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1 Assessment of the summer-autumn bloom in the Bohai
2 Sea using satellite images to identify the roles of wind
3 mixing and light conditions

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12 **Abstract**

In shallow coastal ecosystems, summer-autumn phytoplankton blooms require thorough investigation because of their large variability in space and time. This variability results primarily from the complex interplay of different governing factors, e.g., wind mixing and light availability. To identify the effects of these governing factors on the summer-autumn blooms in the Bohai Sea, we first established a statistical approach to define the biological variables that characterize summer-autumn blooms, i.e., the bloom onset time (denoted as bloom onset), the bloom magnitude, and the rate of chlorophyll-a (Chl-a) increase during the bloom period (denoted as Chl-a increase rate). These variables were quantified using daily Medium Resolu-

tion Imaging Spectrometer (MERIS) satellite scenes from 2003 to 2009. We observed a remarkable onshore-offshore gradient in all three biological variables. For example, bloom onsets were delayed in coastal areas compared to deep offshore waters. Spatially, the bloom onset exhibited a high correlation with wind mixing prior to the bloom period ($R > 0.6$), whereas the Chl-a increase rate and bloom magnitude were highly correlated to the distribution of the light attenuation coefficient ($K_{d(min)}$, $R = -0.65$ and $R = 0.69$, respectively). Furthermore, the empirical orthogonal function (EOF) analysis revealed similar interannual variability in the $K_{d(min)}$, bloom onset and Chl-a increase rate. We also observed similar interannual trends in the bloom magnitude and wind mixing during the bloom period. From the analysis above, we believe that light is a crucial limiting factor for summer-autumn phytoplankton dynamics in the Bohai Sea. Wind influenced Chl-a dynamics in many ways and at various scales. Spatially, weak wind speeds prior to bloom events tended to provide favorable light conditions for the development of blooms. Over the long-term, however, enhanced wind mixing tended to supply the surface layer with nutrients more effectively and thus promoted a higher bloom intensity.

¹³ *Keywords:* Bohai Sea; MERIS Data; phytoplankton bloom; wind mixing;

15 **1. Introduction**

16 The summer-autumn phytoplankton bloom dynamics in coastal waters
17 have been poorly investigated in the past, mostly because of the lack of mea-
18 surements with sufficiently high resolution in space and time (Cloern, 2001).
19 In recent years, a unique means of studying the spatio-temporal distribution
20 of coastal phytoplankton has been provided by high-resolution ocean color
21 sensors (e.g., Brickley and Thomas, 2004; Tang et al., 2003a). Satellite-based
22 studies have clearly identified a strong variability in chlorophyll-a (Chl-a)
23 concentration over different spatio-temporal scales (Iida and Saitoh, 2007;
24 Navarro and Ruiz, 2006; Sackmann et al., 2004). Although many studies
25 have focused on spring blooms (e.g., Tian et al., 2009; Wiltshire et al., 2008),
26 satellite-based data can also help to quantify variability in summer-autumn
27 blooms and, thereby, start pinpointing the mechanisms behind that variabil-
28 ity (Kim et al., 2007; Ueyama and Monger, 2005). In addition, not only can
29 the growing number of satellite images constrain parameterizations of ecolog-
30 ical models (Gohin et al., 2005), multi-scale correlations between biological
31 and environmental variables will help to improve functional representations
32 within the models.

33 The Bohai Sea is a semi-enclosed sea in northeast China (Fig. 1) with an
34 area of approximately 77,000 km². It is a typical shallow water body with a
35 mean depth of 18.7 m and maximum depth of approximately 70 m located
36 near the northern coast of the Bohai Strait. The Bohai Sea experiences low
37 water exchange capacity because the Bohai Strait with a width of ~ 150 km
38 is the only connection to the Yellow Sea (Zhao and Shi, 1993). The Yellow
39 River, the second largest river in China, drains into the Bohai Sea. The
40 run-off shows a very strong seasonal variability reaching over 10,000 m³/s
41 in summer with an annual mean value of only 1,400 m³/s. Connected to
42 this freshwater inflow is a strongly variable input of sediments and nutrients
43 (Martin et al., 1993). The wind field of the Bohai Sea is dominated by the
44 East Asia Monsoon, which is characterized by strong northwesterly winds
45 with a mean speed of 6-7 m/s in winter and weak southeasterly winds with a
46 mean speed of less than 4-6 m/s in summer, both of which are superimposed
47 by stochastically short-period changes on the weather scale and an interan-
48 nual variability dominated by the ENSO signal (Feng et al., 1999). Tides in
49 the Bohai Sea are dominantly semi-diurnal and relatively strong with a tidal
50 range of more than 4 m and maximum tidal velocity of around 2 m/s. Due to
51 the combined effect of tide, wind stress and seasonal stratification, the resid-

52 ual circulation in the Bohai Sea shows a complex pattern (e.g., Hainbucher
53 et al., 2004; Huang et al., 1999; Zhao and Shi, 1993; Sündermann and Feng,
54 2004). These complex and strongly variable conditions thereby result in an
55 additional complication of the ecosystem dynamics.

56 In temperate coastal ecosystems, phytoplankton dynamics reflects a tight
57 balance between nutrient supply and light limitation (Smetacek et al., 1991;
58 Walsh, 1988). It is thought that primary production is primarily controlled
59 by light during spring and by nutrient availability during summer (Colijn and
60 Cadée, 2003; Gomes et al., 2000; Hatcher, 2006; Rousseaux et al., 2012; Yin
61 et al., 1997). In summer and autumn, nutrient concentrations in the upper
62 layer are generally depleted by intense spring blooms, and strong stratifica-
63 tion may inhibit the supply of nutrients from deeper waters or the sea floor
64 (Chen, 2009; Kim et al., 2007; Yin et al., 1997). However, summer-autumn
65 nutrient limitation may weaken in eutrophic waters such as the Bohai Sea.
66 On one hand, the Bohai Sea experiences low nutrient exchange with the outer
67 open seas because of limited water exchange through the Bohai Strait (Zhao
68 and Shi, 1993). On the other hand, the Bohai Sea is heavily affected by
69 nutrient-enriched anthropogenic inputs and exhibits a strong water-sediment
70 exchange (Liu et al., 2011), which can alleviate the nutrient limitation in

71 summer and autumn. The Bohai Sea is dominated by a high concentration
72 of suspended particular matter (SPM), owing mostly to large SPM loads from
73 the Yellow River (Jiang et al., 2004; Saito et al., 2001), which significantly
74 decreases light availability in the water column. Therefore, the impacts on
75 phytoplankton growth posed by enhanced nutrient availability and more lim-
76 ited light conditions in the Bohai Sea might be of similar magnitude during
77 the summer-autumn period.

78 In shallow waters, another critical physical factor for biological dynamics
79 is wind mixing. Wind influences bloom development both positively and
80 negatively, as it changes the relationship between the mixed layer depth
81 and the critical optical depth for growth (Sverdrup, 1953). Wind-related
82 alterations in vertical mixing, destratification, and upwelling can enhance
83 nutrient supply to the upper layers (Findlay et al., 2006; Roegner et al., 2002;
84 Tang et al., 2003a; Wilkerson et al., 2006). Meanwhile, strengthened vertical
85 mixing can limit depth-averaged light availability and entrain phytoplankton
86 below the critical depth (Ueyama and Monger, 2005), which can therefore
87 suppress the initiation of blooms in the upper layers. In the Bohai Sea, wind
88 of high variability with different scales leads to complicated local processes
89 and modulates water stability together with tidal mixing, wave mixing and

90 the buoyancy input (Sündermann and Feng, 2004). Therefore, for the Bohai
91 Sea, the role of wind mixing in modulating the spatial and temporal features
92 of summer-autumn blooms requires further analysis.

93 A synoptic overview of the spatial and temporal features of summer-
94 autumn blooms has not been yet achieved for the Bohai Sea. The spatial
95 Chl-a concentration distribution in summer-autumn, derived from the Medi-
96 um Resolution Imaging Spectrometer (MERIS) product from 2003 to 2009,
97 exhibits an obvious onshore-offshore gradient (Fig. 2a). However, this gradi-
98 ent could not be easily explained by wind mixing (spatially $R < 0.1$, Fig. 2a-b).
99 The spatial pattern of total suspended matter (TSM) derived from MERIS
100 indicates complex and variable light conditions, which may in principle criti-
101 cally affect summer-autumn blooms (Fig. 2c). In this paper, we investigated
102 the spatio-temporal distribution of three biological variables derived from
103 MERIS data to describe phytoplankton blooms in summer and autumn: the
104 summer-autumn bloom onset time (denoted as bloom onset), the normal-
105 ized bloom magnitude during the bloom period (denoted as bloom magni-
106 tude) and the Chl-a increase rate during the bloom period (denoted as Chl-a
107 increase rate). By quantifying the major features of the summer-autumn
108 blooms in the Bohai Sea, we aim to identify the possible underlying mecha-

109 nisms (i.e., wind mixing and light conditions) behind the observed variability
110 in summer-autumn blooms.

111 **2. Dataset and Method**

112 *2.1. MERIS Data*

113 MERIS was developed with the aim of analyzing not only the open ocean
114 but also coastal waters (Doerffer et al., 1999). This ability was supported by
115 the European Space Agency (ESA) in supplying special variables for Case-2
116 waters in standard products. These are, specifically, a Case-2 Chl-a value, a
117 value for TSM, and a measure of absorption due to dissolved and particulate
118 organic matter, called gelbstoff (or colored dissolved organic matter, CDOM).
119 The underlying algorithm for the Case-2 ESA-standard variables was further
120 developed and is also available in several versions as a separate tool, the
121 Case-2 regional processor (Doerffer and Schiller, 2007), including a specific
122 coupled atmospheric correction. Many studies have supported the strength
123 of this concept(e.g., Cui et al., 2010; Martinez-Vicente et al., 2004; Ruddick
124 et al., 2008). MERIS level-1 scenes were processed by the Case-2 regional
125 processor in version 1.4.1 (R. Doerffer, personal communication, May 16,
126 2011) to retrieve a daily level-2 product. These data were further subsampled

127 over the study area (37-41 °N and 117.5-122.8 °E) at a reduced resolution of
128 ~ 1200 m. Because our analysis in this paper is focused on summer-autumn
129 phytoplankton bloom dynamics, we selected MERIS data collected from May
130 to November between 2003 and 2009 for the subsequent analysis.

131 The number of available data for each grid point is weather and trajectory
132 coverage dependent. MERIS collects data every 3 days at the equator and
133 more often at higher latitudes. However, clouds, contrails and sun glint can
134 prevent the observation of the underlying surface. When the satellite passes
135 by, it sometimes captures only part of the Bohai Sea because of the contrail
136 coverage. Therefore, for a large number of days each year, the data were
137 not usable. Fig. 2d presents the number of valid retrievals at individual grid
138 point gathered for the summer-autumn period from 2003 to 2009. There is
139 visibly a weak statistical bias towards the western part of the sea.

140 *2.2. Statistical approach used to derive biological variables*

141 *2.2.1. Bloom period*

142 In shallow coastal waters, a bloom is generally defined as a rapid growth
143 of phytoplankton that leads to a significant increase in biomass (Richardson,
144 1997). Our definition of the summer-autumn bloom was based on the cu-
145 mulative variance of Chl-a concentration (Ueyama and Monger, 2005). The

146 succession of phytoplankton bloom in summer-autumn is influenced by many
147 factors (e.g., grazing and nutrient supply), which complicates the story. How-
148 ever, the environmental factors are presumably identical in space and time
149 before the occurrence of the summer-autumn blooms. Therefore, we focused
150 on the first bloom during summer-autumn period as the beginning of the
151 seasonal succession in each year.

152 We used a least-squares fit curve analysis to determine the bloom period
153 at each $0.025^\circ \times 0.025^\circ$ grid point and for each year (2003-2009). First, we
154 conducted quality control. After filtering extreme values, the data were run
155 through a nine-point spatial median filter. For each year, grid points with
156 more than 10 data points between May and November were then chosen for
157 further analysis. For each grid point, the annual cycle of Chl-a concentration
158 was normalized (hence $\mu = 0$ and $\sigma = 1$) by subtracting the temporal mean
159 and dividing by the standard deviation. Missing values in the time series
160 were filled using linear interpolation (Fig. 3, green line). Second, we robustly
161 defined a bloom event as occurring when there was more than one day with
162 a normalized Chl-a concentration higher than 1.5 (Appendix A). If the time
163 interval between two days with Chl-a concentration (normalized) higher than
164 1.5 was more than 15 days (Appendix B), these days were attributed to two

different bloom events. For this case, we defined it multiple blooms, otherwise single bloom (Fig. 3) so that the first bloom can be separated from the later bloom succession (See the reasoning in Appendix B). Third, we derived the Chl-a variance time series. For each day, the variance was computed over a 15-day period (analogous to running mean, 7 day window). Fourth, we adjusted the Chl-a variance time series (Fig. 3, magenta line). To obtain an ideal “S” curve of the cumulative variance (Fig. 3, red line) focused on the first bloom period, the disturbance related to later blooms should be excluded, and the largest Chl-a variance during the first bloom period should be centered in the variance time series (denoted as the central day) with equal time distances forward and backward (Ueyama and Monger, 2005). The time distance was defined as the minimum of the three time intervals, i.e., from 1 May to the central day, from the central day to 30 November and from the central day to the second possible bloom event (for the case of multiple blooms only, otherwise, this time interval was ignored). Fifth, a time series of the cumulative variance was created by generating a cumulative sum of the daily variance corresponding to the new Chl-a variance time series (Fig. 3, red line). Sixth, based on this cumulative variance time series, a logistic curve was fitted using a nonlinear least-squares method (Fig. 3, black cross)

184 The logistic function

$$f(t) = \frac{C_1}{1.0 + \exp(C_2 - C_3 t)} + C_4 \quad (1)$$

185 contains the time index t and fitted shape constants C_i . Finally, the bloom
186 onset and bloom end time were functionally defined where the slope of the
187 fitted-curve equaled one-tenth of its maximum slope. Typical examples of
188 procedure defining the bloom-period (multiple blooms and single bloom, sep-
189 arately) are illustrated in Fig. 3a-b. At each grid point in the Bohai Sea, this
190 procedure was repeated for each year, from which a 7-year averaged bloom
191 onset was calculated.

192 2.2.2. Bloom magnitude

193 The magnitude of the summer-autumn bloom was expressed as the index
194 of bloom intensity. We used the normalized index instead of the absolute
195 magnitude so that the relative variation would not be overwhelmed by the
196 large variability in areas of high Chl-a concentration over the whole year. The
197 bloom magnitude was computed by averaging the normalized Chl-a concen-
198 tration over the bloom period (Fig. 3). This procedure was repeated at each
199 grid point for each year, and the averaged bloom magnitude for the 7 years
200 was also calculated.

201 2.2.3. *Chl-a increase rate*

202 During the bloom period, absolute Chl-a concentrations were used to cal-
203 culate the Chl-a increase rate. For each grid point, as the Chl-a concentration
204 measurements were rather sparse, we selected two measurements between the
205 bloom onset and the peak day of the bloom to calculate the Chl-a concentra-
206 tion difference (Fig. 3). Then, the Chl-a increase rate was computed through
207 dividing the difference by the time interval between the two measurements.

208 2.2.4. *Light conditions and CDOM during the bloom period*

209 A high correlation between Secchi depth (SD) and diffuse light attenu-
210 ation coefficient K_d has been found both in the ambient waters of the Bo-
211 hai Sea, e.g., the Yellow Sea (Son et al., 2005), and other coastal waters
212 that exhibit remarkable similarities in hydrography with the Bohai Sea, e.g.,
213 the North Sea (Tian et al., 2009; Sündermann and Feng, 2004). Therefore,
214 we used the MERIS-derived diffuse light attenuation coefficient $K_{d(min)}$ to
215 represent the light conditions. $K_{d(min)}$ is the minimum K_d of all available
216 wavelength-bands of MERIS (Doerffer and Schiller, 2007). We calculated
217 the averaged $K_{d(min)}$ during the bloom period for each grid point for each
218 year. The climatologically averaged $K_{d(min)}$ was also computed by averaging
219 the yearly $K_{d(min)}$ during the bloom period over the 7 years.

220 The CDOM data were retrieved as “Yellow Substance” by the Case-2
221 regional processor as well as by the MERIS standard processor. We averaged
222 it over the bloom period for each grid point for each year as well as for the
223 average over 7 years.

224 2.3. QuikSCAT wind data and wind mixing

225 QuikSCAT Level 3 daily wind speed data at a $0.25^\circ \times 0.25^\circ$ resolution
226 were obtained from the NASA/DAAC dataset ([ftp://podaac-ftp.jpl.
227 nasa.gov/](ftp://podaac-ftp.jpl.nasa.gov/)) from 2003 to 2009 and further interpolated to a $0.025^\circ \times 0.025^\circ$
228 grid (Fig. 2b). To evaluate wind mixing, we parameterized it as the cube
229 of the surface wind speed and assumed the bulk aerodynamic constant (α
230 in the following equation) to be 1.0. Similar processing methods have also
231 adopted to study the mixing caused by the surface wind forcing (Brickley
232 and Thomas, 2004; Ueyama and Monger, 2005).

233 In addition to the averaged wind mixing during the bloom period, we
234 obtained the wind mixing preceding and following the bloom to find the lag
235 correlation with the biological variables. Because of missing values, the wind
236 mixing in parts of the Bohai Sea was omitted from the analysis (Fig. 2b).
237 The formula is as follows:

$$M_{wind} = \frac{\sum_{n=T_b-i}^{n=T_e-i} (\alpha * \mu_n^3)}{(T_e - T_b)} \quad (2)$$

238 where M_{wind} is wind mixing, T_b and T_e present the bloom onset time
 239 and the bloom end time, which are calculated as in Section 2.2.1. α is
 240 the bulk aerodynamic constant which is set to be 1.0 in this study. μ is
 241 wind speed derived from the QuikSCAT product. i represents the number of
 242 days preceding (positive value) or following (negative value) the bloom when
 243 calculating the period-averaged wind mixing.

244 2.4. EOF analysis

245 Empirical orthogonal function (EOF) analysis was used to examine the
 246 spatio-temporal variability of the variables. In this study, the principal com-
 247 ponents (PCs) represented the interannual variability, whereas the resultant
 248 spatial eigenfunctions represented spatial patterns that varied with the cor-
 249 responding PCs. Data sets were prepared in two steps before applying the
 250 EOF analysis. First, the original data were converted to anomaly data by
 251 subtracting the temporal mean at each grid point. Second, if a given grid
 252 point contained missing data in any year during the 2003-2009 period, the
 253 data for that grid point were omitted from the EOF analysis. EOF analy-
 254 ses were performed separately on each variable (the bloom onset, the bloom

255 magnitude, Chl-a increase rate, the wind mixing, $K_{d(min)}$ and CDOM during
256 the bloom). Considering that only 7 years of data were available for the anal-
257 ysis, the EOF images were expected to be rather noisy. The temporal and
258 spatial patterns of the second mode and subsequent modes were less coherent
259 and difficult to interpret in terms of possible physical forcing mechanisms.
260 Therefore, we concentrated on the results of the first EOF mode for each
261 variable.

262 **3. Results**

263 *3.1. Long-term averaged spatial pattern*

264 Fig. 4 displays a synoptic overview of the 7-year averaged spatial dis-
265 tribution of the biological variables (left panels) and the possible governing
266 factors (right panels). The bloom onset distribution clearly illustrated an
267 onshore-offshore gradient (Fig. 4a), i.e., later blooms (after August) always
268 occurred in the nearshore coastal areas, whereas earlier blooms occurred in
269 the offshore Central Bohai Sea. The wind mixing exhibited a significant s-
270 patial gradient as well (Fig. 4b). Strong wind mixing was observed in the
271 nearshore areas, which corresponded with the areas of late blooms. Across
272 the southwest-northeast direction in the Central Bohai Sea, the water was

273 dominated by weak wind mixing, indicating that weak wind facilitated the
274 enhancement of early summer-autumn blooms. Spatially, the wind mixing
275 distribution was highly correlated with the bloom onset, with a correlation
276 coefficient as high as 0.69 (Table 1, Exp.1). However, neither the bloom on-
277 set nor the wind mixing displayed a good correlation with bathymetry, with
278 correlation coefficients of -0.26 and -0.33, respectively (Fig. 4a-b).

279 The spatial distribution of Chl-a increase rate exhibited a skewed pattern,
280 i.e., the Chl-a increase rate was low in the Laizhou Bay, the Bohai Bay and
281 the northwestern marginal areas of the Central Bohai Sea (Fig. 4c), whereas
282 the eastern part of the Central Bohai Sea was characterized by high rates
283 of Chl-a accumulation. For the distribution of $K_{d(min)}$ (Fig. 4d), the spatial
284 variation displayed the opposite pattern. Low $K_{d(min)}$ values were observed
285 in the Central Bohai Sea, whereas high $K_{d(min)}$ dominated in the Laizhou
286 Bay and the Bohai Bay, which was consistent with the locations of low Chl-
287 a increase rates. However, the northern Liaodong Bay, characterized by
288 high $K_{d(min)}$, did not exhibit the expected low Chl-a increase rate. The
289 spatial correlation coefficient between the Chl-a increase rate and $K_{d(min)}$
290 was moderate (Table 1, Exp.1, $R = -0.65$).

291 The distribution of bloom magnitude also displayed the opposite pattern

292 to that of the Chl-a increase rate (Fig. 4e). The three bays were characterized
293 by high bloom magnitude, whereas the southwest of the Liaodong Bay and
294 the Bohai Strait were dominated by low bloom magnitudes. This spatial
295 pattern resembled that of $K_{d(min)}$, with a spatial correlation coefficient as high
296 as 0.69 (Table 1, Exp.1). For the spatial pattern of CDOM, high values were
297 concentrated only in the narrow marginal areas and the estuaries, indicating
298 that the land and riverine inputs were the main sources of CDOM.

299 In coastal waters, CDOM interferes with the algorithm to obtain Chl-a
300 concentration in ocean color remote sensing, influencing the accurate es-
301 timation of Chl-a concentration (Van Der Woerd and Pasterkamp, 2008).
302 Therefore, it is necessary to evaluate the perturbation caused by CDOM in
303 our analysis. We performed an experiment, excluding pixels of high CDOM
304 concentration ($> 0.8 \text{ mg m}^{-3}$) when calculating the six variables, and found
305 no significant difference either for the spatial patterns (figures not shown)
306 or for the correlation coefficients (Table 1, Exp.1 and Exp.2) between the
307 two cases. Therefore, we confirmed that CDOM has little influence on the
308 estimation of biological variables, and the analysis was acceptable without
309 considering the influence of CDOM.

310 3.2. Interannual variability

311 The spatial eigenfunctions of the first EOF mode for the bloom onset
312 illustrate high coherence (Fig. 5a). For most parts of the Bohai Sea, the
313 spatial eigenfunctions are positive. The corresponding temporal pattern in-
314 dicates significant increases in 2003 and 2006 (Fig. 6a), implying that in most
315 parts of the Bohai Sea, the summer-autumn blooms were delayed in those
316 years.

317 For wind mixing, the first EOF mode accounted for approximately 26.5%
318 of the total variance. Significant negative signals occurred in the eastern part
319 of the Bohai Sea and the three bays (Fig. 5b), whereas positive signals were
320 observed in the northern and western part of the Central Bohai Sea. For the
321 temporal pattern, there was a strong negative amplitude in 2003 (Fig. 6b),
322 implying weak wind mixing in that year.

323 Spatially, positive eigenfunctions were found in the Bohai Bay, the Laizhou
324 Bay and the western Central Bohai Sea for Chl-a increase rate (Fig. 5c). For
325 $K_{d(min)}$, the most significant interannual variability occurred in the south-
326 eastern Central Bohai Sea and the northern Liaodong Bay (Fig. 5d). The
327 temporal patterns of Chl-a increase rate and $K_{d(min)}$ were remarkably similar
328 to that of bloom onset, with positive values in 2003, 2006 and the opposite

329 in 2004, 2005, 2008 and 2009 (Fig. 6c-d). Combined with the corresponding
330 spatial patterns, the positive values revealed a high Chl-a increase rate and
331 high $K_{d(min)}$ situation in 2003 and 2006.

332 The spatial eigenfunction of the bloom magnitude indicates inverse phases
333 between the southeastern Bohai Sea and other areas (Fig. 5e). The temporal
334 pattern remarkably resembles that of wind mixing, with a strong negative
335 amplitude in 2003 (Fig. 6e) indicating that weaker summer-autumn blooms
336 occurred in the coastal areas of the three bays and the southern part of the
337 Central Bohai Sea whereas at the same time there were intensified blooms in
338 the other parts of the Bohai Sea (Fig. 5e). The positive values in the temporal
339 pattern in combination with the corresponding spatial eigenfunction depict
340 an inverse distribution of the bloom magnitude in the other years.

341 For the spatial eigenfunctions of CDOM, there was high interannual vari-
342 ability in the Bohai Bay with the lowest CDOM concentration in 2009 (Fig. 5f
343 and Fig. 6f). However, in the northern part of the Liaodong Bay and the
344 Yellow River mouth, there existed opposite interannual variations that were
345 characterized by maximum CDOM concentration in 2009. For the other
346 parts of the Bohai Sea, the spatial pattern exhibits strong coherence with
347 slight positive values, implying a weak interannual variability.

348 4. Discussion

349 4.1. *Is the effect of tidal stirring significant?*

350 The timing of a phytoplankton bloom is regulated by the balance between
351 phytoplankton production and losses, which is sensitive to the rate of vertical
352 mixing in the water column (Cloern, 1991). In shallow coastal waters, verti-
353 cal mixing is manipulated by tidal stresses applied at the bottom and wind
354 stresses on the water surface (Cloern, 1996; Simpson et al., 1991). The tide
355 is strong in the Bohai Sea (Huang et al., 1999), and tidal mixing might have
356 an important influence on phytoplankton dynamics there. However, semi-
357 diurnal and diurnal tides are filtered out in the work because the employed
358 observational data do also not resolve the tidal scale explicitly. According
359 to Cloern (1991, 1996), in shallow coastal ecosystems such as the South San
360 Francisco Bay, phytoplankton blooms with short timescale might be regulat-
361 ed by the neap-spring tidal effect, as the phytoplankton biomass increases
362 during periods of weak tidal mixing (neap tides) and declines during spring
363 tides (strong tidal mixing). We selected the year 2008 for a primary analysis
364 (Appendix C). Fig. C.2 shows that in 2008, summer-autumn blooms devel-
365 oped during both neap and spring tide periods, and the Chl-a increase rate
366 had no obvious correlation with tidal energy. This suggests that the effect of

367 the neap-spring tidal effect might be overwhelmed by other processes.

368 From another aspect, in this paper, the first bloom in summer-autumn
369 can be referred to as “the seasonal initiation of summer-autumn bloom suc-
370 cession”. To the first order, tides are sub-daily periodic phenomena, we
371 cannot explain the generation of seasonal signals as resulting from the short
372 periodic physical forcing of tides. Therefore, we ignored the influence of tidal
373 stirring and focused our concentration on the influence of wind mixing.

374 4.2. *Is light a limiting factor in summer and autumn in the Bohai Sea?*

375 The light attenuation coefficient is a good indicator of light availabili-
376 ty for photosynthesis. For the 7-year average, the $K_{d(min)}$ value was higher
377 than 0.2m^{-1} , implying high turbidity and rather limited light availability
378 in summer-autumn all over the Bohai Sea, which was consistent with the
379 observed conditions in 1982-1983 (Fei, 1986). In our analysis, the Chl-a in-
380 crease rate and bloom magnitude exhibited the strongest correlations with
381 $K_{d(min)}$ among the three potential governing factors, revealing that the light
382 condition played an important role in modulating the spatial variability of
383 Chl-a during the bloom period. This conclusion was similar to previous find-
384 ings for the spring blooms in temperate coastal regions (Cloern, 1999; Dore
385 et al., 2002; Yoder et al., 1993). Guo (1994) also drew the conclusion that

386 the spring bloom in the Bohai Sea occurs when the light input and water
387 temperature increase under calm water conditions. However, the traditional
388 views about the triggers of summer-autumn blooms are concentrated on nu-
389 trient replenishment assuming that light availability is sufficient to sustain
390 photosynthesis (Guo, 1994; Iida and Saitoh, 2007; Wei et al., 2004). To fur-
391 ther characterize the role of light limitation in summer-autumn blooms, more
392 in situ measurements concerning water condition and nutrient limitation are
393 required.

394 *4.3. How does wind influence the spatial pattern of summer-autumn blooms*
395 *in the Bohai Sea?*

396 The spatial coherence between wind mixing and bloom onset (Fig. 4a-b)
397 suggests that weak wind over offshore waters stimulates the occurrence of
398 summer-autumn blooms, whereas in coastal areas, strong wind suppresses
399 the blooms. These results differed from previous findings that wind mixing
400 promotes summer-autumn blooms via the nutrient replenishment resulting
401 from vertical-mixing-induced entrainment or the upwelling of nutrient-rich
402 bottom water (Carstensen et al., 2004; Kim et al., 2007; Ueyama and Monger,
403 2005).

404 Phytoplankton growth is affected by light and nutrient limitation (Ben-

405 nett et al., 1986). However, Liu et al. (2011) and Sun et al. (2002) reported
406 that, based on observations, in summer-autumn the Bohai Sea is enriched
407 by a high concentration of nutrients from river discharge, sewage discharge,
408 regeneration from sediments, and subsurface groundwater discharge. These
409 observational data imply that in most parts of the Bohai Sea, nutrients might
410 not be the most significant limiting factor in summer-autumn. On the con-
411 trary, the analysis of light limitation confirmed that light availability still
412 influences phytoplankton growth in summer-autumn. Wind stirring had a
413 negative effect on the development of summer-autumn blooms. Concerning
414 the various mechanisms that relate to wind mixing, the time lag between
415 wind mixing and bloom onset varies. The lag correlation analysis (Fig. 7a)
416 illustrates a high correlation between wind mixing 0-10 days prior to the
417 bloom and the bloom onset but an independence of the bloom onset from
418 wind mixing after the bloom initiation. The time series data of Chl-a concen-
419 tration and the corresponding wind mixing at two grid points also indicated
420 weak wind conditions within 10 days before the bloom onset (Fig. 7b-c). This
421 result confirmed that weak wind conditions preceding blooms created a fa-
422 vorable environment for bloom initiation. This conclusion implies that wind
423 mixing played the same role in triggering both the spring blooms and the

424 summer-autumn blooms, indicating that in the Bohai Sea, there were similar
425 water conditions in spring and in summer-autumn, which were characterized
426 by high turbidity and relatively rich nutrients. This condition in summer is
427 possibly caused by eutrophication.

428 *4.4. Factors driving interannual variability*

429 The large variation in primary productivity is an important characteristic
430 of coastal ecosystem dynamics. Previous observations for the Bohai Sea and
431 adjacent ecosystems indicate that decadal variability in productivity is likely
432 to be modulated by multiple mechanisms (Tang et al., 2003b; Liu et al.,
433 2013). Although it is impossible to derive a reliable correlation between
434 phytoplankton dynamics and climate indices within the limited study period
435 of seven years, the analysis of satellite data can still provide a first explanation
436 of anomalous years such as 2003 and 2006. The resulting hypotheses can then
437 guide the analysis once longer-term time-series data can be introduced.

438 The multiple ways in which Chl-a variation depends on physico-chemical
439 forcing operate in many ways and at various scales, particularly in a shallow
440 coastal sea. This effect can be observed in the data from 2003, when a nega-
441 tive value appeared in the time series for the first EOF mode of wind mixing
442 and bloom magnitude (Fig. 6b and e), presenting low wind mixing associated

443 with a small average bloom magnitude. At small spatial scales, wind is here
444 shown to suppress Chl-a accumulation in the Bohai Sea (Table 1, Exp.1 and
445 Section 4.2). At an annual scale, however, on average reduced wind mixing
446 correlated with a smaller bloom magnitude throughout the summer-autumn
447 period but did not display any correlation with Chl-a increase rate (Fig. 6).
448 Given our previous discussion, it can be hypothesized that diminished nu-
449 trient availability reduces bloom magnitude in a year with weaker average
450 wind mixing. Although weak winds provided favorable light conditions for
451 a bloom, the wind-mixing-induced nutrient replenishment was low. To con-
452 clude, a positive wind influence could be derived at the interannual scale,
453 whereas spatially, bloom development exhibits a negative influence of wind
454 mixing.

455 The year 2006 was also extreme, with a significantly delayed bloom onset
456 but enhanced Chl-a increase rate. This can be explained first by the extreme
457 light conditions. Enhanced light attenuation and reduced light availabili-
458 ty would impede bloom initiation but could stimulate photoacclimation if
459 such conditions occur frequently. This extreme year is also related to El
460 Niño/Southern Oscillation (ENSO). Environmental factors in the Bohai Sea
461 are significantly influenced by ENSO. For example, ENSO events resulted in

462 a decrease of approximately 51% in water discharge from the Yellow River
463 to the Bohai Sea (Wang et al., 2006). Because 2006 was an El Niño year
464 (Kashino et al., 2009; Logan et al., 2008; McPhaden, 2008), river discharge
465 during the flood season was relatively low in that year (Fan et al., 2009).
466 Our results may indicate that lower riverine nutrient inputs cause delays in
467 summer-autumn blooms and diminished bloom magnitude but, surprisingly,
468 also increased Chl-a increase rates. The negative correlation between bloom
469 magnitude and Chl-a increase rate might reflect physiological constraints in
470 phytoplankton. Intense short-term variations in Chl-a (Fig. 3) very likely re-
471 flect effective photoacclimative responses rather than a pure biomass buildup
472 or loss, respectively. Nevertheless, the driving mechanism of summer phy-
473 toplankton blooms could be an interplay of water temperature, nutrients,
474 salinity and hydrodynamic conditions (Peng et al., 2012). To elucidate the
475 governing mechanism of interannual variability, a longer time-series of data
476 should be introduced to the analysis system.

477 **5. Conclusions**

478 In the Bohai Sea, the spatial and interannual characteristics of summer-
479 autumn blooms were studied using satellite data. In contrast to traditional

480 monthly composite products, in this study, we used daily scenes. A high tem-
481 poral resolution is a prerequisite for quantifying the statistical relationships
482 between variables that may drive or characterize summer-autumn blooms.

483 Summer-autumn blooms occurred earlier in the deep offshore waters com-
484 pared to nearshore areas. The spatial correlation between bloom onset and
485 wind mixing preceding the bloom period were extremely high. Higher Chl-a
486 increase rates with lower bloom magnitudes appeared in the deep offshore
487 waters, which reflected better light conditions but also the ongoing photoac-
488 climation of phytoplankton cells. Light still represented a key factor modu-
489 lating bloom intensity and growth during the summer-autumn period in the
490 Bohai Sea, indicating a coexistence of light and nutrient limitation. Inter-
491 estingly, the triggers of the summer-autumn blooms were similar to those
492 of spring blooms, providing new insight into the ecosystem dynamics of a
493 shallow coastal sea with severe eutrophication.

494 Interannual variability revealed, in part, different trends from the spatial
495 analysis, which is a further indication of the complexity of the coupling of
496 physico-chemical and biological dynamics. At an annual scale, light atten-
497 uation $K_{d(min)}$, bloom onset and Chl-a increase rate displayed a clear and
498 positive correlation, which is counterintuitive for $K_{d(min)}$ and the Chl-a in-

crease rate. Also differing from the spatial analysis, annually averaged bloom
magnitude and wind mixing exhibited a positive correlation. We found it
impossible to apply a single theory to explain the causes of interannual variability in the Bohai Sea ecosystem, as it is likely to be regulated by multiple factors. Hence, we suggest incorporating more MERIS and in situ data in future studies and closely connecting those analyses with integrated and mechanistic modeling.

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Appendix A. The critical Chl-a concentration for quantifying the bloom frequencies

In this paper, we used the threshold criterion described by Tett (1987) to preliminarily quantify bloom frequencies. However, the critical Chl-a concentration for the bloom definition varies from region to region. Therefore,

517 we applied normalized data to the analysis. We coarsely assume that the
518 time series of Chl-a concentration at a certain grid point obeys a Gaussian
519 distribution. When converted to a standard normal distribution (with $\mu = 0$
520 and $\sigma = 1$), values higher than 1.5 or less than -1.5 accounted for less than
521 18 percent of the distribution. Therefore, the period with values higher than
522 1.5 can be treated as the bloom period.

523 We also performed a series of experiments to determine the optimal criti-
524 cal value. From Fig. A.1, we can find that the three spatially and temporally
525 averaged biological variables all increased as the critical value increased. N-
526 evertheless, the spatial pattern of the biological variables did not reveal a
527 large difference (not shown). Therefore, we chose the median value (1.5)
528 as the optimal critical value. Although this criterion is not exact, we can
529 reasonably use it to define the first summer-autumn bloom for the further
530 statistical analysis.

531 **Appendix B. The time interval between two blooms**

532 For a certain grid point, if a second summer-autumn bloom occurred, we
533 performed the analysis based on the first bloom. For these instances, we
534 resampled the time series of Chl-a variance from the very beginning of the

535 study period (1 May) to the day before the initiation of the second bloom
536 and then conducted the further statistical analysis. Fig. B.1, a second bloom
537 occurred in early September. For case a), we did the curve fitting before the
538 second bloom and successfully captured the first bloom event and obtained
539 reasonable biological variable estimations (e.g., for bloom onset). For case
540 b), we did the curve fitting without excluding the second bloom. The "S"
541 curve fitting failed to reproduce the first bloom event and therefore resulted
542 in large deviations for the biological variable estimations.

543 We assumed that the time interval between two blooms is no less than 15
544 days so that we could distinguish the second bloom from the first one. With
545 this assumption, we could constrain the time period used for the subsequent
546 logistic curve fitting to dates before the initiation of the second bloom to
547 avoid disturbances to the fitting result caused by second and subsequent
548 blooms.

549 Because the time interval between two blooms is highly variable, we can-
550 not select a single interval value that works optimally all of the time. To find
551 the best assignment for the time interval, we chose 5 days, 10 days, 15 days,
552 20 days and 45 days for the experiments and compared the corresponding
553 results. Fig. B.2 presents the spatial distributions of bloom onset, Chl-a in-

crease rate and bloom magnitude. Fig. B.3 presents the spatial and temporal averages of the three biological variables. Both of the two statistical results indicate inconspicuous differences among the different assignments. Fig. B.3 we can see that the experiment with the interval of 15 days exhibited the smallest bias. Hence, we chose 15 days as the optimal time interval.

Appendix C. The index of neap-spring tide

We obtained hourly sea surface elevation data from the Finite Volume Coastal Ocean Model (FVCOM) model simulation, which is forced by eight major tidal constituents (M2, S2, N2, K2,K1, O1,P1,Q1) from 2007.12.01 to 2008.12.31. For each grid point, we estimated a time series of sea surface elevation from 1 May, 2008 to 30 November, 2008 (Fig. C.1a, blue line). Next, we calculated the daily maximum sea surface elevation (Fig. C.1a, red line). From there, the 2-day running mean was calculated for the time series of daily maximum sea surface elevation (Fig. C.1b, black dashed line). To create the index of neap-spring tide, we constrained the time series within the range of $-1 \sim 1$ by the following linear formula:

$$y = \frac{2x}{(a-b)} - \frac{(a+b)}{(a-b)} \quad (\text{C.1})$$

570 where y is the index of the neap-spring tides, x is the daily maximum sea
 571 surface elevation (2d running mean), a is the maximum sea surface elevation
 572 during the spring tides (the maximum of the black line in Fig. C.1b) and b
 573 is the minimum of the daily maximum sea surface elevation (the minimum
 574 of the black line in Fig. C.1b). For a coarse definition, index values less than
 575 0 could represent neap tides, whereas values greater than 0 could represent
 576 spring tides. We followed the same procedure for all of the grid points in
 577 the Bohai Sea in 2008. Based on the results, we also calculated the spatial
 578 correlation between the index of neap-spring tide and the Chl-a increase rate
 579 (Fig. C.2). We found the bloom onset was not regulated by the neap-spring
 580 tide because the blooms occurred during both the neap tide period (index <
 581 0) and the spring tide period (index > 0). In addition, there is no remarkable
 582 correlation between the neap-spring tide and the Chl-a increase rate.

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Table 1. Correlation coefficients between the biological variables and governing factors. Exp.1 is the experiment with the grid points of high CDOM concentration excluded when calculating the variables. Exp.2 is the experiment with the grid points of high CDOM concentration included when performing the same calculations. The red boxes highlight the maximum correlation of each biological variable with the governing factors in Exp.1 and Exp.2, respectively.

correlation coefficient (R)	Bloom onset		Chl-a increase rate (log)		Bloom magnitude	
	Exp.1	Exp.2	Exp.1	Exp.2	Exp.1	Exp.2
Wind mixing	0.69	0.49	-0.28	-0.11	0.45	0.24
$K_{d(min)}$	0.46	0.10	-0.65	-0.72	0.69	0.68
CDOM	0.44	0.13	-0.47	-0.67	0.54	0.60

Fig. 1. Study area with bathymetric contours (m). The Bohai Sea is divided into 4 regions: the Liaodong Bay, the Bohai Bay, the Laizhou Bay and the Central Bohai Sea. The inlet figure in the upper-left shows the location of the Bohai Sea within the China Seas.

Fig. 2. Spatial distribution of a) Chl-a concentration (Chl-a, mg m^{-3}), b) wind mixing ($\text{m}^3 \text{s}^{-3}$), c) total suspended matter concentration (TSM, mg m^{-3}) averaged over the summer-autumn period (May-November) from 2003 to 2009. Wind mixing intensity was interpolated to a $0.025^\circ \times 0.025^\circ$ grid from the original $0.25^\circ \times 0.25^\circ$ grid (black dots). d) Number of valid pixels from MERIS gathered for the summer-autumn periods from 2003 to 2009.

Fig. 3. Example time series of Chl-a concentration (normalized, green solid line with circle), Chl-a variance (magenta solid line), cumulative variance in Chl-a (solid red line), least-squares fit curve to the cumulative variance (black solid curve with cross), bloom onset (vertical line at X), the bloom period (gray dashed line) and the period used to calculate the Chl-a increase rate during the bloom period (blue solid thin line) during May to November sampled at a) 39.7°N, 120.4°E in 2003 and b) 39.4°N, 119.9°E in 2008, to illustrate the method calculating variables for typical a) multiple blooms and b) a single bloom during the summer-autumn period, respectively. For the condition of multiple blooms a), we derived the variables based on the first bloom.

Fig. 4

763 Fig. 4. Seven year averaged a) bloom onset (month), b) wind mixing during
 764 the bloom period ($\text{m}^3 \text{s}^{-3}$) superimposed by the bathymetry, c) Chl-a increase
 765 rate ($\text{mg Chl m}^{-3} \text{d}^{-1}$), d) light attenuation coefficient ($K_{d(\text{min})}$, m^{-1}), e) bloom
 766 magnitude (dimensionless) and f) colored dissolved organic matter (CDOM, mg
 767 m^{-3}) during the bloom period. Spatial correlations were computed as follows:
 768 between bloom onset and wind mixing $R=0.69$ ($p<0.001$), between CIR (log) and
 769 $K_{d(\text{min})}$ $R=-0.65$ ($p<0.001$), and between bloom magnitude and $K_{d(\text{min})}$ $R=0.69$
 770 ($p<0.001$). A contour line at 0.8 mg m^{-3} CDOM is overlaid in panel (f) to delineate
 771 high CDOM pixels that were excluded from part of our analysis. The spatial
 772 correlations of bloom onset and wind mixing with water depth are -0.26 and -0.33 ,
 773 respectively.

Fig. 5

774 Fig. 5. Spatial eigenfunctions for the first EOF mode of a) bloom onset, b) wind
775 mixing, c) Chl-a increase rate, d) light attenuation coefficient ($K_{d(min)}$), e) bloom
776 magnitude, and f) colored dissolved organic matter (CDOM), for the summer-
777 autumn bloom. Each EOF mode accounts for 23.0%, 28.1%, 25.9%, 26.5%, 32.9%
778 and 27.8% of the total variance, respectively.

Fig. 6. Time series for the first EOF mode of a) bloom onset, b) wind mixing, c) Chl-a increase rate, d) light attenuation coefficient ($K_{d(min)}$), e) bloom magnitude, and f) colored dissolved organic matter (CDOM) during the summer-autumn bloom period.

Fig. 7

779 Fig. 7. a) The time lag correlation between the spatial distribution of summer-
780 autumn bloom onset and (i) the light attenuation coefficient $K_{d(min)}$ (black line)
781 and (ii) wind mixing (blue line). Positive time lag values indicate co-variation after
782 the bloom onset. The highest correlation appeared between the bloom onset and
783 wind mixing 0-10 days prior to the bloom event (period between the dashed lines).
784 b) and c) display typical time series of Chl-a concentration and the correspond-
785 ing wind mixing at certain points sampled in Fig. 3 to illustrate the relationship
786 between wind mixing and bloom onset.

Fig. A.1. The spatially and temporally averaged biological variables with different assigned values of the critical Chl-a concentration that was used as the threshold to determine the occurrence of the bloom.

Fig. B.1. Illustration of the effect of the disturbance caused by a second bloom on the curve fitting results at a certain point sampled in Fig. 3a). In a) the second bloom period was excluded, resulting in a reasonable fitting curve and correct estimation of the timing of bloom onset. In b) the estimations of both the bloom onset and the bloom end time for the first bloom show remarkable inaccuracy because the second bloom had a significant influence on the curve fitting.

Fig. B.2. Spatial distribution of biological variables with different assignments of the time interval between bloom blooms (The same as Fig. 4).

Fig. B.3. The spatially and temporally averaged biological variables with different assignments of the time interval between two blooms.

Fig. C.1

787 Fig. C.1. Example for the procedure calculating the index of neap-spring tides
788 at a certain point sampled in Fig. 3b). a) shows the FVCOM simulated hourly
789 sea surface elevation (blue line) and the daily maximum value (red line). b) shows
790 the 2d running mean (dashed black line) and the dimensionless time series (green
791 line). The dashed-dot lines stand for the maximum and minimum values for the 2d
792 running mean time series, respectively. c) shows the time series of the normalized
793 Chl-a concentration (black line with circle) and bloom onset (vertical line at X) in
794 the sampled point.

Fig. C.2. Index of neap-spring tides on the day of bloom onset versus Chl-a increase rate during the bloom period for each grid point in the Bohai Sea. Blooms occurred during both the neap tide period (index < 0) and the spring tide period (index > 0). There is no good correlation between the spatial distribution of index and the Chl-a increase rate.