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NOTES AND CORRESPONDENCE

Evaluation of Tidal Removal Method Using Phase Average Technique from ADCP Surveys along the Peng-Hu Channel in the Taiwan Strait

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ABSTRACT

Three cruises with shipboard Acoustic Doppler Current Profiler (ADCP) were performed along a transect across the Peng-hu Channel (PHC) in the Taiwan Strait during 2003 - 2004 in order to investigate the feasibility and accuracy of the phase-averaging method to eliminate tidal components from shipboard ADCP measurement of currents. In each cruise measurement was repeated a number of times along the transect with a specified time lag of either 5, 6.21, or 8 hr, and the repeated data at the same location were averaged to eliminate the tidal currents; this is the so-called "phase-averaging method". We employed 5-phase-averaging, 4-phase-averaging, 3-phase-averaging, and 2-phase-averaging methods in this study. The residual currents and volume transport of the PHC derived from various phase-averaging methods were intercompared and were also compared with results of the least-square harmonic reduction method proposed by Simpson et al. (1990) and the least-square interpolation method using Gaussian function (Wang et al. 2004). The estimated uncertainty of the residual flow through the PHC derived from the 5-phase-averaging, 4-phase-averaging, 3-phase-averaging, and 2-phase-averaging methods is 0.3, 0.3, 1.3, and 4.6 cm s^{-1}, respectively. Procedures for choosing a best phase average method to remove tidal currents in any particular region are also suggested.

Key words: Tidal current, Phase-averaging method, Shipboard ADCP, Residual flow

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1. INTRODUCTION

Shipboard Acoustic Doppler Current Profiler (ADCP) has been used extensively to measure three-dimensional flow structures and their vertical profiles in oceans for over twenty years. If one is interested only in the circulation of residual flow, tidal components have to be eliminated from total flow quantity as measured by ADCP. Generally speaking there are three basic ways of dealing with this problem. The first approach is based on using repeated surveys along a given transect to construct time series of currents at selected sites, so that harmonic analysis may be performed on the data (Simpson et al. 1990). This kind of ADCP measurement is capable of providing a synoptic map of the tidal and residual current field that is not obtainable by conventional means. However, the main limitation of this method is relatively small spatial coverage, which does usually not exceed 30 km in length (Geyer and Signell 1990; Vennell 1994). The second approach is to fit specific functions to the ADCP data to determine the spatially varying amplitudes and phases of major tidal constituents and the spatially varying magnitude of the residual flow. Using polynomial or biharmonic functions, this method has been applied successfully in the Yellow Sea (Candela et al. 1992) and the southwest coast of Vancouver Island (Foreman and Freeland 1991). A similar method using Gaussian interpolation functions with local support was proposed by Wang et al. (2004), and they were able to reconstruct the spatial and temporal flow field variability and estimate the

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volume transport through the Peng-hu Channel (PHC), the gate of the Taiwan Strait. The third approach relies on designing the sampling survey in a way that permits measuring at the same location several times within a tidal cycle in order to safely average out the tide. This method is sometimes termed as the "phase-averaging method" because the repeated measurements are designed to be at some specified phases of the semidiurnal or diurnal tidal cycle. Katoh et al. (1996, 2000) first applied this method to remove diurnal and semidiurnal tidal flows from observed flows by performing four round-trip ADCP surveys along each transect during a diurnal tidal period of 24 hr and 50 min. This method is referred to as "4R-phase-averaging method" in this study. Note that "4R" stands for four round-trip surveys, and residual flows at any position along the transect can be derived by averaging out of the eight repeated ADCP data. A similar but simpler approach was used in the Taiwan Strait to eliminate only dominant semidiurnal tidal currents by making two repeated current measurements along the same transect with the time separation being 6 hr and 12 min (Liu et al. 2000; Jan and Chao 2003). It is termed the "2-phase-averaging method" in this study. In cases of limited availability of ship time, the phase-averaging method is fairly convenient and easy to use. In addition to the "4R-phase-averaging" and "2-phase-averaging" methods, some other schemes of phase-averaging methods are also proposed and implemented in this study. Details of these phase-averaging methods will be described in a later section.

The objective of this study is to investigate the feasibility and accuracy of the phase-averaging method to eliminate tidal components from shipboard ADCP measurement of currents. Several schemes of phase averaging such as 2-phase, 3-phase, 4-phase, and 5-phase will be employed in this study and their results will be intercompared and also compared with two other techniques of tidal removal, i.e., the methods following Simpson et al. (1990) and Wang et al. (2004).

This paper is organized as follows. In the second section, the geography and general tidal characteristics of the region are described. In section 3, the various phase-averaging methods and their working principles are presented. The observations of shipboard ADCP and data reduction of the three cruises are briefly described in section 4. In section 5, uncertainties of phase-averaging methods are estimated, and various tidal removal techniques are compared using ADCP data collected in the PHC. Finally, a discussion and conclusion are presented.

2. GEOGRAPHY, TIDES, AND HYDROGRAPHY

The Peng-hu Channel (PHC) is a funnel-shaped deep passage separating the Taiwan Island and the Peng-hu Archipelago (Fig. 1). To the north, the PHC is about 40 km wide and 100 m deep and is connected to the Chang-yuen Rise, which is a shallow seamount of roughly 40 m in depth extending from the western coast of central Taiwan and dividing the Taiwan Strait into its northern and southern parts. The southern portion of the PHC becomes wider and deeper further southward along the channel where it is connected to the continental shelves of the northern South China Sea (SCS). To the west of the southern PHC lies the Taiwan Banks with its depth ranging between 15 and 40 m.

Flow in the PHC is largely controlled by tides, migration of water masses (Kuroshio, South China Sea water, and China Coastal Current) and wind-driven currents. Early observations from moored current meters at 20 m above the bottom from March to July (Chuang 1985, 1986) have indicated that a persistent northward residual flow exists in the PHC. Chuang found the northward flow in the PHC has a mean value of 0.27 cm s^{-1} and a tidal amplitude of roughly 1.0 m s^{-1}. Lagrangian observations of surface flow patterns from two satellite-tracked drifters also provided further evidence of the northward flow in the PHC during October (Tseng and Shen 2003). Analysis of shipboard ADCP data in the PHC revealed that the currents there are essentially barotropic and characterized by strong semidiurnal tides and mean flow (Wang et al. 2004). They found the along-channel averaged tidal velocity amplitudes are 1.2 m s^{-1} and 0.32 m s^{-1} for semidiurnal and diurnal tides, respectively, and the mean current is 0.73 m s^{-1} northward.

The origin of the northward flow in the PHC has been a research topic for many earlier studies. Wang and Chern (1988) suggested that the northward flow is the major inflow

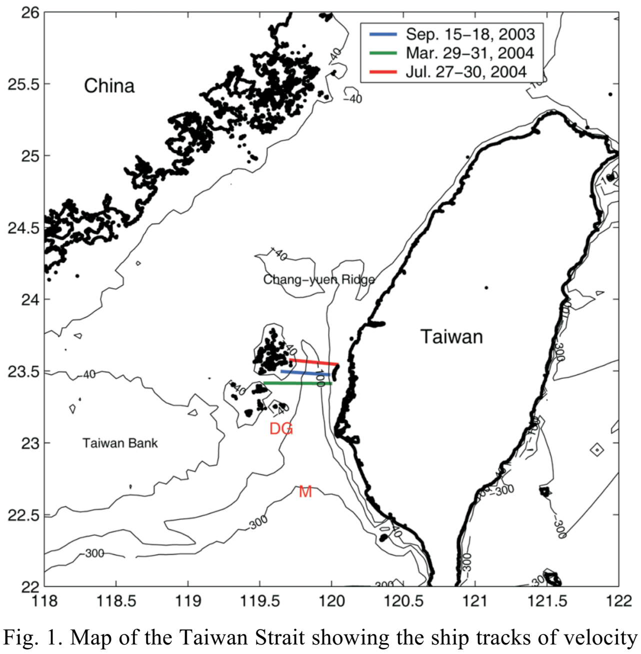

Fig. 1. Map of the Taiwan Strait showing the ship tracks of velocity measurement for the three cruises in the PHC, the position of moored ADCP (marked as M), and wind station of Dongee Island (marked as DG).

entering the Taiwan Strait based on hydrographic data. Chen (2003) indicated that waters across the Taiwan Strait all flow northward in summer, and the waters originate from the South China Sea or the Kuroshio. In winter, on the other hand, strong and steady northeastern monsoon push the fresh, cold, nutrient-rich China coastal water to flow southward along the western part of the Taiwan Strait. On the eastern part of the Strait, including the PHC, some salty and warm, but nutrient-poor SCS or Kuroshio water flows northward. From analysis of eight cruises of shipboard current measurements along the PHC, Jan and Chao (2003) found that the through flow transports in the PHC vary seasonally, being minimal (around 0) during the peak winter monsoon and increase to around 1.5 Sv to the north as the southwest monsoon prevails.

3. PHASE-AVERAGING METHODS

In order to eliminate tidal currents from observed currents, four types of phase-averaging methods are used in this study and their results are inter-compared. These methods are called "2-phase averaging", "3-phase averaging", "4 (or 4R)-phase averaging", and "5-phase averaging", and their schematic diagrams are shown in Fig. 2. The 2-phase averaging is designed to remove the semidiurnal (M_2) tidal flows, and the two repeats (as the survey 1 and 3 in Fig. 2a) are separated by 6.21 hours so that they are out of phase by half a cycle of the semidiurnal tide (Jan and Chao 2003). The 3-phase averaging is designed to remove both the semidiurnal and diurnal tidal flows. Current measurements along the same transect are repeated three times (as the survey 1, 3, and 5 in Fig. 2b), and the time spacing between survey 1 and 3 (or between survey 3 and 5) is roughly 8 hours. Theoretically, the average of these three repeats will safely eliminate the semidiurnal and diurnal tidal flows. Based on a similar principle, current measurements along the same transect are repeated four times in the 4-phase averaging, i.e., the survey 1, 3, 5, and 7 as illustrated in Fig. 2c. The neighboring repeats are separated by roughly 6.21 hours so that the average of these four surveys will eliminate both the semidiurnal and diurnal tidal flows. Note that the 4-phase averaging method is simply the extension of the 2-phase averaging method so that the number of surveys and the total surveying time of the former are exactly twice those of the latter. An adaptation of 4-phase averaging is the 4R-phase averaging in which four round-trip ADCP surveys are performed along the same transect with uniform time spacing during a diurnal tidal period of 24.84 hour (Katoh et al. 2000). That is, each survey along the transect should take exactly 3.105 hr. The average of all eight surveys (as the survey 1, 2, 3, 4, 5, 6, 7, and 8 in Fig. 2c) will eliminate both the semidiurnal (in period of 12.42 hour) and diurnal (in period of 24.84 hour) tidal flows. Finally, in 5-phase averaging the five repeated surveys (as the survey 1, 3, 5, 7, and 9 in Fig. 2d) are separated by a time spacing of approximately 5 hours. The average of these five repeats will eliminate both the semidiurnal and diurnal tidal flows. It is worth mentioning that neither the 3-phase averaging nor 5-phase averaging methods has ever been proposed

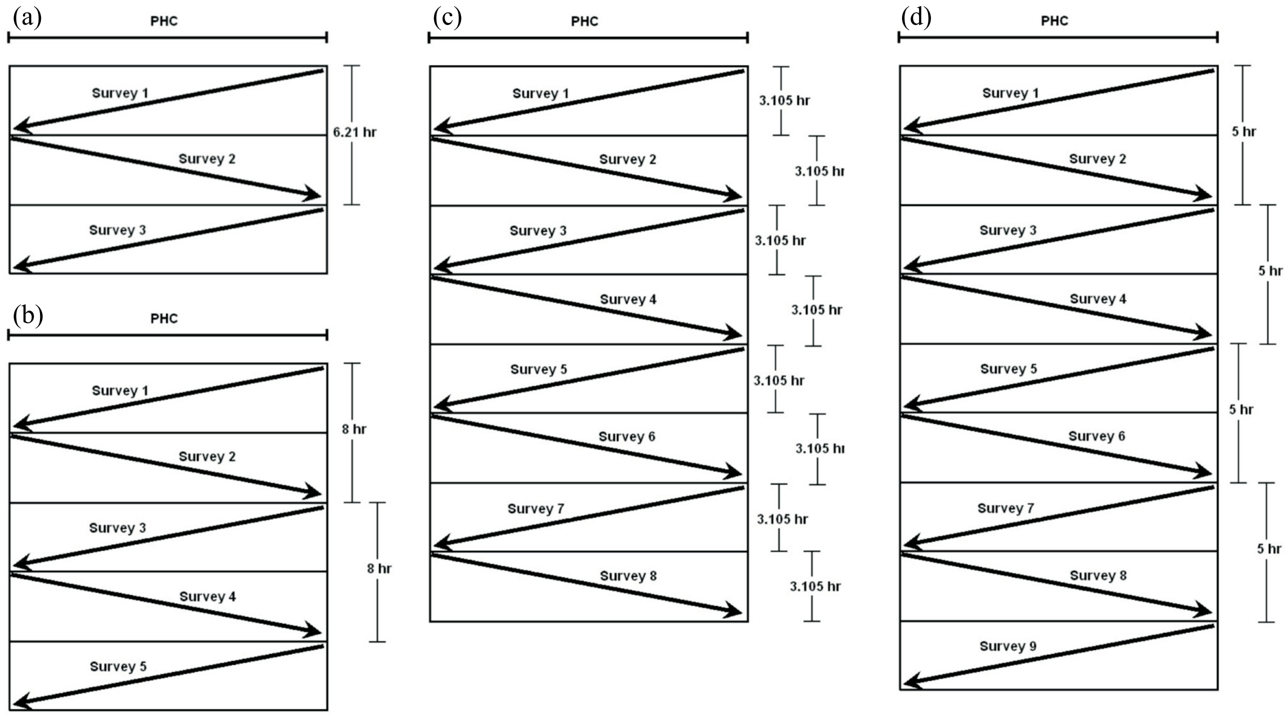

Fig. 2. Various phase-averaging methods used in this study. They are: (a) 2-phase averaging, (b) 3-phase averaging, (c) 4 (and 4R)-phase averaging, and (d) 5-phase averaging. See text for more details.

or used before; we will test their feasibility in this study.

In order to examine the accuracy of various phase averaging methods and to estimate errors induced by the imperfectness of these methods, we have conducted numerical computations which applied the phase averaging methods to a composite of tidal currents. The estimation bias, denoted by V_{EB}, which represents the error of residual flows from phase averaging methods can be estimated from the following mathematical expression:

$$V_{EB} = \frac{1}{N}\sum_{i=0}^{N-1}\{\sum_{q=1}^{M} C_q \cos[\omega_q(t+\Delta t i)-\Phi_q]\} \tag{1}$$

where C_q, ω_q, and Φ_q are the amplitude, angular frequency and phase of the qth constituent tidal current, respectively, the subscript q represents the qth constituent; M is the number of tidal constituents used in the analysis; t is the time and Δt is the time interval between neighboring surveys; N represents the total number of surveys to be averaged ($N = 2, 3, 4, 5$ for 2-phase, 3-phase, 4-phase, and 5-phase averaging, respectively); and the subscript i represents the ith repeated survey. Classification of tidal types is based on the conventional usage of "form ratio" $F = (K_1 + O_1) / (M_2 + S_2)$ of the sum of the amplitudes of the two main diurnal constituents to that of the two main semi-diurnal amplitudes (Pond and Pickard 1983). In our calculation we assumed that the amplitude of M_2 and S_2 (also for K_1 and O_1) is equal, and the sum of M_2, S_2, K_1, and O_1 is 100 cm s^{-1}. Four different tidal types are considered here, that is, F = 0 (semi-diurnal tides, $K_1 = O_1 = 0$, $M_2 = S_2 = 50$ cm s^{-1}), F = 1, (mixed, mainly semi-diurnal tides, $K_1 = O_1 = M_2 = S_2 = 25$ cm s^{-1}), F = 2 (mixed, mainly diurnal tides, $K_1 = O_1 = 33$ cm s^{-1}, $M_2 = S_2 = 16.5$ cm s^{-1}), and F = 3 (diurnal tides, $K_1 = O_1 = 37.5$ cm s^{-1}, $M_2 = S_2 = 12.5$ cm s^{-1}). Considering that the 2-phase averaging is applied to a semi-diurnal tide (F = 0), V_{EB} can be described as:

$$\begin{aligned} V_{EB} = 1/2\ [&C_1\cos(\omega_1 t_1-\Phi_1)+C_1\cos(\omega_1 t_2-\Phi_1) \\ &+C_2\cos(\omega_2 t_1-\Phi_2)+C_2\cos(\omega_2 t_2-\Phi_2)] \end{aligned} \tag{2}$$

where $t_2 = t_1 + \Delta t$, ω_1, ω_2, Φ_1, and Φ_2 are the angular frequency and phase of M_2 and S_2, respectively. Since, $\cos A + \cos B = 2\cos(\frac{A+B}{2})\cos(\frac{A-B}{2})$, Eq. (2) can be reorganized as:

$$\begin{aligned} V_{EB} = &C_1\cos(\omega_1 t_1+\frac{\omega_1\Delta t}{2}-\Phi_1)\cos(\frac{\omega_1\Delta t}{2}) \\ &+C_2\cos(\omega_2 t_1+\frac{\omega_2\Delta t}{2}-\Phi_2)\cos(\frac{\omega_2\Delta t}{2}) \end{aligned} \tag{3}$$

For the case of $\omega_1\Delta t = \pi$, or $\Delta t = T_1/2 = 6.21$ hr, Eq. (3) can be further simplified as: $V_{EB} = C_2 \cos\ (\omega_2 t_1 + \frac{\omega_2\Delta t}{2} - \Phi_2)$ $\cos\ (\frac{\omega_2\Delta t}{2})$. This means that V_{EB} is a function of C_2, Φ_2, and Δt. Generally, V_{EB} of the 3-phase, 4-phase, and 5-phase averaging are also functions of the harmonic constants of the four tidal constituents (C_1, C_2, C_3, C_4, Φ_1, Φ_2, Φ_3, Φ_4) and Δt. Our calculations of V_{EB} were performed for various Δt ranging between 0 and 24 hr with a time increment of 1 min over a total period of 30 days. The averaged V_{EB} over the 30-day period for any Δt is almost invariant with Φ_q, and is plotted in Figs. 3a - d against Δt for 2-phase, 3-phase, 4-phase, and 5-phase averaging, respectively. The V_{EB} derived from various phase averaging methods has minimum values at two optimum Δt for cases of different tidal form ratios (see Table 1). Several conclusions can be drawn from Fig. 3. The 2-phase averaging will yield a minimum V_{EB} of about 0.9 cm s^{-1} at roughly 6.1 hr for the case of F = 0. For the other cases of F > 0, the 2-phase averaging apparently in not a good tide removal method because V_{EB} is always over 10 cm s^{-1}, which is a significant portion of the total tidal amplitude (Fig. 3a). The 3-phase, 4-phase, and 5-phase averaging methods all produce good detiding effect for all tidal types of semi-diurnal, mixed and diurnal tides at a Δt of about 8, 6.1, and 5 hr, respectively (the arrows in Figs. 3b - d). Their corresponding V_{EB} at the first optimum Δt are about 1.8, 1.5, and 1.1 cm s^{-1} (see Table 1). Note that this optimum Δt may shift slightly for different combinations of main tidal constituents. A deviation of ±0.1 hr from the optimum Δt for each phase averaging method and form ratio will increase slightly the V_{EB}. In addition to the first Δt which produces a minimum V_{EB}, a second optimum Δt also exist for various phase averaging methods, e.g., 18.3, 16.3, 18.3, and 9.8 hr for 2-phase, 3-phase, 4-phase, and 5-phase averaging, respectively, and their corresponding V_{EB} are about 2.8, 3.2, 2.8, and 2.5 cm s^{-1} (Table 1). Therefore, computation results as shown in Fig. 3 and Table 1 provide a theoretical and operational basis to determine the Δt for various phase averaging methods.

4. OBSERVATIONS AND DATA ANALYSIS

Three field surveys were carried out along zonal transects across the PHC during 2003 ~ 2004. Flow velocities were measured by using the shipboard ADCP manufactured by RD Instruments with 150 KHz for R/V OR1 or OR3. The bin depth was set to 4 m, and the averaging time interval was 1 min. The ship's absolute movement was determined with bottom tracking, and the cruise track is shown in Fig. 1. Situated at the main section of the PHC, the transects of these three cruises are somewhat different but are parallel to each other and along approximately 23°30'N with the length of the transect about 30 km. Sampling spanned the period 15 - 18 September 2003, 29 - 31 March 2004, and 27 - 30

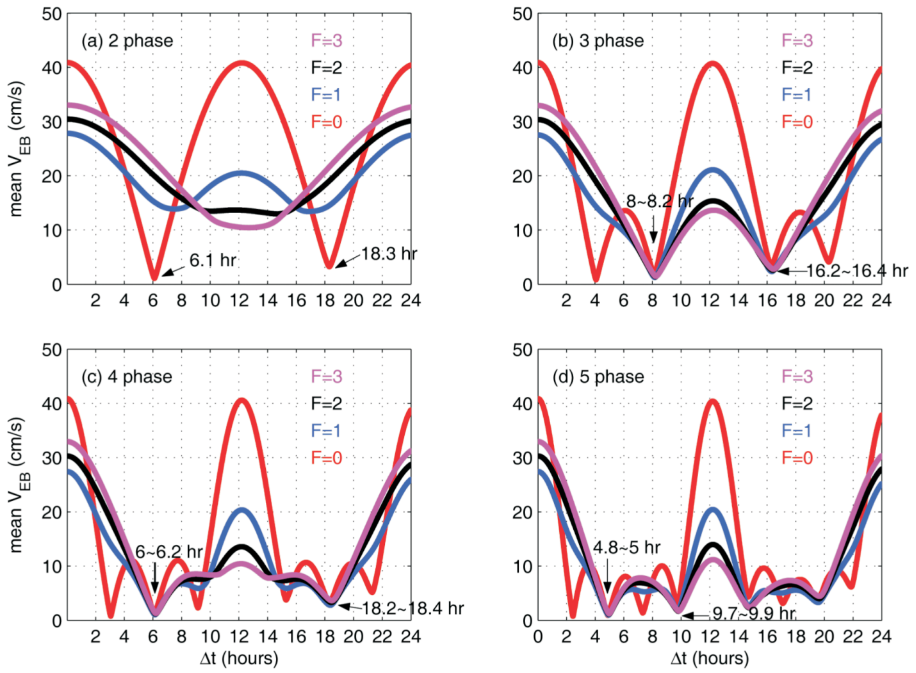

Fig. 3. The mean V_{EB} versus the Δt for: (a) 2-phase, (b) 3-phase, (c) 4-phase, and (d) 5-phase averaging methods in different cases of tidal form ratio (F = 0 ~ 3).

Table 1. The mean residual of tidal current (RT, cm s^{-1}) from: 2-phase, 3-phase, 4-phase, and 5-phase averaging methods for different cases of tidal form ratio (F = 0 ~ 3). Two Δt in the parenthesis produce two minimum V_{EB}.

Method \ Form ratio	**F = 0**	**F = 1**	**F = 2**	**F = 3**
2 phase (Δt = 6.1, 18.3 hr)	0.9 2.8	* *	* *	* *
3 phase (Δt = 8.1, 16.3 hr)	2.0 3.2	1.7 2.3	1.8 2.5	1.8 2.7
4 phase (Δt = 6.1, 18.3 hr)	1.4 2.8	1.5 2.5	1.4 3.1	1.6 3.3
5 phase (Δt = 4.9, 9.8 hr)	1.0 2.5	1.1 1.8	1.1 1.7	1.3 1.7

July 2004 for three cruises. Each cruise consisted of a number of repeated transects with their Δt designed specifically to remove the tidal signals by using various phase-averaging methods.

Table 2 lists the observational period, detiding methods that were used, and other relevant information of three cruises in this study. In the first cruise of September 2003, ten round-trip surveys were made along the same PHC transect, and they consisted of 3-phase averaging, 5-phase averaging, and 2-phase averaging. In the second cruise of March 2004, four round-trip surveys were made along the transect to test the 2-phase averaging, 4-phase averaging, and 4R-phase averaging methods. Note that the 4-phase and 4R-phase averaging is different in that the former is based on the data average of four repeated surveys while the latter is based on the data average of four round-trip (or eight) surveys. Altogether, six sets of 2-phase averaged results and one set of 4R-phase averaged results can be obtained from the westbound and eastbound surveys of this cruise. In the third cruise of July 2004, eleven round-trip surveys were made along the transect,

Table 2. Shipboard ADCP measurement periods, detiding methods, and transports for the three cruises in this study.

Measurement periods	**Methods**	**round-trip surveys**	**R/V**	**Transports (Sv)**
2003/09/15 ~ 2003/09/18	2, 3, and 5 phase, S90	10	OR-1	1.52 ~ 1.87
2004/03/29 ~ 2004/03/31	2 and 4 phase, S90	4	OR-3	1.19 ~ 1.70
2004/07/27 ~ 2004/07/30	3 and 5 phase, S90, W04	11	OR-3	1.22 ~ 1.58

The positive transport is toward the north. (1 Sv = 10^6 m^3 s^{-1})

which consisted of 5-phase averaging and 3-phase averaging surveys. Four sets of 5-phase averaged results and six sets of 3-phase averaged results can be obtained from the westbound and eastbound surveys of this cruise.

Although the observational strategy of the three cruises was originally developed to test the various phase-averaging methods, the repeated surveys along a transect permit the application of stationary analysis techniques (Simpson et al. 1990) or the least squares interpolation techniques using Gaussian interpolation functions with local support (Wang et al. 2004). The former method is abbreviated as S90, and the latter is W04 in this study. These two methods will be used where appropriate to obtain the residual currents at each segment along the transect, and the results of the mean flow profiles and calculated volume transport can be compared with those of the phase-averaging methods.

The first bin of the ADCP data is 10 and 10.6 m for R/V OR1 and OR3, respectively. Velocities of the surface layer from the first bin up to the sea surface are assumed to be constant and equal to the velocity of the first bin. The deepest bin of the ADCP data is determined by the following criteria of data screening: the acceptable data are characterized by percentage with good being greater than 85% and the bin depth being smaller than 85% of the mean water depth. Velocity of the bottom layer is obtained from linear interpolation between the last-bin velocity and the zero bottom velocity. The velocity data along the transect are divided into 10 segments and averaged over each segment.

The averaged velocity is assigned at the midpoint of each segment. For the phase-averaging method, the velocity of each segment and bin for the corresponding tracks were averaged to get the mean velocity. The volume transport through the transect is calculated using the mean velocity perpendicular to the transect as:

$$Q = \sum_{i=1}^{n} \sum_{k=1}^{K_i} v_{(i,\,k)} \cdot d \cdot \Delta z \tag{4}$$

where n is the segment number; k is the layer index; K_i is the bottom layer index of the ith segment; v is the v-component residual velocity; d is the width of each segment; and Δz is the layer thickness.

Hourly wind data, which were collected at an islet weather station, Dongee, near the south of the PHC transect (DG in Fig. 1), were acquired from the Central Weather Bureau of Taiwan for further data analysis.

5. RESULTS

5.1 Estimate of Errors for Phase-Averaging Methods in the PHC

For the four phase-averaging methods used in this study, the 2-phase averaging is the semidiurnal averaging, and the other three methods (3-phase, 4-phase, and 5-phase) are the diurnal averaging. Therefore, it is already clear to conclude that there are some portions of diurnal tidal currents which cannot be eliminated by the 2-phase averaging, and the consequent error of mean velocity and volume transport of the 2-phase averaging will be larger than the other diurnal averaging methods. We estimate the errors of various phase-averaging methods based on a dataset of currents collected near the PHC as follow.

Theoretically, Eq. (1) is only applicable for any fixed location, and the harmonic constants of C_q and Φ_q are location-dependent. Practically, it is quite safe to assume that C_q and Φ_q are invariant along a transect line or studied region and can be obtained from a nearby moored current record. The current data was measured by a bottom-mounted ADCP which was deployed at a station about 90 km south of the PHC (M in Fig. 1). The water depth of the station is approximately 300 m, the bin depth of the ADCP was set to 10 m, and the period of observation is from 22 June to 19 November 1996. Harmonic analysis suggests that tidal current amplitude of M_2, O_1, K_1, S_2, and N_2 for the dominant v-component are 24, 8, 6, 6, and 4 cm s^{-1}, respectively, and the corresponding phases for the five constituents are 243°, 87°, 137°, 282°, and 228°. The blue line in Fig. 4 shows the composite tidal currents over a period of 30 days, which were reconstructed from the amplitude and phase of the five major constituents. The V_{EB} for various phase-averaging methods can be estimated from Eq. (1), in which the Δt is set to be 6.21, 8, 6.21, and 5 hr, respectively for 2-phase, 3-phase, 4-phase, and 5-phase averaging. The green, red, cyan and purple lines in Fig. 4 show V_{EB} versus time for 2-phase, 3-phase, 4-phase, and 5-phase averaging, respec-

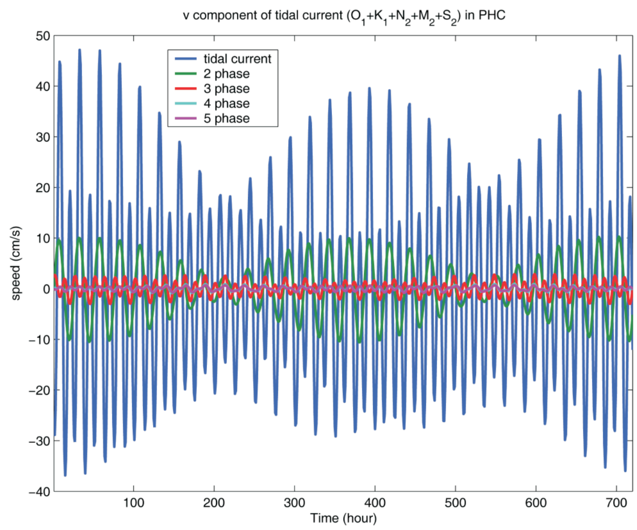

Fig. 4. Time series of v component reconstructed from five tidal constituents ($O_1 + K_1 + M_2 + S_2 + N_2$) at station M in the PHC, and V_{EB} after applying various phase-averaging methods.

tively. Note that the V_{EB} in the PHC from the 2-phase averaging ranges from about ±2.5 cm s^{-1} at the neap tide to about ±10 cm s^{-1} at the spring tide. On the other hand, the V_{EB} in the PHC from the 4-phase and 5-phase averaging remain quite small (less than 2 cm s^{-1}) irrespective of the lunar time. For the 3-phase averaging, the V_{EB} ranges between -2.5 and 2.5 cm s^{-1}. The mean of absolute V_{EB} is 4.6, 1.3, 0.3, and 0.3 cm s^{-1}, respectively for 2-phase, 3-phase, 4-phase, and 5-phase averaging (Fig. 4). The consequent uncertainty of volume transport through the PHC is 0.13, 0.04, 0.01, and 0.01 Sv. It can be concluded that for the PHC region the error of the V_{EB} and the consequent error of volume transport induced by the semi-diurnally 2-phase averaging method are significantly larger than those induced by the diurnally averaging methods of 3-phase, 4-phase, and 5-phase averaging. Among the three diurnally averaging methods used in this study, 4-phase and 5-phase averaging yield slightly better results than 3-phase averaging.

5.2 Velocity Profiles and Volume Transports

Now we turn our attention to the phase-averaged results of the shipboard ADCP data from three cruises. In the first experiment from September 15 to 18 of 2003, three phase-averaging methods were conducted in the PHC sequentially, i.e., in the order of 3-phase averaging, 5-phase averaging, and 2-phase averaging. That is, a total of ten repeated surveys were done along the transect. For each time span the corresponding phase-averaging analysis was applied to the ADCP data to obtain the residual velocity at each segment and vertical bin. In addition, the stationary analysis technique of S90 was also applied to the twenty repeated observations at each location to obtain the mean velocity. A comparison of the 5-phase averaged, 3-phase averaged, 2-phase averaged, and S90-derived velocity contours of the v-component in the transect is provided in Fig. 5. The flow velocities are essentially northward in transport during this cruise. Zonal currents (u-component) are much weaker and therefore are not shown here. It can be seen from the velocity contour plots that a core structure centered in the middle of the transect was developed. The northward velocity in the upper 40 m layer can reach over 80 cm s^{-1} in the 3-phase averaged, 5-phase averaged, and S90-derived velocity contours. The reason for the apparent similarity between Figs. 5a, b, and d can be attributed to their common nature of diurnally averaging analysis. On the other hand, velocity contours from the 2-phase averaging, which eliminate only the semidiurnal tidal currents, are of somewhat different shape (Fig. 5c) such as having a higher core velocity of over 1 m s^{-1}. Also note that the S90 analysis was made based on the least-square interpolation over the entire time span of this experiment, rather than the individual time span of each phase-averaging analysis. As a consequence, the velocity contours derived from the S90 analysis (Fig. 5d) are smoother and in a sense as a combination of the other three contours.

In the second experiment from March 29 to 31 of 2004, four round-trip surveys along the PHC transect were conducted to test the 4R-phase averaging method. Note that the

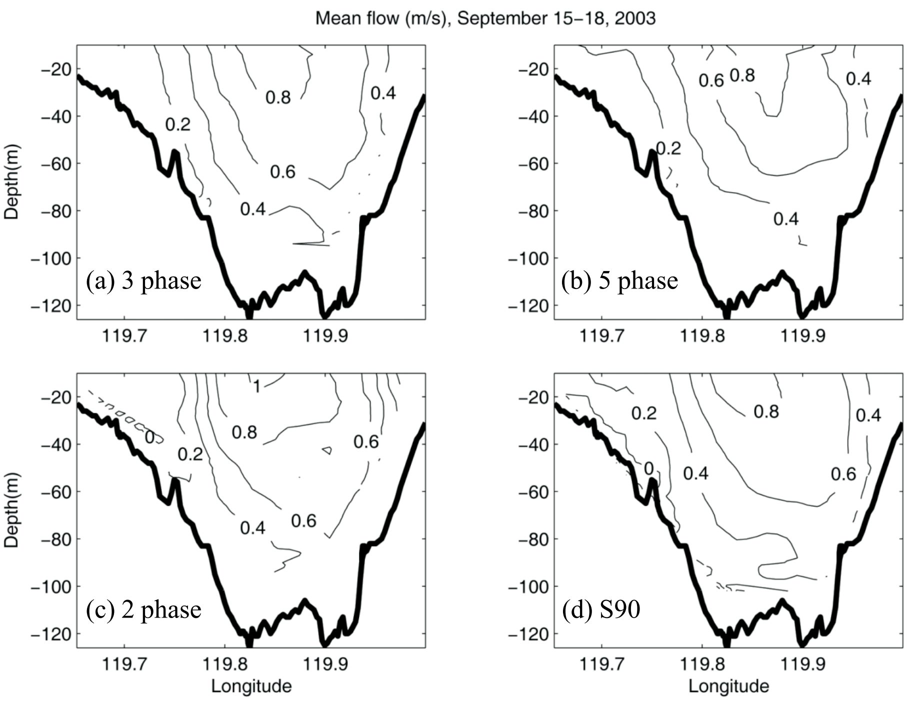

Fig. 5. Velocity contours (m s^{-1}) of PHC from: (a) 3-phase, (b) 5-phase, (c) 2-phase averaging, and (d) S90 analysis (Simpson et al. 1990) in September, 2003.

time span of each survey (either eastbound or westbound) along the transect was maintained constant (3.06 hr). Therefore, six sets of individual 2-phase averaged results can also be obtained from this experiment in addition to the 4R-phase averaged result. Figure 6 shows the contours of mean velocity derived from the six 2-phase averaging analysis, the 4R-phase averaging analysis, and the stationary analysis technique of S90. All contours have similar pattern, with the maximum core velocity reaching around 0.6 m s^{-1} near the central, upper layer of the PHC. The diurnally-averaged velocity contours of 4R-phase averaging have the most resemblance to those of the S90 analysis, which was also fitted to both M_2 and K_1 functions.

In the third experiment from July 27 to 30 of 2004, eleven round-trip surveys were conducted along the PHC transect. The first six round-trips were designed to run in 5-phase averaging scheme, and the next five round-trips were designed to run in 3-phase averaging scheme. The extra surveys, more than that required for each phase-averaging method, allow us to obtain more results to make

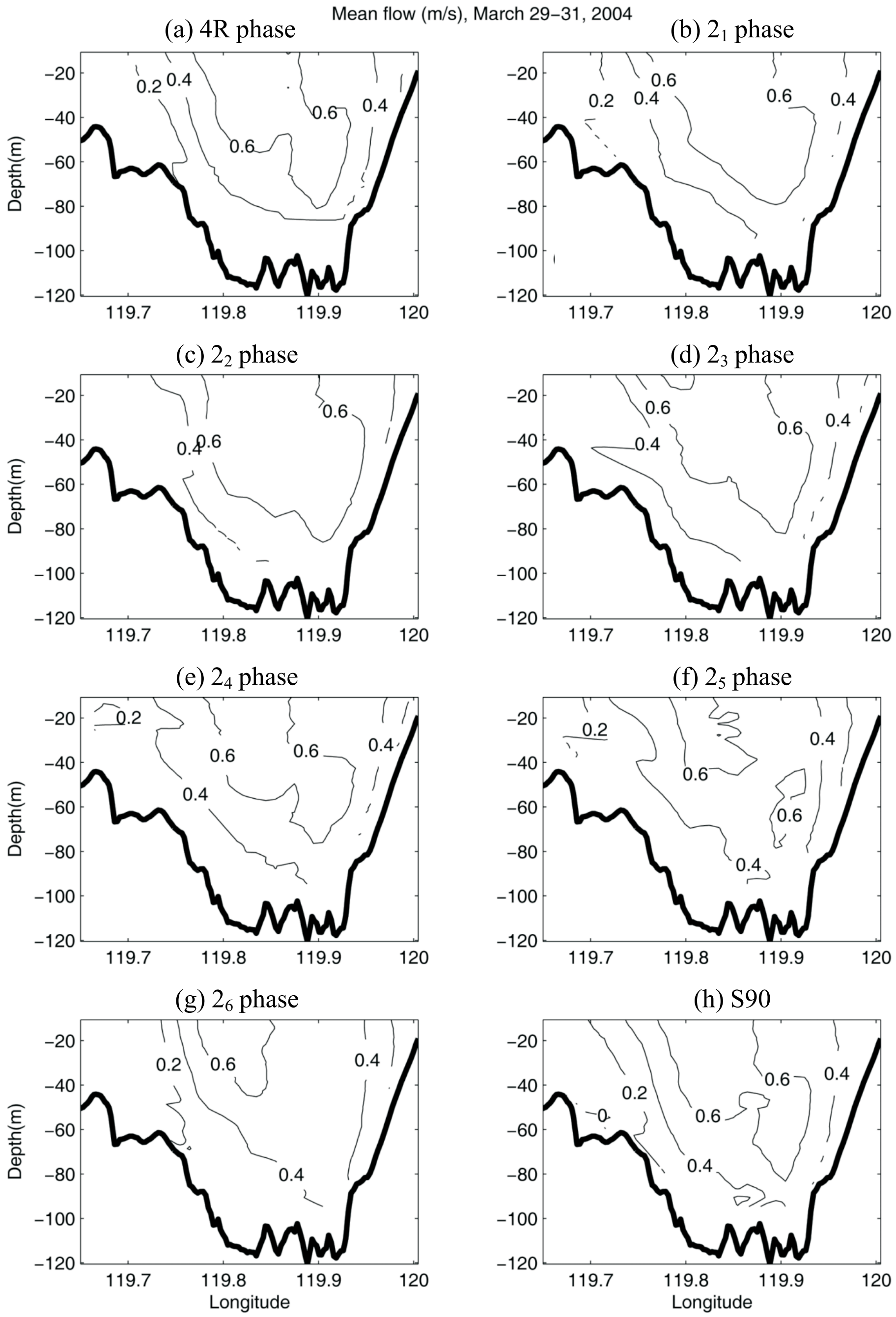

Fig. 6. Velocity contours (m s^{-1}) of PHC from: (a) 4R phase, (b) 2_1 phase, (c) 2_2 phase, (d) 2_3 phase, (e) 2_4 phase, (f) 2_5 phase, (g) 2_6 phase averaging, and (h) S90 (Simpson et al. 1990) in March, 2004.

comparison. In addition to the phase-averaging method, the stationary analysis technique of S90 and the least-square interpolation technique using Gaussian functions of W04 were also applied to the twenty-two observations at each location to obtain the mean velocity. Figure 7 shows the mean velocity contours of PHC for each phase-averaging run and from the technique of S90 and W04. All contours show a maximum speed of about 1 m s^{-1} at the central core region of the PHC.

Because the transects of these three cruises are not

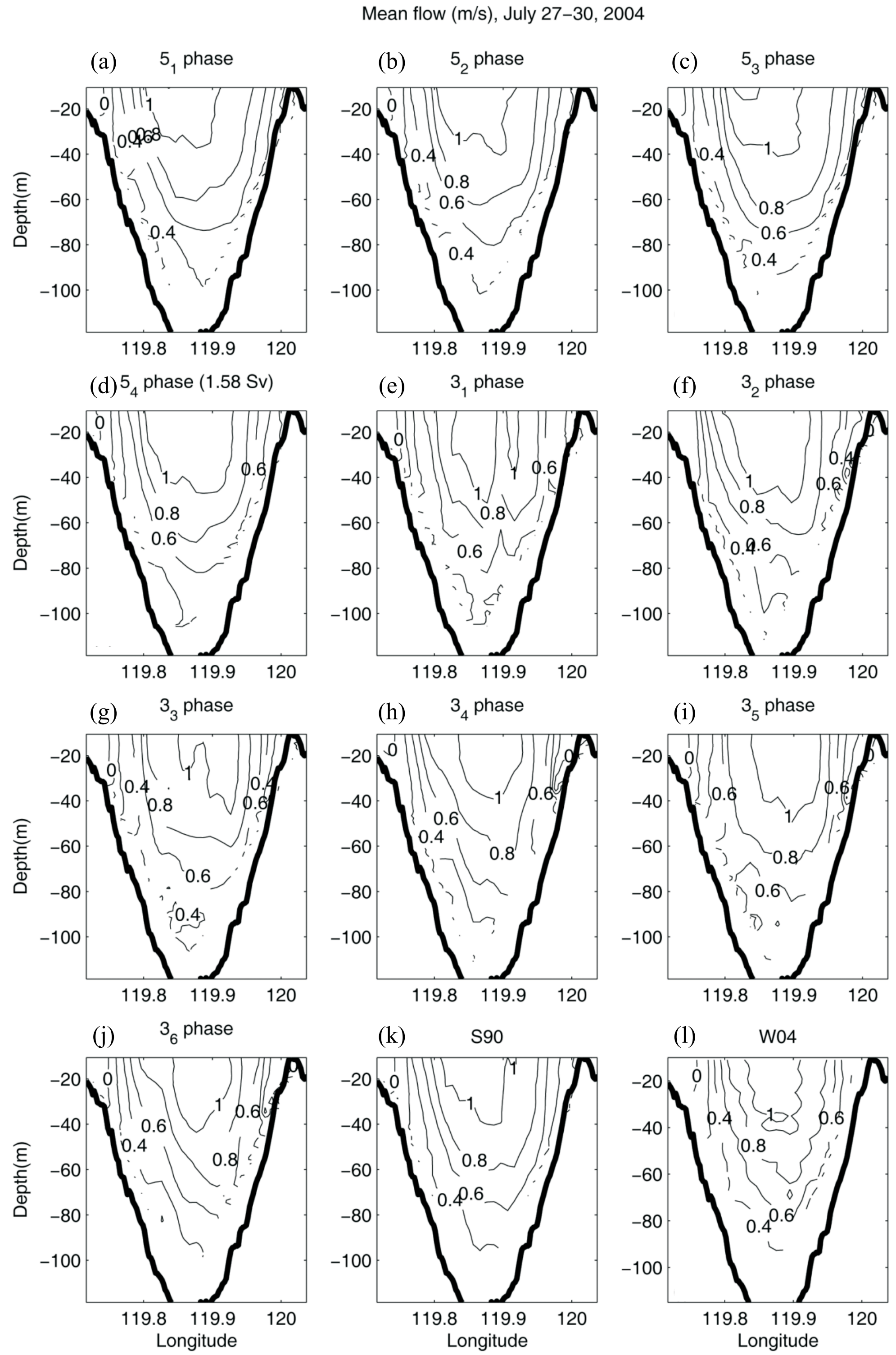

Fig. 7. Velocity contours (m s^{-1}) of PHC from: (a) 5_1 phase, (b) 5_2 phase, (c) 5_3 phase, (d) 5_4 phase, (e) 3_1 phase, (f) 3_2 phase, (g) 3_3 phase, (h) 3_4 phase, (i) 3_5 phase, (j) 3_6 phase averaging, (k) S90 (Simpson et al. 1990), and (l) W04 (Wang et al. 2004) in July, 2004.

completely identical, having a maximum separation of about 20 km apart in between the transects (Fig. 1), it will only be qualitative to compare the detided results of these three cruises. The maximum velocities of the central core in the PHC transect for these three cruises are in accord with the wind speed. For instance, the maximum core velocities are over 100, 80, and 60 cm s^{-1} flowing toward the north respectively for the July 2004, September 2003, and March 2004 cruises during which the local winds are approximately 6 m s^{-1} south wind, 1 m s^{-1} north wind, and 5 m s^{-1} north wind. This finding was confirmed previously by Jan and Chao (2003) and Wang et al. (2004).

6. DISCUSSION

The phase average method can be applied fairly conveniently to either smaller or larger transects or spatial coverage. For shorter channels such as PHC with a length of no more than about 50 km, 2-phase, 3-phase, 4-phase, or even 5-phase averaging is all feasible with a maximum ship speed of 12 knots. In this case the detiding methods of S90 and W04 are also applicable. For larger study regions and longer transects, S90 and W04 may not be useful because usually at least more than 8 observation at any fixed location are needed for least-square interpolation (Geyer and Signell 1990). The phase average method is, however, still good to use in this case. To choose an appropriate phase averaging scheme for any study region, we suggest the following procedures contained here in this example for the region of Taiwan Strait. The length of a transect across the Taiwan Strait is about 150 km, and the nominal ship speed is 10 knots. It will take approximately 8 hours for the ship to finish this transect. The dominant tidal current amplitude for the Taiwan Strait is 31 cm s^{-1} (M_2), 9 cm s^{-1} (S_2), 9 cm s^{-1} (K_1), and 7 cm s^{-1} (O_1) according to the moored current data reported by Lin et al. (2005). The mean V_{EB} for various phase average methods as a function of Δt can then be obtained from Eq. (1) and is plotted in Figs. 8a - d for 2-phase, 3-phase, 4-phase, and 5-phase averaging, respectively. From Fig. 8, some optimum Δt and the corresponding V_{EB} of some phase averaging schemes, which satisfy the condition of $\Delta t \geq 2T$ (16 hours), where T is the time to finish one transect across the Taiwan Strait and their total required ship time are listed below:

(i) 2-phase: $\Delta t = 18.4$ hr, $V_{EB} = 5$ cm s^{-1}, total required time $= 2\Delta t = 36.8$ hr
(ii) 3-phase: $\Delta t = 16.5$ hr, $V_{EB} = 1.5$ cm s^{-1}, total required time $= 3\Delta t = 49.5$ hr
(iii) 4-phase: $\Delta t = 18.4$ hr, $V_{EB} = 1.5$ cm s^{-1}, total required time $= 4\Delta t = 73.6$ hr
(iv) 5-phase: $\Delta t = 17.3$ hr, $V_{EB} = 2$ cm s^{-1}, total required time $= 5\Delta t = 86.5$ hr, or $\Delta t = 19.9$ hr, $V_{EB} = 1.5$ cm s^{-1}, total required time $= 5\Delta t = 99.5$ hr

A trade-off is usually to be made between the phase

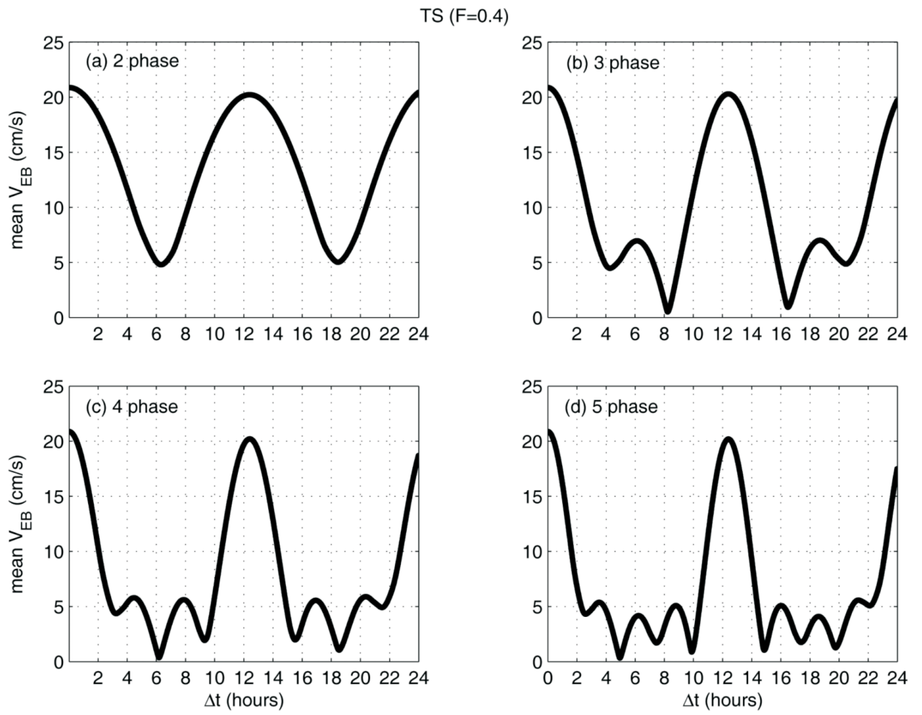

Fig. 8. The mean V_{EB} with respect to the Δt for: (a) 2-phase, (b) 3-phase, (c) 4-phase, and (d) 5-phase averaging methods in the Taiwan Strait based on the reconstructed tidal currents (Lin et al. 2005).

averaging scheme (and thus the total required ship time) and the V_{EB}. For this example, in the Taiwan Strait, the 3-phase averaging appears to be a fairly reasonable and feasible detiding method because total required ship time is less while still obtaining good accuracy. The errors of the residual velocity and the net volume transport induced by the 3-phase averaging are ± 1.5 cm s^{-1} and ± 0.14 Sv in the Taiwan Strait. One of our earlier cruises of August 2002 was conducted using the 3-phase averaging method in the Taiwan Strait and the results of mean flows and transport will be reported elsewhere.

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