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Long-period solar annual and semiannual tidal contributions to the lowest normal low water in seas surrounding China

Yanguang Fu[1], Dongxu Zhou[1], Yikai Feng[1], Xinghua Zhou[1,2]

1 First Institute of Oceanography, Ministry of Natural Resources, Qingdao, Shandong, China

2 Shandong University of Science and Technology, Qingdao, Shandong, China

Abstract

As the chart datum of China, the lowest normal low water (LNLW) was calculated using three tidal constituents, major (Q1, O1, P1, K1, N2, M2, S2 and K2), shallow water (M4, MS4 and M6) and long-period tidal (Sa and Ssa). The construction of a tidal datum is mainly concerned with improvements in the major tidal constituents, and the contribution of the long-period tidal component has been generally neglected. In this study, long-term tide gauge observations and multi-mission satellite altimetry data were used to investigate the spatial distribution of the long-period tidal contribution in Chinese seas and analyze the relative long-period tidal contribution rate into four regions. The results showed that the mean contribution in Chinese seas is 7.63%, with the largest contribution in the Bohai Sea (11.33%) and smallest in the East China Sea (5.27%). Differences between tide gauge and satellite-derived results were compared in detail. The Sa and M2 tidal amplitudes are the main factors affecting the long-period tidal contribution to the LNLW. The relative long-period tidal contribution can be up to 34.18% when tide gauge observations record small M2 and large Sa amplitudes. These results indicate that the long-period tidal constituent cannot be neglected in the establishment of the LNLW datum. Therefore, to improve tidal datum precision, precise extraction and accuracy assessments of long-period tidal constituents should be a research focus.

Keywords: tidal datum, chart datum, long-period tidal, lowest normal low water, China Sea

1. Introduction

The establishment of the surface of a chart datum is fundamental for accurate knowledge of ocean depth (Gill et al., 2000). The lowest normal low water (LNLW) is the chart datum for the seas around China and, as such, is important for safe navigation, maritime baseline determination and

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vertical datums unification (Slobbe et al., 2018).

A chart datum is one type of tidal datum that can be derived from an average of low tidal heights from sea level observations, or calculated by using tidal constituents extracted from tide gauge measurements, satellite altimetry data and ocean tide models. Different types of tidal datums, such as the lowest astronomical tide (LAT), mean lower low water (MLLW) and LNLW, have been adopted as the chart datum in various countries to determine horizontal boundaries and provide accurate vertical references for bathymetry (Wu et al., 2019).

Modern tidal datum model construction is based on an ocean tide model. The near continuous digital expression is achieved through a high resolution grid, and the accuracy of the datum model depends mainly on the tide model. For example, the US-based Vertical Datum Transformation (VDatum) project used a regional ocean tide model to establish the MLLW surface (Parker et al., 2003; Yang et al., 2010). The English Vertical Offshore Reference Frames (VORF) project produced an inlaid tide model that combined a regional and global ocean tide model to establish a LAT model (Iliffe et al., 2013). The advantage of the inlaid tidal model is that it improves the accuracy of diurnal and semi-diurnal tidal constituents, but the LAT value does not include the effects of long-period tidal constituents. In the global ocean tide model assessment (Cheng and Anderson, 2011; Carrere et al., 2015; Egbert and Erofeeva, 2002), the accuracy performance of short-term tidal constituents was analyzed in detail, but did not take into account long-period tidal constituents (Shum et al., 1997; Stammer et al., 2014). Thus, there is a lack of accurate knowledge regarding long-period tidal constituents.

Satellite altimetry data provide a continuous, high spatial resolution sea-level height time series with near global coverage that allows for an accurate evaluation of the temporal–spatial characteristics of long-period tidal constituents. However, satellite altimetry observations showed poor accuracy performance, affected by land–sea interactions (Deng and Featherstone, 2006; Gommenginger et al., 2011) and inaccurate geophysical correction models in coastal areas (Andersen and Scharroo, 2011). In recent years, satellite altimetry has made great progress in reducing instrument error and improving data processing and correction models (Passaro et al., 2014; Verron et al., 2015; Pascual et al., 2015; Cotton et al., 2015), which makes it more feasible to obtain a reasonable spatial distribution and reliable long-period tidal constituents. Handoko et al. (2017) and Fu et al. (2020) carried out a detailed evaluation of the main geophysical corrections to derive accurate sea surface heights in Indonesian seas and the South China Sea, respectively. As a result of

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its current accuracy and maturity, altimetry is considered a fully operational observation system dedicated to scientific and operational applications and more research is investigating the precision of short-term tidal constituents (Fang et al., 2004; Zu et al., 2008;Victor et al., 2015; Cheng et al., 2016). However, the contribution of long-period tidal constituents to the establishment of tidal datums is still rarely studied (Yusof et al., 2017).

Long-period tides (e.g., 8 days, 2 weeks, 1 month, 6 months and 18.6 years) have been studied since the time of Laplace. Wunsch (1967) reviewed the considerable late nineteenth and early twentieth century analytical work by scientists such as Kelvin, Rayleigh, Poincarr and Proudman. The long-period tidal correction, involving annual (Sa) and semi-annual (Ssa) tidal constituents, is a component of the chart datum in China, but Sa and Ssa are not determined accurately. Most global tide models do not provide long-period tidal constituents, except for FES2014 (Carrere et al., 2015) and NAO99b (Matsumoto et al., 2000), but the long-period tidal constituents of those two models only provide simulation results of pure fluid dynamics (amplitudes <1 cm). Thus, there is a large difference with actual data obtained from tide gauge observations.

2. Data and methods

2.1 Tide gauge data

The harmonic constants of this study were obtained from 82 tide gauge observations, of which 61 stations were from the TIdal CONstants (TICON) data set (Piccioni, et al., 2019) and the other 21 stations were Chinese long-term tide gauge results (CLTR; Table 1, Figure 1).

TICON contains information on harmonic constants for 40 tidal constituents, derived from the GESLA-2 tide gauge records (http://www.gesla.org) distributed on a quasi-global scale. The data set is freely available from the PANGAEA repository (https://doi.panga ea.de/10.1594/PANGA EA.896587). The GESLA-2 tide gauge database contains 39,151 station years of data from 1355 stations (Woodworth et al., 2017). Most of these data were sampled hourly and the remainder more frequently. For our analysis, the TICON and CLTR data sets were combined. The Chinese tide gauge records had: 1) observation time series of at least a 3 year period and hourly value sampling, 2) years with less than 85% of hourly values rejected, and 3) years for which the 3 year period was centered on the middle of the year had less than 80% of hourly values rejected.

Table 1. Harmonic constants of annual (Sa) and semi-annual (Ssa) long-period tidal constituents collected from Chinese tide gauge stations. The station locations are depicted in Figure 1.

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Station No.	Name	Lon (deg)	Lat (deg)	Sa amp(cm)	Sa pha(deg)	Ssa amp(cm)	Ssa pha(deg)
1	BYQ	122.10	40.30	29.12	201.39	2.89	32.40
2	CFD	118.51	38.92	27.52	203.63	3.18	344.52
3	CW	118.95	24.88	15.07	296.64	4.87	60.15
4	DG	124.15	39.82	27.55	207.66	3.21	28.94
5	HA	110.13	20.23	10.54	292.42	6.29	76.82
6	JJ	121.47	28.69	14.19	253.30	3.76	23.76
7	JTG	119.01	39.21	28.27	204.85	2.79	352.59
8	LK	120.32	37.65	25.12	209.95	1.47	331.86
9	LCG	121.83	30.83	19.77	227.49	2.52	6.50
10	NA	117.10	23.40	13.06	301.71	5.27	57.36
11	PL	120.74	37.83	24.82	210.42	1.39	346.74
12	PT	119.83	25.47	13.22	283.79	4.61	55.42
13	QLY	121.38	36.27	22.38	216.26	1.48	351.93
14	SS	120.22	26.92	13.61	274.62	4.38	57.26
15	SY	109.50	18.23	14.45	315.19	7.50	69.13
16	ST	116.78	23.22	13.00	302.15	5.67	59.45
17	SD	122.42	36.87	22.15	215.09	1.72	2.79
18	SP	121.97	29.22	16.55	244.01	2.69	38.39
19	TG	117.78	38.98	29.75	203.27	3.51	342.81
20	WZ	109.12	21.02	10.01	273.42	6.03	86.63
21	XCS	122.67	39.23	26.06	208.31	2.22	8.46

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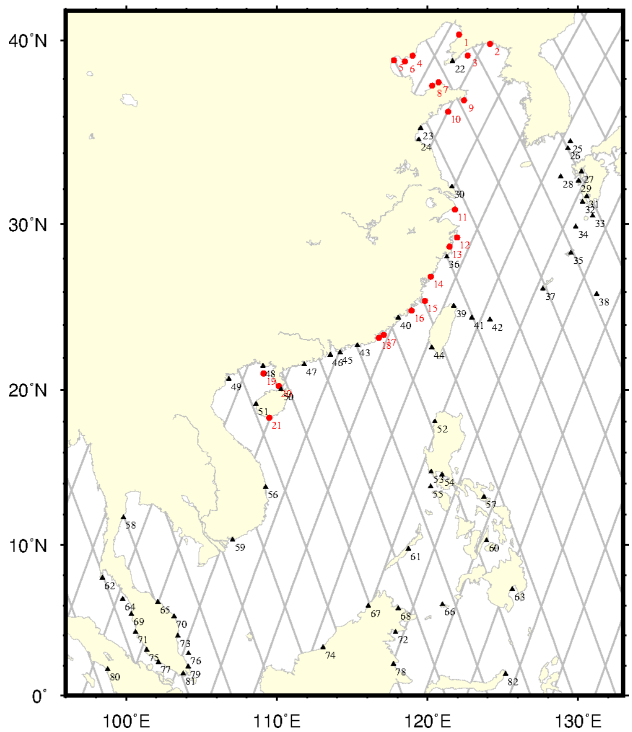

Figure 1. Tide gauge station distribution in the seas surrounding China. The red circles indicate Chinese long-term tide gauge stations, while the black tringles are locations obtained from the TIdal CONstants database. The solid gray lines are the primary mission tracks.

2.2 Satellite altimetry data

We used satellite (TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3) derived tidal constituent data from February 1993 to May 2019. The 26 years long altimetric time series allows an analysis of solar Sa and Ssa at a high level of precision.

The Center for Topographic Studies of the Ocean and Hydrosphere (CTOH; http://ctoh.legos.obs-mip.fr/) is a French National Observation Service, supported by the Institut National des Sciences de l'Universe, that conducts satellite altimetry studies. The CTOH provides access to their frequently updated altimetric databases, including TOPEX/Poseidon, Jason-1, Jason-2, GFO and ENVISAT data; they also provide access to altimetric products they develop. The sea level anomaly time series has been computed for the TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3 data by applying the latest geophysical corrections. Tidal constants were then estimated directly by harmonic analysis of each single time series from the along-track 1 Hz sea level anomalies. The

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CTOH tidal constants contain along-track estimates of amplitude and phase for 43 tidal constituents (primary mission along-tracks in Figure 1).

2.3 Chart datum determination

A chart datum is usually related to the mean of low ocean surface, such as mean lower low water spring, mean low water, low water, LNLW or LAT, and various countries use different levels as the chart datum for their marine administration (Rahibulsadri, et al., 2014).

The LAT has been adopted as the chart datum where tides have an appreciable effect on the water level, as determined by the International Hydrographic Organization (International Hydrographic Bureau, 2010). LAT was defined as the lowest tide level that can be predicted to occur under average meteorological conditions and any combination of astronomical conditions. It was recommended that LAT be calculated either over a minimum period of 19 years using harmonic constants derived from an observation minimum of 1 year or by other methods known to give reliable results.

The LNLW has been adopted as the chart datum of China. LNLW was calculated with 13 tidal constituents, namely, diurnal and semi-diurnal (major; Q1, O1, P1, K1, N2, M2, S2 and K2), shallow water (M4, MS4 and M6) and long-period (Sa and Ssa; Marine Surveying and Mapping Institute of the PLA Navy, 1999):

$$LNLW = L_8 + L_{shallow} + L_{long} \tag{1}$$

where *LNLW* is the chart datum value. L_8 is the major tidal contribution, $L_{shallow}$ is the shallow water tidal contribution, and L_{long} is the long-period tidal contribution:

$$\begin{aligned} L_8 = {} & R_{K_1}\cos\varphi_{K_1} + R_{K_2}\cos(2\varphi_{K_1} + 2g_{K_1} - 180° - g_{K_2}) \\ & - \sqrt{(R_{M_2})^2 + (R_{O_1})^2 + 2R_{M_2}R_{O_1}\cos(\varphi_{K_1} + \alpha_1)} \\ & - \sqrt{(R_{S_2})^2 + (R_{P_1})^2 + 2R_{S_2}R_{P_1}\cos(\varphi_{K_1} + \alpha_2)} \\ & - \sqrt{(R_{N_2})^2 + (R_{Q_1})^2 + 2R_{N_2}R_{Q_1}\cos(\varphi_{K_1} + \alpha_3)} \end{aligned} \tag{2}$$

$$L_{shallow} = R_{M_4}\cos\varphi_{M_4} + R_{MS_4}\cos\varphi_{MS_4} + R_{M_6}\cos\varphi_{M_6} \tag{3}$$

$$L_{long} = R_{S_a}\cos\varphi_{S_a} + R_{S_{Sa}}\cos\varphi_{S_{Sa}} \tag{4}$$

where H and g are the amplitude and phase of each tidal constituent, respectively, f is the focus factor of each constituent, and $R = fH$. The LNLW is the one variable function of φ_{K_1}, which ranges from 0° to 360°. The minimum value of this function is the LNLW. According to the equilibrium relationship between tidal components, an approximate hypothesis was introduced:

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$$\begin{aligned}\varphi_{M_4} &= 2\varphi_{M_2} + 2g_{M_2} - g_{M_4}\\ \varphi_{M_6} &= 3\varphi_{M_2} + 3g_{M_2} - g_{M_6}\\ \varphi_{MS_4} &= \varphi_{M_2} + \varphi_{S_2} + g_{M_2} + g_{S_2} - g_{MS_4}\end{aligned} \tag{5}$$

$$\begin{aligned}\varphi_{M_2} &= \tan^{-1}\left[\frac{(fH)_{O_1}\sin(\varphi_{K_1} + g_{K_1} + g_{O_1} - g_{M_2})}{(fH)_{M_2} + (fH)_{O_1}\cos(\varphi_{K_1} + g_{K_1} + g_{O_1} - g_{M_2})}\right] + 180^\circ\\ \varphi_{S_2} &= \tan^{-1}\left[\frac{(fH)_{P_1}\sin(\varphi_{K_1} + g_{K_1} + g_{P_1} - g_{S_2})}{(fH)_{S_2} + (fH)_{P_1}\cos(\varphi_{K_1} + g_{K_1} + g_{P_1} - g_{S_2})}\right] + 180^\circ\end{aligned} \tag{6}$$

$$\begin{aligned}\varphi_{Sa} &= \varphi_{K_1} - \frac{1}{2}\varepsilon_2 + g_{K_1} - \frac{1}{2}g_{S_2} - 180^\circ - g_{Sa}\\ \varphi_{Ssa} &= 2\varphi_{K_1} - \varepsilon_2 + 2g_{K_1} - g_{S_2} - g_{Ssa}\\ \varepsilon_2 &= \varphi_{S_2} - 180^\circ\end{aligned} \tag{7}$$

3. Regional variability in long-period tidal constituents

The spatial distribution of the satellite-derived along-track amplitude of Sa and Ssa is presented in Figure 2. The Sa maximum was 24.06 cm, with 79.1% of along-track points under 10 cm and 63.9% in the range of 5–10 cm. The Ssa amplitude was smaller than Sa; the maximum amplitude was 10.29 cm, with 93.2% points under 5 cm. We observed that the long-period tidal amplitude showed a gradual change along the spatial gradient, with smaller magnitudes in the deep open ocean and maximum values distributed in the Gulf of Thailand (Figure 2). The accuracy of the satellite-derived long-period tidal data depends, to some extent, on the sea level time series duration of the ascending and descending orbital. Our data indicate that the satellite-derived long-period tidal constituents present high internal accuracy, which can be mainly attributed to the long time series (>25 years; February 1993 to May 2019).

The maximum, minimum and mean amplitude values of satellite-derived Sa and Ssa are listed in Table 2. The seas around China were divided into four regions: the Bohai Sea (38–41°N, 119–127°E), the Yellow Sea (33–38°N, 117–126°E), the East China Sea (23–33°N, 117–131°E), and the South China Sea (0–23°N, 100–122°E). Different sub-oceans have different numbers of along-track satellite points. For example, for 153 along-track points in the Bohai Sea, the Sa and Ssa average values were the largest in this study (Sa = 9.47–17.91 cm; Ssa = 1.74–5.85 cm). Overall, there were 400, 1298 and 4224 along-track points in the Yellow Sea, East China Sea and South China Sea, respectively.

In general, the satellite-derived long-period tidal constituents presented large spatial

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differences and gradual spatial gradients, which suggest that they contribute to spatial variability in the chart datum.

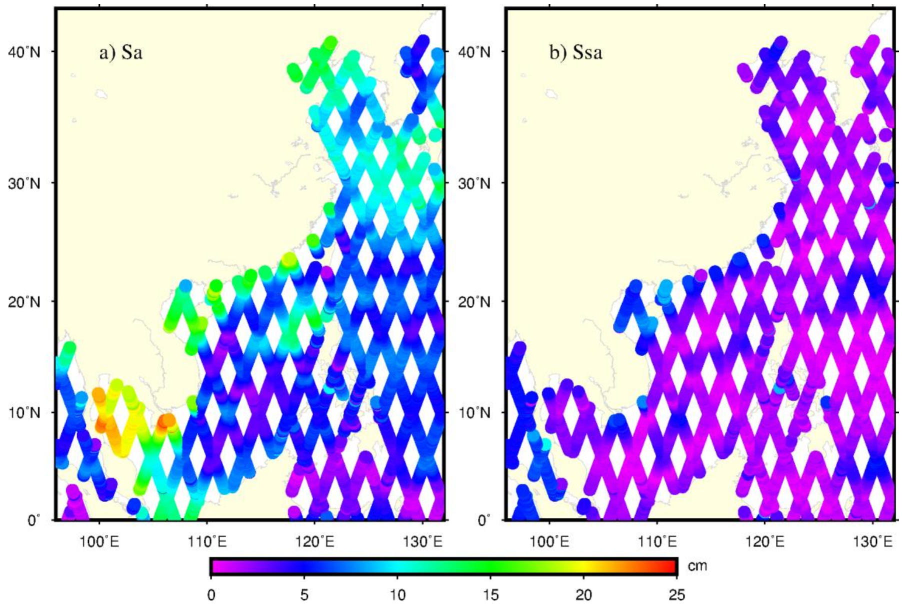

Figure 2. Satellite-derived tidal amplitudes of annual (Sa) and semi-annual (Ssa) long-period tidal constituents.

Table 2. Amplitude of satellite-derived annual (Sa) and semi-annual (Ssa) long-period tidal constituents in different seas (cm).

Sea area	Sa			Ssa		
	min	max	average	min	max	average
Bohai Sea	9.47	17.91	12.65	1.74	5.85	3.31
Yellow Sea	6.19	14.63	9.29	0.10	4.28	1.76
East China Sea	2.46	19.88	8.65	0.04	9.16	1.68
South China Sea	0.28	24.06	8.09	0.03	9.91	2.17

Long-term tide gauge stations provide highly accurate and high resolution tidal height values. In recent studies, tide gauge results have been regarded as true data to ground truth satellite-derived or tide model results. Our 18.61 year time series was ideal to obtain true tidal constituents because there is a relationship between longer durations of tide level data collection and higher tidal constituent precision. At least one full year of tide gauge observations is required to obtain Sa values, although this may include large inaccuracies in the data. To ignore the effects from different tide

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scales, we obtained Sa and Ssa from 82 long-term tide gauge stations (Figure 3).

Compared with the satellite-derived results, the amplitude of Sa varied over a larger scale (0.64–29.75 cm). However, the amplitude of Ssa was more restricted (0.67–8.16 cm). The large difference in Sa and Ssa is mainly a result of their behavior in the Bohai Sea.

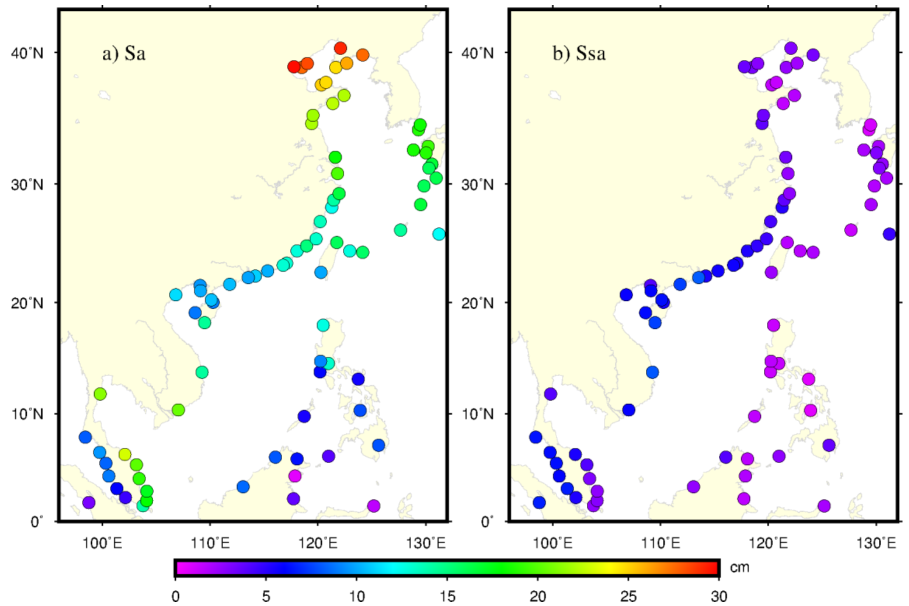

Figure 3. Amplitude of Sa and Ssa tidal in the long-term tide gauge stations.

4. Magnitude of tidal contributions to tidal datum

The long-period tidal correction values and contributions were calculated for each satellite along-track point using Eq. (1). The relative long-period tidal contribution refers to the percentage of long-period tidal corrections in the LNLW.

The satellite-derived results were interpolated onto a 15′ × 15′ grid by using the anti-distance weighted method. The maximum long-period tidal contributions were found in the Gulf of Thailand, the northeastern South China Sea and Japan Sea (Figure 4). Overall, 74.0% of the along-track long-period tidal contribution values were in the range of -20 to -5 cm, 3.0% were under -20 cm and 23.3% were above -5 cm; the average value was 7.48% (Figure 5).

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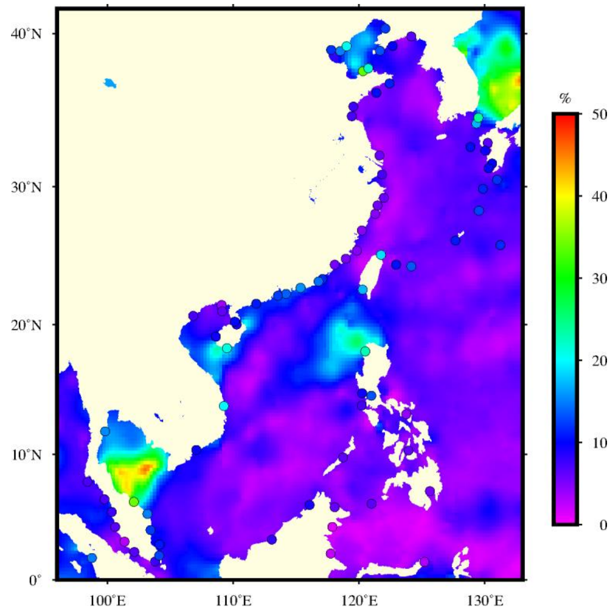

Figure 4. Spatial distribution of satellite-derived long-period tidal contributions. The dots depict results from tide gauge stations.

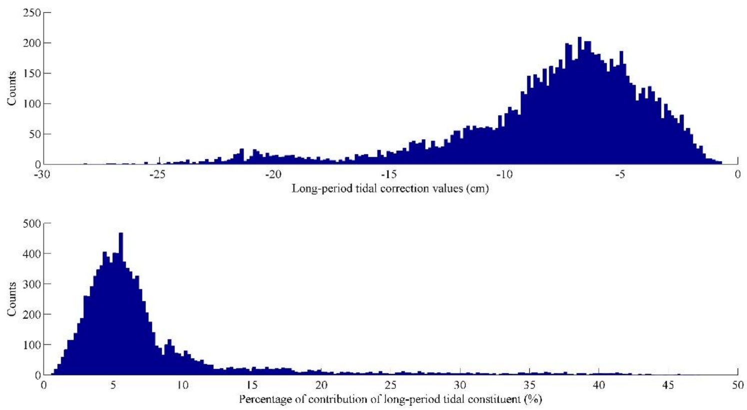

Figure 5. Histograms of the long-period tidal correction values and contribution.

To investigate the relative (%) performance of long-period tidal contributions in Chinese seas, histograms of the contributions were plotted for each of the four regions (Figure 6) with results listed in Table 3. In the Bohai Sea, about 52% of along-track points were above 10% and 92% of the contributions were above 5%; the average value was 20%. Additionally, the average long-period tidal contribution value was -13.58 cm. The long-period tidal contributions were remarkable in this

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area, mainly because of the large amplitude for Sa. In the Yellow Sea, East China Sea and the South China Sea, the relative contributions above 5% were 52%, 62% and 63%, respectively. Some of the variation among the regions is also a result of the different numbers of along-track points in the different ocean basins.

There are three types of tidal constituents, major (diurnal and semi-diurnal), shallow water and long-period, used to establish the LNLW. Our data showed that these three types have different relative contributions in the seas surrounding China. The long-period contribution exceeded 5% in all regions, with maximum values (11.33%) in the Bohai Sea and the South China Sea (8.56%). The overall relative long-period tidal contribution was 7.63%.

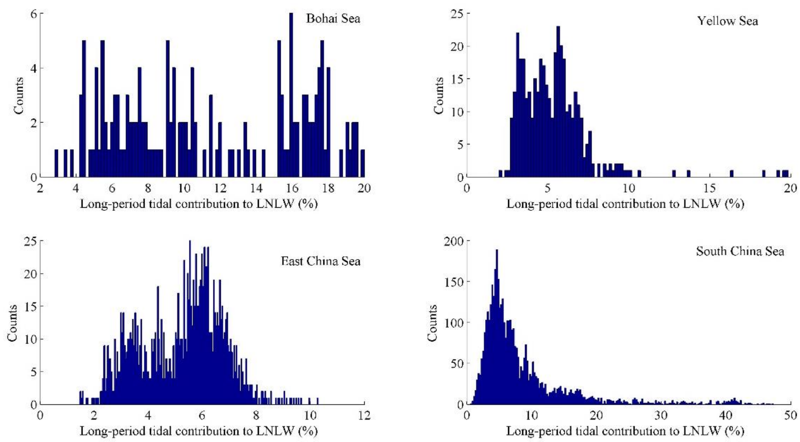

Figure 6. Distribution of the long-period tidal constituent contributions to lowest normal low water (LNLW).

Table 3. Relative contribution (%) of the individual tidal constituents to the lowest normal low water (LNLW).

Sea area	Major tidal contribution	Shallow water tidal contribution	Long-period tidal contribution
Bohai Sea	86.59	2.08	11.33
Yellow Sea	91.63	3.01	5.35
East China Sea	93.68	1.04	5.27
South China Sea	89.71	1.73	8.56

5. Discussion

The long-period tidal constituent amplitude is the main cause of differences in the tidal contributions. An accuracy assessment of the satellite-derived long-period tidal constituents was

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carried out by comparing results from the 82 tide gauge stations with the nearest satellite along-track point. The difference in Sa amplitude was between -5.84 cm and 15.99 cm, and 81.7% of Sa values were under 10 cm (average = 4.20 cm; standard deviation = 5.57 cm). The difference in Ssa amplitude was between -6.54 cm and 5.69 cm, with 84.1% of values ±2 cm (average = 0.16 cm; standard deviation = 1.72 cm).

We can see that differences in Sa amplitudes were larger in the higher latitude areas (Figure 7a); for example, the amplitude difference ranged from 4.47 cm to 9.94 cm in 29.22–34.65°N and 10.76–15.99 cm north of 34.75°N. These results indicate that amplitude differences are bigger in the tide gauge data than satellite-derived results. Figure 7b shows the amplitude difference as a function of distance between a tide gauge station and the nearest satellite along-track point. Distances ranged from 1.93 km to 164.08 km, although a significant correlation between them was not found. Overall, 87% of positions that had amplitude differences of ±10 cm had <60 km between a satellite point and tide gauge station; for distances >60 km, the relevant percentage between ±10 cm decreased to 77%. These results also confirm that long-period tidal constituents have a wide spatial scale.

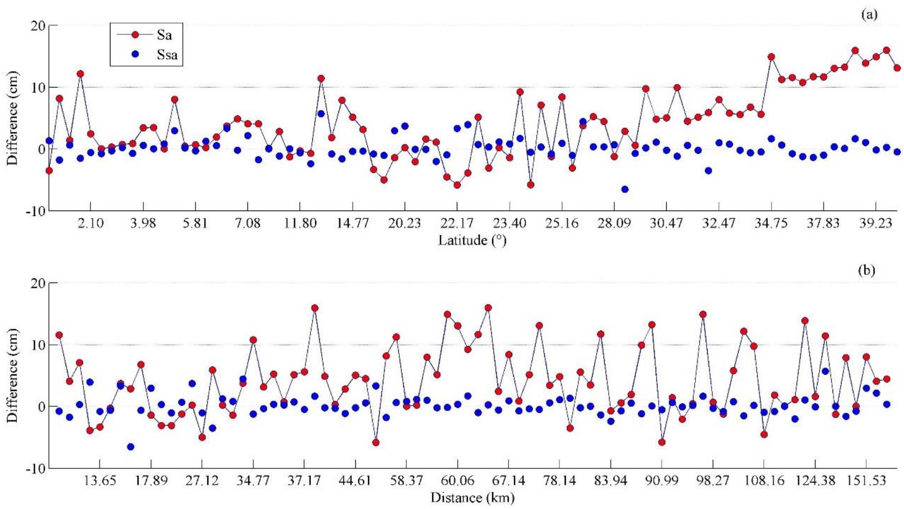

Figure 7. Relationship of annual (Sa) and semi-annual (Ssa) tidal component amplitude differences and (a) the latitudes of tide gauge stations, and (b) the distance between a tide gauge station and the nearest satellite along-track point.

Furthermore, the data processing strategy can be another important source of error between tide gauge data and satellite-derived results. As the long-period tidal constituent can be affected by atmospheric factors, particularly barometric pressure, the inverse barometric correction is one of the main factors needed to obtain long-period tidal information. Because the target chart datum investigated here is mainly used in navigation safety, our aim was to provide a conservative ocean depth; thus, we have not carried out inverse barometric corrections on the tide gauge data.

Figure 8 shows a comparison of relative long-period tidal contributions from tide gauge data and satellite-derived results. The difference between them ranges from -4.20% to 15.27%, with 35.3% of stations within ±2%, and 74.4% of stations within ±5%. The maximum relative contribution was 34.18% (station No. 65, see Figure 1) and the second highest was found in the Yellow Sea (station No. 8, 33.78%). Station No. 8 had a Sa amplitude of 25.12 cm; however, this was not the largest amplitude compared with surrounding stations. For example, station No. 5 showed the largest amplitude (29.75 cm), with long-period tidal correction values of -25.24 cm and -27.22 cm, but a relative long-period tidal contribution of only 11.98%. Actually, the amplitude values at stations No. 8 and No. 5 were mainly influenced by the amplitude of short-period tidal constituents, especially the M2 tidal component. As the largest source of diurnal and semi-diurnal tidal components, the M2 amplitude at stations No. 5 and No. 8 station were 27.56 cm and 102.92 cm, respectively. Major tidal correction values were -112.09 cm (No. 5) and -241.93 cm (No. 8), which resulted in large differences between the relative long-period tidal contribution.

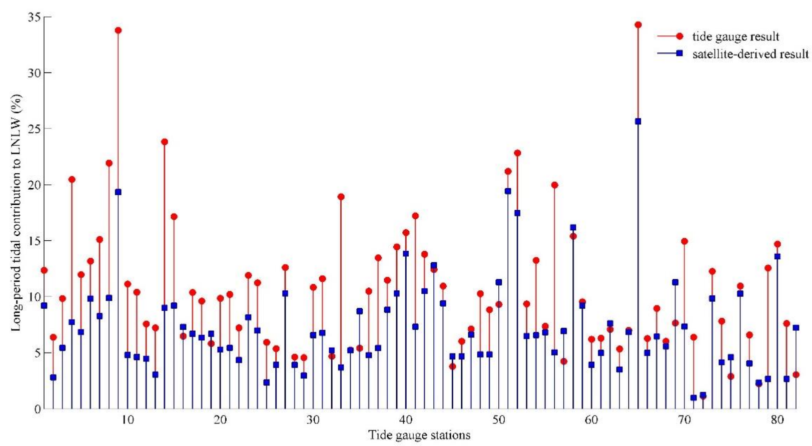

Figure 8. Latitudinal (x-axis) comparison of long-period tidal contributions from tide gauge data. Tide gauge station locations are in Figure 1.

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6. Conclusions

Tide gauge and satellite altimetry data were used to study the long-period tidal contribution of the Sa and Ssa tidal constituents to the LNLW in seas surrounding China. The LNLW was calculated using 13 different tidal constituents (Q1, O1, P1, K1, N2, M2, S2, K2, M4, MS4, M6, Sa and Ssa). A long-period tidal correction was carried out by combining the Sa and Ssa tidal constituents.

The satellite-derived along-track Sa and Ssa amplitudes were 24.06 cm and 10.29 cm, respectively. The maximum long-period tidal correction and relative contribution was -28.26 cm (mean = -7.97 cm) and 47.2% (mean = 7.48%), respectively. The mean relative long-period tidal contribution was largest in the Bohai Sea (11.33%) and smallest in the East China Sea (5.27%); this parameter was affected by the total number of along-track points in the different regions. The Sa amplitude obtained from 82 long-term tide gauge stations was between 0.64 cm and 29.75 cm, and the Ssa was between 0.67 cm and 8.16 cm. The low precision of satellite altimetry data in coastal areas and tidal height data processing are the main factors that contributed to differences between tide gauge data and satellite-derived results. A determination of the effect of inverse barometric corrections on the extraction of long-period tidal constituents will be necessary in subsequent studies. The reasons for differences in the relative long-period tidal contributions between tide gauge data and satellite-derived results were analyzed. Long-period tide corrections result from Sa and Ssa tidal component data, but were affected by the small amplitude of Ssa and influenced by the Sa amplitude. The amplitude of M2 tidal values was found to be another important factor affecting the long-period tidal contribution. The overall relative long-period tidal contribution in the four studied regions was 7.63%, but it was up to 34.18% at some tide gauge stations. The long-period tidal correction is vital to the establishment of the LNLW, and a precise extraction and accuracy assessment of long-period tidal constituents will be the focus of future research.

Acknowledgments

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