Dear Editor,

We'd like to thank both reviewers for their comments and positive appraisal. Based on their comments, we have changed the manuscript. Please find below a point-to-point response marked in blue, with changes in the text cited in green. The page numbers and line numbers in this document refer to the revised version of the manuscript without using the revision mode in the Microsoft Word.

Response to comments by Reviewers #1

(1) OVERVIEW -This study provides an analysis of the seasonal variation (or as I have called it in the past, "seasonality") of the M2, S2, K1, and O1 tides in Bohai Bay. -This is a good an important subject to study, as the seasonal variability of tides (that is not astronomical) may be a significant part of water level variability in certain regions, particularly those subject to strongly seasonal weather patterns (like the monsoons in Asia), or especially shallow regions (like the Gulf of Thailand). -Overall, I think the methods and approach is sound, and the numerical models are sound. I would really like to accept this paper, but I am concerned that the missing data is a big limitation to the trust ability of the results, and this should at least be discussed more. I do have some other major concerns, listed below, and some other minor comments.

Reply:

Thanks a lot for the positive assessment and constructive comments of our paper.

According to your fifth comment and the third comments from Reviewer #2, we have omitted the E1 station, at which there are some gaps in the sea level observations; in addition, the tidal gauge station Dalian, at which there are 17-year sea-level observations, is added to investigate the seasonal variation of principal tidal constituents in the Bohai Sea. Therefore, we have modified the title of the manuscript to be 'Seasonal variation of the principal tidal constituents in the Bohai Sea'.

Changes:

P1L1: Seasonal variation of the principal tidal constituents in the Bohai Sea

P2L24: Hourly sea-level data at the Dalian tidal gauge station were obtained from the

University of Hawaii Sea Level Center and used. After 1979, Dalian shared position with Laohutan (Feng et al., 2015), so the sea-level data at Dalian were comprised of data from Dalian from 1980-1990 and from Laohutan from 1991-1997, as shown in Figure 2b.

(2) -One factor that will have to be addressed in this manuscript is the English writing quality. It is not so bad, but it also not so good, and I can notice a number of small errors and style points (such as too many dependent clauses beginning sentences or paragraphs) that should be addressed to make this a better paper. So I would highly recommend having a native English speaker give this paper a very close read before acceptance.

Reply:

Thank you for your constructive suggestion. We are sorry that the old manuscript was hurriedly written and the English writing was not good. We have carefully modified and employed the professional language editors of Elsevier Language Editing Services to edit the revised manuscript.

The language editing certification is attached in the end of this document.

(3) As far as the “Enhanced harmonic analysis” methods and claims of novelty… There have been multiple improvements to T_TIDE in the past decades, such a R_T_TIDE (Leffler and Jay, 2009), “versatile” tidal analysis (Foreman, 2009) and U_TIDE (Codiga, 2011). Were any of these methods tried in addition to T_TIDE? If you haven’t tried these, then it’s harder to claim that your method is “enhanced” more than T_TIDE when others have already produced “enhanced” methods. How does your method improve on all these past approaches?

Reply:

Thank you for your comment.

The R_T_TIDE (Leffler and Jay, 2009), versatile tidal analysis (Foreman et al., 2009) and U_TIDE (Codiga, 2011), are indeed improved to T_TIDE in different perspectives. According to Equation (8) in Leffler and Jay (2009), Equation (4) in Forman et al. (2009) and Equation (2) in Codiga (2011), it can be found that the harmonic parameters (i.e., amplitude and phase lag) are assumed to be constant. In fact, the harmonic parameters are not constant and have multiscale temporal variations, as shown in Corkan (1934), Kang et al. (1995), Müller et al. (2014), Devlin et al. (2018), and so on.

Jin et al. (2018) and Pan et al. (2018) developed the enhanced harmonic analysis, in which the harmonic parameters (i.e., amplitude and phase lag) are assumed to be temporally varying and computed directly within the least squares fit. In this study, the nodal and astronomical argument corrections are embedded in the least squares fit; in addition, the harmonic parameters of minor constituents are assumed to be constant and computed together with the temporally varying harmonic parameters of principal tidal constituents to resolve more constituents and remain computational stability.

Although in the nonstationary tidal analysis tool NS_TIDE (Matte et al., 2013) the harmonic parameters are also assumed to be temporally varying, the temporally varying harmonic parameters are assumed to be functions of river flow and greater diurnal tidal range at the reference station. Therefore, it just can be applied to the river tides. On the contrary, the enhanced harmonic analysis can be applied in analyzing any time series.

Therefore, the enhanced harmonic analysis used in this study improves on all the past approaches, which has been discussed in the revised manuscript.

Changes:

P9L16: In this study, the EHA developed in Jin et al. (2018) and Pan et al. (2018b) was further improved in order to resolve more tidal constituents by adding the minor constituents whose harmonic parameters were assumed to be constant and computed together with the temporally varying harmonic parameters of the principal tidal constituents. The nodal and astronomical argument corrections were embedded into the least square fit to eliminate the influences of nodal cycle and linearly varying astronomical argument. In fact, there have been multiple improvements to T_TIDE in the past decades, such as R_T_TIDE (Leffler and Jay, 2009), versatile tidal analysis (Foreman et al., 2009), U_TIDE (Codiga, 2011) and NS_TIDE (Matte et al., 2013). In R_T_TIDE, versatile tidal analysis and U_TIDE, the harmonic parameters (i.e., amplitude and phase lag) are assumed to be constant, although they have some improvements to T_TIDE. However, harmonic parameters are not constant and have multiscale temporal variations, as shown in Corkan (1934), Kang et al. (1995), Müller et al. (2014), Devlin et al. (2018), and so on. Neglecting seasonal variation of tides will introduce significant error in sea-level prediction (Fang and Wang, 1986). Therefore, EHA, in which the harmonic parameters of the principal tidal constituents are assumed to be temporally varying and computed directly within the least squares fit, improved T_TIDE in other ways. In NS_TIDE, the harmonic parameters are also assumed to be temporally varying. However, the temporally varying harmonic parameters are assumed to be functions of river flow and greater diurnal tidal range at the reference station, so it can be applied only to river tides, while EHA can be applied in analyzing any time series. On the whole, EHA used in this study is indeed enhanced than other methods.

(4) While one year of hourly water level data is indeed enough to resolve most tides and reveal a seasonal cycle, I have some reservations about how much you can conclude about the seasonality cycle based on one year of observations. It is likely somewhat constant year-by-year, but it is hard to be sure. If you look at Devlin et al, 2018, for example, they looked at 30 years of data to show the seasonal cycle was basically constant, but not identical. If a single year had some sort of rare event (like a particularly strong storm season), this might skew the seasonal pattern a bit. I understand that one year is quite a bit of data to get from mooring, and more data is likely not available, but this is still a limitation that should be discussed somewhere in the paper.

Reply:

Thank you for your constructive suggestion.

The duration of hourly sea-level observations at E2 used in this study was only one year, which is a limitation. Although the rare event might slightly skew seasonal pattern of tides, the seasonal variations of the principal tidal constituents M_2, S_2, K_1 and O_1 obtained using EHA were the same as those using traditional EHA, indicating that the results are not unreasonable and can reflect the seasonal variations of tides in the analysis period. The strong seasonal variations of the principal tidal constituents can be captured by the results of numerical experiments.

Besides, according to your fifth comment and the third comments from Reviewer #2, we have omitted the E1 station, at which there are some gaps in the sea level observations; in addition, the tidal gauge station Dalian, at which there are 17-year sea-level observations, is added to investigate the seasonal variation of principal tidal constituents in the Bohai Sea.

Changes:

P10L1: The duration of hourly sea-level observations at E2 used in this study was only one year, which is a limitation. Although the rare event might slightly skew seasonal pattern of tides, the seasonal variations of the principal tidal constituents M_2, S_2, K_1 and O_1 obtained using EHA were the same as those using traditional EHA, indicating that the results are not unreasonable and can reflect the seasonal variations of tides in the analysis period. The strong seasonal variations of the principal tidal constituents can be captured by the results of numerical experiments. The multi-annually averaged results at Dalian also showed the seasonal variations of the principal tidal constituents, but the results of numerical experiments were not in accordance with the observed results, which may be because only the horizontally homogeneous profiles of the initial temperature and salinity were used and the temporally varying ocean circulation were not considered.

(5) Also, the existence of gaps in the single year dataset is also unfortunate, because it is hard to know the effect of the gaps without comparing them to a full year's data. Are there any ground-based tide gauges nearby to compare to? -I think that the data gaps at E1 are too extensive ti trust this location. Unless you have another nearby location (like a ground-based tide gauge) to compare to, I don't think that these results can be trusted. So maybe this location should be omitted.

Reply:

Thank you for your constructive suggestion. We are sorry that there are no ground-based tide gauge stations nearby to compare to. The gaps at E1 are indeed difficultly evaluated, as you said. According to your suggestion, we have omitted E1 station.

Besides, the tidal gauge station Dalian, at which there are 17-year sea-level observations, is added to investigate the seasonal variation of the principal tidal constituents in the Bohai Sea. Therefore, both the mooring data and the tidal gauge station data are used in the revised manuscript.

(6) My recommendation is for major revision, with more discussions about the effects of missing data, and the comparisons to other methods and the results of other who have analysed seasonality.

Reply:

Thank you for giving us the opportunity to further improve the old manuscript.

According to the suggestions from you and Reviewer #2, we omit the E1 station, at which there are some gaps in the sea level observations; in addition, the tidal gauge station Dalian, at which there are 17-year sea-level observations, is added to investigate the seasonal variation of the principal tidal constituents in the Bohai Sea. Because there are no large gaps in the observations at both E2 and Dalian, the effect of missing data is not discussed in the revised manuscript.

The comparisons to other methods, including R_T_TIDE (Leffler and Jay, 2009), versatile tidal analysis (Foreman et al., 2009), U_TIDE (Codiga, 2011) and NS_TIDE (Matte et al., 2013), have been added in section 5 (discussions) of the revised manuscript, which have been shown in the 'Changes' of the third comment.

The comparisons to other studies have been added in the revised manuscript, as shown in the following 'Changes'.

Changes:

P2L8: Previous studies have primarily focused on the seasonal variation in the M_2 amplitude without considering the seasonality of other tidal constituents and their phase lags (Gräwe et al., 2014). Indeed, several studies have investigated the seasonality of several constituents. For example, Fang and Wang (1986) studied the seasonal variations of M_2, N_2, O_1

and M_4 in the Bohai Sea by introducing astro-meteorological constituents; Devlin et al. (2018) found that the diurnal (K_1 and O_1) and semidiurnal (M_2 and S_2) tidal amplitudes and phase lags exhibited strong seasonal variability in the seas of Southeast Asia. In this study, sea-level observations at one mooring station (E2) and one tidal gauge station (Dalian) in the Bohai Sea were used to investigate the seasonal variability of the principal tidal constituents M_2, S_2, K_1 and O_1 using an enhanced harmonic analysis (EHA)..

P5L10: Compared to the annual averages, the mean M_2 amplitude increased by 6.90 cm (approximately 9.33%) in the summer and decreased by 6.68 cm (approximately 9.03%) in the winter, close to the estimated values in Foreman et al. (1995) (6%), Huess and Andersen (2001) (6%) and Müller et al. (2014) (5%–10%).

P9L11: The spatial distribution of the absolute differences between the M_2 tidal amplitude in summer and that in winter was similar to that in Müller et al. (2014).

(7) -ABSTRACT: -I understand what you are saying in your opening, and I do agree with everything you say, but the English is somewhat awkward right out of the gate, and this will confuse other readers who are not as familiar with tides. The text here just needs some minor refinement.

Reply:

Thank you for pointing this out. According to this suggestion, we have modified the first sentence in the revised manuscript, as shown in 'Changes'.

Changes:

P1L10: The seasonal variation of tides plays a significant role in water level changes in coastal regions.

(8) -INTRODUCTION -Page 2, line 3-4: Devlin et al, 2018 also looked at K1, O1, and S2 seasonality found some interesting patterns of seasonality in K1 and O1 at some locations, though M2 was the primary seasonal variation observed.

Reply:

Thank you for pointing this out. According to this comment, we have rewritten it as shown in following 'Changes'.

Changes:

P2L11: Devlin et al. (2018) found that the diurnal (K_1 and O_1) and semidiurnal (M_2 and S_2) tidal amplitudes and phase lags exhibited strong seasonal variability in the seas of Southeast Asia..

(9) -Line 5: "Several other studies have analysed the seasonal variability…".

Reply:

Thank you for pointing this out. We agree with your comment and have modified it in the revised manuscript.

Changes:

P2L4: Several other studies have analysed the seasonal variability of the M_2 tide in polar regions.

(10) -Line 7: "tidal constants" ---> "tidal constituents".

Reply:

Thank you for pointing this out. We agree with your comment and have modified it in the revised manuscript.

Changes:

P2L5: Kagan and Sofina (2010) showed that the seasonal variability of tidal constituents was widespread in the Arctic Ocean.

(11) -Line 14: "major tidal harmonic parameters" ---> "largest tidal constituents".

Reply:

Thank you for pointing this out. We agree with your comment and have modified it in the revised manuscript.

Changes:

P2L13: In this study, sea-level observations at one mooring station (E2) and one tidal gauge station (Dalian) in the Bohai Sea were used to investigate the seasonal variability of the principal tidal constituents M_2, S_2, K_1 and O_1 using an enhanced harmonic analysis (EHA).

(12) -OBSERVATIONS AND METHODS -Page 2, line 26: How about eustatic sea level rise?

Reply:

Thank you for pointing this out. We are sorry that the eustatic sea level rise was not explicitly shown in Equation (1) in the old manuscript. In the revised manuscript, we have modified the Equation (1) as follows:

$$\begin{aligned}\zeta(t)&=\zeta_0+\sum_{k=1}^{K}\left\{f_k(t)A_k\cos\left[V_k(t)+u_k(t)-g_k\right]\right\}+R(t)\\&=\zeta_0+\sum_{i=1}^{N_{\mathrm{NR}}}\left\{f_i(t)A_i\cos\left[V_i(t)+u_i(t)-g_i\right]\right\}+R(t)+\\&\quad\sum_{j=1}^{N_{\mathrm{R}}}\left\{f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right]+\sum_{n=1}^{N_{\mathrm{I}}}f_n(t)A_n\cos\left[V_n(t)+u_n(t)-g_n\right]\right\}\end{aligned}$$

where $\zeta(t)$ is the total sea level; ζ_0 is the mean sea level; A and g are the amplitude and phase lag (UTC time, the same below), respectively; f and u are the nodal corrections to the amplitude and phase, respectively; V is the astronomical argument; R is the nontidal component; K is the number of tidal constituents; N_{NR} is the number of non-reference constituents; N_{R} is the number of reference constituents; and N_{I} is the number of constituents to be inferred from the j^{th} reference constituent.

Therefore, the eustatic sea level rise is included in $R(t)$.

Changes:

P2L28:

A sea level is composed of components from different sources (Godin, 1972; Foreman, 1977; Fang, 1986; Pawlowicz et al., 2002; Foreman et al., 2009):

$$
\begin{aligned}
\zeta(t) &= \zeta_0 + \sum_{k=1}^{K}\left\{ f_k(t)A_k\cos\left[V_k(t)+u_k(t)-g_k\right]\right\} + R(t) \\
&= \zeta_0 + \sum_{i=1}^{N_{\mathrm{NR}}}\left\{ f_i(t)A_i\cos\left[V_i(t)+u_i(t)-g_i\right]\right\} + R(t) + \\
&\sum_{j=1}^{N_{\mathrm{R}}}\left\{ f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right] + \sum_{n=1}^{N_{\mathrm{I}}} f_n(t)A_n\cos\left[V_n(t)+u_n(t)-g_n\right]\right\}
\end{aligned}
\quad (1)
$$

where $\zeta(t)$ is the total sea level; ζ_0 is the mean sea level; A and g are the amplitude and phase lag (UTC time, the same below), respectively; f and u are the nodal corrections to amplitude and phase lag, respectively; V is the astronomical argument; R is the nontidal component; K is the number of tidal constituents; N_{NR} is the number of non-reference constituents; N_{R} is the number of reference constituents; and N_{I} is the number of constituents to be inferred from the j^{th} reference constituent.

(13) Page 3, line 4: See comment above about improvements to T_TIDE.

Reply:

Thank you for your constructive suggestion.

As shown in the reply of the third comment, the R_T_TIDE (Leffler and Jay, 2009), versatile tidal analysis (Foreman et al., 2009) and U_TIDE (Codiga, 2011), are indeed improved to T_TIDE in different perspectives. According to Equation (8) in Leffler and Jay (2009), Equation (4) in Forman et al. (2009) and Equation (2) in Codiga (2011), it can be found that the harmonic parameters (i.e., amplitude and phase lag) are assumed to be constant. In fact, the harmonic parameters are not constant and have multiscale temporal variations, as shown in Corkan (1934), Kang et al. (1995), Müller et al. (2014), Devlin et al. (2018), and so on.

Jin et al. (2018) and Pan et al. (2018) developed the enhanced harmonic analysis, in which the harmonic parameters (i.e., amplitude and phase lag) are assumed to be temporally varying and computed directly within the least squares fit. In this study, the nodal and astronomical argument corrections are embedded in the least squares fit; in addition, the harmonic parameters of minor constituents are assumed to be constant and computed together with the temporally varying harmonic parameters of principal tidal constituents to resolve more constituents and remain computational stability.

(14) Section 2.3 -I am bit unclear about what you mean by SHA here. Do you mean that you are harmonically analysing datasets that are monthly or shorter? If so, then you will resolve the four major tides, but you will likely not constrain the natural yearly variability that one-year analyses contain (such as SA and SSA). Therefore, any seasonality you observed might actually be just an artefact of the mathematics. If you had more than one year of data, you could perform overlapping one-year HA at one-month steps, then any seasonality revealed would be more “real” Maybe I am missing something, but at least you could explain it better. In any case, this is the obvious issue with only using one single year of data.

Reply:

Thank you for your comments.

In SHA, the sea level observations are divided into monthly segments according to calendar month and CHA with nodal and inference corrections is applied to each monthly segment to obtain the discrete tidal harmonic parameters (i.e., amplitude and phase lag), which has been used in many previous studies (e.g., Foreman et al., 1995; Kang et al., 1995; Müller et al., 2014; Devlin et al., 2018). Then the discrete amplitude and phase lag at each monthly segment are interpolated using cubic spline interpolation to obtain the temporally varying amplitude and phase lag.

It is reasonable to use the monthly analysis to obtain the seasonal variability of principal tide constituents, as long as a valid inference procedure is used. The seasonality in principal tide constituents have been investigated using monthly analysis in many previous studies (e.g., Foreman et al., 1995; Kang et al., 1995; Müller et al., 2014; Devlin et al., 2018).

As pointed out by Reviewer #2, the unresolved constituents in the monthly analysis will cause the spurious seasonality in K_1 and S_2 in the old manuscript. Following the suggestions from you and Reviewer #2, we have redone the data analysis in the revised manuscript. (1) Consider the nodal correction and infer unresolved constituents in SHA using the function in T_TIDE; (2) Embed the nodal correction into EHA to eliminate the influence of 18.6-year nodal modulation and add the minor constituents, whose harmonic parameters are assumed to be constant, to resolve more constituents. The seasonal variations of the principal tidal constituents at E2 and Dalian are shown in Figures 4 and 6, respectively, in the revised manuscript. The unreasonably large semi-annual modulations in S_2 and K_1 have disappeared and the results are reasonable on the whole.

Changes:

P3L13: Following Foreman et al. (1995), Kang et al. (1995), Müller et al. (2014) and Devlin et al. (2018), sea-level observations are divided into monthly segments by calendar month and CHA with nodal and inference corrections is applied to each monthly segment to obtain the discrete tidal harmonic parameters (i.e., amplitude and phase lag). Then the discrete amplitude and phase lag at each monthly segment are interpolated using cubic spline interpolation to obtain the temporally varying amplitudes and phase lags. This methodology is termed segmented harmonic analysis (SHA). Following Kang et al. (1995), the sea-level observations in every monthly segment are analyzed only when the duration of the observations is greater than 26 days.

(15) -Also, 15 days of data within a month as a criteria makes the results much worse, and could be highly spurious. This is less than 50% completeness, while I believe a criteria of 75% to 80% is needed.

Reply:

Thank you for your constructive suggestions. Following this comment and Kang et al. (1995), we have modified the criteria from 15 days to 26 days in the revised manuscript.

Changes:

P3L17: Following Kang et al. (1995), the sea-level observations in every monthly segment are analyzed only when the duration of the observations is greater than 26 days.

(16) RESULTS -Page 5, Line 4: Of course gaps will influence results, especially since you have such a relaxed criterion of completeness (50%) and such a short time-series (~ 1year). This has to be discussed more, and perhaps there is just not enough data to perform this study adequately.

Reply:

Thank you for your constructive suggestion. According to your suggestion and those from Reviewer #2, we have omitted the sea-level observations at E1 and added the multiyear sea-level observations at Dalian tidal gauge station. At both E2 and Dalian, there were no large gaps in the data, as shown in Figure 2 in the revised manuscript.

(17) MECHANISMS -Seasonal variations of sea level are indeed important and there can be a lot of reasons (monsoons, etc.), but can you discuss more what causes these variations, and how these might influence tides physically?

Reply:

Thank you for your constructive suggestions.

According to this suggestion, we have added the discussions of season variations of stratification and tides through physical processes. In winter, the strong northwest Asia monsoon develops a vertically will-mixed condition (Yanagi et al., 2001; Jeon et al., 2014), which will not stabilize the tidal currents and will lose more energy, leading to smaller tidal amplitudes. As the surface heating rate and freshwater discharge increase, the mixing is insufficient to homogenize the input potential energy and cause stratified conditions in summer (Huang et al., 1999; van Haren, 2000), during which the reduced vertical eddy viscosity will increase the tidal amplitudes. However, the S_2 amplitude at Dalian was larger in winter and smaller in summer, which is inconsistent with the other principal tidal constituents and should be further investigated in future studies.

Changes:

P10L9: The seasonal variations of stratification and vertical eddy viscosity and their influences on the tidal amplitudes may be as follows. In winter, the strong northwest Asia monsoon develops a vertically will-mixed condition (Yanagi et al., 2001; Jeon et al., 2014), which will not stabilize the tidal currents and will lose more energy, leading to smaller tidal amplitudes. As the surface heating rate and freshwater discharge increase, the mixing is insufficient to homogenize the input potential energy and cause stratified conditions in summer (Huang et al., 1999; van Haren, 2000), during which the reduced vertical eddy viscosity will increase the tidal amplitudes. However, the S_2 amplitude at Dalian was larger in winter and smaller in summer, which is inconsistent with the other principal tidal constituents and should be further investigated in future studies.

(18) Line 14-15: I think that the importance of sea ice in the reason could still be important to seasonality, if you consider the "back-effect" connection of coastal embayments and open water as discussed by Arbic and Garret, 2010; Arbic, 2009 via resonance mechanisms. So, even if the ice cover is far away from your observations site, it could still be important. These studies should at least be mentioned and discussed here.

Reply:

Thank you for your constructive suggestions. According to the back-effect connection of the coastal shelf and open ocean via resonance mechanisms (Arbic et al., 2009; Arbic and Garrett, 2010), sea ice may be important to the seasonality of principal tidal constituents. However, Zhang et al. (2019) developed a three-dimensional ice-ocean coupled model based on Finite Volume Community Ocean Model (FVCOM) and found that the damping effect of sea ice on the astronomical tides were almost negligible in the Bohai Sea using the numerical experiments.

According to your comment, we have discussed the influences of sea ice in the revised manuscript by citing Arbic et al. (2009), Arbic and Garret (2010) and Zhang et al. (2019).

Changes:

P7L13: According to the back-effect connection of the coastal shelf and open ocean via resonance mechanisms (Arbic et al., 2009; Arbic and Garrett, 2010), sea ice may be important to the seasonality of principal tidal constituents. However, Zhang et al. (2019) found that the damping effect of sea ice on the astronomical tides was almost negligible in the Bohai Sea employing numerical experiments with a three-dimensional ice-ocean coupled model. Therefore, ice coverage was not considered in this study.

(19) -Page 8, line 14: ".. as the differences … larger than 0." is kind of an elementary statement, you can omit this.

Reply:

Thank you for pointing this out. According to your suggestions, we have deleted this sentence in the revised manuscript.

(20) -Page 6, Line 16-19: Can you restate this as a statement instead of a question? It doesn't read well in the middle of the paragraph as written.

Reply:

Thank you for pointing this out. According to your suggestions, we have deleted this sentence in the revised manuscript.

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Response to comments by Reviewers #2

(1) The seasonal variation of the principal tidal constituents M2, S2, K1 and O1 is studied in this discussion paper by analyzing the sea level observations at two stations in the Bohai Bay. The authors emphasize that in the previous studies the seasonal variation of the M2 constituent has been fully investigated, while the other three have not been investigated. The authors further show that large semi-annual variation exists in S2 and K1 in their analyzed results. Since the paper contains some important improper treatments in data analysis, this paper needs major revision before publication.

Reply:

Thanks a lot for the positive assessment and constructive comments of our paper. The improper treatments have been modified in the revised manuscript and shown in the reply of following comments.

(2) The paper analyzes the observations monthly (month by month) to reveal seasonal variations of the obtained harmonic constants. The S2 and K1 results (Figures 3-5) show unreasonably large semi-annual (6-month period) modulation. I judge that this is due to the improper treatment in the harmonic analysis. That is, the unresolved constituents have not been removed in the analysis, resulting in spurious seasonality. To explain this, let us consider, as an example, the superposition of K1 and P1.

… ….

In the above we only show the influence of P1 on K1. In fact, the constituent ϕ_1 may also cause (but with smaller magnitude) semi-annual modulation in K1; while ψ_1, and S1 may cause annual modulation in K1, and π_1 may cause ter-annual (four-month) modulation in K1. Furthermore, it should be noticed that the S1 constituent actually contains two parts: the astronomical part having an amplitude ratio of 0.78% to K1; and the radiational part with magnitude depending on the strength of diurnal meteorological forcing. The latter part is generally much greater than the former in the coastal seas, and is actually not separable from the annual variation of K1 by means of data analysis.

Reply:

Thank you for pointing out these improper treatments in the old manuscript and demonstrating the influences of unresolved constituents on the corresponding principal tidal constituents using the theoretical method. We have learned a lot from this comment and thanks again.

According to this comment and the fifth comment, we have redone the data analysis. (1) Consider the nodal correction and infer unresolved constituents in SHA using the function in T_TIDE; (2) Embed the nodal correction into EHA to eliminate the influence of 18.6-year nodal modulation and add the minor constituents, whose harmonic parameters are assumed to be constant, to resolve more constituents. The details are as follows:

(1) Selection of the unsolved constituents

The power spectral densities of the observed sea level at E2 are shown in Figure R1 (i.e., Figure 3 in the revised manuscript), which indicated that P_1 was significant, while S_1 was not significant. So only P_1 was considered to be the unsolved constituent near K_1 and the other unsolved constituents with minor influences were ignored. Similarly, only K_2 was considered to be the unsolved constituents near S_2. At tidal gauge station Dalian, which was added according to the second comment, P_1 and K_2 were considered to be the unsolved constituents in the diurnal and semidiurnal frequency bands, respectively, according to the power spectral densities of the sea level observations in Figure R2 (i.e., Figure 5 in the revised manuscript).

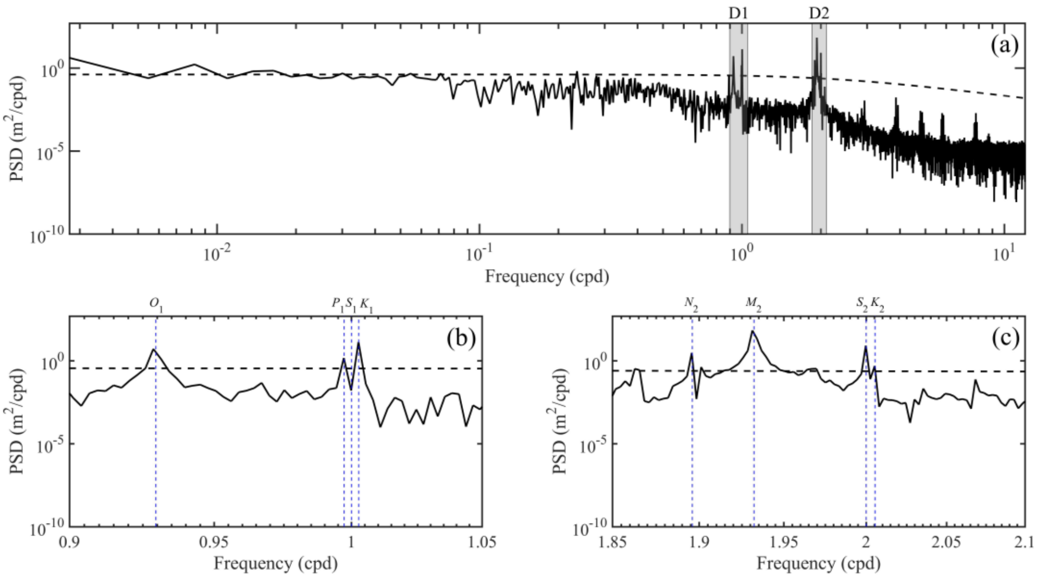

Figure R1. Power spectral densities of the observed sea level at E2 (black line) in (a) all frequency bands, (b) the diurnal frequency band, and (c) the semidiurnal frequency band. In all panels, black dashed lines denote the corresponding 5% significance level against red noise.

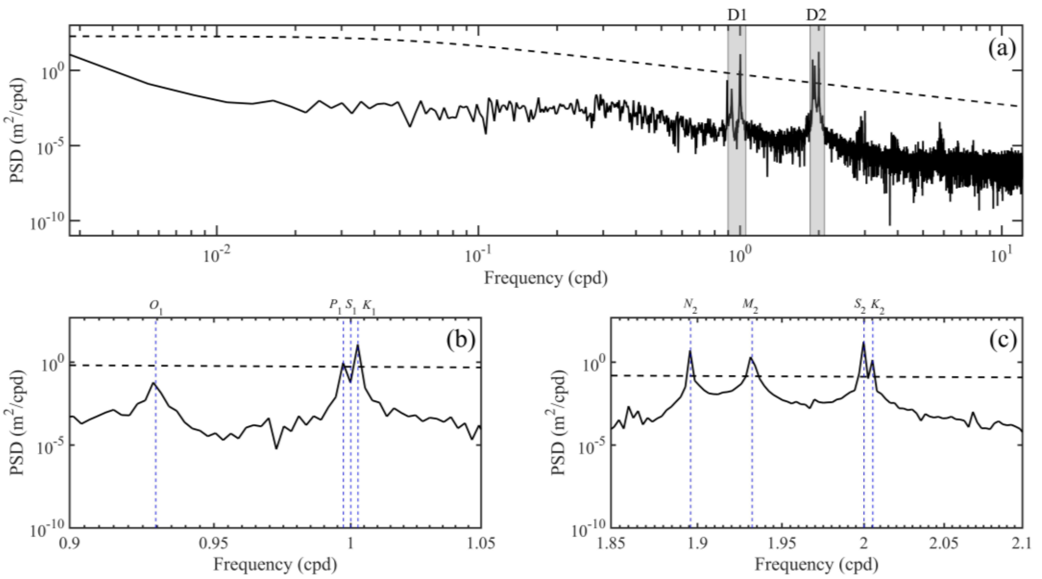

Figure R2. Similar to Figure R1, but for those at Dalian.

(2) Consider the influence of nodal correction and unresolved constituents in CHA and SHA

The sea level is composed of components from different sources (Fang, 1986; Foreman et al., 2009; Foreman, 1977; Godin, 1972; Pawlowicz et al., 2002):

$$
\begin{aligned}
\zeta(t) &= \zeta_0 + \sum_{k=1}^{K}\left\{ f_k(t)A_k\cos\left[V_k(t)+u_k(t)-g_k\right]\right\} + R(t) \\
&= \zeta_0 + \sum_{i=1}^{N_{\mathrm{NR}}}\left\{ f_i(t)A_i\cos\left[V_i(t)+u_i(t)-g_i\right]\right\} + R(t) + \\
&\sum_{j=1}^{N_{\mathrm{R}}}\left\{ f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right] + \sum_{n=1}^{N_{\mathrm{I}}} f_n(t)A_n\cos\left[V_n(t)+u_n(t)-g_n\right]\right\}
\end{aligned} \tag{1}
$$

where $\zeta(t)$ is the total sea level; ζ_0 is the mean sea level; A and g are the amplitude and phase lag, respectively; f_k and u_k are the nodal corrections to the amplitude and phase, respectively; V is the astronomical argument; R is the nontidal component; K is the number of tidal constituents; N_{NR} is the number of non-reference constituents; N_{R} is the number of reference constituents; and N_{I} is the number of constituents to be inferred from the j^{th} reference constituent.

The mean sea level, amplitude and phase lag of each constituent can be solved by analyzing a time series of sea-level observations at a specific point using classical harmonic analysis (CHA). With different assumptions and conditions, CHA can be performed using the T_TIDE (Pawlowicz et al., 2002), U_TIDE (Codiga, 2011) or Institute of Ocean Sciences Tidal Package (Foreman et al., 2009). In this study, T_TIDE, in which the astronomical argument varies linearly and the nodal correction is performed after least squares fit, is used to realize CHA.

As shown above, the influence of P_1 on K_1 and that of K_2 on S_2 can be removed by using the inference correction, which were performed using the function for inferring unresolved constituents in T_TIDE in MATLAB. Although the 18.6-year nodal modulation had little influence on the temporal variation of the principal tidal constituents in one month or one year, the 18.6-year nodal modulation was corrected in the revised manuscript.

(3) Improve EHA by introducing nodal corrections and minor constituents

In EHA (Jin et al. 2018; Pan et al., 2018), the mean sea level, amplitude and phase lag are assumed to be temporally varying. Following Foreman et al. (2009), the nodal and astronomical argument corrections were embedded into the least squares fit. In addition, the harmonic parameters (i.e., amplitude and phase lag) of minor tidal constituents were assumed to be constant to resolve more constituents and remain computational stability. Therefore, the total sea level in EHA was as follows:

$$\zeta(t)=\zeta_0+\sum_{i=1}^{I}\left\{f_i(t)A_i(t)\cos\left[V_i(t)+u_i(t)-g_i(t)\right]\right\}+\sum_{j=1}^{J}\left\{f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right]\right\} \quad (2)$$

Similar to Jin et al. (2018) and Pan et al. (2018b), the independent point scheme and cubic spline interpolation are used to jointly determine solve the temporally varying and constant harmonic parameters, which are not shown here for brevity.

(4) The estimated temporally varying harmonic parameters of principal tidal constituents

The estimated temporally varying tidal hormonic parameters of the principal tidal constituents at E2 were shown in Figure R3 (Figure 4 in the revised manuscript). Indeed, the semi-annual and annual variations existed in S_2 and K_1 were not large, as Reviewer #2 said. The estimated results obtained using EHA had the same variation trend with those obtained using SHA, showing that the improved EHA in the revised manuscript was useful.

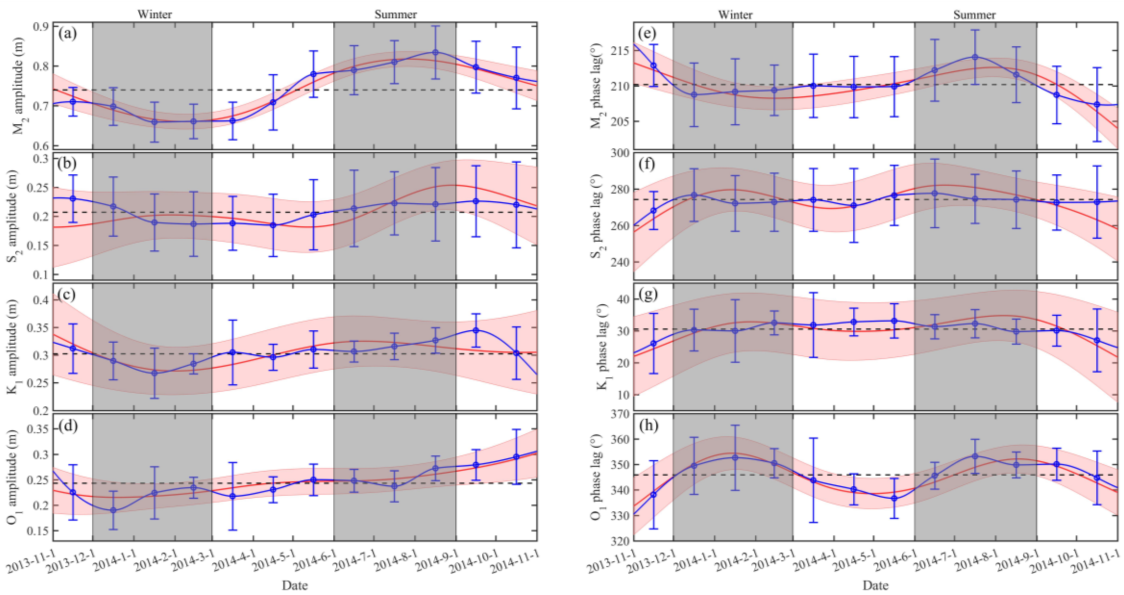

Figure 4. Time series of the estimated temporally varying tidal amplitudes of principal tidal constituents, including (a) M_2, (b) S_2, (c) K_1 and (d) O_1, at E2 when CHA (black dashed lines), SHA (blue lines) and EHA (red lines) were used. (e-h) Similar to (a-d), but for the estimated temporally varying tidal phase lags. Blue vertical bars and pink shading indicate the corresponding 95% confidence intervals.

Besides, as an example, the sea level observations at Dalian from 1981-1-1 to 1997-1-1 were directly analyzed using SHA and EHA with and without considering the 18.6-year nodal modulation. In SHA, the CHA was performed overlapping one-year at one-month steps. The results are shown in Figure R4. No matter the 18.6-year nodal modulation was considered or not, the estimated temporally varying amplitudes obtained using the improved EHA had same variation trend with those obtained using SHA, showing the improved EHA was effective. As the seasonal variations were investigated in this paper, this part of verifying EHA was not shown in the revised manuscript.

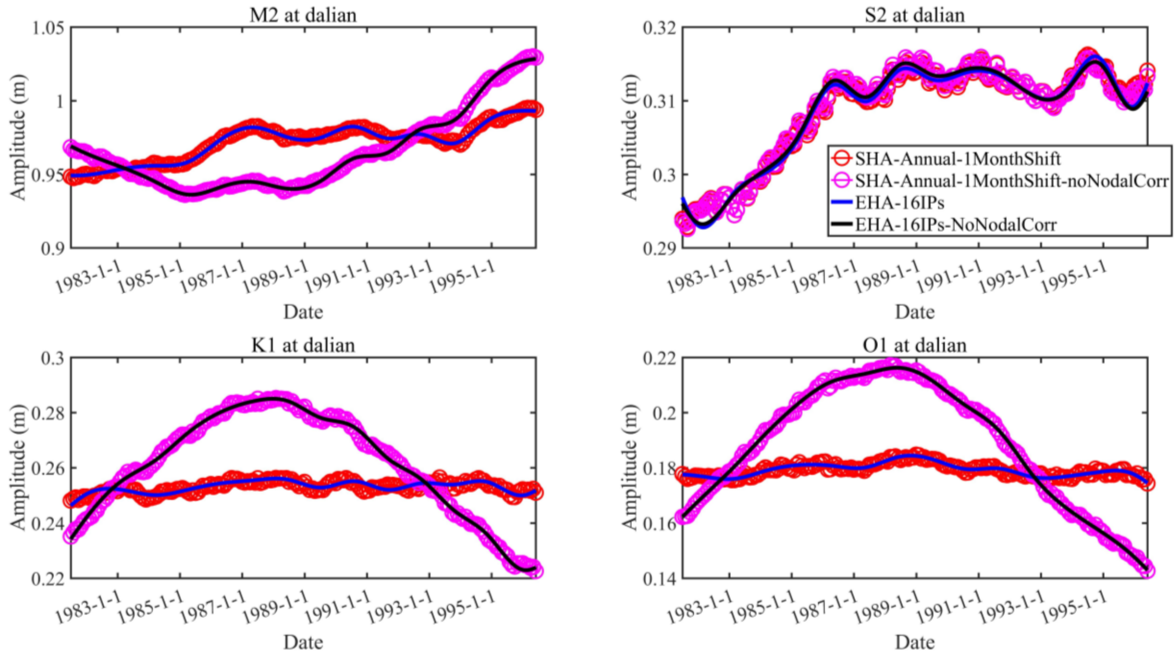

Figure R4. The estimated temporally varying amplitudes of (a) M_2, (b) S_2, (c) K_1, and (d) O_1 at Dalian using SHA with nodal correction (red lines), those obtained using SHA without nodal correction (magenta lines), those obtained using EHA with nodal correction (blue lines) and those obtained using EHA without nodal correction (black lines).

(3) The signals of seasonality are usually weak, especially for the constituents S2, K1 and O1, and the semi-annual variations. Thus the results derived from only one-year observations are not robust. It is suggested that authors use multiyear tidal gauge station data instead of one-year mooring data.

Reply:

Thank you for your constructive suggestions. The multiyear tidal gauge station data is indeed the most suitable observations to investigate the seasonality. But one-year mooring data is infrequent. We think the mooring data can be used to show the seasonal variation of the principal tidal constituents in the observation period, although the results may be not robust.

Considering this comment and those from Reviewer #1, we omit the E1 station, at which there are some gaps in the sea level observations; in addition, the tidal gauge station Dalian, at which there are 17-year sea-level observations, is added to investigate the seasonal variation of principal tidal constituents in the Bohai Sea. Therefore, both the mooring data and the tidal gauge station data are used in the revised manuscript. Besides, we have modified the title of the manuscript to be ‘Seasonal variation of the principal tidal constituents in the Bohai Sea’.

Changes:

P1L1: Seasonal variation of the principal tidal constituents in the Bohai Sea

P2L24: Hourly sea-level data at the Dalian tidal gauge station were obtained from the University of Hawaii Sea Level Center and used. After 1979, Dalian shared position with Laohutan (Feng et al., 2015), so the sea-level data at Dalian were comprised of data from Dalian from 1980-1990 and from Laohutan from 1991-1997, as shown in Figure 2b.

(4) Page 1, lines 24-30: Fang and Wang (1986) first studied the seasonal variation of the constituents M2, N2, O1 and M4 in the Bohai Sea by introducing, as they called, the astrometeorological constituents.

Reply:

Thank you for your comment. We are sorry that we did not read this literature in the preparation of the old manuscript. According to this comment, we have added this literature in the revised manuscript.

Changes:

P2L10: Fang and Wang (1986) studied the seasonal variations of M_2, N_2, O_1 and M_4 in the Bohai Sea by introducing astro-meteorological constituents.

(5) Page 2, lines 5-20: When the monthly analysis is performed, the major part of influence of the unresolved constituents can be removed by using an inference procedure. Almost all classical tidal harmonic analysis programs have the function for inferring unresolved constituents (see, e. g., Foreman (1977); Wang and Fang (1981); Pawlowicz et al. (2002). An alternative approach can be found in Devlin et al. (2018).

Reply:

Thank you for your constructive suggestions.

According to your suggestions, we used the inference procedure in the T_TIDE to remove the major part of influence of the unresolved constituents, when the monthly analysis was performed in SHA.

When EHA was used, the one-year sea-level observations were directly analyzed, so the unresolved constituents in the monthly analysis can be resolved. However, those constituents were generally minor and the seasonal variations were not concerned. Therefore, the harmonic parameters of those minor constituents were assumed to be constant and were solved together with the temporally varying harmonic parameters to remove the influence on the principal tidal constituents, which was the improvement compared to those in Jin et al. (2018) and Pan et al. (2018).

Besides, the nodal and astronomical corrections, as described in Foreman et al. (2009), were also embedded into the least squares fit in EHA, which was also the improvement in the revised manuscript.

Changes:

P2L28: A sea level is composed of components from different sources (Godin, 1972;

Foreman, 1977; Fang, 1986; Pawlowicz et al., 2002; Foreman et al., 2009):

$$\begin{aligned}\zeta(t)&=\zeta_0+\sum_{k=1}^{K}\left\{f_k(t)A_k\cos\left[V_k(t)+u_k(t)-g_k\right]\right\}+R(t)\\&=\zeta_0+\sum_{i=1}^{N_{\mathrm{NR}}}\left\{f_i(t)A_i\cos\left[V_i(t)+u_i(t)-g_i\right]\right\}+R(t)+\\&\quad\sum_{j=1}^{N_{\mathrm{R}}}\left\{f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right]+\sum_{n=1}^{N_{\mathrm{I}}}f_n(t)A_n\cos\left[V_n(t)+u_n(t)-g_n\right]\right\}\end{aligned} \tag{1}$$

where $\zeta(t)$ is the total sea level; ζ_0 is the mean sea level; A and g are the amplitude and phase lag (UTC time, the same below), respectively; f and u are the nodal corrections to amplitude and phase lag, respectively; V is the astronomical argument; R is the nontidal component; K is the number of tidal constituents; N_{NR} is the number of non-reference constituents; N_{R} is the number of reference constituents; and N_{I} is the number of constituents to be inferred from the j^{th} reference constituent.

P3L13: Following Foreman et al. (1995), Kang et al. (1995), Müller et al. (2014) and Devlin et al. (2018), sea-level observations are divided into monthly segments by calendar month and CHA with nodal and inference corrections is applied to each monthly segment to obtain the discrete tidal harmonic parameters (i.e., amplitude and phase lag).

P3L24: In this study, nodal and astronomical argument corrections are embedded into the least square fit, following Foreman et al. (2009); in addition, the harmonic parameters of the minor tidal constituents are assumed to be constant and computed together with the temporally varying harmonic parameters of the principal tidal constituents to resolve more constituents and retain computational stability. The sea level in EHA is as follows:

$$\zeta(t)=\zeta_0(t)+\sum_{i=1}^{I}\left\{f_i(t)A_i(t)\cos\left[V_i(t)+u_i(t)-g_i(t)\right]\right\}+\sum_{j=1}^{J}\left\{f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right]\right\} \tag{2}$$

where I is the number of principal tidal constituents with temporally varying harmonic parameters; J is the number of minor tidal constituents with constant harmonic parameters; and the mean sea level and nontidal component are included in $\zeta_0(t)$.

P4L16: As shown in Figure 3, the significant constituent near K_1 was P_1, which was unresolved when analysing one-month observations (Fang and Wang, 1986), while that for S_2

was K_2 in the semidiurnal frequency band. Therefore, when the monthly analysis was performed in SHA, the automated constituent selection algorithm in T_TIDE was used to determine the analysed constituents; in addition, the unresolved constituents P_1 and K_2 were inferred from K_1 and S_2, respectively, with the inference parameters taken from a yearly harmonic analysis of the one-year sea-level observations at E2 (Kang et al., 1995; Foreman et al., 2009). When EHA was used to directly analyse the sea-level observations at E2, the harmonic parameters of M_2, K_1, S_2, O_1, P_1 and K_2 were estimated together; in detail, the harmonic parameters of M_2, K_1, S_2 and O_1 were assumed to be temporally varying and those of P_1 and K_2 were assumed to be constant.

(6) Page 6, line 16: "Chen (2015)" was not given in the references.

Reply:

In the old manuscript, Chen et al. (2015) was shown in the first literature in the reference list, as follows:

Chen, Y., Liu, R., and Long, h.: Change Analysis of the Spatio-temporal Characters of Sea Ice in the Bohai Sea Based on MODIS Images, Bulletin of Surveying and Mapping, 9, 83-86 (in Chinese with English abstract), 2015.

According to the comments from Reviewer #1, we have used other reason to omit the influences of sea ice in the revised manuscript by citing Arbic et al. (2009), Arbic and Garret (2010) and Zhang et al. (2019) and removed Chen et al. (2015).

Changes:

P7L13: According to the back-effect connection of the coastal shelf and open ocean via resonance mechanisms (Arbic et al., 2009; Arbic and Garrett, 2010), sea ice may be important to the seasonality of principal tidal constituents. However, Zhang et al. (2019) found that the damping effect of sea ice on the astronomical tides was almost negligible in the Bohai Sea employing numerical experiments with a three-dimensional ice-ocean coupled model. Therefore, ice coverage was not considered in this study.

(7) Page 7, line 26 and page 17, caption of Figure 9: The word “rate” is improperly used.

Reply:

Thank you for pointing this out. In the revised manuscript, we have deleted Figure 9 in the old manuscript and the corresponding content.

(8) Page 11, Tables 1 and 2: In the literatures on ocean tides, “phase lag” is convectional used instead of “phase”. In addition, the reference time should be specified in relation to the phase lag.

Reply:

Thank you for pointing these out. We have changed all of the “phase” to “phase lag” and added the reference time in the revised manuscript.

Changes:

P3L2: A and g are the amplitude and phase lag (UTC time, the same below), respectively.

(9) The English writing needs substantial improvement. Better ask a native English speaker to edit the manuscript.

Reply:

Thank you for your suggestions. We sorry that the old manuscript was hurriedly written and the English writing was not good. We have carefully modified and employed the professional language editors of Elsevier Language Editing Services to edit the revised manuscript.

The language editing certification is attached in the end of this document.

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Pawlowicz, R., Beardsley, B., and Lentz, S.: Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE, Computers & Geosciences, 28, 929-937, 2002.

Zhang, N., Wang, J., Wu, Y., Wang, K.-H., Zhang, Q., Wu, S., You, Z.-J., and Ma, Y.: A modelling study of ice effect on tidal damping in the Bohai Sea, Ocean Engineering, 173, 748-760, 2019.

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Seasonal variation of the principal ~~main~~ tidal constituents in the Bohai ~~Bay~~Sea

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Abstract. The seasonal variation ~~variability~~ of tides plays a significant role in water level changes in coastal regions. ~~the M_2 tidal amplitude has been observed widely, especially in the coastal regions, but the seasonal variations in several major tidal constituents have not been investigated sufficiently.~~ In this study, ~~the~~ seasonal variations ~~in~~ of ~~the~~four principal ~~major~~ tidal constituents, including M_2, S_2, K_1, and O_1, in the Bohai ~~Bay~~Sea, China, ~~are~~ were studied by analysing one~~one~~-year sea-level observations ~~of the sea level~~ at ~~two stations, E1 and~~ E2 and 17-year sea-level observations at Dalian with an enhanced harmonic analysis. ~~,~~ At E2, the ~~frequencies of the~~ M_2 tidal amplitude and phase lag ~~are~~ had annual frequencies, with large values in summer and small values in winter, while the frequencies of ~~the~~ S_2 and K_1 tidal amplitudes are also nearly ~~semi-~~annual. ~~Furthermore~~In contrast, the O_1 tidal amplitude increased~~s~~ constantly from winter to autumn. The maxima of ~~the~~ phase lags appeared~~r~~ twice in one year for ~~the~~ S_2, K_1~~,~~ and O_1 ~~tides~~, ~~which~~ taking~~e~~ place near~~ly in~~ winter and summer. The seasonal~~ly varying~~ variation trends ~~at E1~~ estimated by the enhanced harmonic analysis at Dalian are ~~similar to~~different from those at E2, except for the ~~the O_1, tidal amplitude~~M_2 phase lag. The M_2 and S_2 tidal amplitudes varied semi-annually and annually, respectively and were relatively significant at Dalian. The results of ~~the~~ numerical experiments indicate that the seasonality of ~~the stratification and the corresponding~~ the vertical eddy viscosity ~~coefficient~~ induced seasonal variations ~~in~~ of~~the phases and amplitudes for all the major~~ principal tidal constituents~~, respectively~~at E2, while the variations at Dalian were due to the seasonality of stratification and vertical eddy viscosity.

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1 Introduction

Although there is no primary seasonal cycle in the moon's orbit, a significant seasonal variation in the ~~main~~ principal lunar tidal constituent has been observed~~, which~~ and is dominant in ~~the~~ coastal and polar regions (Müller et al., 2014). In particular, ~~The~~ the seasonal variation in the major tidal constituent M_2 has received considerable attention (Gräwe et al., 2014).

~~In several coastal regions, significant seasonal variations in the M_2 tide have been observed and investigated.~~ Corkan (1934) inferred a seasonal modulation of the ~~the~~ M_2 tide by analysing several sea-level records near the British coast. Foreman et al. (1995) observed a~~the~~ seasonal cycle of~~in~~ the M_2 amplitude at Victoria, which is on the southern tip of Vancouver Island off Canada's Pacific coast. Kang et al. (1995) revealed the seasonal variability of the M_2 tidal harmonic constants in the seas adjacent to Korea. Huess and Andersen (2001) found a~~the~~ seasonal variation in the M_2 constituent in the north-west European shelf. Kang et al. (2002) investigated the seasonal variability of the M_2 tide in the Yellow and East China Seas. Georgas (2012) observed seasonal episodes of significant tidal damping and ~~tidal~~ modulation in the Hudson River estuary. Müller et al. (2014) studied the global seasonal cycle of the M_2 tide and found significant seasonal variations in several coastal areas, ~~e.g.,~~including the North Sea, East China Sea and Yellow Sea, Sea of Okhotsk and ~~the~~ regions of the Banda, Timor, and Arafura Seas north of Australia. Tazkia et al. (2017) found that the M_2 amplitude ~~showed~~ changed markedly~~ed~~ ~~changes~~ between ~~the~~ winter and summer ~~seasons~~ in the northern Bay of Bengal. ~~Devlin et al. (2018) found that the M_2 tidal amplitude exhibited strong seasonal variability in Southeast Asia.~~

~~Furthermore, se~~Several other studies have analysed ~~been carried out to present and study~~ the seasonal variability of the M_2 tide in ~~the~~ polar regions. Mofjeld (1986) observed ~~the~~ seasonal fluctuations of the tidal harmonic parameters on the north-eastern Bering Sea shelf. Kagan and Sofina (2010) showed that the seasonal variability of tidal constants was ~~a~~ widespread ~~phenomenon~~ in the Arctic Ocean. Further, Müller et al. (2014) studied the global seasonal cycle of the M_2 tide and ~~found~~ likewise identified significant seasonal variations in the Arctic regions.

Previous studies have primarily focused on the seasonal variation in the M_2 amplitude without considering the seasonality of other tidal constituents and their phase lags (Gräwe et al., 2014). Indeed, several studies have investigated the seasonality of several constituents. For example, Fang and Wang (1986) studied the seasonal variations of M_2, N_2, O_1 and M_4 in the Bohai Sea by introducing astro-meteorological constituents; Devlin et al. (2018) found that the diurnal (K_1 and O_1) and semidiurnal (M_2 and S_2) tidal amplitudes and phase lags ~~M_2 tidal amplitude~~ exhibited strong seasonal variability in the seas of Southeast Asia.

~~In the Bohai Sea, Yellow Sea, and East China Sea, the M_2 tide has a large seasonal cycle (Müller et al., 2014), but there are few studies regarding the seasonal variability of other constituents in the Bohai Bay, which is a coastal bay in the Bohai Sea. Fang and Wang (1986)~~In this study, ~~the~~ sea-~~l~~level observations at one mooring station (E2) and one tidal gauge station (Dalian) ~~at two stations~~ in the Bohai ~~Bay~~ Sea ~~are~~ were used to investigate the seasonal variability of the ~~major~~ principal tidal constituents M_2, S_2, K_1 and O_1 using an enhanced harmonic analysis (EHA)~~, considering both the amplitude and phase~~. The ~~details of the~~ rest of the paper ~~are~~ is organised as follows.~~:~~ In Section 2, the sea-level observations ~~observations~~ in the Bohai Sea are reported ~~of sea level in the Bohai Bay~~ and the analysis methods are described ~~in Section 2.;~~ ~~in~~ In Section 3, the seasonal variability of the ~~major~~ principal tidal constituents ~~in the Bohai Bay~~ is estimated by analysing ~~the~~ observations.~~;~~ ~~the~~ The mechanisms ~~for~~ underlying the seasonal variability ~~of the major tidal harmonic parameters~~ are discussed by using

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numerical experiments in Section 4.~~;~~ ~~and t~~Further~~he~~ discussions and ~~-~~conclusions ~~can be found in~~occupy ~~section~~ Sections 5 and 6, respectively.~~.~~

2 Observations and methods

2.1 Observations

From 0000 UTC 1 November 2013 to 0000 UTC 1 November 2014,~~ the~~ total sea levels were observed hourly using ~~the~~ a moored pressure gauge~~, which was~~ accurate to within 5 cm (Lv et al., 2018), at ~~two~~ E2 station~~s, E1 and E2,~~ in the Bohai Bay, China (Figure 1). The time serie~~s~~s of the total sea levels at ~~E1 and~~ E2 ~~are~~ is shown in Figure 2a, demonstrating the continuous coverage of the observations.

~~. It is obvious that there were some gaps in the sea-level observations at E1, while the sea-level observations at E2 were covered continuously.~~Hourly sea-level data at the Dalian tidal gauge station were obtained from the University of Hawaii Sea Level Center and used. After 1979, Dalian shared position with Laohutan (Feng et al., 2015), so the sea-level data at Dalian were comprised of data from Dalian from 1980-1990 and from Laohutan from 1991-1997, as shown in Figure 2b.

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2.2 Classical harmonic analysis

A sea level is composed of components from different sources (Godin, 1972; Foreman, 1977; Fang, 1986; Pawlowicz et al., 2002; Foreman et al., 2009):~~Besides the steric sea level associated with the seawater thermal expansion, the sea level is composed of components from different sources :~~

$$\zeta(t)=\zeta_0+\sum_{k=1}^{K}\left\{f_k(t)A_k\cos\left[V_k(t)+u_k(t)-g_k\right]\right\}+R(t)$$

$$=\zeta_0+\sum_{i=1}^{N_{\mathrm{NR}}}\left\{f_i(t)A_i\cos\left[V_i(t)+u_i(t)-g_i\right]\right\}+R(t)+$$

$$\sum_{j=1}^{N_{\mathrm{R}}}\left\{f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right]+\sum_{n=1}^{N_{\mathrm{I}}}f_n(t)A_n\cos\left[V_n(t)+u_n(t)-g_n\right]\right\}$$

$$\cancel{\zeta(t)=\zeta_0+\zeta_{tide}(t)+\zeta_{meteorology}(t)} \qquad (1)$$

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where $\zeta(t)$ is the total sea level; ζ_0 is the mean sea level; A and g are the amplitude and phase lag (UTC time, the same below), respectively; f and u are the nodal corrections to amplitude and phase lag, respectively; V is the astronomical argument; R is the nontidal component; K is the number of tidal constituents; N_{NR} is the number of non-reference constituents; N_{R} is the number of reference constituents; and N_{I} is the number of constituents to be inferred from the j^{th} reference constituent.~~, and the three terms in the right of Equation (1) are the mean sea level, sum of the tidal components and the response of the ocean to meteorological forcing, respectively.~~

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The mean sea level, ~~The~~ amplitude and phase lag of each constituent~~, which are subsequently termed as harmonic parameters,~~ can be ~~determined~~ solved by analyz~~s~~ing a time series of sea~~-~~level observations at a specific point using classical harmonic analysis (CHA). With different assumptions and conditions, CHA can be performed using the T_~~Tide~~ TIDE ~~toolkit in MATLAB~~ (Pawlowicz et al., 2002), U_TIDE (Codiga, 2011) or Institute of Ocean Sciences Tidal Package (Foreman et al., 2009). In this study, T_TIDE, in which the astronomical argument varies linearly and the nodal correction is performed after least squares fit, is used to realize CHA.~~.~~

2.3 Segmented harmonic analysis

Following Foreman et al. (1995), Kang et al. (1995), Müller et al. (2014) and Devlin et al. (2018)~~, To obtain the temporally varying tidal harmonic parameters,~~ sea~~-~~level observations are ~~traditionally~~ divided into ~~several~~ monthly segments~~,~~ by calendar month and CHA with nodal and inference corrections is applied to each monthly segment to obtain the discrete tidal harmonic parameters (i.e., amplitude and phase lag). Then the discrete amplitude and phase lag at each monthly segment are interpolated using cubic spline interpolation to obtain ~~.~~ t~~T~~he temporally varying amplitudes and phase lags.~~of a constituent are obtained by interpolating the discrete amplitude and phase at each segment.~~ Th~~e~~is ~~aforementioned~~ methodology is termed segmented harmonic analysis (SHA)~~, which has been used in several previous studies (e.g., Foreman et al. (1995); Kang et al. (1995); Kang et al. (2002); Müller et al. (2014); Tazkia et al. (2017))~~. Following Kang et al. (1995),

~~In this study, the sea-level observations are divided into monthly segments according to the calendar month in SHA, as the four estimated tides, including~~ ~~M_2, S_2, K_1~~ ~~and~~ ~~O_1~~~~, can be stably resolved from monthly time series. In addition, cubic spline interpolation will be used to interpolate the discrete value at each segment. Furthermore, when SHA is used,~~ the sea~~-~~level observations in every monthly segment are analyz~~s~~ed only when the ~~length~~ duration of the ~~sea-level~~ observations ~~for this segment~~ is greater than 26~~15~~ days.

2.4 Enhanced harmonic analysis

~~Through~~ By combining CHA with ~~the~~ independent point scheme and cubic spline interpolation, Jin et al. (2018) developed ~~enhanced harmonic analysis (~~EHA~~)~~ to directly obtain temporally varying mean sea level and tidal harmonic parameters. In contrast, the harmonic parameters are assumed to be constant in CHA and SHA. ~~rs.~~ A MATLAB ~~toolbox~~toolkit, S_TIDE, was released to ~~realize~~ support EHA ~~in~~ by Pan et al. (2018b). In this study, nodal and astronomical argument corrections are embedded into the least square fit, following Foreman et al. (2009); in addition, the harmonic parameters of the minor tidal constituents are assumed to be constant and computed together with the temporally varying harmonic parameters of the principal tidal constituents to resolve more constituents and retain computational stability. The sea level in EHA is as follows:

$$\zeta(t)=\zeta_0(t)+\sum_{i=1}^{I}\left\{f_i(t)A_i(t)\cos\left[V_i(t)+u_i(t)-g_i(t)\right]\right\}+\sum_{j=1}^{J}\left\{f_j(t)A_j\cos\left[V_j(t)+u_j(t)-g_j\right]\right\} \quad (2)$$

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where I is the number of principal tidal constituents with temporally varying harmonic parameters; J is the number of minor tidal constituents with constant harmonic parameters; and the mean sea level and nontidal component are included in $\zeta_0(t)$.

Similar to Jin et al. (2018) and Pan et al. (2018b), the independent point scheme and cubic spline interpolation are used to jointly determine solve the temporally varying and constant harmonic parameters, which are not shown here for brevity. As mentioned in Pan et al. (2018b), the temporally varying harmonic parameters obtained using EHA with different numbers of independent points represent~~ed~~ oscillations on different time scales. ~~Therefore~~In this study, six independent points are used to obtain the ~~seasonal~~ seasonal variability of the ~~the major~~ principal tidal constituents ~~will be directly obtained by using EHA with 6 independent points in this study~~.

3 Results

~~To select the estimated constituents, t~~One~~he~~ -year sea~~-~~level observations at ~~E1 and~~ E2 were analy~~s~~zed using CHA with the automated constituent selection algorithm (Pawlowicz et al., 2002). According to ~~the consideration of nodal modulations. As a result, the four most significant constituents, including M_2, K_1, S_2 and O_1, were selected to be analysed according to~~ the signal-to-noise ratio (Pawlowicz et al., 2002; Matte et al., 2013), M_2, K_1, S_2 and O_1 were selected as the principal tidal constituents to be investigated in this study. ~~In the following, the sea level observations at E1 and E2 were analysed using CHA, SHA, and EHA by considering the M_2, K_1, S_2, and O_1 tides.~~

3.1 Seasonal variability at E2

As shown in Figure 3, the significant constituent near K_1 was P_1, which was unresolved when analysing one-month observations (Fang and Wang, 1986), while that for S_2 was K_2 in the semidiurnal frequency band. Therefore, when the monthly analysis was performed in SHA, the automated constituent selection algorithm in T_TIDE was used to determine the analysed constituents; in addition, the unresolved constituents P_1 and K_2 were inferred from K_1 and S_2, respectively, with the inference parameters taken from a yearly harmonic analysis of the one-year sea-level observations at E2 (Kang et al., 1995; Foreman et al., 2009). When EHA was used to directly analyse the sea-level observations at E2, the harmonic parameters of M_2, K_1, S_2, O_1, P_1 and K_2 were estimated together; in detail, the harmonic parameters of M_2, K_1, S_2 and O_1 were assumed to be temporally varying and those of P_1 and K_2 were assumed to be constant.

As shown in Figure 4~~3~~, the estimated harmonic parameters obtained with SHA and EHA, including the temporally varying amplitudes and phase lags, ~~using SHA and EHA~~ were nearly equal ~~to each other~~ and~~, which were varying~~ near those estimated using CHA, indicating that the temporal variations in the harmonic parameters of the ~~major~~ principal tidal constituents at E2 can be reasonably estimated~~precisely obtained~~ using both SHA and EHA. Based on ~~Zhang et al. (2017) and~~ Wei and Wang (2012) and Zhang et al. (2017), spring, summer, autumn~~,~~ and winter were defined as March to May, June to August, September to November~~,~~ and December to February of the ~~next~~ following year, respectively. The temporally

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varying harmonic parameters of the principal tidal constituents showed ~~The~~ seasonal variations ~~of the major tidal constituents were significant~~ (Figure ~~3~~4). For ~~the~~ M_2 ~~tide~~, the seasonal variations were significant; in detail, the amplitude reached maximum in summer and minimum in winter, just as the phase did, ~~which were the same as those obtained~~as in Müller et al. (2014). The seasonality of the S_2 amplitude was not significant, but the estimated results using EHA increased significantly in summer. The temporal variation of the K_1 amplitude spanned one period, with maxima and minima in summer and winter, respectively. ~~There were two periods in the temporal variations of the harmonic parameters, for the S_2 tide and K_1 tide, but the trends were not similar. The maxima of the amplitude appeared in early spring and autumn for the S_2 tide, while maxima occurred in early winter and summer for the K_1 tide. On the contrary, the minima appeared in early winter and summer for the S_2 tide and early spring and autumn for the K_1 tide. The maxima of the phase for the S_2 tide were in winter and summer, while there was an approximately 1.5-month lag for the K_1 tide. Dramatically~~In stark contrast, the O_1 amplitude ~~of the O_1 tide~~ increased from winter to autumn. The phase lags of the S_2, K_1 and O_1 components varied semi-annually, in which the phase lags were larger in summer and winter and smaller in spring and winter, respectively. In the four principal tidal constituents, only the M_2 amplitude had the similar variation trend as the phase lag.~~, while the trend of the phase varied similarly to that for the S_2 tide.~~

The seasonally averaged amplitudes and phase lags of the ~~major~~ principal tidal constituents are listed in Table 1. The variation trends of the averaged harmonic parameters of these constituents were the same as those obtained using EHA in Figure 4. Compared to the annual averages, ~~For the seasonal variations of the S_2 tidal amplitude, the trend of the averaged values was not the same as that shown in Figure 3b, as the averaged value in summer was slightly larger than that in spring. Although there was a local minimum in early summer for the S_2 tidal amplitude, in fact, the values in late summer were larger than the maximum of early spring, which resulted in the aforementioned discrepancy. A similar case appeared in the M_2 tidal phase. For other harmonic parameters of the major constituents, the trends in Table 1 varied in the same manner as those in Figure 3. T~~the ~~averaged~~ mean M_2 ~~tidal~~ amplitude increased by ~~7.00~~6.90 cm (approximately 9.33~~47~~%) in the summer ~~compared to the annually averaged value~~ and decreased by ~~nearly~~ 6.~~79~~ 68 cm (approximately 9.~~19~~03%) in the winter, ~~which were near~~ close to the estimated values ~~obtained from the observations~~ in Foreman et al. (1995) (6%)~~and~~, Huess and Andersen (2001) (6%)~~,~~ and ~~from the model results and observations in~~ Müller et al. (2014) (5%–10%). For ~~the~~ S_2 (K_1) ~~tide~~, the averaged amplitudes decreased by ~~0.38~~4.71% (7.72%) in the winter and increased by ~~14.10~~7.93% (5.91%) in the summer ~~and winter, respectively~~, indicating a nearly annual variation as shown in Figure 4.~~. On the contrary, the averaged amplitudes for the K_1 tide increased in summer and winter, in agreement with those shown in Figures 3b and 3c.~~ The ~~averaged~~ mean O_1 ~~tidal~~ amplitude in the summer increased by ~~2.70~~3.45 cm ~~in summer~~ compared to that in the winter. Only the M_2 ~~tidal~~ phase lag in winter was ~~less~~ smaller than the annual~~ly~~ average~~d value~~, and ~~all of~~ the ~~other~~ phase lags in both winter and summer were larger than the corresponding annual~~ly~~ average~~d~~ ~~value~~ for the ~~these four~~other three ~~major~~ principal tidal constituents.

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3.2 Seasonal variability at Dalian~~E1~~

The multiyear data at Dalian shown in Figure 2b were analysed year by year. In each year, one-year sea-level observations were analysed using CHA, SHA and EHA with settings similar to those used for data from E2. As shown in Figure 5, P_1 and K_2 were the significant constituents unresolved in the monthly analysis, just like at E2. Therefore, P_1 and K_2 were inferred from K_1 and S_2 in SHA and taken as minor constituents with constant harmonic parameters in EHA. The estimated harmonic parameters from various years were then averaged (Fang and Wang, 1986) and are shown in Figure 6. The estimated harmonic parameters using both the SHA and EHA were near to those obtained using CHA, showing that the estimated results were reasonable. In addition, the estimated harmonic parameters obtained using EHA were much closer to those obtained using SHA for data from Dalian than those from E2.

~~The estimated harmonic parameters of the major tidal constituents at E1 are shown in Figure 4. As there were some gaps in the sea-level observations at E1, the estimated discrete results for December 2013 and January 2014 were missing when the SHA was used, which resulted in the trends of the estimated harmonic parameters in winter differing considerably from those when the EHA was used.~~

~~To test the possible effect of the data missing at E1, the sea-level observations at E2 at the temporal positions of the missing data at E1 were deleted. The estimated harmonic parameters of the major tidal constituents, using CHA, SHA, and EHA, are shown in Figure 5. It is evident that the harmonic parameters obtained by using EHA were much closer to the results without considering the data missing than those using SHA, although neither of them was exactly equal to the results without the data missing. When the SHA was used, neither the local minimum during winter for the S_2 tide and the local maximum during winter for the K_1 tide was reproduced, which was successfully obtained when the EHA was used. These results indicated that the gaps in the observations had a certain influence on the estimated harmonic parameters. On the whole, the results estimated by using EHA were more reasonable.~~

The variation trends of the harmonic parameters estimated~~ by~~ using EHA at ~~E1 ~~Dalian were different from ~~varied similarly to ~~those at E2, except for the M_2 phase lag (Figure 6). The M_2 amplitude at Dalian varied semi-annually, with large values in summer and winter and small values in spring and autumn, respectively. The S_2 amplitude had significant annual variation, with maximum in winter and minimum in summer, which is opposite of the variation trend of S_2 amplitude at E2. The K_1 amplitude was nearly constant from winter to spring and increased during the summer. The O_1 amplitude reached the minimum in the winter and summer while increasing slightly in the spring and autumn. The estimated S_2 phase lag reached the maximum in the spring with small variation. The K_1 and O_1 phase lags trended the same, increasing in the winter and summer while decreasing in the spring and early autumn.

~~, except the O_1 tidal amplitude and the M_2 tidal phase. From t~~The averaged amplitudes and phase lags of the ~~the major~~principal tidal constituents at Dalian~~ at E1~~, as listed in Table 2, show a seasonal variation that was generally smaller than that at E2. All of the seasonal changes of the principal tidal constituents were less than 1.80 cm, a variation that only appeared in the S_2 amplitude at E2. In addition, all of the seasonal changes of the phase lags were less than 2.20°, while the

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S_2 and K_1 phase lags at E2 changed by at least 5.00° in the summer and winter, respectively. The rate of change in the M_2 amplitude at Dalian was less than 1%, which was significantly less than that at E2. The rates of changes in all phase lags were less than 1%, except for the M_2 phase lag, which was larger than 2% in both summer and winter compared to the annual averages, and larger than those at E2. A~~an~~ n increase in the ~~*the* O~~S_2~~1~~ ~~tidal~~ amplitude of ~~7.22~~5.34% ~~was obtained~~occurred in the winter, larger than its decrease in the winter at E2.

~~while a reduction of 5.36% was obtained in summer. Furthermore, the averaged M_2 tidal phase in winter increased by 0.60% compared to the annually averaged value, which was contrary to that at E2. However, it could not be directly determined whether the results were correct or not, as the true values at the gaps were unknown and the oceanic environment at E1 was not the same as that at E2. Similar to those at E2, the variation in both the K_1 tidal amplitude and phase was larger than those for the other constituents.~~

In summary, the harmonic parameters of ~~the~~ the ~~major~~ principal tidal constituents at ~~E1 and~~ E2 and Dalian~~, including amplitude and phase,~~ ~~exhibited~~ varied ~~significant~~ seasonally~~ variations~~, and~~.~~ the seasonality of the tides at E2 was significantly different from that at Dalian. The amplitude of the principal tidal constituent M_2 at E2 varied annually, while that at Dalian was semi-annual. The M_2 phase lags at E2 and Dalian had the similar variation trend, with lager values in summer and small values in winter. The S_2 amplitude in winter at E2 was less than that in summer, which was opposite that at Dalian. The K_1 amplitude at E2 had an annual frequency, with large values in summer and small values in winter, while the O_1 amplitude increased steadily. In contrast, the variations of the K_1 and O_1 amplitudes at Dalian were small. The maxima of the S_2, K_1 and O_1 phase lags at E2 appeared twice, like those of K_1 and O_1 and different from that of S_2 at Dalian.

~~For the M_2 tide, the frequencies of the amplitudes at both E1 and E2 were annual, with large values in summer and small values in winter, which also characterised the variation of the phase at E2. The frequencies of the S_2 tidal amplitude and the K_1 tidal amplitude were semi-annual, with large (small) values in early spring (early winter) and early autumn (early summer) for the S_2 tide and in winter (early spring) and early summer (autumn) for the K_1 tide, at both E1 and E2. The O_1 tidal amplitude increased constantly from winter to autumn at E2, but there was a local maximum in winter at E1, which may be related to the data missing at E1. For the S_2, K_1 and O_1 tides, the maxima of the phase appeared twice in one year, which were nearly in winter and summer at both E1 and E2.~~

4 Mechanisms for the seasonal variability

Several previous studies have investigated the seasonal variability of the ~~the~~ M_2 ~~tidal~~ amplitude.~~,~~ ~~in which t~~Three main mechanisms have been proposed~~ as follows~~:

1) Seasonal variations of the mean sea level. Corkan (1934) related the seasonal modulation of the ~~the~~ M_2 tide near the British coast to seasonal variations of sea level and atmospheric pressure. Tazkia et al. (2017) pointed out that the seasonal variability of the sea level generated by many processes can induce a seasonal variation of the ~~the~~ M_2 tide, as ~~the~~ tidal wave propagation was controlled by water depth on the first order.

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2) Seasonally varying stratification. Foreman et al. (1995) presumed that the seasonal variability of the ~~the~~ M_2 ~~tidal~~ amplitude at Victoria, Canada was induced by the changes in stratification ~~changes~~ due to ~~the~~ seasonal ~~changes~~ variability in ~~the~~ estuarine flow. Kang et al. (2002) used a two-layer numerical model to investigate the baroclinic response of the tide and tidal currents in the Yellow and East China Seas, and found that ~~the~~ seasonal stratification had several noticeable effects on the tides, including varying degrees of current shear, ~~varying~~ frictional dissipation, and ~~varying~~ barotropic energy flux. Müller (2012) indicated that in shallow seas, ~~the~~ seasonal variations in stratification were a major factor for the observed seasonal modulation in tides. Müller et al. (2014) pointed out that the seasonal changes in stratification on the continental shelf affected the vertical profile of the eddy viscosity to further cause the seasonal variability of the ~~the~~ M_2 tide.

3) Seasonally varying ice coverage. St-Laurent et al. (2008) ~~thought~~ proposed that the significant seasonal variations of the ~~the~~ M_2 surface elevation in all regions of the Hudson Bay system were essentially caused by ~~the~~ under-ice friction. Georgas (2012) pointed out that the seasonal episodes of significant tidal damping (reductions in tidal amplitudes by as much as 50%) observed in the Hudson River estuary were primarily caused by the under-ice friction as well. Müller et al. (2014) found that the frictional effect between the sea ~~-~~ice and ocean surface ~~ocean~~ layer lead~~ed~~ to the seasonal variability of the M_2 tide.

Other mechanisms, including long-term changes in the tidal potential (Molinas and Yang, 1986), interactions with other physical phenomena (Huess and Andersen, 2001; Pan et al., 2018a), changes in the internal tide with corresponding small changes in its surface expression (Ray and Mitchum, 1997; Colosi and Munk, 2006), as well as ~~and~~ a number of other more technical reasons, ~~can~~ may also change the M_2 tidal amplitude on various time scales. ~~, which~~ The above reasons have been presented or discussed in Woodworth (2010), Müller (2012), Müller et al. (2014)~~,~~ and Tazkia et al. (2017).

4.1 Design of numerical experiments

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The Bohai Sea in north China freezes to varying degrees every winter for approximately 3–4 months (Su and Wang, 2012). According to the back-effect connection of the coastal shelf and open ocean via resonance mechanisms (Arbic et al., 2009; Arbic and Garrett, 2010), sea ice may be important to the seasonality of principal tidal constituents. However, Zhang et al. (2019) found that the damping effect of sea ice on the astronomical tides was almost negligible in the Bohai Sea employing numerical experiments with a three-dimensional ice-ocean coupled model~~However, the coverage area of the sea ice is mainly concentrated in the Liaodong Bay in February 2014 during the observation period (Chen et al., 2015)~~. Therefore, ~~the~~ ice coverage was~~is~~ not considered ~~to be the main reason~~ in this study. ~~Can the first two mechanisms, indicated as the reason for the M_2 tidal amplitude in previous studies, be the cause of the seasonal variability of the harmonic parameters for the major tidal constituents, including the M_2, S_2, K_1, and O_1 tides, in the Bohai Bay?~~ Several numerical experiments (Exp1–Exp4) were carried out to simulate the four principal ~~major~~ tidal constituents in the Bohai Sea under different conditions using MITgcm (Marshall et al., 1997), ~~to~~ testing the influence of seasonal variations of ~~the~~ mean sea level and stratification on the seasonal variability of ~~the~~ the ~~major~~ principal tidal constituents.

~~4.1 Design of numerical experiments~~

~~The same~~Identical model settings were used in all of the numerical experiments ~~were~~ and described as follows. The ~~computing~~ simulation area was the Bohai Sea~~,~~ as shown in Figure 1b. The horizontal resolution was 2′×2′,~~.~~ ~~There were~~with 16 layers in the vertical direction ~~and the~~with thicknesses ~~varied~~ ranging from 2–~~ m to~~ 5 m. The four principal ~~major~~ tidal constituents~~, including the~~ M_2, S_2, K_1, and O_1 ~~tides,~~ were implemented as tidal forcing ~~-~~at the east open boundary, whose ~~information w~~data were~~as~~ predicted using the constant harmonic parameters extracted from the TPXO model (Egbert and Erofeeva, 2002). ~~The~~ Sea surface boundary conditions were not considered. The horizontal eddy viscosity coefficient was set to 1.0×10^{3} m^2/s, and the quadratic bottom drag coefficient was set to 1.3×10^{-3} (Wang et al., 2014). The integral time step was 60 s~~,~~ and the total simulation time was ~~45~~ 60 d.~~ays~~ ~~starting from 0000 UTC 15 February 2014 in winter and 0000 UTC 15 July 2014 in summer.~~ The results of the final ~~fifteen~~ 30 d~~ays~~ were used to calculate the harmonic parameters using ~~the~~ CHA.

Details of the model settings for ~~The detailed different model settings of the~~ numerical experiments Exp1~~–~~–Exp4 are listed in Table 3. In Exp1, the simulation started from 0000 UTC 1 January 2014, while the simulation started from 0000 UTC 1 July 2014 in Exp2-Exp4. In Exp1, ~~The~~ horizontally homogeneous profiles of the initial temperature and salinity (Figure 7) were extracted from the HYCOM global analysis results in winter, while those in summer were used in Exp2–Exp4. The vertical eddy viscosity coefficient was specified directly and no turbulence closure schemes were used. ~~in winter and summer, as shown in Figure 6, were extracted from the HYCOM global analysis results, which were implemented for the numerical experiments in winter and summer. To test the influence of the stratification solely, i.e., just considering the change in the temperature and salinity, the vertical eddy viscosity coefficient was specified directly, and no turbulence closure scheme was used.~~ In Exp1~~ and Exp2~~, the vertical eddy viscosity coefficient was set to 2.0×10^{-3} m^2/s through a trial and error procedure. According to Müller et al. (2014), the eddy viscosity ~~during~~ in summer was reduced by orders of magnitude compared to well-mixed conditions ~~during~~ in winter, as the stratification stabilized the water column. Therefore, the vertical eddy viscosity coefficient was decreased by one-half in Exp3 to test the influence of the vertical eddy viscosity caused by the stratification. As shown in Figure ~~7~~8, ~~the~~ monthly ~~averaged values~~means of the low-pass sea levels,~~,~~ filtered using a cosine-Lanczos filter with a high frequency cut-off of 0.8 cpd,~~,~~ were nearly equal to the estimated mean sea level using SHA. ~~and~~They exhibited the same variation trend ~~and the same order of magnitude~~ as those~~at~~ obtained ~~of the estimated mean sea level~~ using ~~the~~ EHA, with ~~. The trends of the mean sea levels using SHA and EHA varied similarly:~~ large values ~~appeared~~ in summer~~,~~ and small values ~~appeared~~ in winter. ~~According to~~Given the difference between the averaged ~~values of the~~ mean sea level in summer and that in winter, Exp4 included 1 0.2-m increase of water depth ~~the increase in the water depth in Exp4 was set to 0.2 m~~ to test the influence of ~~the~~ mean sea level. ~~The detailed different model settings of the numerical experiments Exp1–Exp4 are listed in Table 3.~~

4.2 Results ~~and discussions~~

The simulated harmonic parameters of the ~~the~~ four ~~major~~ principal tidal constituents in ~~all~~ the numerical experiments and ~~the results~~those obtained from ~~the~~ observations~~,~~ at ~~E1~~ E2 and Dalian ~~E2,~~ are shown in Figure ~~8~~9. ~~It was noted that t~~The simulated harmonic parameters were a little far from the observed results, except the M_2 ~~tidal~~ amplitude at E2 ~~in winter~~ simulated in Exp1 and that ~~in summer~~ simulated in Exp2 ~~at E2~~, ~~which may be~~possibly because the constant bottom drag coefficient was used (Wang et al., 2014). ~~However~~Still, the differences between the ~~the~~ simulated results in the different numerical experiments can be used to test the influence of ~~the~~ potential factors on the seasonal variability of the principal ~~the major~~ tidal constituents.

~~As the seasonal variations of the major tidal constituents at E2 were coincident when the SHA and EHA were used, the trends in all the numerical experiments at E2 will primarily be investigated.~~ The observed amplitudes at E2 in summer were larger than those in winter for all ~~the~~ four ~~major~~ principal tidal constituents, as shown in Figure ~~8~~9, but ~~the differences between~~ the simulated amplitudes ~~of the K_1 and O_1 tides~~ in Exp2 were nearly equal to ~~and~~ those in Exp1 ~~decreased~~. ~~On the contrary~~In contrast, both the decreased ~~in the~~ vertical eddy viscosity coefficient in Exp3 and the increased ~~in the~~ mean sea level in Exp4 ~~induced the~~ increased ~~in~~ the amplitudes for all ~~the major~~ principal tidal constituents. The increases of the observed M_2 and S_2 amplitudes at E2 from winter to summer were 13.58 cm and 2.62 cm, respectively, while those were 13.34 cm (2.08 cm) and 2.75 cm (0.56 cm) for simulated results in Exp3 (Exp4) compared to those in Exp1. In addition, the increases of the observed K_1 and O_1 amplitudes were also captured better by the simulated results in Exp3 than those in Exp 4, as shown in Figure 9. ~~The simulated results in Exp3 captured a majority of the observed change rates of the amplitude in summer to that in winter simulated in Exp1, with a factor of 2 for the M_2, S_2, and K_1 tide, which had better performance than those in Exp4, as shown in Figure 9.~~ Therefore, ~~the seasonal variation of the vertical eddy viscosity coefficient had a large effect on~~ the seasonally ~~variation of the~~varying amplitudes ~~for~~ of all ~~the major~~ principal tidal constituents were primarily impacted by the seasonal variation of vertical eddy viscosity. ~~.~~

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~~The d~~Differences between the simulated phase lags in Exp3~~2~~ and those in Exp1 indicated that the ~~trends in the~~ seasonal variation of vertical eddy viscosity~~the stratification~~ caused the same ~~behaviour~~ trends as the changes between the observed ~~trends of the~~ phase lags ~~between~~ in summer and those in winter for all ~~the major~~ principal tidal constituents except K_1. In contrast, the changes in stratification in Exp2 and mean sea level in Exp4 only captured the variation trend of the S_2 and O_1 phase lags, respectively. ~~The increase in the vertical eddy viscosity coefficient in Exp3 decreased the K_1 tidal phase, which was contrary to the observed trends from winter to summer. The differences between the simulated results in Exp4 and those in Exp2 showed that the increase in the mean sea level will decrease the phases of the M_2 and K_1 tides, which was opposite of the observed results between summer and winter.~~ The aforementioned results demonstrated that ~~the~~ seasonal variation in the vertical eddy viscosity~~stratification~~ was the most important mechanism ~~for~~ influencing the seasonal~~ly~~ variability of ~~the phase for all the major~~ principal tidal constituents at E2.

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The seasonal variation of the S_2 amplitude was the most significant at Dalian, but the decrease in the simulated result from winter (Exp1) to summer (Exp2) was less than 1 cm and the simulated S_2 amplitudes in Exp3 and Exp4 were larger than that in Exp1, indicating the seasonality of stratification as a possible reason. However, the simulated seasonal variation was too weak, possibly because the simple horizontally homogeneous temperature and salinity profiles could not reflect reality. The water depth is large in the eastern part of Bohai Sea (Figure 1b), so the stratification and ocean circulation were noteworthy and had significant effects on the tides. The increases of the M_2 and O_1 amplitudes were only captured by the changes in the vertical eddy viscosity coefficient in Exp3 and stratification in Exp2, respectively, while the increases of K_1 amplitudes in Exp3 and Exp4 agreed with the observed results at Dalian. The variation lags of the M_2 and S_2 phase lags were not captured well and the simulated results in Exp2 were the best results, while those for K_1 and O_1 were best captured by the decrease of the simulated results in Exp3 compared to those in Exp1. On the whole, the seasonal variations of the principal tidal constituents at Dalian were determined by the seasonality of stratification and vertical eddy viscosity.

~~The seasonal variations in all the potential factors, including the stratification, vertical eddy viscosity, and mean sea level, caused the M_2 tidal amplitude at E2 in summer to be larger than that in winter, which was consistent with the observed results. Thus, when only the M_2 tidal amplitude was considered, the conclusion about the main mechanisms were dramatically different. Although the increase in the tidal amplitude from winter to summer was smaller for the S_2, K_1 and O_1 tides than that for the M_2 tide, the change was greater than 9.72%, which was much greater than the magnitude of the variation caused by the 18.6-year nodal modulation in the observation period (less than 1%). Therefore, the seasonal variations in the four major constituents should be considered synchronously. As mentioned above, the seasonal variability of the stratification and the vertical eddy viscosity coefficient were the mechanisms responsible for the seasonal variation of the phases and amplitudes for the major tidal constituents, respectively.~~

~~Similar to those at E2, the simulated amplitudes of the four major tidal constituents in summer were larger than those in winter, as the differences between the simulated amplitudes in Exp3 and those in Exp1 were larger than 0. According to the simulated results in Exp2 and Exp1, the M_2 and K_1 tidal phases increased, and the O_1 tidal phase decreased from winter to summer, which was the same behaviour as that exhibited at E2 and opposite to the behaviour of the estimated results at E1 using EHA, further indicating that the data missing at E1 influenced the estimated results.~~

The variations ~~in~~ of the simulated amplitudes ~~for the four major constituents~~ from winter (~~simulated in~~ Exp1) to summer ~~simulated in~~ (Exp3) in the entire Bohai Sea ~~w~~are~~as~~ shown in Figure 10. T~~It was evident that t~~he spatial distribution of the ~~the~~ variations in ~~the~~ M_2 tidal amplitude had a strong ~~was significantly~~ positive~~ly~~ correlation (R=0.98) ~~correlated~~ with that in the ~~the~~ S_2 tidal amplitude, ~~which was the same as~~ similar to that for the diurnal tides (R=0.98~~6~~). Furthermore, the distributions were possibly related ~~with~~ to ~~the~~ tidal wave propagation ~~of the tidal wave~~ as their patterns ~~y had~~ were similar ~~patterns as~~ to the co-phase lines, as shown in Figure 10. For the semi-diurnal tides~~, including the~~ M_2 and S_2 ~~tides~~, the simulated amplitudes in summer were larger than those in winter in ~~the~~ Bohai Bay, ~~the~~ Laizhou Bay, ~~the~~ Liaodong Bay, and smaller than those in winter in the middle of the Bohai Sea. The spatial distribution of the absolute differences between the M_2 tidal amplitude in summer and that in winter was similar to ~~had the similar pattern with~~ that in Müller et al. (2014). For

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the diurnal tides~~, including the~~ K_1 and O_1~~ tides~~, the simulated amplitudes in summer were larger than those in winter in~~ the~~ Bohai Bay,~~ the~~ Laizhou Bay, Liaodong Bay and ~~other southern~~the middle areas, while ~~less~~ smaller than those in winter in the northeast part of the Bohai Strait~~Liaodong Bay and other northern areas~~.

5 Discussions

In this study, the EHA developed in Jin et al. (2018) and Pan et al. (2018b) was further improved in order to resolve more tidal constituents by adding the minor constituents whose harmonic parameters were assumed to be constant and computed together with the temporally varying harmonic parameters of the principal tidal constituents. The nodal and astronomical argument corrections were embedded into the least square fit to eliminate the influences of nodal cycle and linearly varying astronomical argument. In fact, there have been multiple improvements to T_TIDE in the past decades, such as R_T_TIDE (Leffler and Jay, 2009), versatile tidal analysis (Foreman et al., 2009), U_TIDE (Codiga, 2011) and NS_TIDE (Matte et al., 2013). In R_T_TIDE, versatile tidal analysis and U_TIDE, the harmonic parameters (i.e., amplitude and phase lag) are assumed to be constant, although they have some improvements to T_TIDE. However, harmonic parameters are not constant and have multiscale temporal variations, as shown in Corkan (1934), Kang et al. (1995), Müller et al. (2014), Devlin et al. (2018), and so on.~~Müller et al. (2014b)(Leffler and Jay, 2009)~~ Neglecting seasonal variation of tides will introduce significant error in sea-level prediction (Fang and Wang, 1986). Therefore, EHA, in which the harmonic parameters of the principal tidal constituents are assumed to be temporally varying and computed directly within the least squares fit, improved T_TIDE in other ways. In NS_TIDE, the harmonic parameters are also assumed to be temporally varying. However, the temporally varying harmonic parameters are assumed to be functions of river flow and greater diurnal tidal range at the reference station, so it can be applied only to river tides, while EHA can be applied in analyzing any time series. On the whole, EHA used in this study is indeed enhanced than other methods.

The duration of hourly sea-level observations at E2 used in this study was only one year, which is a limitation. Although the rare event might slightly skew seasonal pattern of tides, the seasonal variations of the principal tidal constituents M_2, S_2, K_1 and O_1 obtained using EHA were the same as those using traditional EHA, indicating that the results are not unreasonable and can reflect the seasonal variations of tides in the analysis period. The strong seasonal variations of the principal tidal constituents can be captured by the results of numerical experiments. The multi-annually averaged results at Dalian also showed the seasonal variations of the principal tidal constituents, but the results of numerical experiments were not in accordance with the observed results, which may be because only the horizontally homogeneous profiles of the initial temperature and salinity were used and the temporally varying ocean circulation were not considered.

The seasonal variations of stratification and vertical eddy viscosity and their influences on the tidal amplitudes may be as follows. In winter, the strong northwest Asia monsoon develops a vertically will-mixed condition (Yanagi et al., 2001; Jeon et al., 2014), which will not stabilize the tidal currents and will lose more energy, leading to smaller tidal amplitudes. As the surface heating rate and freshwater discharge increase, the mixing is insufficient to homogenize the input potential

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energy and cause stratified conditions in summer (Huang et al., 1999; van Haren, 2000), during which the reduced eddy viscosity will increase the tidal amplitudes. However, the S_2 amplitude at Dalian was larger in winter and smaller in summer, which is inconsistent with the other principal tidal constituents and should be further investigated in future studies.

~~5~~ 6 Conclusions

In this study, based on one~~one~~-year sea-level observations ~~of the sea level at two stations (E1 and E2)~~at E2 and 17-year sea-level observations in the Bohai ~~Bay, China~~Sea, the seasonal variability of ~~the~~ the ~~major~~ principal tidal constituents was investigated using different methods. When the sea~~-~~level observations at ~~–~~ E2 and Dalian were analysed, the seasonal variations of all ~~the~~ ~~major~~ principal tidal constituents ~~estimated~~obtained ~~by~~ using ~~the~~ EHA were nearly equal to those ~~estimated~~obtained ~~by~~ using SHA (Figures 4 and 6~~3~~), indicating that the seasonal variations were ~~robust and~~ not related to the applied methods. ~~However, the gaps in the observations at E1 had an effect on the estimated results, which was demonstrated by the experiment in which the gaps were implemented in the observation at E2 (Figure 5).~~ At both E2~~1~~ and ~~E2~~Dalian, the ~~major~~ principal tidal constituents~~, including the~~ M_2, S_2, K_1~~,~~ and O_1 ~~tides,~~ exhibited ~~significant~~ seasonal variations (Figures 4 and 6). ~~For the M_2 tide, both the large amplitude and phase were exhibited in summer, and the small values appeared in winter (Figures 3 and 4). The O_1 tidal amplitude increased constantly from winter to autumn at E2 (Figure 3d), but there was a local maximum in winter at E1 (Figure 4d), which may be related with the data missing at E1. The frequencies of *all the other harmonic parameters* at E1 and E2 were semi-annual, with larger values in summer and winter and small values in spring and autumn, without considering the detailed time, except the S_2 tidal amplitude.~~ The M_2 amplitude at E2 varied annually, while that at Dalian was semi-annual. The M_2 phase lags at E2 and Dalian had the similar variation trend, with large values in summer and small values in winter. The S_2 amplitude in winter at E2 was less than that in summer, which was opposite that at Dalian. The K_1 amplitude at E2 had an annual variation, with large values in summer and small values in winter, while the O_1 amplitude increased steadily. On the contrary, the variations of the K_1 and O_1 amplitudes at Dalian were small. The maxima of the S_2, K_1 and O_1 phase lags at E2 appeared twice, which was the same as those of K_1 and O_1 and different from that of S_2 at Dalian.

~~The local maxima of the S_2 tidal amplitude were in early spring and early autumn, while the local minima occurred in early winter and early summer.~~

Through several numerical experiments, the mechanisms of the seasonal variability of the ~~the major~~principal tidal constituents were ~~discussed~~investigated. ~~The results showed that t~~The seasonal variations of the principal tidal constituents~~the phases for all the major tidal constituents~~ at E2 were caused by the seasonality ~~in~~ of the vertical eddy viscosity, while the seasonal variations at Dalian were mainly induced by the seasonality of stratification and vertical eddy viscosity, although the simulated results were not consistent well with the observed results. ~~the stratification, while the seasonality of the vertical eddy viscosity coefficient caused by the stratification resulted in the seasonal variations of the~~

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~~amplitudes.~~ Therefore, the synchronous simulation of ~~the~~ circulation and ~~the~~ tides, ~~,~~ and ~~the~~ a reasonable parameterization scheme to convert the ~~the~~ variations in ~~the~~ stratification to ~~that~~ those in ~~the~~ vertical eddy viscosity were essential for ~~the~~ precise simulation of the tides ~~with~~ when ~~the~~ consider~~at~~ing~~on~~ ~~of~~ the temporally varying harmonic parameters.

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Data availability

The HYCOM global analysis data is available at http://hycom.org. New version of S_TIDE package can be downloaded from https://www.researchgate.net/project/Adaptation-of-tidal-harmonic-analysis-to-nonstationary-tides. The hourly sea level observations at Dalian are available at https://uhslc.soest.hawaii.edu/datainfo/. The hourly sea level observations at E2 used in this work are available from the authors upon request (xqinglv@ouc.edu.cn).

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Table 1. ~~The a~~Averaged amplitudes (cm) and phase (°) of ~~the~~ the ~~major~~ principal tidal constituents obtained using EHA at E2

Constituents	Parameter	Annual	Winter	Spring	Summer	Autumn
M_2	Amplitude	73.97 ~~73.92~~	67.29 ~~67.13~~	71.56 ~~71.49~~	80.87 ~~80.92~~	76.04 ~~76.02~~
	Phase	210.03 ~~210.13~~	209.11 ~~209.98~~	209.42 ~~209.48~~	212.04 ~~212.23~~	209.52 ~~209.81~~
S_2	Amplitude	20.81 ~~21.07~~	19.83 ~~18.10~~	18.87 ~~20.81~~	22.46 ~~20.99~~	22.06 ~~24.34~~
	Phase	273.74 ~~273.91~~	276.69 ~~282.12~~	272.81 ~~269.59~~	279.67 ~~282.10~~	265.80 ~~261.90~~
K_1	Amplitude	30.30 ~~31.17~~	27.96 ~~33.14~~	29.99 ~~26.19~~	32.09 ~~36.36~~	31.13 ~~29.01~~
	Phase	30.57 ~~30.94~~	31.31 ~~37.61~~	30.39 ~~25.96~~	33.55 ~~39.13~~	27.01 ~~21.14~~
O_1	Amplitude	24.43 ~~24.45~~	21.92 ~~22.40~~	24.13 ~~24.21~~	25.37 ~~25.10~~	26.27 ~~26.07~~
	Phase	345.91 ~~345.82~~	351.35 ~~352.42~~	340.62 ~~340.68~~	348.00 ~~346.99~~	343.79 ~~343.32~~

Table 2. ~~The a~~Averaged amplitudes (cm) and phase (°) of ~~the~~ the ~~major~~ principal tidal constituents obtained using EHA at Dalian~~E1~~

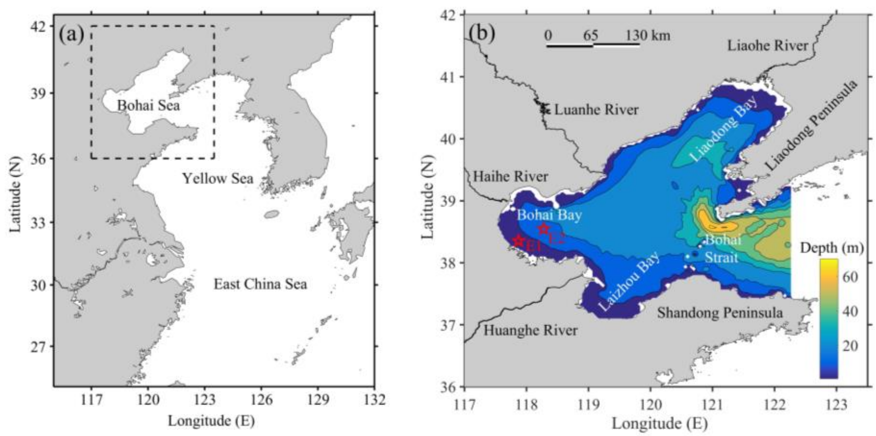
Constituents	Parameter	Annual	Winter	Spring	Summer	Autumn
M_2	Amplitude	97.32~~99.94~~	97.53~~97.23~~	96.79~~98.47~~	97.96~~103.89~~	97.00~~100.11~~
	Phase	54.25~~218.28~~	52.93~~219.59~~	53.43~~217.08~~	55.34~~218.69~~	55.28~~217.8~~
S_2	Amplitude	30.89~~28.92~~	32.54~~24.06~~	30.91~~31.77~~	29.1~~27.77~~	31.02~~31.99~~
	Phase	100.12~~281.06~~	99.45~~282.31~~	102.47~~283.64~~	101.08~~288.09~~	97.44~~270.11~~
K_1	Amplitude	25.32~~34.46~~	25.02~~40.25~~	24.78~~29.23~~	26.18~~38.46~~	25.3~~29.99~~
	Phase	240.94~~34.52~~	242.44~~42.28~~	239.91~~30.16~~	239.31~~41.27~~	242.15~~39.09~~
O_1	Amplitude	17.91~~27.42~~	17.41~~29.4~~	18.05~~26.21~~	17.88~~25.95~~	18.29~~28.18~~
	Phase	210.29~~349.44~~	212.4~~354.77~~	208.54~~345.53~~	209.62~~349.91~~	210.65~~347.66~~

Table 3. Model settings for the numerical ~~simulation~~ experiments

No.	Season	A_z [a] (m^2/s)	Depth (m)

Exp1	Winter	2.0×10^{-3}	Original
Exp2	Summer	2.0×10^{-3}	Original
Exp3	Summer	1.0×10^{-3}	Original
Exp4	Summer	2.0×10^{-3}	Original+0.2

[a] ~~The v~~Vertical eddy viscosity coefficient.



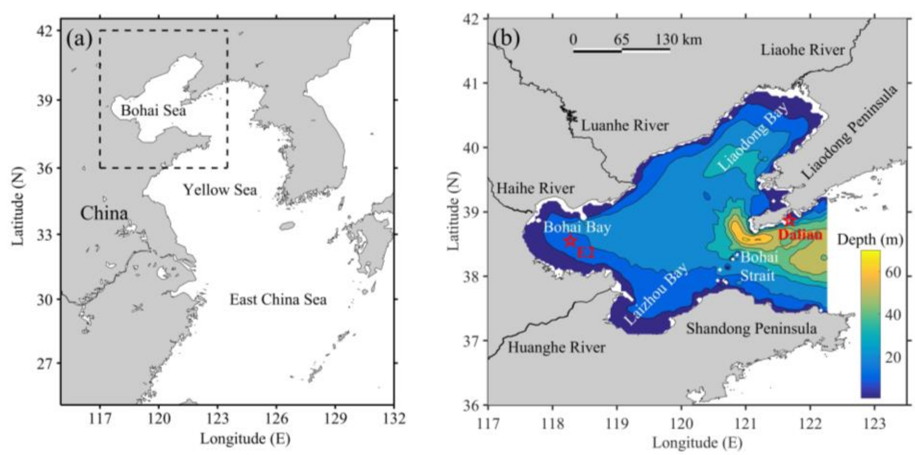
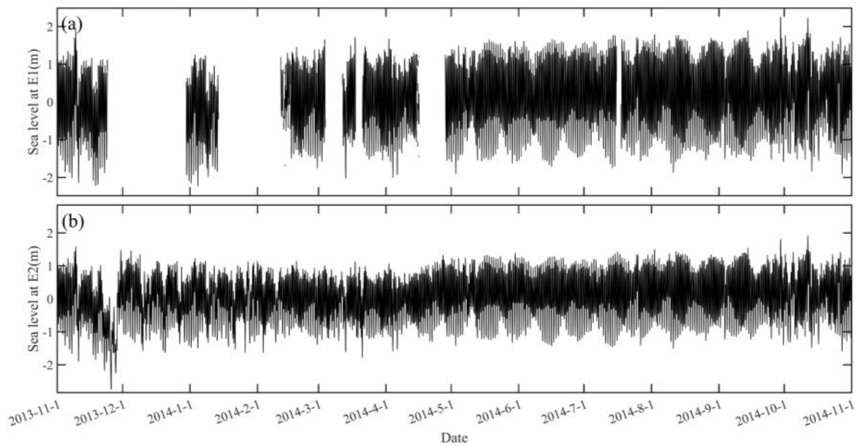


Figure 1. (a) ~~Map showing the g~~General location of the Bohai Sea (rectangle with dashed lines); and (b) ~~map:~~ locations of the observation stations (red stars), E2~~1~~ and ~~E2~~Dalian, in the Bohai ~~Bay~~Sea, and ~~the~~ bathymetry of the Bohai Sea (colours).



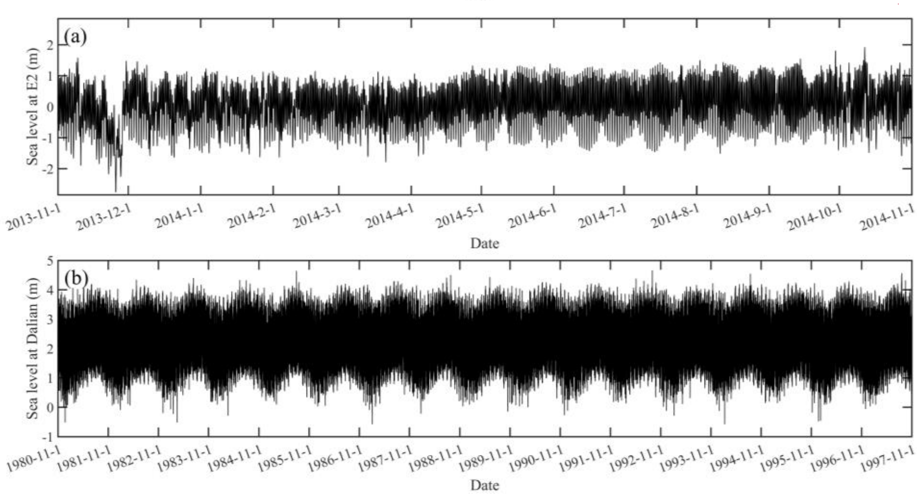


Figure 2. Time series of the observed sea level at (a) E2~~1~~ and (b) ~~E2~~Dalian.

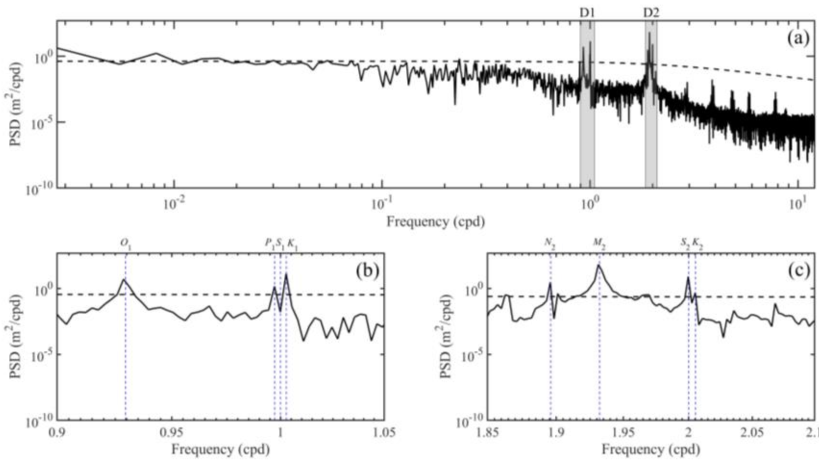
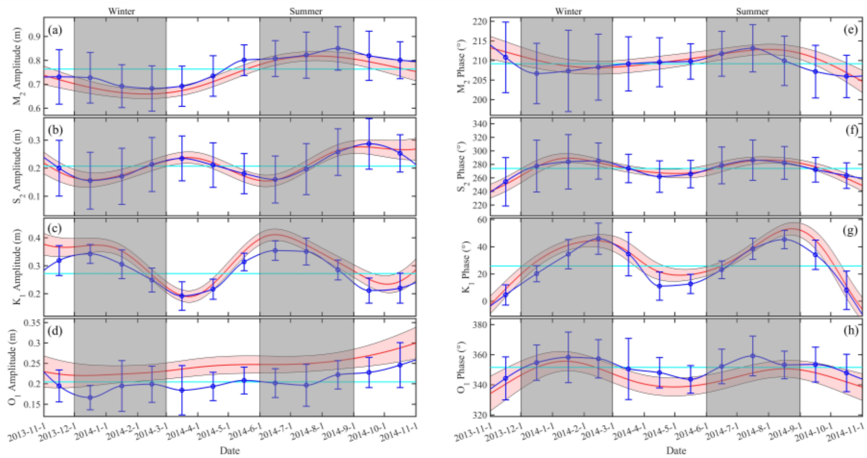


Figure 3. Power spectral densities of the observed sea level at E2 (black line) in (a) all frequency bands, (b) the diurnal frequency band, and (c) the semidiurnal frequency band. In all panels, black dashed lines denote the corresponding 5% significance level against red noise.



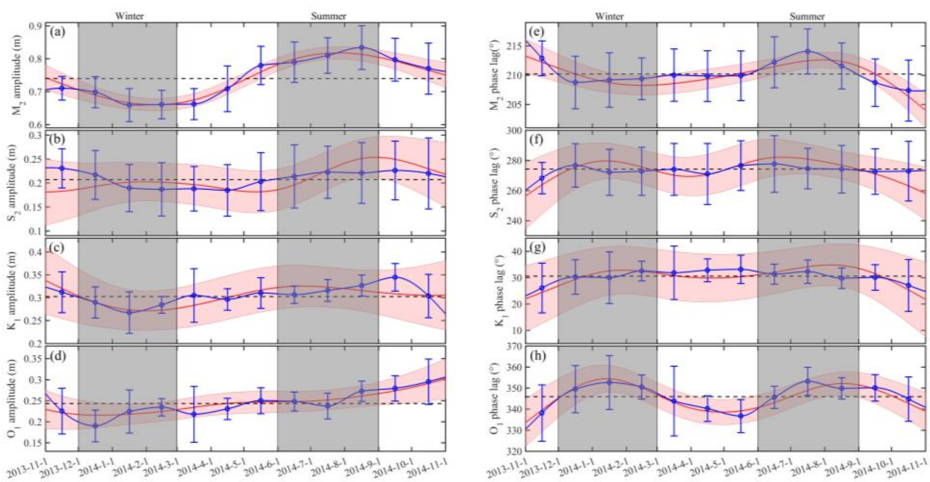


Figure ~~3~~4. Time series of the estimated temporally varying tidal amplitudes of ~~the major~~ principal tidal constituents, including (a) M_2, (b) S_2, (c) K_1 and (d) O_1, at E2 when CHA (~~cyan~~ black dashed lines), SHA (blue lines) and EHA (red lines) were used. (e–h) Similar to (a-d), but for the estimated temporally varying tidal phase lags. ~~The b~~Blue vertical bars and ~~the~~ pink shading~~s~~ indicate the corresponding 95% confidence intervals.

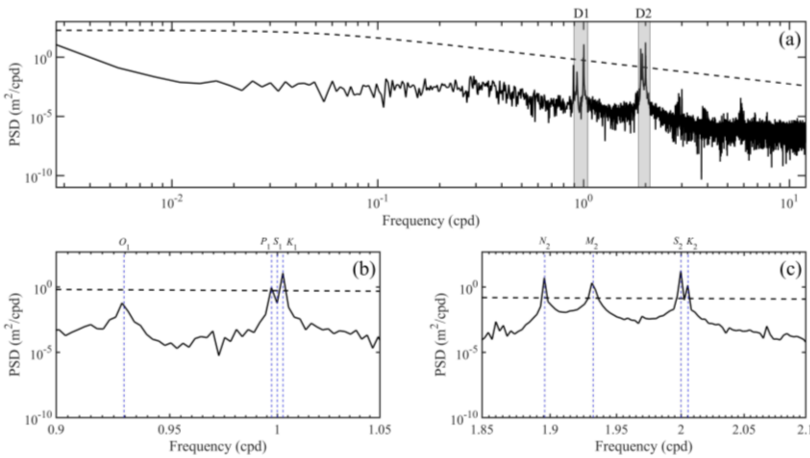
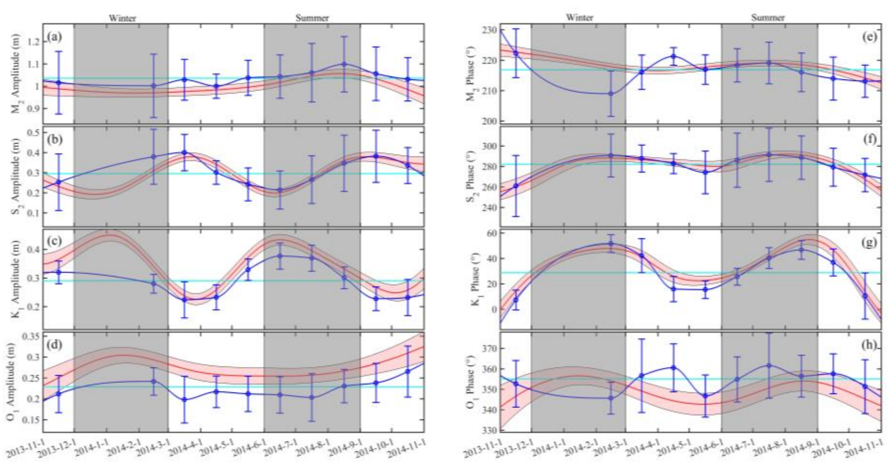


Figure 5. Similar to Figure 3, but for those at Dalian.



~~**Figure 4. Similar to Figure 3, but for those at E1.**~~

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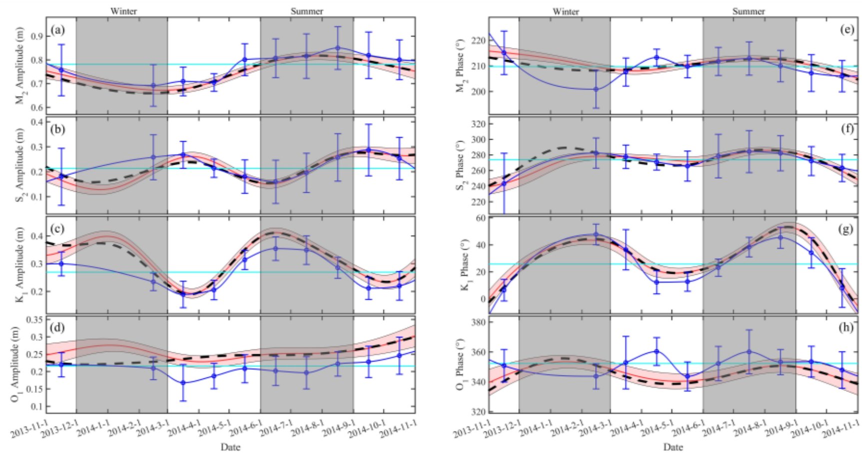

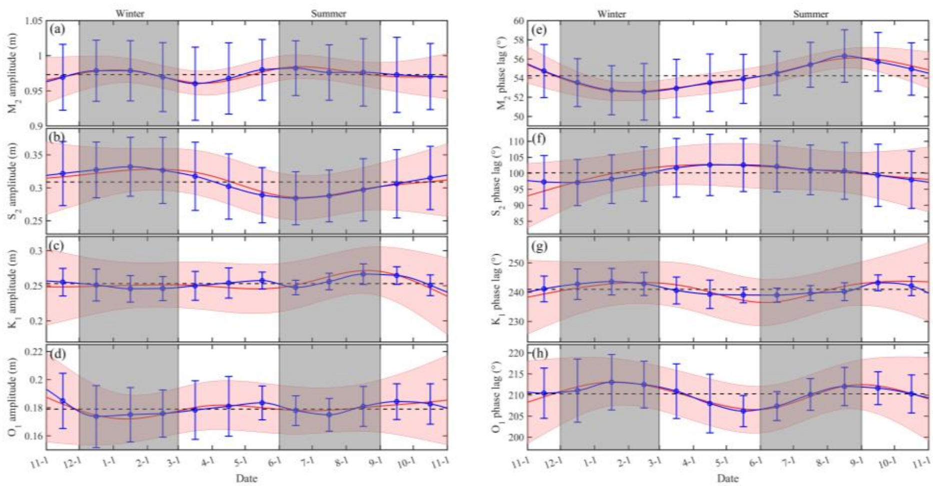

Figure ~~5~~6. Similar to Figure 4, but for multi-yearly averaged values at Dalian~~Time series of the estimated temporally varying tidal amplitudes of the major tidal constituents, including (a) M_2, (b) S_2, (c) K_1 and (d) O_1, at E2 when CHA (cyan lines), SHA (blue lines) and EHA (red lines) were used, when the gaps in E1 were applied in E2. (e-h) Similar to (a-d), but for the estimated temporally varying tidal phases. The black dashed lines in all the subgraphs were the~~

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~~results when the original observations in E2 were analysed using EHA. The blue vertical bars and the pink shadings indicate the corresponding 95% confidence intervals~~.

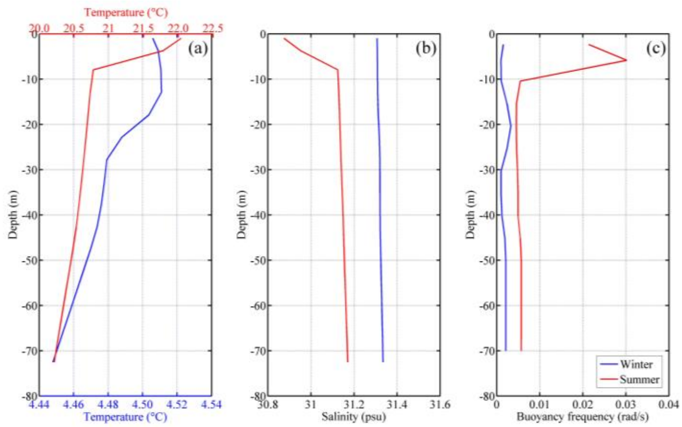
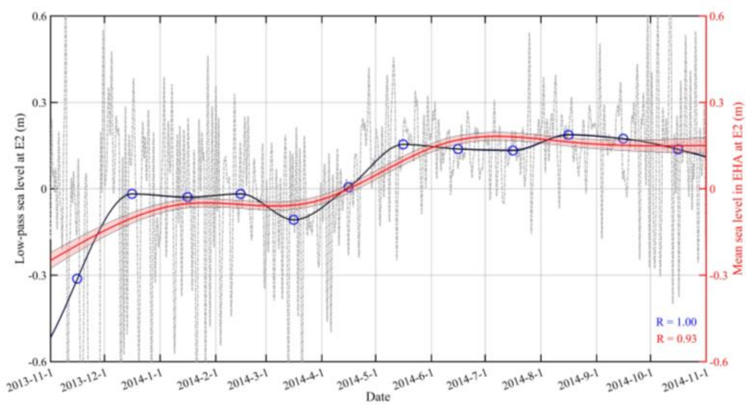


Figure ~~6~~7. Horizontally homogeneous profiles of the initial (a) temperature, (b) salinity and (c) buoyancy frequency used in the numerical experiments, in winter (blue solid lines) and in summer (red solid lines).



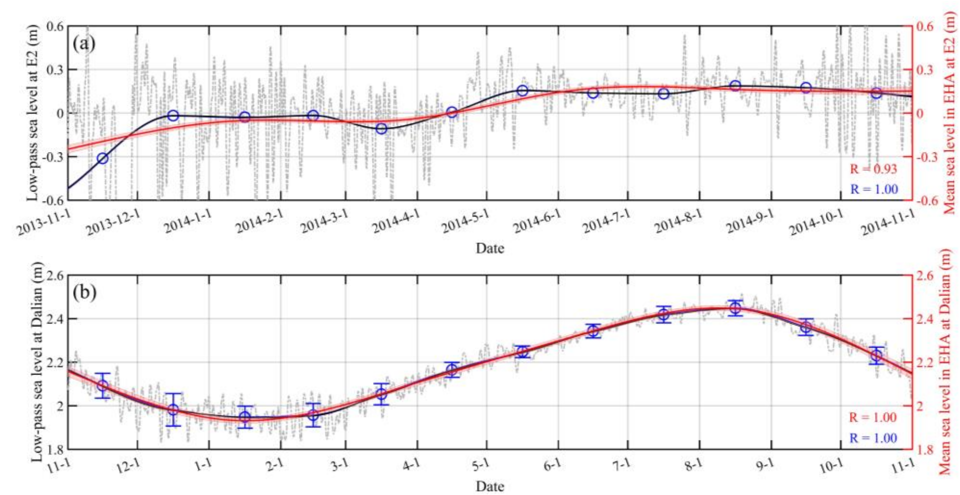
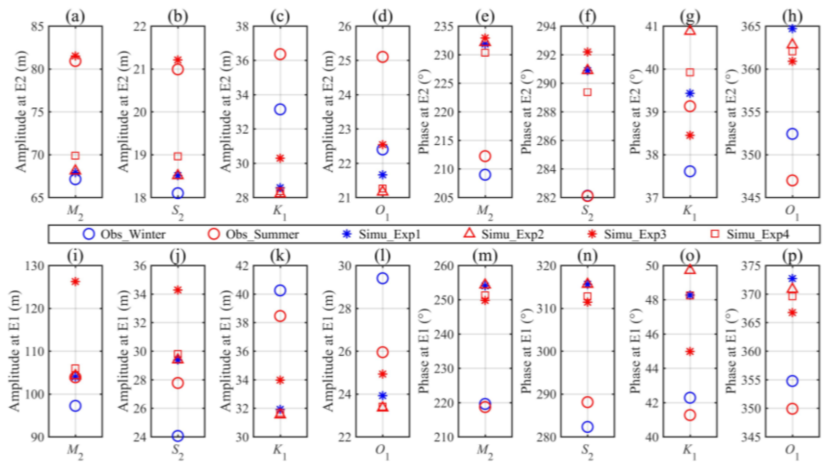


Figure ~~7~~8. Time series of the original low-pass sea level (grey line), the monthly average~~d values~~s of the original low-pass sea level (blue circles), the interpolated values of the monthly averaged low-pass sea level using the cubic spline interpolation (blue line) and the estimated mean sea level using SHA (black line) and EHA (red line), at (a) E2 and (b) Dalian. ~~It was noted that o~~Only the original low-pass sea levels with absolute values less than 0.6 m ~~were~~ are shown in panel (a). ~~and t~~P~~he p~~ink shadings indicates the corresponding 95% confidence intervals, while blue vertical bars designate the standard deviation in multi-yearly averaging.



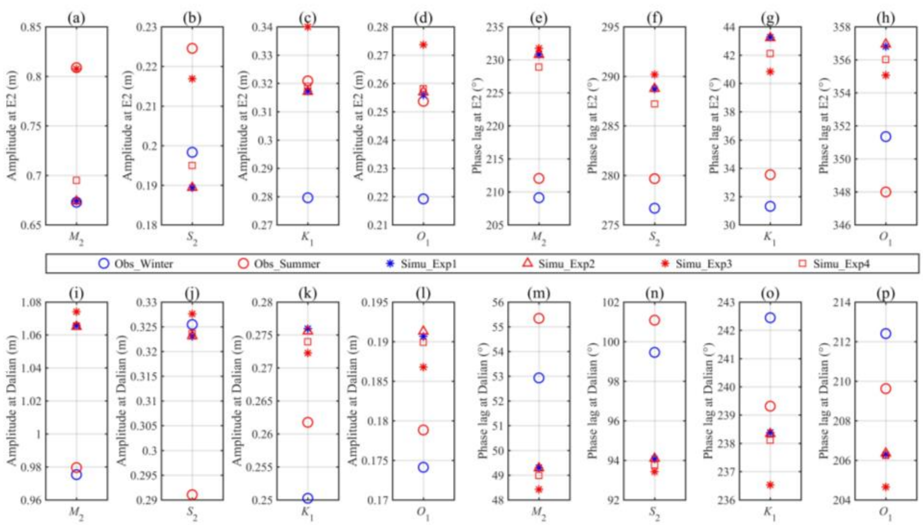
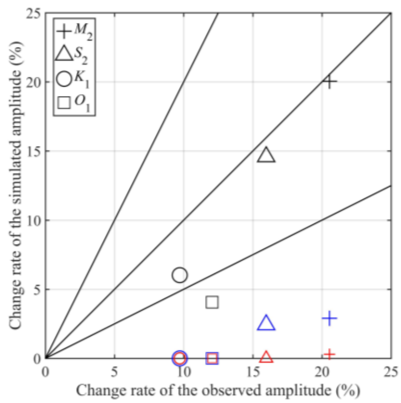
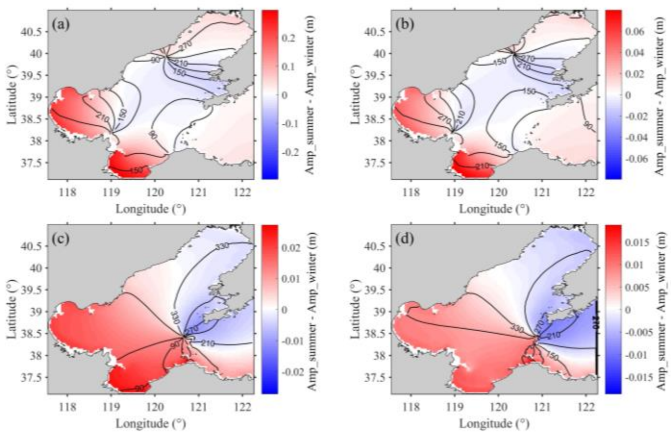


Figure ~~8~~9. (a) ~~The a~~Averaged M_2 tidal amplitude in winter (blue circle) and~~ in~~ summer (red circle) by analysing ~~the~~ observations at E2 using EHA, and ~~that~~ those obtained by analysing the simulated results in Exp1 (blue asterisk),

Exp2 (red triangle), Exp3 (red asterisk) and Exp4 (red square). (b-d) Similar to (a), but for ~~the~~ S_2, K_1 and O_1 ~~tides~~ at E2~~1~~, respectively. (e-h) Similar to (a-d), but for the phase lags at E2. (i-p) Similar to (a-h), but for those at ~~E1~~Dalian.



~~**Figure 9. Comparison of simulated and observed change rate of the amplitude, for the *M*2 tide (plus sign), *S*2 tide (triangle), *K*1 tide (circle) and *O*1 tide (square), in Exp2 (red line), Exp3 (black line) and Exp4 (blue line). The 1:2, 1:2, and 2:1 lines are shown for reference. It is noted that the change rate is set to 0 when it is less than 0.**~~


(a)
(b)
(c)
(d)
Latitude (°)
Longitude (°)
Amp_summer - Amp_winter (m)
40.5
40
39.5
39
38.5
38
37.5
118
119
120
121
122

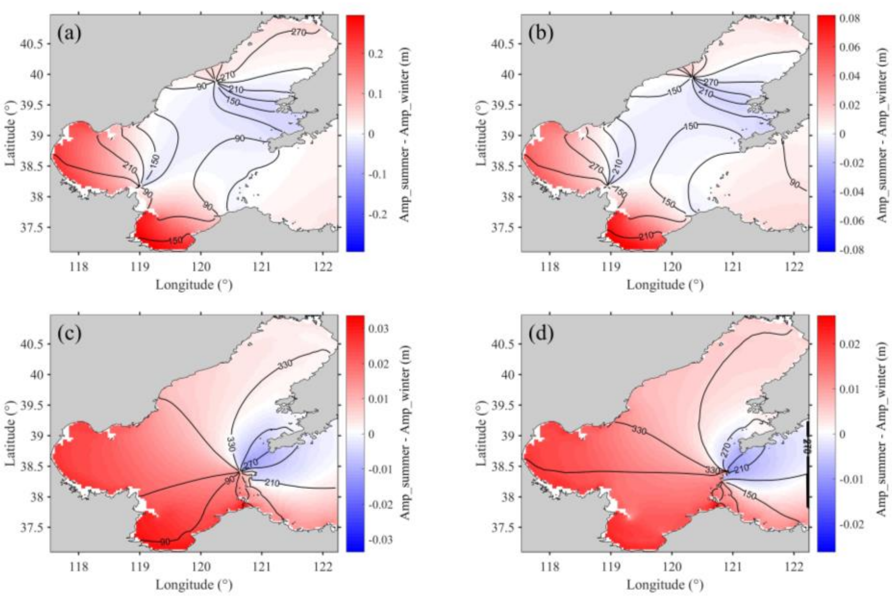

(a)
(b)
(c)
(d)
Latitude (°)
Longitude (°)
Amp_summer - Amp_winter (m)
40.5
40
39.5
39
38.5
38
37.5
118
119
120
121
122

Figure 10. (a) ~~The d~~Difference between the simulated M_2 tidal amplitudes in summer ~~simulated in (~~Exp3) and ~~that~~ those in winter ~~simulated in (~~Exp1) (colours), and the co-phase lines of the M_2 tide in winter ~~simulated in(~~Exp1) (black lines). (b-d) similar to (a), but for S_2, K_1 and O_1, respectively.