Analysis of tidal and residual currents across semi-enclosed bay mouth based on shipboard ADCP measurements

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Abstract: Based on 25 hours shipboard ADCP measurements across semi-enclosed bay mouth(Kemen Channel), time series of tidal currents over 12 sites, which distribute evenly along the transect, were constructed to improve our understanding of tidal characteristics and residuals in this region. The tidal currents in Kemen Channel were identified as the regular semidiurnal and reversing tidal flows, with its behaviour more like standing waves. Moreover, the flood currents in the lower layers were found to be ahead of that in the upper layers and vice versa for ebb tides. The major of tidal ellipse for M_2 constituent was found to be larger close to the southern side of the channel, with its incline also increasing toward the south. The signs of M_4 constituent were also found mainly nearby the end points of this transect, indicating the importance of nonlinearity in tidal dynamics due to the shallower topography. A two-layer structure was found for the residual currents in Kemen Channel, flowing northeastwardly out of the Bay in upper 20 m and southwestwardly into the bay in the lowers. Besides approximate 4.81×10^8 m^3 water exchanges were determined between the Luoyuan Bay and outer seas by the calculation of tidal flux through Kemen Channel.

Keyword: shipboard ADCP; tidal currents; residuals; tidal transport

Luoyuan Bay (26°19' to 26°31' N, 119°34' to 119°50' E) is located in the northeast of Fujian province, whose Geographic characteristics distribution were shown in Fig. 1. Luoyuan Bay is surrounded by mountains, only through the northeastern part of Kemen

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channels connecting to the East China Sea. As the only connection of Luoyuan Bay and open sea, Kemen channels show northeast-southwest direction substantially, with terrain undulating, and the depth range is approximately 20 m to 80 m; Along the southwest into the bay, Luoyuan Bay is overall widened and folded along the northwest-southeast direction, it is a typical semi-enclosed bay type with big mouth and small belly [1,2]. As the only connection of the inside and outside of bay water, the Kemen channels plays a key role in the process of water and material exchange. Structure and property studies of transect tides and residual currents will help better understanding of the entire long-term hydrodynamic environmental and material transport processes in Luoyuan bay.

ADCP(coustic Doppler Current Profile) calculates velocity and direction of water flow by observing the movement of scatterers suspended in seawater, whose accuracy is much higher than the traditional way. In addition, the ADCP observations also give finer vertical distribution of water currents, which can constitute a space-time continuous sequence of sea currents observation [3,4]. This allows us to have a more completed and detailed understanding of flow structure in Kemen channels. Therefore, the main objective of this article is to separate the tidal and residual signals and analyze the structures and properties of tidal and residual currents based on shipboard ADCP observation data of Kemen channels transect, in order to improve our understanding hydrodynamics of Luoyuan Bay estuary.

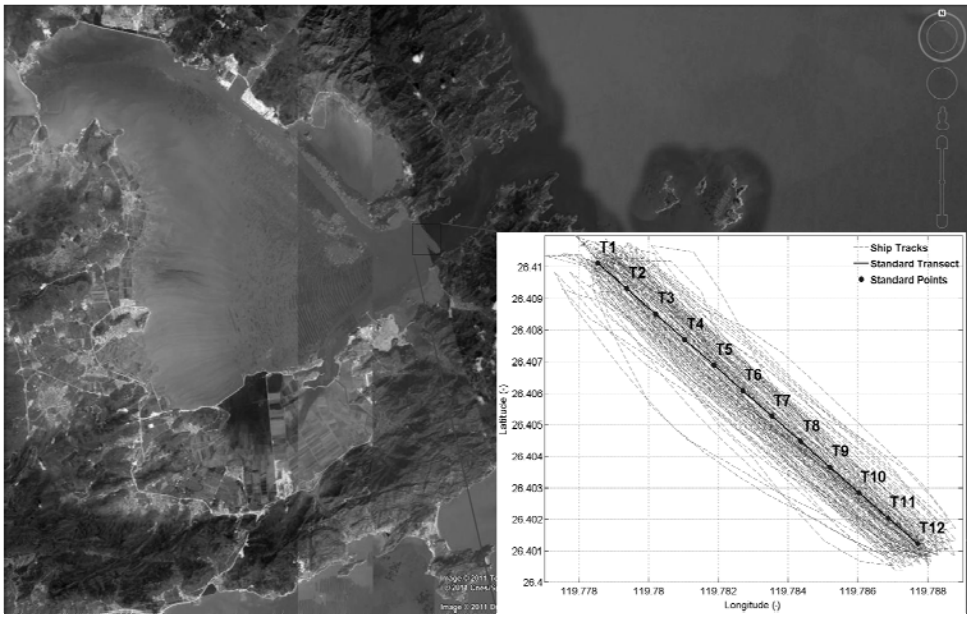

Fig. 1 Geographical features of Luoyan Bay and shipboard ADCP track

1 Data and processing

Data analyzed in this paper is from 25 hours, continuous shipboard ADCP observation of Kemen channels transect by Ocean University of China during the time period of 13:28 on Sept. 28, 2005 to 15:13 on Sept. 29, the location of the transect is as shown in Fig. 1. The direction of the transect is basically perpendicular to the water spindle direction. The observation instrument is the 307.2 kHz WorkHorse series ADCP from the US. RDI Company. Vertical direction includes a total of 30 measured layers with thickness of 2 m, and 1 minute short-term average data is selected for analysis. Observation section width of Luoyuan Bay mouth is about 1.5 km, and sailing speed underway is approximately 2 to 2.5 m/s. The single trip require about 10 mins. Data quality control includes sailing speed calculation by combining bottom tracking and DGPS, excluding the abnormal values and data Percent Good less than 80%, and all missing data were interpolated. Through quality control, standard section is divided into 11 parts and 12 standard points (T1 to T12 see Fig. 1). In this paper, the follow-up analysis is based on equal interval sea current observations with time series in 12 standard points.

2 Time series

Tidal current with time series from 12stations (T1 to T12) showed similar space distribution characteristics. T5 station with the deepest water depth was done time series analysis, and results are shown below(see Fig. 2). In 22 hours from 17:00 on Sept. 28, 2005 to 15:00 the next day, tidal level with time series of T5 station showed two high levels(20:00 on Sept. 28 and 8:00 the next day) and two low levels (2:00 on Sept. 28 and 14:00 the next day), and time interval of the two adjacent wave crests was about 12.5 hours, which displayed regular semidiurnal tidal characteristics.

During high tide(14:00 to 20:00 on Sept. 28th and 2:00 to 8:00 the next day), tidal current flowed southwestward and entered the bay, average high tidal flow direction is about 210°. During low tide(20:00 on Sept. 28 to 2:00 the next day and 8:00 to 14:00 the next day), tidal current flowed northeastward away from the bay, and average low tidal flow direction was about 30°. The high and low tidal directions were basically along the axial direction of the Kemen channel, and tidal current at the bay mouth was mainly the transmeridional U component with maximum value about 0.4 m/s, and the north-south V component was relatively weak with value only about 0.2 m/s. In additon, tidal currents displayed two high tides and two low tides within 25 hours, it is regular semidiurnal tide. The maximum velocity of high tidal flow was about 0.5 m/s, three hours before the climax(17:00 on Sept. 28 and 5:00 the next day); The maximum velocity of low tidal flow was about 0.4 m/s, three hours after the climax(23:00 on Sept. 28 and 11:00 the next day), so the maximum flow velocity appeared at half-tide level moments and minimum flow velocity appeared at the high and low tide time. Standing wave characteristics were obvious, above all, they were consistent with the semi-enclosed bay tidal wave characteristics.

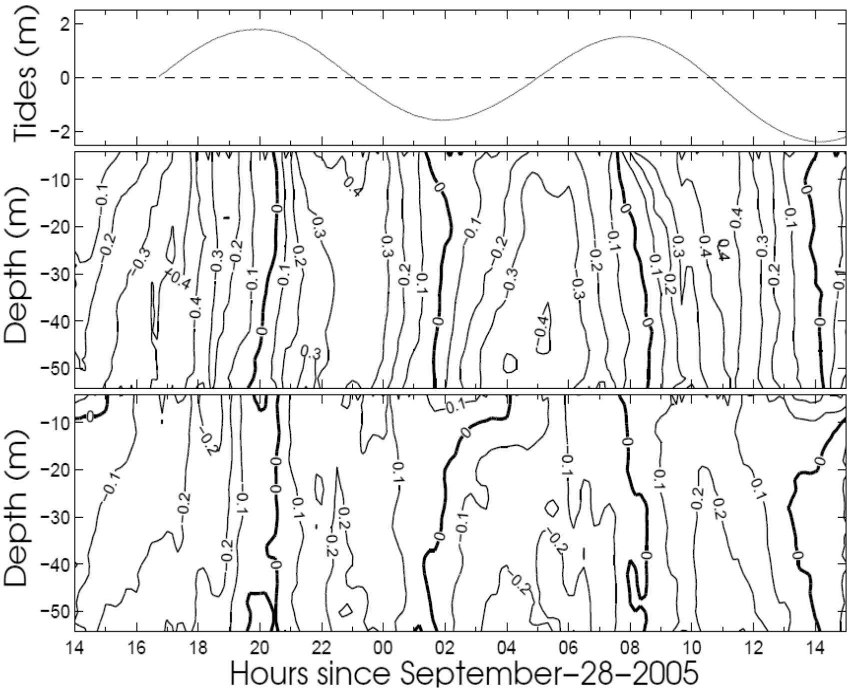

Fig. 2 Tidal level(up), transmeridional U component (middle) and north-south V component(low) distribution with time series

From the vertical direction, the spacial distribution of flow velocity is not even. Generally, the high value of high tidal current appeared in the middle and low area, high tidal current velocity was weaker near the surface. For ebb current, ebb current velocity was higher in the middle and up area, especially near the surface area, and ebb current velocity was weaker in the low area. As a whole, high tidal current velocity was slightly higher than the ebb current velocity. Along the vertical direction the occurrence of high tide and low tide also displayed inconsistent, which can be seen from the triangular structure of the velocity isopleth map. During flood tide, water in the low area of Kemen channel first began to flow, after about 0.5 to 1 hours water in the surface area began to flow. As a whole, the ebb tide time was longger than the high tidal current in the surface area, and the bottom area is the opposite.

3 Residule current

The previous analysis has shown that the tidal current in the area of Kemen channel was M2 tidal component with 12.42 hours cycle, and other tidal component proporation was smaller. Thereby, by averaging 25 hours current with time series, after eliminating and suppressing most of the tidal signals in the observational data, the spatial distribution of the residual current of the Kemen channel cross sections was obtained. The result is as shown in Fig. 3.

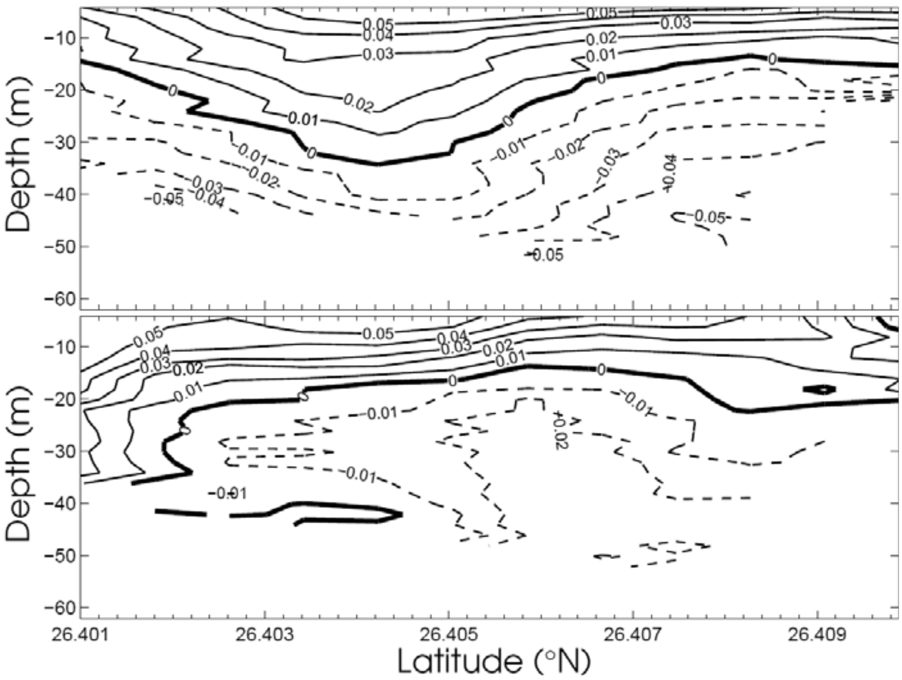

Fig. 3 Transmeridional U component(up) and north-south V component(low) of residual current structure of Kemen channel cross section

(Wherein, the solid line represents the velocity component is positive(U eastward, V northward), and the dotted line represents the velocity component is negative(U westward, V southward), and the black thick line represents zero velocity.)

The transmeridional U component of residual current distribution displayed basically two-layer structure on the vertical direction. In the upper layer, water flowed eastward, towards outside the bay, and the core outflow area was located the surface area near 26.404°N, where near the south tip of the channel. And to the north of the core outflow area, eastward outflow distribution in the horizontal direction is relatively uniform and isopleth is rather straight. In the middle and lower layers of channel water flowed uniformly westward, that flowed into the bay. And there were two core areas that water flow westward, which located at 26.402°N and 26.408°N, respectively near the bottom area, in which, flow in the north core area of 26.408° was stronger than the south one, especially area of the flowing. This indicates that the west inflow of Kemen channel flowed into the Luoyuan bay mainly through the middle and lower regions of the north side of the channel. Possible reason of this phenomenon is due to the role of the coriolis force in the northern hemisphere, which made the flood tide into the bay converging at the northwest side of the channel and the ebb tide out of the bay converging at the southeast side of the channel. Therefore, the upper outflow district position was southward.

Two-layer structure on the vertical direction of the north-south V component of residual current was sill visible basically, especially obvious at the north side area of the channel. However, some area of southernmost to 26.402°N displayed northward outflow at all the depths, and amplitude of the northward outflow weakened with water depth increasing. In the area near the surface, intensity of northward outflow was about 0.05 m/s, and near the bottom area, its intensity decreased approximately 0 m/s. Area from 26.402°N to the north of the northernmost, the depths that northward outflow could reach were basically consistent. It was about 20 m, and horizontal distribution of northward outflow was relatively uniform, and only that in the northernmost area of the channel showed a certain horizontal change. The core inflow area of north-south V component mainly appeared in the region where depths were deeper than 20 m from north of 26.402°N to the northernmost, and the core position of inflow area was near the 26.408°N bottom area, which was basically consistent with transmeridional inflow. The north-south outflow intensity of Kemen channel was close to the transmeridional component, and maximum value was about 0.05 m/s. While the inflow was somewhat different, and maximum inflow intensity was about -0.03 m/s along the north-south direction of the Kemen channel, and obviously it was weaker than transmeridional inflow intensity -0.05 m/s. Furthermore, there was only one inflow core area of north-south component along the cross section direction, which was also different from transmeridional component.

Overall, along the transect, northeast outflow was mainly concentrated in the upper layer and shallower area whose depth less than 20 m, and the outflow core position was to the south of the channel, and intensity of northeast outflow was a bit stronger but inflow area was relatively small; However, southwest inflow mainly located in the middle and lower layers, and the core inflow position located near the bottom of the northern channel, and the intensity of southwest inflow was relatively weak but the inflow area is relatively larger.

For further revealing distribution characteristics of residual field, vertical distribution of residual vector along cross section was given, and results were as shows in Fig. 4. We can see that basically the middle and upper layers were northeast outflow, and outflow direction was about 40° - 80° basically along the channel axis direction in most area except T1 and T2 stations. However, inflow southwest with direction about 190° - 230° was mainly located in the middle and lower layers at the north side of the channel, basically opposite to the major inflow direction. For the vertical distribution of residual vector, residual vector inside Kemen channel basically displayed Clockwise rotation with depths except some rare stations of both ends, which was related to the effect of Coriolis force in the northern hemisphere.

4 Tidal flux

During the observation, tidal flux through the entire transect was calculated based on the 25 hours, tidal currents with time series, and was compared with previous results. By tidal flux observation the following formula was used to calculate:

$$T = \int_{t=t_{Start}}^{t=t_{End}} \int_{z=Z_{Bot}}^{z=0} \int_{x=0}^{x=x_{Total}} \int_{y=0}^{y=y_{Total}} (u \cdot dx + v \cdot dy) \cdot dz \cdot dt$$

In the formula, t_{Start} and t_{End} stand for the starting and ending time of the observation; dt is observation time interval, defined as 10 mins; Z_{Bot} stands for depths of observation section, dz is thickness of vertical unit, defined as 2 m; x_{Total} and y_{Total} are the east-west and north-south lengths of the observation transect. By calculation, we got tidal flux sequence along the time integral cross the channel section. Results are as shown in Fig. 5.

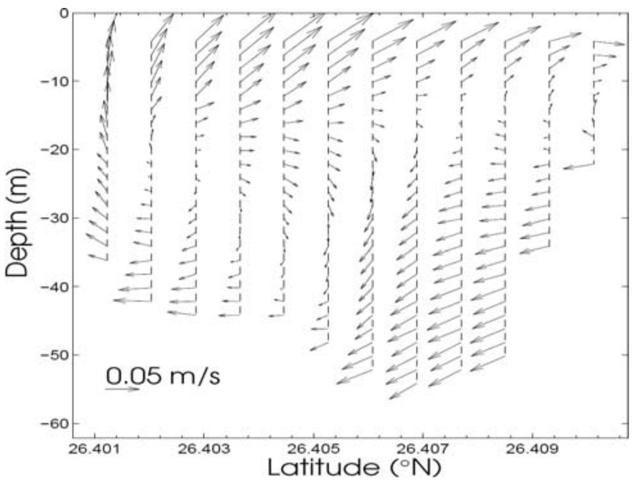

Fig. 4 Residual vertical vector of Kemen channel cross the section

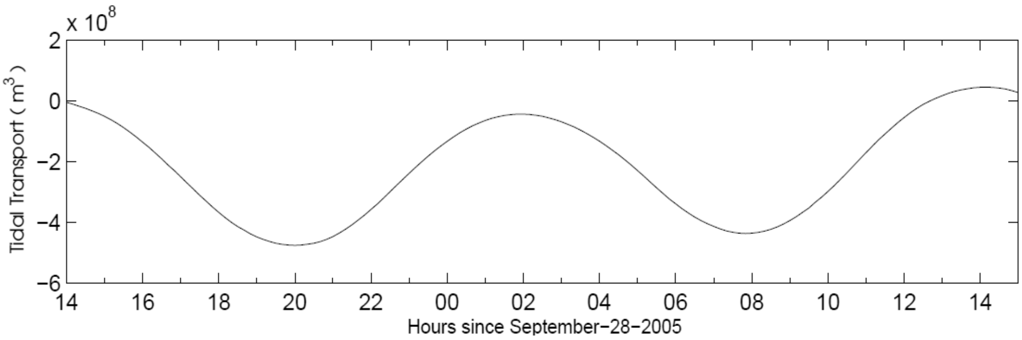

Fig. 5 Cumulative tidal flux along the cross-section integral, and that flowing into the bay is positive

From 20:00 on Sept. 28, 2005 to 02:00 next day, tidal flux into the bay was about $4.32x10^8$ m^3. From 2:00 to 8:00 on Sep. 29, 2005, tidal flux out of the bay was $3.92x10^8$ m^3. From 8:00 to 14:00 of the same day, tidal flux into Luoyuan bay reached the observation maximum value, approximately $4.81x10^8$ m^3.

5 Conclusion

Based on 25 hours, shipboard ADCP measurements across Kemen channel, time series of tidal currents over 12 sites(T1 to T12) were constructed. Tidal current, risidual current and tidal flux of Luoyuan channel section were analyzed based on tidal current with time series from 12 stations(T1 to T12), and results are as follows:

(1) Water current of Kemen channel cross section was dominated by tidal currents, which displayed two complete high and ebb tides with 25 hours, and it had obvious regular semidiurnal tidal characteristics. Tidal velocity was minimum during high and ebb tide moments, which showed obvious standing wave feature. High tides first displayed near the middle and low layer of the channel, but ebb tides occurred in the near surface area, and time of ebb tidal currents was longer in the surface and the lower area is opposite.

(2) Residual currents of Kemen channel displayed two-layer structure on the vertical direction, which flowed northeastward out of the bay in the upper layer with water depth shallower than 20 m, and the position of core outflow area was slightly to the south; Residual currents displayed southwestward flowing into the bay in the middle and lower layer of the channel, and the position of inflow core area was comparatively to the north side of the channel. Spatial distribution of the inflow and outflow core position should be related to the influence of the Coriolis force.

(3) Estimation of tidal flux indicates that tidal flux in the Luoyuan bay through the observation transect was about 4.81x10^8 m^3

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基于船载 ADCP 观测对半封闭海湾湾口断面潮流及余流的分析

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摘 要：基于对罗源湾可门水道的25小时连续走航ADCP观测，本文成功构建了沿走航断面共12个站位的连续海流时间序列，并对这些站位的潮流、余流以及潮通量等进行了分析。结果表明可门水道内的潮流为正规半日潮流，驻波性质明显，涨潮首先出现在水道中下层而退潮则首先发生在水道上层。水道内潮流为往复流，水道南部M_2分潮流流速较大，并且其倾角自北向南逐渐增加。此外，水道两端的浅水区域内浅水分潮M_4振幅较显著。可门水道内余流呈现出两层结构，20 m以浅余流沿东北向流出海湾，并且出流的核心位置偏南，而20 m以深的余流沿西南向流入湾内，入流的流核位于偏北的近底层区域。对潮通量的积分计算表明通过可门水道进入罗源湾的潮通量约为4.81x10^8 m^3。

关键词：走航ADCP；潮流；余流；潮通量