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Quantification of tidal asymmetry and its non-stationary variations

Leicheng Guo [a, *], Zheng Bing Wang [a, b, c], Ian Townend [a, d], Qing He [a]

[a] State Key Lab of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China

[b] Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft 2600GA, the Netherlands

[c] Marine and Coastal Systems Department, Deltares, Delft 2629 HV, the Netherlands

[d] School of Ocean and Earth Sciences, University of Southampton, Southampton, UK

* Corresponding author, E-mail: lcguo@sklec.ecnu.edu.cn

Key points

1. Both harmonic and statistical methods are effective in indicating tidal asymmetry.
2. Statistical methods are applicable in quantifying non-stationary variations.
3. We find non-linear effects of river discharge on tidal asymmetry in long estuaries.

Abstract

Tidal wave deformation and tidal asymmetry widely occur in tidal estuaries and lagoons. Tidal asymmetry has been intensively studied because of its controlling role on residual sediment transport and large-scale morphological evolution. There are several methods available to characterize tidal asymmetry prompting the need for an overview of their applicability and shortcomings. In this work we provide a brief review and evaluation of two methods, namely the harmonic method and the statistical method. The latter comprises several statistical measures that estimate the probability density function and various forms of skewness. We find that both the harmonic and statistical methods are effective and have complementary advantages. The harmonic method is applicable to predominantly semi-diurnal or diurnal regimes, while the statistical methods can be used in mixed tidal regimes. Assisted by harmonic data, a modified skewness measure can isolate the contribution of different tidal interactions on net tidal asymmetry and also reveal its subtidal variations. The application of the skewness measure to non-stationary river tides reveals stronger tidal asymmetry during spring tides than neap tides, and the non-linear effects of river discharges on tidal asymmetry in the upper and lower regions of long estuaries.

Key words: Tidal asymmetry; Harmonic; Skewness; Residual sediment transport

Plain Language Summary

Astronomical tide is the primary forcing that drives water motion and subsequent sediment transport and morphological changes in coastal and estuaries waters. Tidal waves propagating from open oceans into tidal estuaries and lagoons often experience changes in wave amplitude, speed, and shape, displaying tidal wave deformation and associated tidal asymmetry that is featured by unequal rising and falling tidal periods. This work first provides a brief review of the methods available for the quantification of tidal asymmetry in varying tidal environments, and discusses their applicability based on constructed data. The application of these two methods to measured non-stationary tides in a long estuary, under significant time-varying river discharges, reveals strongly non-linear and non-uniform features of tidal asymmetry. The findings of this work have implications for the interpretation of high water levels in flood management and large scale estuarine morphological evolution.

1. Introduction

Sediment transport is a focal point in coastal management, particularly in tidal estuaries and lagoons where there is conflicting interest between coastal developments and tidal wetland conservation under sea-level rise. Other than the controlling impacts of sediment source availability, the dynamic processes leading to residual (tide-averaged) sediment transport are of significant relevance in examining erosion and deposition and consequent morphological changes (Dronkers, 1986). Tidal asymmetry is recognized as one of the most important processes in creating residual sediment transport and associated large-scale morphological changes in tidal environments including estuaries, tidal inlets and lagoon systems, and coastal waters (de Swart and Zimmerman, 2009). Tidal asymmetry in general refers to the phenomenon of tidal wave deformation (Pugh, 1987; Friedrichs and Aubrey, 1988). This leads to an unequal duration of the rise and fall of the height of the tide (vertical tide) and consequently, offsets between the strength of the flood and ebb velocities (horizontal tide). Moreover, examination of tidal wave deformation and tidal asymmetry also deepens our understandings of tidal dynamics in shallow coastal waters and has implication as regards coastal flooding and management (Godin, 1985, 1999; Guo et al., 2015). Overall, tidal asymmetry has been well-examined regarding its behavior and variability (Dronkers, 1986; Friedrichs and Aubrey, 1988; Wang et al. 1999) and its controlling effects on residual sediment transport and large-scale morphodynamics (Postma, 1961; Guo et al., 2016a, b; Gatto et al., 2017).

In this work we discuss three types of tidal asymmetry: (1) unequal rising and falling tidal durations of vertical tides, called *tidal duration asymmetry*, (2) uneven peak ebb and flood velocities, called *peak current asymmetry*, and (3) unequal high water and low water slack durations in tidal currents, called *slack water asymmetry* (Dronkers, 1986; Gong et al., 2016; Guo et al., 2018). A shorter rising tide than falling tide, stronger peak flood currents than ebb currents, or a longer high water slack than low water slack result in flood dominance. Conversely a shorter falling tide, stronger ebb currents, or longer low water slack promote ebb dominance. Flood dominance will cause flood-directed residual sediment transport, sediment import and tidal basin infilling, while ebb dominance will cause seaward sediment flushing, sediment export and tidal estuary emptying.

Tidal duration asymmetry has been more widely examined compared to peak current asymmetry, and slack water asymmetry because tidal water level data are readily more available than tidal currents. Tidal duration asymmetry and peak current asymmetry are coherently connected, such that a shorter rising tide will lead to stronger flood currents in the absence of significant river discharges. In addition, non-tidal forcing such as river discharge and storm surges etc. can profoundly modulate tidal propagation and deformation, thus altering tidal asymmetry as well. Storm surges affect tidal waves given their comparable space and time scales in shallow waters (LeBlond, 1991). River discharge is usually non-stationary and can raise mean water level (Cai et al., 2016), reduce tidal amplitudes, retard tidal phases (Godin, 1985, 1991), and enhances wave deformations (Guo et al., 2015) inside tidal estuaries. The duration of rising tides become shorter and falling tides become longer under a significant river discharge, suggesting enhanced tidal wave deformation. Moreover, non-tidal forcing and/or hypsometric effects of inter-tidal flats may cause modification of tidal currents such that tidal duration asymmetry and peak current asymmetry may become inconsistent, e.g., shorter rising tide coexists with stronger ebb currents in tidal estuaries with a significant river discharge (Friedrichs and Aubrey, 1988; Guo et al., 2014). These variations ask for more specific examinations of tidal asymmetry by different quantification methods.

A number of studies have examined the nature and variability of tidal asymmetry in varying tidal environments (Aubrey and Speer, 1985; Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988; Wang et al., 1999, 2002; Nidzieko, 2010; Song et al., 2011; Guo et al., 2018). Different methods are used to characterize and quantify tidal asymmetry, but so far the applicability, advantages and shortcomings of these methods have not been addressed. In this work we provide a review and evaluation of two methods available as hydraulic measures of tidal asymmetry, namely: (1) harmonic method, which is based on the phase differences and amplitude ratios of the interacting tidal constituents, and (2) a set of statistical measures that estimate probability density function (PDF) and various forms of skewness using tidal heights or tidal currents. Other than the hydraulic measures, there are morphological metrics which are used to characterize tidal asymmetry and residual sediment transport, e.g., the proxy using tidal amplitude to water depth ratio and inter-tidal storage volume to channel volume ratio (Friedrichs and Aubrey, 1988), and an indicator based on relative change rates of high water and low water surface area (Dronkers, 1986). These morphological metrics have recently been reviewed by Zhou et al. (2018) and link closely to the hydraulic measure examined in this work.

2. Data used

We apply the methods to two types of data to provide a comprehensive evaluation of their applicability in varying environments. The first data are reconstructed tidal signals based on the harmonic constants of user-selected constituents, e.g., the reconstructed signals based on M_2+M_4 or M_2+O_1+K_1 constituents with different amplitudes and phases. These datasets are used to check the effectiveness of different methods when the nature of tidal asymmetry is straightforward to detected from the signals. Application and discussion of these data follows the descriptions of the methods in section 3.

The second type of data are actual tidal height measurements in the Changjiang River estuary in China that is used to demonstrate the advantages and shortcoming of the methods (Figure 1). The Changjiang River estuary is a meso-tidal coastal plain estuary physically forced by mixed tides with tidal ranges up to 5 m and a river discharges seasonally varying in the range of 10,000-60,000 m^3/s at Datong (the tidal wave limit) (Guo et al., 2015). Tidal wave propagation in the Changjiang River estuary is modulated by basin geometry, shallow water effects, and highly varying river discharges, thus exhibiting strong tidal wave deformation and non-stationary behaviors and associated spatial variability. For instance, strong tidal wave amplification and tidal bores take place in the landward portion of the North Branch, e.g., at Qinglonggang (QLG, because of high convergence and the limited influence of river discharge; Figure 1), displaying a different behavior to the South Branch (see section 4.1). Moreover, we also collect one-year tidal height data (hourly interval) at 80 gauges along the US coasts from websites of NOAA (https://co-ops.nos.noaa.gov) (see Figure S1). Only the gauges along the open coasts are selected (those inside estuaries and lagoons are omitted to avoid river influences). Furthermore, we also include tidal current data which are from a numerical model of a short tidal estuary, the Newport Bay in southern California (see section 3.2). More descriptions of the tidal data in the Changjiang River estuary and in Newport Bay can be found in Guo et al. (2015) and Guo et al. (2018), respectively, thus are not repeated here. Tidal harmonic analysis is then performed to the tidal height and tidal current data by using the T_Tide function (Pawlowicz et al., 2002), which outputs tidal harmonics (amplitudes and phases) for quantification of the tidal asymmetry.

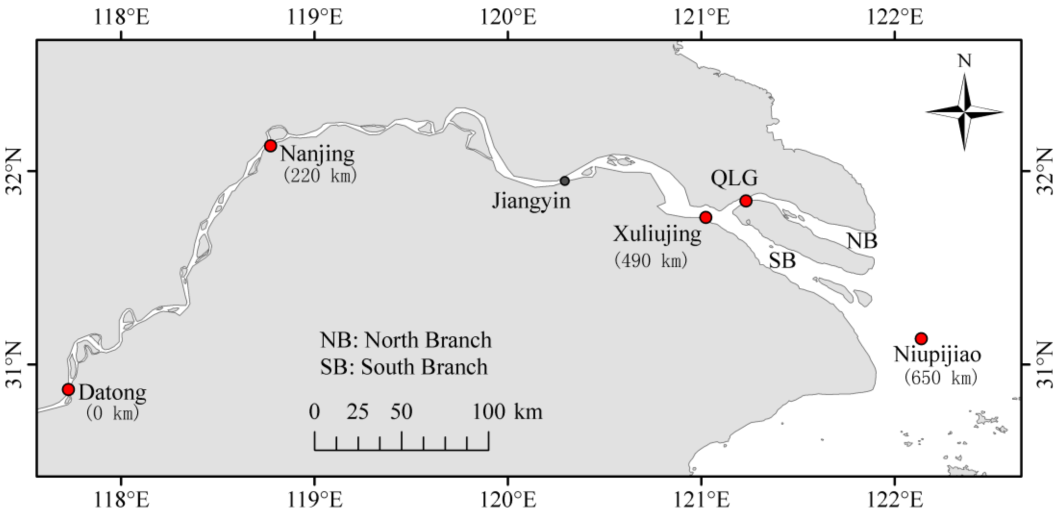

Figure 1. Sketch of the Changjiang River estuary and tidal gauges. The numbers in the brackets indicate the seaward distance to Datong, the tidal wave limit in the dry season. Niupijiao represents the river mouth, and Xuliujing and Nanjing represents the lower and upper estuary, respectively, with the division roughly at Jiangyin (Guo et al., 2015). QLG is the abbreviation of Qinglonggang. The smaller dots indicate other tidal gauges though their data are not included in this work.

3. Methods review

In this section we present two types of method, namely the harmonic method and the statistical method. The harmonic method has been widely used in previous studies, and the occurrence of tidal asymmetry is evaluated based on the phase differences of the tidal constituents (resolved by harmonic analysis of tidal water levels or tidal currents) that interact and create tidal wave deformation (section 3.1). The statistical methods have several forms, including calculating the probability distribution function of tidal heights and (rising and falling) tidal durations (section 3.2), and evaluating the skewness of the time derivative of tidal water levels or the transformed skewness of tidal water levels (section 3.3). These statistical methods do not rely on harmonic analysis but, instead, examine the statistical properties of tidal waves to infer wave deformation and consequent tidal asymmetry.

3.1 Harmonic method

The harmonic method used to characterize tidal asymmetry is based on the tidal harmonics (amplitudes and phases of tidal constituents) resolved from actual tidal data. Two indicators are included, i.e., the phase differences and amplitude ratios between two or more tidal constituents that interact and generate tidal asymmetry. As indicated in Song et al. (2013), the interacting tidal constituents satisfying a frequency relationship such as $2\omega_1=\omega_2$, $3\omega_1=\omega_2$, $\omega_1+\omega_2=\omega_3$ (ω is frequency, the subscript indicates different tidal constituents) can generate tidal asymmetry. Hence the phase differences such as $2\theta_1-\theta_2$, $3\theta_1-\theta_2$, and $\theta_1+\theta_2-\theta_3$ (θ is phase) are used to indicate the nature of tidal asymmetry. For instance, the M_2-M_4 interactions ($2\omega_{M2}=\omega_{M4}$) are widely recognized as the dominant cause of tidal wave deformation and associated tidal asymmetry (Speer and Aubrey, 1985; Friedrichs and Aubrey, 1988). Therefore a phase difference of $2\theta_{M2}-\theta_{M4}$ in the range of 0~180º leads to a shorter rising tide than falling tide thus flood dominance (Figure 2b), while a phase difference in the range of 180~360º leads to a shorter falling tide and ebb dominance (Figure 2d). A $2\theta_{M2}-\theta_{M4}$ phase difference of exactly 0 or 180º will lead to equal rising and falling tides thus no tidal asymmetry though the wave shape is statistically skewed (Figures 2a and 2c). Under the same phase difference, the A_{M4}/A_{M2} amplitude ratio (A is tidal amplitude) is used to indicate the magnitude of the tidal asymmetry. A larger amplitude ratio implies stronger tidal wave deformation and tidal asymmetry. Successful applications of the harmonic method to predominantly semi-diurnal regimes, e.g., US Atlantic coasts

(Friedrichs and Aubrey, 1988), Dutch coasts (Wang et al., 1999), and idealized tidal basins driven by M_2 tide only (Guo et al., 2014), have confirmed its effectiveness.

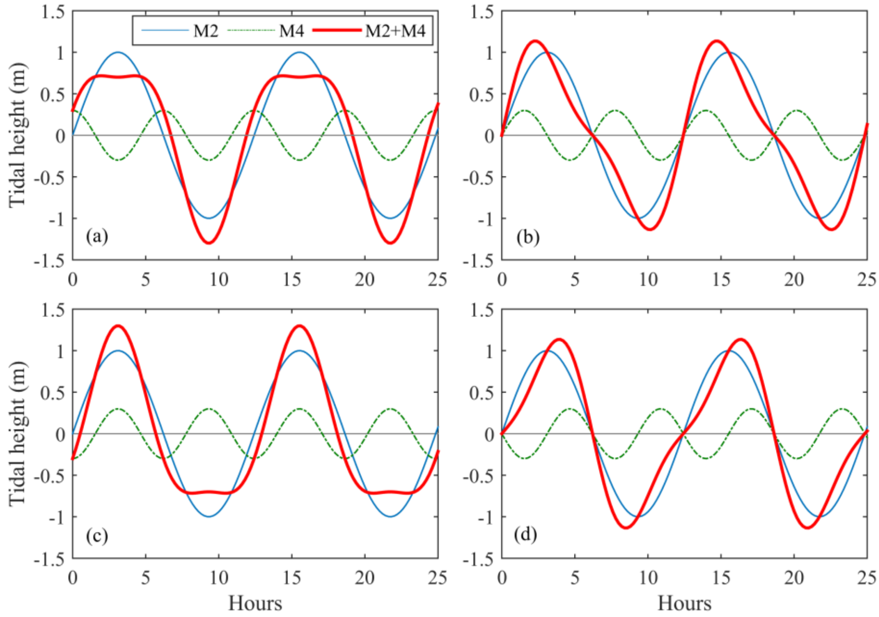

Figure 2. Tidal heights by M_2, M_4 and M_2+M_4 tides with a phase difference $2\theta_{M2}-\theta_{M4}$ of (a) 0, (b) 90º, (c) 180º, and (d) 270º. The A_{M4}/A_{M2} amplitude ratio is 0.3.

Similarly, the dual tidal interactions such as M_2-M_6 ($3\omega_{M2}=\omega_{M6}$) and K_1-K_2 ($2\omega_{K1}=\omega_{K2}$) can generate tidal asymmetry, and they can be quantified by phase differences such as $3\theta_{M2}-\theta_{M6}$ (Blanton et al., 2002) and $2\theta_{K1}-\theta_{K2}$ (Jewell et al., 2012), respectively. Moreover, triad tidal interactions such as M_2-M_4-M_6 ($\omega_{M2}+\omega_{M4}=\omega_{M6}$), M_2-S_2-MS_4, M_2-N_2-MN_4, M_2-O_1-K_1, and S_2-K_1-P_1 have been shown to generate measurable tidal asymmetry in tidal estuaries, and accordingly the tidal asymmetry can be quantified by phases differences of $\theta_{M2}+\theta_{M4}-\theta_{M6}$, $\theta_{M2}+\theta_{S2}-\theta_{MS4}$, $\theta_{M2}+\theta_{N2}-\theta_{MN4}$, $\theta_{O1}+\theta_{K1}-\theta_{M2}$, and $\theta_{K1}+\theta_{P1}-\theta_{S2}$, respectively (van de Kreeke and Robaczewska, 1993; Hoitink et al., 2003; Song et al., 2011; Guo et al., 2016a). A phase difference in the range of 0~180º will cause a shorter rising tide than falling tide and flood dominance, similar in the $2\theta_{M2}-\theta_{M4}$ case.

The harmonic method can be used to indicate peak current asymmetry in a similar way as tidal duration asymmetry based on the harmonics of resolved tidal currents. In short tidal basins with limited inter-tidal flats and insignificant river discharge where standing waves form, vertical tides and horizontal tides are in quadrature (Nidzieko, 2010). Therefore, a phase difference of tidal currents, e.g., $2\Phi_{M2}$-Φ_{M4} or Φ_{O1}+Φ_{1}-Φ_{M2} (Φ is phase of horizontal tides), in the range of 90~270º indicates ebb dominance and that between -90º and 90º indicates flood dominance (Friedrichs and Aubrey, 1988; Guo et al., 2014, 2016a). For instance, the phase differences of θ_{O1}+θ_{K1}-θ_{M2} and Φ_{O1}+Φ_{1}-Φ_{M2} are 253º and 181º, respectively, in Newport Bay, both indicating ebb dominance (Guo et al., 2018). It is understandable because a shorter falling tide than rising tide needs larger ebb currents to convey the same tidal prism, thus ebb dominance takes place.

3.2 Statistical method, measure I- probability density function

In addition to the harmonic method, tidal asymmetry has been characterized by statistical measures. One approach is to use the PDF of the time series of tidal heights (referenced to mean water level); referred to as the Tidal Height PDF, or TH-PDF. We see that a symmetric sinusoidal tidal signal has a bimodal distribution for the TH-PDF. Deviation from this bimodal distribution suggests wave shape deformation although not necessarily tidal asymmetry (Ranasinghe and Pattiaratchi, 2000). For instance, the TH-PDFs of the constructed tidal signals (reconstructed based on M_2 and M_4 constituents as shown in Figure 2) with or without tidal asymmetry are similarly symmetric, thus we can not tell which one is flood or ebb dominant (Figure 3). To overcome that, Castanedo et al. (2007) reported a wave-by-wave method to characterize tidal statistics by estimating the PDFs of four variables, i.e., the time series of wave crest (*a*) and trough (*b*) amplitudes, mean level (*m*), and standard deviation (*s*) of the tidal height. A sinusoidal wave without tidal asymmetry will have a=b=A, m=0, and $s=\sqrt{2}\mathrm{A}/2$. Based on a long time series of tidal height data, a scatter plot of the four variables against tidal height will exhibit deviations from their values for symmetric sinusoidal waves, thus possibly indicating tidal asymmetry. However, this wave-by-wave method only indicates the occurrence of tidal asymmetry but not its nature (flood or ebb dominance).

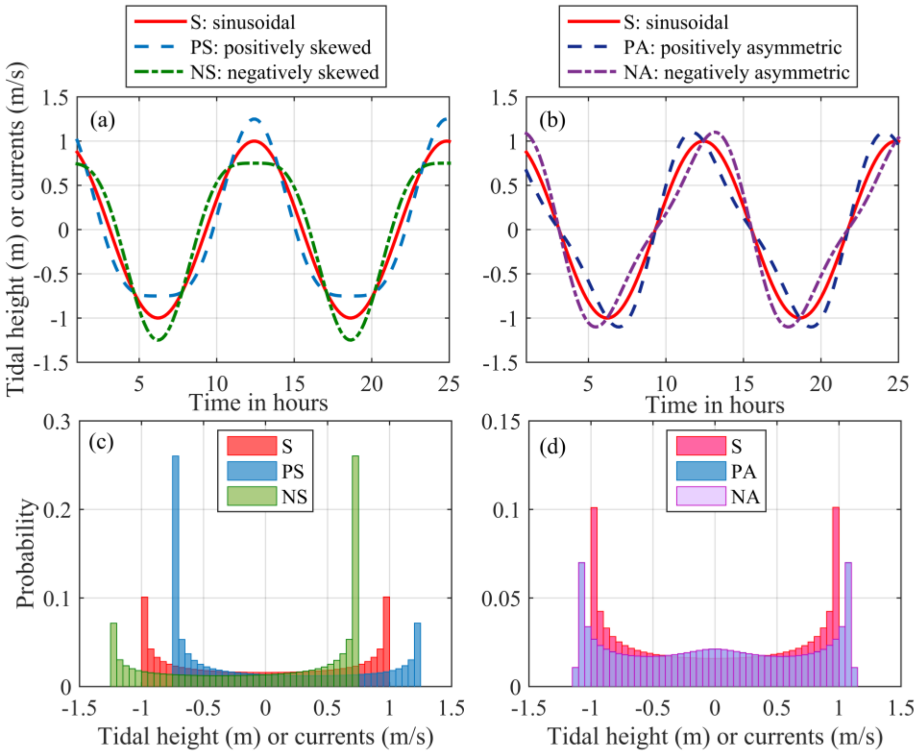

Figure 3. (a) Skewed and (b) asymmetric tidal wave or tidal current curves, and (c, d) their corresponding PDFs. The positively and negatively asymmetric curves in pane (b) have the same PDF thus they are overlapped in panel (d). The flood currents are positive and ebb currents are negative in panel (a) and (b).

Another approach is based on the PDF measure of the time series of rising (indicated with a positive sign) and falling (indicated with a negative sign) tidal durations; referred to as the Tidal Duration PDF, or TD-PDF. The rising and falling tidal durations are directly derived from the tidal water level data. Statistical indicators of the TD-PDF are then used to quantify tidal duration asymmetry, e.g., the skewness indicator (see section 3.3). In a simplified form, an equal percentage of rising and falling tidal durations indicates no tidal asymmetry, whilst food dominance occurs when the average rising tidal duration is <50% of the total period, and the converse is true for ebb dominance (Lincoln and Fitzgerald, 1988; Jewell et al., 2012). Such a definition is consistent with the concept of tidal duration asymmetry, and it is theoretically applicable to all tidal regimes. Application of the TD-PDF to the constructed tidal signals (see Figure 2) suggests a percentage of rising tidal durations of 36% and 64% for the composite M_2+M_4 tides in Figure 2b and Figure 2d, respectively, suggesting flood dominance and ebb dominance that agrees with the harmonic method. Note that hourly tidal water level data are not enough to provide an accurate estimation of the falling and rising tidal durations, thus long-time series of data with a high time resolution are needed to accomplish significant differences between falling and rising tidal durations and to get rid of short-term periodic variability when the tidal signals are complex (see section 4.1).

The PDF measure also applies to the characterization of peak current asymmetry by examining the PDF of tidal currents; referred to here as the Tidal Current PDF, or TC-PDF. Being similar to the TD-PDF, a larger percentage (>50%) of flood currents than ebb currents, i.e., a higher probability of the occurrence of flood currents, indicates flood dominance, when assuming flood currents are positive and ebb currents are negative (Ranasinghe and Pattiaratchi, 2000). Moreover, the TC-PDF is better estimated by using u^3 instead of u (u is tidal current) to account for the non-linear relationship between sediment transport and velocity, i.e., an exponentially higher sediment transport capacity for larger current velocities (see Figure S2). A larger percentage of the cubed flood currents than cubed ebb currents indicate flood dominance. The TC-PDF is similar to the skewness measure that considers a cubic numerator of currents (see Eq. 1 in section 3.3).

3.3 Statistical method, measure II **-** skewness

Statistical skewness

Skewness is a statistical measure of the asymmetry present in the PDF of an input signal compared to a normal distribution. The skewness measure characterizes the degree of asymmetry about the horizontal axis (up-and-down asymmetry) and the asymmetry measure represents the degree of asymmetry about the vertical axis (front-and-back asymmetry) of a PDF. The skewness indicator is calculated as follows:

$$Sk(x) = \frac{\frac{1}{N-1}\sum_{t=1}^{N}(\eta_t - \overline{\eta})^3}{[\frac{1}{N-1}\sum_{t=1}^{N}(\eta_t - \overline{\eta})^2]^{3/2}} \qquad \text{(Eq. 1)}$$

where Sk is the skewness indicator, x_t is the time series of the input signal, $\overline{\eta}$ is the mean value, and N is the length of equidistant time series data. The skewness method has been used in a wide variety of geophysical fields, such as for the characterization of turbulence non-linearity in fluid mechanics and acoustic wave transformation etc. (Shepherd et al., 2011; Reichman et al., 2016). A positive skewness of an input signal indicates a longer and/or flatter tail on the right side of its PDF (median value<mean value), and conversely a negative skewness indicates a longer and/or flatter tail on the left side (median value>mean value).

When applying Eq. (1) to tidal water levels, we see that the skewness indicators are non-zero for both the positively and negatively skewed signals in Figure 3a (i.e., skewed TH-PDF), whereas actually both signals have equal rising and falling tidal durations (i.e., no tidal asymmetry). Similarly, the skewness indicators are zero for both the positively and negatively asymmetric signals in Figure 3b (i.e., non-skewed TH-PDF), whereas the two signals actually have unequal rising and falling durations (i.e., with tidal asymmetry). It thus implies that using the tidal water levels as input signals in Eq. (1) can not indicate tidal asymmetry, and some modification of this method are outlined in the following sections.

Transformed skewness

One solution is to use an asymmetry proxy, a transformed skewness measure. It is a skewness measure of the imaginary part of a Hilbert-transformed input signal. It reads as:

$$As = Sk\{imag[H(\eta)]\} \qquad \text{(Eq. 2)}$$

where As is the transformed skewness measure, $H(\cdot)$ indicates the Hilbert transform, and $imag(\cdot)$ indicates the imaginary part (the real part of the output of a Hilbert transform is the input signal itself). The transformed skewness measure has been used in characterizing wave-induced current asymmetry under short wave impacts (Ruessink et al., 2009). For a time-series of tidal water levels, the imaginary part of a Hilbert-transformed tidal height leads to positive and negative outputs for falling and rising tides, respectively (see Figure S3). Therefore, a positive value of the transformed skewness measure suggests longer rising tidal durations than falling tide durations on average (i.e., ebb dominance), and a negative value indicates longer falling tidal durations (i.e., flood dominance) (Bruder et al., 2014). To further validate the general effectiveness of the transformed skewness, we apply it to the constructed signals in Figure 3 and find that the transformed skewness is consistently zero for the sinusoidal signal (S), and the positively (PS) and negatively (NS) skewed signals in Figure 3a, thus implying no tidal asymmetry. The transformed skewness is -0.48 and 0.48 for the positively (PA) and negatively (NA) asymmetric signals in Figure 3b, suggesting longer falling and rising tidal durations, respectively. The evaluation by the transformed skewness measure is therefore consistent with the harmonic method, demonstrating its effectiveness as a suitable measure of tidal asymmetry.

Derivative skewness

Another option of is to use the time derivatives of tidal height as the input signal in Eq. (1) instead of tidal height itself (Nidzieko, 2010), called derivative skewness, as follows:

$$Sk_{TDA} = Sk(d\eta/dt) \qquad \text{(Eq. 3)}$$

where TDA stands for tidal duration asymmetry. The time derivative ($\mathrm{d}\eta/\mathrm{d}t$) transforms rising and falling tidal water levels into positive and negative gradients (see Figure S3), thus enabling tidal duration asymmetry estimation in a similar way to the Hilbert transform in Eq. 2. A positive derivative skewness indicates a shorter rising tide than falling tide and flood dominance, while a negative derivative skewness demonstrates a shorter falling tide and ebb dominance. Applying the derivative skewness measure to the constructed signals will give zero value for signals S, PS and NS in Figure 3a, but 0.76 and -0.76 for signals PA and NA, respectively, in Figure 3b, implying its applicability. Note that the transformed and derivative skewness measures have opposite sign for the same tidal asymmetry. The derivative skewness method was further extended and used to isolate the contribution of tidal interactions like M_2-M_4, M_2-O_1-K_1, and S_2-K_1-P_1 etc. on the total tidal asymmetry (Song et al., 2011), and to uncover fortnightly variations of tidal duration asymmetry when applying Eq. (3) using a moving window (e.g., 3 days) (Guo et al., 2016b).

When applying the transformed skewness (Eq. 2) and derivative skewness (Eq. 3) measures in their present form, we find that the cubic numerator in the skewness indicator (in Eq. 1) will amplify the rising and falling rates of tidal height and this nonlinear amplification may cause misleading results. Preliminary tests of the derivative skewness method on artificially generated signals (with fixed falling and rising tidal duration but different rising and falling limbs) suggested that the derivative skewness varies in a considerable range, e.g., -0.1~1.2, and can be even negative when the rising tide is actually shorter than falling tide (see Figure S4). A similar discrepancy also occurs for the transformed skewness given by Eq. 2 (see Figure S4). The discrepancies occur because the cubic numerator in Eq. 1 will significantly increase the statistical importance of large derivatives (e.g., large tidal height rising and falling rates). With respect to the shape of a PDF, the statistical skewness does not distinguish the impacts of a long or a flat tail; therefore zero skewness may indicate a symmetric PDF, or an asymmetric PDF with a long tail and a flat tail on either side when the asymmetry evens out. To overcome this, Guo et al. (2018) suggested an improvement by employing the derivative skewness to the time series of high water (HW) and low water (LW), thus the nonlinear variations in the rising and falling limbs of the tidal water level curves are removed and only the duration differences between HW-LW or LW-HW will affect the skewness measure. The calculation then reads as follow:

$$Sk_{TDA} = Sk(d\eta_{HW-LW}/dt) \qquad \text{(Eq. 4)}$$

where $\eta_{HW\text{-}LW}$ indicates the filtered time series signals with HW and LW only (with linear interpolation between HW and LW to obtain equidistance data if necessary). The same HW-LW series of data can be also used as input to the transformed skewness measure. Preliminary application of the filtered derivative skewness has demonstrated its effectiveness to accurately indicate tidal duration asymmetry (Guo et al., 2018). When taking the derivative skewness of the filtered data as reference and applying both Eq. (3) and Eq. (4) to the tidal height data collected along the US coasts, we see that usage of the original signals will predominantly overestimate the magnitude of tidal asymmetry and the overestimation becomes larger for stronger tidal asymmetry (see Figure S5).

Skewness measure applied to tidal currents

The skewness measure is also applicable for quantification of peak current asymmetry and slack water asymmetry (Bruder et al., 2014; Gong et al., 2016; Guo et al., 2018). Skewed current curves (preponderance of large crests or troughs) have unequal peak ebb and flood currents, demonstrating the presence of peak current asymmetry but not slack water asymmetry (see Figure 3a). Similarly, asymmetric current curves have equal peak currents but uneven slack waters, thus indicating the presence of slack water asymmetry but not peak current asymmetry (see Figure 3b). The asymmetric current curves can be seen as acceleration-skewed, thus it is in line with the definition of slack water asymmetry. To use the skewness measure for quantification of peak current asymmetry (PCA), the input signal is tidal currents:

$$Sk_{PCA} = Sk(u) \qquad |u| > u_c \qquad \text{(Eq. 5)}$$

and for quantification of slack water asymmetry (SWA), the input signal is the acceleration of the currents:

$$Sk_{SWA} = Sk(du/dt) \qquad |u| < u_c \qquad \text{(Eq. 6)}$$

where u is a time series of tidal currents, and u_c is a velocity threshold to filter the tidal currents needed for transport of coarse sediments and for settling of fine sediments (Guo et al., 2018). Considering that sediment transport is a power function of velocity by an order of 3-5 (van Rijn, 1993), the skewness measure might be expected to a good measure for quantifying the peak current asymmetry because the cubic numerator in Eq. 1 emphasizes the sediment transport capacity of higher (both ebb and flood) current velocities. Hence, it can be taken to be an effective sediment-related tidal asymmetry indicator. When assuming flood currents are positive, a positive PCA skewness indicates stronger flood currents and flood dominance, and a positive SWA skewness indicates shorter low water slack and flood dominance as well. When taking the signals in Figure 3 as tidal currents (and assuming u_c=0.2 m/s), the PCA skewness of S, PS, and NS signals (see Figure 3a) is 0, +0.49 (flood dominance), and -0.49 (ebb dominance), respectively, and the SWA skewness of S, PA, and NA signals (see Figure 3b) is 0, +1.33 (flood dominance), and -1.33 (ebb dominance), respectively. Gong et al. (2016) and Guo et al. (2018) had applied the skewness method (Eq. 6) to indicate slack water asymmetry in estuaries. These results demonstrate that the skewness measures (Eq. 5 and Eq. 6) can indicate the peak current asymmetry and slack water asymmetry.

4. Applications and evaluation

4.1 Application to actual data

So far, we have shown that both the harmonic and statistical methods are effective in indicating tidal asymmetry, when using constructed data. To further elaborate their applicability and their advantages and shortcomings, we apply these methods to actual tidal data obtained in the Changjiang River estuary. The tides in the Changjiang River estuary are dynamically highly non-linear and non-stationary (Guo et al., 2015) hence a single method is not able to characterize all tidal features and associated variations. The harmonic method, the PDF measure and the filtered derivative skewness measure are applied and evaluated. The transformed skewness measure works in a similar way as the derivative skewness thus it is not discussed.

One year of tidal height data at three tidal gauges in the upper estuary, lower estuary and estuary mouth are used to indicate along-river changes (see Figure 1). Harmonic analysis suggests that the Changjiang River estuary has a mixed tidal regime with an $(A_{O1}+A_{K1}+A_{P1})/(A_{M2}+A_{S2}+A_{N2})$ amplitude ratio of 0.24 at the mouth

(Guo et al., 2015). M_2 is the largest constituent, followed by S_2, K_1, O_1, N_2 etc. Overtide and compound tides such as M_4 and MS_4 are small outside the estuary but become considerable inside the estuary (Guo et al., 2015). Past studies have shown that any combination of more than two constituents (both principal and higher and lower frequency harmonics) satisfying frequency relationships such as $2\omega_i=\omega_j$, $\omega_i+\omega_j=\omega_k$, and $\omega_i+\omega_j+\omega_k=\omega_s$ etc. can create tidal asymmetry, e.g., M_2-M_4, M_2-O_1-K_1, and M_2-S_2-N_2-MSN_2 interactions (Le Provost, 1991; Song et al., 2011). Therefore, tidal wave deformation and tidal asymmetry inside the Changjiang River estuary can be induced by M_2-M_4, M_2-O_1-K_1, M_2-S_2-MS_4, M_2-N_2-MN_4 interactions etc (Guo et al., 2015). The $2\theta_{M2}$-θ_{M4} phase difference is ~70º and varies little along the estuary, suggesting flood dominance if considering M_2-M_4 interactions only. The harmonic analysis results show that the phase differences of $2\theta_{M2}$-θ_{M4}, $\theta_{M2}+\theta_{S2}-\theta_{MS4}$, and $\theta_{M2}+\theta_{N2}-\theta_{MN4}$ are nearly the same, and the $\theta_{O1}+\theta_{K1}-\theta_{M2}$ phase difference varies between 0 and 50º along the estuary (Guo et al., 2016a). It implies that all of these tidal interactions will cause flood dominance. This result is in line with a shorter rising tide than falling tide (see next paragraph). But it remains unknown which interaction plays a bigger role in dominating the flood dominance. Note that the flood dominance here refers to tidal water levels but not tidal currents (the ebb currents are always stronger than flood currents because of significant river discharges). The non-stationarity in the tidal signals induced by river discharge imposes a challenge to resolve tidal harmonics precisely, particularly in the upper estuary where non-stationary river influences are strong (Guo et al., 2015).

Strong tidal wave deformation and formation of tidal bores in the North Branch of the Changjiang River estuary induce another difficulty for the harmonic method. The tidal waves are much more deformed on spring tides than neap tides in the North Branch, and tidal bores can be generated. The rising tides become much shorter while the falling tides are prolonged under the occurrence of tidal bores (suggesting flood dominance). These variations induce non-stationary behavior of tidal asymmetry. Moreover, the high water may persist as long as 2.5 hours while the change from falling to rising tide is sharp (see Figure S6). These peculiar features pose a challenge for conventional harmonic analysis. With 38 tidal constituents resolved at QLG (see Figure 1), the harmonic methods show an identical phase difference of $2\theta_{M2}$-θ_{M4}, $\theta_{M2}+\theta_{S2}-\theta_{MS4}$, $\theta_{M2}+\theta_{N2}-\theta_{MN4}$ of ~82º (suggesting flood dominance) but the phase difference of $\theta_{O1}+\theta_{K1}-\theta_{M2}$ is ~350º (suggesting ebb dominance). It is thus not possible to tell the nature of the net tidal asymmetry based on the harmonic method alone. Moreover, comparison of the reconstructed signals based on the resolved harmonic constants with the measured tidal heights shows that the harmonic analysis can not capture the flat high tide and sharp transition from falling to rising tide, leading to considerable discrepancies in the estimation of rising and falling tidal periods (see Figure S6).

Estimation of the average falling and rising tidal durations based on one-year tidal height data suggests that the mean falling tide duration is slightly longer (~0.03 hours) than rising tide at the estuary mouth and the duration inequality increases in the landward direction (e.g., falling tide is on average ~2.0 hours longer than rising tide in the upper estuary), reflecting a more distorted tidal wave in the inner estuary, owing to the combined impacts of friction, estuarine geometry, and river discharge. The PDFs of tidal heights show upstream tidal damping but not tidal asymmetry (Figures 4a-c), while the PDFs of falling and rising tidal durations confirm the observation that falling tides become increasingly longer in the landward direction (Figures 4d-f).

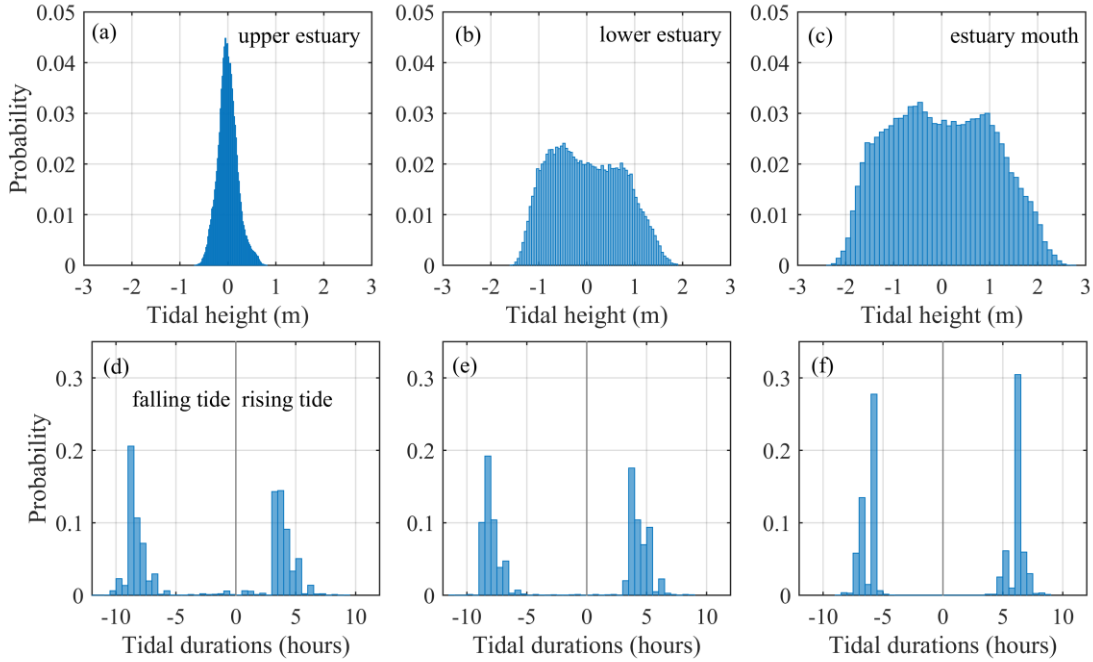

Figure 4. The TH-PDFs (a, b, c) and TD-PDFs (d, e, f) at stations in the upper estuary (landward regions, Nanjing in Figure 1) (a, d), lower estuary (seaward regions, Xuliujing) (b, e) and estuary mouth (Niupijiao) (c, f) based on 2-year data (2009-2010) in the Changjiang River estuary. The tidal heights are referenced to local mean water level. Rising tidal duration is positive and falling tidal duration is negative.

Application of the filtered derivative skewness method to the non-stationary river tides in the Changjiang River estuary reveals strong subtidal variations of tidal ranges and tidal duration asymmetry (Figures 5b and 5c) and associated non-uniform changes in response to high and low river discharges (Figures 5d and 5e). The mean water level and lower low tide are observed higher at spring tide than neap tide, in particular in the upper estuary (LeBlond, 1991; Sassi and Hoitink, 2013; Guo et al., 2015). To remove the influences of mean water levels, high-pass filtered data are used for the derivative skewness measure. The derivative skewness for one-year data is 0.13, 1.37 and 2.32 at the mouth, in the lower and upper estuary, respectively, suggesting overall shorter rising tides than falling tides throughout the estuary. Larger derivative skewness in the upper estuary suggests enhanced tidal wave deformation in the landward regions, particularly in the dry seasons when the river discharge is significant but not too large (Figures 5b and 5c). At fortnightly time scales, the derivative skewness is larger during spring tide than neap tide in both upper and lower estuary, suggesting stronger wave deformation and tidal asymmetry during spring tides (Figure 5d). At seasonal time scales, the derivative skewness decreases with increasing river discharges in the upper estuary but increases in the lower estuary (Figure 5e). It suggests that tidal duration asymmetry is stronger under high river discharge in the lower estuary while it is smaller in the upper estuary. This result is consistent with decreasing A_{D4}/A_{D2} ratios (the amplitude ratio of quarter-diurnal to semi-diurnal species) in the upper estuary and increasing ratios in the lower estuary with increasing river discharges in Guo et al. (2015). Analyses from a tidal energy perspective also confirms the above finding. Work by Zhang et al. (2016) suggests that the tidal asymmetry is one of the degrees-of-freedom used by the estuary to maintain a state of minimum work, by adjusting tidal wave deformation and tidal asymmetry along the estuary under varying river discharges.

The non-uniform behavior of tidal wave deformation between upper (landward) and lower (seaward) regions of long tidal estuaries with significant river influence are not unique to the Changjiang River estuary. Godin (1985, 1999) reported that a larger river discharge will cause accelerated low water and retarded high water in the upper St. Lawrence Estuary, whereas it will hasten the progress of high water and delay low water in the lower estuary. Similar non-uniform changes also occur in the Amazon Estuary (Gallo and Vinzon, 2005). Model results also reveal non-linear variations of tidal asymmetry in response to increasing river discharges (Guo et al., 2016a). These findings do not violate our intuitional understanding of the impacts of river discharge in causing more tidal damping and wave distortion (throughout an estuary) because both low and high river discharges will prolong falling tides and shorten rising tides compared to the situation with zero river discharge.

The variations of the A_{D4}/A_{D2} amplitude ratios in response to increasing river discharge in Guo et al. (2015) are consistent with the derivative skewness variations in this work and it may imply that the M_2-M_4 interaction is the dominant contribution to net tidal duration asymmetry. Based on tidal harmonics and the decomposition method suggested by Song et al. (2011), we estimate that the summed skewness of the four major interactions, i.e., M_2-M_4, M_2-O_1-K_1, M_2-S_2-MS_4, and M_2-N_2-MN_4, is 0.17 and 1.11, at the mouth and in the lower estuary, respectively. They are in good agreement with the derivative skewness (0.13 and 1.37, respectively) obtained from tidal height data. We see that the M_2-M_4 interaction is indeed the major contribution to the net tidal asymmetry, with a contribution >45% in the lower estuary, followed by M_2-S_2-MS_4 (30%) and M_2-N_2-MN_4 (5%) interactions. The M_2-O_1-K_1 interaction is of relatively minor importance (<1%) because of smaller O_1 and K_1 amplitudes compared to M_2 and S_2. Similarly, we quantify that the derivative skewness of tidal height is 2.32 at QLG in the North Branch, and the contribution of M_2-M_4 interaction is 47% and that of M_2-O_1-K_1 interaction is -2% (negative value indicates a effect causing ebb dominance).

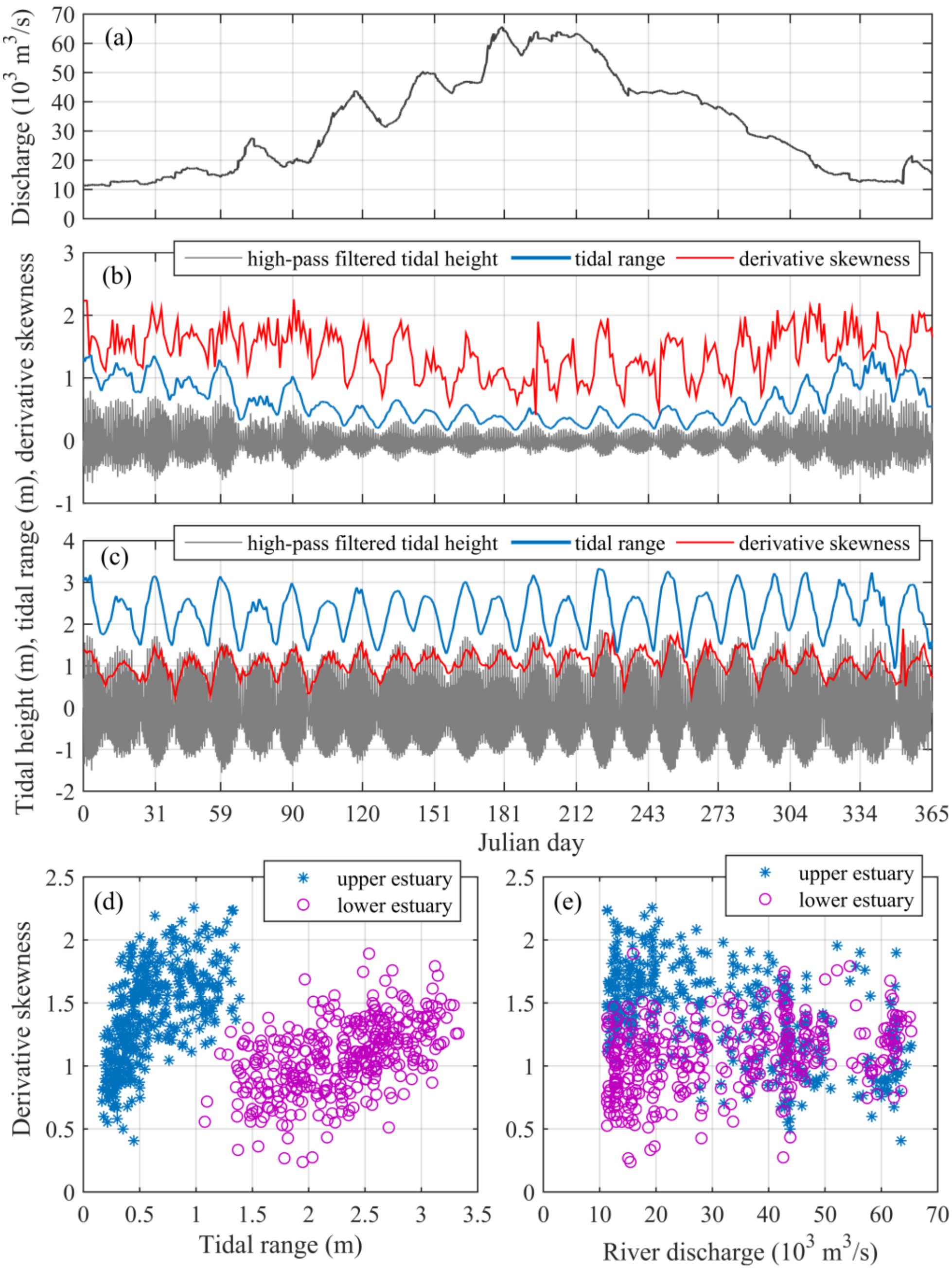

Figure 5. (a) River discharge in calendar year 2010, (b) high-passed filtered tidal height, tidal ranges, and filtered derivative skewness in the (b) upper estuary (Nanjing, see Figure 1) and (c) lower estuary (Xuliujing), and (d) derivative skewness vs. tidal range, and (e) derivative skewness vs. river discharge in the Changjiang River estuary.

Quantification of peak current asymmetry under the influence of river discharges needs separate consideration. River discharge induces a seaward mean current (i.e., $-u_o$, the negative sign indicates seaward) and enlarges ebb currents, causing overall ebb dominance although the rising tides are shorter than the falling tides. Even though, we find that the tide-related oscillatory currents (i.e., $\Sigma u_i\cos(\omega_i t+\theta_i)$, the subscript i indicates the name of the tidal constituent), i.e., the high-pass filtered currents with the mean current removed, are still stronger in the flood direction than the ebb direction. For instance, with one-year of tidal current data at Xuliujing in the Changjiang River estuary (Guo et al., 2015), we find that the high-pass filtered currents have a positive PCA skewness of 0.03 based on Eq. 5 (assuming flood currents are positive), suggesting stronger flood tidal currents and flood dominance. It is also validated by a $2\Phi_{M2}$-Φ_{M4} phase difference of ~25º (in the range of -90~90º thus indicating flood dominance). Modeled tidal currents in a schematized estuary have also confirmed flood dominance of tide-induced oscillatory currents although the ebb currents are stronger than flood currents due to river discharge (Guo et al., 2014). Note that it is the asymmetry in the total currents (i.e., $-u_o+\Sigma u_i\cos(\omega_i t+\theta_i)$) that controls the net residual sediment transport, although the contribution of river and tide-related asymmetry, and river-tide interaction can be decomposed (Guo et al., 2014, 2016a).

4.2 Advantages and shortcomings of the methods

The abovementioned applications and discussions suggest that both the harmonic method and the statistical methods are effective in indicating and quantifying tidal asymmetry although their applicability differs slightly (Table 1). The advantages of the harmonic method include: (1) having a solid physical background and being applicable to a large proportion of estuaries worldwide, where M_2 is the most important principal constituent; (2) easy to use because of the availability of harmonic constituent data for many locations, and (3) the impacts of non-tidal forcing are accounted for by altered tidal amplitudes and phases. Its shortcoming lies in its inability to characterize net tidal asymmetry in mixed tidal regimes where multiple tidal interactions may either augment or cancel each other in creating tidal asymmetry, as that has been identified by Jewell et al. (2012).

Table 1. A summary of the methods available for quantification of tidal asymmetry

and their applicability and criterions in indicating flood or ebb dominance.

<table>
<tr><th rowspan="2"></th><th rowspan="2">Harmonic method</th><th colspan="3">Statistical methods</th></tr>
<tr><th>PDF</th><th>Derivative Skewness</th><th>Transformed Skewness</th></tr>
<tr><td>Tidal Duration Asymmetry</td><td>phase differences e.g., $2\theta_{M2}-\theta_{M4}$, $\theta_{O1}+\theta_{K1}-\theta_{M2}$ phase differences in the range of 0~180º indicate flood dominance and that in the range of 180~360 º indicates ebb dominance</td><td>TD-PDF of rising and falling durations, an average rising tidal duration > or < falling duration indicate ebb or flood dominance</td><td>skewness of time derivative of the time series of HW and LW, a derivative skewness > or <0 indicates flood or ebb dominance, respectively</td><td>skewness of the imaginary part of Hilbert-transformed tidal water levels, a transformed skewness > or <0 indicates ebb or flood dominance, respectively</td></tr>
<tr><td>Peak Current Asymmetry</td><td>phase differences e.g., $2\Phi_{M2}-\Phi_{M4}$, $\Phi_{O1}+\Phi_{K1}-\Phi_{M2}$, phase differences in the range of 90~270º indicate ebb dominance and that in the range of -90~90 º indicates flood dominance</td><td>TC-PDF of the cubed ebb and flood currents, a percentage of cubed flood currents > or < cubed ebb currents indicate flood or ebb dominance</td><td>skewness of tidal currents, a skewness > or <0 indicates flood or ebb dominance, respectively (assuming flood currents are positive)</td><td rowspan="2">not applicable</td></tr>
<tr><td>Slack Water Asymmetry</td><td>not applicable</td><td>applicable but has not been used</td><td>skewness of tidal current accelerations, a skewness > or <0 indicates flood or ebb dominance, respectively (assuming flood currents are positive)</td></tr>
</table>

On the other hand, we see that the derivative and transformed skewness measures have advantages in terms of their ability to: (1) cope with complex tidal signals in semi-diurnal, diurnal or mixed tidal regimes, (2) indicate net asymmetry caused by multiple interactions and the separated contribution of individual interaction, (3) reveal subtidal variations, and (4) quantify both tidal duration asymmetry and peak current asymmetry. A weakness of the skewness method is the lack of strong physical foundation. The sign of the derivative and transformed skewness measures indicates the ebb or flood nature of tidal asymmetry, while its absolute value only indicates the strength of tidal asymmetry in a relative manner. A physical understanding of the connections between tidal wave deformation and the skewness proxy has yet to be fully investigated.

Overall, we see that the harmonic, statistical PDF and skewness methods have complementary advantages and are best used in combination. When plotting the derivative skewness against the amplitude ratio (using the constructed signals consisting of M_2+M_4 and M_2+O_1+K_1 constituents with different amplitude ratios and phase differences) we clearly see that the derivative skewness is zero for phase differences of 0 and 180º while it is maximal for phase differences of 90º and 270º regarding both M_2-M_4 and M_2-O_1-K_1 interactions (Figure 6). The tidal asymmetry induced by M_2-M_4 interaction tends to be strongest when the A_{M4}/A_{M2} ratio is 0.3-0.5 with a phase difference $2\theta_{M2}-\theta_{M4}$ of 90º or 270º (Figure 6a). We also see that the derivative skewness is overall larger for the M_2-M_4 interaction (Figure 6a) than the M_2-O_1-K_1 interaction (Figure 6b), suggesting possibly stronger effects of M_2-M_4 interaction in causing tidal asymmetry. These analyses suggest that the evaluations by the harmonic method and the skewness measures can be somehow transformed. Regarding their applicability, the harmonic method is preferred in predominantly semi-diurnal or diurnal tidal regimes where single tidal interaction such as M_2-M_4 or M_2-O_1-K_1 controls the tidal asymmetry. The statistical PDF and skewness methods are the alternative options and have advantages in mixed tidal regime where multiple tidal interactions occur.

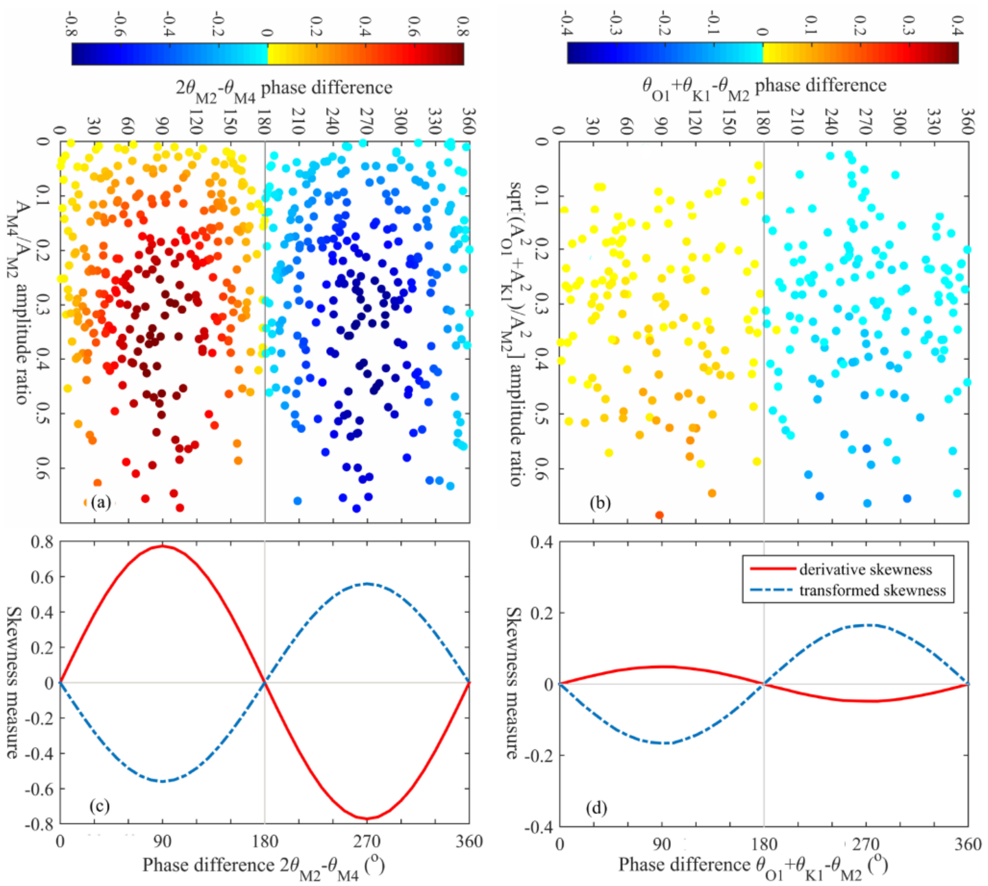

Figure 6. Scatter plot of filtered derivative skewness of tidal duration asymmetry due to (a) M_2-M_4 and (b) M_2-O_1-K_1 interactions for ideally constructed signals with different phase differences and amplitude ratios, and (c, d) variations of derivative skewness and transformed skewness for an amplitude ratio of 0.3 but different phase differences. Positive derivative skewness and negative transformed skewness suggest flood dominance.

5. Conclusions

In this work we provide a brief review of two methods, i.e., the harmonic and statistical methods, available for quantification of tidal asymmetry and find that they have complementary advantages. By estimating phase differences and amplitude ratios, the harmonic method has a well-defined physical foundation and is applicable to semi-diurnal, or diurnal, tidal regimes. The statistics of the PDF of rising and falling tidal periods can be used to indicate tidal duration asymmetry and that of cubed tidal currents to indicate peak current asymmetry. We consider several forms of skewness measure and conclude that a filtered derivative skewness has better explanatory power. The skewness measure is applicable for all tidal environments and in particular for mixed tidal regimes. The skewness measure is able to reveal subtidal variations of tidal asymmetry and the relative contribution of different tidal interactions under mixed regimes. The harmonic and statistical skewness methods are not mutually exclusive but can be qualitatively linked.

Using the skewness measure, we find that the M_2-M_4 interaction induces much stronger tidal asymmetry even with small M_4 amplitude compared to other tidal interactions. We confirm that tidal asymmetry is stronger during spring tide than neap tide and it exhibits distinctive behaviors in response to low and high river discharges between the upper and lower regions of long estuaries. We see that slack water asymmetry is relatively poorly studied compared to peak current asymmetry and more work is needed regarding its controlling effect on residual fine sediment transport.

Acknowledgements

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Captions of Table and Figures

Table 1. Summary of the methods available for quantification of tidal asymmetry. θ and Φ indicate the phase of vertical and horizontal tidal components, respectively. A and U are amplitudes of vertical and horizontal tides, respectively.

Figure 1. Sketch of the Changjiang River estuary and tidal gauges. The numbers in the brackets indicate the seaward distance to Datong, the tidal wave limit in the dry season. Niupijiao represents the river mouth, and Xuliujing and Nanjing represents the lower and upper estuary, respectively, with the division roughly at Jiangyin (Guo et al., 2015). QLG is the abbreviation of Qinglonggang. The smaller dots indicate other tidal gauges though their data are not included in this work.

Figure 2. Tidal heights by M_2, M_4 and M_2+M_4 tides with a phase difference $2\theta_{M2}$-θ_{M4} of (a) 0, (b) 90º, (c) 180º, and (d) 270º. The A_{M4}/A_{M2} amplitude ratio is 0.3.

Figure 3. (a) Skewed and (b) asymmetric tidal wave or tidal current curves, and (c, d) their corresponding PDFs. The positively and negatively asymmetric curves in pane (b) have the same PDF thus they are overlapped in panel (d). The flood currents are positive and ebb currents are negative in panel (a) and (b).

Figure 4. The PDFs of tidal heights (a, b, c) and tidal durations (d, e, f) at stations in the upper estuary (landward regions, Nanjing in Figure 1) (a, d), lower estuary (seaward regions, Xuliujing) (b, e) and estuary mouth (Niupijiao) (c, f) based on 2-year data (2009-2010) in the Changjiang River estuary. The tidal heights are referenced to local mean water level. Rising tidal duration is positive and falling tidal duration is negative.

Figure 5. (a) River discharge in calendar year 2010, (b) high-passed filtered tidal height, tidal ranges, and filtered derivative skewness in the (b) upper estuary (Nanjing, see Figure 1) and (c) lower estuary (Xuliujing), and (d) derivative skewness vs. tidal range, and (e) derivative skewness vs. river discharge in the Changjiang River estuary.

Figure 6. Scatter plot of filtered derivative skewness of tidal duration asymmetry due to (a) M_2-M_4 and (b) M_2-O_1-K_1 interactions for ideally constructed signals with

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