ACOUSTIC MEASUREMENT OF TIDAL CURRENT AND VOLUME TRANSPORT THROUGH THE QIONGZHOU STRAIT

Ze-Nan Zhu, Chuanzheng Zhang, Xiao-Hua Zhu

State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography, State Oceanic Administration, Hangzhou, 310012, China

Contact author: Xiao-Hua Zhu, Second Institute of Oceanography, State Oceanic Administration, 36 Baochubei Road, Hangzhou, 310012, China. Fax: 86-571-88839374; E-mail: xhzhu@sio.org.cn

Abstract: *A 15-day coastal acoustic tomography (CAT) experiment was carried out at four acoustic stations in March 2013, to measure the tidal current in the strait. The horizontal distributions of the tidal currents were calculated by inverse analysis of CAT data. The diurnal tidal current constituents were found to dominate: the ratio of the amplitudes O1, K1, M2, S2, and MSF was 1.00 : 0.60 : 0.47 : 0.21 : 0.11. The residual currents flowed westward in the northern QS and turned southward in the southern QS. The residual current velocities were larger in the northern area than in the southern area, with a maximum westward velocity of 12.4* $cm{\cdot}s^{-1}$ *in the northern QS. Volume transport estimated using the CAT data varied between -0.710 Sv and 0.859 Sv, with residual current transport of -0.044 Sv, where negative values indicate westward. This is the first estimation, from synchronous measurements, of major tidal current constituents, residual currents, and volume transport in this strait.*

Keywords: *Tidal and residual currents, volume transport, coastal acoustic tomography, Qiongzhou Strait, South China Sea*

1. INTRODUCTION

The Qiongzhou Strait (QS) is a channel and key point of water exchange between the northern South China Sea and the Beibu Gulf (Fig. 1a).

Analysis of current meter data and tide gauge data from 1963 to 1999 revealed a westward residual current through the QS throughout the year [1]. They also roughly estimated the corresponding volume transport: approximately 0.2-0.4 Sv in winter and spring. These results agree with the more recent current meter mooring data collected at several stations and at different times [2]-[4], drifting bottle data [5], and numerical studies [6]. However, synchronous data measurements to directly probe the spatial structure of the tidal and residual currents and the resulting volume transport through the strait have not yet been performed.

To measure the current in the QS, we carried out a 15-day experiment using coastal acoustic tomography (CAT) systems. To the best of our knowledge, this study is the first synchronous measurement that separates the major tidal current constituents and residual current in the QS.

2. SITE AND METHODS

Four CAT systems measured the currents in the QS (Fig. 1b) over a 15-day experiment period (March 17 to April 1, 2013), which covered one fortnightly spring/neap tidal cycle. The CAT systems were set up using fishing ships anchored on both sides of the QS, at four stations numbered C1-C4, spanning an 11.5 km ×16.5 km area. The broadband transducers were suspended at a depth of about 7 m using a rope. During the CAT observation period, 26 along-line tracks of shipboard ADCP (RDI Workhorse 300-kHz) were performed across the QS (Fig. 1b).

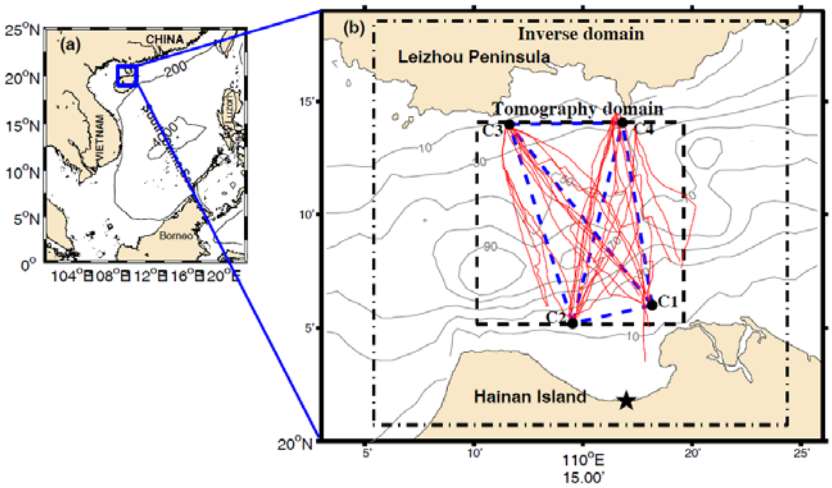

Fig. 1: (a) Bathymetry of the South China Sea; (b) Bathymetry of the Qiongzhou Strait. The solid circles (C1-C4) indicate the positions of the CAT stations. The blue dash lines indicate the sound transmission lines, the red lines indicate the shipboard ADCP tracks.

The inverse method [7] reconstructed the horizontal distribution of depth averaged tidal currents from the differential travel-time data obtained from the reciprocal sound transmissions for all the CAT station pairs. The inverse domain is 33 km×33 km (Fig. 1b), and the grid size for the data display is 2.8 km×2.8 km.

3. ALONG-STRAIT CURRENT VELOCITY AND TRANSPORT

The reciprocal sound transmission method [8] determines the section-averaged current velocity between two acoustic stations to be

$$u_m \approx \frac{c_m^2}{2L}\Delta\tau \qquad (1),$$

where c_m and u_m are the sound speed and current velocity averaged along the ray path, respectively; $\Delta\tau$ is the differential reciprocal travel time; and L the station-to-station distance.

Hourly mean section-averaged current velocity u_m along each transect (Fig. 2a-f) was estimated from $\Delta\tau$ using Eq. (1). $\bar{V}_{ADCP}$ denotes the shipboard ADCP velocities averaged over the entire section. u_m for each transect agrees well with $\bar{V}_{ADCP}$; the root-mean-squares differences (RMSD) between the two variables are 0.041 m·s^{-1}, 0.036 m·s^{-1}, 0.029 m·s^{-1}, and 0.030 m·s^{-1} for station pairs C1-C3, C1-C4, C2-C3, and C2-C4, respectively. Station pair C3-C4 u_m reaches a maximum of about ±1 m s^{-1} in the direction nearly parallel to the strait. The u_m of station pairs C1-C4 and C2-C3 are small because these two sections are nearly perpendicular to the strait.

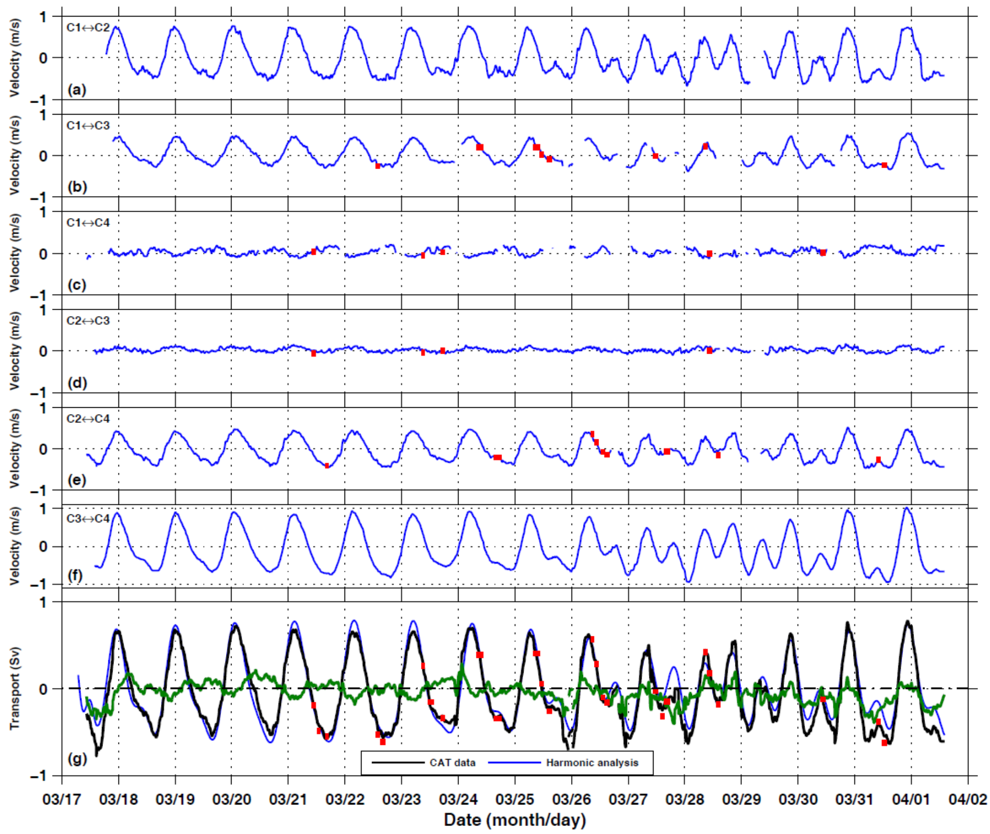

Fig. 2: (a)-(f): Time series of the section-averaged velocity along the sound transmission lines (C1-C2, C1-C3, C1-C4, C2-C3, C2-C4, C3-C4); (g) The volume transport (Q_{CAT}, black line), its prediction based on harmonic constants (blue line) and the volume transport due to the residual current (green line)through the Qiongzhou Strait. Red rectangles in (b)-(e) and (g) indicate the section-averaged ADCP velocity and the volume transport given by ADCP velocity. Positive (negative) value indicates the eastward (westward) velocity or volume transport.

To acquire a time series of volume transport through the QS that allows for harmonic analysis, we established an empirical relationship between Q_{ADCP} and $\Delta\tau$, and applied this relation to all $\Delta\tau$ to obtain a $\Delta\tau$-based volume transport through the QS (Q_{CAT}).

Q_{ADCP} and $\Delta\tau$ are linearly related for the mean of station pairs C1-C3 and C2-C4. Therefore, the empirical formulae that relate $\Delta\tau$ to volume transport are

$$Q_{CAT} = 0.100 \times \Delta\tau_{mean} - 0.016 \qquad (2),$$

where Q_{CAT} is the volume transport estimated from a $\Delta\tau$; $\Delta\tau_{mean}$ are the mean differential travel time for station pairs C1-C3 and C2-C4.

Q_{CAT} varied temporally with tide (Fig. 2g). Its value ranged from -0.710 to 0.859 Sv, with -0.044 Sv mean residual volume transport. Time dependent volume transport due to residual current (green line in Fig. 2g) is defined as the difference between the volume transport measurement (black line in Fig. 2g) and prediction (blue line in Fig. 2g), estimated by a tidal harmonic analysis. This transport also varied with diurnal tide..

4. TIDAL CURRENT AND RESIDUAL CURRENT STRUCTURES

Fig. 3 presents tidal ellipse spatial distributions of tidal constituents O_1, K_1, M_2, S_2 and *MSF* (Figs. 3a-3e), as well as the temporal mean of the residual current (Fig. 3g). The diurnal tidal constituent O_1 (Fig. 3a) is the greatest among the five tidal constituents, while the *MSF* (Fig. 3e) is the smallest among them. The spatially averaged amplitudes of O_1, K_1, M_2, S_2 and *MSF* follow the proportions 1.00 : 0.60 : 0.47 : 0.21 : 0.11. The major axis directions (anticlockwise from due east) of the tidal ellipses for the five constituents are generally along the strait direction of 8º. The temporal mean of the residual current was larger in the northern area than in the southern area; the spatially averaged westward speed was 7.3±1.7 $cm \cdot s^{-1}$ and the spatially averaged direction (anticlockwise from the east) was 227.3±34.7° (Fig. 3g). The maximum temporal mean of the westward residual current speed was 12.4 cm s^{-1} in the northern QS.

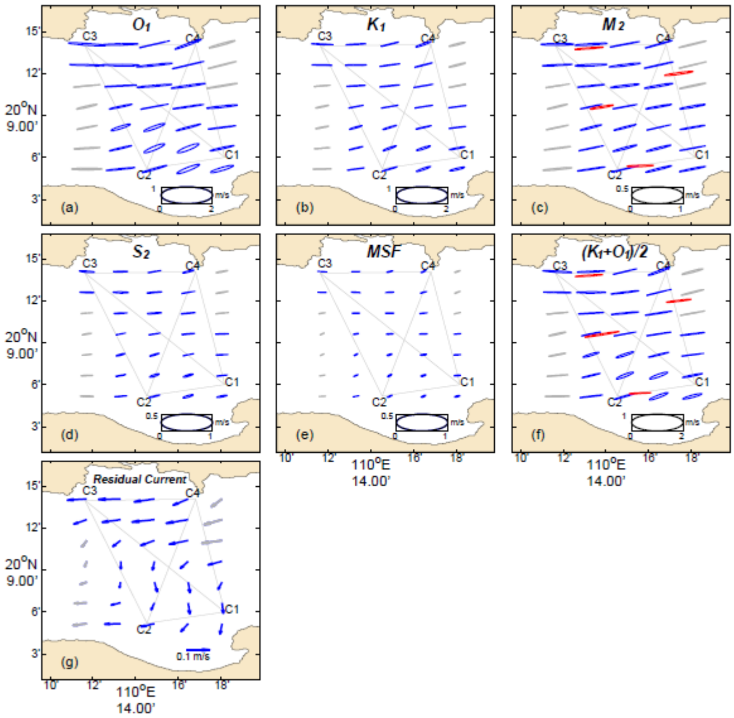

Fig. 3: Depth-averaged tidal current ellipses for the tidal constituents (a) O_1, (b) K_1, (c) M_2, (d) S_2, (e) *MSF* and (f) diurnal $((K_1+O_1)/2)$, and (g) the temporal mean of residual current. The red tidal current ellipses in (c) and (f) are from Shi et al. (2002). Note that the length scale for the diurnal tidal current ellipses is different from the others.

To evaluate the accuracy of our estimated tidal currents, we compared our results with previous independent measurements. Estimated tidal current data from this study agreed well with results reported by Shi et al. [1]. They collected all available current data from observations in the QS from 1963 to 1999, which included the four data sites covered by our CAT observations. The diurnal $((O_1+K_1)/2)$ and semidiurnal tidal currents estimated from our CAT data (black ellipses) are consistent with those reported by Shi at al. [1] (red ellipses) (Figs. 3c and 3f). The RMSD of the major axes, minor axes and diurnal tidal current ellipses orientations at the four sites are 14.3 $cm{\cdot}s^{-1}$, 4.0 $cm{\cdot}s^{-1}$ and 12.3°, respectively; the RMSD of the major axes, minor axes and semidiurnal tidal current ellipses orientations at the four sites are 1.8 $cm{\cdot}s^{-1}$, 2.8 $cm{\cdot}s^{-1}$ and 9.6°, respectively.

5. CONCLUSIONS

We present the first synchronous observations of tidal current, residual current, and volume transport in the QS. A 15-day coastal acoustic tomography experiment measured the tidal currents in the QS using four acoustic stations during March, 2013.

The Q_{CAT} for the entire CAT experiment period, predicted using the empirical regression formula between Q_{ADCP} and $\Delta\tau$, ranges from -0.710 to 0.859 Sv, with a 0.044 Sv mean westward volume transport of residual current. The major axes of the tidal ellipses of the five constituents were generally directed along the strait. The ratios of O_1, K_1, M_2, S_2 and *MSF* tidal currents amplitudes were 1.00 : 0.60 : 0.47 : 0.21 : 0.11. The residual current flowed westward, stronger in northern area than in southern area and turned from a westward direction in the northern area to southward in southern area of the strait.

The easy handling of the CAT system and its performance (as shown in this study) suggest that the CAT system is potentially a highly viable way to achieve a long-term current measurement.

ACKNOWLEDGMENTS

This study was supported by the National Key Research and Development Program of China (2016YFC1400104); the National Natural Science Foundation of China (41606113, 41476020, 41621064, 41576001 and 41576031); the Scientific Research Fund of SIO under grant JT1604 and JG1621; the National Programme on Global Change and Air-Sea Interaction (GASI-IPOVAI-01-02); the Zhejiang Provincial Natural Science Foundation of China (LQ17D060003); the Project of State Key Laboratory of Satellite Ocean Environment Dynamics, Second Institute of Oceanography(SOEDZZ1701).

REFERENCES

[1] **Shi M.C., Chen C.S., Xu Q.C., Lin H., Liu G., Wang H., Wang F., Yan J.**, The role of Qiongzhou Strait in the seasonal variation of the South China Sea circulation, *Journal of Physical Oceanography*, 32 (1), pp. 103-121, 2002.

[2] **Chen D. S., Chen B., Yan J. H., Xu H. F.**, The seasonal variation characteristics of residual currents in the Qiongzhou Strait, *Transactions of Oceanology and Limnology*, 2, pp. 12-17, 2006. (in Chinese with English abstract)

[3] **Chen B., Yan J. H., Wang D. R., Shi M.C.**, The transport volume of water through the Qiongzhou Strait in the winter season, *Periodical of Ocean University of China*, 37(3), pp. 357-364, 2007. (in Chinese with English abstract)

[4] **Yan C., Chen B., Yang S., Yan J.**, The transportation volume of water through the Qiongzhou Strait in winter season, *Transactions of Oceanology and Limnology*, 1, pp.1-9, 2008.

[5] **Bao X.W., Hou Y. J., Chen C.S., Chen F., Shi M.C.**, Analysis of characteristics and mechanism of current system on the west coast of Guangdong of China in summer, *Acta Oceanologica Sinica*, 24(4), pp. 1-9, 2005.

[6] **Chen C.L., Li P.L., Shi M.C., Zuo J.C., Chen M.X., Sun H.P.**, Numerical study of the tides and residual currents in the Qiongzhou Strait, *Chinese Journal of Oceanology and Limnology*, 27(4), pp. 931-942, 2009.

[7] **Park J. H., Kaneko A.**, Computer simulation of the coastal acoustic tomography by a two-dimensional vortex model, *Journal of Oceanography*, 57, pp. 593-602, 2001.

[8] **Munk W., Worcestor P. F., Wunsch C.**, *Ocean Acoustic Tomography*, Cambridge Univ. Press, pp.1-433, 1995.