Ocean Sci. Discuss.,
https://doi.org/10.5194/os-2019-133-AC2, 2020

Ocean Science Discussions
Open Access
EGU

Interactive comment on "Predicting tidal heights for extreme environments: From 25 h observations to accurate predictions at Jang Bogo Antarctic Research Station, Ross Sea, Antarctica" *by* Do-Seong Byun and Deirdre E. Hart

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Received and published: 19 May 2020

Reply to interactive comment of 14 Feb 2020 on "Predicting tidal heights for extreme environments: From 25 h observations to accurate predictions at Jang Bogo Antarctic Research Station, Ross Sea, Antarctica" by Glen Rowe

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Format This review has been useful in helping to improve our paper. Below we have copied each individual reviewer comment, and written below it a response, and then pasted the text of the paper as it now reads.

Individual reviewer comments and our responses

Line 9: The words 'as represented' are unnecessary and at the start of the next sentence change Though to However Response: Both of these wording changes have been made exactly as suggested. The paper now reads: "Accurate tidal height data for the seas around Antarctica are much needed, given the crucial role of tidal processes in regional and global climate, ocean and marine cryosphere models. However obtaining long term sea level records for traditional tidal predictions is extremely difficult around ice affected coasts".

Line 20: This sentence could end at regimes as the following words repeat what has already been stated. Response: Upon reflection we decided that this sentence was not needed, since the previous sentence detailed the level of success of the method, so this former line 20 sentence has been deleted. The preceding sentence now reads: "Results reveal the CTSM+TCC method can produce accurate (to within $\sim$5 cm Root Mean Square Errors) tidal predictions for JBARS when using short-term (25 hr) tidal data from periods with higher than average tidal ranges (i.e. those at high lunar declinations and/or spring periods)".

Line 29: : : :based on as little as 25 h of sea level records when combined: : : Also, h, as used here and elsewhere in the paper, would be clearer if abbreviated to hr (or better still, written in full). Response: Regarding the second point above, the unit for hour, 'h' has been changed to 'hr' throughout the manuscript. Regarding the first point, the text has been altered as suggested (see below). The paper now reads: "However, Byun and Hart (2015) developed a new approach to successfully predict tidal heights based on as little as 25 hr of sea level records when combined with

neighbouring reference site records, using their Complete Tidal Species Modulation with Tidal Constant Corrections (CTSM+TCC) method, on the coasts of Korea and New Zealand".

Line 35: I'm not aware of the US operating a gauge in McMurdo Sound and would be interested to know where/when. NZ has a gauge at Scott Base. Does Italy have a long-term gauge at MZS? Response: Padman et al. (2003) mentions a 1 year record from McMurdo Station. Also a tide gauge was set up at Mario Zucchelli Station (formerly named Terra Nova Station) from 1996 (see https://www.geoscience.scar.org/geodesy/perm_ob/tide/terranova.htm). We are currently attempting to track down these and any other available Ross Sea records for a further paper on the tides of this very interesting area. We have added these references to our paper so that our readers can clearly see the data sources behind our comment. The paper now reads (and includes the references below): "Long-term, quality sea level records in the Ross Sea are few and far between, and include observations from gauges operated by New Zealand at Cape Roberts (ROBT); by the United States in McMurdo Sound (see reference to this data in Padman et al., 2003); and by Italy at Mario Zucchelli Station (see: Gandolfi, 1996), all in the eastern Ross Sea". The reference list now includes: Gandolfi, S.: Terra Nova Bay Permanent Tide Gauge Observatory Site, https://www.geoscience.scar.org/geodesy/perm_ob/tide/terranova.htm, last access 4 Feb. 2020, 1996. Padman, L., Erofeeva, S. and Joughin, I.: Tides of the Ross Sea and Ross Ice Shelf cavity. Antarctic Science 15(1), 31-40, 2003

Line 36: Only the Italian base is in Terra Nova Bay – the others aren't anywhere near this bay. Response: Thank you – this error has now been corrected to 'eastern Ross Sea' (see full revised sentence above in response to comment on line 35).

Line 37: There is also the problem of securing against damage any cable connection from a subsurface device to datalogging/power equipment ashore. Response: Yes, though this is a challenge for any cabled shoreline instrument deployed for a long time in any coastal environment, we can imagine that it is particularly difficult in the harsh

environment of Antarctica. We have added this issue to the text. The paper now reads: “There is also the challenge of securing, and preventing damage to, the cables that join the subsurface instruments to their onshore data loggers and power supplies, across the seasonally dynamic and harsh coastal and subaerial environments of Antarctic shorelines”.

Line 42: Of course, hydrographic surveys are ideally carried out when there is minimal sea ice; whether or not there is a permanent gauge site (line 40-41) is not the main factor when deciding when to conduct such surveys. Response: Yes, agreed – in order to better separate out these two pieces of information we have split one sentence into two. The paper now reads: “In the absence of a suitable permanent gauge site, hydrographic surveys have been conducted at the Korean Jang Bogo Antarctic Research Station (JBARS). Such surveys are best conducted during the summertime predominantly sea ice free window around mid-January to mid-February”.

Line 72: : : : in the austral summertime : : : Response: Yes, the word austral has been added here as well as in another place in the paper. The paper now reads: “The Korea Hydrographic and Oceanographic Agency (KHOA) survey team went to JBARS in Northern Victoria Land’s Terra Nova Bay, Ross Sea, Antarctica, in the austral summertime of 2017 (Fig. 2) for a preliminary fieldtrip to conduct hydrographic surveys and produce a nautical chart”.

Line 81: Residuals – observed compared to predicted? Response: Yes, that’s correct. We added the text in brackets below. The paper now reads: “Of these, the 20.54 day record produced between 29 December 2018 and 18 January 2019 comprised relatively high quality data with small residuals (i.e. observed minus predicted)”.

Line 83: : : : the absence of a permanent tide station at JBARS, : : : Response: The text has been altered as suggested. The text now reads: “Due to the short duration of the KHOA survey team’s 2017 and 2018 to 2019 forays into the Ross Sea, and in the absence of a permanent tide station at JBARS, it was not possible to collect

the year-long sea level records that are commonly employed to obtain reliable tidal constituents".

Line 94: Pairs in brackets unnecessary repetition from lines 92 and 93. Response: Your comment alerted up to the wordy nature of these two sentences, so instead of just deleting the pairs in brackets we rewrote both sentences as one replacement sentence, shortening our explanation of this step while retaining the key details. The text now reads: "The inference method was used to separate out neighbouring diurnal (K1 and P1) and semidiurnal (S2 and K2) tide constituents, with their amplitude ratios and phase lag differences obtained from harmonic analysis of the long-term ROBT reference station records".

Lines 96 – 98: As Table 1 will be inserted here this sentence is redundant as it is just repeating what the table contains. Line 100: : : : phase lags showed only slightly different values. Response: With regard to your line 96-98 comment, we deleted the text that unnecessarily highlighted the numbers displayed in Table 1, and in just kept the interpretive text found it best to merge two sentences together for tighter expression of the results. According to your line 100 comment we removed the hyphen from 'phase lag' throughout the paper – the below sentence provides an example. The text now reads: "Analysis revealed that the two main diurnal (O1 and K1) and semidiurnal (M2 and S2) tides had similar amplitudes at the two stations (Table 1), with the diurnal amplitudes being slightly larger at ROBT than at JBARS, the semidiurnal amplitudes being slightly smaller at ROBT than at JBARS, and the phase lags of all four tides having only slightly different values".

Line 101: for completeness, should the formula for F be stated? Response: Yes, agreed – we have now added explanation of this parameter to Table 1 caption, where it is now mentioned first in the paper. The Table 1 caption note now reads: "F is the ratio of the K1 and O1 diurnal tide amplitudes to the M2 and S2 semidiurnal tide amplitudes".

Lines 103 – 111: Is this paragraph necessary? This study relates to a part of the

Ross Sea – the tidal regimes around other parts of Antarctica are of no relevance to this investigation. Or maybe you are hinting that as the Ross Sea is different to the rest of the continent the results of this study may not be applicable elsewhere. If this paragraph is deleted then Figures A1 and A2 are no longer required. Response: According to your suggestion and comments by the Editor regards these lines, the whole paragraph has been deleted, as have the former Appendix 1 figures.

Line 113: Delete the '-' in front of CTSM. Response: This typo has been deleted, and the sentence has been altered significantly as a result of the Editor's suggestion that section 3 should be rewritten to describe the methodology more simply, removing much of the math. The text now reads: "Having analysed the tidal harmonic constants at the two stations based on their concurrent short-term records, we then employed the CTSM+TCC method (Byun and Hart, 2015) to generate tidal height predictions for JBARS, our 'temporary' tidal observation station (subscript o), using ROBT as the 'reference' station (subscript r).".

Lines 114 – 115: Are the italics necessary? Response: No they were unnecessary so have been removed in accordance with your comment. This sentence has been modified as a result of the section 3 rewrite. The text now reads: "This prediction approach (see Appendix 1 for the detailed calculations, and Byun and Hart (2015) for explanation of procedure development) is based on: using long-term ($\geq$183 days) reference station records (LHr) and CTSM calculations to make an initial anytime (τ) tidal prediction (η_r (τ)), which involves summing tidal species' heights for the reference station (Fig.3); and comparing the tidal harmonic constants (amplitude ratios and phase lag differences) of representative tidal constituents (e.g., M2 and K1) for each tidal species between the temporary and reference stations, calculated using T_TIDE and concurrent short-term records ($\geq$25 hr duration, starting at midnight) from the temporary (SHo) and reference (SHr) stations; and using the step (ii) comparative data and the TCC calculations for each tidal species to adjust the η_r (τ) tidal species' heights in order to generate accurate, anytime tidal height predictions for the temporary tidal station (η_o (τ))".

Line 116: Similar tidal characteristics at the reference and temporary site is given as one of the requirements of the CTSM+TCC method. However, it has been noted in lines 101 – 102 that ROBT is diurnal and JBARS is mixed, mainly diurnal. Are these regimes sufficiently alike to be considered 'similar' for the purposes of this method? Response: Thank you, due to your question we have improved the text to really hone in on the similarity required. The text now reads: "Importantly, this method assumes that the reference and temporary tidal stations are situated in neighbouring regimes with similar dominant tidal constituent and tidal species characteristics, and that the tidal properties between the two stations remain similar through time. As explained above, both JBARS and ROBT have tidal regimes that are primarily dominated by diurnal tides. LHr must comprise high quality (e.g. few missing data) tidal height observations from anytime".

Lines 121 – 122: The records are not temporary – the records are from a temporary site. Response: Yes, thank you. We have made sure that this word placement mistake does not now occur in our paper. This particular sentence has also been deleted as part of the Section 3 re-write, recommended by the Editor.

Line 124: My record from ROBT does not have any gaps early February 2017. Response: ROBT data were downloaded from LINZ website. There are still no data files until 12 February 2017 as you can see at http://apps.linz.govt.nz/ftp/sea_level_data/ROBT/2017/00/ (last access: 29 February, 2020). We have, however, now received a file containing the full 2017 records, after finding out that they existed when consulting you with regards to the ROBT set up by telephone – thank you very much for supplying these excellent data. Please note that these data are not available on the Permanent Service for Mean Sea Level (PSMSL) website, where ROBT records are recorded as existing up until 2009. We have found finding the existence of, and then obtaining, good observational tidal data for the Ross Sea and elsewhere in Antarctic quite a challenging exercise. Since your LINZ records represent one of the best in existence, it might benefit Antarctic tide research to up-

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date the PSMSL website: https://www.psmsl.org/data/obtaining/stations/1763.php, including the comments made there on the low data quality of recent ROBT records. Currently this website says: “Documentation added 2011-11-17. There is no data available for 2010. Although the site is still working the data is of low quality and therefore unreliable. Plans are in place to repair the tide gauge when possible". We have re-written this sentence as a part of our Section 3 re-write. The text now reads: “This slight adjustment in approach arose since for the 2017 JBARS observation time period, the concurrent 2017 ROBT records available online (LINZ, 2019) had multiple missing data”.

Lines 127 – 129: This sentence reiterates the essence of the preceding sentence and, although it begins ‘In short’, is longer than the previous one. One of these two sentences could be deleted. Response: In our re-write of Section 3 we deleted the last of these two sentences as suggested here. The remaining sentence reads: “We solved this issue by producing a year-long synthetic 2017 record for ROBT using T_TIDE (Pawlowicz et al., 2002) and the 2013 (i.e. LHr) observational record as input data”.

Lines 148 – 154: Is the first sentence in this block of lines necessary? The following two sentences describe the process and can stand on their own. Response: This section of text has now been cut and pasted into an appendix detailing the math behind the CTSM+TCC approach (in response to a suggestion by the Editor to rewrite Section 3 more clearly and simply). In its new Appendix 1 location, the first sentence in this block has been modified to convey different/ extra information according to a comment by Reviewer 1, and terms that were repeated in the next two sentences have been deleted, eliminating overlap that you drew our attention to. The text now reads: “As the second step, under the ‘credo of smoothness’ assumption that the admittance or ‘ratio of output to input’ does not change significantly between constituents of the same species (Munk and Cartwright, 1966; Pugh and Woodworth, 2014), the amplitude ratio and phase lag difference of each representative tidal constituent for each tidal species between the temporary and reference stations were calculated from the results of tidal harmonic

analyses of concurrent 25 hr data slices (starting at 00.00) from the temporary tidal observation and reference tidal stations (i.e. from SHo and SHr). The process of selecting the optimal 25 hr window for these concurrent data slices from amongst the 17.04 days of available records is explained in Section 3 of this paper".

Line 154: Which are the 'initial tidal predictions'? It is not clear to me. Response: Thank you – this was not as clear as it could be: we meant 'tidal predictions at the reference station' calculated from the CTSM, and have improved the text accordingly. The text (cut and pasted into in Appendix 1) now reads: "Once the optimal 2017 short-term data window was selected, the third step involved adjusting the tidal predictions at the reference station calculated from Eq. (A1), to represent those for the temporary station (η_o (τ)), by substituting the daily (i.e. SHo and SHr) amplitude ratios ((a_oˆ((s)))/(a_rˆ((s)))) and phase lag differences (G_oˆ((s))-G_rˆ((s))) for the tidal constituents (K1 and M2) representing the diurnal and semidiurnal tidal species between the temporary and reference stations into Eq. (A1) as follows. . .".

Line 163: Calculations, not experiments? Line 164: 'in shorthand' seems unnecessary. Response: Yes to both – 'experiments' has been removed in the re-write of this text and we now describe these as 'prediction data sets', as opposed to experiments, at the end of the revised section 3. We also removed the 'in shorthand' text. The text now reads: "Each paired data set was then used with LHr to generate tidal height predictions for JBARS covering both the 2017 and 2019 KHOA temporary observation campaign time periods. Comparisons were made between the JBARS observations and the 17 prediction data sets generated for each observation campaign to identify which 25 hr short-term data window produces optimal η_o (τ) results".

Lines 169 - 171: I had to read the first part of this sentence a few times to figure out what is going on. My take is that you obtained 17 datasets each one of which included 10-minute interval predictions spanning 17 days as derived from the harmonic analysis of each of the (17 in total) 25 hr slices of observed data. Is this correct? If not then I have clearly misunderstood, and if it is then that is good but, regardless, I'm not

confident that I have it right. Response: Yes, that is correct and thank you for pointing out the difficulty of this sentence. This sentence has been re-written. Moreover the previous Section 3 description of the method applied has been improved significantly such that we anticipate readers will be much clearer by the time they reach section 4 about what we mean here. The text now reads: CTSM+TCC was used to produce 17 different JBARS tidal prediction datasets for the period 29 January to 14 February 2017, based on harmonic analysis results of their 'daily' (25 hr) K1 and M2 amplitudes and phase lags between our two tidal observation stations (Fig. 4)".

Lines 177 – 187: This discussion about the correlation of tidal range and RMSEs and R2 values is more difficult to follow than it could be. I feel the two sentences about the February 2 tide 'sandwiched' between the discussions about the results at greater tidal ranges has made the explanation somewhat convoluted. Dealing with the circumstances of the good statistics before moving on to the poorer results will enable this discussion to be expressed in a more succinct manner (and easier to follow). Response: Yes, agreed. We have reordered the text according to your helpful comment here. The text now reads: "RMSEs between observations and predictions ranged from 4.26 cm to 20.56 cm while R2 varied from 0 to 0.94 across the 17 'daily' experiments. Eleven of the experiments produced accurate results (i.e. excluding those based on 25 hr input data derived from 31 January; and 1 to 4 and 14 February records). Daily datasets from periods with relatively high tidal ranges (>83.5 cm) produced predictions with RMSEs <5 cm and R2 values >0.92. The maximum spring tidal range occurred on 9 February: the short-term data from this date produced predictions with a low (but not the lowest) RMSE (4.81 cm). The predictions with the lowest RMSE (4.259 cm) and highest R2 value (0.941) were produced using inputs derived from 25 hr data recorded one day earlier, on 8 February 2017. In contrast to the majority of successful experiments, the experiment based on data derived from the '2 February' 25 hr data slices produced predictions with very high RMSE (20.56 cm) and very low R2 (0.00) values. Notably, the 2 February tides were characterised by the smallest tidal range (11.95 cm) of the JBARS record, during a period of low lunar declination".

Lines 188 – 192: Are these two sentences saying the same thing in different ways? Response: They concerns the same idea, but the second sentence details the idea for a specific example case (Fig. 7) amongst the total 17 cases (Fig. 6). We have added "For example" to indicate this. The text now reads: "As with the 2017 predictions, RMSEs between the 2019 summertime predictions and observations were lower when generated using input data derived from 25 hr data slices from the 2017 spring tide periods at high lunar declination (as opposed to during neap tides and/or periods at low lunar declination) (Fig.6). For example, as in the earlier experiments, the 2019 summertime predictions made using input data derived from the 8 February 2017 (25 hr) data slices produced the lowest RMSE (5.3 cm) and highest R2 (0.913) values of the 2019 summertime experiments (Fig. 7)".

Lines 208, 209, 211, 212 and 213: I find the use of the adjectives 'maximum' and 'minimum' in association with declination to be confusing. Minimum could be taken to be on the celestial equator (δ = 0°) and maximum could be greatest declination either north or south. Better to use phrases like 'greatest southern declination' and 'greatest northern declination' to be more specific. Response: Thank you for your useful suggestion – we have applied this change as recommended. The text now reads: "That is, maximum range tide days can be estimated for JBARS based on the day of the Moon's greatest southern (GS) and northern (GN) declinations. The time between the Moon's semi-monthly GN and GS declinations and their effects on tidal range, called the age of diurnal inequality (ADI), is commonly 1 to 2 days. As shown in Fig. 8, the GN and GS lunar declinations during our temporary station summertime observation periods occurred on 8 February 2017 (GN) and on 6 January 2019 (GS) respectively, with the maximum diurnal tides at JBARS expected approximately 1 day after each lunar declination peak".

Line 227: Delete 'and'. Response: Yes, this typo has been removed. The text now reads: "The ADI values were 0.57 and 0.23 or 0.30 days, while the AT values were -2.30 and -1.44 or -2.87 days, for ROBT and JBARS respectively (Table 1)".

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Lines 245 – 246: It would be helpful to give the dates for the two periods (ETT and TET). Is the 'minus' in front of tropic on line 246 a typo or does it mean the southernmost declination? Line 247: : : : CTSM+TCC considering only 2 major tidal species : : : Response: In response to the suggestion from the Editor that we significantly shorten section 5.1 (he suggested 5-6 lines instead of 39 lines) we have deleted much of this detail (including mention of ETT and TET, and the sentence with the minus sign typo you mentioned). We also made the suggested '2 tidal species' change suggested above. The text now reads: "However, as shown in Fig. 7, our results contain a changing fortnightly timescale bias in estimates. This error pattern likely resulted from our application of CTSM+TCC considering only 2 major tidal species (diurnal and semidiurnal) whilst ignoring several long period tides".

Lines 249 – 256: Could this be shortened to just summarise the conclusion arrived at by the other authors. Is there a need to describe what they did – people interested can refer to the references. Response: Yes, we have removed most of the text explaining details and just left their findings that focus on what other constituents might be important. The remaining text has also been shifted slightly within the section. The text now reads: "Similarly, Rosier and Gudmundsson (2018) found that ice flows are modulated at various tidal frequencies, including that of the MSf tide. . . Nevertheless, studies indicate that incorporating major and minor tidal constituents, including long period tides, into tidal predictions may be advantageous for their use in ice flow and ice-ocean front modelling (e.g. Rignot et al., 2000; Rosier and Gudmundsson, 2018)".

Lines 267 - 268: Srun excluded : : : Run1 excluded : : : Run2 incorporated : : : (I think) Response: We have clarified this text as suggested. The text now reads: "Three 2019 tidal prediction experiments were conducted: Srun excluded all long-period tides (see list of exclusions in Table 2); Run1 was based on Srun but incorporated the Mf; and Run2 was based on Srun but incorporated the Mf and MSf".

Lines 269 and 270: Should both instances if 'exclusion' be 'inclusion'? Response: No, 'exclusion' is correct. We have reworded this part to avoid this confusion. The text now

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reads: “Comparisons between Run1 and Srun predictions show that exclusion of the Mf tide (2.7 cm amplitude) can produce prediction biases during periods of lunar declination change (Fig. 9a), with comparisons between Run2 and Run1 results showing that the additional exclusion of the MSf tide (1.2 cm amplitude) intensifies the biases (Fig. 9b)”.

Lines 270 – 271: Is there any reason why this suggested line of investigation has not been pursued in this paper? Response: Yes, basically, this is because the tidal constants for the long-period tides cannot be derived from short-term (25 hr) records, so it is beyond the scope of the present study, which was an initial assessment if the CTSM+TCC method could be used to generate predictions for JBARS, a temporary tidal station in an extreme environment with imperfect data record conditions. Now that we have demonstrated the usefulness of the method for making reasonable predictions here, we feel that further work could be done to hone the prediction approach for ice affected coasts if the data is to be used in ice flow modelling. Generating data for ice flow modeling was not the primary focus of our paper though, as this was an initial paper to see if predictions could be generated using a reference station, and in this diurnal tide dominated environment (whereas Byun and Hart 2015 has more complete data conditions and semidiurnal dominated tidal regimes). Further work beyond our paper, examining the long-period tidal constituents, could help inform the objectives of future Antarctic tidal measurement fieldwork campaigns.

Line 273: Section 5.2 does not seem to contribute to the main aim of the paper, i.e. to predict tides from 25 hr observations. 5.2 looks at the contrasting tidal environments of two areas and tries to explain why they differ. I think 5.2 could be removed. Response: In response to this comment, and additional detailed comments on this section from the Editor, we have substantively tightened section 5.2, removing much text exploring nodal modulation correction factors (including Fig. 13). We have also better explained the role of this section in our paper, being to show how the Ross Sea tides compare to the other diverse and out of phase regimes around Antarctica. The text now reads:

"5.2 Understanding the contrasting tidal environments around Antarctica Figure 11 illustrates the form factors of tidal regimes in the seas surrounding Antarctica, according to FES2014 model data. There are large areas characterised by 'diurnal' (F>3); 'mixed, mainly diurnal' (1.5>F<3); and 'mixed, mainly semidiurnal' (0.25>F<1.5) forms. Only in a small area half-way along the Weddell Sea coast of the Antarctic Peninsula (at 72°S) do tides exhibit a 'semidiurnal' form (F<0.25). Strong 'diurnal' tides predominate in the Ross Sea area of West Antarctica, around to the Amundsen Sea. In addition, a small area near Prydz Bay (Fig. 2) in East Antarctica exhibits diurnal and mixed mainly diurnal tides. The rest of the seas surrounding Antarctica, including the Weddell Sea, are predominantly characterised by 'mixed, mainly semidiurnal' tides. Since diurnal tides have larger nodal factor and nodal angle variations than semidiurnal tides (Pugh and Woodworth, 2014), areas like the Ross Sea will have larger variations in tidal height across the 18.61 yr lunar nodal cycle compared to areas like the Weddell Sea (see details for ROBT in Byun and Hart, 2019). As the nodal angle variations of the diurnal and semidiurnal tides are out of phase, this leads to differing tidal responses around Antarctica over 18.61 years, particularly between the Ross and Weddell Seas. Given that CTSM+TCC is based on modulated tidal constant corrections for each diurnal and semidiurnal species, it is applicable in studying a continent with such a diversity of tidal regime types. Accurate (cm scale) quantification of the contrasting tidal behaviours and environments around Antarctica's margins are not only of use for polar station maritime operations, they are essential for estimating ice flows to the sea. This paper has shown how the CTSM+TCC approach may be used to complement existing efforts to quantify variations in tidal processes around Antarctica, in particular for places with sparse in situ tidal monitoring, such as the Ross Sea".

Figures A1 and A2: If the paragraph at lines 103 -111 is deleted then these figures are no longer required. Response: Yes - these two pages of figures have now been deleted, as has the above mentioned paragraph.

Figure 2: Readers might find this more informative if the map covered the Ross Sea

only. Response: A map focusing on the Ross Sea area only has been added to Fig. 2 (see (b)). We retained the Antarctica map (a) as well since it is of use when interpreting Fig. 11. This figure has been uploaded with this reply and its full caption now reads: “Figure 2. Maps showing (a) the locations of the two tidal observation stations employed in this study within a wider Antarctic context: Jang Bogo Antarctic Research Station (JBARS, âŰš) and Cape Roberts (ROBT, âůŔ); and (b) the case study station locations relative to two other (previous) temporary tidal observations stations, McMurdo Station (âŰă), and Mario Zucchelli Station (âůŔ), in the Ross Sea”.

Figure 3: The x-axis label should be ‘Time (month/day)’. The description starts ‘Seventeen day time series: : :”. Isn’t it seventeen sets of daily (25 hr) data slices as stated in line 130? Response: Yes, this x-axis label has been fixed. Also, the figure caption has been improved as suggested, and colour added to the lines and key. This figure has been uploaded with this reply and its full caption now reads: “Figure 3. Modulated tidal (a) species amplitudes and (b) phase lags for the diurnal and semidiurnal tidal species, calculated from Cape Roberts (ROBT) tidal prediction data (29 January to 14 February 2017), using Appendix 1 Eqs. (A1) and (A3)”.

Figure 4: The x-axis for all four plots needs a label (Time (month/day)”. The description refers to daily slices of the 17 day ROBT tidal predictions in the first sentence, but the second sentence refers to results of the 369 day 2013 ROBT analysis. Is this correct? Response: The x-axis labels of all four Fig. 4 plots have been fixed, and colour added to the lines and key. Note that this figure has been re-drawn to include the two plots (a and f) that were formerly Figure 5. The words ‘harmonic’ and “In addition” have been added to make this caption clearer. This figure (combining the previous Figures 4 and 5 together) has been uploaded with this reply and its full caption now reads: “Figure 4. Daily amplitudes (a, c); phase lags (b, d); amplitude ratios (e); and phase lag differences (f) of the K1 and M2 tides (representative diurnal and semidiurnal tide species) at ROBT (a, b) and JBARS (c, d), and between JBARS and ROBT (e, f), calculated from 25 hr ‘daily’ slices of the 29 January to 14 February 2017 ROBT tidal

predictions and JBARS sea level observations. In addition, thick blue (K1) and thin pink (M2) horizontal lines in the panels indicate the amplitudes and phase lags derived from harmonic analyses of the 369 day 2013 ROBT sea level records (a, b) and of the 17 day 2017 JBARS sea level records (c, d), along with their amplitude ratios and phase lag differences (e, f)".

Figure 5: Both plots need a label for the x-axis. The description refers to dashed lines in the plots but these are not shown. Response: Thank you for spotting this typo. Plot x-axis labels have been added (now Figure 4 e and f). Also the caption description has been amended (see figure and caption in the response to the comment immediately above).

Figure 6: X-axis label (for both plots) should read Time (month/day). In the key, should the Moon's maximum declination be qualified as being either north or south? Line 429: the symbol (open circle) does not match the plot. Response: The label in x-axis of this figure (now Fig. 5) has been fixed. The qualifier 'northern' has been added, and the description has been changed to the Moon's greatest northern declination in the figure key. In the caption the symbol âŮŃ has been swapped to âŹę. This figure (formerly 6, now 5) has been uploaded with this reply and its full caption now reads: "Figure 5. (a) Time series (29 January to 14 February 2017) of Root Mean Square Errors (RMSE, thick blue line with âŮŘ) and coefficients of determination (R2, thin black line with âŮŃ) between JBARS 10 min interval sea level observations and the CTSM+TCC prediction datasets, generated for this site using harmonic analysis results from the JBARS daily (25 hr) sea level data slices and concurrent daily (25 hr) 2017 tidal prediction data slices and harmonic analysis results from ROBT station's year-long (2017) tidal predictions. (b) Time series of predicted 2017 tidal heights (thin blue line) and daily tidal ranges (thick black line with âŹę) for ROBT, based on harmonic analysis of this station's 2013, 5 min interval sea level records, plus an indication of the moon's phase and declination".

Figure 7: X-axis label could be consistent with the other figures. Line 435 has the

word ‘plus’ – this makes me confused about the description. My take is that the plot compares predictions for day x of 2019 (as derived from analysis of data from day y of 2017) with observations made on day x of 2019. Have I got this correct? Response: The x-axis label has been amended to match that of the other figures, and colour has been added. Yes, your understanding is correct and we have taken on board the comment regards caption readability. To make this caption easier to read we replaced the word ‘plus’ with ‘along with’, and added brackets around details of the CTSM+TCC data inputs. This figure (formerly 7) has been uploaded and its full caption now reads: Figure 6. Time series of Root Mean Square Errors (RMSE, thick blue line with âŮŔ) and coefficients of determination (R2, thin black line with âŮŃ) between JBARS 10 min interval sea level observations (29 December 2018 to 18 January 2019) and the CTSM+TCC prediction data sets generated for this site (using harmonic analysis results from daily (25 hr) summertime 2017 sea level data slices from JBARS along with concurrent daily (25 hr) tidal prediction slices and harmonic analysis results from ROBT station’s year-long (2017) tidal predictions).

Figure 8: X-axis labels again. As with Figure 7, I am confused by the statement that follows ‘(dashed box in (a)),’. Response: Thank you - the plot x-axis labels have been fixed. We have amended the (now second to last) confusing sentence of this caption to make it precise and easier to interpret, and added redrawn the plot. This figure (formerly 8, now 7) has been uploaded and its caption now reads: “Figure 7. Time series of JBARS sea level observations, predicted tidal heights, and sea level residuals (i.e. observations minus predictions) from (a) 29 January to 14 February 2017; and (b) 29 December 2018 to 18 January 2019. The JBARS predictions were generated via the CSTM+TCC method (using a daily (25 hr) slice of local sea level observations from 8 February 2017 (dashed box in (a)), along with concurrent (to time periods a and b) ROBT predictions; and year-long (2017) 5 min interval ROBT tidal predictions). RMSE and R2 denote the comparison Root Mean Square Errors and coefficients of determination, respectively”.

Figure 9: X-axis labelling differs from all other figures – could be altered for consistency. Line 444: should 'estimated' be 'calculated'? Response: The axis has been amended for consistency. 'Estimated' has been changed to 'calculated'. This figure (formerly numbered 9, now numbered 8) has been uploaded and its full caption now reads: "Figure 8. Time series of the Moon's declination, calculated at daily intervals for two observation periods: (a) 1 January to 15 February 2017; and (b) 16 December 2018 to 30 January 2019. Dashed boxes indicate the sea level observation windows examined in this study".

Figure 10: X-axis labels again. Response: The plot x-axis labels have been fixed (note this figure is now numbered 9). This figure's plot x-axes all now read: "Time (month/day)". This figure (formerly 10, now 9) has been uploaded and its caption now reads: "Figure 9. Time series of ROBT tidal predictions (a) made without long-period constituents ('SRun', i.e. excluding the constituents listed in Table 2) versus with the Mf tide ('Exp1'); and (b) time series of ROBT tidal predictions made ('SRun') without the long-period constituents versus ('Exp2') with the MSf and Mf tides. All predictions were generated based on tidal harmonic analysis results from the year-long (2013) ROBT sea level records".

Figure 11: If Section 5.2 is deleted then these figures are no longer required. If retained then the word 'Horizontal' in the description is redundant. Is the area in the Weddell Sea coloured magenta? Response: Fig. 12 has been deleted in shortening section 5.2. In Fig. 11 the word 'Horizontal' has been deleted. Yes, there is a magenta area shown in the Weddell Sea, indicating an area with a semi-diurnal tidal regime (F<0.25). We have added '(72°S) to make locating this spot easier. The Fig. 11 caption now reads: "Figure 11. Distribution of tidal form factor (F) values around Antarctica. Note the magenta area (72°S) on the Antarctic Peninsula's Weddell Sea coast denotes the only area with a properly semidiurnal tide regime (F<0.25) in the Antarctic region".

Table 2: I would delete the Period and Angular speed columns. Not only are the amplitudes of most constituents in this table small, but by my analysis they also have small

signal-to-noise ratios so are weakly determined. This caution about the reliability of these values should be noted. Response: Yes, the period and angular speed columns have been deleted while columns indicating amplitude standard errors and signal-to-noise ratios have been added, and a caution has been added into the text as follows. This sentence has been added to the last paragraph of section 5.1: "However, because these tides' amplitudes have small signal-to-noise ratios (SNR) (<1) with large standard errors (Table 2), caution should be exercised when elucidating fortnightly tide effects using these constituents". Table 2 will be included in the merged 'reply to all 3 reviews' file, and its caption now reads: "Table 2. Harmonic constants for 6 long-period tidal constituents, derived from harmonic analyses of year-long observations (2013) measured at the Cape Roberts sea level gauge (ROBT), using T_Tide (Pawlowicz et al., 2002). Phase lags are referenced to 0°, Greenwich and SNR denotes the signal-to-noise ratios.

Table 3: My records from ROBT for 2011 commence 21 November so the values given for that year can't come from yearlong observations (as is the case for the others in the table). Response: We have deleted this data and Table 3, in response to a comment in the Editor's review, so this point is no longer included in the paper. However we have re-checked our data records and found that we were correct in our original description of the full year of 2011 data, starting 1 January 2011. These data are available via: http://apps.linz.govt.nz/ftp/sea_level_data/ROBT/2011/00/. Please check this page as it may need to be altered: http://apps.linz.govt.nz/ftp/sea_level_data/ROBT/ROBT_readme.txt

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Interactive comment on Ocean Sci. Discuss., https://doi.org/10.5194/os-2019-133, 2020.

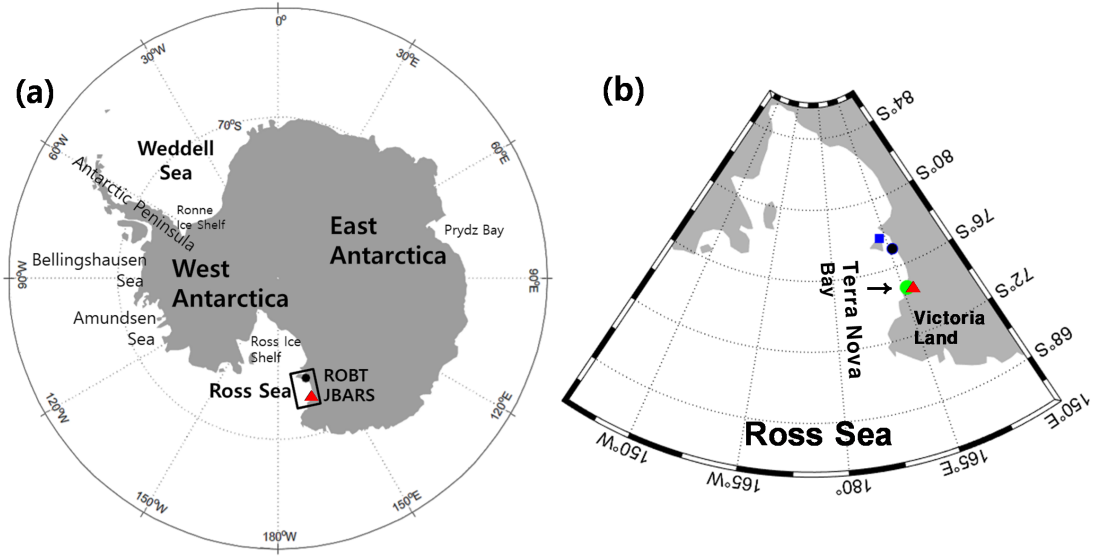

Fig. 1. Figure 2. Maps showing (a) the locations of the two tidal observation stations employed in this study within a wider Antarctic context: Jang Bogo Antarctic Research Station (JBARS, âŰš) and Cape Roberts

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Discussion paper

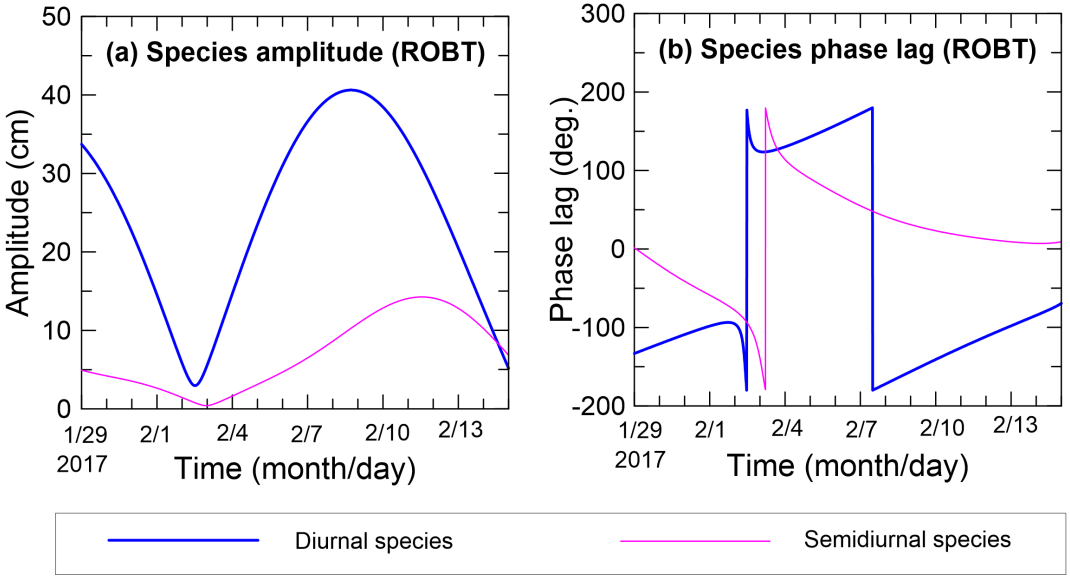

Fig. 2. Figure 3. Modulated tidal (a) species amplitudes and (b) phase lags for the diurnal and semidiurnal tidal species, calculated from Cape Roberts (ROBT) tidal prediction data (29 January to 14 February

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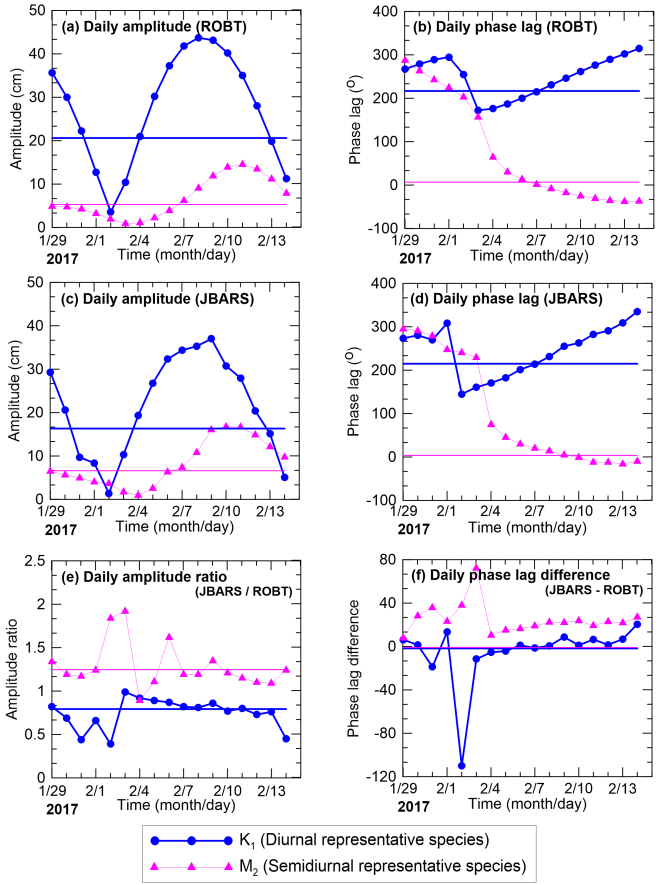

Fig. 3. Figure 4. Daily amplitudes (a, c); phase lags (b, d); amplitude ratios (e); and phase lag differences (f) of the K1 and M2 tides (representative diurnal and semidiurnal tide species) at ROBT (a, b) an

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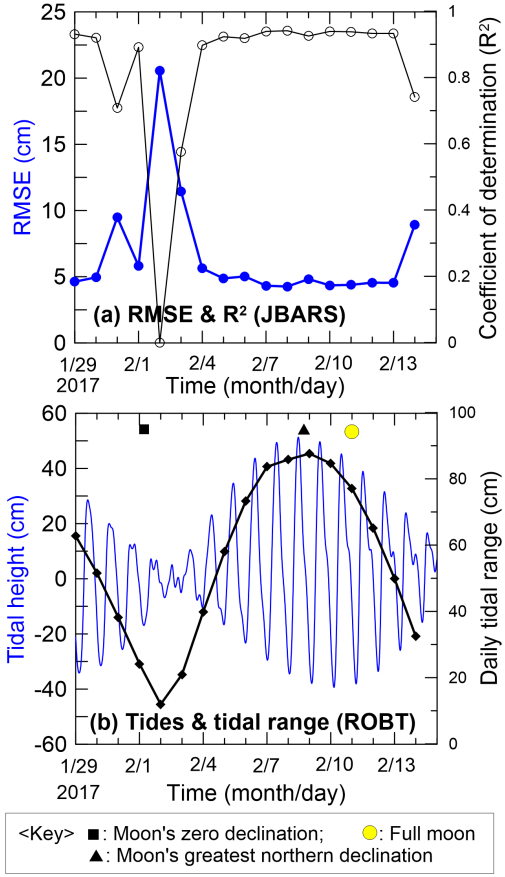

Fig. 4. Figure 5. (a) Time series (29 January to 14 February 2017) of Root Mean Square Errors (RMSE, thick blue line with âŮŘ) and coefficients of determination (R2, thin black line with âŮŃ) between JBARS 10 min

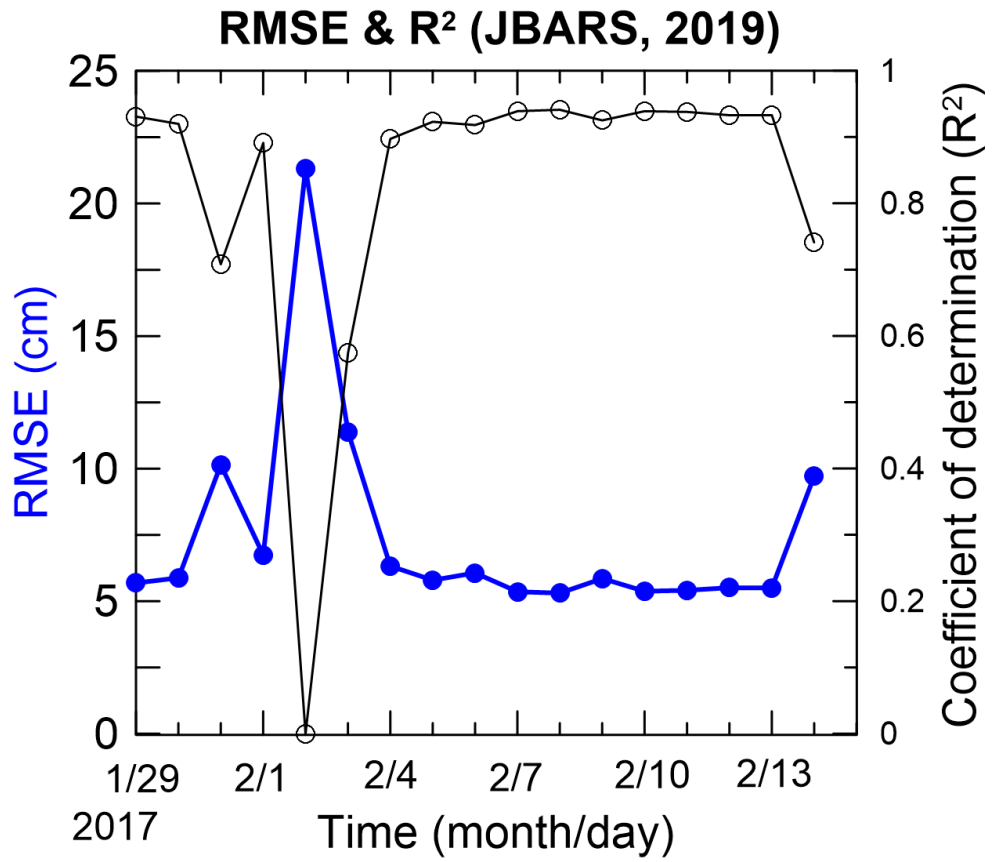

Fig. 5. Figure 6. Time series of Root Mean Square Errors (RMSE, thick blue line with âŮŔ) and coefficients of determination (R2, thin black line with âŮŃ) between JBARS 10 min interval sea level observations (29

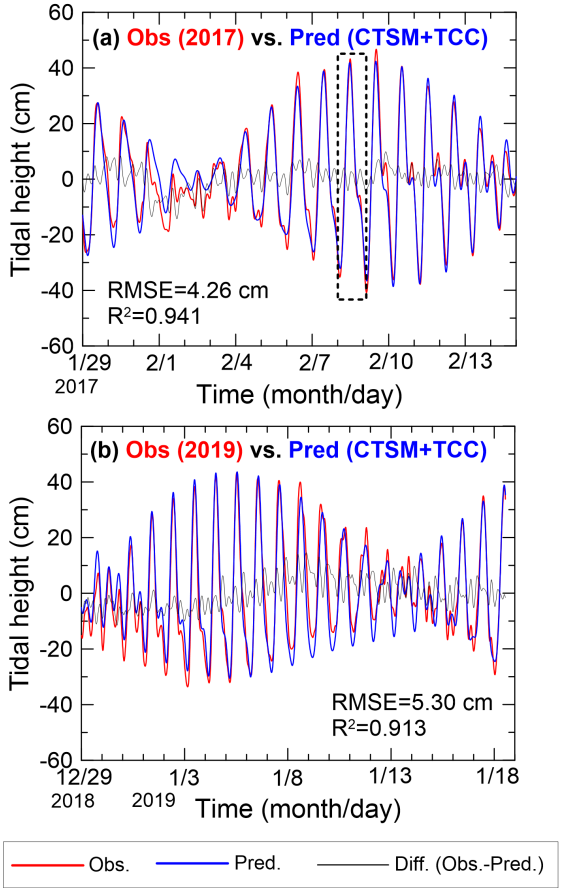

Fig. 6. Figure 7. Time series of JBARS sea level observations, predicted tidal heights, and sea level residuals (i.e. observations minus predictions) from (a) 29 January to 14 February 2017; and (b) 29 Decemb

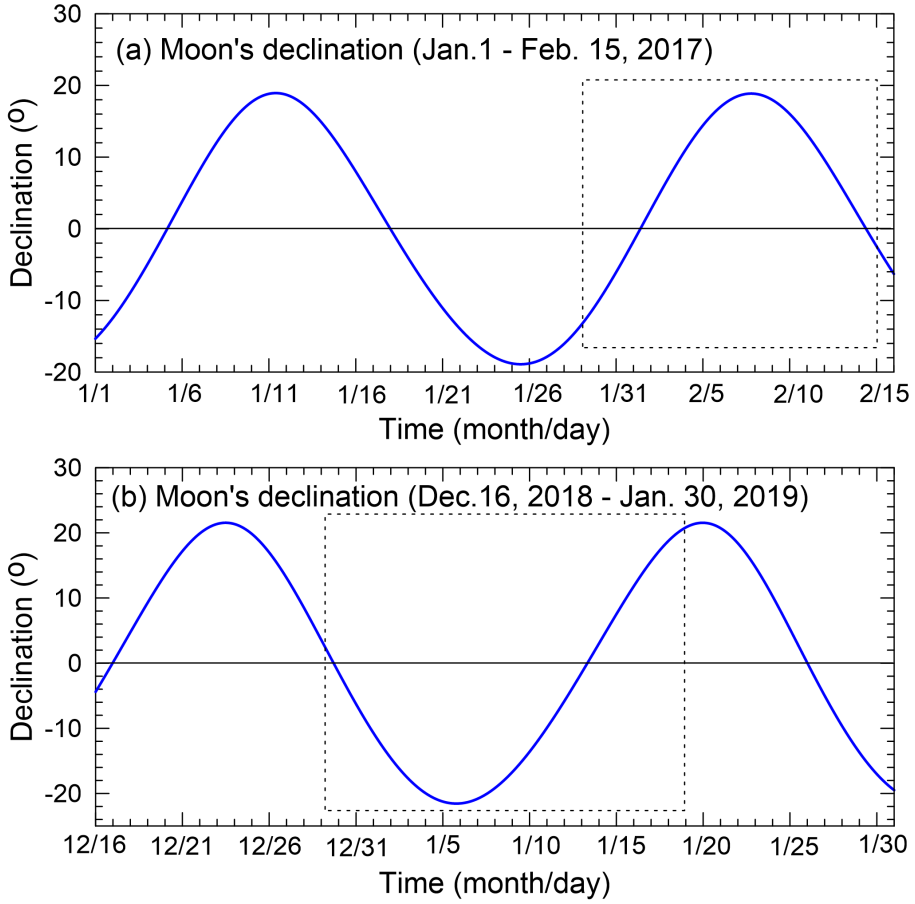

Fig. 7. Figure 8. Time series of the Moon's declination, calculated at daily intervals for two observation periods: (a) 1 January to 15 February 2017; and (b) 16 December 2018 to 30 January 2019. Dashed boxes

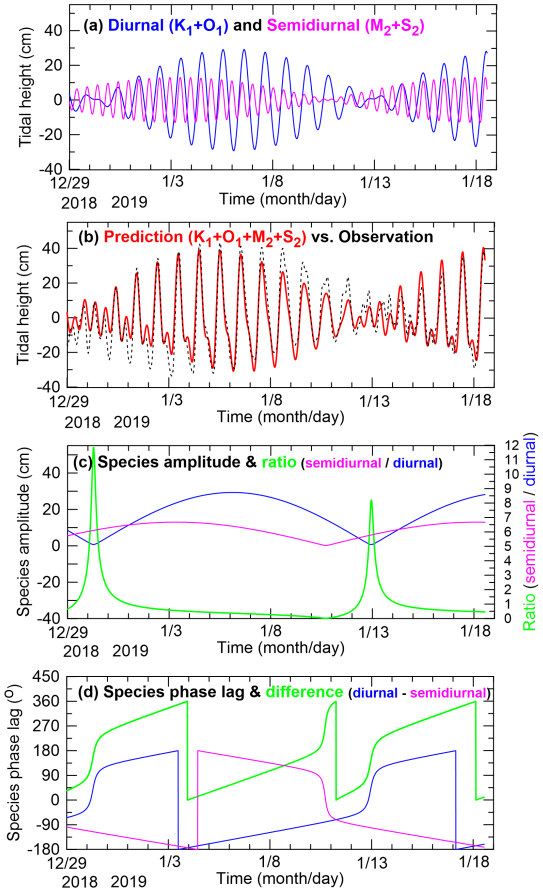

Fig. 8. Figure 9. Time series of ROBT tidal predictions (a) made without long-period constituents ('SRun', i.e. excluding the constituents listed in Table 2) versus with the Mf tide ('Exp1'); and (b) time ser