

Rapid changes in the near-bottom temperature of the bottom aquaculture area around the Zhangzi Island in summer

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Abstract

Rapid changes in the near-bottom water temperature are important environmental factors that can significantly affect the growth and development of species in the bottom culture. The object of this research is to investigate the mechanism causing these rapid changes within a bottom culture area near the Zhangzi Island. The hydrographic transects observations in the North Yellow Sea (NYS) suggest that our mooring station is very close to the tidal mixing front. The horizontal advection of the tidal front has induced the observed tidal change of bottom temperature at the mooring station. Analysis of the mooring near-bottom temperature and current measurements show that the angle between the tidal current horizontal advection and the swing of the tidal front is crucial in determining the variation trend of temperature. When the angle equals 90°, the horizontal tidal current advects along the isotherms so the temperature remains the same. When the angle is between 0° and 90°, the seawater moves from deep water to the warmer coastal zone and the temperature decreases. In contrast, the horizontal tidal advection moves the coastal warm water to the mooring station and the water temperature increases when the angle is between 90° and 180°. The amplitude of the temperature change is proportional to the magnitude of the horizontal temperature gradient and the tidal excursion in the direction of the temperature gradient. This study may facilitate the choice of culture area in order to have a good aquaculture production.

Key words: near-bottom temperature, horizontal advection, tidal mixing front, bottom culture area, Zhangzi Island

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1 Introduction

As marine-capture fishery production has been fully exploited since the late 1980s, aquaculture is now essential for meeting the great human demand for fishery products (FAO, 2018). Among the various aquaculture methods, bottom culture is widely accepted as it is environmentally sustainable (Pauly and Zeller, 2017). The region surrounding Zhangzi Island is now the largest Yesso scallop (*Patinopecten yessoensis*) bottom-culture farm in China (Zhao et al., 2019). However, in recent years, unexpected Yesso scallop mortalities have occurred in this bottom-culture area, which caused great economic losses during October 2014 and January 2018 (Zhao et al., 2019). The causes of scallop mortality have not been identified, but there were some suggested reasons including environmental factors or over-stocking. To investigate the possible factors that may cause the death of Yesso scallop, it is vital for us to have a deeper knowledge of the surrounding marine environment.

The water temperature is an important environmental factor that can influence all marine organisms. Many studies have demonstrated that the frequency of water temperature fluctuations can noticeably affect the respiration, excretion, and enzyme activity of shellfish (His et al., 1989; Verween et al., 2007; Rico-Villa et al., 2009; Jiang et al., 2016). Gao et al. (2017) found that fluctuations in the surrounding temperature can greatly influence the growth of scallops, and large fluctuation may even

lead to high mortality. Therefore, it is necessary to investigate the mechanisms controlling the changes of near-bottom water temperature within a bottom culture area (BCA). This is very important for us to develop a more suitable aquaculture strategy.

One important water mass that may influence the BCA (38.73°–39.36°N, 122.34°–123.45°E) near the Zhangzi Island is the North Yellow Sea Cold Water Mass (NYSCWM) that appears in summer. The 8°C and 10°C isotherms were considered to be the horizontal and vertical boundaries of the NYSCWM (Guan, 1963; Zhao, 1985). Due to tidal mixing, a tidal front that separates the NYSCWM and coastal water were generated near the coastal area, and the temperature changes rapidly in the horizontal direction within the front. The BCA around the Zhangzi Island has an average depth of 40 m lying between the NYSCWM and the coastal water. Therefore, the BCA is easily influenced by the tidal fronts as the fluctuating temperature signals appeared to be mainly caused by the tidal advection of the frontal zone (Van Haren and Maas, 1987).

To date, many studies have investigated the seasonal evolution and long-term variation of the NYSCWM and the surrounding water masses (Wang et al., 2014; Li et al., 2016). However, little attention has been paid to the relatively high-frequency (such as tidal) changes in the near-bottom temperature. Yesso scallop is a cold-tolerant shellfish that often inhabits areas with water temperatures ranging from 5 to 20°C (Yuan et al., 2010).

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Temperature changes within a short period can directly influence the growth of scallops. The rapid temperature changes induced significant increases in oxygen consumption and ammonia-N excretion rates and decreased ingestion (Jiang et al., 2016). Previous studies show that rapid temperature change could cause a high mortality rate from 13% to 33% (Gao et al., 2017). The advection of fronts by tidal currents could induce rapid temperature changes at a fixed location.

In this study, we aim to investigate the characteristics and mechanisms of the high-frequency changes of the near-bottom temperature in the BCA around the Zhangzi Island in summer. A set of 47-day mooring current velocity and near-bottom temperature observations were used in the present study. Section 2 presents the data and observation methods. The results are described in Section 3. Section 4 discusses the properties and causes of the rapid changes in the near-bottom water temperature. Section 5 presents the conclusions.

2 Data and methods

Station ZZD (39.02°N, 123°E) includes a bottom mooring frame that carries an upward-facing 300 kHz Acoustic Doppler Current Profiler (ADCP, RDI 300 K) and a conductivity-temperature-depth sensor (CTD, RBR 420) (Fig. 1). The water depth at Station ZZD is approximately 38 m. Mooring measurements were collected from July 10 to August 26, 2017. The ADCP measures the velocity with a vertical interval of 2 m and the sampling frequency of 15 s and also measures the temperature every 15 s. The

data were averaged over 10 min in the following analysis to minimize the noise level. The ADCP measures a depth range from 4.42 m above the bottom (mab) to approximately 4 m below the sea surface, covering approximately 84% of the water column.

We intended to use the RBR 420 to measure the near-bottom water temperature and salinity at 0.75 mab. However, the device failed to record data after August 4 owing to the low battery. Therefore, in the following analysis, the temperatures measured by the ADCP are used, which was calibrated with the temperatures measured by the RBR 420. The two measurements exhibited a high linear correlation ($R^2 = 0.99$), and the linear-regression results are shown in Fig. 2.

Four hydrology transects were carried out with a calibrated CTD (RBR 620) onboard the R/V *Dongfanghong 2* from September 10 to 12, 2017. RBR 620 was used to measure the vertical temperature and salinity profiles at every transect station with a sampling rate of 6 Hz. The measurements for each profile were then averaged into 0.2 m bins. The transect observations were plotted to help understanding the surrounding hydrological conditions (Fig. 3).

3 Results

3.1 Spatial distribution of temperature and salinity

Figure 3a shows the horizontal distribution of the near-bottom temperature (4 mab). The low-temperature zone is located in the middle of the trough, where the depth is greater than 60 m.

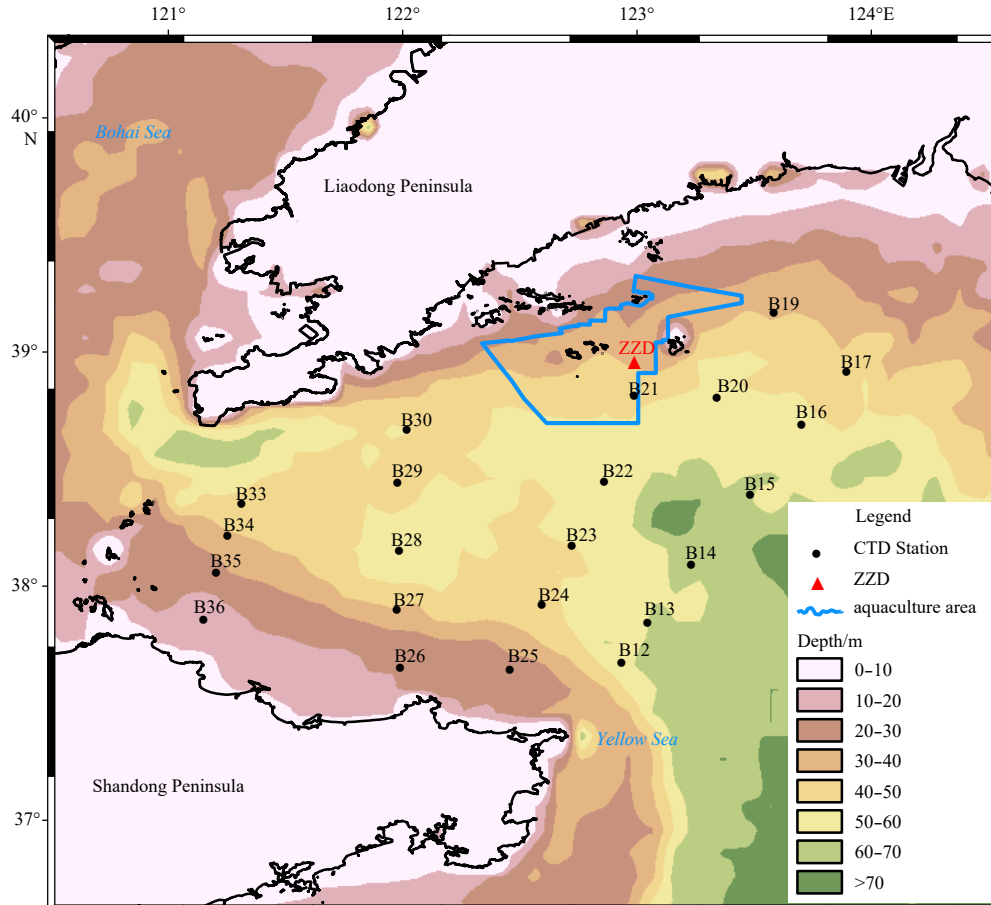


Fig. 1. Topography of the NYS with the mooring location of ZZD (red triangle) from July 10 to August 26, 2017, the CTD survey stations (black dots) during a cruise in the NYS from September 10 to 12, 2017, and the extent of the aquaculture area (blue line).

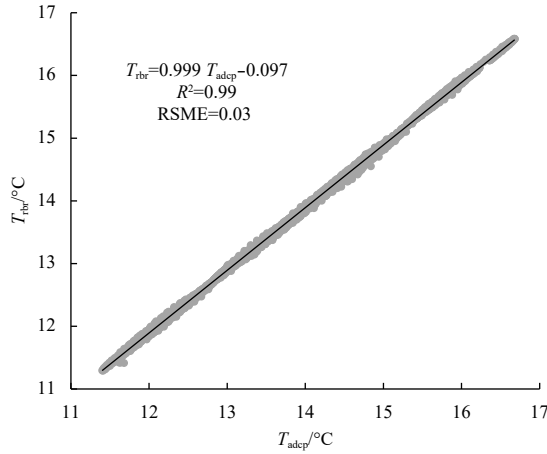


Fig. 2. Linear regression of the temperatures measured by AD-CP (horizontal axis) and RBR (vertical axis) from July 10 to August 4, 2017.

This is consistent with previous observational results (Weng et al., 1989). The lowest temperature is 7.2°C occurring at station B29. Figure 3b shows a cross-section of the temperature distribution. The section from B25 to B19 is a typical north-south section that can reflect the features at Station ZSD. The main thermocline appears between 20 and 25 m. The distribution of salinity (Figs 3c, d) generally coincides with temperature, with the

highest salinity 32.3 also appearing at B29. This reflects the low temperature and high salinity feature of the NYSCWM.

Near the coastal zone, tidal fronts are typically formed between the coastal waters where tidal mixing is strong, and the inner stratified areas where tidal mixing is weak (Simpson and Hunter, 1974). Figures 3b, d show that tidal fronts are formed at the northern and southern edges of section B19–B25. Station B21, near the BCA, is mainly located near the 17°C isotherm, which was the boundary between the NYSCWM and surrounding water masses (Zhao, 1985).

Although there are several criteria for determining the location of tidal fronts, the most widely used one was the Simpson-Hunter (SH) parameter (Simpson and Hunter 1974), which is defined as

$$SH = \log_{10} \left(\frac{H}{U^3} \right), \quad (1)$$

where U is the averaged velocity speed over a period of 25 h in spring tides and H is the water depth. The frontal area is defined when the SH parameter is around 1.8–2.0 (Simpson and Hunter, 1974). Previous studies have shown that the SH number around ZSD is about 2.2–2.8 which is within the tidal front area in NYS (Zhao, 1985; Wei et al., 2003; Huang et al., 2011). The calculated SH parameter at our mooring station is 2.33–2.61 which is close to the typical value as estimated for the front region. It is shown that the study area in the transitional zone between the tidal mix-

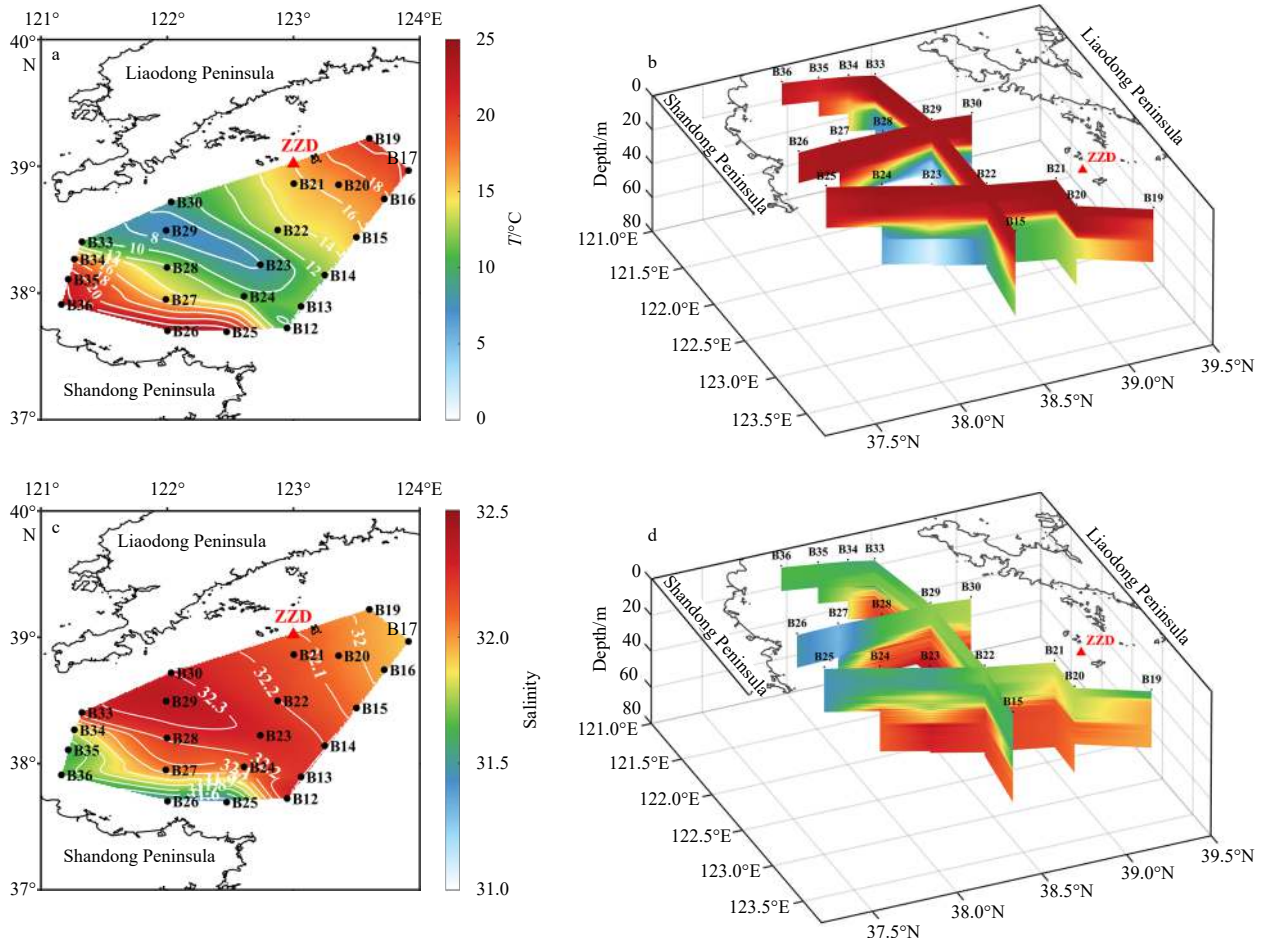


Fig. 3. Horizontal distribution of the temperature (a) and salinity (c) at 4 mab in the NYS; and spatial distribution of the temperature (b) and salinity (d) along four transects: B19–B25, B26–B30, B33–B36, and B15–B33.

ing zone and the stratification zone (Zhao, 1985). Therefore, our mooring station ZZD within the BCA can be affected by the tidal mixing fronts.

3.2 Mooring observation

3.2.1 Near-bottom temperature changes

Figure 4a shows the temporal variation of the near-bottom water temperature which exhibits a warming trend. Besides this long-term trend, the temperature also shows clear high-frequency variations in the tidal cycle. As shown in Fig. 6d, the high-frequency variations mainly consist of the contributions from the diurnal and semidiurnal variations. The amplitudes of the high-

frequency variations in the near-bottom temperature vary with time. The amplitude was high (1.5°C) during August 10–15 and small at July 20. To study the high-frequency variations in detail, we calculated the near-bottom water temperature variation parameter following Li et al. (2016):

$$T' = \sqrt{\frac{(t - t_{2-})^2 + (t - t_{1-})^2 + (t - t_{1+})^2 + (t - t_{2+})^2}{4}}, \quad (2)$$

where t_{2-} , t_{1-} , t_{1+} and t_{2+} are the temperature values at time intervals before (–) and after (+) time t , and the time interval is 10 min. This parameter indicates the degree of variation in the temperature.

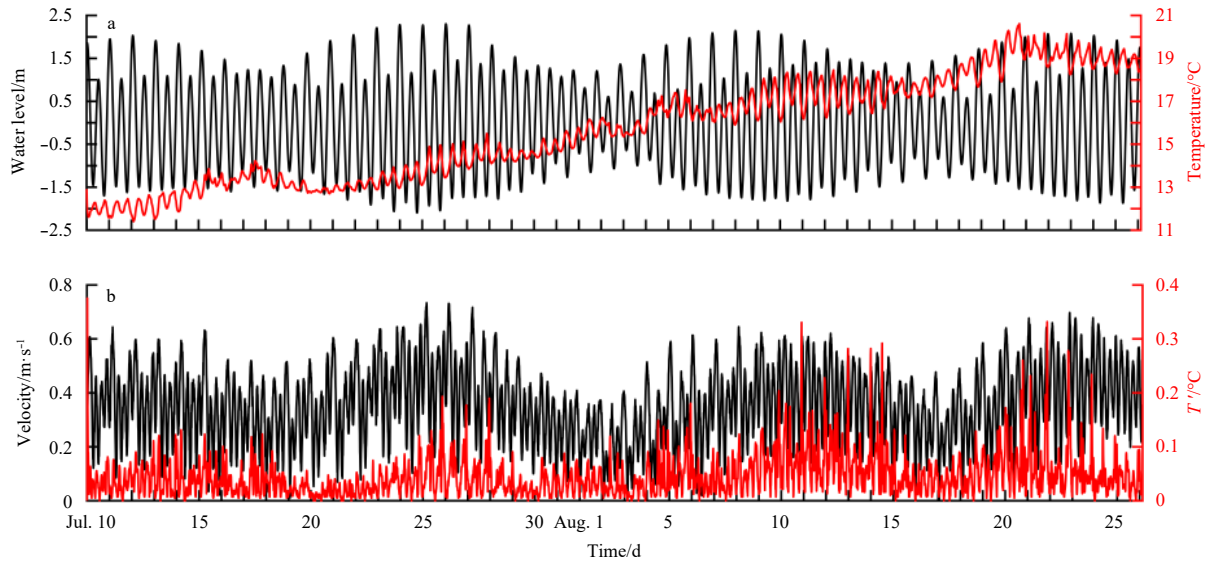


Fig. 4. Time-series of near-bottom temperature (red line) and water level (black line) (a); and time series of T' (red line) and depth-averaged velocity magnitude (black line) (b).

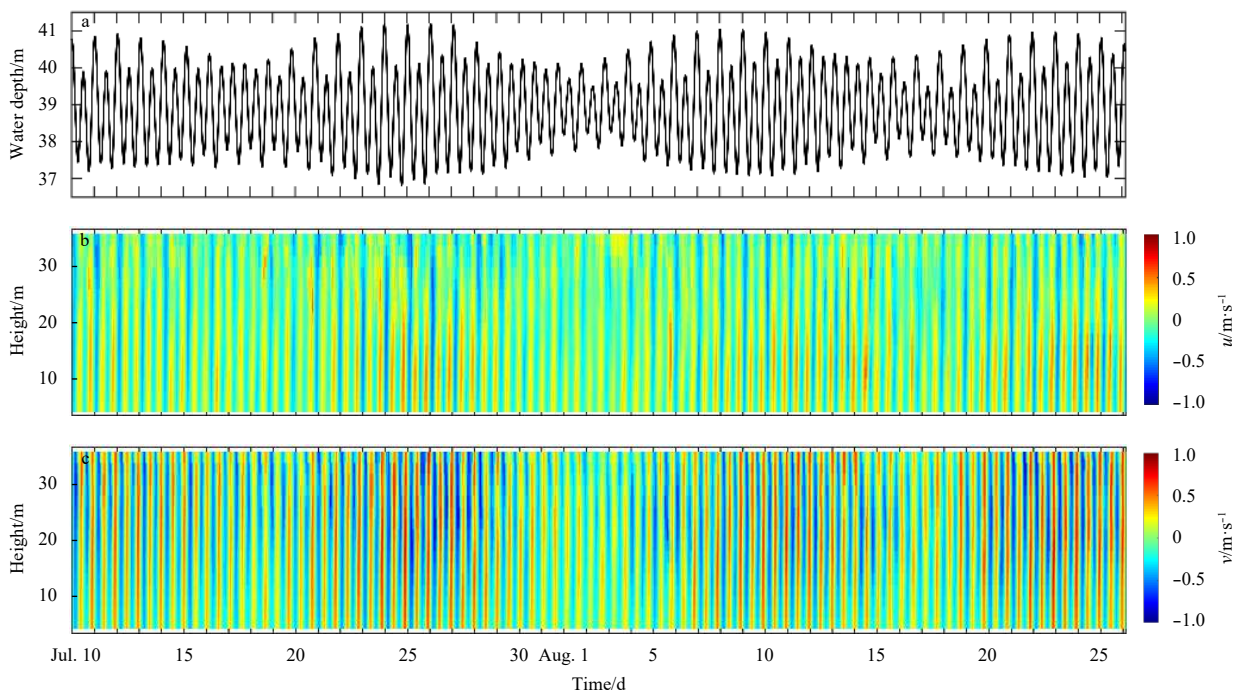


Fig. 5. Time-series of water depth (a), time-depth series of zonal (b) and meridional velocity (c).

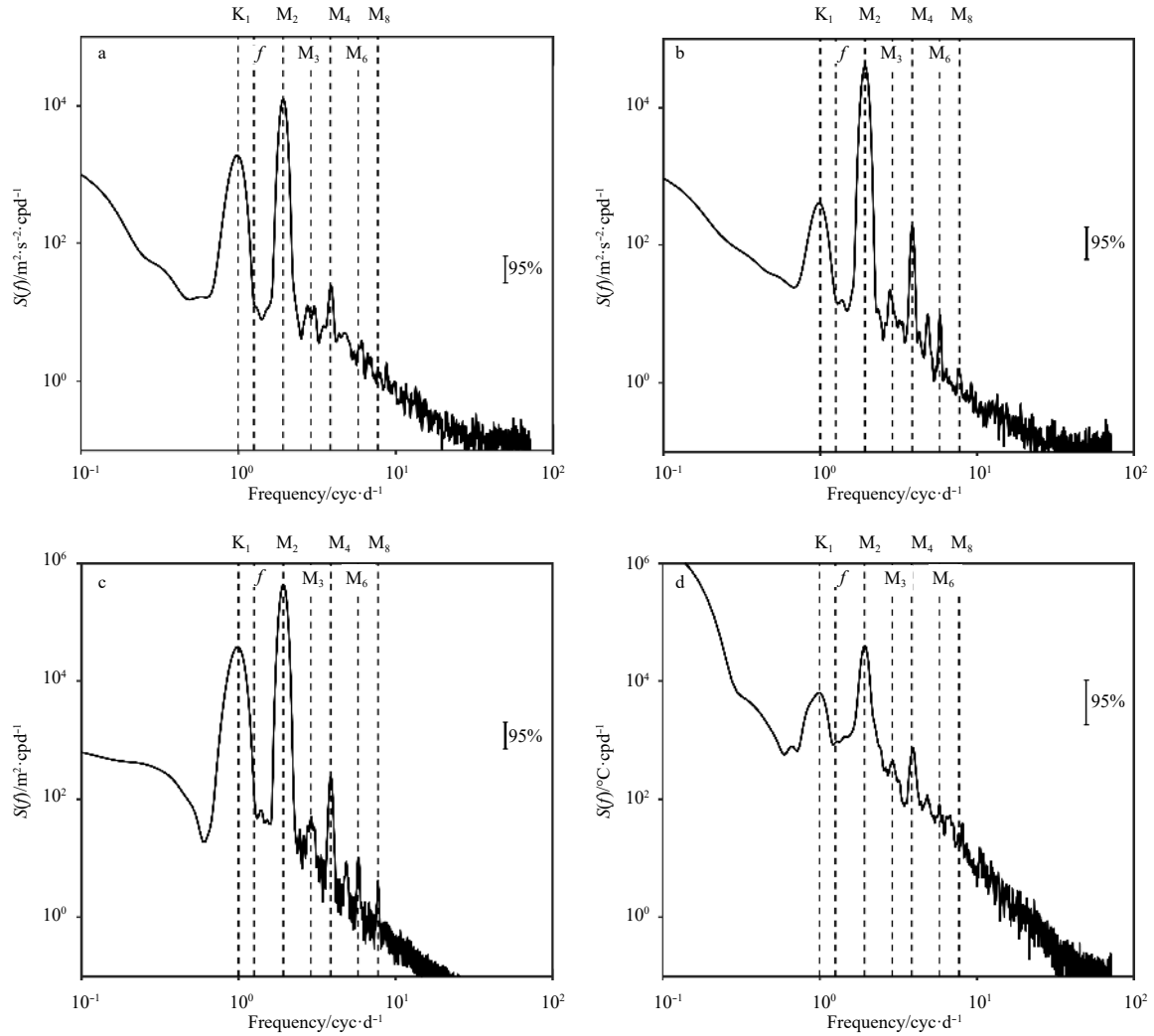


Fig. 6. Spectra analysis of the depth-averaged u (a), depth-averaged v (b), surface elevation (c), and near-bottom water temperature (d) within the entire observation period. The 95% confidence interval of the spectra is also shown.

The near-bottom temperature rapidly changes throughout the tidal cycle (Fig. 4b). It shows a larger amplitude during spring tides than that during neap tides. As mentioned above, the rapid variation of the near-bottom water temperature may significantly influence bottom-sown scallops. Figure 6d shows that this high-frequency variation mainly includes the diurnal and semi-diurnal periods which suggest the horizontal advection of water as driven by tidal currents.

3.2.2 Current velocity

Figure 5 shows the temporal variations of the observed current velocity. Along with the changes in the water depth, the horizontal velocity exhibits clear semidiurnal variations that superposed on a spring-neap cycle. The largest amplitudes of the zonal and meridional components can reach approximately 1.1 and 1.7 m/s, respectively. Both the zonal and meridional components show predominant barotropic structure. To study current in detail, we next perform the harmonic analysis to get the dominant tidal constituents by using t_tide_v 1.3 (Pawlowicz et al., 2002). The largest tidal constituent at the mooring station is M_2 which has an amplitude of 42.9 cm/s, followed by S_2 which has an amplitude of 13.5 cm/s. This is consistent with the semidiurnal features of tides in the NYS that have been reported in previ-

ous studies (Fang, 1986).

3.2.3 Spectral analysis

Frequency spectra were calculated using the depth-averaged u , v , surface elevation, and temperature. Figure 6 shows that they all have larger peaks in the semidiurnal frequencies (M_2 and S_2) than those in the diurnal-band (K_1 and O_1). The power spectra of the zonal velocity show larger peaks in the diurnal-band than those of the meridional velocity (Figs 6a, b). Besides this, the significant spectral peaks at higher-order harmonics (M_4) suggest the presence of non-linear coupling. The power spectra of the surface elevation show similar features to that of the zonal velocity with clear peaks in the diurnal, semidiurnal, and tidal harmonics frequencies (Fig. 6c). There are three spectral peaks for the near-bottom temperature (Fig. 6d). Only the M_2 constituent could pass the 95% confidence test which means that the temperature has dominant semidiurnal variations.

4 Discussion

The semidiurnal variations in the near-bottom water temperature are due to the advection of seawater driven by M_2 . This is depicted more clearly in Fig. 7, which plots the tidal current ellipses and near-bottom water temperatures for every five-day

period. The corresponding time series of the near-bottom water temperature and tidal level is shown at the bottom. The M_2 tidal current rotates in the clockwise direction on the shelf off ZZD, and the inclination of the semimajor axis of M_2 is towards the northeast and southwest.

We selected four typical periods to illustrate the near-bottom

water temperature variations. The near-bottom water temperature increases during ebb and decreases during flood from July 10 to 15 (Fig. 7a). This is similar to Fig. 7b, although it presents the tide from neap to spring from July 20 to 25. There are several peaks during the semidiurnal tide cycle on August 3 and 4. The variation in temperature during neap tides is irregular and fre-

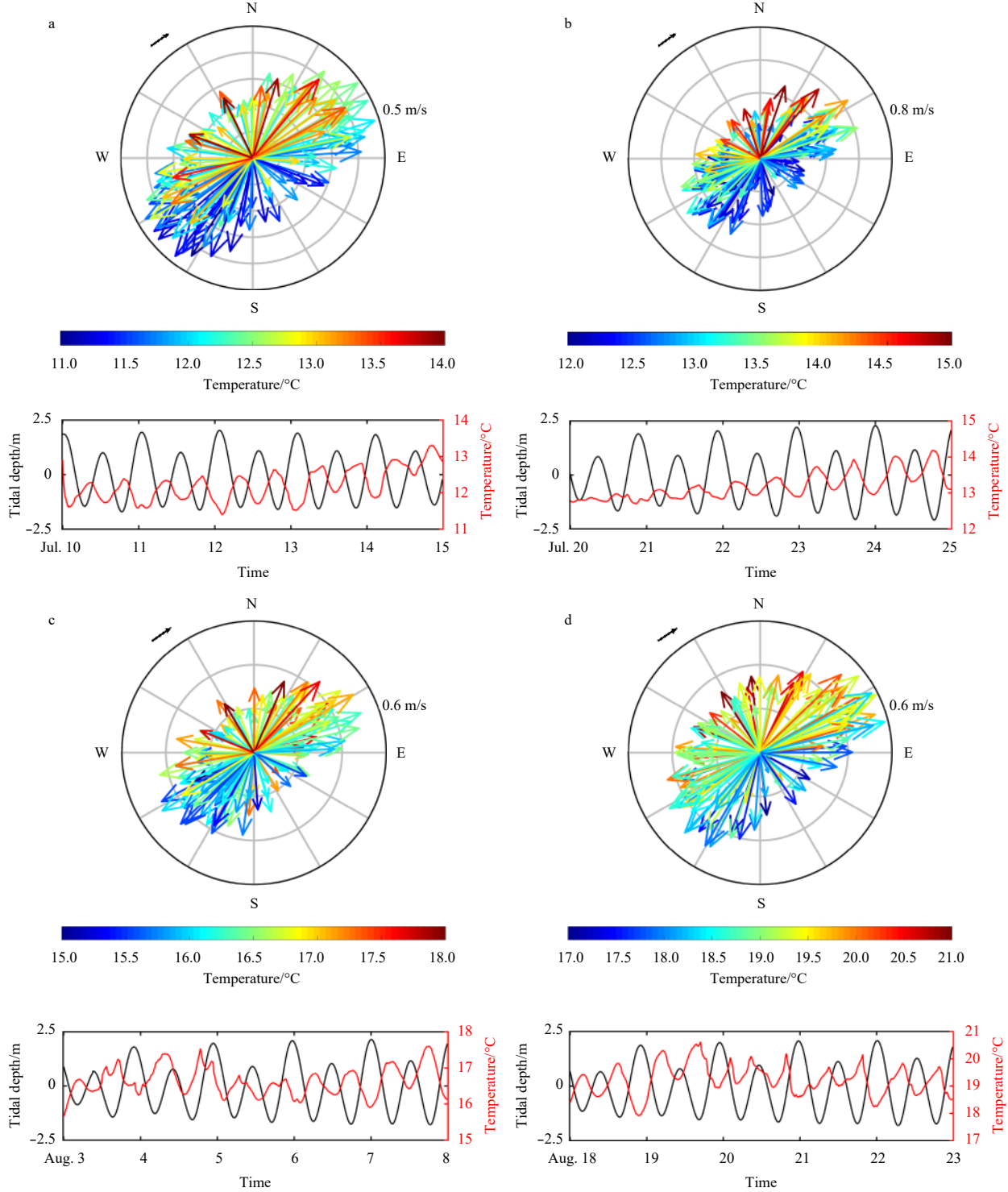


Fig. 7. Compass plot of the five-days depth-averaged currents at station ZZD during 10–15 July (a), 20–25 July (b), 3–8 August (c), and 18–23 August (d). The colors of the arrows correspond to the value of near-bottom water temperature. The velocity vectors and temperatures were averaged over one-hour intervals. The corresponding time series of the near-bottom water temperature and tidal level is shown at the bottom of each panel.

quent (Fig. 7c). As shown in Fig. 7d, there is a repetitive process. The temperature first rises, then decreases, and then rises in ebb from August 20 to 21.

Assuming that the changes in the near-bottom water temperature are only caused by horizontal advection, the local temperature advection can be defined as follows:

$$\frac{\partial T}{\partial t} = -\bar{u} \frac{\partial T}{\partial x} - \bar{v} \frac{\partial T}{\partial y}, \quad (3)$$

where T is the time series of the near-bottom water temperature; t is the time; x and y represent the zonal and meridional directions, respectively; and $\bar{u}$ and $\bar{v}$ are the depth-averaged zonal and meridional velocities, respectively. The time gradients of temperature $\left(\frac{\partial T}{\partial t}\right)$ and velocity $(\bar{u}, \bar{v})$ were directly measured using RBR420 and ADCP, respectively. $\frac{\partial T}{\partial x}$ and $\frac{\partial T}{\partial y}$ are the zonal and meridional temperature gradients, respectively. If the temperature gradient is constant within the one-hour period, the mean horizontal temperature gradient can be estimated following the least-squares method. Figure 8 shows that the temporal temperature gradients measured by RBR420 correlate well with the regression results ($R^2 = 0.94$).

The horizontal temperature gradient can be defined as a vec-

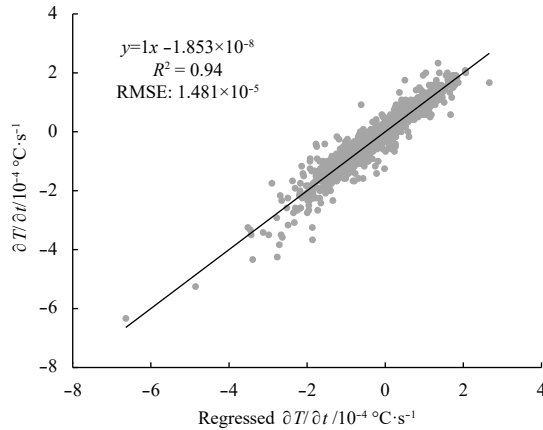


Fig. 8. The directly observed temperature time derivatives within one-hour periods (vertical axis) versus the regressed-temperature time derivatives estimated by the least-squares method (horizontal axis). The line is the regression line.

tor $\mathbf{G} = \left(\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y} \right)$. $\mathbf{G} \cdot \mathbf{U}$ is the dot product of vectors $\mathbf{G}$ and $\mathbf{U}$, where $\mathbf{U} = (\bar{u}, \bar{v})$,

$$\mathbf{G} \cdot \mathbf{U} = |\mathbf{G}| |\mathbf{U}| \cos \theta = \bar{u} \frac{\partial T}{\partial x} + \bar{v} \frac{\partial T}{\partial y}, \quad (4)$$

where θ is the angle between the two vectors, which can be computed by

$$\cos \theta = \frac{\mathbf{G} \cdot \mathbf{U}}{|\mathbf{G}| |\mathbf{U}|} = \frac{\bar{u} \cdot \frac{\partial T}{\partial x} + \bar{v} \cdot \frac{\partial T}{\partial y}}{|\mathbf{G}| |\mathbf{U}|} = \frac{-\frac{\partial T}{\partial t}}{|\mathbf{G}| |\mathbf{U}|}. \quad (5)$$

So we get

$$\frac{\partial T}{\partial t} = -|\mathbf{G}| |\mathbf{U}| \cos \theta. \quad (6)$$

The magnitudes of both $\mathbf{G}$ and $\mathbf{U}$ are positive. Therefore, whether $\frac{\partial T}{\partial t}$ is positive or negative is determined by the angle between these two vectors.

$\frac{\partial T}{\partial t}$ is proportional to the magnitude of the temperature gradient $|\mathbf{G}|$, and the projection of the depth-averaged velocity in the direction of the temperature gradient is $|\mathbf{U}| \cos \theta$ (Figs 9c, d). The velocity direction and spatial temperature gradient direction are perpendicular to each other if $\theta = 90^\circ$. Their dot product then equals to zero. In this case, the direction of current is along the isotherms, the temperature thus remains constant. The water moves from the NYSWM to the warmer coastal zone if $0^\circ \leq \theta < 90^\circ$. Therefore, the study area can be occupied by colder water from the NYSWM and the temperature decreases. If $90^\circ < \theta \leq 180^\circ$, the current advects the coastal warm water to the observation. The temperature at the mooring station then increases.

As described above, the near-bottom water temperature variations in the tidal cycle are mainly affected by the angles between the temperature gradients and tidal currents. Thus, the reason for the complicated rapid variations in the bottom water temperature during the tidal cycle is the change of the angle between the tidal current and the main temperature direction of the tidal front. $\frac{\partial T}{\partial t}$ is proportional to the magnitudes of the temperature gradient and the projections of the depth-averaged velocity in the direction of the temperature gradient. This mechanism accounts for the complicated high-frequency variations in the near-bottom water temperature. Explorations of the numerical prediction skill of the near-bottom high-frequency water temperature variations are essential for the growth of bottom-sowing organisms which will be pursued this in future studies.

5 Conclusions

Long-term observations (47 d) from a seabed-mounted ADCP and RBR420 within the BCA near the Zhangzi Island were used to investigate high-frequency variations of the near-bottom temperature. The properties of the observed current velocity and near-bottom temperature have been analyzed. The main conclusions are summarized below.

The currents observed at the mooring station are dominated by semidiurnal tides. The near-bottom water temperature is significantly affected by semidiurnal tides which shows clear semidiurnal variations. Based on the transect observations of temperature and salinity and the calculation of Simpson-Hunter parameter at the mooring station, we conclude that the mooring station locate close to the tidal mixing front during our observation period. The temperature changes rapidly in horizontal direction within tidal mixing front. The horizontal advection of water driven by tidal currents contribute most to the rapid changes in temperature.

Analysis of the current and temperature observations show that the angle between the tidal current horizontal advection and the main direction of the tidal front determines the rapid change of temperature. The seawater moves from deep water to the warmer coastal zone and the temperature decreases when the angle is between 0° and 90° . In contrast, the water temperature increases when the angle is between 90° and 180° . The amplitude of the temperature change is proportional to the magnitude of

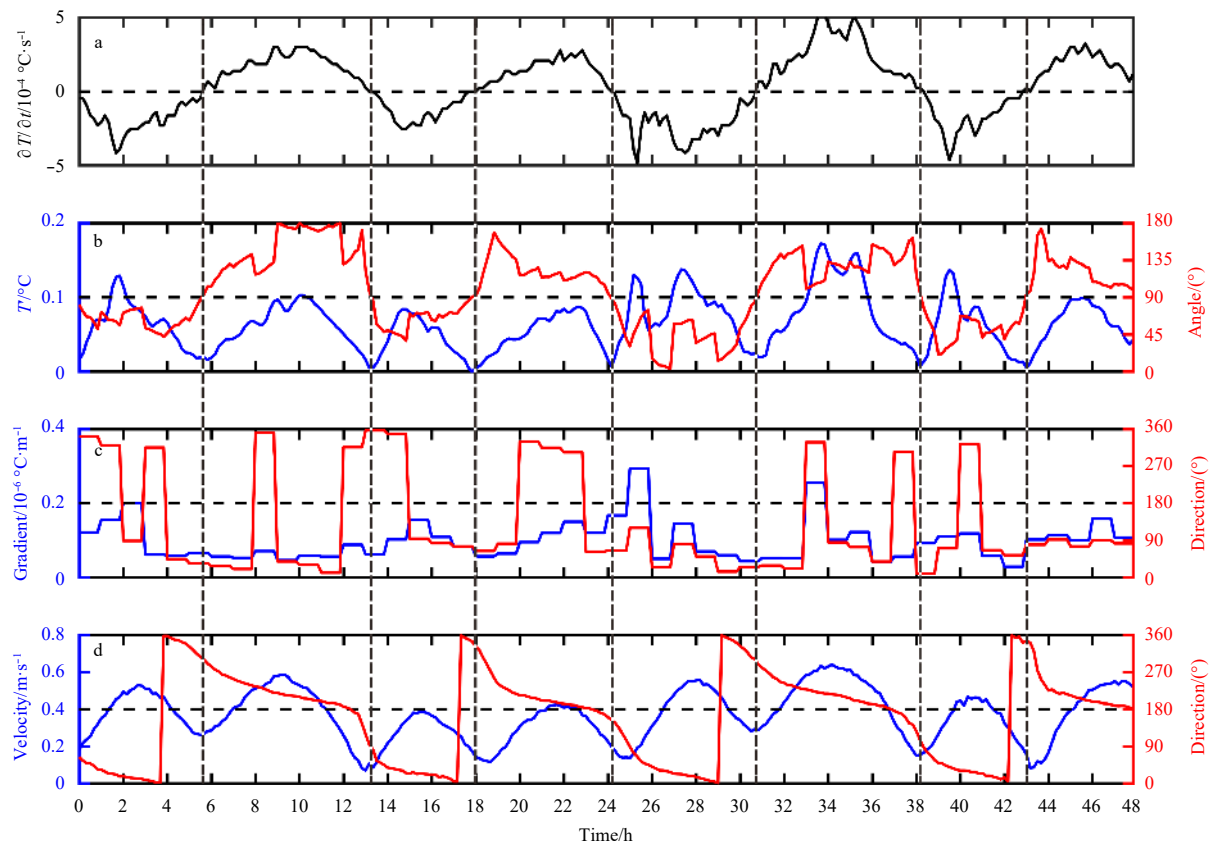


Fig. 9. Temperature time derivatives from August 19 to 21, 2017 (a), bottom temperature variation parameters T' (blue line) and the angle between the temperature gradient and tidal current (red line) (b), temperature gradient (blue line) and its direction (red line) (c), velocity (blue line) and direction (red line) (d). The dashed black lines represent the dot product of zero.

the horizontal temperature gradient and the tidal excursion in the direction of the temperature gradient. This study shows that there exist rapid temperature changes near the tidal front area due to the horizontal advection effect of tidal current. In order to have a good aquaculture production, we may better avoid sowing near the front zone due to the potential frequent temperature variations. Numerical studies which may facilitate the prediction of near-bottom high-frequency temperature variations will be pursued in the future.

Acknowledgements

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