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Aquaculture-induced boundary circulation and its impact on coastal frontal circulation

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## Abstract

With the development of coastal suspended aquaculture industry, aquaculture facilities have extended into the open sea to depths of up to 30 m. This practice will likely affect the natural ocean circulation in such areas. For a case study in the high-density aquaculture region of the coastal Yellow Sea, an aquaculture-induced boundary circulation (ABC) is identified and its effects on the background frontal circulation and cross-shore nutrient supply are examined. The ABC is composed of a southward along-boundary current and a counterclockwise cross-boundary cell. The southward along-boundary current ( $\sim 5 \text{ cm s}^{-1}$ ) along with the natural frontal current ( $\sim 5 \text{ cm s}^{-1}$ ) forms a strong coastal current ( $\sim 10 \text{ cm s}^{-1}$ ) along 20–30 m isobaths. The counterclockwise cross-boundary cell exhibits the opposite direction to the natural clockwise cross-frontal cell in the frontal area, which reduces the cross-shore nutrient supply by nearly 25%. Our results suggest that aquaculture boundaries and densities should be considered when planning high-density aquaculture activities.

## 1. Introduction

Over recent years, aquaculture has developed into offshore area or open seas (Watson-Capps and Mann 2005, Radiarta *et al* 2008, Byron *et al* 2011, Wu *et al* 2014) where natural ocean circulation has rarely been affected by human activity. For a case study in the high-density aquaculture region of the coastal Yellow Sea, the aquaculture is developing, expanding, and intensifying in numerous coastal regions (figure 1(a), red dots). The dominant type of aquaculture in this area is suspended aquaculture, which uses net cages, ropes, or other structures suspended in the water column to cultivate aquatic organisms (Wartenberg *et al* 2017). In order to meet the increasing demand for aquatic food products, high-density aquaculture facilities have been expanded into the open sea to depths of up to 30 m, thus broadening the range of aquaculture activities, which were previously restricted to intertidal mudflats or bays. As such, aquaculture facilities are clearly visible in satellite images (e.g., Google Maps); for example, the aquaculture facilities (figure 1(a), red rectangle). Previous studies have noted that suspended aquaculture acts as a physical barrier and significantly reduces the ocean currents passing through an aquaculture area (Gibbs *et al* 1991, Boyd and Heasman 1998, Grant and Bacher 2001, Pilditch *et al* 2001, Shi *et al* 2011). However, the impact of suspended aquaculture on coastal circulation and nutrient supply following the expansion of high-density aquaculture facilities into open seas remains unclear.





frontal circulation.

Frontal circulation has been investigated as the major dynamic in near-coastal areas (Simpson and Hunter 1974, Garrett *et al* 1978, Griffiths *et al* 1981, Van Heijst 1986, Loder *et al* 1993). In general, frontal circulation is composed of an along-frontal current on the shallow side of front and a clockwise cross-frontal cell in the middle shelf (Tee 1985, Dong *et al* 2004). Figure 1(c) illustrates the generation of frontal circulation. A frontal zone frequently occurs in near-coastal areas during the warm season, mainly because of frontogeneses induced by tides and wind (Simpson and Hunter 1974, Lü *et al* 2010). The frontal zone can be characterized as a narrow transition region that separates the cold stratified water on the offshore side from the warm, well-mixed, shallow water on the coastal side. Then, an along-frontal current is generated according to the thermal wind relationship. Because of frontal instability, a clockwise cross-frontal cell is initiated by ageostrophic adjustment,



which tries to re-stratify the frontal structure by collapsing the near-vertical isopycnals. This clockwise crossfrontal cell includes upward vertical velocities on the light (warm) side and downward vertical velocities on the heavy (cold) side. Since the vertical velocity in the ocean is on the order of  $10^{-3}$  cm s<sup>-1</sup>, it is difficult to make direct measurements of the weak cross-frontal cell. Alternatively, numerical models have been widely employed to quantitatively study the clockwise cross-frontal cell (Garrett and Loder 1981, James 1984, Van Heijst 1986, Su and Huang 1995, Dong *et al* 2004, Lü *et al* 2010).

Both satellite observations and numerical models have identified a noticeable tidal mixing front in 20–50 m isobaths near the Lunan Coast (Lie 1986, Liu *et al* 2003, Lü *et al* 2010). Because this aquaculture area has been expanded to the 30 m isobath and has a crossover to the frontal zone, it probably affects background currents such as frontal circulation. As depicted in figure 1(b), a strong southward current, as observed by high-frequency ground wave radar, occurs outside the boundary of the kelp monoculture area. This enhanced current may be very different from the natural frontal circulation. The influence of suspended aquaculture on currents and water exchange inside the aquaculture area has been well-studied (Grant and Bacher 2001, Fan *et al* 2009, Shi *et al* 2011, Zeng *et al* 2015). However, there is no relevant research on the entire frontal circulation following the development of high-density aquaculture. This is especially true for the boundary of the aquaculture region, even though boundary circulation may be of particular importance in relation to coastal water exchange and nutrient supply. Therefore, in the present work, a high-resolution model was established to explore the influence of aquaculture on frontal circulation.

#### 2. Methods

#### 2.1. Model configurations

In order to simulate the extended aquaculture area and its impact on coastal circulation, the Finite-Volume Coastal Ocean Model (Chen *et al* 2003) was used to establish high-resolution simulations inside the aquaculture area and external forces outside the aquaculture area. Previously, a large-domain simulation (figure 2(a)) was successfully conducted for the entire coastal China Sea, part of the Japan/East Sea, and part of the Pacific Ocean (Xuan *et al* 2016, Xuan *et al* 2017). In all, 20 vertical layers were specified in the water column in a sigma-stretched coordinate system. The topography of the large domain was obtained from the General Bathymetric Chart of the Oceans, with a resolution of  $0.5' \times 0.5'$ . Key tides were derived from the Oregon State University global inverse tidal model TPXO.7.0 (Egbert *et al* 1994, Egbert and Erofeeva 2002). The three-hourly wind stress and 10 m wind speed data were obtained from the ERA-Interim re-analysis and the daily mean heat fluxes were based on objectively analyzed air–sea fluxes (Yu and Weller 2007). Open boundary conditions, including daily temperature, salinity, and fluxes, at the Taiwan Strait, the western Pacific Ocean, and the Japan/East Sea, were obtained from the Hybrid Coordinate Ocean Model (Bleck 2002) and interpolated onto the model grid points.

Based on the above large-domain simulation, the model resolution was further improved in the aquaculture area (figure 2(b)). In the Sanggou Bay and its adjacent area (36.95°-37.25 °N, 122.4°-122.75 °E), the model resolution was increased to 50–200 m inside the Sanggou Bay and to approximately 400 m near the aquaculture boundary. A recent sea map with a resolution of 100 m, provided by the Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, was used to supplement the bathymetry in Sanggou Bay. Two types of drag were also added in the aquaculture area: a surface stress brought about by the facilities and a body force caused by kelp (Shi *et al* 2011). The surface stress was parameterized as  $\vec{\tau} = \rho C_{ds} |\vec{U}_s|$ , where  $\rho$  is the water density,  $\vec{U}_s$  is the surface velocity, and  $C_{ds}$  is the averaged surface drag coefficient.  $C_{ds}$  is derived by fitting the vertical profiles of tidal current observed in April 2011; it is in the range 1.5  $\times$  10<sup>-4</sup>–2.5  $\times$  10<sup>-1</sup>. Such an approach has been commonly used in previous studies (Fan et al 2009, Shi et al 2011, Lin et al 2016). A parameterization of the drag per plant, as proposed by Jackson and Winant (1983), was used in the form  $D_0 = C_d \rho u^2 dl$ , where l and d is the length and diameter of the kelp; u is the ambient velocity; and  $C_d$  is the drag coefficient (approximately 0.5 for flow perpendicular in a cylinder) (Batchelor 2000). Based on statistics of kelp in Sanggou Bay, provided by the Yellow Sea Fisheries Research Institute, the term *l* was linearly increased from 1.8 m at January 01, 2011 to 2.7 m at April 30, 2011 and maintained with 2.7 m until the kelp was harvested at June 30, 2011. The term *d* was linearly increased from 0.25 m at January 01, 2011 to 0.42 m at June 30, 2011. The kelp density in Sanggou Bay was about 12 individuals per square meter. The surface stress was applied throughout the whole year and kelp-induced body forces were applied during the kelp growth period.

Since the currents and temperature in 2011 could partly be validated by means of available observational data (see figure 1(b) and section 2.3), the hindcast outputs of sea surface height, temperature, salinity and velocities for the simulation of 2011 are used, following three spin-up years (2008–2010) initiated with the temperature and salinity taken from the Hybrid Coordinate Ocean Model and velocity set to zero. Because of the high model resolution in aquiculture area, the model time step was reduced to 4 s for the 2D barotropic mode





and 8 s for the 3D baroclinic mode. Based on the kelp cultivation period, the model output from January to May 2011 was used for further analysis.

#### 2.2. Model experiments

Four experiments were carried out to investigate the relative importance of tides, wind, and aquacultureinduced friction on the circulations. A model under natural conditions with tides and wind was firstly set up; this was termed the tides and wind experiment (TWE). An experiment considering aquaculture-induced friction was termed the tides, wind, and kelp experiment (TWKE). To distinguish the contributions of tides and wind, we performed further experiments without wind in comparison with TWE and TWKE; these were termed the tide experiment (TE) and the tide and kelp experiment (TKE).

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#### 2.3. Validation of tidal currents and temperature

Because tidal currents are the major dynamic factor affecting mixing, frontal circulation, and water exchanges in the research area (Liu *et al* 2003, Lü *et al* 2010), the simulated tidal currents in TWKE using long-term mooring observations were first validated. The observations included 16 stations dispersed on the continental shelf (figure 2(c), red ellipses) and 8 stations inside the aquaculture area (figure 2(d), red ellipses), which are operated by the Second Institute of Oceanography, Ministry of Natural Resources. All tidal currents were depth-averaged, with integration over the entire water column. Tidal harmonic constants of the  $M_2$  constituent were analyzed because of its dominance in the model domain. The results of the comparison, as indicated in figures 2(c) and (d), suggest a generally satisfactory reproduction of the  $M_2$  tide in both the continental shelf and the aquaculture area.

Simulated sea surface temperature (SST) in April was further validated with a composite satellite image, which was derived from the Daily Sea Surface Temperatures product provided by Japan Meteorological Agency (Guan and Kawamura 2004). Both the observed and simulated SST shows a low temperature (<10 °C) patch situated in near coast areas (figure 3), which suggests that our simulation could well reproduce the temperature structure and its related dynamics in frontal area.

## 3. Results

#### 3.1. Frontal circulation in natural conditions

The TWE results show that the frontal circulation structure mainly has two components: an along-frontal current (figure 4(a)) and a clockwise cross-frontal cell (figure 5(a), vectors), which is in agreement with the previous studies (Van Heijst 1986, Dong *et al* 2004). Both the along-frontal current and the clockwise cross-frontal cell are located in the frontal zone between the 10–50 m isobaths. The along-frontal current always has a southward direction, and its magnitude (figure 5(a), blue color) rapidly weakens from 5 cm s<sup>-1</sup> in the surface layer to 1 cm s<sup>-1</sup> at the bottom in section A. Upwelling appears on the inshore side of the front and a large value of  $2 \times 10^{-3}$  cm s<sup>-1</sup> (figure 5(b), red curve) extends from the bottom of the 30 m isobath to almost the surface of the 10 m isobath.

The along-frontal current is mainly affected by the geostrophic effect and is constrained by the thermal wind relationship, as indicated by Van Heijst (1986). Temperature in the shallow water is vertically uniform owing to strong tidal mixing, and it is higher than the temperature in the stratified deep water (figure 5(b), color). The isostatic surface on the nearshore side is elevated; therefore, the thermal wind effect stimulates a southward current along the tidal mixing front. The unstable temperature structure shown in figure 5(b) has a tendency to collapse offshore and result in restratification; hence, strong upwelling (>2 × 10<sup>-3</sup> cm s<sup>-1</sup>) appears between the 10 m and 30 m isobaths.

#### 3.2. Circulation induced by aquaculture

The TWKE results indicate that kelp cultivation has a significant effect on both the circulation (figures 4(c) and 5(c)) and the temperature structure (figure 5(d)). First, the difference between TWE and TWKE (figures 4(e) and





**Figure 4.** Sea surface currents and height anomalies for (a) and (b) the TWE, (c) and (d) the TWKE, and (e) and (f) their difference. All the data are monthly averaged in April. The blue curve shows the boundary of the kelp monoculture area. Section A is a representative section across the frontal area. Area A is a representative area affected by aquaculture.

5(e)) shows that the southward current near the aquaculture boundary is enhanced, with a magnitude of  $3-6 \text{ cm s}^{-1}$  on average. Second, there is a counterclockwise cross-boundary cell around the aquaculture boundary, with its magnitude exceeding the clockwise cross-frontal cell (figure 5(e), vectors). Consequently, the upwelling structure in TWE (figure 5(b), red curve) is detached by a downwelling (figure 5(d), the middle blue curve) on the inshore side of the aquaculture boundary. Third, the near-coast temperature (figure 5(f), inshore side of 10 m isobath) becomes higher because the cold-water supply from upwelling is probably restrained. The temperature becomes lower above the thermocline but higher under the thermocline (figure 5(f), around the aquaculture boundary), which is affected by the counterclockwise cross-boundary cell around the aquaculture boundary.

Since kelp cultivation mainly affects circulation near the aquaculture boundary, we term the change (figures 4(e) and 5(e)) as the aquaculture-induced boundary circulation (ABC). The ABC consists of a southward along-boundary current and a counterclockwise cross-boundary cell. Sea surface height on the inshore side of the aquaculture boundary is much higher than that on the offshore side (figure 4(f)) because of the strong friction in the aquaculture area, suggesting that there is a water converge on the inshore side of the aquaculture boundary. This water converge consequently drives the counterclockwise cross-boundary cell (figure 5(e)) around the aquaculture boundary.



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and blue curves in panels (b), (d), and (f) show the vertical velocity contours of  $2 \times 10^{-3}$  and  $-2 \times 10^{-3}$  cm s<sup>-1</sup>, respectively. The black line shows the boundary of the kelp monoculture area.

#### 3.3. Variations in the frontal circulation and the ABC

In order to quantify the frontal circulation and the ABC, we used meridional velocity (V) and meridional vorticity ( $\Omega_y = \partial U/\partial z - \partial 10^6 W/\partial x$ , where the W and U are vertical and zonal velocities respectively) to estimate currents and cross-shore cells induced by the frontal circulation and the ABC. The frontal circulation with negative V and negative  $\Omega_y$  (figure 6(a)) and the ABC with negative V and positive  $\Omega_y$  (figure 6(c)) are well simulated under the tidal effect, while under the wind effect, both two circulations (figures 6(b), (d) and (f)) show intra-seasonal oscillations and could be neglected in seasonal mean. Therefore, the tidal-induced frontal circulation and ABC will be focused for further studies.

Tidal-induced frontal circulation (figure 6(a)) shows that the southward along-frontal current and clockwise cross-frontal cell are generally prominent across entire seasons and vary with neap-spring cycles. Both the two components gradually becomes stronger from winter to spring, which probably follows an enhancement of the coastal front. The intra-seasonal variations of the two components are almost opposite of one another, indicating that the strengthening of the clockwise cross-frontal cell (figure 6(a), red curve) originates from a weakening of the tidal currents as well as tidal mixing. This verifies that the clockwise cross-frontal cell arises from baroclinic instability (Lü *et al* 2010).

The tidal-induced ABC (figure 6(e)) shows that both the along-boundary current and counterclockwise cross-boundary cell are strong most of the time. The ABC is enhanced in spring because the kelp is mature and friction is increased. In May, the counterclockwise cross-boundary cell (figure 6(d), red curve) becomes stronger than the natural circulation of the clockwise cross-frontal cell (figure 6(d), red curve), indicating that the current aquaculture density is sufficiently high to disrupt the background circulations.

#### 4. Discussion

A matter of great concern in the current aquaculture industry is that its density has reached such a high level that the supply of nutrients is insufficient. For example, in kelp cultivation in the coastal Yellow Sea, inorganic nitrogen is a major factor controlling kelp growth (Shi *et al* 2010). Zhang *et al* (2010) indicated that nitrate from





**Figure 6.** Meridional velocities (V, blue curves) and meridional vorticities  $(\Omega_y = \partial U/\partial z - \partial I0^0 W/\partial x, \text{ red curves})$  under conditions of TE (a), TWE-TE (b), TKE (c), TWKE-TKE (d), TKE-TE (e) and (TWKE-TKE)-(TWE-TE) (f). All the data are spatially averaged in Area A (finger 4e, black rectangular).

the open sea is the most important component of inorganic nitrogen in Sanggou Bay. Since a significant reduction in horizontal currents was observed in early studies (Zhao *et al* 1996, Sun *et al* 1998, Shi *et al* 2010), it was concluded that the weakening of circulations inside an aquaculture area generally obstructs the supply of nutrients. According to the above studies, aquaculture density is the major factor affecting nutrient supply. However, Zeng *et al* (2015) pointed out that kelp aquaculture has little effect on the total water exchange because enhanced transport in bottom layer compensates for the weakened transport in the upper layer. Our results further show that the ABC in the aquaculture boundary reduces natural upwelling, which indicates another potential mechanism to explain nutrient deficiency in the aquaculture area.

In order to demonstrate the connection between the ABC and nutrient deficiency in the aquaculture area, we set up three nitrate tracing experiments driven by TWKE, TWE, and TKE. The initial nitrate condition was set to approximately zero inside the aquaculture area and to 20  $\mu$ mol l<sup>-1</sup> outside the aquaculture area (figure 7(a)). After 15 days of tracing, the nitrate was transported into the aquaculture area in all three experiments but in different quantities. In TWKE (figure 7(b)), the simulated nitrate distribution is similar to the survey results (figure 7(a), black contours), especially the result that high concentrations (>15  $\mu$ mol l<sup>-1</sup>) of nitrate are limited to the area outside of the Sanggou Bay. The high nitrate concentration water is detached from the aquaculture boundary, which demonstrates that the ABC plays an important role in nitrate supply. Without the effect of the ABC in TWE (figure 7(c)), the high nitrate concentrations distribute more widely in the southeast of Sanggou Bay. In comparison with the total nitrate in the aquaculture area between TWKE and TWE, the ABC reduced the nitrate supply by approximately 25%. In addition, comparison between TWKE (figure 7(b)) and TKE (figure 7(d)) shows that the nitrate concentration distribution changes little when there is no wind, indicating that the wind has only a small effect in the aquaculture area.

Since the ABC can reduce the nitrate supply in the aquaculture area, the relative importance between the ABC and frontal circulation should be quantified when planning aquaculture regions and their density. There are two essential conditions under which the ABC could affect the frontal circulation: (i) where the boundary of the ABC is close to the frontal area and (ii) where the strength of the ABC is comparable with the frontal circulation. The location of the frontal circulation can be determined by the tidal mixing area, which varies based







on the conditions of the tidal currents, surface heat, and momentum fluxes in the coastal area (Simpson and Hunter 1974). In our research area, the frontal zone is approximately located between the 10 and 50 m isobaths (Zhao 1987); therefore, the ABC, which is located around the 20 m isobath in the coastal Yellow Sea, will inevitably interact with the frontal circulation.

Even though the magnitudes of the ABC and frontal circulation are difficult to observe, except through numerical simulations, we have roughly approximated the relative magnitude of the two circulations through the surface southward currents. Both the underwater counterclockwise cross-boundary cell and the southward along-boundary current in the ABC are enhanced with an increase in aquaculture density (figure 6(e)), indicating that the two components in the ABC exhibit a strong relationship. Furthermore, the ABC induced counterclockwise cell overcomes the clockwise cell in frontal circulation (figure 6(c), red curve) when the southward current is much enhanced from April to May with the growth of kelps, suggesting that there is a critical value of the southward current to estimate the relative magnitude of the two circulations. In this work, the ABC became dominated when the surface southward along-boundary current reached 5 cm s<sup>-1</sup> (figure 5(e)) or the total southward current exceeded 10 cm s<sup>-1</sup> (figure 6(c)). This southward along-boundary current induced by bottom friction. Because tidal mixing fronts generally occur on continental shelves worldwide, such as the Gulf of Maine (Garrett *et al* 1978) and Hudson Bay in Canada (Griffiths *et al* 1981), the environmental effect of the ABC should be carefully considered when planning high-density aquaculture activities.



## 5. Conclusions

High-density aquaculture generates an ABC, which has two components: a southward along-boundary current and a counterclockwise cross-boundary cell. The southward along-boundary current ( $\sim 5 \text{ cm s}^{-1}$ ) along with the natural frontal current ( $\sim 5 \text{ cm s}^{-1}$ ) forms a strong coastal current ( $\sim 10 \text{ cm s}^{-1}$ ) along 20–30 m isobaths. The counterclockwise cross-boundary cell overcomes the natural clockwise cross-frontal cell with the growth of kelps in April and May. Strong friction in the aquaculture area ensures that water converges on the inshore side of the aquaculture boundary, which consequently drives the counterclockwise cross-boundary cell around the aquaculture boundary.

The ABC plays an important role in the cross-shore nutrient supply from the open sea to the aquaculture area. Owing to the interruption of the frontal circulation induced upwelling on the inshore side of the aquaculture boundary, the ABC reduces nutrient supplies in the aquaculture area by approximately 25%. These results suggest that the location of the aquaculture boundary should not be close to the frontal area when the magnitude of the ABC is comparable with the frontal circulation.

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