual bands ranged from hundreds of meters to tens of kilometers. Fig. 2a shows a photograph of the macroalgae taken from a research vessel on July 6, 2008. Two bands of macroalgae are visible in this photograph. The distribution of macroalgae and surface waves were observed more clearly from an aircraft (Fig. 2b).

Fig. 2c is an image obtained from the SAR of COSMO-2 on July 13, 2008 with spatial resolution of 30 m, and Fig. 2d is magnified from the part of Fig. 2c enclosed by the yellow rectangle. The satellite image of Fig. 2c covers an area of about 10,500 km$^2$. The green lines denote bands resulting from the presence of the macroalgae. The small-scale roughness of the sea surface to which SAR is sensitive is reduced near bands or patches of algae. This effect is most notable when comparing the roughness of the sea surface downwind and up-wind of an algal patch as shown, for example, in Fig. 2b. The sea surface is rougher, up-wind, at the top left than downwind at the bottom right. The reduction in roughness can

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**Fig. 1.** The macroalgae accumulated on the beach and coastal area of Qingdao (on July 6, 2008).

extend to some 100 m from an algal patch, and so what may be detected in a SAR image is the surface area affected by macroalgae, instead of the macroalgae itself. A band of macroalgae may consequently be detectable as a band by SAR with resolution limit that exceeds the width of the macroalgal band itself.

The bands of macroalgae cover much of the nearshore area of Qingdao. Although in places twisted, perhaps by variations in wind, eddies and tidal flows, the bands are generally almost parallel to one-another.

## 3. The distance between neighboring bands

Seven available satellite images of the Qingdao coastal area, including SAR of COSMO-2 and RADARSAT-1, and CCD of Cbers-02B, were collected and the distances between neighboring bands of algae were measured. The selected satellite images are listed in Table 1.

For a selected image, the separation distance was calculated only when neighboring bands were almost parallel to each other and their lengths exceeded one kilometer. An example is shown in Fig. 2c and d, where the red lines denote the path along which the distance was calculated. A total of 408 distances were obtained for the seven satellite images.

The distances range from 0.3 to 6.2 km (Fig. 3a). About 24% of the distances are smaller than one kilometer, 38% are in the range from 1 to 2 km, and 22% are from 2 to 3 km. The remaining 16% were larger than 3 km. Some 5% of distances exceed 4 km.

The probability distribution function (pdf) of the distances between neighboring bands has been examined and $\chi$-squared tests have been applied to determine its similarity to two standard

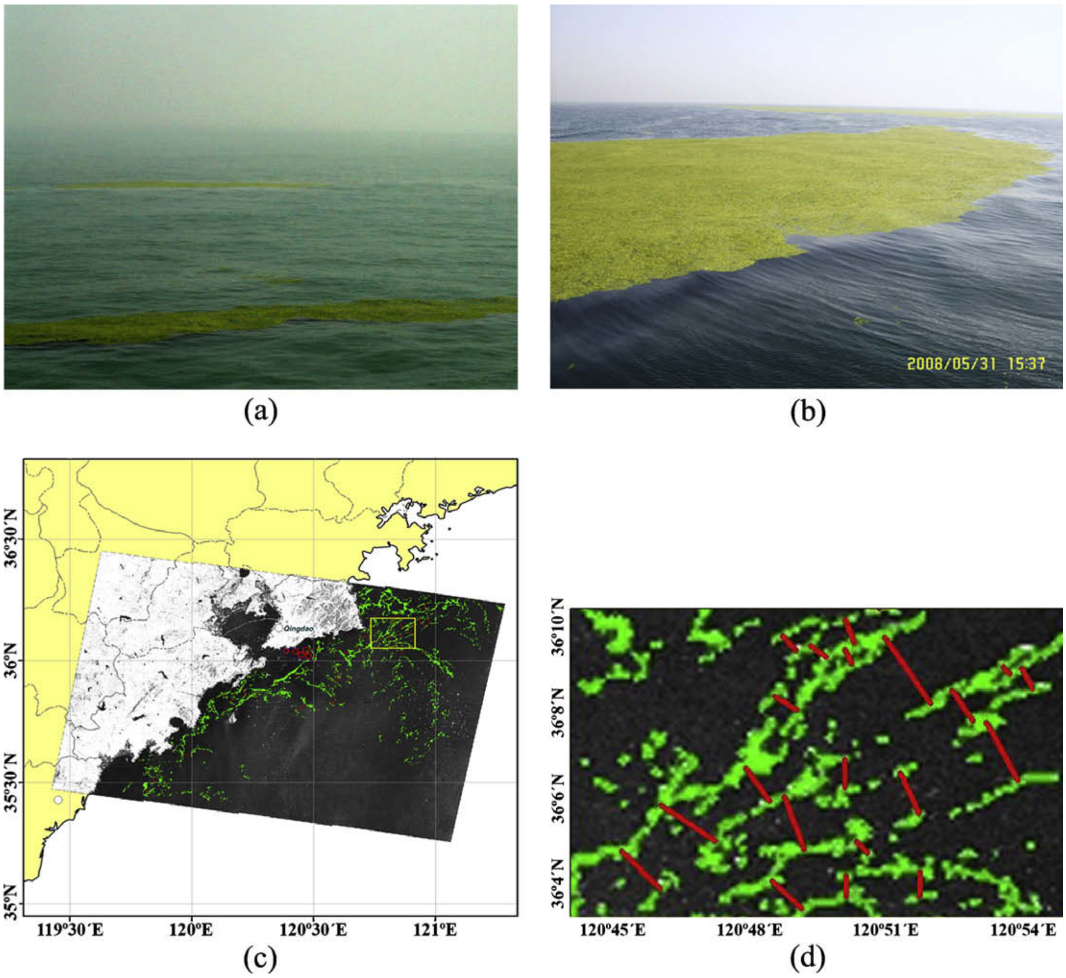


**Fig. 2.** The banded structure of the drifting macroalgae on the sea surface. (a) A photograph from a surface vessel on July 6, 2008 at (36°00′18″N, 120°29′48″E). The two bands of macroalgae are about 400 m apart; (b) a photograph taken from an aircraft at 15:37, May 31, 2008 off Qingdao. The width of macroalgae band is about 30 m; (c) SAR images of the macroalgae obtained from COSMO-2 on July 13, 2008; (d) subfigure magnified from the part of figure (c) enclosed by the yellow rectangle.

**Table 1**
Satellite images used to calculate the distance between neighboring bands.

| Satellite | Sensor | Resolution (m) | Imaging time | Monitoring ocean area (km$^2$) | Central coordinate of image | Number of measured distances |
|---|---|---|---|---|---|---|
| CBERS-02B | CCD | 19.5 | 10:10, July 6, 2008 | 16,470 | 35°50′N, 120°20′E | 54 |
| COSMO-2 | SAR | 30 | 18:16, July 8, 2008 | 9,400 | 35°55′N, 120°E | 39 |
| COSMO-2 | SAR | 30 | 5:08, July 9, 2008 | 7,700 | 36°N, 120°20′E | 45 |
| RADARSAT-1 | SAR | 30 | 6:34, July 11, 2008 | 9,800 | 35°50′N, 120°30′E | 128 |
| COSMO-2 | SAR | 30 | 6:02, July 12, 2008 | 13,000 | 36°10′N, 120°50′E | 69 |
| COSMO-2 | SAR | 30 | 18:16, July 13, 2008 | 10,500 | 35°50′N, 120°20′E | 37 |
| RADARSAT-1 | SAR | 30 | 6:16, July 18, 2008 | 8,800 | 35°45′N, 120°20′E | 36 |

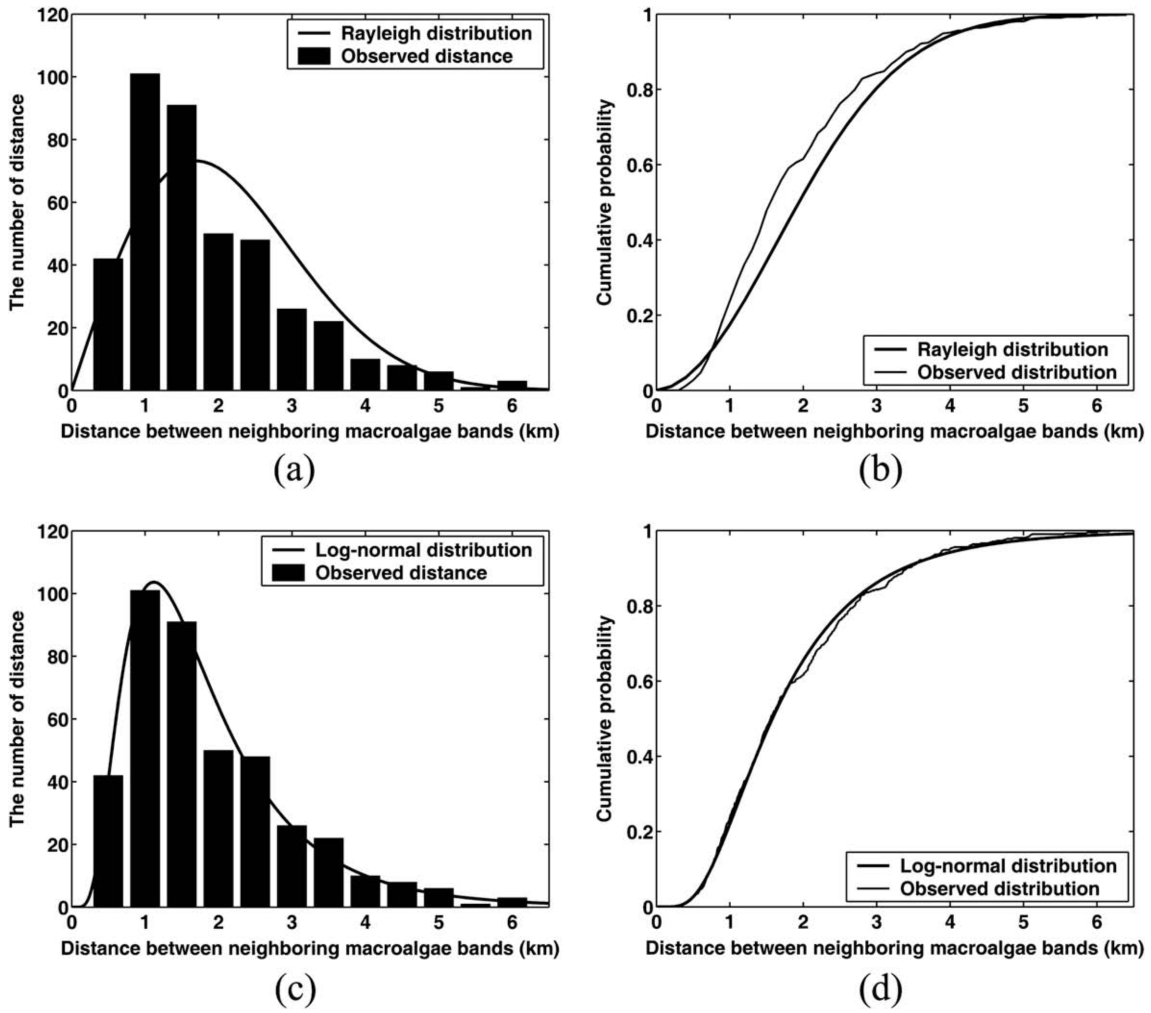


**Fig. 3.** The probability distribution (left) and the cumulative distribution (right) of the distance between neighboring macroalgae bands from seven satellite images. (a) and (b) show the data fitted to a Rayleigh distribution for the band separation, $x$: $f(x) = (x/\mu^2)\exp[-x^2/(2\mu^2)]$, with $\mu = 1.69$ km. (c) and (d) show the data fitted to the log-normal distribution, $f(x) = \{1/[\sigma(2\pi)^{1/2}]\}\exp\{-[\ln x - \mu]^2/(2\sigma^2)\}$, where $\mu = 0.458$ and $\sigma = 0.591$ when the band separation $x$ is measured in kilometers. The mean, $\mu$, corresponds to the mean of $\ln x$ at $x = 1.58$ km.

distributions. The observed data are found to differ from a Rayleigh distribution at the 5% level (Fig. 3a and b). At the same level percentage of confidence, the pdf of the data does not, however, differ from a log-normal distribution (Fig. 3c and d).

## 4. Discussion

Franks (1997) discusses two processes that are known to cause the accumulation of floating algae in linear bands. Internal waves produce regions of converging and diverging flows at the sea surface, floating material becoming concentrated over the wave troughs where the integrated convergence is greatest. The waves do not carry floating algae with them, but bands are continually formed and dispersed as waves pass by. In Frank's model the concentration of alga in the densest bands reaches three times that between bands[1], a small amount in comparison with the relatively dense bands of Fig. 2. No observations of internal waves were made at the time of the macroalgal bloom. While their effect cannot be discounted entirely, it seems unlikely that internal waves are a signifi-

[1] This concentration factor is about $(h + a)/(h - a)$, where h is the thickness of the mixed layer and $a$ is the amplitude of the internal waves, and is equal to 3 if $a/h$ = ½, a relatively large wave amplitude. The concentration might, however, be increased further if, when brought closer together by the internal waves, clumps of algae bond with one another to form floating mats of algae.

cant cause or contributor to the formation of the very long and concentrated bands of algae.

Franks' second process of algal accumulation is a front. This might lead to single lines of accumulation but not the multiple bands observed off Qingdao. Franks' figure (his Fig. 1c) illustrating algal accumulation at a front does, however, point to a further process that he does not discuss: Langmuir circulation. The front shown in his figure is orientated roughly normal to the wind direction, and the broad strip of algae floating at the front is disrupted and drawn out into bands lying along the wind direction, and so across the line of the front itself.

Langmuir's attention was first drawn to the presence of the pattern of circulation on seeing bands of floating *Sargassum* weed in the North Atlantic in 1927. His subsequent paper (Langmuir, 1938) describes how floating matter is drawn into lines of convergence between pairs of vortices (or 'Langmuir cells') aligned downwind. The distance between the lines is twice the width of individual cells. Langmuir reports distances between the floating bands of *Sargassum* as being 100–200 m, while he found windrows in Lake George to have a separation of 5–25 m. Measurements by subsequent authors reviewed by Pollard (1977), Leibovich (1983) and Thorpe (2004) report scales ranging from 2 m to a few hundred meters, but with a range or hierarchy of scales at any one time. In general the dominant separation distance once the cells are well-developed is about twice the depth of the pycnocline (e.g., see Leibovich, 1983; Smith, 1992). In shallow water where cells extend to the seabed the distance between convergence lines seems to be related to water depth. Hunter and Hill (1980) and Marmorino et al. (2005) report spacing of the order of ten times the local water depth, and Gargett et al. (2004) described 'Langmuir supercells' with widths of about 45–70 m in a water depth of 15 m, giving a distance between convergence lines of 6–10 times the water depth.

The maximum water depth in the Qingdao coastal area is less than 40 m, and so the observed spacing of the macroalgae, 300–6000 m, is far greater than expected in Langmuir circulation. The pdf of the separation distances between bands (Fig. 3) does not, however, differ significantly from a log-normal distribution that is found by Csanady (1994) to represent the distance between Langmuir convergence lines, and which he argues represents the result of convergences at random times and locations on the sea surface.

In addition, the large separation of algal bands may be caused by instability of tidal current. Dong (1997) had investigated the formation mechanism of modern tidal current sand ridges whose spatial distribution is periodic with the alterative ridges and troughs and the distance between neighboring ridges ranges from 1 km to 10 km. He suggested that the sand ridges may be caused by instability of tidal current. From his results, the most instable pattern corresponded to the pertubation with wave length, 1.3 km, of the sand ridges when the water depth is 40 m as the parameters were properly selected. The spatial scale is similar to the observed spacing of the algal band in the Qingdao coastal area. It leads us to consider that the observed large spacing of the macroalgae may be caused by the instability of tidal current. However, further research is still needed.

## 5. Summary

In view of the discrepancy between the scales of the bands and those expected in Langmuir circulation, Langmuir circulation appears not to directly account for the bands of macroalgae even though the pdf of the band spacing distance is log-normal, similar to that of Langmuir convergence lines. The dynamical and/or biological processes responsible for the banded structure need further investigation. The accompanying paper by Thorpe (2009) proposes two statistical models to describe the rearrangement and dispersion of the floating algae as a result of Langmuir turbulence, and points out that the surface wave may be an alternative mechanism to generate bands of floating algae.

From a chemical and biological viewpoint, the non-toxic macroalgae bloom in the coastal water off Qingdao may be beneficial for water quality and for the ocean environment, since macroalgae can consume the nutrients in the sea water. However, such a large quantity of macroalgae transferred and gathered in Qingdao coastal area is too heavy burden and, as such, the bloom may be classed as harmful, and becomes a natural disaster.

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