

Dynamics of a fish-killing dinoflagellate *Karenia mikimotoi* red-tide captured by composite data sources

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1 **Dynamics of a fish-killing dinoflagellate *Karenia mikimotoi* red-tide**
2 **captured by composite data sources**

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26 **Abstract**

27 Bloom dynamics of *K. mikimotoi* during summer 2015 in the Yatsushiro Sea, Japan,
28 which caused fish mortality was studied using field survey data and satellite data. The
29 bloom initially formed in the western area, subsequently appeared in the southern area,
30 and finally expanded to the central area. The field-survey detected the horizontal
31 displacement of the bloom which was also assessed by satellite data. Acoustic
32 backscattering intensity of the current meter captured the modulation of the diurnal
33 vertical migration of *K. mikimotoi*. After the modulation, *K. mikimotoi* distributed at a
34 shallower depth in the nighttime than the period prior to the modulation. Factors affecting
35 the modulation are suggested to be **the continuous low nutrient conditions**.
36 Synchronization between the shallowed distribution during the nighttime and the wind
37 driven surface northeastward current enabled a sudden horizontal transport toward the
38 central area. Satellite and acoustic backscattering data are beneficial subsidiary tools for
39 detecting blooms.

40

41

42 *Keywords:* *Karenia mikimotoi*, diurnal vertical migration, GOCI, DIN, backscattering
43 intensity

44

45 1. Introduction

46 Harmful algal blooms have frequently occurred and lead to negative influences on
47 human activity in coastal waters characterized by being shallow and adjacent to land
48 (Kudela et al., 2018). Indeed, blooms of the dinoflagellate *Karenia* species particularly
49 have negatively impacts on the economic activities in coastal waters such as *K. brevis* in
50 the Gulf of Mexico, *K. selliformis* in the Mediterranean and Asian waters and *K.*
51 *mikimotoi* in the European, African and Asian waters (Stumpf et al., 2003; Davidson et
52 al., 2009; Robin et al., 2013; Feki-Sahnoun et al., 2017; Aoki et al., 2017; Chen et al.,
53 2021; Kuroda et al., 2021). It is noteworthy that physical displacement plays a critical
54 role in *Karenia* bloom dynamics (Miyamura et al., 2005; Soto et al., 2018; Aoki et al.,
55 2019). The drastic horizontal displacement of blooms was occurred by currents in short-
56 term (Aoki et al., 2015; 2019). In the case of the rapid bloom development, mitigation
57 strategies can not be efficiently operated in the short-term, consequently mass fish
58 mortality occurs. Therefore, understanding the short-term dynamics of the bloom is
59 critically important.

60 *K. mikimotoi* is adapted to a wide range of temperatures of 4-30 °C and salinities of
61 9-35 (Gentien, 1998; Li et al., 2019). *K. mikimotoi* is motile and undergoes diurnal vertical
62 migration (DVM) distributing in shallower depths during the daytime and at deeper
63 depths during the nighttime (Koizumi et al., 1996; Li et al., 2019). DVM is inhibited by
64 strong light, nutrient deficiency and strong stratification of the water column in the field
65 (Shikata et al., 2015; Yuasa et al., 2018; Shikata et al., 2020).

66 Previous studies showed the utility of satellite observations for detecting blooms
67 (Stumpf and Tyler, 1988; Ahn et al., 2006; Onitsuka et al., 2010). Satellite data have also
68 enabled the detection of specific harmful species not only to estimate the chlorophyll-a
69 concentration (e.g. Kurekin et al., 2014). Siswanto et al. (2013) suggested the detection

70 method of *K. mikimotoi* blooms using Moderate Resolution Imaging Spectroradiometer
71 (MODIS) in the Seto Inland Sea, Japan, which is located near our study area (Fig. 1).

72 An acoustic current profiler also can measure the backscattering intensity in the
73 water. Using the backscattering intensity, previous studies have attempted to estimate the
74 suspended sediment concentration, zooplankton biomass and micronekton behavior
75 (Heywood, 1996; Luo et al., 2000; Takikawa et al., 2008). Moreover, diurnal vertical
76 migration of zooplankton could be demonstrated using backscattering intensity data (e.g.,
77 Heywood, 1996; Berge et al., 2009). Kim et al. (2012) confirmed the increase of
78 backscattering intensity with an increasing in cell abundance of the bloom causing
79 microalga, *Chattonella antiqua*, by a laboratory experiment. Subsequently in the field,
80 the acoustic method was confirmed to be applicable for *Akashiwo sanguinea* and
81 *Alexandrium affine* (Kim et al., 2019).

82 The Yatsushiro Sea is a semi-enclosed sea area located in the coastal region of
83 western Japan (Fig. 1). Harmful blooms have recurrently occurred in the Yatsushiro Sea
84 and resulted in mass mortality of cultured fishes in fish farms located in the southern area
85 of the Yatsushiro Sea (Onitsuka et al., 2011; Aoki et al., 2015; Nakajima et al., 2019). In
86 the southern area, salinity is higher than that of the inner part because the Yatsushiro Sea
87 is connected with the East China Sea through two channels located in the southern area
88 (Takikawa et al., 2004). Extensive fish aquaculture is conducted around the islands in the
89 southern area.

90 A *K. mikimotoi* bloom formed in 2015 summer in the Yatsushiro Sea and killed ca.
91 8000 cultured immature yellowtails with an approximate value of ca. US\$ 100000 (at an
92 exchange rate ¥120 = \$1). However, the mechanism of the short-term variation of the
93 bloom which is necessary information for mitigation systems, remains unclear. This study
94 described the short-term dynamics of the *K. mikimotoi* bloom in 2015 and the relationship

95 with hydrostatic condition using data observed by the ship survey. In addition, usage of
96 satellite data and backscattering intensity data enable tracking the horizontal distribution
97 and vertical migration of the *K. mikimotoi* blooms in the field. Sonar data such as
98 backscattering of the current meter has been already observed in many monitoring
99 programs of harmful blooms in various coastal waters. In addition, the satellite data can
100 be used in any coastal waters. However, studies using a combination of satellite and sonar
101 data for detecting blooms remain uncommon.

102

103 2. Materials and Methods

104 2.1. Description of field observations

105 In order to understand the short-term variation of the bloom, field surveys were
106 conducted by the Kumamoto Prefectural Fisheries Research Center (KPFRC), the
107 Kagoshima Prefectural Fisheries Technology and Development Center, the Azuma-cho
108 Fishery Cooperative Association and the Fisheries Research and Education Agency
109 (FRA). The cell density was counted in the weekly surveys during the pre-bloom period
110 and daily surveys during the bloom. Water samples were collected with a Van-Dorn
111 sampler or Kitahara water sampler at depths of 0, 2, 5, 10 m depth for cell counts. Samples
112 were stored in cooler boxes filled with water until cell counts for preventing a temperature
113 increase and sunlight, and cell counts were partially conducted on the ship and the
114 remaining just after getting off a ship using microscopes.

115 In order to understand the short-term variation of environmental conditions, vertical
116 profiles of the water temperature and salinity were measured using AAQ-RINKO (JFE
117 Advantec Inc.) and dissolved inorganic nitrogen (DIN) and PO₄-P were measured at 0, 5,
118 10, 20, 30, 40 and 1 m above the bottom using a Van-Dorn water sampler and
119 autoanalyzer (QuAAtro 39, BL-TEC, Japan) at Stations 1-8 (Fig. 1) by KPFRC. The

120 Monod coefficient ($= N/(N+K_h)$; N: nutrient density; K_h ; a half saturation constant) for
121 DIN and $PO_4\text{-P}$ was calculated to examine the nutrient condition for the growth of *K.*
122 *mikimotoi* in the same manner of Aoki et al. (2017). The half saturation constants for DIN
123 and $PO_4\text{-P}$ are $0.78 \mu\text{M}$ and $0.14 \mu\text{M}$, respectively (Yamaguchi, 1994; Shikata et al.,
124 2020). The Monod coefficient less than 0.5 means that nutrient concentration is less than
125 the half saturation constant in the environment. Moreover, the Monod coefficient of DIN
126 is directly comparable to the Monod coefficient of $PO_4\text{-P}$ for discussing the limiting
127 nutrient. In this study, the minimum value of the Monod coefficient of DIN and $PO_4\text{-P}$
128 was called for a minimum Monod coefficient.

129 In order to understand the short-term variation of flow conditions and the vertical
130 profile of *K. mikimotoi*, vertical profiles of the current velocity and backscattering
131 intensity of the water were observed at Station 8 (Fig. 1) using a Nortek Aquadopp
132 Current Profiler Z-cell installed in floating buoys by FRA. Backscattering intensity and
133 current velocity were measured at 1.5-m depth and every 1-m from 3 m to 34 m depth.
134 The amplitude and phase of major 16 tidal components ($M_2, S_2, K_1, O_1, N_2, K_2, I_2, P_1, L_2,$
135 $S_a, S_{sa}, M_m, MS_f, M_f, Q_1, M_1$) were estimated using the hourly current velocity data and
136 harmonic analysis. The tidal components of the hourly data were eliminated using
137 estimated amplitudes and phases. Moreover, the detided hourly data was filtered by 5-
138 hour low-pass filter.

139

140 2.2 Wind data

141 Wind speed and direction data were provided by the Japan Meteorological Agency
142 at Minamata (Fig. 1).

143

144 2.3 Procedure of satellite data

145 A detection method of *K. mikimotoi* bloom has been suggested using data of
146 Aqua/MODIS (Siswanto et al., 2013). However, we used the data of the Geostationary
147 Ocean Color Imager (GOCI) of the Communication Ocean and Meteorological Satellite
148 of Korea (Ryu et al., 2012) rather than that of Aqua/MODIS, because sufficient data of
149 Aqua/MODIS could not be obtained during 2015 bloom due to the extensive cloud cover.
150 As every hour data of GOCI during daytime can be used for the eastern Asian area, more
151 extensive data could be obtained during the 2015 *K. mikimotoi* bloom in the Yatsushiro
152 Sea. As the spectral bands of GOCI do not match with Aqua/MODIS, we used the
153 alternative spectral bands of GOCI which are listed in Table 1.

154

155 *2.4 Estimation of horizontal transport*

156 Horizontal transport distance induced by the current was evaluated using current
157 velocity data at Stn. 8. Considering the DVM of *K. mikimotoi*, daily horizontal transport
158 distance was assumed in two cases. Based on observed results of Koizumi et al. (1996),
159 simplified DVM was assumed in case (a) in which velocity in 5-m depth was used during
160 daytime (5:00-17:00), and 25-m depth during nighttime (0:00-4:00, 18:00-24:00). Based
161 on our result shown in section 3.3, DVM with shallowing of the nighttime distribution
162 was assumed in case (b) in which velocity in 5-m depth was used during daytime (5:00-
163 17:00), and 15-m depth during nighttime (0:00-4:00, 18:00-24:00).

164

165 **3 Results**

166 *3.1. Horizontal evolution of the bloom*

167 Cell density of the *K. mikimotoi* increased to 18000 cells ml⁻¹ cells in Kusuura Bay
168 which is a semi-enclosed area located in the western area of the Yatsushiro Sea,
169 meanwhile cell density in the eastern area of Yatsushiro Sea ranged 0-3 cells ml⁻¹ on 22

170 July (Fig. 1 and 2). Higher cell density over 10000 cells ml⁻¹ distributed to the area outside
171 Kusuura Bay on 28 July. Then, cell density increased to 5000 cells ml⁻¹ also around
172 Nagashima and Shishi Islands on 6 and 11 August. High cell density area drastically
173 changed on 13 August, and part of the bloom reached the central area. The northeastern
174 edge of the bloom moved northeastward over 15 km during 11-13 August. Two days later
175 (15 August), the high cell density water distributed along the shore area of the
176 southeastern coast, while it disappeared around Nagashima Island. The cell density in the
177 Yatsushiro Sea suddenly decreased within 2 days from 15 to 17 August. The bloom
178 declined until 24 August.

179 During the bloom (6-15 August), high chlorophyll-a concentration over 3 mg m⁻³
180 was detected also in the northern area of the Yatsushiro Sea by satellite data (Fig. 3).
181 Nevertheless, in the northern area, the *K. mikimotoi* bloom was not detected (lower panels
182 of Fig. 3). These results indicate that the high chlorophyll concentration of the northern
183 area was caused by the bloom of another phytoplankton rather than *K. mikimotoi*. Satellite
184 data demonstrated that *K. mikimotoi* bloom occurred mainly in the central and
185 southwestern area, the same as the field observations (Fig. 2 and 3)

186

187 3.2. Temporal changes of the environment

188 Off Kusuura Bay (Stn. 8), sea surface temperature gradually increased from 24.7 to
189 27.3 °C during late July-middle August when the bloom occurred (Fig. 4). A thermocline
190 and halocline developed in the same period (Fig. 4 and 5). The thermocline temporarily
191 was weakened in the inner area (Stns. 1-6) on 18 August. In Stn. 8, the sea surface salinity
192 slightly increased from 30.9 to 31.3 during late July-early August, while the 30-m depth
193 salinity suddenly increased from 31.8 to 32.6 during 4-11 August (Fig. 4). High salinity
194 (>32.5) water was not observed on 28 July in the surface waters and occurred from the

195 depth of 20-m to the bottom in the bay mouth (Stn. 7; Fig. 5). Subsequently, the high
196 salinity water intruded to the bottom of Stn. 8 on 11 August and Stn. 6 on 18 August (Fig.
197 4 and 5).

198 The low surface nutrients and high bottom nutrients were observed from early to
199 mid-July on St. 8 with the stable density stratification (Fig. 4). During mid-July-early
200 August, nutrients in the depth of 20-30 m and Monod coefficient gradually decreased (Fig.
201 4 and 6). On 28 July and 4 August, minimum Monod coefficient (Monod coefficient of
202 $\text{PO}_4\text{-P}$) was less 0.5 in the depth of 20-30 m. On 11 August, Monod coefficient of DIN
203 decreased to ca. 0.5 at sea surface, while the Monod coefficient of $\text{PO}_4\text{-P}$ increased in
204 synchrony with bottom salinity increased (Fig. 4 and 6). In the results, Monod coefficient
205 of $\text{PO}_4\text{-P}$ exceeded that of DIN on 11 August. The results indicated the limiting nutrient
206 for the growth of *K. mikimotoi* temporally changed from phosphate to nitrogen on 11
207 August. Therefore, the minimum Monod coefficient of less 0.6 was maintained until 11
208 August regardless of the $\text{PO}_4\text{-P}$ increasing on 11 August.

209 In early August when the bloom occurred also in Nagashima and Shishi islands (Fig.
210 2), a southwestward current was observed in the depth shallower than 10-m at Stn. 8 (Fig.
211 1 and 7). Meanwhile a northeastward current was observed at the depth deeper than 20-
212 m forming a typical two-layer flow pattern of a stratified estuary. The flow pattern
213 apparently changed during 11-12 August when the bloom expanded eastward, and a
214 northeastward current ($> 0.05 \text{ m s}^{-1}$) occurred in the depth shallower than 20-m at Stn. 8
215 which synchronized with a strong northwestward-northward wind (Fig. 7a-c).

216

217 3.3 Backscattering intensity of current profilers

218 Clear diurnal variability was observed in the hourly composite of the backscattering
219 anomaly during the bloom (6-13 August) at Stn. 8 (Fig. 8a). The intensified backscatter

220 was found in the depth shallower than 3-m during daytime and in the depth deeper than
221 5-m during nighttime.

222 Interestingly, the backscattering intensity captured a remarkable nighttime vertical
223 distribution in the later stage of the bloom when the bloom expanded to the central area
224 (Fig. 8b). The intensified backscatter was distributed also in the depth deeper than 20-m
225 at nighttime from 6-9 and 12-14 August. **The depth of the high backscattering intensity**
226 **at nighttime was 6-18 m on 10 August and gradually became shallower from 10 to 12**
227 **August.**

228

229 *3.4 Horizontal transport*

230 During 28 July-14 August, the direction of transport was mainly to the north to
231 northeast in both cases of a and b (Fig. 7d and e). The difference between case a and b is
232 clearly visible on 12 August. In case (b), highlighted northeastward transport over 7.5 km
233 occurred on 12 August, but not in case (a). **Summation of the transport distances in 11-**
234 **13 August, when the northeastward bloom expansion occurred (Fig. 2), was ca. 6.6 km**
235 **in case (a) and ca. 11.8 km in case (b), respectively.**

236

237 **4 Discussion**

238 The *K. mikimotoi* bloom initially occurred in a semi-enclosed area of the
239 southwestern area during the summer of 2015 (Fig. 2). Subsequently, the bloom occurred
240 also around the islands in the southern area in early August, and central area in mid-
241 August. In the field survey, bloom transition remained unclear in the northern area during
242 11-13 August. Satellite observations showed no indication of the bloom occurrence in the
243 northern area in the period (Fig. 3). Therefore, results of the ship survey showed the
244 possibility of two steps of horizontal transport of the bloom. One is transport from

245 Kusuura Bay to the vicinity area around the islands in the southern area during 28 July-6
246 August. The other is the transport from the vicinity of the area around the islands in
247 southern area to the central area during 11-13 August. The direction of the horizontal
248 transport in both cases of (a) and (b) estimated by the observed current velocity data was
249 northeastward from 28 July to 6 August (southwestward; Fig. 7). The estimated direction
250 was entirely different from the displacement of the bloom area (Fig. 2). Thus, our results
251 suggested that the bloom occurrence around the islands in the southern area on 6 August
252 resulted from local growth of *K. mikimotoi* in the area rather than transport by the currents.
253 Meanwhile, the direction of the estimated transport in case (a) assumed the default DVM
254 (5-m depth during daytime and 25-m depth during night) was northeastward the same as
255 the displacement of the bloom area during 11-13 August (Fig. 2 and 7). However, the
256 estimated distance of 6.6-km in the case (a) was underestimated in comparison with the
257 displacement of the bloom (over 15 km). Here, we verified the vertical distribution of *K.*
258 *mikimotoi* during 11-13 August. The backscattering data of the current meter indicated
259 the DVM pattern during the *K. mikimotoi* bloom and the shallowing in the night
260 distribution of the intensified backscattering (Fig. 8). The diurnal pattern of high
261 backscattering is analogous to the DVM of *K. mikimotoi* reported by previous studies
262 (Koizumi, 1996; Shikata et al., 2015). Thus, the result implies that the intensified
263 backscatter indicates the dominance of *K. mikimotoi* during the bloom rather than
264 zooplankton or fishes. Moreover, the shallowed night distribution of intensified
265 backscattering possibly indicates the shallowing of the *K. mikimotoi* distribution during
266 the night (i.e. modulation of the DVM of *K. mikimotoi*) and at least the absence of the
267 high cell density of *K. mikimotoi* in the lower depth during 11-13 August. Thus, case (a)
268 was inadequate for estimating the transport distance during 11-13 August. The estimated
269 distance of 11.8 km in the case (b) assuming the above shallowed night distribution was

270 slightly underestimated, but not largely different from the displacement of the bloom (Fig.
271 2 and 7e). Moreover, the direction of the estimated transport in case (b) was northeastward
272 the same as the displacement of the bloom area during 11-13 August (Fig. 2 and 7).
273 Therefore, our results implied that the bloom occurring in the central area on 13 August
274 originated from the bloom around the islands in the southern area on 11 August. The
275 displacement of the bloom released aquaculture farms around the islands in the southern
276 area from the stress and damage by the bloom. In fact, the damage of US\$ 100,000 during
277 the 2015 *Karenia* bloom was much smaller than the damages (US\$ 44,000,000 and
278 58,000,000) during the blooms in 2009 and 2010 (Aoki et al., 2012; Aoki et al., 2015).
279 One factor of the mitigated damages is the exposure time for the bloom was shortened by
280 the displacement of the bloom.

281 This study attempted the detection method of the *K. mikimotoi* bloom using GOCI
282 partially differing from Aqua/MODIS (Siswanto et al., 2013). The results were in good
283 agreement with the field survey (Fig. 2 and 3). Therefore, it is suggested that the method
284 of Siswanto et al. (2013) is useful also for GOCI data. As mentioned in section 2.2, GOCI
285 supplies hourly products of a fixed area in East Asian during daytime because of the
286 geostationary orbit. The GOCI data enable measurements of harmful algal blooms even
287 under cloudy conditions. The combination of the method of Siswanto et al. (2013) and
288 hourly products of GOCI will facilitate the detection of *K. mikimotoi* blooms.

289 The bloom detection method of Siswanto et al. (2013) used remote sensing reflectance
290 of the 6 spectral bands listed in Table 1. The band resolution of the sensor is slightly
291 coarse for resolving the color transition of the ocean which is blue in default state and a
292 reddish brown during the bloom of *K. mikimotoi*. Therefore, it is difficult to develop the
293 method for a more precise measurement of cell density rather than the presence or absence
294 of the bloom. The launch of the satellite installed the high band resolution sensor may

295 enable to detect the cell density of *K. mikimotoi*.

296 In previous studies, the acoustic detection was confirmed for the bloom of
297 *Chattonella antiqua*, *Akashiwo sanguinea* and *Alexandrium affine* (Kim et al., 2012; Kim
298 et al., 2019) but not for *K. mikimotoi*. As the cell size of *K. mikimotoi* is not much smaller
299 than the *C. antiqua* and *A. sanguinea*, acoustic backscattering is expected to capture the
300 cell density of the *K. mikimotoi*.

301 In the period of the bloom expansion from the southern area to the central area, the
302 night distribution of *K. mikimotoi* was shallowed in comparison with the distribution prior
303 to the expansion (Fig. 8). During the shallowed distribution, a strong northwest-northward
304 wind induced the northeastward current in the depth shallower than 20m (Fig. 7a-c). In
305 case b, *K. mikimotoi* fully received the effect of the northeastward current, long
306 northeastward transport was evaluated same as the measured bloom expansion but not in
307 case a (Fig. 2 and 7d, e). These results indicated that two key factors of the horizontal
308 transport in mid-August are a shallowed night distribution of *K. mikimotoi* and strong
309 wind-induced current.

310 The continuous low nutrient condition and alternation of the limiting nutrient from
311 P to N occurred prior to the shallowing in the night distribution of *K. mikimotoi* (Fig. 6).
312 Unclear DVM was shown in N-depleted condition and no DVM in P-depleted in a
313 laboratory experiment (Yuasa et al., 2018). In addition, the vertical migration distance of
314 *K. mikimotoi* correlated to P concentration in the field rather than N concentration
315 (Shikata et al., 2020). Therefore, it suggested that the shallowing of the night distribution
316 during 10-12 August was contributed by the continuous low nutrient condition rather than
317 the alternation of limiting nutrient. The nutrient dynamics are difficult to interpret. The
318 high salinity bottom water gradually intruded into the Yatsushiro Sea through the
319 Nagashima Strait from offshore during 4-18 August (Fig. 4 and 5). The high salinity

320 bottom water did not include high PO₄-P in the strait (Stn. 8) on 4 August. In addition,
321 increasing the PO₄-P is clearer in the upper layer (above 20-m) than the lower layer. These
322 results showed no indication of a clear contribution of the intrusion of high salinity bottom
323 water. It is known that a benthic flux of DIN and PO₄-P from the bottom sediment occurs
324 in the coastal sea areas (Callender and Hammond, 1982; Friedrich et al., 2002). On 11
325 August, DIN decreased on Stn. 8 rather than increased (Fig. 6). There is also no indication
326 of the contribution of the benthic nutrient flux. Therefore, it is assumed that DIN
327 decreasing and PO₄-P increasing were affected by a combination of multiple factors
328 (utilization for the growth, offshore high salinity water intrusion and benthic flux).

329 For modeling of the horizontal transport of plankton, vertical distribution of the
330 target is critically important as shown in Fig. 7de and previous studies (Stenevik et al.,
331 2003; Lett et al., 2007; Xiong et al., 2022). In the modeling of *K. mikimotoi* blooms in
332 previous studies (Vanhoutte-Brunier et al., 2008; Gillibrand et al., 2016), the rhythm and
333 swimming speed was not taken into account or does not depend on the development stage
334 of the bloom and/or nutrient condition. The problem is possibly included also in the full-
335 fledged pioneering modeling work targeting *Alexandrium fundyense* in the Gulf of Maine
336 (McGillicuddy et al., 2008). DVM of *A. fundyense* was observed in the laboratory and a
337 salt pond, but not in the ocean (Anderson and Stolzenbach, 1985; Macintyre et al., 1997;
338 Townsend et al., 2005). **The dynamics of DVM remain unclear even in well-studied**
339 **harmful algae (e.g., *A. fundyense* and *K. mikimotoi*).** The continuous vertical profiling of
340 the chlorophyll fluorescence in the field and laboratory experiments using columnar
341 aquariums are effective tools for clarifying the dynamics (Koizumi et al., 1996; Shikata
342 et al., 2015; Sakaguchi et al., 2017; Yuasa et al., 2018). **Finally, it is hoped that clarifying**
343 **the dynamics of DVM will enable prediction of the development and/or decline of blooms**
344 **using real-time monitoring data.**

345

346 **5 Conclusion**

347 This study showed that the *Karenia* bloom occurring in Yatsushiro Sea in 2015,
348 which initially developed in the western and southern area, subsequently expanded to the
349 central area. Satellite detection method of *K. mikimotoi* blooms developed by a previous
350 study using Aqua/MODIS could be applied to the bloom in Yatsushiro Sea using GOCI.
351 The satellite detected bloom area matched with the field survey and complemented the
352 field survey. The sudden horizontal displacement of the bloom during mid-August was
353 driven by the wind driven surface northeastward current and modulation of DVM of *K.*
354 *mikimotoi*. The modulation of DVM was documented by the acoustic backscattering data
355 of the current meter. **The modulation possibly resulted from the continuous low nutrient**
356 **conditions.**

357

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364

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525

526 Figure captions

527 Fig. 1. Map of the study area in Yatsushiro Sea, Japan. Numbered circles and closed
528 square indicate locations of monitoring stations for the vertical profiles of the water
529 quality (Stations 1-8) and meteorological station at Minamata, respectively. At Stn. 8,
530 current velocity and backscattering intensity was observed by floating buoy.

531 Fig. 2. Spatio-temporal variation of the maximum cell density of the *Karenia mikimotoi*
532 in Yatsushiro Sea during 6 July-24 August 2015.

533 Fig. 3. Horizontal distribution of the satellite chlorophyll concentration (upper panels)
534 and detected *K. mikimotoi* bloom by GOCI (gray pixels in lower panels) during 6-15
535 August.

536 Fig. 4. Hovmoller diagram of temperature, salinity, DIN and PO₄-P at Stn. 8.

537 Fig. 5. Vertical sections of temperature (left panels) and salinity (right panels) in
538 Yatsushiro Sea during 28 July-18 August.

539 Fig. 6. Hovmoller diagram of Monod coefficient for DIN (upper panel), PO₄-P (middle
540 panel) and minimum Monod coefficient (lower panel) at Stn. 8.

541 Fig. 7. Hovmoller diagram of eastward velocity(a) and northward velocity (b) at Stn. 8.
542 Time series of wind vectors at Minamata meteorological station (c). Horizontal
543 transport distance of case a (panel d) and b (panel e).

544 Fig. 8. Hourly composite of the backscattering intensity anomaly (a) and hovmoller
545 diagram of the backscattering intensity anomaly (b) at Stn. 8 during 6-14 August. Black
546 and white bars on both graphs indicate the light-dark cycle.

547

548

Table 1. Spectral bands used for detecting the *K. mikimotoi* bloom.

Aqua/MODIS (nm)	GOCI/COMS (nm)
412	412
443	443
488	490
547	555
667	660
678	680

549

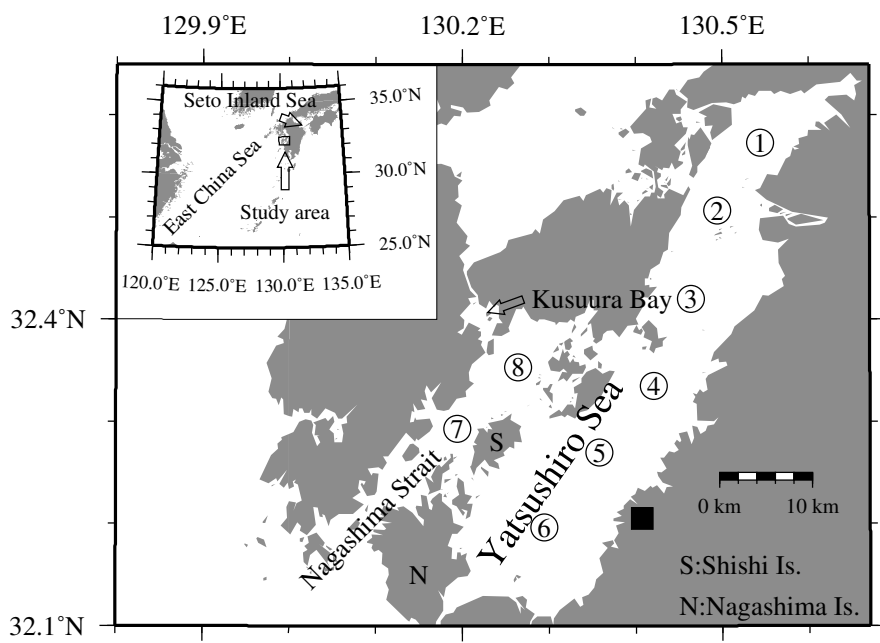


Fig.1 Aoki et al.

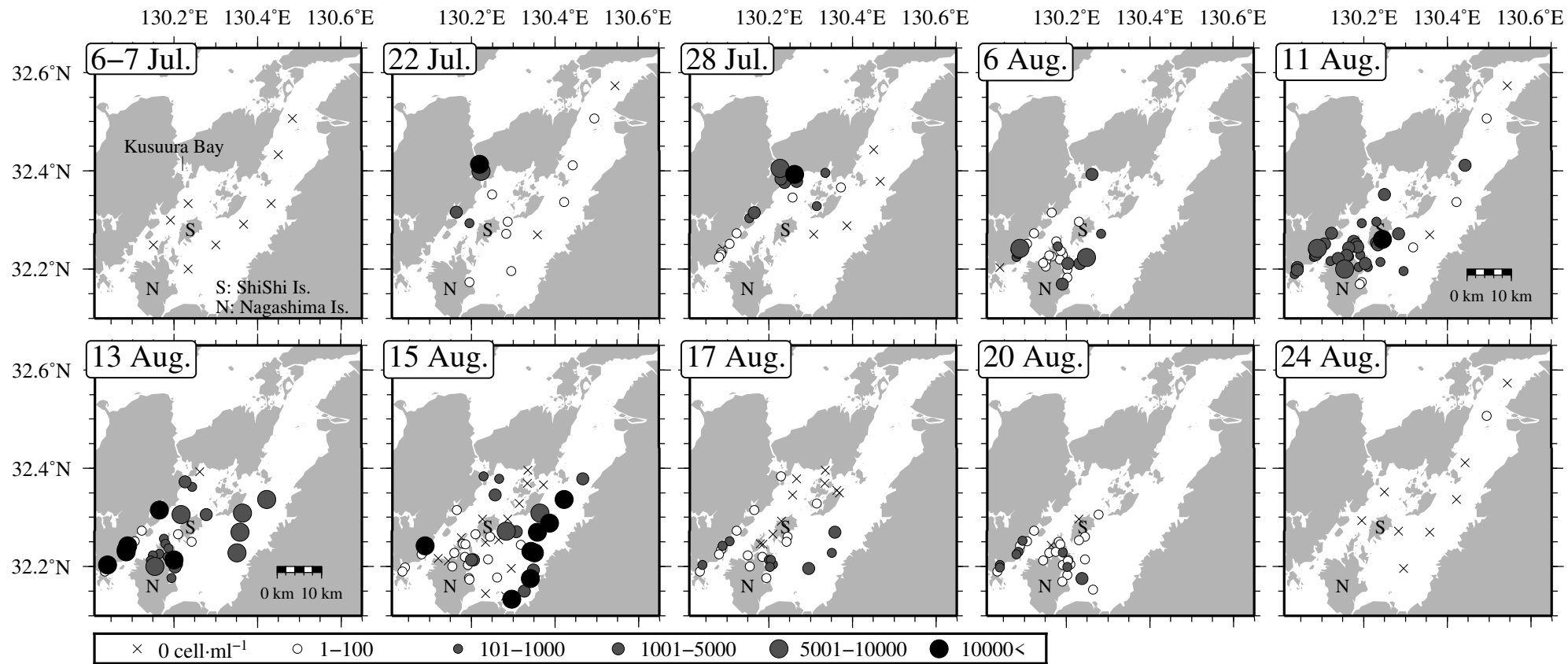


Fig.2 Aoki et al.

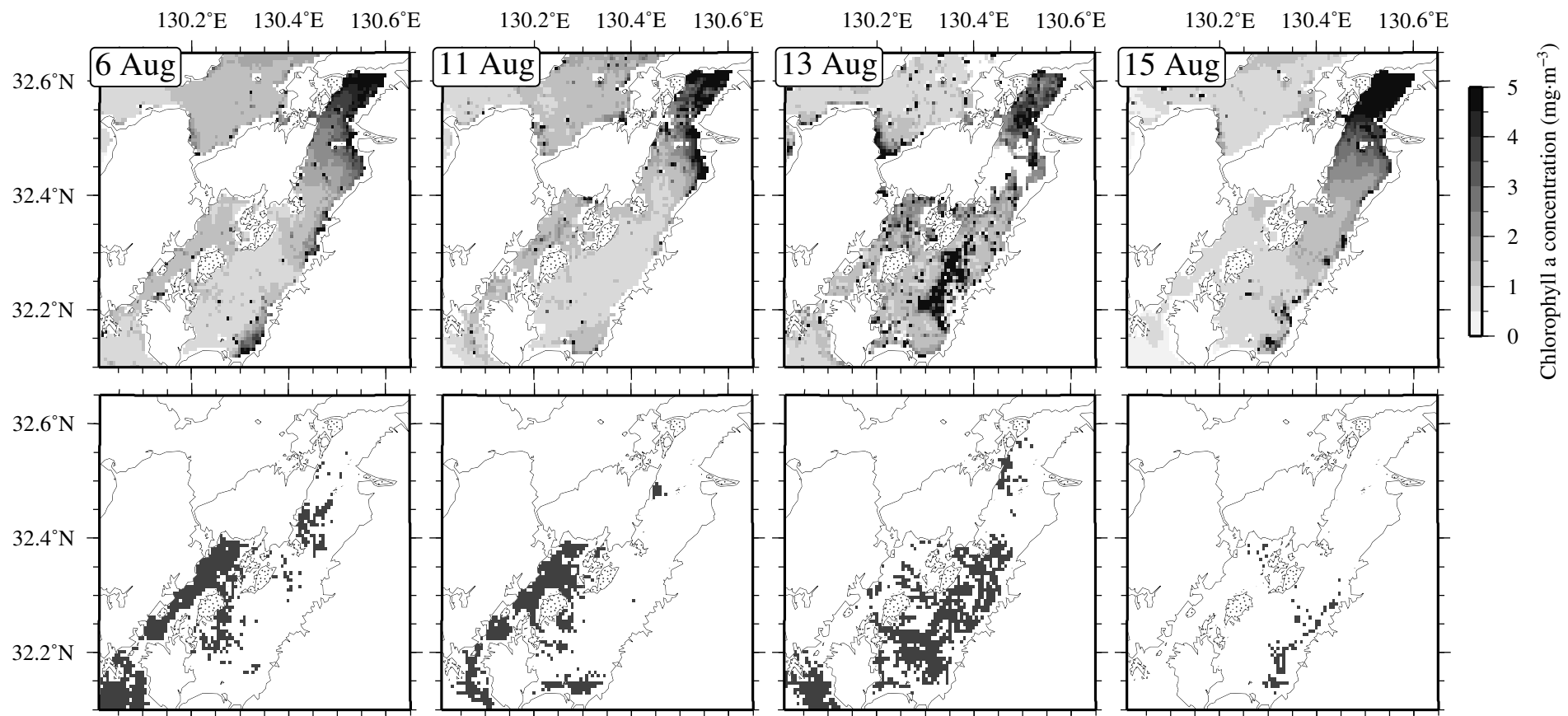


Fig.3 Aoki et al.

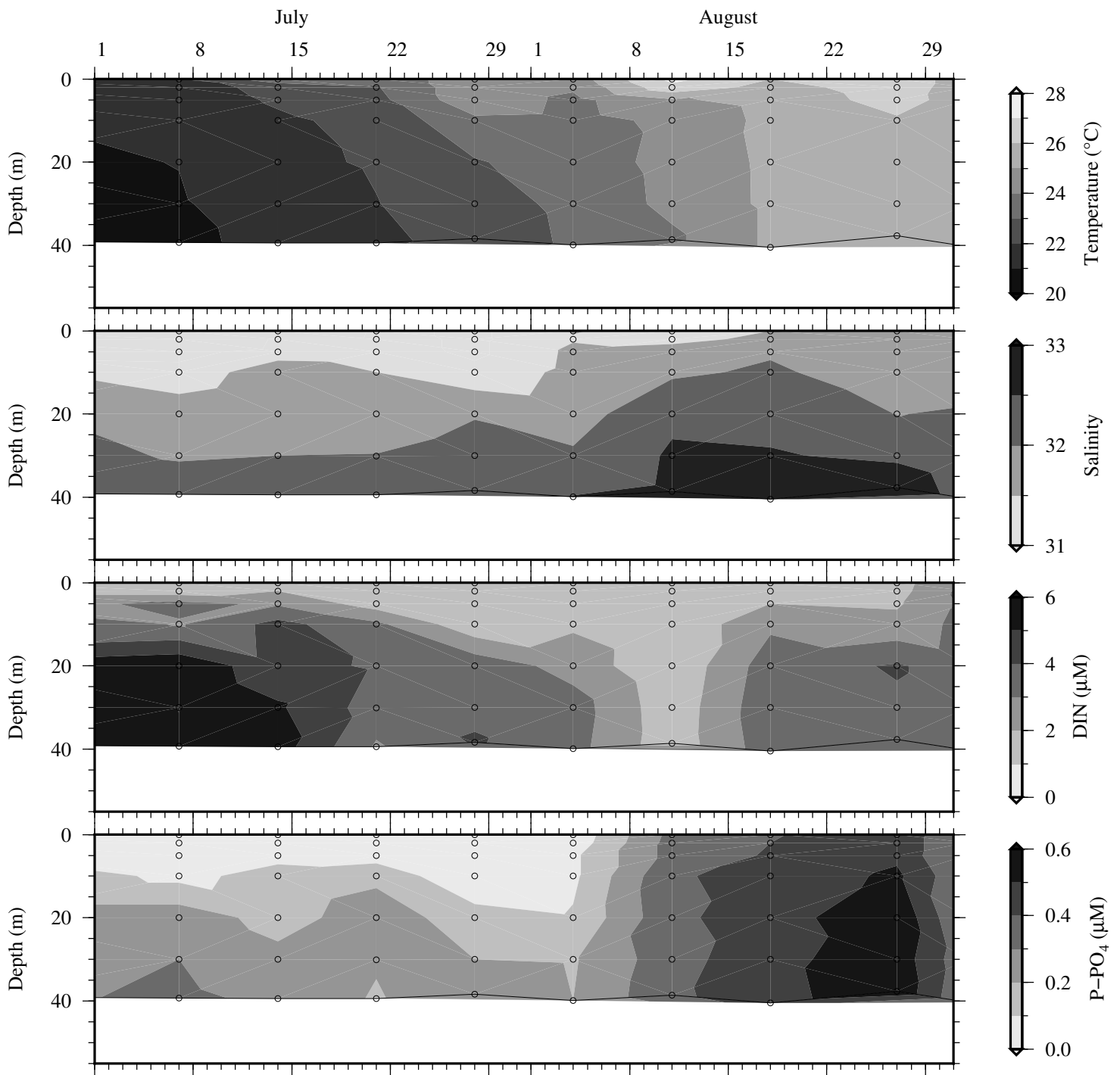


Fig.4 Aoki et al.

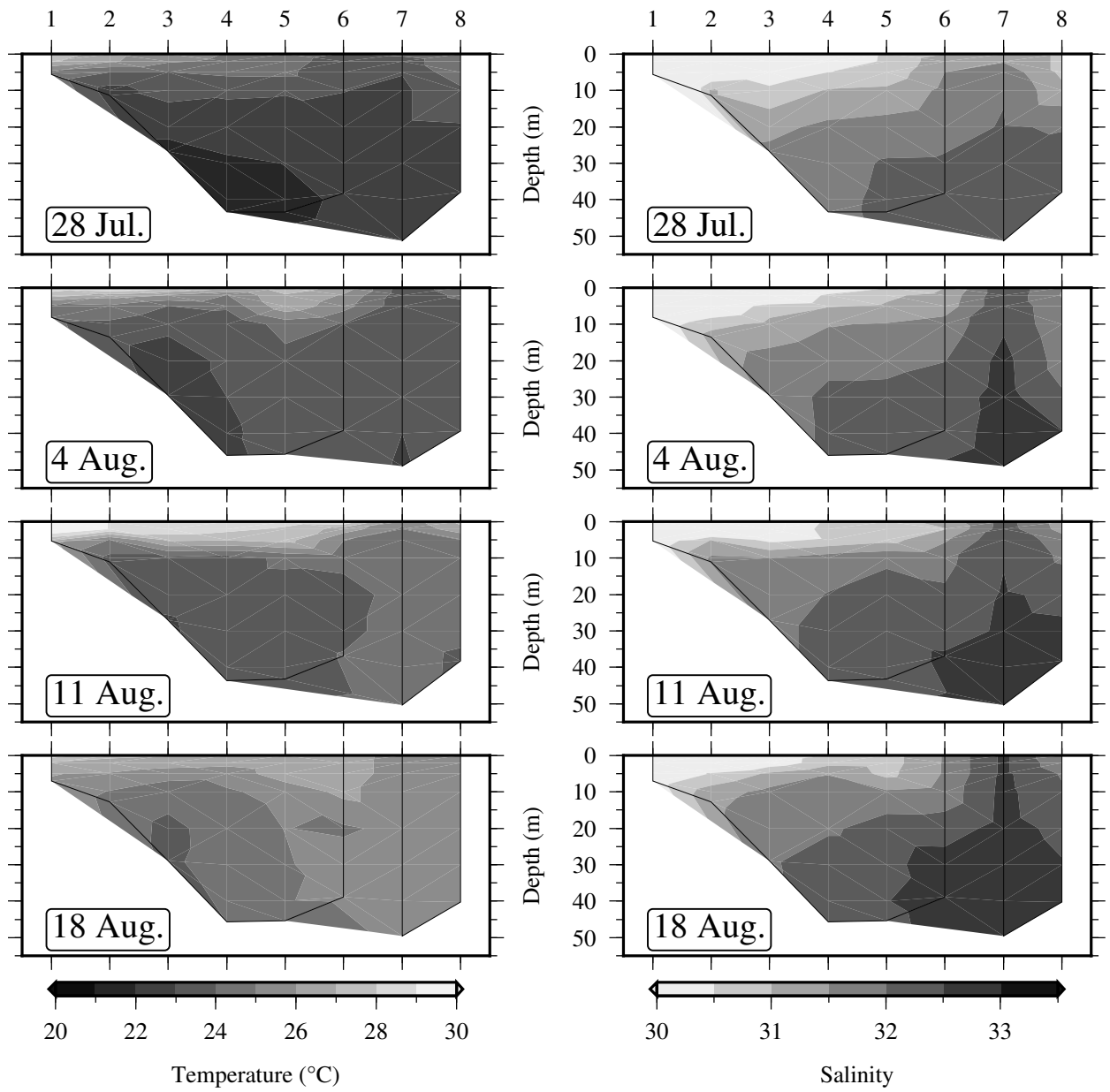


Fig.5 Aoki et al.

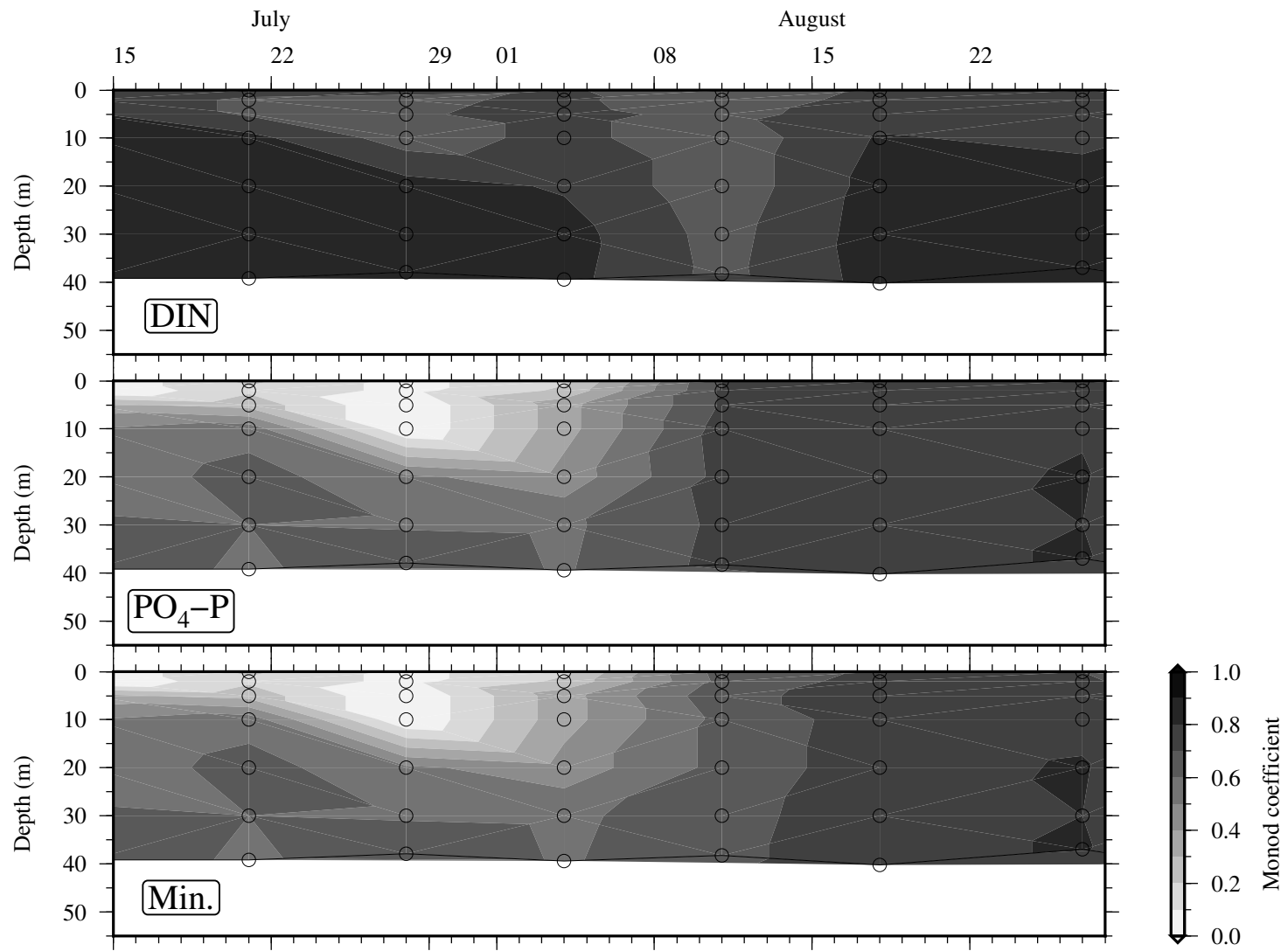


Fig.6 Aoki et al.

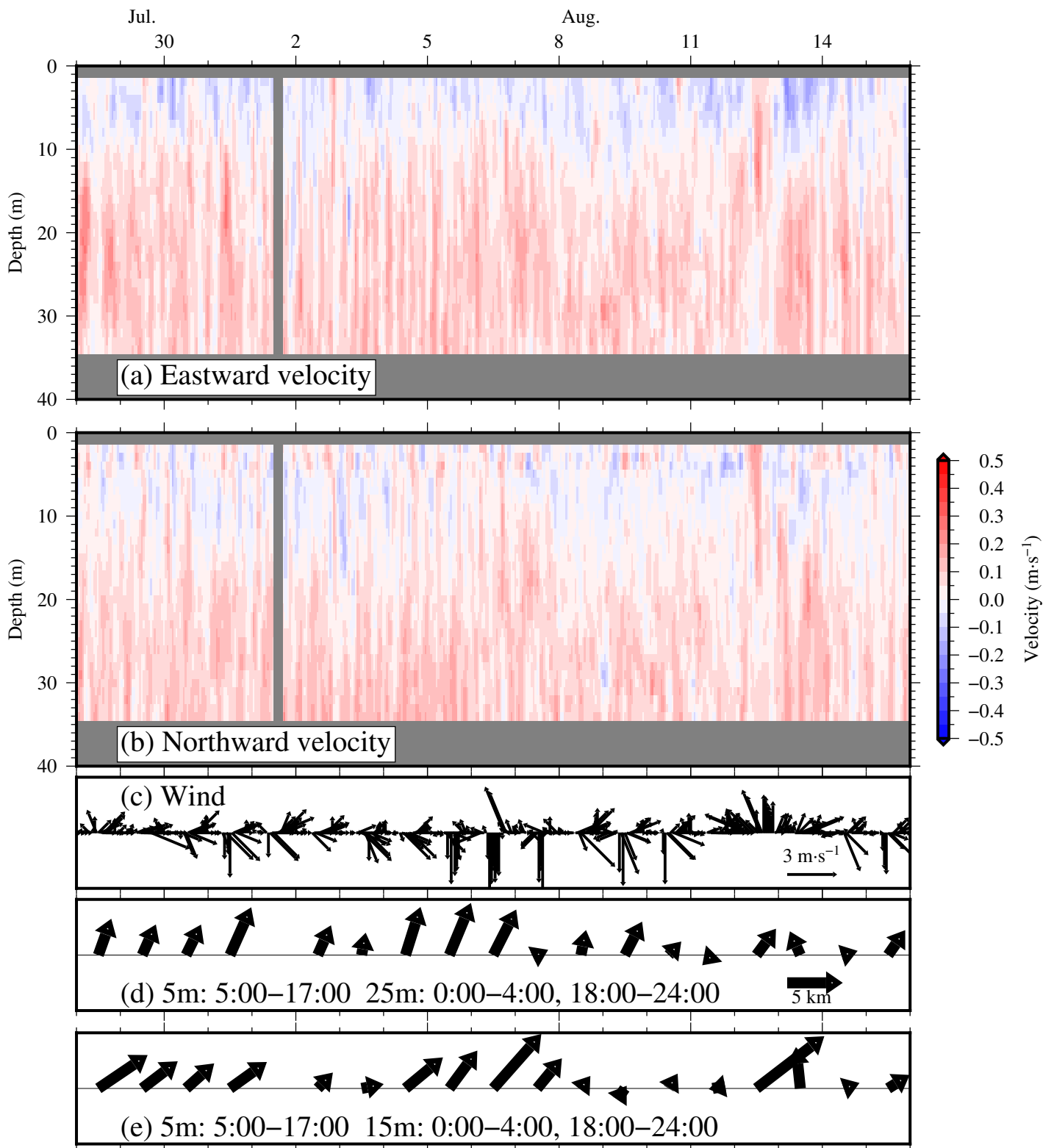


Fig.7 Aoki et al.

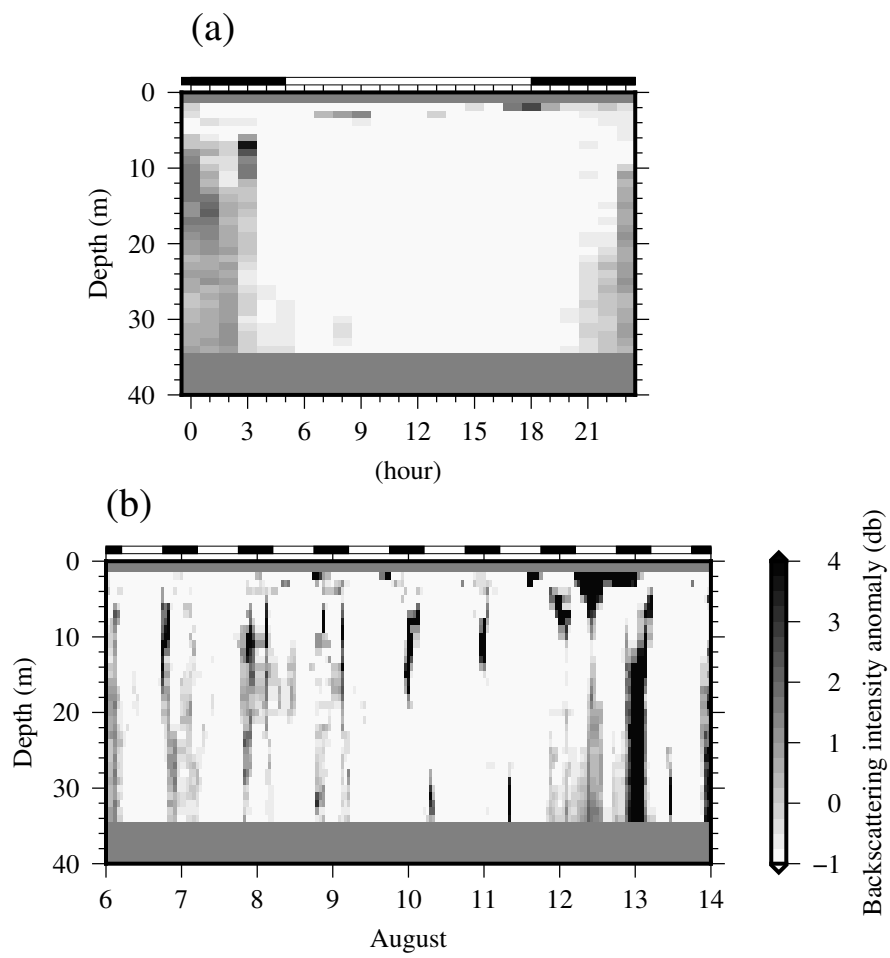


Fig.8 Aoki et al.