Observation and analysis of tidal and residual current in the North Yellow Sea in the spring

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Abstract. In order to study the current characteristics of the North Yellow Sea (NYS), 4 moored ADCPs (Acoustic Doppler Current Profilers) were deployed and Current characteristics were analyzed based on the observations. Results show that tidal current is the dominant and M2 is the main constituent. Shallow water constituents are obvious in the near-shore area, and tidal current ellipses directions have relations with topography. Residual currents in the Bohai Strait point to the Bohai Sea interior and the magnitude have a connection with terrain. Residual current in south NYS can be divided into two layers, and energy of residual current only accounts for about 13% of the total energy. Barotropic eddy kinetic energy plays a major role and the average in NYS accounts for 87%, baroclinic mean kinetic energy is larger in north NYS, in other regions barotropic mean kinetic energy take the leading position.

1. Introduction

As a semi-enclosed shallow sea, the North Yellow Sea (NYS) is surrounded by Shandong, Liaodong and Korea Peninsulas, and connects with the Bohai Sea through the Bohai Strait in the west [1]. It is elliptical shape, with an average depth of 46 meters. A trough lies in the middle in the east-west direction. The unique topography and depth make the current and tide extremely complex in NYS, and continuous measurement of currents are very difficult to obtain because of the intense fishing and trawling in near-shore area.

Ogura studied the tides first [2], then Nishida, Larsen, Fang studied the current based on coastal and island measurements [3-5]. Some scholars used satellite altimeter data but more tried numerical model to study tidal current [6-10]. However, due to the lack of observation data within NYS, numerical simulation results can only select the near-shore observation data for verification. In recent years, along with the emergence of moorings observations this awkward situation has been improved. Korea Ocean Research and Development Institute (KORDI) and Florida State University (FSU) deployed many moorings in the eastern Yellow Sea in the early 1980s [11], results showed that tidal currents in the Yellow Sea were much stronger than residual currents. In 1995, several ADCPs were deployed in the Yellow Sea interior utilizing ‘trawl resistant’ instrument mounts by U.S. Naval Oceanographic Office, further analysis showed that currents varied in magnitude and direction [12]. Using ADCP data in the southern NYS, Yu pointed out that the baroclinic tidal current was weak and the average baroclinic energy was only 5% of the barotropic energy [13]. Song analyzed the seasonal variation of tidal current and found a two-layer structure of residual current in summer [14].

To capture the current characteristics in NYS, Four ADCPs were moored in NYS in the spring 2007, two of them located in the Bohai strait, one located in the trough of NYS, and the other located...
in the near-shore region in the north of NYS. The main purpose of these measurements was to get a better understanding of the current and circulation there. In this paper, data of the four ADCPs were analyzed in order to figure out the tidal and residual current characteristics and the energy composition of tidal current.

2. Observation and data
Four moored ADCPs were deployed in NYS in the spring 2007 and successfully retrieved. Distribution of the stations is shown in Figure 1. Bathymetry data in Figure 1 extracted from Scripps Institution of Oceanography Dataset (http://topex.ucsd.edu/marine_topo/). The observation time and data information are shown in Table 1. Sampling period was 5 minutes. The data was reprocessed by National Marine Data and Information Service using high quality control methods then long-term high-precision data sequence was formed.

| Station | Start day | End day | Observation Depth(m) | Bin(m) | Water Depth(m) |
|---------|-----------|---------|----------------------|--------|----------------|
| A       | 107       | 140     | 2-42                 | 2      | 52             |
| B       | 105       | 135     | 2-12                 | 1      | 18             |
| C       | 120       | 158     | 2-31                 | 1      | 35             |
| D       | 114       | 159     | 2-64                 | 2      | 70             |

![Figure 1. Topography and Mooring locations A, B, C and D, indicated by black triangles.](image)

3. Current characteristics
The time series of currents are presented for the moorings in Figure 2. The alternating vertical blue and red stripes indicate the cyclical characteristics of the current. Current vertical distributions at
station A, B and C are uniform, which indicate a quite strong barotropic attribute, while magnitude at station D is obviously depth-dependent and shows some baroclinic characteristics. For U component, larger value appears in the upper layer while for V component it occurs in the middle layer. U component value, whose maximum exceeds 1m/s, is bigger than V component at Station A and B, yet at station D, The situation is right the opposite, the maximum V component is about twice as much as U component. U and V component are of the same magnitude at station C. In order to further understand the information contained in the current data, empirical orthogonal function (EOF) method was introduced here. EOF method is used to analyze the structural features of the matrix data and extract the main temporal and spatial features of the data. It has better advantage in analyzing the long time series of the elements. The method could reflect the overall variable characteristics of spatial and temporal changes in the region and has been widely used in ocean and other subjects since it was first introduced to meteorological and climate research in the 1950s [15-16]. EOF analysis was adopted for hourly mean U component, the resulting modal variance contribution rate is showed in Table 2 and the first spatial mode is shown in Figure 3.

Figure 2. Unfiltered velocity time series of the u component and v component.
Table 2. Contributions of the first 3 EOF modes of U component.

| station | Mode | Variance (%) | Accumulative variance (%) |
|---------|------|--------------|---------------------------|
| A       | EOF1 | 99.41        | 99.41                     |
|         | EOF2 | 0.47         | 99.88                     |
|         | EOF3 | 0.08         | 99.96                     |
| B       | EOF1 | 99.11        | 99.11                     |
|         | EOF2 | 0.47         | 99.58                     |
|         | EOF3 | 0.18         | 99.76                     |
| C       | EOF1 | 92.65        | 92.65                     |
|         | EOF2 | 3.74         | 96.39                     |
|         | EOF3 | 1.49         | 97.88                     |
| D       | EOF1 | 73.5         | 73.5                      |
|         | EOF2 | 11.31        | 84.81                     |
|         | EOF3 | 5.41         | 90.22                     |

Figure 3. Spatial component for EOF1 of U component.

Variance contribution rate of EOF1 has absolute advantage except at station D (EOF1 accounts for 73.5% of the variance contribution), so only mode 1 (EOF1) was analyzed here. U component in EOF1 remains the same sign at all depth, which indicates all points at all depth keep in the same phase and contain a large barotropic component. Spatial mode gradually become larger from surface to bottom at station A, B and C, yet at Station D, spatial mode is generally stable at all depth except for surface layer. Power spectrum analysis was used for time factor of EOF1, results are shown in Figure 4. Semidiurnal and diurnal period changes can be clearly seen, and energy of semidiurnal period is larger than diurnal. In fact, the first three spectrum peak corresponds to 12.42, 23.93 and 25.82 hour at station A, B and C, which is the period of M2, K1 and O1 tidal constitute, respectively. At station D, results are 12.42, 12 and 23.93 hours and corresponds to M2, S2 and K1 tidal constitute. The results are the same for V component and they are not shown here. This indicates that the spring current in the NYS is mainly characterized by tidal current; M2, K1 and O1 are the main tidal constituent.
4. Tidal current

Tidal analyses of the current data were performed using a classic harmonic tidal analysis package [17]. Amplitude and Greenwich phase over depth of the main constituents are shown in Figure 5. It is obvious that M2 constituent is the most important. At station A, amplitude of U is greater than that of V component overall, M2 amplitude increases slowly with depth in the upper layer, and decreases shapely below middle depth. The other constituents are broadly characterized by the gradual decrease in amplitude as depth increases and bottom boundary effect is evident.

Also located in the Bohai Strait, station B shows a lot of similarities with station A on the constituent features. For instance, U amplitude is larger than that of V component and is gradually deceasing with depth. But there are many differences, the most obvious is that V amplitude is largely depth-independent, while the shallow water constituents are more obvious, MS4 and M4 amplitudes can reach up to 8cm/s. Station C shows different features, firstly, amplitudes are of the same magnitude for U and V. Secondly, amplitude displays a more complicated change over depth, for example, M2 constituent of V component increase in the upper, steady in the middle, and decrease in the lower depth. Thirdly, shallow water constituent MSF is more evident, especially in U component. At station D, amplitude of V component is greater than that of U, amplitude in the surface is very small, maximum M2 amplitude of V component occurred at middle depth. In general, M2 amplitude is the largest, baroclinic property at station D is the most distinct. Shallow water constituents at station B and C are more obvious and this is caused by topography. In fact, water depth at station B is 18 meters and 35 meters at station C, all of them are located in the near-shore area, station A is situated in the deepest area of the Bohai Strait and D in the NYS trough, Shallow water constituent is not obvious.

Tidal analyses of the vertical averaged current were performed, the vertical averaged current can be seen as the barotropic section of the current. Current ellipses of M2, S2, K1 and O1 are shown in Figure 6. The form of the current movement can be expressed by the elliptical rotation rate K, which is the ratio of the minor to major of current ellipse. When absolute value of K is greater than 0.25, movement performs a strong rotation form and small than 0.25 performs reversing. M2 is the largest, especially at station B and D, semi-major exceeds 50cm/s, the first three constituents in D is semidiurnal tide (M2, S2 and N2) and semidiurnal has an overwhelming advantage over diurnal tide, station D performs a regular semidiurnal tide characteristic. All the other stations are irregular semidiurnal tide. Semidiurnal tide (M2, S2) rotation is clockwise and diurnal is counterclockwise at station A and B, rotation at station C is just the opposite, at station D all the tide constituents are counterclockwise. For O1, movement form is reversing at station B, C and rotation at station A, D. For M2 and S2, movement form is rotation at station C and all the other station is reversing form, especially at station A, K is only 0.01 and reversing current is particularly strong. Major axis
orientation of M2, K1, O1, S2 is perpendicular to the Bohai Strait at station A and B, at station D, the orientation is north-south, parallel to the trough, orientation of diurnal tide (K1 and O1) is west-east, parallel to the isobaths, and semidiurnal tide is northeast-southwest, parallel to Continental shoreline of the Liaodong Peninsula. In general, tidal current characteristics in NYS is semidiurnal and M2 is primary, shallow water constituent is obvious where water depth is shallow such as in the southern part of the Bohai strait and in the northern part of NYS. Major axis orientation is related to topography.

**Figure 5** Amplitudes for individual tidal constituents for U and V velocity component.
Figure 6. Current ellipse with sense of rotation for M2, O1, K1 and S2 (black solid line is counterclockwise and red is clockwise, note the different velocity scales shown in the upper left corner in each part).

5. Residual current

5.1. current structures
Tidal currents were removed from original current using tidal analysis package. Time series of the residual U and V velocity component are presented in Figure 7. Current direction often change and the change period varies at different stations. In general, the period is 1-2 days or even less than 1 day. For instance, U component at station B and D change rapidly and the period is less than 1 day. Current magnitudes are quite variable over depth and time, especially at station D, whose maximum can reach up to 40 cm/s. The vertical change of U and V is uniform at station A, B and C, while station D is clearly divided into two layers, with obvious boundaries between depth less than 30 meters and deeper. The upper layer has a larger magnitude and direction change more rapidly. Depth of U maximum is about 14 meters, V maximum locates between 14 and 20 meters and V magnitude is larger than U, the current feature at station D may be related to the local internal tidal characteristics. Another notable feature is that there are several periods in which flow are strong or weak in the time series, for instance, V component in 108-116 days is strong and 122-132 days is weak at station A; at station B, V component in 108-112 days is strong and 116-124 days is weak and there is a significant maximum value in 117 days for U component.
The steady part of residual current is acquired after timely mean, vertically averaged mean currents with standard deviation ellipses of confidence interval 95% are shown in Figure 8. The center of the standard deviation ellipse is at the tip of the arrowhead and reflects the area within which 95% probability current vector tip lies. Direction at station A and B is similar, 290º and 320º, respectively, perpendicular to the Bohai Strait and points to Bohai Sea. Current direction at station C is 246º, points to the Bohai Strait along the isobaths. At station D, direction is 36º, points to the northeast. Current at station B is the swiftest with magnitude of 7.2 cm/s, the next is station C with a magnitude of 5.9 cm/s, station A and D are the slowest, 1.6 cm/s and 0.8 cm/s, respectively. Current vertical structures are shown in Figure 9-11.
Figure 8. Vertically averaged mean current vectors and standard deviation ellipses after tide removal.

Figure 9. Residual current vector vertical structure.
Current direction at station A changes slightly, especially from surface to 12 meters, then deflect to north as depth increase and this trend maintains to 40 meters (Figure 9). U component is positive at all depth. It’s very small at depth lower than 12 meters and increases as water become deeper. V component is negative at all depth, the change has a variation of increase at first and then decrease from surface to bottom (Figure 11). Velocity presents ‘reverse S’ trend, getting maximum and minimum at sub-surface and sub-bottom layer, respectively. The maximal and minimal velocities are 2.4cm/s and 1.3cm/s, respectively (Figure 10). The residual current shows a characteristic of wind-driven with an obvious Ekman spiral feature.

Current direction at station B presents two variation trends. Direction rotates counterclockwise from north to northwest at depth lower than 8 meters, and it basically remains the same with depth (figure 9). U remains positive but gradually decreases from surface to bottom, magnitude of V component increases first and then decreases, reach the maximum at 8 meters. At all depth V is negative (figure 11). The overall velocity characteristics express as single peak, the maximum is 8.4cm/s at 6 meters and 3.5 times as large as that at station A (figure 10).
Current direction at station C generally shows a trend from west to southward, which is slightly different at the bottom (figure 9). U and V components are both negative and U is bigger than V at depth lower than 20 meters. U value decreases as depth increase; the maximum is 9.5 cm/s and appear in the surface, while at the bottom the value close to 0. V value presents a ‘reverse S’ trend, getting maximum and minimum at 6 meters and 16 meters, respectively (figure 11). The overall velocity characteristics present as linear trend and keep decreasing from surface to bottom, the extrema are 9.7 cm/s and 0.3 cm/s, which occur at the surface and bottom, respectively (figure 10).

Magnitude and direction in station D have complex variations (figure 9), as depicted in figure 7. There are obvious boundaries between depth less than 30 meters and deeper. U and V are generally positive in the upper layer, direction is east-north, and negative in the lower layer, direction is west in sum. U shows a stair-step downward trend, maximum occur in the surface and minimum at the bottom and a number of peaks in the middle, getting minimum and maximum in 8 meters and 18 meters respectively, basically unchanged when water deeper than 30 meters (figure 11). The curve of overall velocity is similar to the S-type, the maximum and minimum occur in the upper layer and the depth corresponding to that of V component (figure 10). Direction and velocity are basically synchronized, changes at 8, 18 and 32 meters.

In general, direction at station A and B are similar, perpendicular to the Bohai Strait and point to Bohai Sea interior, the surface layer in station C is parallel to isobaths and point to Bohai Sea, the bottom layer is perpendicular to isobaths and point to the offshore. Upper and lower layer at station get opposite directions. Velocity at station A and B differ in an obvious way, the reason may due to area location. Station A is in the downstream of Long Islands and it is located on the back side of the island, so velocity at station A is largely affected by the lee wave. Station B is in the upstream of shallow water, current is hampered then forced to lift, thus velocity is relatively small.

5.2. Residual current energy
In order to evaluate the energy of tidal and residual current in NYS quantitatively, a formula was adopted to calculate the ratio of residual current energy to the total current, the formula is as follows:

\[ R(z) = \frac{u'_{o}(z) + v'_{o}(z)}{u^{2}(z) + v^{2}(z)} \]

(1)

R represents the ratio of residual current energy to total current energy, \( (u'_{o}, v'_{o}) \) are residual current, \((u,v)\) are total current. Results are shown in figure 12.

R at station A and B are stable, it is larger in the surface and bottom at station C, the maximum is about 0.4. At station D, R gradually decreases as depth increases, maximum exists in the surface and the value is 0.88. In average, station C is 0.23, station B and D is 0.13, station A is 0.05 and is the lowerest. The total average is 0.13. That is to say, residual current energy in NYS account for 13%, tidal current energy is 87% and plays a main role.
6. Barotropic and baroclinic energy

The baroclinic energy was analyzed in two ratios: $R_{mke}$ and $R_{eke}$. $R_{mke}$ is the ratio of the mean baroclinic kinetic energy to the total mean kinetic energy, and $R_{eke}$ is the ratio of the mean baroclinic eddy kinetic energy to the total eddy kinetic energy. Calculations given by Teague are [12]:

$$R_{mke}(z) = \frac{\overline{u_d^2(z)} + \overline{v_d^2(z)}}{\overline{u^2(z)} + \overline{v^2(z)}}$$  \hspace{1cm} (2)

$$R_{eke}(z) = \frac{\overline{u_d^2(z)} + \overline{v_d^2(z)}}{u^{22}(z) + v^{22}(z)}$$  \hspace{1cm} (3)

Liu had improved $R_{mke}$ as [1]:

$$R_{mke}(z) = \frac{\overline{u_d^2(z)} + \overline{v_d^2(z)}}{u^{22}(z) + v^{22}(z)}$$  \hspace{1cm} (4)

$(u_{dd}(z,t), v_{dd}(z,t))$ is the baroclinic part of current, $(\overline{u_{dd}(z)}, \overline{v_{dd}(z)})$ is timely mean of baroclinic current, $(u'_{dd}(z,t), v'_{dd}(z,t))$ is the eddy part of baroclinic current. Calculations are as follows:

$$\overline{u(z)} = \frac{1}{T} \int_0^T u(z,t)dt, \quad \overline{u^2(z)} = \frac{1}{T} \int_0^T u^2(z,t)dt$$

$$\overline{u'^2(z)} = \frac{1}{T} \int_0^T u'^2(z,t)dt, \quad \overline{u'^2_{dd}(z)} = \frac{1}{T} \int_0^T u'^2_{dd}(z,t)dt$$

$$\overline{u_{dd}(z)} = \frac{1}{T} \int_0^T u_{dd}(z,t)dt, \quad \overline{u_{dd}^2(z)} = \frac{1}{T} \int_0^T u_{dd}^2(z,t)dt$$  \hspace{1cm} (5)

among which, $u'(z,t) = u(z,t) - \overline{u}(z)$  \hspace{1cm} (6)

However, both $R_{mke}$ calculations are somewhat unreasonable. For Teague’s calculation formula, when barotropic and baroclinic current have opposite directions, a large $R_{mke}$ will be there, and the value does not directly reflect the proportion of the mean baroclinic kinetic energy, because barotropic energy at this time is also great. This is the same case for $R_{eke}$. For Liu’s calculation formula, when
the timely mean current is very small (and indeed the case), Rmke is nearly equal to Reke, Rmke cannot reflect the mean kinetic energy situation but the eddy kinetic energy situation.

Therefore, another calculation formula is used here:

\[
R_{mke}(z) = \frac{\overline{u^2}_{zd}(z) + \overline{v^2}_{zd}(z)}{(\overline{u^2}_{zd}(z) + \overline{v^2}_{zd}(z)) + (\overline{u^2}_{zd}(z) + \overline{v^2}_{zd}(z))}
\] (7)

\[
R_{eke}(z) = \frac{\overline{u^2}_{zd}(z) + \overline{v^2}_{zd}(z)}{(\overline{u^2}_{zd}(z) + \overline{v^2}_{zd}(z)) + (\overline{u^2}_{zd}(z) + \overline{v^2}_{zd}(z))}
\] (8)

Where \((\overline{u}_{zd}(z), \overline{v}_{zd}(z))\) is timely mean of barotropic current, it is a constant in the vertical. \((u'_{zd}(z,t), v'_{zd}(z,t))\) is the eddy part of barotropic current. Profiles of \(R_{mke}\) and \(R_{eke}\) are shown in figure 13.

![Figure 13. Profile of Rmke and Reke at station A, B, C and D.](image)

Profiles of Rmke at station A and C is similar, larger Rmke exist in sub-surface and at bottom, minimum exist in the middle and close to 0. That is to say, in the middle layer mean baroclinic kinetic energy is very small and barotropic kinetic energy take absolute advantage. For the average, Rmke in station A is 0.28 and station C is 0.29. Station B has maximum at the surface and decreases as depth increases, but has a tendency of increasing in 8 meters and bottom. The total average is 0.08, it means baroclinic kinetic energy is very small. Station D can be divided into two parts taking 30 meters as boundary, which quite in accordance with the above. The upper part changes intensely while the lower is gentle. The maximum and minimum all locate in the upper part. Rmke are 0.96 and 0.34, respectively. The average at station D is 0.81, that is to say, mean baroclinic kinetic energy take absolute advantage. This is totally different with the other three stations.

Reke at station A and B are very similar, very small in all depth especially in the middle. Reke is large in the surface and bottom at station C, which means baroclinic eddy kinetic energy is more important at these depths. For station D, Reke is close to 0.5 in the surface, the value decrease sharply as depth increases indicates that in the surface barotropic and baroclinic eddy kinetic energy are nearly equal. The total average is 0.03, 0.04, 0.20 and 0.24, respectively. Reke in station A and B is far less than that in station C and D.

In spring, the baroclinic energy in station C and D is greater than that in station A and B, indicating that the baroclinic process in the eastern part of NYS is more important than that in the west. This is consistent with Naimie's results [18].
7. Conclusions
Current in the spring in NYS is mainly barotropic. It shows different tidal and residual current characteristics in different regions. M2 is the main constituent. Shallow water constitute is obvious in regions where water depth are small. Residual current direction at the Bohai Strait points to the Bohai Sea, and velocity in the south of the Straits is greater than that in the north. Current direction in the northern NYS is mainly pointing to the Bohai Strait. In the southern NYS, residual current is divided into upper and lower layers. The upper is large than the lower and the direction is basically opposite. Residual current energy only accounts for 13% of the total energy; tidal current takes the lead position.

Baroclinic mean kinetic energy plays a major role and accounts for more than 80% in the southern NYS. In other regions barotropic kinetic energy is more important especially in the Bohai Strait. Barotropic eddy kinetic energy takes up 87% in NYS, the largest exists in the southern and the smallest in Bohai Strait.

Residual current is greatly influenced by the season and shows different characteristics in different seasons.

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