Article

Seasonal Variation of GPS-Derived the Principal Ocean Tidal Constituents' Loading Displacement Parameters Based on Moving Harmonic Analysis in Hong Kong

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Abstract: The classical harmonic analysis (CHA) method only can be used to obtain the harmonic constants (amplitude and phase) of ocean tide loading displacement (OTLD). In fact, there are significant seasonal variations in the harmonic constants of OTLD. A moving harmonic analysis (MHA) method is proposed, which can effectively capture the seasonal variation of OTLD parameters. Based on 5 years of kinematic coordinate time series in direction U of six Global Positioning System (GPS) stations in Hong Kong, the MHA method is used to explore the seasonal variation of the OTLD parameters of the 6 principal tidal constituents (M2, S2, N2, K1, O1, Q1). The influence of mass loading on the seasonal variation of OTLD parameters is analyzed. The results show that there are obviously seasonal variations in OTLD parameters of the 6 principal tidal constituents in Hong Kong. The OTLD's amplitude's changes of the 6 principal tidal constituents are around 4–25.1% and the oscillation ranges of OTLD's phase parameters vary from 8.8° to 20.4°. Among the seasonal variations of OTLD parameters, the annual signal, the semi-annual signal, and the ter-annual signal are the most significant. By analyzing the influence of atmospheric loading on the seasonal variation of OTLD parameters, it is found that atmospheric loading has certain contribution to the seasonal variation of OTLD parameters. Hydrological loading and non-tidal ocean loading have little influence on the seasonal variation of OTLD parameters.

Keywords: ocean tide loading displacement; seasonal variation; GPS; mass loading; Hong Kong

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1. Introduction

Tidal forces can deform the earth, causing solid earth tide and ocean tide. The periodic redistribution of ocean mass due to ocean tide results in a periodic loading of the solid earth known as ocean tide loading (OTL) [1,2]. Most of the methods to estimate the ocean tide loading displacement (OTLD) are to obtain the harmonic constants (amplitude and phase) of each tide constituent by classical harmonic analysis (CHA) [3–6]. Many studies have found that the harmonic constants of each tide constituent have significant seasonal variation rather than a constant value [7–10], which will also indirectly lead to the seasonal variation of OTLD parameters. With the advancement of science and technology, the effect of OTL has become more and more widely used in the global navigation satellite system (GNSS), geodesy, ocean dynamics, geophysics, and geodynamics. The requirements for its accuracy are getting higher and higher [11]. When performing precise data processing, the seasonal variation of OTLD parameters is also an important factor to be considered.

The OTL is usually obtained by discrete convolution integration of tide height data using the Green function based on the earth model. Due to the wide application of

GNSS in geodesy, coastal GNSS stations are sensitive to ocean tide, and the “deviations” caused by the OTL can also be accurately obtained through GNSS observations [12,13]. Penna et al. [13] showed that postprocessed kinematic precise point positioning (PPP) with appropriately tuned process noise constraints is capable of recovering synthetic tidal displacements inserted into real data, with a typical accuracy of 0.2 mm depending on the time series noise. The PPP technique is used to estimate OTLD parameters in the Antarctic region, and the amplitude and phase of the eight principal tide constituents in the vertical component are estimated. The results show that GPS is feasible to estimate the OTLD in the polar regions [14,15]. The OTLD parameters estimated by GNSS are compared with the results predicted by the ocean tide model, and it is found that there is a systematic deviation between the OTLD parameters estimated by GPS and the ocean tide model predictions, and that the inversion effect of each tide constituent is different [11,16–19]. However, the above studies do not take into account the seasonal variation of OTLD parameters.

The seasonal signal in GNSS observations not only contains the ocean tide signal, but also includes certain other geophysical signals, collectively making periodical variation in station coordinates. Among them, non-tidal ocean loading (NTOL), atmospheric loading (ATL), and hydrological loading (HYDL) are the main contributing sources of mass loading, causing the non-linear motion of the station [20]. By studying the influence of atmosphere, ocean and land water on the coordinate time series of GNSS stations, it is found that the correction of the mass loading can weaken the non-linear motion of most stations [21,22].

This paper aims to study the seasonal variation of OTLD parameters using the moving harmonic analysis (MHA) method based on the kinematic coordinate time series of the direction U in Hong Kong, and to analyze the influence and contribution of mass loading to the seasonal changes of OTLD parameters. In Section 2, details of the MHA method are presented and the data used in this paper is described. In Section 3, the reliability of the MHA method is verified, and the seasonal variation characteristics of the 6 principal ocean tidal constituents (M2, S2, N2, K1, O1, Q1) are studied by using the MHA method. In Section 4, the influence of mass loading on the seasonal variation of OTLD parameters is discussed. Finally, the conclusion is given in Section 5.

2. Materials and Methods

2.1. Study Region

The region selected in this paper is Hong Kong, whose geographical distribution is shown in Figure 1. Hong Kong is located in the low latitude coastal area, close to the South China Sea, and the OTL is greatly affected by the change of the offshore ocean tide. The South China Sea is the largest tropical marginal sea in the western Pacific Ocean, with vast waters and complex regions. The central part is a basin with a depth of 6000 m, while the northwest and southwest parts are continental shelves with a depth of less than 100 m [23].

2.2. GPS Data

The GNSS data at 6 stations (HKOH, HKKT, HKST, HKNP, HKMW, and HKSC) in Hong Kong (see Figure 1) were used. GNSS data are released by Système d’Observation du Niveau des Eaux Littorales (SONEL) (<http://www.sonel.org>). The data span 5 years (2014–2019), and the sampling rate is 30 s. The geographical distribution of stations is shown in Figure 1.

The GNSS data at 6 stations (HKOH, HKKT, HKST, HKNP, HKMW, and HKSC) are processed using the Bernese v5.2 software in kinematic PPP mode, obtaining a solution every 30 s. The hourly solution is obtained by averaging all solutions in an hour. No ocean tidal correction is made in the data processing. The cut-off altitude of the satellite is set to 10°. The tropospheric zenith delay model is the Saastamoinen model [24,25]. Final orbits, satellite clocks, and earth orientation parameters are provided by the Center for Orbit Determination in Europe (CODE) Global Analysis Center. The correction of the solid earth tide and polar tide models are based on the International Earth Rotation and Reference Systems Service (IERS) Conventions 2010 [26].

Figure 1. Geographical distribution of Global Navigation Satellite System (GNSS) station (Black spot) and tide gauge station (Black pentagram).

2.3. Tide Gauge Data

To verify the reliability of seasonal variation of MHA-derived OTLD parameters, the tide gauge records of Quarry Bay (22.18°N, 114.13°E) in Hong Kong also are analyzed using MHA. The location of tide gauge station is shown in Figure 1. Hourly sea level data of 2014–2017 at the Quarry Bay tidal gauge station used in this study were obtained from the University of Hawaii Sea Level Center (<https://uhslc.soest.hawaii.edu/>).

2.4. Mass Loading Data

Mass loading considered mainly includes ATL, HYDL, and NTOL. The ATL data are released by the Global Geophysical Fluid Center (GGFC) (<http://loading.u-strasbg.fr/ITRF/>). The ATL with a time interval of 3 hours and a grid size of 0.25° is estimated by using the surface pressure from the operational model of the European Centre for Medium-Range Weather Forecasts (ECMWF). The provisional product of NTOL deformation released by the GeoForschungsZentrum (GFZ) is adopted (<http://loading.u-strasbg.fr/ITRF/>). The NTOL with a time interval of 12 hours and a grid size of 1° is derived from non-tidal ocean bottom pressure from the ocean model for circulation and tides (OMCT) [27]. The provisional product of HYDL deformation released by the GFZ (<http://rz-vm115.gfz-potsdam.de:8080/repository>) is also adopted. The HYDL with a time interval of 24 h and a grid size of 0.5° are predicted from the global land surface discharge model (LSDM) [28].

2.5. Moving Harmonic Analysis Method

In order to obtain higher frequency time-varying signals, observations are divided into monthly segments by calendar month [7,9,29]. Moving window is 1 day to form several time periods, and each time period is processed by the CHA method to obtain discrete tidal harmonic parameters (i.e., amplitude and phase lag). This is equivalent to getting a value every day. So, the time resolution of MHA is one day, which is much larger than that of enhanced harmonic analysis (EHA). Therefore, MHA can obtain higher frequency changes. Besides, moving has certain advantage in terms of suppressing non-common signals (noises). The expression of MHA is:

$$F_m = [F_c(t_1 \sim t_{1+30}), F_c(t_2 \sim t_{2+30}), F_c(t_3 \sim t_{3+30}), \dots, F_c(t_{n-30} \sim t_n)] \quad (1)$$

where F_c are the results of CHA, t_n is n th data of time series, and F_m is a set of discrete harmonic constants.

The MHA method is based on the CHA, so the following is a brief introduction of the CHA method. The time series of coordinate changes in three directions can be expressed as:

$$y_i(t) = b_0 + b_1 t + \sum_{k=1}^M H_k \cos(\delta_k t + V_k(t_0) - \Phi_k), \quad (2)$$

where $y_i(t)$ is the time series of station coordinates in three directions ($i = N, E, U$), k is the tidal constituent, and M is the number of ocean tidal constituents. Only 6 principal constituents (M2, S2, N2, O1, K1, Q1) are studied, so M is 6. t is Greenwich time. H_k and Φ_k are the amplitude and Greenwich phase lag, respectively. δ_k is the constituent's angular frequency, $\delta_k = 2\pi f u_k$ in which $f u_k$ is the frequency of tidal constituent. V_k is the constituent's astronomical argument at reference time t_0 .

2.6. Enhanced Harmonic Analysis

The expression of EHA [30] is:

$$y_i(t) = b_0 + b_1 t + \sum_{k=1}^M H_k(t) \cos(\delta_k t + V_k(t_0) - \Phi_k(t)), \quad (3)$$

where $H_k(t)$ and $\Phi_k(t)$ are the function of time. Other variables refer to Equation (2).

Similar to Jin et al. [30] and Pan et al. [31], the independent point scheme and cubic spline interpolation are used to jointly solve the temporally varying harmonic parameters. The independent point scheme is a kind of methodology to connect unresolved parameters in the methodology of harmonic analysis.

3. Results

The MHA method is proposed to study the seasonal variation of OTLD parameters in Hong Kong. The results are verified by using CHA and EHA [30,31]. At the same time, fast Fourier transform (FFT) is used to detect the periodic signals in time-varying sequence of amplitude and phase.

The OTLD parameters with a signal-to-noise ratio less than 2 are eliminated in the MHA results, and the values greater than 3 times standard deviation in the OTLD parameter time-varying sequence are eliminated. Finally, SSA interpolate [32,33] is used to fill in missing data.

In addition, because the frequencies of K1 and P1, S2 and K2 is very close, it cannot be clearly separated by using the data of one month [29,31,34]. The unresolved constituents P1 and K2 are inferred from K1 and S2, respectively. Those for the inferred constituents are computed using the prescribed amplitude ratios and phase differences [34]. The inference parameters are taken from a yearly harmonic analysis of the 5-year observation data [29,34]. The use of an admittance largely eliminates the predictable seasonal variability due to unresolved frequencies (e.g., the effects of P1 and K2 on K1 and S2, respectively) and allows the examination of factors not involving astronomy, such as seasonal climatic variability [9].

3.1. Analysis of Time-Varying Characteristics of Amplitude

MHA is used to estimate time-varying OTLD parameters from kinematic coordinate time series. The time-varying results of amplitude are shown in Figures 2–7.

Figure 2. Seasonal variation of the amplitude parameter of K1 ocean tide loading displacement (OTLD).

Figure 3. Seasonal variation of the amplitude parameter of O1 OTLD.

Figure 4. Seasonal variation of the amplitude parameter of Q1 OTLD.

Figure 5. Seasonal variation of the amplitude parameter of M2 OTLD.

Figure 6. Seasonal variation of the amplitude parameter of S2 OTLD.

Figure 7. Seasonal variation of the amplitude parameter of N2 OTLD.

From Figures 2–7, it can be seen that the amplitude parameters of the 6 principal tidal constituents in Hong Kong have obvious seasonal variation. The seasonal variation of amplitude by MHA is consistent with that by EHA, and the mean of the estimated results

of MHA is approximately equal to the estimated results of CHA. This also shows that the use of MHA can effectively estimate the seasonal variation of the harmonic parameters of the principal tidal constituents in Hong Kong. In addition, as shown in Figures 2–7, the MHA method can capture more detailed changes.

The time-varying trend of amplitude parameters of the same tidal constituent at different stations is similar. The amplitude of K1 at HKOH and HKSC has a downward trend. The amplitude relative change of K1 is about 8.3–11.2% at Hong Kong. The time-varying trend of amplitude parameters of O1 at HKKT, HKMW, HKNP, and HKOH is similar. The amplitude relative change of O1 is about 4–7% at Hong Kong. The amplitude relative change of Q1 is about 17.6–25.1%. The oscillation range of the M2 at HKNP is minimum among all the stations. The amplitude relative change of M2 is about 4–8.2%. Mueller et al. [7] and Wang et al. [10] also found changes in the principal harmonics of around 5–10%. The amplitude changes of S2 at each station are similar, and the relative changes are up to 14.7–22.2%. The amplitude relative change of N2 is about 13.8–21.1%.

The FFT is used to analyze the time-varying sequence of OTLD parameters. As the periodic signals contained at each station are relatively similar, only HKKT station is taken as an example for discussion, and the results are shown in Figure 8.

Figure 8. Spectrum analysis of amplitude parameters of 6 principal tidal at HKKT station.

From Figure 8, it can be seen that amplitude parameters of K1, Q1, S2, and N2 have annual signal, the semi-annual signal, and the ter-annual signal, but the power of ter-annual signal is very weak. The power of periodic signals in K1 is the strongest, followed by the power of periodic signals in O1, and the power of periodic signal in N2 is the smallest. This is consistent with the seasonal variation of the amplitude of each tidal constituent. Except Q1, the power of the annual signal of other ocean tide constituents is the largest, followed by the semi-annual signal. The power of ter-annual period of other stations is also very weak by comparing with the annual and semi-annual signals.

3.2. Analysis of Time-Varying Characteristics of Phase

The MHA method is used to detect the time-varying signal of the phase parameters. The time-varying results of the phase parameters are listed in Table 1.

It can be seen from Table 1 that the average oscillation ranges of phase parameters of M2, S2, N2, K1, O1, and Q1 are 9.3°, 9.3°, 15.9°, 13.1°, 19.6°, and 18.7°, respectively. It shows that the oscillation range of diurnal tide is larger than that of semidiurnal tide. The time-varying sequence of phase parameters mainly includes annual, semi-annual, and ter-annual periods. The power of ter-annual period is very weak by comparing with the annual and semi-annual signals.

Table 1. Oscillation range of phase parameters (unit: degree) and the main cycle (unit: year).

Site	Index	M2	S2	N2	K1	O1	Q1
HKKT	Range	9.7	9.3	15.2	13.8	20.2	20.4
	Cycle	1,1/2,1/3,1/4	1,1/2,1/3	1,1/2	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3
HKMW	Range	9.4	9.6	15.3	12.5	19.3	21.5
	Cycle	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3
HKNP	Range	9.6	9.4	16.9	12.8	19.9	18.6
	Cycle	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3
HKOH	Range	8.9	9.5	14.2	12.3	18.6	15.7
	Cycle	1,1/2,1/3	1,1/2,1/3,1/4	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2
HKSC	Range	9.2	8.8	16.7	13.6	20.1	17.5
	Cycle	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3
HKST	Range	9.0	9.3	17.1	14.1	19.5	18.9
	Cycle	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3	1,1/2,1/3

It is widely known that the OTL is caused by the redistribution of ocean mass due to ocean tides. Seasonal variations in ocean tides are bound to cause seasonal variation in OTLD. Seasonal variation of sea level changes will cause seasonal variation in ocean tides [35]. Seasonal stratification also has several noticeable effects on the ocean tides [7,10,36,37]. All of these factors will indirectly cause the seasonal variation of OTLD parameters.

3.3. Accuracy Verification of Moving Harmonic Analysis

To verify the reliability of MHA, the mean (MEAN), maximum (MAX), minimum (MIN), standard deviation (STD) of root mean squared errors (RMSE) of MHA-derived OTLD parameters over 5 years are counted, and the results are listed in Table 2.

Table 2. Root mean squared error (RMSE) statistics of moving harmonic analysis (MHA)-derived OTLD parameters.

Ocean Tidal Constituents		O1	K1	Q1	M2	S2	N2
Amplitude (mm)	MAX	0.81	0.79	0.56	0.80	0.68	0.48
	MIN	0.05	0.07	0.02	0.09	0.07	0.03
	MEAN	0.49	0.54	0.25	0.31	0.44	0.22
	STD	0.12	0.15	0.09	0.10	0.10	0.09
Phase (°)	MAX	5.21	10.25	11.2	7.24	6.25	10.24
	MIN	0.75	2.01	3.61	1.01	1.32	2.68
	MEAN	2.33	7.15	7.14	3.49	4.41	3.21
	STD	1.15	1.51	1.44	1.31	1.03	1.21

It can be seen from Table 2 that the mean RMSE of amplitude and phase of K1 is the largest, that of O1 is the second, and that of N2 is the smallest. The mean RMSE of amplitude and phase of K1 in direction U is the largest, reaching 0.54 mm and 7.15°, respectively. The STD of RMSE of amplitude and phase of K1 in direction U is the largest, reaching 0.15 mm and 1.51°, respectively. The mean RMSE of amplitude of N2 is the smallest. The mean RMSE of amplitude of 6 constituents are 0.2–0.5 mm. Those results show that it is feasible to use MHA to study the seasonal variation of OTLD parameters.

To verify the reliability of seasonal variation of MHA-derived OTLD parameters, the tide gauge records of Quarry Bay in Hong Kong also are analyzed using MHA and EHA. The seasonal variation of ocean tides in Hong Kong is shown in Figure 9. From Figure 9, it can be seen that the 6 principal ocean tidal constituents M2, S2, N2, K1, O1, and Q1 in Hong Kong have obvious seasonal changes of annual and semi-annual, which is similar to the seasonal variation of MHA-derived OTLD parameters by GNSS.

Figure 9. Seasonal variations of amplitude parameters of 6 principal tidal constituents at Quarry Bay.

At the same time, the seasonal variations of the OTLD's amplitude by GNSS and the seasonal variations of the ocean tide's amplitude by tide gauge are statistically and comparatively analyzed. The results are listed in Table 3.

Table 3. The statistics of variation of the amplitude parameter by GNSS and tide gauge.

Tidal Constituents	Variation of the OTLD's Amplitude by GNSS	Variation of the Ocean Tide's Amplitude by Tide Gauge
K1	About 8.3–11.2%	About 26.0%
O1	About 4–6.3%	About 6.3%
Q1	About 17.6–25.1%	About 26.3%
M2	About 4–8.2%	About 4.8–5.1%
N2	About 13.8–21.2%	About 22.2%
S2	About 14.7–22.2%	About 20.8%

It can be seen from the statistical results in Table 3 that the seasonal variations of OTLD parameters of M2, S2, N2, K1, Q1, and O1 estimated by GNSS are about 4–8.2%, 14.7–22.2%, 13.8–21.2%, 8.3–11.2%, 17.6–25.1%, and 4–6.3%, respectively. The seasonal variations of ocean tide parameters of M2, S2, N2, K1, Q1, and O1 estimated by tide gauge are about 4.8–5.1%, 20.8%, 22.2%, 26%, 26.3%, and 6.25%, respectively. The seasonal variations of OTLD parameters of M2, S2, N2, Q1, and O1 constituents base on GNSS and the seasonal variations of ocean tide parameters of M2, S2, N2, Q1, and O1 constituents base on tide gauge station are very similar. The seasonal variation of OTLD parameter of K1 base on GNSS is slightly smaller than the seasonal variation of ocean tide parameter of K1 base on tide gauge. The GPS satellite orbit errors and multipath effects related to the two periods result in large uncertainties of K1 OTLD estimates [14,38]. So, the GPS satellite orbit errors and multipath effects may be the two of reasons of the difference between the seasonal variation of OTLD parameter of K1 base on GNSS and those of K1 base on tide gauge.

MHA is developed on the basis of segmented harmonic analysis. Segmented harmonic analysis has been widely used in the study of seasonal variation of ocean tides, and its reliability has been verified [7,9,29]. Besides, the mean of the estimated results of MHA is approximately equal to the estimated results of CHA. All of the above indicates that the MHA method is reliable.

4. Discussion

Although GNSS technique has many advantages in studying OTLD, it is also affected by many other geophysical factors, such as mass loading including NTOL, ATL, and HYDL, which may be mixed with ocean tidal signals in time series [39].

In order to study the influence of mass loading on the seasonal variation of OTLD parameters, the seasonal variations of OTLD parameters with/without mass loading correction are studied. The difference of the seasonal variation sequence of amplitude parameters with/without the mass loading correction is analyzed, and the results are listed in Tables 4–6.

Table 4. Difference of seasonal variation sequence of amplitude parameter with/without hydrological loading (HYDL) correction (mm).

Ocean Tidal Constituents		M2	S2	N2	K1	O1	Q1
HKKT	MAX	0.4	0.3	0.3	0.1	0.5	0.4
	MIN	−1.2	−3.8	−2.4	−1.6	−0.8	−1.8
	MEAN	−0.1	−0.4	−0.5	−0.3	−0.1	−0.3
	STD	0.3	0.2	0.2	0.3	0.1	0.2
HKMW	MAX	1.0	5.0	2.2	1.3	0.8	0.7
	MIN	−1.6	−1.5	−0.9	−1.4	−0.9	−1.0
	MEAN	−0.2	0.1	0.2	−0.2	−0.1	−0.1
	STD	0.4	0.3	0.4	0.3	0.1	0.3
HKNP	MAX	5.2	7.2	2.6	4.7	3.4	1.5
	MIN	−1.1	−1.7	−1.1	−1.1	−0.3	−1.1
	MEAN	0.2	0.4	0.4	0.1	0.6	0.4
	STD	0.3	0.5	0.4	0.7	1.01	0.5
HKOH	MAX	0.7	0.2	0.6	0.5	0.4	0.3
	MIN	−1.6	−2.0	−1.2	−0.7	−0.9	−0.7
	MEAN	−0.3	−0.5	−0.4	−0.1	−0.2	−0.2
	STD	0.3	0.3	0.2	0.3	0.1	0.2
HKSC	MAX	6.2	8.1	2.5	5.2	3.3	1.7
	MIN	−1.3	−2.5	−1.8	−1.6	−1.3	−1.0
	MEAN	1.1	1.3	0.6	1.2	0.4	0.4
	STD	2.0	2.4	0.9	2.2	1.0	0.6
HKST	MAX	0.8	2.7	0.7	0.4	1.4	0.8
	MIN	−1.5	−2.3	−0.9	−1.3	−1.1	−1.2
	MEAN	−0.3	−0.3	0.2	−0.2	0.1	−0.3
	STD	0.2	0.6	0.1	0.2	0.3	0.2

As is listed in Table 4, the seasonal variation of OTLD parameters after HYDL correction does not change significantly. Except for HKSC, the mean and standard deviations of the difference of the seasonal variation with/without the HYDL correction are around 0 mm at most stations. This shows that the HYDL has little influence on the seasonal variation of OTLD parameters. HYDL is mainly caused by surface water, groundwater, and snow cover. The main periodic signals are annual and semi-annual signals [40,41]. Therefore, it is reasonable that HYDL has little influence on seasonal change of OTLD parameters. The kinematic GPS coordinate time series at HKSC station was checked. The STD of HKSC station time series is about 2.2 times of those of other stations, reaching 0.026 m. Therefore, we think that the accuracy of the coordinate time series of HKSC station is lower than that of other stations. We think that this may be one of the reasons for the abnormality of HKSC station.

Table 5. Difference of seasonal change sequence of amplitude parameter with/without atmospheric loading (ATL) correction (mm).

Ocean Tidal Constituents		M2	S2	N2	K1	O1	Q1
HKKT	MAX	0.6	0.2	0.4	0.1	1.1	0.6
	MIN	−2.4	−3.2	−2.8	−2.4	−0.9	−1.5
	MEAN	−1.1	−1.4	−1.5	−1.2	0.7	−0.8
	STD	1.1	1.2	1.2	1.2	0.6	0.9
HKMW	MAX	1.3	5.4	2.6	1.5	0.6	1.2
	MIN	−2.2	−2.3	−2.5	−1.5	−1.3	−1.6
	MEAN	−1.1	−1.2	−0.8	−0.9	−0.7	−1.1
	STD	1.0	1.3	1.4	1.2	0.6	1.1
HKNP	MAX	5.5	7.4	5.6	4.5	3.5	3.4
	MIN	−2.3	−2.2	−1.8	−2.4	−0.8	−1.5
	MEAN	1.2	1.3	1.2	1.3	0.6	1.7
	STD	2.3	2.2	1.9	1.6	1.2	1.1
HKOH	MAX	0.6	0.4	1.0	0.5	0.7	1.2
	MIN	−1.8	−2.4	−2.5	−1.7	−0.9	−1.1
	MEAN	−1.1	−1.3	−1.4	−1.1	0.1	0.6
	STD	1.0	1.1	1.3	0.8	0.4	0.9
HKSC	MAX	6.7	8.4	7.5	5.7	3.0	4.8
	MIN	−1.4	−2.7	−3.2	−1.3	−1.1	−0.9
	MEAN	1.3	1.6	2.4	1.1	0.5	2.0
	STD	2.2	2.8	2.3	2.0	1.1	1.3
HKST	MAX	0.7	2.9	1.9	0.3	1.4	2.0
	MIN	−2.1	−2.5	−2.6	−2.0	−1.2	−1.6
	MEAN	−1.4	−1.4	−1.3	−1.1	0.8	0.8
	STD	1.2	1.1	1.3	1.0	0.9	0.7

The mean differences of seasonal variation of the amplitude parameters with/without the ATL correction have absolute values in the range 0.1–2.4 mm. The standard deviations of the difference of the seasonal variation of the amplitude parameters with/without the ATL correction are 0.4–2.0 mm at most stations. The standard deviation's means of difference for M2, S2, N2, K1, O1, and Q1 at six stations are 1.5, 1.6, 1.6, 1.3, 0.8, and 1.0 mm, respectively. This shows that the ATL has certain influence on the seasonal change of OTLD parameters. Many studies have found that there are obvious diurnal and semi-diurnal signals of ATL [42,43]. These signals may be mixed with ocean tide signals, which have certain impact on the seasonal changes of OTLD parameters. Devlin et al. [9] analyzed the water level time series from 20 tide gauges in Southeast Asia and the results shown that diurnal and semidiurnal astronomical tides exhibit strong seasonal variability of both amplitude and phase. It is found that the tidal properties are coherent with the western North Pacific monsoon index, indicating that monsoonal mechanisms are the cause. Monsoon circulation is an important part of atmospheric circulation.

It can be concluded from Table 6 that the means of the standard deviation of the difference for M2, S2, N2, K1, O1, and Q1 at each station after NTOL correction are 0.43, 0.46, 0.53, 0.50, 0.51, and 0.60 mm, respectively. The mean difference for M2, S2, N2, K1, O1, and Q1 at each station is almost less than 0.5 mm. Therefore, the seasonal variation of OTLD parameters at each station has not changed significantly after the NTOL correction. NTOL is caused by a redistribution of the ocean's internal mass that is driven by atmospheric circulation, a change in the mass entering or leaving the ocean, and/or a change in the integrated atmospheric mass over the ocean areas, with a main periodic signal of annual signal [44,45]. This may be the reason why it has little effect on the seasonal variation of OTLD parameters.

Table 6. Difference of seasonal change sequence of amplitude parameter with/without non-tidal ocean loading (NTOL) correction (mm).

Ocean Tidal Constituents		M2	S2	N2	K1	O1	Q1
HKKT	MAX	1.5	2.5	1.6	1.5	3.5	2.8
	MIN	−1.7	−3.2	−1.7	−1.4	−2.2	−2.5
	MEAN	−0.2	−0.4	−0.3	−0.2	−0.1	0.2
	STD	0.5	0.2	0.3	0.4	0.7	0.5
HKMW	MAX	1.6	6.1	0.9	1.1	3.0	3.4
	MIN	−2.7	−4.1	−1.6	−3.2	−2.4	−2.5
	MEAN	−0.2	0.1	−0.5	−0.2	−0.2	0.4
	STD	0.5	0.6	0.6	0.6	0.7	0.8
HKNP	MAX	5.2	7.5	4.2	4.6	3.9	3.8
	MIN	−1.4	−2.1	−2.1	−1.5	−1.6	−1.5
	MEAN	0.2	0.8	0.9	0.3	0.6	0.9
	STD	0.2	0.7	0.8	0.9	0.3	0.6
HKOH	MAX	2.5	3.5	1.9	1.3	2.4	2.7
	MIN	−2.1	−3.7	−2.1	−1.1	−2.5	−2.6
	MEAN	−0.2	−0.5	−0.3	−0.3	0.1	0.3
	STD	0.6	0.1	0.5	0.5	0.7	0.6
HKSC	MAX	6.6	8.3	4.2	5.5	4.2	3.9
	MIN	−1.7	−2.7	−3.8	−1.6	−2.5	−2.6
	MEAN	1.6	0.5	0.3	0.3	0.6	0.4
	STD	0.3	0.1	0.3	0.1	0.2	0.5
HKST	MAX	1.6	3.7	2.2	1.7	2.6	2.1
	MIN	−2.4	−3.5	−3.2	−1.4	−2.5	−2.6
	MEAN	−0.1	−0.3	−0.5	0	0	−0.1
	STD	0.5	1.1	0.7	0.5	0.5	0.6

At the same time, the contribution of mass loading to the seasonal variation of the OTLD parameter is analyzed. The results are shown in Table 7. The formula [20] is:

$$\text{Contribution} = 1 - (A_2/A_1)^2 \quad (4)$$

where A_2 and A_1 are the average amplitudes of the series with/without mass loading correction, respectively. Contribution can also be called power explained.

It can be seen from Table 7 that ATL has some contribution to the seasonal variation of the OTLD parameter. The average contributions of the ATL to the seasonal variation of 6 principle tide constituents' OTLD parameters are 9.01%, 6.77%, 5.20%, 6.20%, 5.55%, and 3.22%, respectively. The average contributions of HYDL to the seasonal variation of 6 principal tidal constituents' OTLD parameters are 0.33%, 0.35%, 0.25%, 0.60%, 0.43%, and 0.25%, respectively. The average contributions of NTOL to the seasonal variation of 6 principal tidal constituents' OTLD parameters are 0.87%, 0.71%, 0.60%, 0.72%, 0.71%, and 0.47%, respectively. NTOL and HYDL contribute very little to the seasonal variation of OTLD parameters and can be ignored.

Table 7. Contribution rate of the mass loading at each station to the seasonal variation of OTLD parameter.

Correction	Site	M2	S2	N2	K1	O1	Q1
ATL	HKKT	9.17%	12.74%	5.21%	7.54%	4.04%	4.31%
	HKMW	11.05%	4.79%	4.24%	5.54%	5.62%	3.24%
	HKNP	10.11%	5.13%	6.16%	10.17%	9.14%	3.99%
	HKOH	9.40%	10.01%	5.67%	5.01%	2.96%	2.10%
	HKSC	7.46%	3.95%	4.09%	6.72%	4.68%	2.07%
	HKST	6.87%	7.26%	5.81%	6.18%	6.85%	3.61%
HYDL	HKKT	0.43%	0.16%	0.09%	0.57%	0.84%	0.12%
	HKMW	0.06%	0.21%	0.11%	0.61%	0.75%	0.09%
	HKNP	0.29%	0.69%	0.41%	0.34%	0.23%	0.47%
	HKOH	0.58%	0.03%	0.08%	0.18%	0.40%	0.29%
	HKSC	0.29%	0.64%	0.54%	0.21%	0.26%	0.34%
	HKST	0.34%	0.37%	0.24%	1.69%	0.11%	0.18%
NTOL	HKKT	0.96%	0.35%	0.34%	1.01%	0.67%	0.38%
	HKMW	0.27%	1.01%	0.71%	0.64%	0.61%	0.51%
	HKNP	1.30%	0.62%	0.59%	0.94%	0.54%	0.49%
	HKOH	1.04%	0.85%	0.61%	0.54%	0.41%	0.24%
	HKSC	0.78%	0.71%	0.54%	0.69%	1.14%	0.62%
	HKST	0.89%	0.69%	0.83%	0.51%	0.87%	0.58%

5. Conclusions

Based on 5 years of kinematic coordinate time series in direction U of six GNSS stations in Hong Kong, the MHA method is proposed to explore the seasonal variation of the OTLD parameters of the 6 principal tidal constituents (M2, S2, N2, K1, O1, Q1). Additionally, the influence of mass loading on the seasonal variation of OTLD parameters is analyzed. The results show that the MHA method can effectively detect the seasonal variation of OTLD parameters, of which the annual periodic signal, semi-annual periodic signal, and ter-annual periodic signal are the most obvious. The OTLD's amplitude parameters changes of the 6 principal tidal constituents are around 4%–25.1% and the oscillation ranges of OTLD's phase parameters vary from 8.8° to 20.2°. ATL has certain influence on the seasonal variation of OTLD parameters. The influence of HYDL and NTOL on the seasonal variation of OTLD parameters is very little and can be ignored.

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