Merged reply to three reviews of "Predicting tidal heights for extreme environments: From 25 h observations to accurate predictions at Jang Bogo Antarctic Research Station, Ross Sea, Antarctica"

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Format We are very grateful for the two reviewers' and Editor's reviews of our paper received. Collectively, these reviews have been useful in improving this paper. Below we reply to the reviews in chronological order, with each individual reviewer comment copied in blue, a response written below it, and then the final modified text, table or figure copied below the response.

1. Reply to Reviewer 1's interactive comments of 17 Jan. 2020

p1, line35: Could you add these neighbouring sites to the map? And it would be good to find out what data is publicly available, and use them for further validation if possible.

- **Response:** According to reviewer's comment, these sites have been added. Thank you for the suggestion regards validation and other publically available records. Unfortunately it is relatively difficult to find recent online available records, but we found mention of a 1 year record from McMurdo Station in a Padman et al. (2003) paper and of a tide gauge being 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 will indeed attempt 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 out authors can see the data sources behind our comment.
- **The paper text and reference list now read: "**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 data in Padman et al., 2003); and by Italy at Mario Zucchelli Station (Gandolfi, 1996), all in the eastern Ross Sea".

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.

p4, line22: thanks for mentioning atmospheric conditions, too often ignored.

- **Response:** Yes, agreed. We have ensured that this point remains in the re-drafted methods section.
- **This text still reads:** "Byun and Hart (2015) recommended the use of short-term records gathered during periods of calm weather, to minimise errors due to atmospheric influences".

p4, line148: you could mention somewhere here that bundling all the constituents in a species together is valid due to the "credo of smoothness" assumption.

- **Response:** Yes, according to your comment, this has been added. Please note that this and other calculation explaining method details have been shifted into a new Appendix 1.
- **The paper 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 observation and reference tidal stations (i.e. from SH_o and SH_r)".

p6, line206: In figure 6, it looks like the ADI is negative as the peak is before the max declination?

- **Response:** Thank you for this query – upon checking, we found that location of symbols for Moon's maximum (▲) and zero declination (■) was not correct. The Moon's maximum declination is 19:00 7/2/2017 (18.867º) and the zero declination is around 09:30 1/2/2017. We have now fixed these in the figure.
- **Figure 5 (formerly Fig. 6) now looks like:**

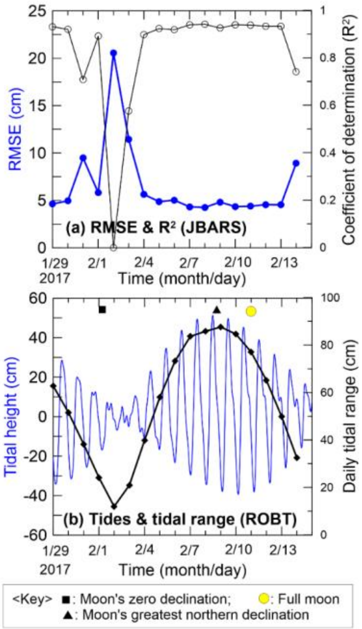


Figure 5. (a) Time series (29 Jan. to 14 Feb. 2017) of Root Mean Square Errors (RMSE, thick blue line with ●) and coefficients of determination (R^2, thin black line with ○) between JBARS 10 min interval sea level observations and the CTSM+TCC prediction datasets, generated for this site using harmonic 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 ♦) 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.

p7, line 251: (And elsewhere, please check all), Msf should be MSf [Moon-Sun-fortnight]. Similarly Msm should be MSm [Moon-Sun-month].

- **Response:** Yes, these have both been fixed throughout.
- **For example, the Sect. 5.1 text now reads:** "Table 2 summarises the characteristics of 6 long-period tides (S_a, S_{sa}, MS_m, M_m, M_f, MS_f) at the ROBT station, derived from tidal harmonic analysis of year-long (2013) in situ observation records".

p7, line 270: Given MSf is important, I wonder if it might be worth including MS4? It might mop up the high frequency residual in figure 8. Worth checking the amplitude in the long record.

- **Response:** Thank you for this suggestion - we checked the MS_4 amplitude from the one year (2013) harmonic analysis results of ROBT. The amplitude was 0.69 cm, indicating that the MS4 tide is not a major constituent here.

p8, line 302: So the tides in the Ross Sea will be almost 1.5 times larger in 2025 than in 2016? I wonder how aware the ice modelling community are of this?

- **Response:** Yes, it is interesting to consider. However, due to comments from the second reviewer and Editor, who pointed out that Sect. 5.2 contained a bit of a digression from the aim and topic focus of this paper, we have cut a lot of this detail from Sect. 5.2 including this the nodal factor discussion. But we have started drafting a new paper focused on exploring such features in the tides of the Ross and Weddell Seas, so the point is not lost but deferred to another piece of work.
- **The shortened Section 5.2 text relating to this point now reads:** "Since diurnal tides have larger nodal amplitude 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 year lunar nodal cycle compared to areas like the Weddell Sea".

fig 6: Is the split y axis really necessary here?

- **Response:** We originally thought to employ a split y-axis scale in order to show as clearly as possible (magnify) the difference in RMSE results between Fig. 6(a) and Fig. 7. However, the effect of the split was a minor one, so we have changed these axes in line with your comment as you are right that it was not fully necessary. Please see above for the new Fig. 5 (formerly Fig.6), and below for the new Fig. 6 (formerly 7).

- **The new Fig. 6 (formerly 7) now looks like:**

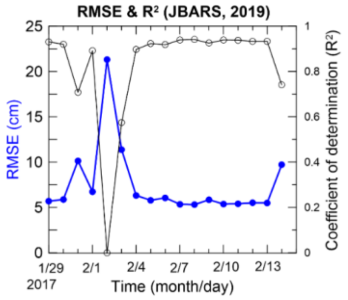


Figure 6. Time series of Root Mean Square Errors (RMSE, thick blue line with ●) and coefficients of determination (R^2, thin black line with ○) between JBARS 10 min interval sea level observations (29 Dec. 2018 to 18 Jan. 2019) and the CTSM+TCC prediction data sets generated for this site (using harmonic 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).

Language:
I am particularly impressed by how clearly written this paper is - I thank the authors for making the reviewing task easy. I wish I wrote as well!

- **Response:** Thank you – we really appreciated this comment and hope that you find the revised paper clear to read.

p1,line9: "Though" should be "However"

- **Response:** This has been changed as suggested.
- **The revised text now reads:** "However obtaining long term sea level records for traditional tidal predictions is extremely difficult around ice affected coasts".

p7 line 246: -tropic ?

- **Response:** Thank you for spotting this -the hyphen had been misplaced. However, in response to comments from the Editor, we have removed this mention of tropic tides (including the hyphen) and replaced it with discussions of lunar declination.
- **The relevant replacement text reads:** However, as shown in Fig. 7, our results contain a changing fortnightly timescale bias in estimates... Comparisons between *Run1 and Srun* predictions show that exclusion of the M_f 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 MS_f tide (1.2 cm amplitude) intensifies the biases (Fig. 9b).

p8 line 275: The abreviations DD etc aren't used again, delete.

- **Response:** Yes, these have been deleted.

References:
P&W 2014: Pugh, D.T. and Woodworth, P.L. 2014. Sea-level science : understanding tides, surges tsunamis and mean sea-level changes. Cambridge University Press https://doi.org/10.1080/00107514.2015.1005682 M&C 1966: Tidal spectroscopy and prediction, Walter Heinrich Munk and David Edgar Cartwright
https://doi.org/10.1098/rsta.1966.0024
Oh, and you need to add doi to some of your other references!

- **Response:** We have added these 2 references, and added reference doi numbers where missing elsewhere.
- **The reference list now contains:**
  Munk, W. H. and Cartwright, D. E.: Tidal spectroscopy and prediction, Math. Phys. Sci., 259, 533-581, doi.org/10.1098/rsta.1966.0024, 1966.
  Pugh, D. T. and Woodworth, P. L.: Sea-level science: Understanding tides, surges, tsunamis and mean sea-level changes, Cambridge University Press, United Kingdom, doi.org/10.1080/00107514.2015.1005682, 2014.

2. Reply to Glen Rowe Review 2 interactive comments of 14 Feb. 2020

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 these tides in regional and global ocean, marine cryosphere, and climate processes. 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 ~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 declination)".

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 data in Padman et al., 2003); and by Italy at Mario Zucchelli Station (Gandolfi, 1996), all in the eastern Ross Sea".

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– in order to better separate out these two pieces of information we have split the 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 Dec. 2018 and 18 Jan. 2019 comprised relatively high quality data with small residuals (i.e. observations minus predictions)".

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 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 harmonic constants for tidal prediction".

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 and only once stating the pairs in brackets.
- **The text now reads:** "Also the inference method was used to separate out neighbouring diurnal (K_1 and P_1) and semidiurnal (S_2 and K_2) 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 entire paper – the below sentence provides an example.
- **The text now reads:** "Analyses revealed that the two main diurnal (O_1 and K_1) and semidiurnal (M_2 and S_2) tides had similar amplitudes at the two stations, with the diurnal (semidiurnal) amplitudes being slightly larger (smaller) at ROBT than at JBARS, and the phase lags of all four tides having only slightly different values. The amplitude differences result in slightly different tidal form factors at the two sites (e.g., F in Table 1)".

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 note now includes:** "F is the amplitude ratio of the $(K_1 + O_1)/(M_2 + S_2)$ tides".

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, 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 also 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:

(i) using long-term (1 year, in our case) reference station records (LH_r) and CTSM calculations to make an initial anytime (τ) tidal prediction ($\eta_r(\tau)$), which involves summing tidal species' heights for the reference station (Fig.3);
(ii) comparing the tidal harmonic constants (amplitude ratios and phase lag differences) of representative tidal constituents (e.g., M_2 and K_1) for each tidal species between the temporary and reference stations, calculated using T_TIDE and concurrent short-term records (≥25 hr duration, starting at midnight) from the temporary (SH_o) and reference (SH_r) stations; and
(iii) using the step (ii) comparative data and the TCC calculations for each tidal species to adjust the $\eta_r(\tau)$ tidal species' heights in order to generate accurate, anytime tidal height predictions for the temporary tidal station ($\eta_o(\tau)$)".

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. LH_r 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 Sect. 3 rewrite, 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 discovering 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 update 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 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. LH_r) 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 maths 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, 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 the overlap that you drew our attention to with this comment.
- **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 observation and reference tidal stations (i.e. from SH_o and SH_r). The process of selecting the optimal 25 hr window for the concurrent data slices from amongst the 17.04 days of available records is explained in Sect. 3".

Line 154: Which are the 'initial tidal predictions'? It is not clear to me.

- **Response:** Yes, this was not as clear as it could've been - 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 this 2017 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 ($\eta_o(\tau)$), by substituting the daily (i.e. SH_o and SH_r) amplitude ratios $\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)$ and phase lag differences $\left(G_o^{(s)} - G_r^{(s)}\right)$ for the tidal constituents (K_1 and M_2) 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 of these suggestions – '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 Sect. 3. We also removed the 'in shorthand' text.
- **The text now reads:** "Each paired data set was then used with LH_r to generate tidal height predictions for JBARS covering both the 2017 and 2019 KHOA observation campaign time periods. Comparisons were made between the JBARS observations and the 17 prediction data sets generated for each campaign to identify which 25 hr short-term data window produced optimal $\eta_o(\tau)$ 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 Sect. 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 Jan. to 14 Feb. 2017, based on harmonic analysis results of the 'daily' (25 hr) K_1 and M_2 amplitudes and phase lags at our two tidal observation stations (Fig. 4)".

Lines 177 – 187: This discussion about the correlation of tidal range and RMSEs and R^2 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 R^2 varied from 0 to 0.94, across the 17 'daily' experiments. Eleven of the experiments produced accurate results (i.e. excluding those derived from 31 Jan.; and 1 to 4 and 14 Feb. data slices). Daily datasets from periods with relatively high tidal ranges (>83.5 cm) produced predictions with RMSEs <5 cm and R^2 values >0.92. The maximum spring tidal range occurred on 9 Feb.: the data slices 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 R^2 value (0.941) were produced using data slices from one day earlier, 8 Feb. 2017. In contrast to the majority of successful experiments, the experiment based on data derived from the 2 Feb. 2017 data slices produced predictions with very high RMSE (20.56 cm) and very low R^2 (0.00) values. The 2 Feb. 2017 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 concern the same idea, but the second sentence details the idea for a specific example (Fig. 7) amongst the total 17 cases (Fig. 6). We have adjusted the text and added "For example" to distinguish these sentences.
- **The text now reads:** "As with the 2017 predictions, RMSEs between the 2019 predictions and observations were lower when generated using data slices from 2017 periods at high lunar declination (Fig.6). For example, 2019 predictions made using input data derived from the 8 Feb. 2017 data slices produced the lowest RMSE (5.3 cm) and highest R^2 (0.913) values of the 2019 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 ($\delta = 0°$) 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 tidal range days can be estimated for JBARS based on the day of the Moon's greatest northern (GN) and southern (GS) 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 Feb. 2017 (GN) and on 6 Jan. 2019 (GS) respectively, with the maximum diurnal tides at JBARS expected around 1 day after each lunar declination peak".

Line 227: Delete 'and'.

- **Response:** Yes, this typo has been removed. We also removed the numbers from this sentence and left only their interpretation, since the numbers will appear in Table 1, which is cited here. This latter adjustment we thought to do based on a your 'redundancy' point in the comment on lines 96-98 above.
- **The text now reads:** "Results revealed that the *ADI* are very similar, and there is <1 day *AT* difference, between ROBT and JBARS (Table 1), indicating that the tidal characteristics of the representative tidal constituents for each species between the two stations are very similar, in particular the dominant diurnal species".

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 '2 tidal major 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 and small amplitude short 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:** 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:** "Rosier and Gudmundsson (2018) found that ice flows are modulated at various tidal frequencies, including that of the MS_f tide. However, because these tides' amplitudes have small signal-to-noise ratios (<1) with large standard errors (Table 2), caution should be exercised when elucidating fortnightly tide effects using these constituents. 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 specifically (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 also incorporated the M_f; and
  - *Run2* was based on *Srun* but also incorporated the M_f and MS_f".

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 reads:** "Comparisons between *Run1 and Srun* predictions show that exclusion of the M_f 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 MS_f 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 detailed ice flow modelling. Generating data for ice flow modelling was not the primary focus of our paper, 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 had more complete data conditions, and semidiurnal tide dominated 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 deleting 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 shorter Sect. 5.2 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 amplitude 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 year lunar nodal cycle compared to areas like the Weddell Sea. 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 (see details for ROBT in Byun and Hart, 2019). Given that CTSM+TCC is based on modulated tidal amplitude and phase lag 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 now looks like:**

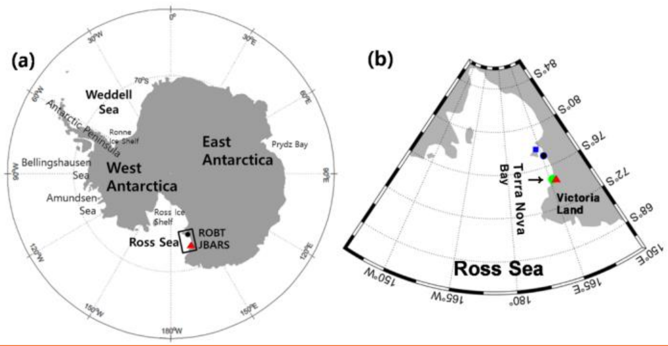


Figure 2. Maps showing (a) the locations of the two tidal observation stations employed in this study within a wider Antarctic context: Jang Bogo Antarctic Research Station (JBARS, ▲) and Cape Roberts (ROBT, ●); and (b) the case study station locations relative to two other (previous) temporary tidal observations stations, McMurdo Station (■), and Mario Zucchelli Station (●), 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 now looks like:**

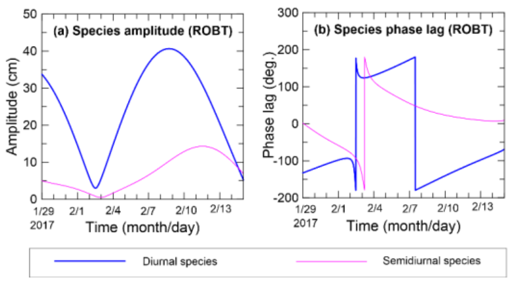


Figure 3. Modulated tidal (a) species amplitudes and (b) phase lags for the diurnal and semidiurnal tidal species, calculated from Cape Roberts (ROBT) tidal prediction data (29 Jan. to 14 Feb. 2017), using Appendix 1 Eqs. (A1) and (A3).

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 (e 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 original Fig. 4 and 5 together) now looks like:**

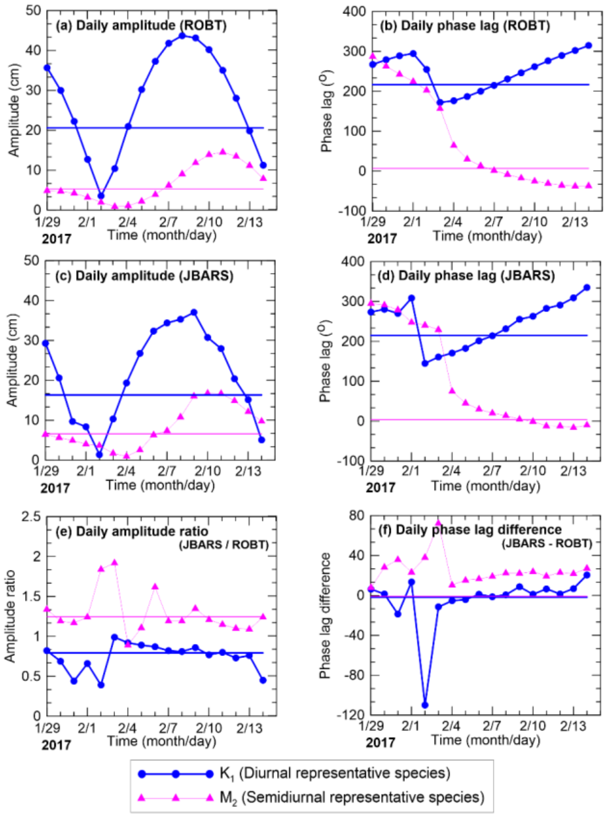


Figure 4. Daily amplitudes (a, c); phase lags (b, d); amplitude ratios (e); and phase lag differences (f) of the K_1 and M_2 tides (representative diurnal and semidiurnal tide species) at ROBT (a, b) and JBARS (c, d), and between JBARS and ROBT (e, f), calculated from 'daily' slices of the 29 Jan. to 14 Feb. 2017 ROBT tidal predictions and JBARS sea level observations. In addition, thick blue (K_1) and thin pink (M_2) 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 ○ has been swapped to ♦. Please see response to review 1 for the new version of Fig. 5 (formerly Fig. 6) and caption.

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. Please see response to review 1 for the new version of Fig. 6 (formerly Fig. 7) and caption.

Figure 8: X-axis labels again.
As with Figure 7, I am confused by the statement that follows '(dashed box in (a)),'.

- **Response:** 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.
- **Figure 7 (formerly 8) now looks like:**

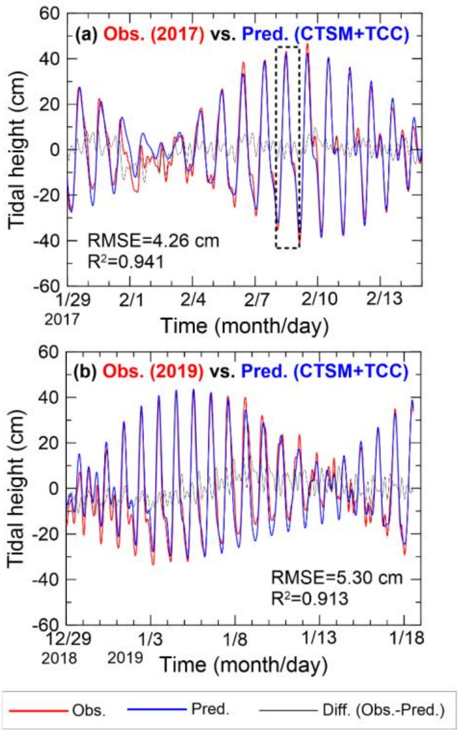


Figure 7. Time series of JBARS sea level observations (Obs.), predicted tidal heights (Pred.), and sea level residuals (Diff.) from (a) 29 Jan. to 14 Feb. 2017; and (b) 29 Dec. 2018 to 18 Jan. 2019. The JBARS predictions were generated via the CSTM+TCC method (using a daily (25 hr) slice of local sea level observations from 8 Feb. 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 R^2 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) now looks like:**

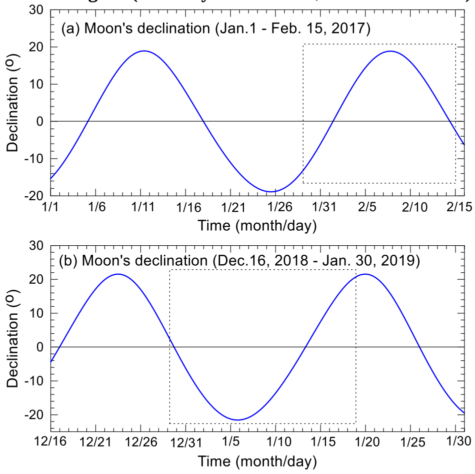


Figure 8. Time series of the Moon's declination, calculated at daily intervals for two observation periods: (a) 1 Jan. to 15 Feb. 2017; and (b) 16 Dec. 2018 to 30 Jan. 2019. Dashed boxes indicate the sea level observation windows examined in this study.

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) looks like:**

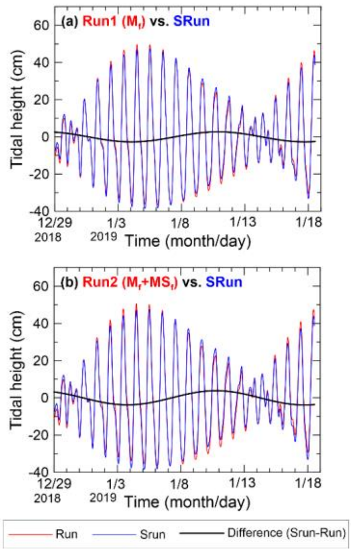


Figure 9. Time series of ROBT tidal predictions (a) made without long-period constituents (SRun, i.e. excluding the constituents listed in Table 2) versus with the M_f tide (Exp1); and (b) time series of ROBT tidal predictions made (SRun) without the long-period constituents versus (Exp2) with the MS_f and M_f 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 <u>*these figures*</u> *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 Sect. 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 now looks like:**

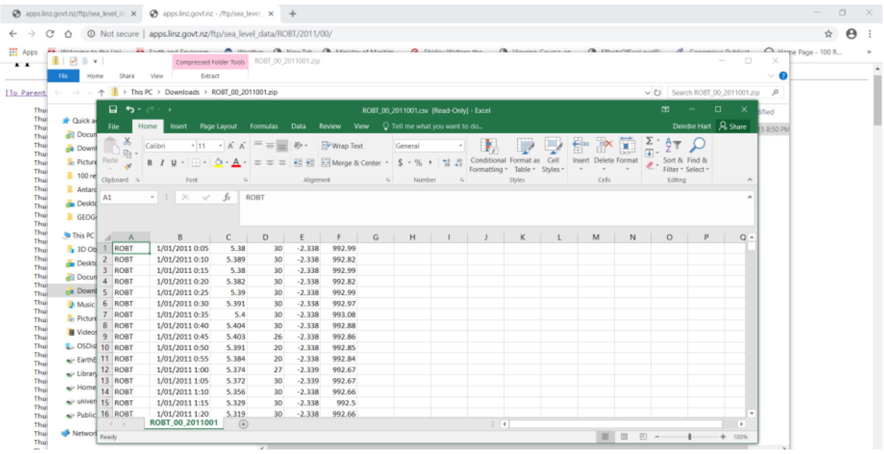
Table 2. Harmonic constants for 6 long-period tidal constituents, derived from harmonic analyses of year-long observations (2013) measured at the Cape Roberts sea level gauge (ROBT), using T_Tide (Pawlowicz et al., 2002)

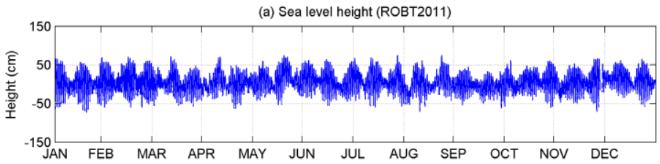
Constituent		Amplitude (cm)	Amplitude standard error (cm)	Phase lag (°)	Phase lag standard error (°)	SNR
Solar annual	S_a	5.8	4.8	75	50	1.5
Solar semi-annual	S_{sa}	0.1	3.3	352	194	0.06
Lunar monthly	MS_m	0.4	3.5	57	254	0.02
	M_m	2.9	3.8	139	102	0.59
Lunar fortnightly	MS_f	1.2	3.0	281	189	0.14
	M_f	2.7	3.9	153	101	0.47

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




(a) Sea level height (ROBT2011)
Height (cm)
150
50
-50
-150
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

1. Reply to Philip Woodworth (Editor) Review 3 interactive comments of 14 Feb. 2020

My comments seem to be closer to those of Reviewer 2 than Reviewer 1. It will be best if all three sets of comments are taken together for any new version (see below). In the following I give a list of comments on the writing (there are several sentences without verbs, for example). But the main thing is that I thought there were 3 sections that either need considerable improvement or should be dropped.

- **Response:** According to this useful suggestion, we have completed replies and paper adjustments in response to Review 2 (by Rowe) and Review 3 (the present review) together, occasionally cross-referencing the two replies.

(1) Section 3. I understand that the method is some kind of response method, and I have read the authors' 2015 paper. However, I defy anyone to understand this section as it stands. It is made worse by not defining many variables (e.g. line 128, what are r, eta and tau. I believe s is species; line 136, what are k,m etc.). And I am sure there must be errors in equation 2 although I am not sure what e.g. it has a parameter j which is a subscript of a constituent like 'i', but which is not summed over but used only as a lower limit i=(j,m), but the left side of the equation is not a function of j. That cannot be right. Then also, what is a 'representative harmonic constituent'? I think a simpler thing to have done would have not included the little bits of maths here which just confuse everyone but just referred the reader to the 2015 paper for the method. I have many detailed comments on this section also which I list below.

- **Response:** From this comment we appreciated the need to improve our method communication. As a result we redrafted a simpler Sect. 3, and cut and pasted the maths parts from the original Sect. 3 into the new Appendix 1. In this new appendix we defined all undefined terms and fixed the issues you identified. The newly focused Sect. 3 does a better job of highlighting differences in application of the Byun and Hart (2015) approach applied in this paper (i.e. the use of prediction data for SH_r; and the procedure to select an optimal 25 hr data window in a diurnal tide dominated setting), differences that arose due to the extreme and particular diurnal dominated environment of the Ross Sea.
- **The text of section 3 now reads:**

"3 Using the CTSM+TCC tidal prediction methodology in the Ross Sea

Having analysed the tidal harmonic constants at the two stations, 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*). 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 (1 year, in our case) reference station records (LH_r) and CTSM calculations to make an initial anytime (τ) tidal prediction ($\eta_r(\tau)$), which involves summing tidal species' heights for the reference station (Fig.3);
comparing the tidal harmonic constants (amplitude ratios and phase lag differences) of representative tidal constituents (e.g., M_2 and K_1) for each tidal species between the temporary and reference stations, calculated using T_TIDE and concurrent short-term records (≥25 hr duration, starting at midnight) from the temporary (SH_o) and reference (SH_r) stations; and
using the step (ii) comparative data and the TCC calculations for each tidal species to adjust the $\eta_r(\tau)$ tidal species' heights in order to generate accurate, anytime tidal height predictions for the temporary tidal station ($\eta_o(\tau)$).
In this Ross Sea case study we used the 2017 JBARS tidal observation records (i.e. 17.04 days from 00:00 29 Jan. to 01:00 15 Feb.) as a source of SH_o, keeping the second JBARS 2019 observation record for evaluation purposes.
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. LH_r must comprise high quality (e.g. few missing data) tidal height observations from anytime.
Byun and Hart (2015) recommended the use of short-term records gathered during periods of calm weather, to minimise errors due to atmospheric influences. They employed observational data for both SH_o and SH_r but as demonstrated in this paper the method can also be applied using tidal predictions as a source of SH_r. This 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. 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. LH_r) observational record as input data. The 17.04 days of predicted tides that were concurrent with the 2017 JBARS observation record were then used as our SH_r source. While this CTSM+TCC method adjustment was procedurally small, it represents an important adaptation in the context of generating tidal predictions for stations situated in extreme environments, since concurrent temporary and reference station observations might be rare in such contexts.
When using CTSM+TCC, if the available temporary tidal station observation record covers multiple days, it is best practice to experiment by generating multiple $\eta_o(\tau)$, each using different concurrent pairs of SH_o and SH_r daily data slices in step (ii) above, to produce daily amplitude ratios and phase lag differences between the two stations for the diurnal K_1 and semidiurnal M_2 tidal constituents. Comparisons are then made between the different $\eta_o(\tau)$ data sets produced and the original temporary station observations, to determine the optimal 25 hr window to use: once selected, tidal height predictions can be generated for the temporary observation station for any time period. Thus, 17 individual 25 hr duration data slices were clipped from the 2017 JBARS observation records and from the concurrent ROBT predictions, forming 17 pairs of SH_o and SH_r 'daily' slices. Each paired data set was then used with LH_r to generate tidal height predictions for JBARS covering both the 2017 and 2019 KHOA observation campaign time periods. Comparisons were made between the JBARS observations and the 17 prediction data sets generated for each campaign to identify which 25 hr short-term data window produced optimal $\eta_o(\tau)$ results".

- **And the new Appendix 1 (complimenting the new Sect. 3) now reads:**

Appendix 1

This appendix describes the calculations involved in using the CTSM+TCC approach as employed in this Ross Sea, Antarctica, case study. For a fuller description of the development of this approach and its application in semidiurnal and mixed, mainly semidiurnal tidal regime settings, see Byun and Hart (2015).

As explained in the main body of this paper, we used 25 hr slices of the 2017 short-term observations from JBARS (SH_o), our temporary tidal observation station (subscript *o*), and 2013 year-long observations (LH_r) and 2017 short-term tidal predictions (SH_r, concurrent with SH_o) from ROBT, our reference tidal station (subscript *r*), as the basis of JBARS tidal prediction calculations. We then employed the full 17.04 day 2017 JBARS tidal observation data set, and an additional 21.54 day 2019 JBARS tidal observation dataset, to evaluate the success of the CTSM+TCC tidal prediction calculations for this site.

The CTSM+TCC, expressed as the summation of each tidal species cosine function, includes three key steps:

(i) calculating each tidal species' modulation at the reference tidal station;

(ii) comparing the tidal harmonic constants between the temporary observation and reference stations (e.g., the tidal amplitude ratios and phase lag differences of each representative tidal constituent for each tidal species calculated from concurrent observation records between two stations); and

(iii) adjusting the tidal species modulations calculated in the first step using the correction factors calculated in the second step to produce predictions for the temporary tidal station.

As a first step, tidal height predictions for the temporary station ($\eta_o(\tau)$) were initially derived from reference station predictions ($\eta_r(\tau)$) on the assumption that the tidal properties between the two stations remain similar through time. Using the modulated amplitude ($A_r^{(s)}$) and the modulated phase lag ($\varphi_r^{(s)}$) for each tidal species, this step is expressed as:

$$\eta_r(\tau) = \sum_{s=1}^{k} A_r^{(s)}(\tau) \cos\left(\omega_R^{(s)} t - \varphi_r^{(s)}(\tau)\right) \qquad \text{(A1)}$$

with

$$A_r^{(s)}(\tau) = \sqrt{\sum_{i=1}^{m}\left[f(\tau)_i^{(s)} a_i^{(s)}\right]^2 + 2\sum_{i=1}^{m-2}\sum_{j=i+1}^{m}\left[f(\tau)_i^{(s)} a_i^{(s)}\right]\left[f(\tau)_j^{(s)} a_j^{(s)}\right] \cos\left\{\left(\omega_i^{(s)} - \omega_j^{(s)}\right)t + \left[V(t_0)_i^{(s)} + u(\tau)_i^{(s)} - G_i^{(s)}\right] - \left[V(t_0)_j^{(s)} + u(\tau)_j^{(s)} - G_j^{(s)}\right]\right\}}$$

(A2)

and

$$\varphi_r^{(s)}(\tau) = tan^{-1}\left(\frac{\sum_{i=1}^{m} a_i^{(s)} \sin[(\omega_i^{(s)} - \omega_R^{(s)})t + V(t_0)_i^{(s)} + u(\tau)_i^{(s)} - G_i^{(s)}]}{\sum_{i=1}^{m} a_i^{(s)} \cos[(\omega_i^{(s)} - \omega_R^{(s)})t + V(t_0)_i^{(s)} + u(\tau)_i^{(s)} - G_i^{(s)}]}\right) \qquad \text{(A3)}$$

where superscript *s* denotes the type of tidal species (e.g., 1 for diurnal species and 2 for semidiurnal species); *m* is the number of tidal constituents; t_0 is the reference time; *t* is the time elapsed since t_0; and $\tau = t_0 + t$; $\omega_i^{(s)}$ are the angular frequencies of each tidal constituent (subscripts *i* and *j*); $\omega_R^{(s)}$ are the angular frequencies of each tidal constituent representing a tidal species (subscript *R*); with the dominant tidal constituent of each tidal species used as the representative for that species (e.g., K_1 and M_2 are used as representative of the diurnal and semidiurnal species, respectively). For each tidal constituent, $a_i^{(s)}$ and $G_i^{(s)}$ are the tidal harmonic amplitudes and phase lags (referenced to Greenwich); $f(\tau)_i^{(s)}$ is the nodal amplitude factor of each tidal constituent; $u(\tau)_i^{(s)}$ is the nodal angle; and $V(t_0)_i^{(s)}$ is the astronomical argument. T_TIDE was used for tidal harmonic analysis as well as for calculation of the nodal amplitude factors; nodal angles; and astronomical arguments; for the representative tidal constituents.

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 observation and reference tidal stations (i.e. from SH_o and SH_r). The process of selecting the optimal 25 hr window for the concurrent data slices from amongst the 17.04 days of available records is explained in Sect. 3.

Once this 2017 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 ($\eta_o(\tau)$), by substituting the daily (i.e. SH_o and SH_r) amplitude ratios $\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)$ and phase lag differences $\left(G_o^{(s)} - G_r^{(s)}\right)$ for the tidal constituents (K_1 and M_2) representing the diurnal and semidiurnal tidal species between the temporary and reference stations into Eq. (A1) as follows (Byun and Hart, 2015):

$$\eta_o(\tau) = \sum_{s=1}^{k} A_o^{(s)}(\tau) \cos\left(\omega_R^{(s)} t - \varphi_o^{(s)}(\tau)\right) \qquad \text{(A4)}$$

with $A_o^{(s)}(\tau) = A_r^{(s)}(\tau)\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)$, and (A5)

$$\varphi_o^{(s)}(\tau) = \varphi_r^{(s)}(\tau) + G_o^{(s)} - G_r^{(s)} \qquad \text{(A6)}$$

Substituting Eqs. (A5) and (A6) into Eq. (A4), $\eta_o(\tau)$ can be expressed as:

$$\eta_o(\tau) = \sum_{s=1}^{k} A_r^{(s)}(\tau)\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right) \cos\left[\omega_R^{(s)} t - \left(\varphi_r^{(s)}(\tau) + G_o^{(s)} - G_r^{(s)}\right)\right] \qquad \text{(A7)}$$

The T_TIDE based CTSM code is available from https://au.mathworks.com/matlabcentral/fileexchange/73764-ctsm_t_tide.

(2) Section 5.1. You have records of the order of a fortnight so I dare say it is inevitable that there will be mismatches on that timescale between your method and the data. However, do you need a page to say that? I suggest that this aspect should be summarised in 5-6 lines in the Discussion section where it can be a pointer to improvements in the method. Also I wondered if you considered the missing fortnightly tide was consistent with that in FES2014.

- **Response:** Yes, we have reduced Sect. 5.1 significantly, deleted Table 3 altogether, and re-ordered some sentences, so that this section makes a clear point for future research improving the prediction work specifically to make it useful for ice flow studies. Interannual harmonic analysis results at ROBT show that the fortnightly tide has large variations with large standard errors and small signal to noise ratios. We do not think that they are easily comparable with those in FES2014.
- **The first 2/3 of section 5.1 (excluding the double tide peaks explanation – see further below) text now reads:**

"**5.1 Explaining fortnightly tide effects and double tide peaks in the Ross Sea tidal predictions**

We have demonstrated that the CTSM+TCC approach can produce reasonably accurate tidal predictions (RMSE <5 cm, R^2 >0.92) for a new site in the Ross Sea, Antarctica, based on 25 hr temporary station observation records from periods with above average tidal ranges, plus neighbouring reference station records. Our results compare favourably with those of Han et al. (2013), who reviewed the tidal height prediction accuracy of 4 models for Terra Nova Bay, Ross Sea: these models generated similar quality results to our CTSM+TCC results, with R^2 values between 0.876 and 0.907, and RMSEs ranging from 3.6 to 4.1 cm. 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 and small amplitude short period tides.
Table 2 summarises the characteristics of 6 long-period tides (S_a, S_{sa}, MS_m, M_m, M_f, MS_f) at the ROBT station, derived from tidal harmonic analysis of year-long (2013) in situ observation records. To investigate the main cause of the apparent fortnightly prediction biases in our JBARS results, in particular that in the 2019 predictions (Fig. 7b), we examined the effects of two fortnightly tidal constituents (M_f, and MS_f) at ROBT. 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 also incorporated the M_f; and
- *Run2* was based on *Srun* but also incorporated the M_f and MS_f.

Comparisons between *Run1 and Srun* predictions show that exclusion of the M_f 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 MS_f tide (1.2 cm amplitude) intensifies the biases (Fig. 9b).
Rosier and Gudmundsson (2018) found that ice flows are modulated at various tidal frequencies, including that of the MS_f tide. However, because these tides' amplitudes have small signal-to-noise ratios (<1) with large standard errors (Table 2), caution should be exercised when elucidating fortnightly tide effects using these constituents. 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 specifically (e.g. Rignot et al., 2000; Rosier and Gudmundsson, 2018). Consideration of additional, long period tides in predictions is one recommendation we have for future work on improving tidal predictions for Ross Sea coasts".

*(3) Section 5.2. Having shown that the Ross and Weddell Seas have different dominant tides (and form factors), end of story to me, you embark on generating predictions over 18.6 years which lo and behold have the ranges (you don't explain range = 2*amplitude) which have exactly the equilibrium amounts that T-Tide must be coded with. So what have you learned? Nothing. The finding is presented as some kind of new result. I suggest, having indicated the map of form factors, you just say that because diurnal tides have larger 'f' and 'u' variations than semidiurnal tides (reference a text book) then they will have larger ranges of tide over 18.6 years.*

- **Response:** Yes, agreed. We have significantly shorted this section to better situate the task of understanding Ross Sea tides within the different regimes that occur around Antarctica. Also, we added explanation of the term 'tidal range' near its first use, after the abstract, in Sect. 4.1. Please see the new Sect. 5.2 text in the earlier response to Review 2 by Rowe.
- **The section 4.1 text now includes:** "As illustrated in Fig. 5, the RMSE and R^2 results varied in relation to the JBARS tidal range (range being twice amplitude), with greater accuracy evident in predictions made using data derived from periods with above average tidal ranges".

In 5-6 lines again. Also, on line 67, you say that section 5 will discuss double tidal peaks. I can't see anything about that in the section or the paper. Because of the problems with these 3 sections, which make up most of the paper, I expect that it will not be acceptable for OS without considerable improvements. Anyway, I am unclear what has been learned new here which you didn't learn from NZ and Korea data in the 2015 paper - I realise this is a different tidal regime but a step change might have been to write a larger paper with as many regimes as possible if you wanted to demonstrate that your method works well.

- **Response:** We have added explanation of the occurrence of double tidal peaks at the end of Sect. 5.1, and also included the new Fig. 10 to explain their occurrence.
  Thank you for the suggestions regards a step change paper – we agree that this is a very good idea for showing the method works well in a range of different tidal environments. We still feel that this, now shorter and significantly

improved, paper is of use for showing the method can fulfil a need specifically for tidal predictions in extreme environments where data may be scarce, with the added bonus that this case study is of diurnal dominated tides, contrasting the Byun and Hart (2015) paper, which focused on semidiurnal dominated environments. We hope that you feel we have given proper consideration and response to your comments throughout.

- **The last part of section 5.1 now reads:** "Another characteristic of our results needing explanation is the double tidal peaks evident in both the tidal observations and predictions at JBARS. These peaks occur, for example, in Fig. 7b between Jan. 11th and 17th, 2019. To explore why these double peaks occur, we generated JBARS tidal height predictions using Eq. (A1) and the 2019 tidal constants listed in Table 1 for the two major diurnal and semidiurnal tides. Fig. 10a shows separately the resulting diurnal (with their period of 13.66 days) and semidiurnal (with their period of 14.77 days) species' tide predictions. The combination of these out-of-phase tidal species generates double peaks (or double troughs) around low tide (Fig. 10b) for periods when the diurnal tide amplitudes are low, and the amplitude ratio of the semidiurnal to diurnal tide species is >0.5 (Fig. 10c). Double peaks also occur around high tide during periods of low lunar declination (Fig. 8b), when the semidiurnal to diurnal species amplitude ratio is >1, and the phase lag difference between the diurnal and semidiurnal species is between -78° and 46° (Fig. 10). Since the semidiurnal tides are slightly stronger, and the diurnal tides are slightly weaker, at JBARS compared to at ROBT (Table 1), these double tide peaks occur more commonly at JBARS (e.g., compare Fig. 5b and Fig. 7)".
- **The new Fig. 10 looks like:**

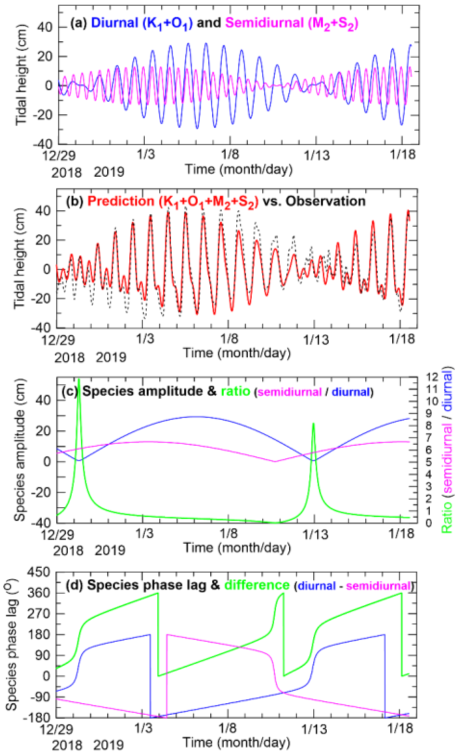


Figure 10. Time series (29 Dec. 2018 to 18 Jan. 2019) of (a) predictions of the diurnal (K_1+O_1) tides (blue line) and the semidiurnal (M_2+S_2) tides (magenta line) for JBARS; (b) their combined JBARS predictions (red line) and observations (black dashed line); (c) the ROBT diurnal (blue line) and semidiurnal (magenta line) species amplitudes and their ratio (green line); and (d) the ROBT diurnal (blue line) and semidiurnal (magenta line) species phase lags and their difference (diurnal – semidiurnal) (green line).

Detailed comments:

9-10 - sentence 'Though obtaining'. This sentence has no verb.

- **Response:** The verb in this sentence is "is" (line 10 of submitted PDF abstract). In response to Review 2, we have altered the qualifier at the beginning by swapping "Though" for "However".
- **The text now reads: "**However obtaining long term sea level records for traditional tidal predictions is extremely difficult around ice affected coasts".

13 - by a different tidal regime

- **Response:** We have added the word “tidal”.
- **The text now reads:** “… to accurately predict tides for a temporary tidal station in the Ross Sea, Antarctica, using records from a neighbouring reference station characterised by a similar tidal regime”.

18 - I have never seen this ’tropic-spring’ description before (there are other examples below). Could you not just replace this simply with ’at high lunar declination’, or whatever, which means something physical rather than poetic.

- **Response:** Yes, “tropic” has been removed from all but one place in the paper and replaced with “at high lunar declination”.
- **The text now reads:** “Results reveal the CTSM+TCC method can produce accurate (to within ~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 declination)”.

28 - the Rignot reference is rather old. There has been a lot of work using GPS for tides under ice sheets, and there new data sets (IceSAT etc.). I am sure you can find a couple of better references.

- **Response:** We have removed the Rignot et al. (2000) reference from this first Introduction paragraph and instead inserted some text referring to more recent work improving tide models for shallow, ice affected seas including that using IceSAT data.
- **The text now reads:** “Obtaining long term records for such tidal analyses is extremely difficult for sea ice affected coasts like that surrounding Antarctica. As a compliment to in situ tidal records, recent work has significantly advanced our understanding of tide models for the shallow seas around Antarctica and Greenland via the assimilation of laser altimeter data and use of Differential Interferometric Synthetic Aperture Radar (DInSAR) imagery, amongst other methods (Padman et al., 2008; 2018; King et al., 2011; Wild et al., 2019)”.

46 - though –> although

- **Response:** This change has been made as suggested.
- **The text now reads:** “Accurate tidal records from the Ross Sea and other areas around Antarctica are thus scarce compared to those available from other regions, although these data are much needed given the crucial role of tidal processes around this continent (Han et al., 2005; Jourdain et al., 2018; Padman et al., 2003; 2018).

50 - transfers –> transfer

- **Response:** This has been changed as suggested.
- **The text now reads:** “…and control heat transfer and ocean mixing in cavities beneath the marine cryosphere…”.

59 - GPS is usually called GNSS these days

- **Response:** This has been changed as suggested.
- **The text now reads:** “Ice thickness is typically measured via the subtraction of tidal height oscillations from highly accurate, but relatively low frequency, satellite based observations of ice surface elevation and/or from in situ Global Navigation Satellite System (GNSS) instrument observations (Padman et al., 2008)”.

67 - see above

- **Response:** Yes, as indicated above we have now added an explanation of the double tidal peaks to Sect. 5.1.

75 - what does high-frequency mean?

- **Response:** This text has been improved to properly indicate the frequency, and of what.
- **The text now reads:** “High-frequency sea level oscillations (<3 hr) were removed from the observation record using a fifth-order low-pass Butterworth filter”.

89 - year-long

- **Response:** The term ‘yearlong’ has been replaced with ‘year-long’ throughout the paper.
- **For example, this line now reads:** “…it was not possible to collect the year-long sea level records that are commonly employed to obtain reliable tidal harmonic constants for tidal prediction”.

92 - this needs rewording. the 2 main diurnal and semidiurnal tides are K1 and O1 and M2 and S2 of course - what you mean here are the 2 main relationships taken from Cape Roberts
97 - they have similar amplitudes. not ’characterised by’
97 - between –> at
98 - for S2 respectively.
99 - close –> short
But I don’t consider 269 km a short distance. I am sure the tide around Korea or NZ, for example, changes enormously in that distance. And what does ’in tidal terms’ mean?

- **Response:** Thank you for each of these comments. We are replying to them together since we have re-worded several stanzas in this paragraph to make all of the suggested changes and modifications. Specifically, we modified the ‘line

92' sentence to correct it according to the issues you identified in our description of the inference method and with our previous adjective choices. The two 'line 97' changes have also been made as indicated, while the line 98 text was deleted in response to a comment in Review 2. Regards 'line 99', both 'close distance' and 'in tidal terms' have been deleted.

- **This paragraph now reads:** "Using the T_TIDE toolbox (Pawlowicz et al., 2002), we obtained the tidal harmonic constants of the 8 and 6 major tidal constituents for ROBT and JBARS, respectively (Table 1). Also the inference method was used to separate out neighbouring diurnal (K_1 and P_1) and semidiurnal (S_2 and K_2) tide constituents, with their amplitude ratios and phase lag differences obtained from harmonic analysis of the long-term ROBT reference station records. Analyses revealed that the two main diurnal (O_1 and K_1) and semidiurnal (M_2 and S_2) tides had similar amplitudes at the two stations, with the diurnal (semidiurnal) amplitudes being slightly larger (smaller) at ROBT than at JBARS, and the phase lags of all four tides having only slightly different values".

100 - phase lag usually has no hyphen

- **Response:** Phase-lag has been amended to phase lag throughout the text of the entire paper (deleting the hyphen).

101 - what does tidal patterns mean? You mean tidal characteristics?

- **Response:** Yes, agreed – this word has been changed (and *F* has also been explained in Table 1, due to a Review 2 comment).
- **The text now reads:** "The amplitude differences result in slightly different tidal characteristics as indicated by the two sites' tidal form factors (e.g., *F* in Table 1)".

104 - database –> model
105 - drop horizontal
105-111 - there are amplitudes and phase lags, and there are co-amplitude (or sometimes co-range) and co-phase charts, sometimes combined as co-tidal charts. But there is no such thing as an 'increasing co-amplitude'. Please rewrite this paragraph. See below for the figures also.

- **Response:** This entire paragraph has been deleted in response to a comment in Review 2.

113 - why a minus before CTSM?
114-115 - why the italics?

- **Response:** Thank you for picking up this minus sign typo: it was fixed, as indicated in the response to Review 2, before this section was rewritten, cutting and pasting the maths into a new Appendix 1. Regarding the italics, we intended to highlight these terms but removed them in response to a similar comment in Review 2 (see details of new text there).

125 - remove simply
126 - remove accurate. You have no way of showing how accurate they are.
127 - remove sentence 'In short'. This is obvious.
128 - see above. Also mention that phase lags are Greenwich lags.

- **Response:** All of these changes have been implemented in the rewritten Sect. 3 (see comment explaining this towards the beginning of this reply).
- **This particular part of the new Sect. 3 text now 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. LH_r) observational record as input data. The 17.04 days of predicted tides that were concurrent with the 2017 JBARS observation record were then used as our SH_r source. While this CTSM+TCC method adjustment was procedurally small, it represents an important adaptation in the context of generating tidal predictions for stations situated in extreme environments, since concurrent temporary and reference station observations might be rare in such contexts".

130 - sentence 'Note that'. Again I think that assumes you understand the method

- **Response:** We have explained this much more clearly in the new Appendix 1, which includes improved text from the old Sect. 3. Please see Appendix 1 towards the start of this reply.

134 - peculiarities –> properties?

- **Response:** This amendment has been made.
- **The text, now in Appendix 1, now reads:** "As a first step, tidal height predictions for the temporary station ($\eta_o(\tau)$) were initially derived from reference station predictions ($\eta_r(\tau)$) on the assumption that the tidal properties between the two stations remain similar through time".

169 - again, I guess the reader will have to read the 2015 paper to understand why you produce 17 data sets? This has to be clearer.

- **Response:** The 17 data sets were produced since we had 17.04 days of quality input data from the temporary tidal station observation records of 2017. In fact the 2017 JBARS record spanned 19 days, but the first and last days' data were incomplete, so not useful for creating daily (25 hr) datasets. We have now made the origin of the 17 data sets clearer in Sect. 2.1 of the paper, in response to this query. We also hope that our clearer Sect. 3 eliminates the confusion created here.

- **Sect. 2.1 text 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. This mission collected the first, 19 day sea level records for JBARS: 10 min interval observation data, recorded between 28 Jan. and 16 Feb. 2017 using a bottom-mounted pressure sensor (WTG-256S AAT, Korea). High-frequency sea level oscillations (<3 hr) were removed from the observation record using a fifth-order low-pass Butterworth filter. Note that the first and last days of this campaign comprised partial day records, so we excluded these end days from our tidal prediction experiments, since our method requires continuous 25 hr input data (for convenience, starting at midnight). That left 17 days and 1 hour of useable tidal observation data as the basis of the primary JBARS observation record".

175 - where –> when

- **Response:** This change has been made.
- **The text now reads:** "As illustrated in Fig. 5, the RMSE and R^2 results varied in relation to the JBARS tidal range (range being twice amplitude), with greater accuracy evident in predictions made using data derived from periods with above average tidal ranges".

227 - versus –> and day –> days add respectively at end of sentence

- **Response:** This sentence has been modified to delete the numbers, in response to comments by Review 2 regarding the redundancy of listing numbers when they are in the table. We have added respectively as suggested.
- **The text now reads:** "Results revealed that the *ADI* are very similar, and there is <1 day *AT* difference, between ROBT and JBARS respectively (Table 1), indicating that the tidal characteristics of the representative tidal constituents for each species between the two stations are very similar, in particular the dominant diurnal species".

229-230 - sentence 'Hence the' has no verb

- **Response:** This sentence has been amended.
- **The text now reads:** "This similarity explains why we found the CTSM+TCC method successful in generating our Ross Sea tidal predictions".

246 - remove the minus sign. Replace the tropic jargon business.

- **Response:** The minus sign typo, and all mention of *tropic to equatorial tides (TET)* and of *equatorial to tropic tides (ETT)* has been deleted in shortening Sect. 5.1, with brief mention made of "lunar declination" changes instead.
- **The text of this section, for example, now reads:** "However, as shown in Fig. 7, our results contain a changing fortnightly timescale bias in estimates… Comparisons between *Run1 and Srun* predictions show that exclusion of the M_f 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 MS_f tide (1.2 cm amplitude) intensifies the biases (Fig. 9b)".

249-256 - I think I would replace this woffle with simply saying that good knowledge of tides is important for understanding ice shelf dynamics and give one reference as an example.

- **Response:** We have deleted most of this text, including the details of the methods used by different authors, in response to this comment and one in Review 2, leaving points that are of use for discussion later in the paper.
- **The text now reads:** "Rosier and Gudmundsson (2018) found that ice flows are modulated at various tidal frequencies, including that of the MS_f tide… 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 specifically (e.g. Rignot et al., 2000; Rosier and Gudmundsson, 2018). Consideration of additional, long period tides in predictions is one recommendation we have for future work on improving tidal predictions for Ross Sea coasts".

265 - .. periods, rather than seasonal. (I think)

- **Response:** We were not referring to seasonal effects with our 'summertime' adjective but rather to the monitoring period. We have clarified the text by removing the adjective and, thus, any ambiguity created by its inclusion.
- **The text now reads:** "To investigate the main cause of the apparent fortnightly prediction biases in our JBARS results, in particular that in the 2019 predictions (Fig. 7b), we examined the effects of two fortnightly tidal constituents (M_f, and MS_f) at ROBT".

270 - with additional exclusion (I think)

- **Response:** Yes, this has been modified as suggested.
- **The text now reads:** "Comparisons between *Run1 and Srun* predictions show that exclusion of the M_f 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 MS_f tide (1.2 cm amplitude) intensifies the biases (Fig. 9b)".

272 - well, you don't do that do you?! You have spent a page showing that the method could be improved with a digression into the ice shelves. There is very little in this section (see above also).

- **Response:** This section has been significantly reduced in response to your comments and those in Review 2, including deletion of almost all the digression into ice shelves. Please see the new text early in this reply, and the response to Review 2 regarding section 5.1.

273 - Decadal timescale .

- **Response:** The section 5.2 title has been changed to reflect the significantly truncated text and more focussed purpose of this section.
- **The section title now reads:** "Understanding the contrasting tidal environments around Antarctica".

274 - drop daily

- **Response:** This modification has been made.
- **The text now reads:** "Figure 11 illustrates the form factors of tidal regimes in the seas surrounding Antarctica, according to FES2014 model data".

276 - I don't understand this. The small magenta blob on the west coast of the Weddell Sea indicates a large (diurnal) form factor, right? Not semidiurnal. (You might also mention its latitude rather than 'half-way'). Most of the Weddell Sea is blue (semidiurnal).

- **Response:** This magenta blob represents an area where tides are characterised by semidiurnal form factors (<0.25). The rest of the Weddell Sea is characterised by 'mixed, mainly semidiurnal' tides (F between 0.25 and 1.5). We have amended our key (colour bar) to end at 0.25 to remove confusion regards classification of the majority area of the Weddell Sea. We have also added the latitude note, as suggested. See further below for the new figure caption.
- **The paper text now reads:** "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)".

279 - drop 'the increase in'
286 - drop 'feature ..tidal' which is just repetition. influences –> influence
292- 298 - see above. This is just an inevitable consequence of the way T-Tide is coded with the equilibrium nodal dependencies.

- **Response:** These sentences have been deleted in the shortening of Sect. 5.2.

302 - Drop 'Of note', unless you want to refer to a tidal text book

- **Response:** These lines (formerly 292-304) have been deleted in response to your comments and to Review 2.

328 - drop database

- **Response:** This change has been made.
- **The text now reads:** "Details of the FES2014 tide model are found in Carrère et al. (2016) and via https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html".

Fig A1 caption - drop horizontal.
co-amplitudes –> amplitudes. co-tides –> phase lags (Greenwich)
In the caption of the 4 figures, remove the dot after deg as there is no dot after cm.
remove all the co- things. And co-tide should be Greenwich phase lag.
Figure A2 ditto the above. In (b) and (d) there is a mess of annotation of phase lags at a couple of amphidromic places. Please remove that mess.

- **Response:** Both figures (i.e. the entire original Appendix 1) have been deleted in response to Review 2 comments.

Table 1. Please move the information in the Note column to be extra lines under ROBT etc. You give only one set of ADI and AT for JBARS but there must be two different sets of values in 2017 and 2019.
day –> days. No hyphen in phase lag.

- **Response:** All of these changes have been made in Table 1.
- **Table 1 now looks like:**

Table 1. Major tidal harmonic results for diurnal and semidiurnal constituents from harmonic analyses of sea level observations: year-long (2013) records from Cape Roberts (ROBT), and 17.04 day records (29 Jan. to 15 Feb. 2017) and 20.54 day records (29 Dec. 2018 to 18 Jan. 2019) from Jang Bogo Antarctic Research Station (JBARS) in the Ross Sea (see source details in Sect. 2). For the JBARS tidal harmonic analyses, the inference method was applied to separate out the K_1 (S_2) and P_1 (K_2) tidal constituents, using inference parameters estimated from the ROBT 2013 harmonic analysis.

Tidal constituents & characteristics	ROBT (2013) 369 days		JBARS (2017) 17.04 days		JBARS (2019) 20.54 days	
	Amp. (cm)	Pha. (°)	Amp. (cm)	Pha. (°)	Amp. (cm)	Pha. (°)

Diurnal	O_1	21.1	202	19.6	208	16.0	208
	K_1	20.5	217	16.3	214	14.9	216
	P_1	6.6	215	5.2	213	4.8	214
	Q_1	4.4	190	-	-	-	-
Semidiurnal	M_2	5.3	5	6.7	4	6.3	34
	S_2	4.9	309	6.4	329	5.7	320
	N_2	3.8	255	-	-	-	-
	K_2	1.8	315	2.4	333	2.4	328
F		4.1 (diurnal form)		2.7 (mixed, mainly diurnal)		2.6 (mixed, mainly diurnal)	
ADI (day)		0.57		0.23		0.30	
AT (day)		-2.30		-1.44		-2.87	

Note: Amp. denotes amplitude; Pha. denotes phase lag, referenced to 0° Greenwich; *F* is the amplitude ratio of the (K_1 + O_1)/(M_2 + S_2) tides; and *ADI* and *AT* denote the age of diurnal inequality and the age of the tide.

Table 2. .. harmonic analysis of year-long .. No hyphen in phase lag

- **Response:** All of these changes have been made in Table 2, as well as throughout the paper. Please see the new Table 2 in response to Review 2 above.

Figure 1 caption. Please say year and month this photo was taken

- **Response:** This has been added.
- **The Fig. 1 caption now reads:** "Figure 1. Drifting ice, including icebergs and mobile sea ice, around the Jang Bogo Antarctic Research Station (JBARS), photographed on 29 Jan. 2017".

Figure 3 - y-axis phase lag should be (deg) and not (cm)

- **Response:** This has been fixed. Please see details of Figure 3 changes in the response to Review 2.

Figure 4 caption should say what (a), (b) etc. are and not just have text. Anyway I think the last two sentences contradict each other

- **Response:** These improvements have been made as indicated. Please see details of Figure 4 caption changes in the response to Review 2.

Figure 5 - under (b) you should have Time (month/day) as for Figure 6
I think the last line should say JBARS and ROBT

- **Response:** Both of these corrections have been made as indicated, and also this figure has been combined with the former Fig. 4 as its new panels e and f. Please see details of Fig. 4 (formerly 5) changes in the response to Review 2.

Figure 6 - Time (day) should be Time (month/day). (a) and (b) are missing from the plots.
Line 429 - (thick line with o) should have a filled and not open o to correspond to the plot

- **Response:** These errors have all been fixed. See details of Fig. 5 (originally 6) changes in response to Review 1.

Figure 7 - why the == on the y-axis? There is no break in the numeration. Time (day) should be Time (month/day)

- **Response:** These errors have been fixed. See details of Fig. 6 (originally 7) changes in the response to Review 1.

Figure 8 - Time(month/day).
A difference like this is usually defined as an Obs minus Pred but I guess it doesn't matter too much.
The caption says 15 February, but the x-axis in (a) only goes up to 14 Feb. The caption should say what RMSE and R-squared are.

- **Response:** The x-axis label (month/day), and the caption (regarding 14 Feb) have been amended. RMSE and R^2 definitions have been added to the caption. We have also altered this figure to show observations minus predictions, as suggested. Please see details of Fig. 7 (formerly 8) changes in the response to Review 2.

Figure 9 - the caption and the x-axis in (a) say 15 Feb, but the header says 16 Feb
In (b), the caption and x-axis say 30 Jan but the header says Jan 18. I thought at first you were referring to the dates of the dashed boxes but it seems not.
line 1 of caption - estimated –> shown

- **Response:** The two header errors have been corrected. 'Estimated' has been replaced by 'calculated' in the caption. Please see details of Fig. 8 (formerly 9) changes in the response to Review 2.

Figure 10 - Time (month/day)
450 - Msf and Mf tides ('Exp2'). At least I think that is what is meant.

- **Response:** The axis label and caption have been fixed as indicated. Please see details of Fig. 9 (formerly 10) changes in the response to Review 2.

Figure 11 - please have an arrow on the colour scale to indicate values over 3. The longitudes on the map are fuzzy. caption - drop horizontal.

- **Response:** Improvements in relation to all three points have been made.
- **This figure now looks like:**

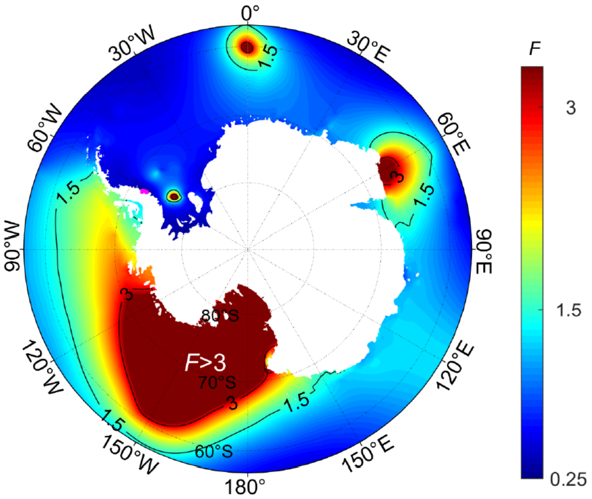


Figure 11. Distribution of tidal form factor (*F*) values around Antarctica. Note the magenta area (72°S) on the Antarctic Peninsula's Weddell Sea coast denotes the only area with a properly semidiurnal tide regime (*F*<0.25) in the Antarctic region.

Figure 12. What you are showing here are the 'f' and 'u' nodal factors. They are both nodal factors, not just 'f'. They are not 'estimated', they are hard coded into T-Tide and can be found in any tides text book.

- **Response:** This figure has been deleted due to the shortening/ tightening of focus of section 5.2.

So you can tell I found many small problems with the paper, in addition to the problems with the three sections mentioned above. I hope you can produce a considerable better (and probably shorter) version.

- **Response:** Thank you for your detailed review. We have made the changes suggested to deal with all of the small problems. We have also have taken on board your more major criticisms, and these have helped us to significantly improve the 3 sections you identified as problematic, with the result being a more focused and shorter paper.

Predicting tidal heights for extreme environments: From 25 hr observations to accurate predictions at Jang Bogo Antarctic Research Station, Ross Sea, Antarctica

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Abstract. Accurate tidal height data for the seas around Antarctica are much needed, given the crucial role of these tidesal processes as represented in regional and global climate, ocean, and marine cryosphere, and climate modelsprocesses. ThoughHowever obtaining long term sea level records for traditional tidal predictions is extremely difficult around ice affected coasts. This study evaluates the ability of a relatively new, tidal species based approach, the Complete Tidal Species Modulation with Tidal Constant Corrections (CTSM+TCC) method, to accurately predict tides for a temporary tidal observation station in the Ross Sea, Antarctica, using records from a neighbouring reference station characterised by a similar tidal regime. Predictions for the 'mixed, mainly diurnal' regimes of Jang Bogo Antarctic Research Station (JBARS) were made and evaluated based on summertime (2017; and 2018 to 2019) short-term (25 hr) observations at this temporary station, along with tidal prediction data derived from year-long observations (2013) from the neighbouring 'diurnal' regime of Cape Roberts (ROBT). Results reveal the CTSM+TCC method can produce accurate (to within ~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. thosearound at high lunar declinationstropic spring periods). Predictions were successful due to the similar relationships between the main tidal constituents' (K_1 and O_1 tides) phase-lag differences at the prediction and reference stations, and despite these tidal stations being characterized by different tidal regimes according to their form factors (i.e. mixed, mainly diurnal versus diurnal).We demonstrate how to determine optimal short-term data collection periods based on the Moon's declination and/oror the modulated amplitude ratio and phase lag difference between the diurnal and semidiurnal species predicted from CTSM at ROBT (i.e. or the long-termreference tidal station). The importance of using long period tides to improve tidal prediction accuracy is also considered, and, finally, the unique tidal regimes of the Ross Sea examined in this paper are situated within a wider long with the characteristics of the different decadal scale tidal variations around Antarctic tidal contexta using , from the four major FES2014 tidal harmonic constants model data.

1 Introduction

Conventionally, year-long sea level records are used to generate accurate tidal height predictions via harmonic methods (e.g. Codiga, 2011; Foreman, 1977; Pawlowicz et al., 2002). Obtaining long term records for such tidal analyses is extremely difficult for sea ice affected coasts, like that surrounding Antarctica (Rignot et al. 2000). As a compliment to in situ tidal records, recent work has significantly advanced our understanding of tide models for the shallow seas around Antarctica and Greenland via the assimilation of laser altimeter data and use of Differential Interferometric Synthetic Aperture Radar (DInSAR) imagery, amongst other methods (Padman et al., 2008; 2018; King et al., 2011; Wild et al., 2019). 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 nearby 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. Demonstrating the usefulness of this method for generating accurate tidal predictions for new sites on sea ice affected coasts is the motivation for this study. We focus on the Ross Sea, Antarctica, as our case study area.

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 data in Padman et al., 2003); and by Italy at Mario Zucchelli Station (Gandolfi, 1996), all in the eastern Ross Sea~~Terra Nova Bay~~. Permanent sea level gauge installations in this extreme environment must accommodate or somehow avoid surface vents freezing over with sea ice, and~~s well as~~ damage to subsurface instruments from icebergs. 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. At ROBT, these issues have been avoided by sheltering the sea level sensor towards the bottom of a 10 m long hole, drilled through a large, shoreline boulder, from its surface ~2 m above the sea and sea ice level, to ~6 m below sea level, below the base of the sea ice (Glen Rowe, Technical Leader Sea Level Data, New Zealand Hydrographic Authority, *pers. comm.* 13 Dec. 2019). In the absence of a suitable permanent gauge site, hydrographic surveys have been conducted~~, such as the current situation~~ at the Korean Jang Bogo Antarctic Research Station (JBARS)~~, hydrographic surveys~~. Such surveys are best conducted during the summertime predominantly sea ice free window around mid-January to mid-February. Even then, mobile ice (Fig.~~ure~~ 1) and severe weather events frequently hinder ~~such~~ surveys via instrument damage or loss, not to mention the logistical difficulties of instrument deployment and recovery (Rignot et al. 2000). Accurate tidal records from the Ross Sea and other areas around Antarctica are thus scarce compared to those available from other regions, although these data are much needed given the crucial role of tidal processes around this continent (~~Han and Lee, 2018;~~ Han et al., 2005; Jourdain et al., 2018; Padman et al., ~~2002;~~ 2003~~; 2008~~; 2018).

Floating ice shelves occupy around 75% of Antarctica's perimeter (Padman et al., 2018). Tidal oscillations at the ice-ocean interface influence the location and extent of grounding zones (Padman et al., 2002; Rosier and Gudmundsson, 2018), and control heat transfer~~s~~ and ocean mixing in cavities beneath the marine cryosphere (Padman et al., 2018; Wild et al., 2019) and the calving and subsequent drift of icebergs (Rignot et al. 2000). Tides also affect variability in polynyas; patterns of seasonal sea ice; and thus the functioning of marine ecosystems~~ (Han and Lee, 2018)~~. ~~In addition,~~And tides affect the dynamics of landfast sea ice, which provides aircraft landing zones for Antarctic science operations (Han and Lee, 2018).

Accurate Antarctic region tidal input data are needed for models examining changes in global climate and ocean circulation, including for the generation of Antarctic bottom water (Han and Lee, 2018; Wild et al., 2019). Data on coastal tides are also essential for studies of ice mass balance~~s~~ and motion~~s~~ (Han and Lee, 2018; Padman et al., 2008; 2018; Rignot et al. 2000; Rosier and Gudmundsson, 2018; Wild et al., 2019). Ice thickness is typically measured via the subtraction of tidal height oscillations from highly accurate, but relatively low frequency, satellite ~~imagery~~ based observations of ice surface elevation and/or from in situ Global ~~Positioning~~Navigation Satellite System (GNS~~P~~S) instrument observations (Padman et al., 2008). For floating ice, this procedure is relatively straightforward but where ice shelves and glacier tongues occur, the mechanics of grounding zones and ice flexure render the determination of ice thickness and motion ~~very~~ challenging (Padman et al. 2018; Rosier and Gudmundsson, 2018), making the accuracy of ~~the~~ tidal height inputs crucial for effective ice modelling (Wild et al. 2019).

In this study, we tested applicability of Byun and Hart's (2015) CTSM+TCC method in an extreme observation environment using 25 hr short-term records from JBARS, our temporary tidal observation station, and year-long data from ROBT, the ~~nearby~~neighbouring reference station. Sect. 2 of this paper details the JBARS and ROBT observation data sets used to generate harmonic tidal analysis results and CTSM+TCC tidal predictions. Sect. 3 explains how the CTSM+TCC method was applied and adapted in this case study (with Appendix 1 detailing the calculations)~~and settings~~, while Sect.~~ion~~ 4 demonstrates the CTSM+TCC tidal prediction capability. Sect. 5 discusses the generation of fortnightly tide effects and double tidal peaks~~,~~

~~particularly during low tides~~~~; the fortnightly tide effects,~~ and situates the Ross Sea tides examined in this paper ~~decadal timescale~~ within the wider context of ~~tidal characteristics around~~ Antarctica tidal regimes.

2 Antarctica's major tides: Observations and background

2.1 Study sites and data records

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. This mission collected the first, 19 day sea level records for JBARS: 10 min interval observation data, ~~were~~ recorded between 28 Jan.~~uary~~ and 16 Feb.~~ruary~~ 2017 using a bottom-mounted pressure sensor (WTG-256S AAT, Korea). High-~~-~~frequency sea level oscillations (<3 hr)~~signals~~ were removed from the observation record using a fifth-order low-pass Butterworth filter~~, with a cut-off frequency of 3 hr~~. Note that the first and last days of this campaign comprised partial day records, so we excluded these end days from our tidal prediction experiments, since our method requires continuous 25 hr input data (for convenience, starting at midnight). That left 17 days and 1 hour of useable tidal observation data as the basis of ~~We use these data in our study's tidal prediction experiments as~~ the ~~temporary tidal station's~~ primary JBARS observation record.

For the purposes of a full-scale survey, three ~~3~~ additional, discontinuous sea level observation records were measured by KHOA at JBARS between 29 Dec.~~ember~~ 2018 and 11 Mar~~ch~~. 2019, all at 10 min intervals using the same ~~type of~~ instrument. Of these, the 20.54 day record produced between 29 Dec.~~ember~~ 2018 and 18 Jan.~~uary~~ 2019 comprised relatively high quality data with small residuals (i.e. observations minus predictions). We used this additional dataset (hereafter referred to as the JBARS 2019 observations) to verify ~~the~~ CTSM+TCC method tidal predictions generated from input parameters derived from 'daily' (25 hr) slices of the 2017 sea level records. 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~~in situ instruments~~, it was not possible to collect the year-long sea level records that are commonly employed to obtain reliable tidal ~~constituents'~~ harmonic constants for tidal prediction.

Approximately 269 km south of JBARS, there is a permanent tidal observation station named after its location on Cape Roberts (ROBT), operated by Land Information New Zealand (LINZ) and recording at intervals since November 1990 (Fig. 2). Five minute interval sea level data have been collected at ROBT since November 2011 using Standard Piezometers (Model 4500, GEOKON). Part of the 2017 record from this site was unavailable online at the time of starting this research, so instead we chose as our reference records the 2013 ROBT sea level data, a quality year-long dataset with few missing points.

2.2 Tidal characteristic analyses and descriptions

Using the T_TIDE toolbox (Pawlowicz et al., 2002), we obtained the tidal harmonic constants of the 8 and 6 major tidal constituents for ROBT and JBARS, respectively (Table 1). Also the inference method was used ~~In order~~ to separate out ~~the two major~~neighbouring diurnal (K_1 ~~versus~~ and P_1) and semidiurnal (S_2 and~~versus~~ K_2) tide constituents, with their ~~from the short term records at JBARS, we used the inference method. That is, we used inference parameters (i.e.,~~ amplitude ratios and phase -lag differences ~~) for each tidal constituent pair (K_1 versus P_1; and S_2 versus K_2) derived~~ obtained from harmonic analysis of the long-term ~~records from the nearby~~ ROBT reference station records. ~~Analysis~~ Analyses revealed that the two main ~~dominant tides in this area are~~ diurnal (O_1 and K_1) and ~~, with the second most important tides being~~ semidiurnal (M_2 and S_2) tides had similar amplitudes at the two stations~~(Table 1)~~,. with ~~These four tides were characterized by similar amplitudes between ROBT and JBARS: 21.1 and 19.6 cm for O_1; 20.5 and 16.3 cm for K_1; 5.3 and 6.7 cm for M_2; and 4.9 and 6.4 cm for S_2. Note that~~ the diurnal (semidiurnal) amplitudes being~~were~~ slightly larger (smaller) at ROBT than at JBARS, ~~whereas the semidiurnal amplitudes were slightly smaller at ROBT than at JBARS. Despite the relatively close distance (269 km) between~~

ROBT and JBARS in tidal terms, the phase -lags of all four tides having only slightlyshowed slightly different values. The amplitude differences result in slightly different tidal characteristics as indicated by the two sites' tidal form factors at the two sites (e.g., *F* in Table 1). At ROBT *F* is 4.1 while at JBARS *F* is 2.7: that is, ROBT has 'diurnal' type tides whereas JBARS has 'mixed, mainly diurnal' type tides which are close to diurnal.

Next we explored the characteristics of the four main tidal constituents around the entire Antarctic continent, using the FES2014 database (Carrère et al., 2016). The horizontal distributions of the co-amplitudes and co-tides for K_1, O_1, M_2 and S_2 show that the diurnal tides rotate in an anticlockwise direction around Antarctica, with increasing co-amplitudes towards the south, in particular, towards the Ronne and Ross ice shelves and hinterlands (Figure A1). In contrast, the M_2 and the S_2 tides exhibit more complex patterns, with 5 and 7 amphidromic points respectively around Antarctica. Most of the semi-diurnal tides rotate clockwise around their amphidromic points, except at one amphidromic point occurring ~150° W, where the S_2 tide rotates in an anticlockwise direction (Figure A2). The semi-diurnal co-amplitudes increase landwards in the Weddell Sea but reduce across the entire Ross Sea quadrant, with relatively low semi-diurnal tide co-amplitudes (>7 cm) in this area. These FES2014 results reveal that the tides of the Ross Sea are very different to regimes elsewhere in Antarctica.

3 Using the CTSM+TCC tidal prediction methodology in the Ross Sea

Having analysed the tidal harmonic constants at the two stations, 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*). This prediction approach (see Appendix 1 for the detailed calculations, and Byun and Hart (2015) for explanation of procedure development) is based on:

(i) using long-term (1 year, in our case) reference station records (LH_r) and CTSM calculations to make an initial anytime (τ) tidal prediction ($\eta_r(\tau)$), which involves summing tidal species' heights for the reference station (Fig.3);

(ii) comparing the tidal harmonic constants (amplitude ratios and phase lag differences) of representative tidal constituents (e.g., M_2 and K_1) for each tidal species between the temporary and reference stations, calculated using T_TIDE and concurrent short-term records (≥25 hr duration, starting at midnight) from the temporary (SH_o) and reference (SH_r) stations; and

(iii) using the step (ii) comparative data and the TCC calculations for each tidal species to adjust the $\eta_r(\tau)$ tidal species' heights in order to generate accurate, anytime tidal height predictions for the temporary tidal station ($\eta_o(\tau)$).

In this Ross Sea case study we used the 2017 JBARS tidal observation records (i.e. 17.04 days from 00:00 29 Jan. to 01:00 15 Feb.) as a source of SH_o, keeping the second JBARS 2019 observation record for evaluation purposes.

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. LH_r must comprise high quality (e.g. few missing data) tidal height observations from anytime.

Byun and Hart (2015) recommended the use of short-term records gathered during periods of calm weather, to minimizse errors due to atmospheric influences. They employed observational data for both SH_o and SH_r but as demonstrated in this paper the method can also be applied using tidal predictions as a source of SH_r. This 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. 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. LH_r) observational record as input data. The 17.04 days of predicted tides that were concurrent with the 2017 JBARS observation record were then used as our SH_r source. While this CTSM+TCC method adjustment was procedurally small, it represents an important adaptation in the context of generating tidal predictions for stations situated in extreme environments, since concurrent temporary and reference station observations might be rare in such contexts.

When using CTSM+TCC, if the available temporary tidal station observation record covers multiple days, it is best practice to experiment by generating multiple $\eta_o(\tau)$, each using different concurrent pairs of SH_o and SH_r daily data slices in step (ii) above, to produce daily amplitude ratios and phase lag differences between the two stations for the diurnal K_1 and semidiurnal M_2 tidal constituents. Comparisons are then made between the different $\eta_o(\tau)$ data sets produced and the original temporary station observations, to determine the optimal 25 hr window to use: once selected, tidal height predictions can be generated for the temporary observation station for any time period. Thus, 17 individual 25 hr duration data slices were clipped from the 2017 JBARS observation records and from the concurrent ROBT predictions, forming 17 pairs of SH_o and SH_r 'daily' slices. Each paired data set was then used with LH_r to generate tidal height predictions for JBARS covering both the 2017 and 2019 KHOA observation campaign time periods. Comparisons were made between the JBARS observations and the 17 prediction data sets generated for each campaign to identify which 25 hr short-term data window produced optimal $\eta_o(\tau)$ results.

In this study, we used the CTSM+TCC method (Byun and Hart, 2015) to predict tidal heights for JBARS. This prediction approach is based on the idea of being able to use comparisons between the tidal harmonic constants at a temporary observation station (JBARS in our study) and at a nearby reference tidal observation station (ROBT in this case) that is situated in an area with similar diurnal dominated tidal characteristics to that of the temporary observation station. It requires three data sets: long-term (ideally ≥183 days duration, from anytime) sea level records (LH_R) from the reference station, plus concurrent 25 h25 hr sea level records from both the temporary observation station (SH_O) and the reference station (SH_R). Note that Byun and Hart (2015) recommend using short-term data from periods with larger than average tidal ranges (e.g., in their situation these were spring tide periods due to their study site having a semidiurnal tidal regime) to produce accurate CTSM+TCC predictions, with periods of below average tidal ranges (e.g., neap records) producing less accurate predictions. They also recommended the use of temporary records gathered from a temporary site during periods of calm weather, to minimize errors due to atmospheric influences.

A complicating factor in this study was that, for the 2017 summertime period when SH_O were recorded at JBARS, the ROBT records were poor quality, including multiple missing data up until 12 February 2017. As such we did not start with two quality, concurrent short-term observation records from our 2 stations. This issue was solved simply, using T_TIDE (Pawlowicz et al., 2002) to produce accurate 10 min interval 2017 yearlongyear-long tidal height predictions for ROBT, based on LH_R – that station's 2013 yearlongyear-long and high quality record. In short, the LH_R dataset was harmonically analyzed to obtain harmonic constants for the tidal constituents. In turn, these harmonic constants were used to produce the modulated amplitudes ($A_{r\eta}^{(s)}(\tau)$) and phase lagphase lags ($\varphi_{r\eta}^{(s)}(\tau)$) over the 2017 tidal prediction period. Note that the period of the modulated species amplitudes and phase lagphase lags determine the tidal prediction period. Seventeen days of daily (25 h25 hr) data slices from the resulting 2017 tidal prediction data, overlapping temporally with the SH_O dataset, was then used as our SH_R dataset. Figure 3 shows the modulated amplitudes and phase lagphase lags for the diurnal and semidiurnal species, calculated from this SH_R summertime 2017 tidal prediction data.

Using the CTSM+TCC approach, tidal predictions for the temporary station ($\eta_o(\tau)$) were initially derived from reference tidal station predictions ($\eta_r(\tau)$) on the assumption that the tidal peculiarities properties between the two stations remain similar through time. This step is expressed in Byun and Hart (2015) as:

$$\eta_r(\tau) = \sum_{s=1}^{k} A_r^{(s)}(\tau) \cos\left(\omega_R^{(s)} t - \varphi_r^{(s)}(\tau)\right) \qquad (1)$$

With

$$A_r^{(s)}(\tau) = \sqrt{\sum_{i=1}^{m} \left[f(\tau)_i^{(s)} a_i^{(s)}\right]^2 + 2\sum_{i=1}^{m-2} \sum_{j=i+1}^{m} \left[f(\tau)_i^{(s)} a_i^{(s)}\right]\left[f(\tau)_j^{(s)} a_j^{(s)}\right] \cos\left\{\left(\omega_i^{(s)} - \omega_j^{(s)}\right)t + \left[V(t_0)_i^{(s)} + u(\tau)_i^{(s)} - g_i^{(s)}\right] - \left[V(t_0)_j^{(s)} + u(\tau)_j^{(s)} - g_j^{(s)}\right]\right\}}$$

(2)

and

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$$\varphi_r^{(s)}(\tau) = tan^{-1}\left(\frac{\sum_{i=1}^{m} a_i^{(s)} \sin[(\omega_i^{(s)}-\omega_R^{(s)})t+V(t_0)_i^{(s)}+u(\tau)_i^{(s)}-g_i^{(s)}]}{\sum_{i=1}^{m} a_i^{(s)} \cos[(\omega_i^{(s)}-\omega_R^{(s)})t+V(t_0)_i^{(s)}+u(\tau)_i^{(s)}-g_i^{(s)}]}\right) \quad (3)$$

where superscript s denotes the type of tidal species (e.g., 1 for diurnal species and 2 for semidiurnal species), τ is time, m is the number of tidal constituents and $\omega_i^{(s)}$ are the angular frequencies of each tidal constituent (subscripts i and j) and $\omega_R^{(s)}$ are the angular frequencies of each representative tidal constituent (subscript R) for each species. The dominated tidal constituent among each tidal species can denoted as representative tidal constituent (e.g., K_1 and M_2 used as representative diurnal and semidiurnal species, respectively). For each tidal constituent, $a_i^{(s)}$ and $g_i^{(s)}$ are the tidal harmonic amplitudes and phase lags, $f(\tau)_i^{(s)}$ is the nodal amplitude factor, $u(\tau)_i^{(s)}$ is the nodal angle and $V(t_0)_i^{(s)}$ is the astronomical argument. T_TIDE was used for tidal harmonic analysis as well as for calculation of the nodal amplitude factors, nodal angles and astronomical arguments for the representative species.

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 $\left(\frac{a_{o\eta}^{(s)}}{a_{r\eta}^{(s)}}\right)$ and phase lag difference $(g_{o\eta}^{(s)} - g_{r\eta}^{(s)})$ of each representative tidal species between the temporary tidal observation station (subscript o) and the reference station (subscript r) were then calculated from tidal harmonic analysis of concurrent 25 hr tidal records from both stations. In order to explore the best 25 hr data window to use during this step, we sliced the 17 day SH_O and SH_R records (from 29 January to 14 February 2017) into individual 'daily' data slices, each starting at 00:00 and 25 hr in duration. The 17 daily data slices from each station were harmonically analyzed (Figure 4) to calculate daily amplitude ratios $\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)$ and phase lag differences $(g_o^{(s)} - g_r^{(s)})$ for the diurnal and semidiurnal representative species (i.e., K_1 and M_2), as illustrated in Figure 5. The initial tidal predictions at the reference station calculated from Eq. (1) were then adjusted to represent those for the temporary station ($\eta_o(\tau)$) by substituting the above amplitude ratios and phase lag differences between the temporary and reference stations into Eq. (1) as follows (Byun and Hart, 2015):

$$\eta_o(\tau) = \sum_{s=1}^{k} A_o^{(s)}(\tau) \cos\left(\omega_R^{(s)} t - \varphi_o^{(s)}(\tau)\right) \quad (4)$$

with $A_o^{(s)}(\tau) = A_r^{(s)}(\tau)\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)$ and (5)

$$\varphi_o^{(s)}(\tau) = \varphi_r^{(s)}(\tau) + g_o^{(s)} - g_r^{(s)} \quad (6)$$

Substituting Eqs. (5) and (6) into Eq. (4), $\eta_o(\tau)$ can be expressed as:

$$\eta_o(\tau) = \sum_{s=1}^{k} A_r^{(s)}(\tau)\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)\cos[\omega_R^{(s)} t - (\varphi_r^{(s)}(\tau) + g_o^{(s)} - g_r^{(s)})] \quad (7)$$

where t_0 is the reference time, t is the time (t) elapsed since t_0 and $\tau = t_0 + t$.

In addition to the 2017 tidal height prediction experimentscalculations, we examined the capacity of the CTSM+TCC method to generate tidal predictions for the period 29 December 2018 to 18 January 2019 (hereafter referred to in shorthand as '2019 summertime'), using the same 2017 input data (i.e. using data from Figure 3 and Figure 5 in Eq. (7)). This 2019 summertime prediction period corresponds to the second tidal observation mission made to JBARS by KHOA surveyors.

4 Results

4.1 Tidal prediction evaluations

The CTSM+TCC was used to experiments produced seventeen 17 different JBARS tidal prediction datasets for the period 29 Jan. to 14 Feb. 2017, each comprising 17 day long, 10 min interval tidal height predictions for JBARS, together based onwith harmonic analysis results of the data on the 'daily' (25 hr) K_1 and M_2 amplitudes and, ratios and phase -lags , and their ratios

~~differences~~ ~~between~~at our two tidal observation stations (Fig. 4) ~~(JBARS and ROBT~~). In order to evaluate these ~~CTSM+TCC~~ results, each predicted tidal height data set was compared with the concurrent JBARS field observations via Root Mean Square Error (RMSE) and coefficient of determination (R^2) statistics.

As illustrated in Fig. ~~5~~6, the RMSE and R^2 results varied in relation to the JBARS tidal range (range being twice amplitude)~~s~~, with greater accuracy evident in predictions made using data derived from ~~25 h~~ periods with above~~where~~ ~~when the tidal range was~~ ~~higher than~~ average tidal ranges.

In the JBARS ~~'mixed, mainly diurnal' type tide~~ area of the Ross Sea~~,~~ during our 2017 observation period, ~~,~~ above ~~greater than~~ average tidal ranges corresponded to the ~~spring tide~~ period when the moon was near its ~~maximum (tropic)~~ greatest northern declination. RMSEs between observations and predictions ranged from 4.26 cm to 20.56 cm, while R^2 varied from 0 to 0.94, across the 17 'daily' experiments. Eleven of the experiments produced accurate results (i.e. excluding those derived ~~based on 25 h input data derived~~ from 31 Jan.~~uary~~; and 1 to 4 and 14 Feb.~~ruary~~ data slices ~~records), with their RMSEs <5 cm and R^2 values >0.9)~~2. Daily datasets from periods with relatively high tidal ranges (>83.5 cm) produced predictions with RMSEs <5 cm and R^2 values >0.92. The maximum spring tidal range occurred on 9 Feb.: the data slices 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 R^2 value (0.941) were produced using data slices from one day earlier, 8 Feb. 2017. In contrast to the majority of successful experiments, the experiment based on data derived from the ~~'~~2 Feb. 2017~~ruary' 25 h~~ data slices produced predictions with very high RMSE (20.56 cm) and very low R^2 (0.00) values. ~~Notably~~T~~, t~~he 2 Feb.~~ruary~~ 2017 tides were characterised by the smallest tidal range (11.95 cm) of the ~~temporary~~ JBARS record, during a~~n equatorial tide~~ period of low lunar declination.

~~The maximum spring tidal range occurred on 9 February: the data slice from this occasion produced predictions with a low (but not the lowest) RMSE (4.81 cm). The predictions with the lowest RMSE (4.259 cm) and highest R^2 value (0.941) were produced using inputs derived from 25 hr data recorded one day earlier, on 8 February 2017.~~

As with the 2017 predictions, RMSEs between the 2019 ~~summertime~~ predictions and observations were lower when generated using ~~input data derived from 25 h~~ data slices from ~~the~~ 2017 ~~tropic – spring~~ periods at high lunar declination ~~(as opposed to equatorial and/or neap) tide periods~~ (Fig. ~~6~~7). For example, ~~As in the earlier experiments, the~~ 2019 ~~summertime~~ predictions made using input data derived from the 8 Feb.~~ruary~~ 2017 ~~(25 h)~~ data slices produced the lowest RMSE (5.3 cm) and highest R^2 (0.913) values of the 2019 ~~summertime~~ experiments (Fig. ~~7~~8).

These results show~~demonstrate~~ that the CTSM+TCC method can be -used ~~can be~~ successfully to ~~employed to~~ predict tidal heights for JBARS, when ~~for any particular period,~~ using ~~25 h~~ observation records gathered from periods at high lunar declination (sometimes called tropic tides)~~tropic or tropic-spring tide periods~~, with relatively calm weather, together with ~~yearlong sea level~~ observation or prediction records from the neighbouring reference station ROBT~~, despite the two stations having slightly different types of tidal regime~~.

4.2 Determining the ideal short-term sea level observation period when using CTSM+TCC

The previous section verified that the CTSM+TCC method can be used to generate accurate tidal predictions based on 25 hr sea level records, from periods with ~~higher than~~above average tidal ranges, for a temporary station in a 'mixed, mainly diurnal' regime and a reference station in a 'diurnal' regime. The question arises as to how to determine ~~the ideal~~ optimal observation days in such settings ~~from which to source the 25 h observation records in order~~ to produce the most accurate tidal predictions. For semidiurnal or mixed, mainly semidiurnal tidal regimes, we can estimate preferred temporary station observation days, those with the largest tidal ranges, based on the moon's phase, without reference to tide tables. That is, spring tides commonly occur just a day or two after the full and new moon, which reoccurs at a period of 14.7653 days. The time lag between the full or new moon and the spring tide is called the age of the tide (*AT*).

Similarly, in a "diurnal" tide regime or a "mixed, mainly diurnal" tide regime (Fig. 56), the preferred temporary station observation days can be estimated based on the lunar declination, which varies at a period of 13.6608 days. That is, maximum tidal range tropic tide days can be estimated for JBARS based on the day of the Moon's greatest northernsouthern (GN) and northernsouthern (GS) maximum and minimum declinations. The time between the Moon's semi-monthly greatest northern (GN) and southern (GS) and northernmaximum (and minimum) declinations and its maximumtheir effects on tidal range, called the age of diurnal inequality (*ADI*), is commonly 1 to 2 days.

As shown in Fig.ure 89, the maximum GN and GSminimum Moon's lunar declinations during our 2 temporary station summertime observation periods occurred on 8 Feb.ruary 2017 (GNmax) and on 6 Jan.uary 2019 (GSmin) respectively, with , tThe diurnal maximum diurnal tides at tends to JBARS occurexpected ~around 1 day after each lunar declination peakafter the maximum GN declination, during one half of the tropic month and about 2 ~1 days after the GSminimum declination during the other half of the tropic month.

Thus, when planning to use the CTSM+TCC tidal prediction method for places characterised by diurnal or mixed, predominantly diurnal tidal regimes, we can use knowledge of the moon's declination to select potential sea level observation days.

4.3 Comparison of ROBT and JBARS tidal species characteristics

The CTSM+TCC tidal prediction method is based on the assumption that the tidal harmonic characteristics of each tidal species are very similar between the temporary observation and reference stations. This is because the reference station tidal species' CTSMs, derived from yearlong reference station sea level records or tidal harmonic analysis results, form the basis of the tidal predictions for the temporary observation station. To test the validity of this assumption, we examined the phase -lag (*G*) differences of the 2 two major diurnal (K_1 and O_1) and 2 major semidiurnal tidal constituents (M_2 and S_2) tidal constituents using the age of diurnal inequality (*ADI*) and the age of the tide (*AT*), calculated as:

$$ADI\ (day) = \left(\frac{gG_{K_1} - Gg_{O_1}}{\omega_{K_1} - \omega_{O_1}}\right)/24\ , \text{ and} \qquad (781)$$

$$AT\ (day) = \left(\frac{gG_{S_2} - gG_{M_2}}{\omega_{S_2} - \omega_{M_2}}\right)/24\ , \qquad (892)$$

where ω_{K_1} (= 15.0410686° hr^{-1}), ω_{O_1} (= 13.9430356° hr^{-1}), ω_{M_2} (= 28.9841042° hr^{-1}) and ω_{S_2} (= 30.0000000° hr^{-1}), and ω_{M_2} (= 28.9841042° hr^{-1}) are the angular speeds of the K_1, O_1, SM_2 and MS_2 tides, respectively. RResults revealed that the *ADI* are very similar, and there is <1 day *AT* difference, between ROBT and JBARS respectively (Table 1)the two2 stations,: the *ADI* values were 0.57 versus and 0.23 or 0.30 day, while the and *AT* values were -2.30 3087 versus and -1.44 or -2.87 days, for ROBT versus JBARS, respectively (Table 1). These values indicatinge that the tidal characteristics of the representative tidal constituents for each species between the two stations ROBT and JBARS are very similar, in particular the dominant diurnal species. Hence This similarity explains why we found the applicability and success of the CTSM+TCC method successful in for generating our Ross Sea JBARS tidal predictions, using concurrent 25 h records from both stations and reference records from ROBT.

5 Discussion

~~5.1 Fortnightly tide effects around Antarctica~~

5.1 Explaining fortnightly tide effects and double tide peaks in the Ross Sea tidal predictions

We have demonstrated that the CTSM+TCC approach can produce reasonably accurate tidal predictions (RMSE <5 cm, R^2 >0.92) for a new site in the Ross Sea, Antarctica, based on 25 hr temporary station observation records from periods with above average tidal ranges, plus neighbouring reference station records. Our results compare favourably with those of Han et al. (2013), who reviewed the tidal height prediction accuracy of 4 models for Terra Nova Bay, Ross Sea: these models generated similar quality results to our CTSM+TCC results, with R^2 values between 0.876 and 0.907, and RMSEs ranging from 3.6 to 4.1 cm. 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 and small amplitude short period tides.

Table 2 summarises the characteristics of 6 long-period tides (S_a, S_{sa}, MS_m, M_m, M_f, MS_f) at the ROBT station, derived from tidal harmonic analysis of year-long (2013) in situ observation records. To investigate the main cause of the apparent fortnightly prediction biases in our JBARS results, in particular that in the 2019 predictions (Fig. 7b), we examined the effects of two fortnightly tidal constituents (M_f, and MS_f) at ROBT. 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 also incorporated the M_f; and
- *Run2* was based on *Srun* but also incorporated the M_f and MS_f.

Comparisons between *Run1 and Srun* predictions show that exclusion of the M_f 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 MS_f tide (1.2 cm amplitude) intensifies the biases (Fig. 9b).

Rosier and Gudmundsson (2018) found that ice flows are modulated at various tidal frequencies, including that of the MS_f tide. However, because these tides' amplitudes have small signal-to-noise ratios (<1) with large standard errors (Table 2), caution should be exercised when elucidating fortnightly tide effects using these constituents. 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 specifically (e.g. Rignot et al., 2000; Rosier and Gudmundsson, 2018). Consideration of additional, long period tides in predictions is one recommendation we have for future work on improving tidal predictions for Ross Sea coasts.

Another characteristic of our results needing explanation is the double tidal peaks evident in both the tidal observations and predictions at JBARS. These peaks occur, for example, in Fig. 7b between Jan. 11th and 17th, 2019. To explore why these double peaks occur, we generated JBARS tidal height predictions using Eq. (A1) and the 2019 tidal constants listed in Table 1 for the two major diurnal and semidiurnal tides. Fig. 10a shows separately the resulting diurnal (with their period of 13.66 days) and semidiurnal (with their period of 14.77 days) species' tide predictions. The combination of these out-of-phase tidal species generates double peaks (or double troughs) around low tide (Fig. 10b) for periods when the diurnal tide amplitudes are low, and the amplitude ratio of the semidiurnal to diurnal tide species is >0.5 (Fig. 10c). Double peaks also occur around high tide during periods of low lunar declination (Fig. 8b), when the semidiurnal to diurnal species amplitude ratio is >1, and the phase lag difference between the diurnal and semidiurnal species is between -78° and 46° (Fig. 10). Since the semidiurnal tides are slightly stronger, and the diurnal tides are slightly weaker, at JBARS compared to at ROBT (Table 1), these double tide peaks occur more commonly at JBARS (e.g., compare Fig. 5b and Fig. 7).~~We have so far demonstrated that the CTSM+TCC approach can produce reasonably accurate tidal predictions (RMSE <5 cm, R^2 >0.92) for a new site in the Ross Sea, Antarctica, based on 25 h temporary observation records from periods with higher than average tidal ranges, plus neighboring reference station records.~~

Our results compare favourably with those of Han et al. (2013), who reviewed the tidal height prediction accuracy of 4 models for Terra Nova Bay, Ross Sea: that is, TPXO7.1 developed by Egbert and Erofeeva (2002), FES2004 from Lyard et al (2006); the Circum-Antarctic Tidal Solution (CATS2008a) from by Padman et al. (2008), and the Ross Sea Height-Based Tidal Inverse Model (Ross_Inv_2002) from Padman et al. (2003). Han et al. (2013) compared the model datasets to 11 days of February 2011 in situ sea level observations, corrected for inverse barometer effects, and considered model usefulness for investigating tidal signals in satellite data from the Campbell Glacier tongue. The 4 models generated similar quality results to those generated by the CTSM+TCC method in this study, with R^2 values varying between 0.876 and 0.907, and RMSEs ranging from 3.6 and 4.1 cm.

However, as shown in Fig. 8, our results appear to contain a changing bias in estimates occurring at fortnightly timescales, with predictions slightly underestimating (from 3 Feb. to 9 Feb., 2017) or overestimating (from 29 Dec., 2018 to 5 Jan., 2019) tides during the period from the equatorial to tropic tides (the ETT), and slightly overestimating (from 10 Feb. to 14 Feb., 2017) or underestimating (from 6 Jan., 2019 to 13 Jan., 2019) tides from the period between the tropic to equatorial tides (the TET). This error pattern likely resulted from our application of CTSM+TCC only considering 2 major tidal species, those representing diurnal and semi-diurnal constituents, whilst ignoring long period tides.

In their GPS field measurement and modelling study of the Ronne Ice Shelf in the Weddell Sea, Rosier and Gudmundsson (2018) found that ice shelf and ice stream horizontal flows are strongly modulated at a variety of tidal frequencies, with a significant M_{sf} tide correlated signal occurring across their field site. Modelling without vertical tidal oscillations produced horizontal ice flow rates almost 30% lower than observed. In an earlier Synthetic Aperture Radar (SAR) interferometry and tide model comparison study of the Ronne and Filchner Ice Shelves, Rignot et al. (2000) found that eight 'major' tidal constituents (M_2, S_2, K_2, N_2, O_1, K_1, Q_1, and $2N_2$) plus an additional 18 'minor' constituents measurably influenced patterns of ice flexure and motion. The authors of both of these papers recommend the inclusion of both major and minor tidal constituents, including long period tides, for successful ice flow and ice-ocean front modelling.

Long period tides cycle across timeframes including 18.61 y, seasons, months and fortnights (Woodworth, 2012). Table 2 summarizes the characteristics of 6 long-period tides (S_a, S_{sa}, MS_{sm}, M_m, M_f, M_{sf}) at the ROBT station, derived from tidal harmonic analysis of yearlong (2013) in situ records. Comparisons between Tables 1 and 2 reveal that the S_a amplitude (5.8 cm) was similar to that of the M_2 (5.3 cm), the amplitudes of the M_m and M_f tides were >50 % of the M_2 (≥2.7 cm), while the S_{sa} and MS_{sm} amplitudes were all minor (≤0.4 cm). While the 2013 S_a amplitude was equivalent to that of the M_2, inter-annual variation in the S_a harmonic constant is large (1.2 cm to 9.1 cm for amplitude; 75° to 131° for phase-lag, Table 3). This is because the S_a constituent comprises both astronomical and seasonal components (Pugh, 1987). Hence our focus here on the error bias between the ETT and TET periods.

In order to verify the main cause of the apparent fortnightly prediction biases, in particular that found in the 2019 summertime results (Figure 8b), we examined the effects of two fortnightly period tidal constituents (M_f, and M_{sf}) at ROBT. Three 2019 summertime tidal prediction experiments were conducted: 1) *Srun* excluding all long period tides (i.e. those in Table 2); 2) *Run1* incorporating the M_f alone; 3) *Run2* incorporating the M_f and the M_{sf} alone.

Results revealed that exclusion of the M_f tide (2.7 cm amplitude) alone can produce ETT and TET prediction biases (Figure 10a), with exclusion of the M_{sf} tide (1.2 cm amplitude) intensifying the biases (Figure 10b). Thus, consideration of additional, fortnightly timescale tidal constituents in predictions is our recommended next step for improving tidal prediction accuracies for JBARS.

5.2 Understanding the cDecadal timescale tidal variations around Antarcticaontrasting tidal environments around Antarctica

Figure 11 illustrates the Tidal form factorsregime characteristics of tidal regimes inin the seas surrounding Antarctica, according tomostly fall into three of the four daily form factor types, as revealed by FES2014 model data. Figure 12 showsT

~~t~~here are large areas characterised by ~~of '~~diurnal ~~' (DD)~~($F>3$); mixed, mainly diurnal ~~' (MD)~~ ($1.5<F<3$); 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 ($F<0.25$). ~~Only in a small area half-way (72°S) along the Weddell Sea coast of Antarctic Peninsula do tides exhibit a 'semidiurnal' form.~~ Strong diurnal tides ~~($F>3$)~~ 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 amplitude 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 year lunar nodal cycle compared to areas like the Weddell Sea ~~(see details for ROBT in Byun and Hart, 2019)~~. As ~~As Byun and Hart (2019) also~~ the ~~showed that the relationship of~~ nodal angle variations ~~between~~of the diurnal ~~tides~~ and semidiurnal tides ~~is~~are out of phase, this leads to differing ~~e different~~ tidal responses around Antarctica ~~(particularly, the Ross Sea and the Weddell Sea)~~ over 18.61 years, particularly between the Ross and Weddell Seas (see details for ROBT in Byun and Hart, 2019). Given that CTSM+TCC is based on modulated tidal amplitude and phase lag corrections for each diurnal and semidiurnal species, it is applicable in studying a continent with such a diversity of tidal regime types. ~~should be understood. Based on understanding Antarctic tides,~~ 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 ~~sheet and glacier~~ flows to the sea ~~(Wild et al., 2019)~~. This paper has shown how the CTSM+TCC~~Our paper offers an~~ approach ~~that~~ may be used to ~~compliment~~complement~~, and further refine,~~ existing efforts to quantify variations in tidal processes around Antarctica, in particular for places with sparse in situ ~~long-term~~tidal monitoring ~~records~~, such as ~~in~~ the Ross Sea.

~~Tides around the Weddell Sea coast are significantly amplified due to shoreline shape and bathymetric shoaling effects, with the increase in semidiurnal amplitudes ($a_{M_2}+a_{S_2}$) being more pronounced than those of the diurnal tides ($a_{K_1}+a_{O_1}$). Tidal ranges >2 m are largely confined to the Weddell Sea region, with the exception of the area surrounding the M_2 tide amphidromic point at the head of the Weddell Sea embayment, where relatively large 'mixed, mainly semidiurnal' tides occur thanks to the pronounced M_2 and S_2 amplitudes there.~~

~~The contrasting tidal environments of the Weddell and Ross Seas feature different tidal dynamics and, thus, different tidal influences on their environments, across the full 18.61 y tidal cycle. Accurate (cm scale) quantification of the contrasting tidal environments around Antarctica's margins tidal cycle patterns resulting from these different regimes are not only of use for polar station maritime operations, they are essential for calculating estimating ice sheet and glacier flows to the sea ice-sheet motion near Antarctica's different ocean margins, based on the subtraction of ice flexure and tidal elevation changes from land ice elevation measurements (Wild et al., 2019). Such studies contribute to our understanding of global climate models, providing estimates of ice sheet and glacier flows to the sea. Our paper offers an approach that may be used to compliment, and further refine, existing efforts to quantify variations in tidal processes around Antarctica, in particular for places with sparse long-term monitoring records, such as in the Ross Sea.~~

~~A question arises as to how much the Weddell and Ross Sea tidal form differences can be explained by tidal height changes. To answer this, we explored variation in nodal modulation correction factors (nodal factors and nodal angles) over an 18.61 y cycle. Daily nodal modulation correction factor values for the 3 major lunar tide constituents (K_1, O_1 and M_2) were estimated for JBARS over the 40 yr period 2001 to 2040, as illustrated in Figure 1213a,b. Interestingly the diurnal, O_1 tide variations in nodal modulation correction factors were the largest (nodal factor range = 0.3833; nodal angle range = 22.659°), with those of the K_1 tide being second largest (nodal factor range = 0.2320; nodal angle range =~~

17.986°). In comparison, those of the semidiurnal, M_2 tide were relatively small (nodal factor range = 0.0754; nodal angle range = 4.439°).

These nodal modulation correction factor variations have different implications for the Weddell and Ross Seas due to their differing tidal regimes. 2040) The resulting variations in tidal height are less pronounced in semidiurnalWeddell Sea, while the diurnal regime of the Ross Sea experiences large tidal range variations across 18.61 y cycles(Fig. 13c), tidal range at LAR2 are less pronounced in the semidiurnal Weddell Sea (Fig. 13d) due to the influence of diurnal nodal amplitude factor variation, which is greater than that of the semidiurnal Fig. 13a). Furthermore, variations in the 18.61 yr tidal range in between the diurnal and semidiurnal tidal regime are out of phase (Fig. 13c,d) since variations in the nodal amplitude factors of the O_1 and K_1 tides are out of phase with that of the M_2 tide (Fig. 13a,b). Of note, variations in the nodal angle of the K_1 tide is in phase with that of the M_2 tide but out of phase with that of the O_1 tide (Figure 12b).

6 Conclusions

This paper has demonstrated the usefulness of the CTSM+TCC method for tidal prediction in extreme environments, where long-term tidal station installations are difficult, using the Ross Sea in Antarctica for our case study. Here CTSM+TCC methods can be employed for accurate tidal height predictions for a temporary tidal observation station using short-term (≥25 hr) sea level records from this site, plus long-term (1 year) tidal records from a neighbouring reference tidal station. Essentially the temporary and reference station sites must share similarities in their main tidal constituent and tidal species characteristics for CTSM+TCC to produce accurate acceptable results.

Using this approach, an initial tidal prediction time series is generated for the temporary station using CTSM and the reference station long-term records. The temporary station predicted time series can then be adjusted via TCC of each tidal species, based on harmonic comparisons between the short-term temporary station observation record and its corresponding modelled predictions, leading to improved accuracy in the tidal predictions. The modulated amplitude ratio and phase lag difference between diurnal and semidiurnal species predicted from CTSM at the reference station can be used as an indicator for selecting optimal short term observation dates at a temporary tidal station.

This paper has further demonstrated that the CTSM+TCC approach can be employed successfully in the absence of concurrent short-term (25 hr) records from the reference station, since a tidal harmonic prediction program can be used to produce a synthetic short-term record for the reference station, based on a quality long-term (1 year) record from that site.

The proper consideration of long-period tides in the CTSM+TCC approach remains a challenge, as outlined in this study, with the solutions to this issue likely to improve the accuracy of CTSM+TCC tidal predictions even further. However, this study demonstrates that the CTSM+TCC method can already produce tidal predictions of sufficient accuracy to aid local polar station maritime operations, as well as starting to help resolve gaps in the spatial coverage of tidal height predictions for scientists studying important issues, such as the rate and role of ice loss along polar coastlines.

Code Availability

The T_TIDE based CTSM code is available from https://au.mathworks.com/matlabcentral/fileexchange/73764-ctsm_t_tide.

Data Availability

The sea level data used in this paper are available from LINZ (2019) for selected ROBT records, with the remaining ROBT records available by email application (customersupport@linz.govt.nz); and the JBARS records used are available on request from KHOA (infokhoa@korea.kr). Details of the FES2014 tide model ~~database~~ are found in Carrère et al. (2016) and via https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html.

Appendix 1

This appendix describes the calculations involved in using the CTSM+TCC approach as employed in this Ross Sea, Antarctica, case study. For a fuller description of the development of this approach and its application in semidiurnal and mixed, mainly semidiurnal tidal regime settings, see Byun and Hart (2015).

As explained in the main body of this paper, we used 25 hr slices of the 2017 short-term observations from JBARS (SH_o), our temporary tidal observation station (subscript *o*), and 2013 year-long observations (LH_r) and 2017 short-term tidal predictions (SH_r, concurrent with SH_o) from ROBT, our reference tidal station (subscript *r*), as the basis of JBARS tidal prediction calculations. We then employed the full 17.04 day 2017 JBARS tidal observation data set, and an additional 21.54 day 2019 JBARS tidal observation dataset, to evaluate the success of the CTSM+TCC tidal prediction calculations for this site.

The CTSM+TCC, expressed as the summation of each tidal species cosine function, includes three key steps:

(iv) calculating each tidal species' modulation at the reference tidal station;

(v) comparing the tidal harmonic constants between the temporary observation and reference stations (e.g., the tidal amplitude ratios and phase lag differences of each representative tidal constituent for each tidal species calculated from concurrent observation records between two stations); and

(vi) adjusting the tidal species modulations calculated in the first step using the correction factors calculated in the second step to produce predictions for the temporary tidal station.

As a first step, tidal height predictions for the temporary station ($\eta_o(\tau)$) were initially derived from reference station predictions ($\eta_r(\tau)$) on the assumption that the tidal properties between the two stations remain similar through time. Using the modulated amplitude ($A_r^{(s)}$) and the modulated phase lag ($\varphi_r^{(s)}$) for each tidal species, this step is expressed as:

$$\eta_r(\tau) = \sum_{s=1}^{k} A_r^{(s)}(\tau) \cos\left(\omega_R^{(s)} t - \varphi_r^{(s)}(\tau)\right) \qquad \text{(A1)}$$

with

$$A_r^{(s)}(\tau) = \sqrt{\sum_{i=1}^{m}\left[f(\tau)_i^{(s)} a_i^{(s)}\right]^2 + 2\sum_{i=1}^{m-2}\sum_{j=i+1}^{m}\left[f(\tau)_i^{(s)} a_i^{(s)}\right]\left[f(\tau)_j^{(s)} a_j^{(s)}\right] \cos\left\{\left(\omega_i^{(s)} - \omega_j^{(s)}\right)t + \left[V(t_0)_i^{(s)} + u(\tau)_i^{(s)} - G_i^{(s)}\right] - \left[V(t_0)_j^{(s)} + u(\tau)_j^{(s)} - G_j^{(s)}\right]\right\}}$$

(A2)

and

$$\varphi_r^{(s)}(\tau) = tan^{-1}\left(\frac{\sum_{i=1}^{m} a_i^{(s)} \sin[(\omega_i^{(s)} - \omega_R^{(s)})t + V(t_0)_i^{(s)} + u(\tau)_i^{(s)} - G_i^{(s)}]}{\sum_{i=1}^{m} a_i^{(s)} \cos[(\omega_i^{(s)} - \omega_R^{(s)})t + V(t_0)_i^{(s)} + u(\tau)_i^{(s)} - G_i^{(s)}]}\right) \qquad \text{(A3)}$$

where superscript *s* denotes the type of tidal species (e.g., 1 for diurnal species and 2 for semidiurnal species); *m* is the number of tidal constituents; t_0 is the reference time; *t* is the time elapsed since t_0; and $\tau = t_0 + t$; $\omega_i^{(s)}$ are the angular frequencies of each tidal constituent (subscripts *i* and *j*); $\omega_R^{(s)}$ are the angular frequencies of each tidal constituent representing a tidal species (subscript *R*); with the dominant tidal constituent of each tidal species used as the representative for that species (e.g., K_1 and M_2 are used as representative of the diurnal and semidiurnal species, respectively). For each tidal constituent, $a_i^{(s)}$ and $G_i^{(s)}$ are the tidal harmonic amplitudes and phase lags (referenced to Greenwich); $f(\tau)_i^{(s)}$ is the nodal amplitude factor of each tidal constituent; $u(\tau)_i^{(s)}$ is the nodal angle; and $V(t_0)_i^{(s)}$ is the astronomical argument. T_TIDE was used for tidal harmonic analysis as well as for calculation of the nodal amplitude factors; nodal angles; and astronomical arguments; for the representative tidal constituents.

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 observation and reference tidal stations (i.e. from SH_o and SH_r). The process of selecting the optimal 25 hr window for the concurrent data slices from amongst the 17.04 days of available records is explained in Sect. 3. Once this 2017 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 ($\eta_o(\tau)$), by substituting the daily (i.e. SH_o and SH_r) amplitude ratios $\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)$ and phase lag differences $\left(G_o^{(s)} - G_r^{(s)}\right)$ for the tidal constituents (K_1 and M_2) representing the diurnal and semidiurnal tidal species between the temporary and reference stations into Eq. (A1) as follows (Byun and Hart, 2015):

$$\eta_o(\tau) = \sum_{s=1}^{k} A_o^{(s)}(\tau) \cos\left(\omega_R^{(s)} t - \varphi_o^{(s)}(\tau)\right) \qquad \text{(A4)}$$

with $A_o^{(s)}(\tau) = A_r^{(s)}(\tau)\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right)$, and (A5)

$$\varphi_o^{(s)}(\tau) = \varphi_r^{(s)}(\tau) + G_o^{(s)} - G_r^{(s)} \qquad \text{(A6)}$$

Substituting Eqs. (A5) and (A6) into Eq. (A4), $\eta_o(\tau)$ can be expressed as:

$$\eta_o(\tau) = \sum_{s=1}^{k} A_r^{(s)}(\tau)\left(\frac{a_o^{(s)}}{a_r^{(s)}}\right) \cos\left[\omega_R^{(s)} t - \left(\varphi_r^{(s)}(\tau) + G_o^{(s)} - G_r^{(s)}\right)\right] \qquad \text{(A7)}$$

The T_TIDE based CTSM code is available from https://au.mathworks.com/matlabcentral/fileexchange/73764-ctsm_t_tide.

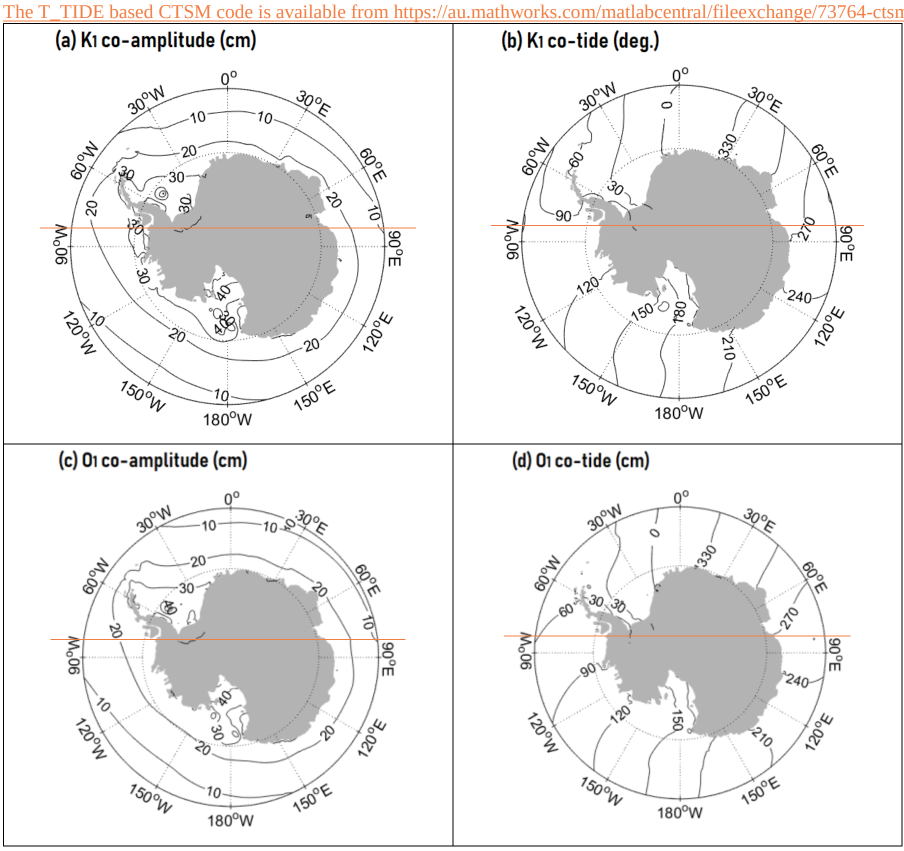

Figure A1. Horizontal distributions of the K_1 and O_1 constituents' co-amplitudes (a, c) and co-tides (b, d) around Antarctica.

Author contribution

D-SB conceived of the tidal prediction idea behind this paper, and wrote the results sections. Both authors worked on initial and final versions of the full manuscript.

Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Special issue statement (will be included by Copernicus)

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~~Table 1. Major tidal harmonic results for diurnal and semi-diurnal constituents from harmonic analyses of yearlong (2013) sea level observations recorded at Cape Roberts (ROBT), and from 17 day sea level observations (29 January to 15 February 2017) and 20.54 day sea level observations (29 December 2018 to 18 January 2019) recorded at the Jang Bogo Antarctic Research Station (JBARS), in Antarctica. For the JBARS tidal harmonic analyses, the inference method was applied to separate out the K_1 (S_2) and P_1 (K_2) tidal constituents, using inference parameters estimated from the ROBT 2013 harmonic analysis. Phase-lags are referenced to 0°, Greenwich.~~

Tidal constituents		ROBT (2013) 369 days		JBARS (2017) 17 days		JBARS (2019) 21 days		Note
		$a_{r\eta}$ (cm)	$g_{r\eta}$ (°)	$a_{o\eta}$ (cm)	$g_{o\eta}$ (°)	$a_{o\eta}$ (cm)	$g_{o\eta}$ (°)	
Diurnal	O_1	21.1	202	19.6	208	16.0	208	ROBT: Diurnal
	K_1	20.5	217	16.3	214	14.9	216	tides (F=4.1)
	P_1	6.6	215	5.2	213	4.8	214	ADI=0.57 day
	Q_1	4.4	190	-	-	-	-	AT=-2.30 days
Semi-diurnal	M_2	5.3	5	6.7	4	6.3	34	
	S_2	4.9	309	6.4	329	6.6	324	JBARS: Mixed,
	N_2	3.8	255	-	-	-	-	mainly diurnal tides (F=2.7)
	K_2	1.8	315	2.4	333	2.4	328	ADI=0.23 day AT=-1.44 days

Table 1. Major tidal harmonic results for diurnal and semidiurnal constituents from harmonic analyses of sea level observations: year-long (2013) records from Cape Roberts (ROBT), and 17.04 day records (29 Jan. to 15 Feb. 2017) and 20.54 day records (29 Dec. 2018 to 18 Jan. 2019) from Jang Bogo Antarctic Research Station (JBARS) in the Ross Sea (see source details in Sect. 2). For the JBARS tidal harmonic analyses, the inference method was applied to separate out the K_1 (S_2) and P_1 (K_2) tidal constituents, using inference parameters estimated from the ROBT 2013 harmonic analysis.

Tidal constituents & characteristics		ROBT (2013) 369 days		JBARS (2017) 17.04 days		JBARS (2019) 20.54 days	
		Amp. (cm)	Pha. (°)	Amp. (cm)	Pha. (°)	Amp. (cm)	Pha. (°)
Diurnal	O_1	21.1	202	19.6	208	16.0	208
	K_1	20.5	217	16.3	214	14.9	216
	P_1	6.6	215	5.2	213	4.8	214
	Q_1	4.4	190	-	-	-	-
Semidiurnal	M_2	5.3	5	6.7	4	6.3	34
	S_2	4.9	309	6.4	329	5.7	320
	N_2	3.8	255	-	-	-	-
	K_2	1.8	315	2.4	333	2.4	328
F		4.1 (diurnal form)		2.7 (mixed, mainly diurnal)		2.6 (mixed, mainly diurnal)	
ADI (day)		0.57		0.23		0.30	
AT (day)		-2.30		-1.44		-2.87	

Note: Amp. denotes amplitude; Pha. denotes phase lag, referenced to 0° Greenwich; F is the amplitude ratio of the (K_1 + O_1)/(M_2 + S_2) tides; and ADI and AT denote the age of diurnal inequality and the age of the tide.

Table 2. Harmonic constants for 6 long-period tidal constituents, derived from harmonic analyses of yearlong observations (2013) measured at the Cape Roberts sea level gauge (ROBT)

Constituent		Period (day)	Angular speed (°·hr^{-1})	Amplitude (cm)	Phase lag (°)
Solar annual	S_a	365.24	0.0410686	5.8	75
Solar semi-annual	S_{sa}	182.62	0.0821373	0.1	352
Lunar monthly	M_{sm}	31.81	0.4715280	0.4	57
	M_m	27.55	0.5443747	2.9	139
Lunar fortnightly	M_{sf}	14.77	1.0158958	1.2	281
	M_f	13.66	1.0980331	2.7	153

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)

Constituent		Amplitude (cm)	Amplitude standard error (cm)	Phase lag (°)	Phase lag standard error (°)	SNR
Solar annual	S_a	5.8	4.8	75	50	1.5
Solar semi-annual	S_{sa}	0.1	3.3	352	194	0.06
Lunar monthly	MS_m	0.4	3.5	57	254	0.02
	M_m	2.9	3.8	139	102	0.59
Lunar fortnightly	MS_f	1.2	3.0	281	189	0.14
	M_f	2.7	3.9	153	101	0.47

Phase lags are referenced to 0°, Greenwich, and SNR denotes the signal-to-noise ratios.

Table 3. Harmonic constants for the S_a constituent derived from harmonic analyses of 4 separate year-long observation records (2008; 2011; 2012; 2013) measured at the Cape Roberts sea level gauge (ROBT)

Year	Amplitude (cm)	Phase lag (°)
2008	9.1	131
2011	1.2	90
2012	3.4	108
2013	5.8	75

Phase lags are referenced to 0°, Greenwich.

Figure 1. Drifting ice, including icebergs and mobile sea ice, around the Jang Bogo Antarctic Research Station (JBARS), photographed on 29 Jan. 2017.

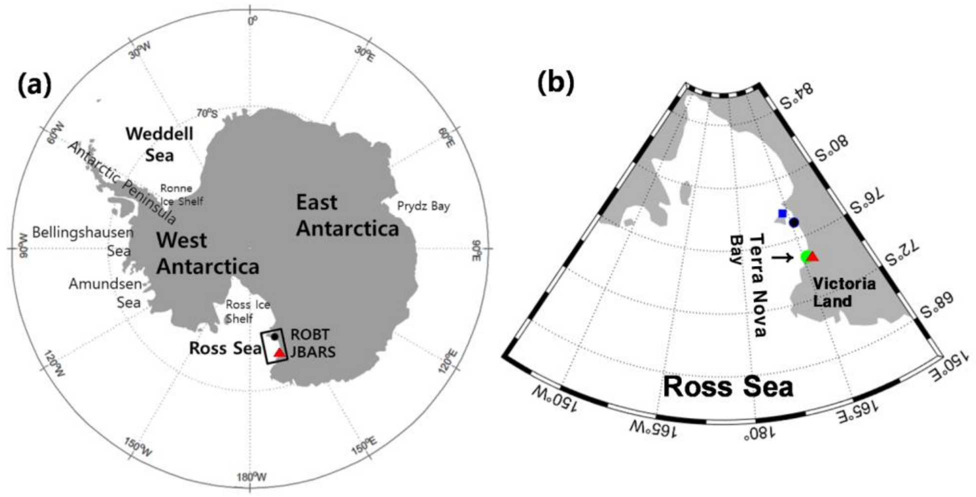
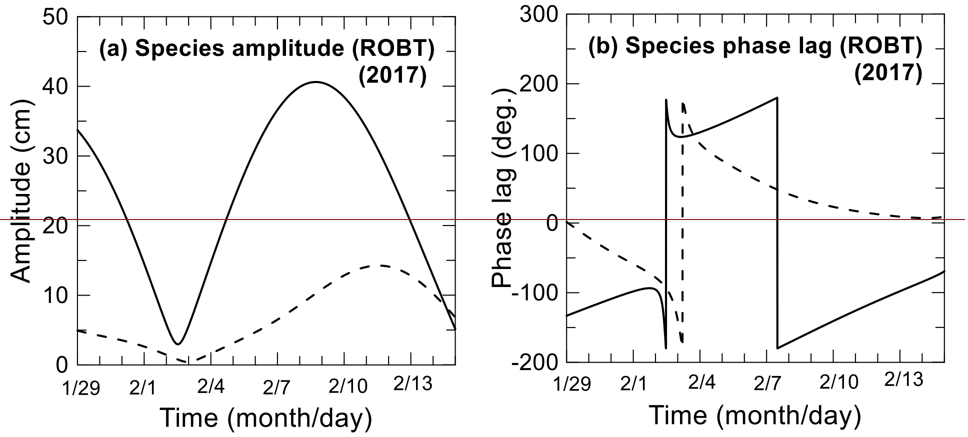


Figure 2. ~~(a)~~ **Maps showing (a) the locations of the two tidal observation stations employed in this study within a wider Antarctic context~~in the Ross Sea of Antarctica~~: Jang Bogo Antarctic Research Station (JBARS, ▲) and Cape Roberts (ROBT, ●); and (b) the case study station locations relative to two other (previous) temporary tidal observations stations, McMurdo Station (■), and Mario Zucchelli Station (●), in the Ross Sea.**



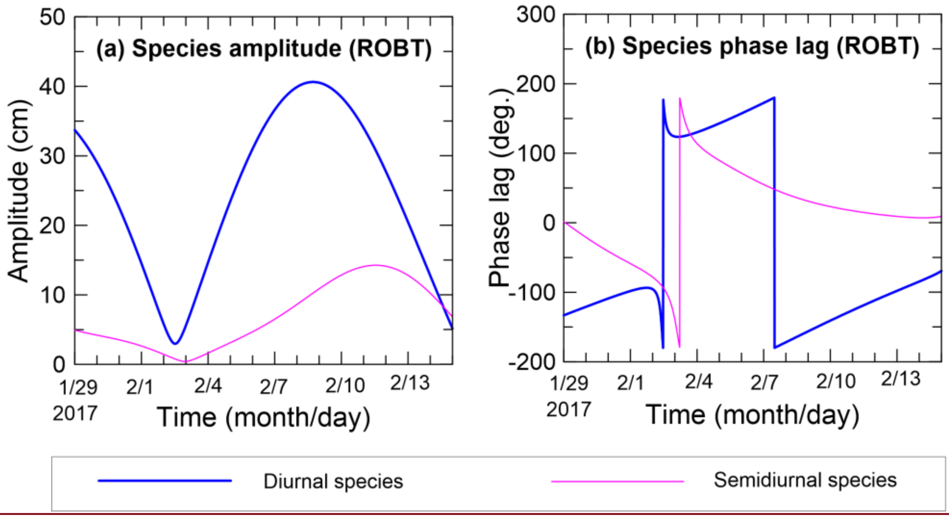
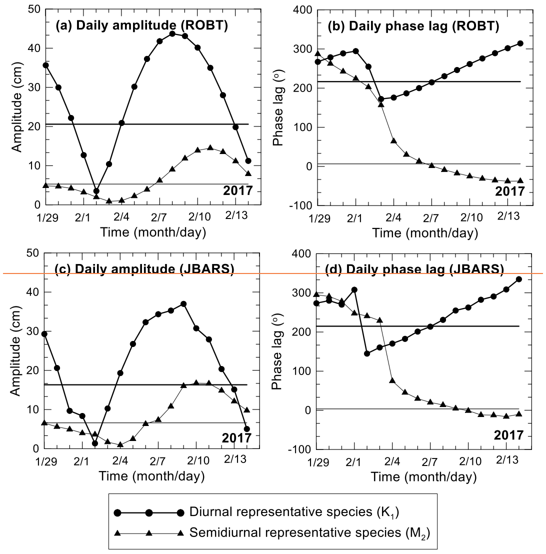


Figure 3. Modulated tidal (a) species amplitudes and (b) phase lags for the diurnal and semidiurnal tidal species, calculated from Cape Roberts (ROBT) tidal prediction data (29 Jan. to 14 Feb. 2017), using Appendix 1 Eqs. (A1) and (A3).Figure 3. Seventeen day time series (29 January to 14 February 2017) of the modulated tidal (a) species amplitudes and (b) phase lags for the diurnal (solid lines) and semidiurnal tides (dashed lines), calculated from the 2017 Cape Roberts (ROBT) tidal prediction data.


(a) Daily amplitude (ROBT)
Amplitude (cm)
Time (month/day)
(b) Daily phase lag (ROBT)
Phase lag (°)
Time (month/day)
(c) Daily amplitude (JBARS)
Amplitude (cm)
Time (month/day)
(d) Daily phase lag (JBARS)
Phase lag (°)
Time (month/day)
2017
1/29
2/1
2/4
2/7
2/10
2/13
Diurnal representative species (K_1)
Semidiurnal representative species (M_2)

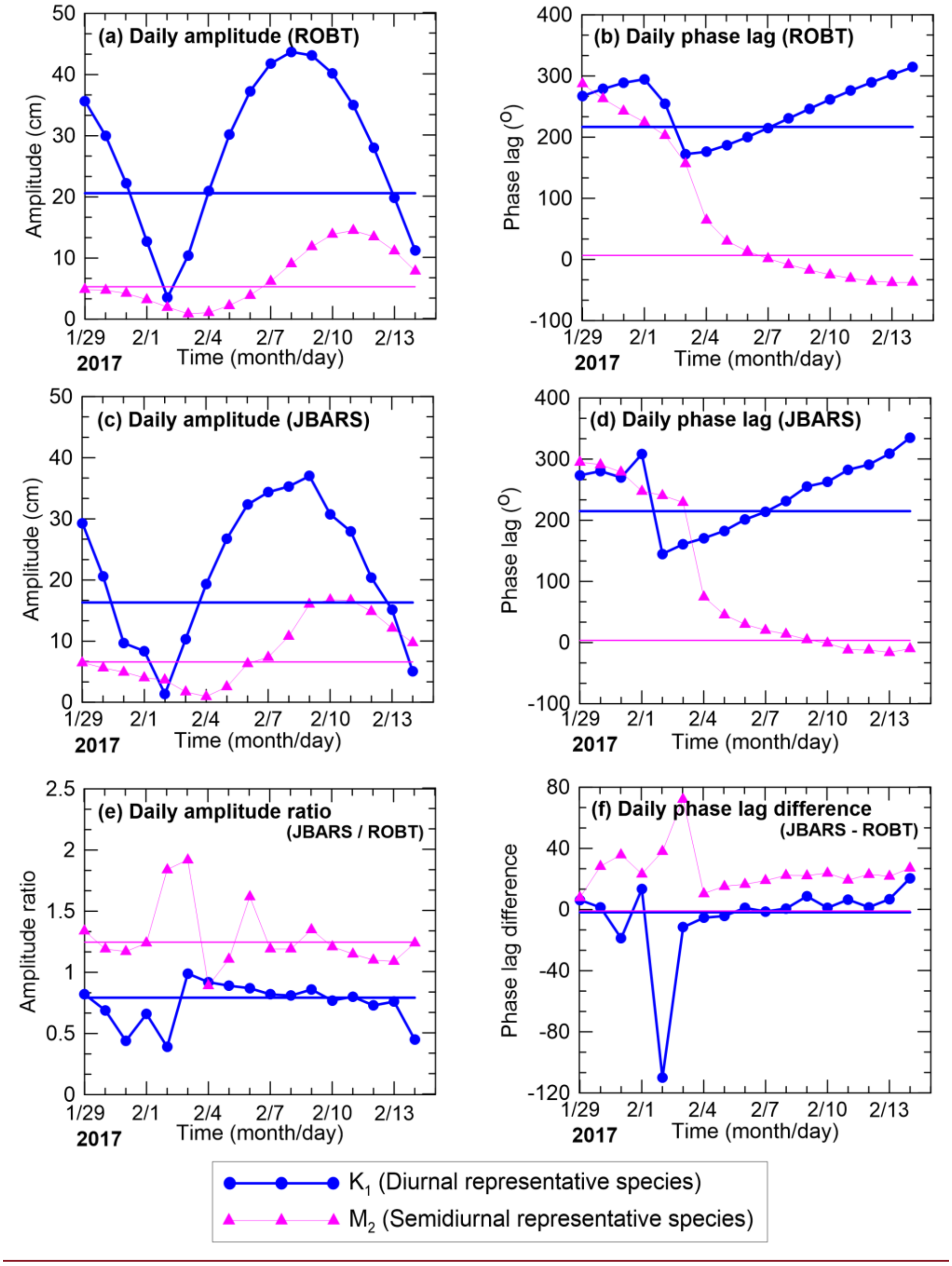


Figure 4. Daily amplitudes (a, c); phase lags (b, d); amplitude ratios (e); and phase lag differences (f) of the K_1 and M_2 tides (representative diurnal and semidiurnal tide species) at ROBT (a, b) and JBARS (c, d), and between JBARS and ROBT (e, f), calculated from 'daily' slices of the 29 Jan. to 14 Feb. 2017 ROBT tidal predictions and JBARS sea level observations. In addition, thick blue (K_1) and thin pink (M_2) 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 4. Daily amplitudes and phase lags of the K_1 tide (diurnal representative species) and M_2 tide (semi-diurnal representative species) at ROBT and JBARS, calculated from 25 hr daily data slices of the 17 day ROBT tidal predictions and JBARS sea level observations, 29 January to 14 February 2017. Thick solid (K_1) and thin gray (M_2) lines in each panel indicate the amplitude and phase lag derived from results of the 369 day 2013 ROBT and 17 day 2017 summertime JBARS sea level record harmonic analyses, respectively.

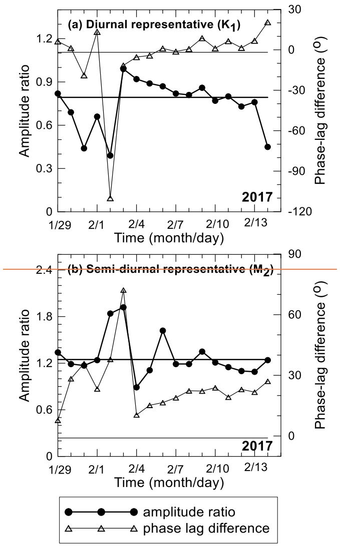
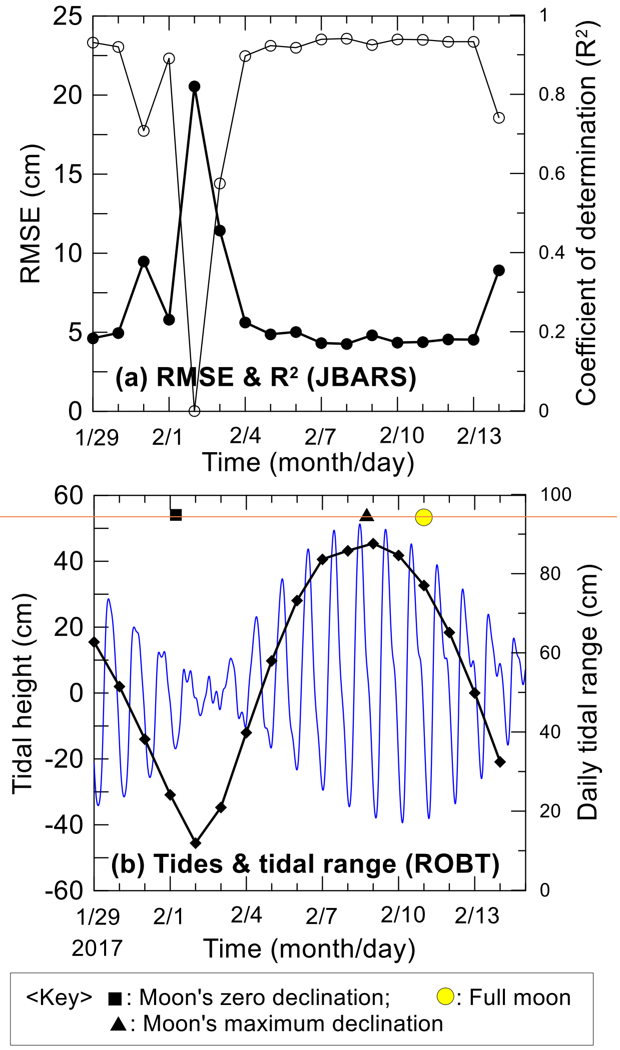


Figure 5. The daily amplitude ratios and phase lag differences of the (a) diurnal (K_1) and (b) semi-diurnal (M_2) species representative tidal constituents, calculated harmonically from JBARS sea level data and ROBT predicted tidal height data, using harmonic inputs derived from analysis of 'daily' (25 hr) data slices. Thick solid and dashed lines in each panel indicate the amplitude ratio and phase lag differences, respectively for each tide, derived from harmonic analysis of the 17 day 2017 JBARS sea level data.


(a) RMSE & R² (JBARS)
RMSE (cm)
Coefficient of determination (R²)
Time (month/day)
1/29
2/1
2/4
2/7
2/10
2/13
(b) Tides & tidal range (ROBT)
Tidal height (cm)
Daily tidal range (cm)
2017
<Key> ■: Moon's zero declination; ●: Full moon
▲: Moon's maximum declination

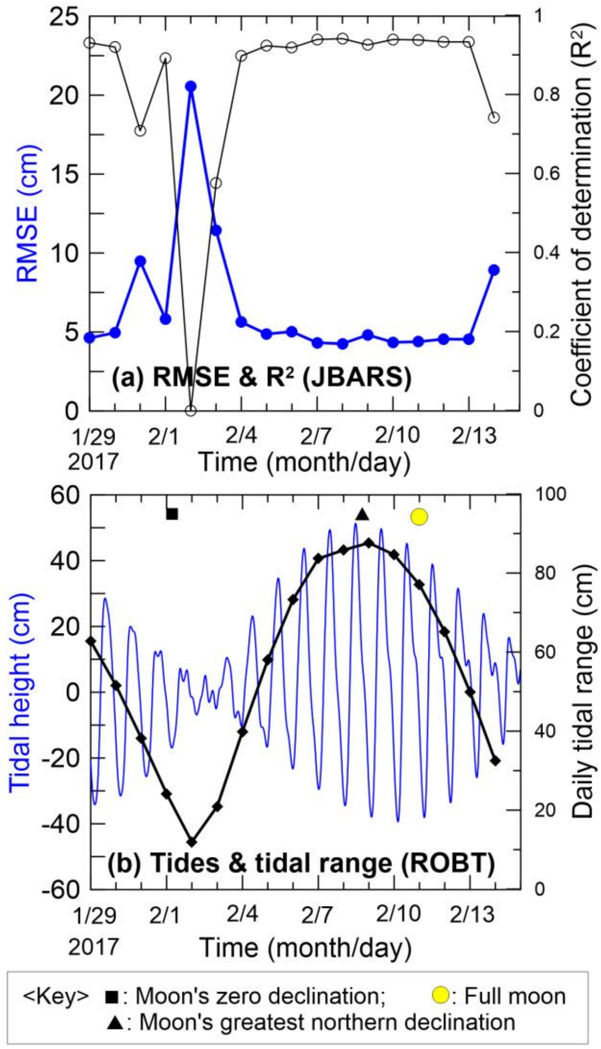
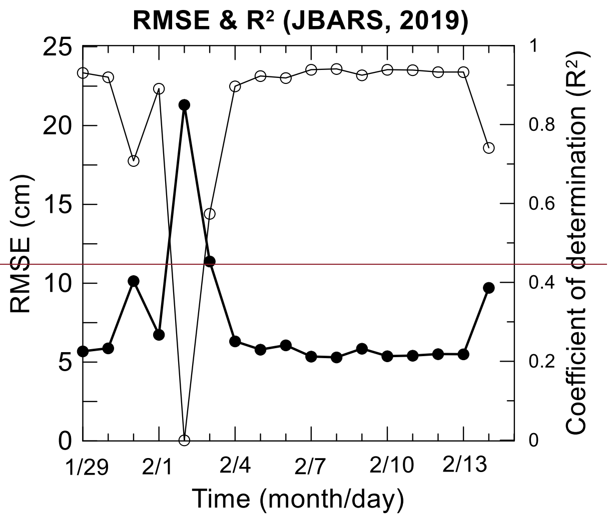


Figure ~~6~~ 5. (a) Time series (29 Jan. to 14 Feb. 2017) of Root Mean Square Errors (RMSE, thick blue line with ●) and coefficients of determination (R^2, thin black line with ○) between JBARS 10 min interval sea level observations ~~(29 January to 15 February 2017)~~ and the CTSM+TCC prediction datasets, generated for this site using harmonic analysis results from the JBARS daily (25 hr) sea level data slices ~~from JBARS plus~~ 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 ~~○~~♦) 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.



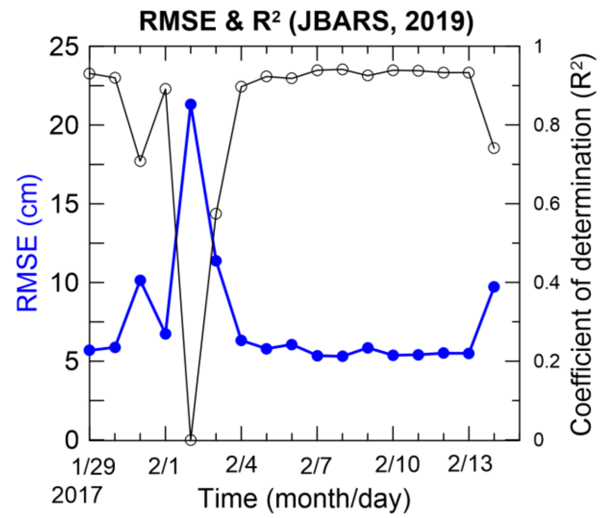
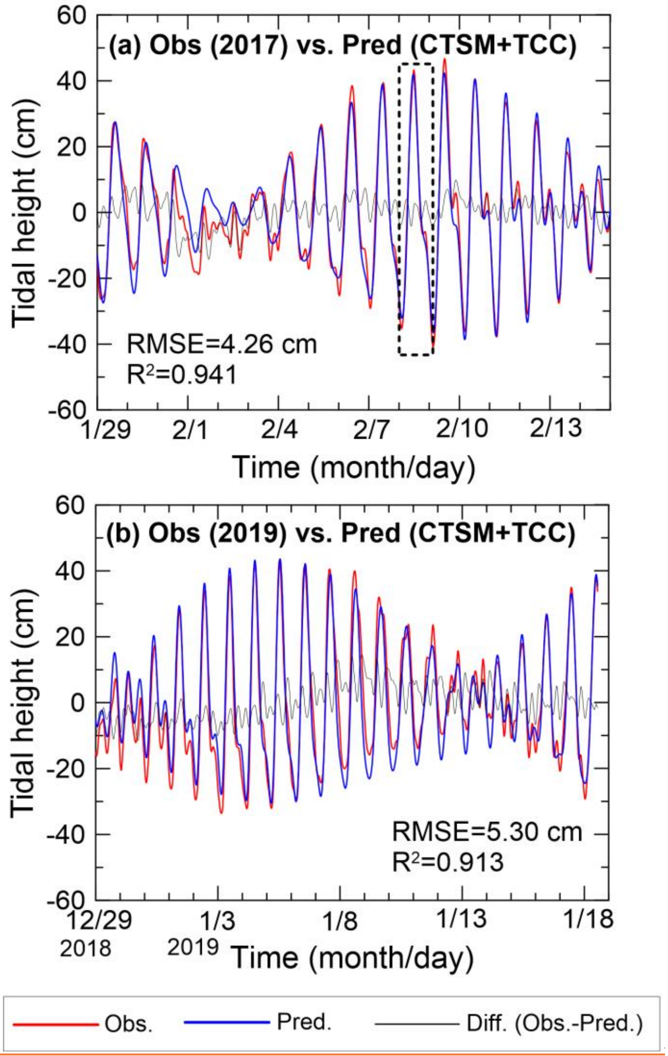


Figure 6~~7~~. Time series of Root Mean Square Errors (RMSE, thick blue line with ●) and coefficients of determination (R^2, thin black line with ○) between JBARS 10 min interval sea level observations (29 Dec.~~ember~~ 2018 to 18 Jan.~~uary~~ 2019) and the CTSM+TCC prediction data sets generated for this site (using harmonic analysis results from daily (25 hr) summertime 2017 sea level data slices from JBARS ~~plus~~ along with concurrent daily (25 hr) tidal prediction slices and harmonic analysis results from ROBT station's year-long (2017) tidal predictions).

1802 
(a) Obs (2017) vs. Pred (CTSM+TCC)
RMSE=4.26 cm
R²=0.941
Tidal height (cm)
Time (month/day)
1/29
2/1
2/4
2/7
2/10
2/13
(b) Obs (2019) vs. Pred (CTSM+TCC)
RMSE=5.30 cm
R²=0.913
12/29 2018
1/3 2019
1/8
1/13
1/18
Obs.
Pred.
Diff. (Obs.-Pred.)

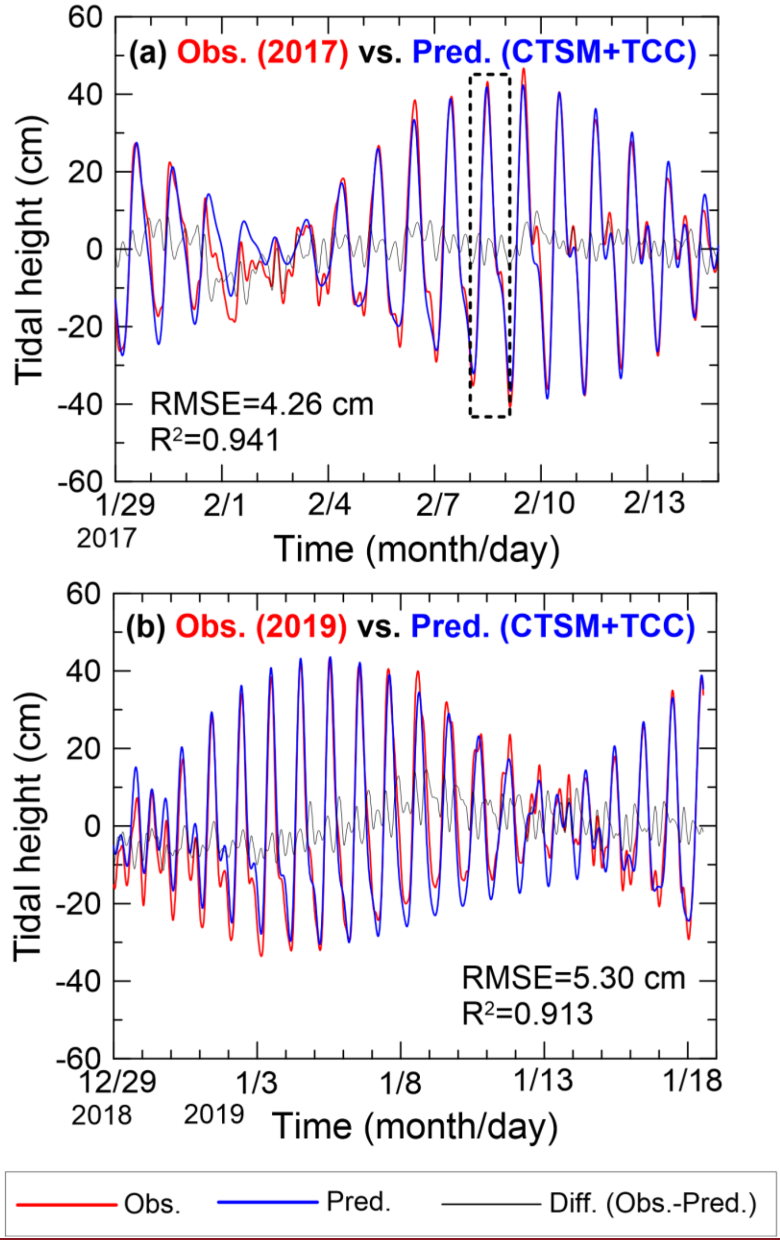


Figure 7~~8~~. Time series of JBARS sea level observations (Obs.), predicted tidal heights (Pred.), and sea level residuals (Diff.~~i.e. predictions minus observations~~) from (a) 29 Jan.~~uary~~ to 14 Feb.~~ruary~~ 2017; and (b) 29 Dec.~~e mber~~ 2018 to 18 Jan.~~uary~~ 2019. The JBARS predictions were generated ~~using~~ via the CSTM+TCC method (using~~, with~~ a daily (25 hr) slice of local sea level observations from 8 Feb.~~ruary~~ 2017 (dashed box in (a)), ~~plus~~ along with concurrent (to time periods a and b) ROBT predictions; and year-long (2017)~~,~~ 5 min interval ROBT tidal predictions). RMSE and R^2 denote the comparison Root Mean Square Errors and coefficients of determination, respectively.

1811

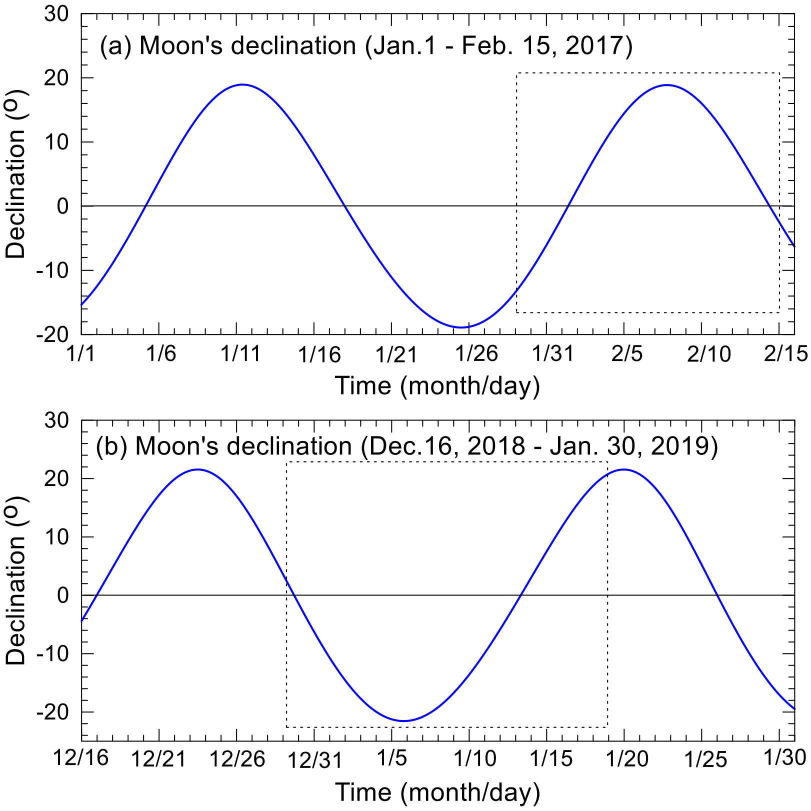
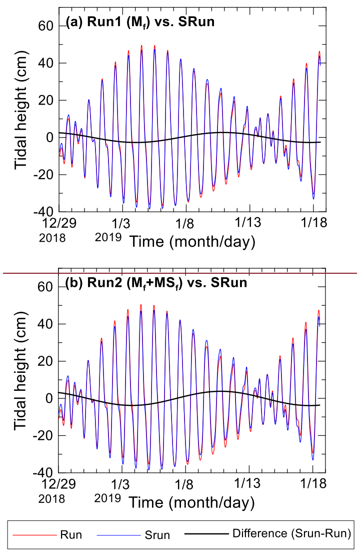


Figure ~~8~~9. Time series of the Moon's declination, ~~estimated~~ calculated at daily intervals for two observation periods: (a) 1 Jan.~~uary~~ to 15 Feb.~~ruary~~ 2017; and (b) 16 Dec.~~ember~~ 2018 to 30 Jan.~~uary~~ 2019. Dashed boxes indicate the sea level observation windows examined in this study.


(a) Run1 (Mf) vs. SRun
Tidal height (cm)
60
40
20
0
-20
-40
12/29
2018
1/3
2019
1/8
1/13
1/18
Time (month/day)
(b) Run2 (Mf+MSf) vs. SRun
Tidal height (cm)
Run
Srun
Difference (Srun-Run)

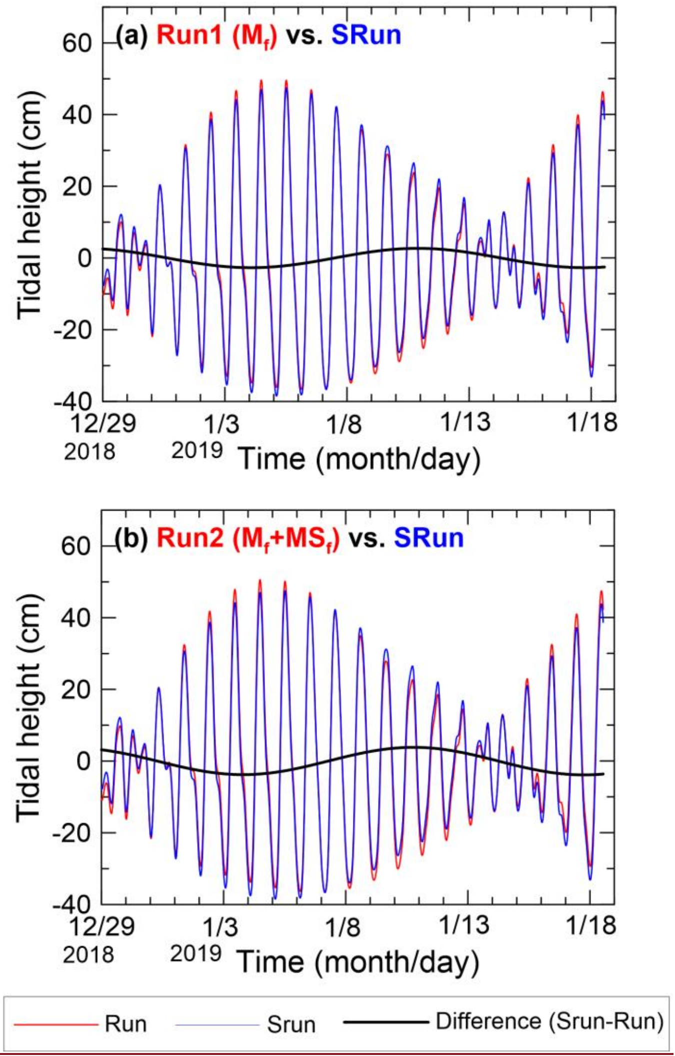


Figure 9~~10~~. Time series of ROBT tidal predictions (a) made without long-period constituents (‘SRun’, i.e. excluding the constituents listed in Table 2) versus with the M_f tide (‘Exp1’); and (b) time series of ROBT tidal predictions made (‘SRun’) without the long-period constituents versus (‘Exp2’) with the MS~~s~~$_f$ and M_f tides. All predictions were generated based on tidal harmonic analysis results from the year-long (2013) ROBT sea level records.

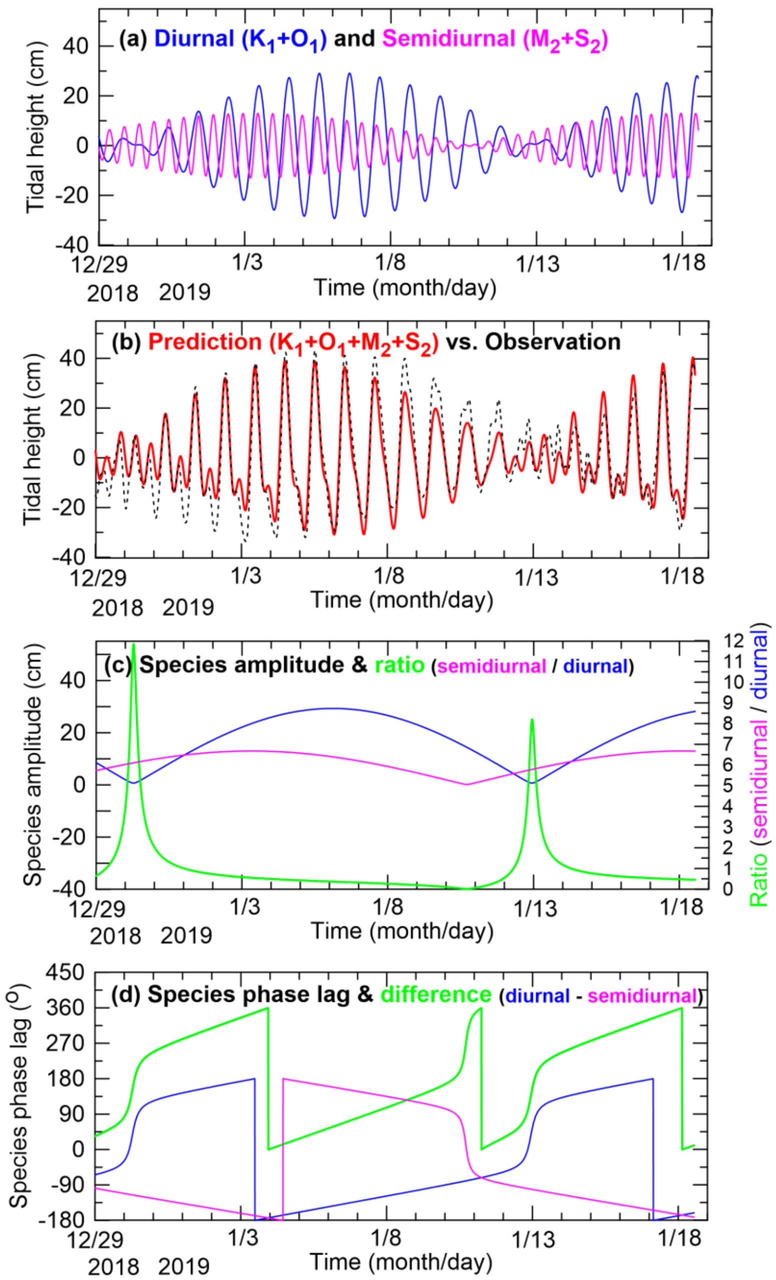
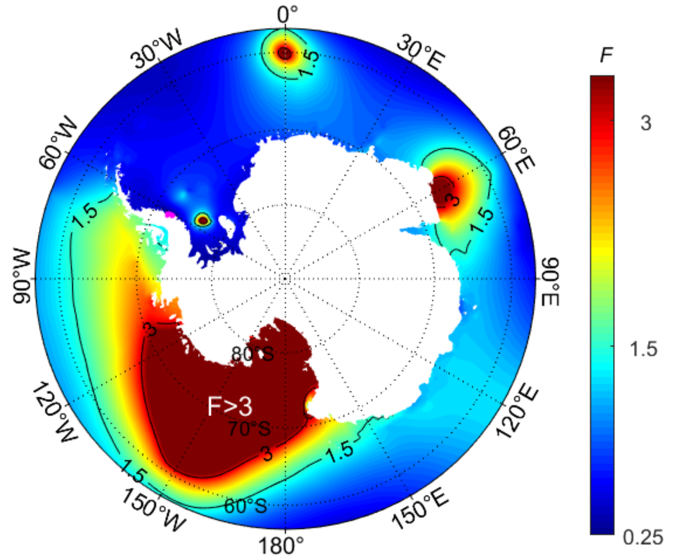


Figure 10. Time series (29 Dec. 2018 to 18 Jan. 2019) of (a) predictions of the diurnal (K_1+O_1) tides (blue line) and the semidiurnal (M_2+S_2) tides (magenta line) for JBARS; (b) their combined JBARS predictions (red line) and observations (black dashed line); (c) the ROBT diurnal (blue line) and semidiurnal (magenta line) species amplitudes and their ratio (green line); and (d) the ROBT diurnal (blue line) and semidiurnal (magenta line) species phase lags and their difference (diurnal – semidiurnal) (green line).



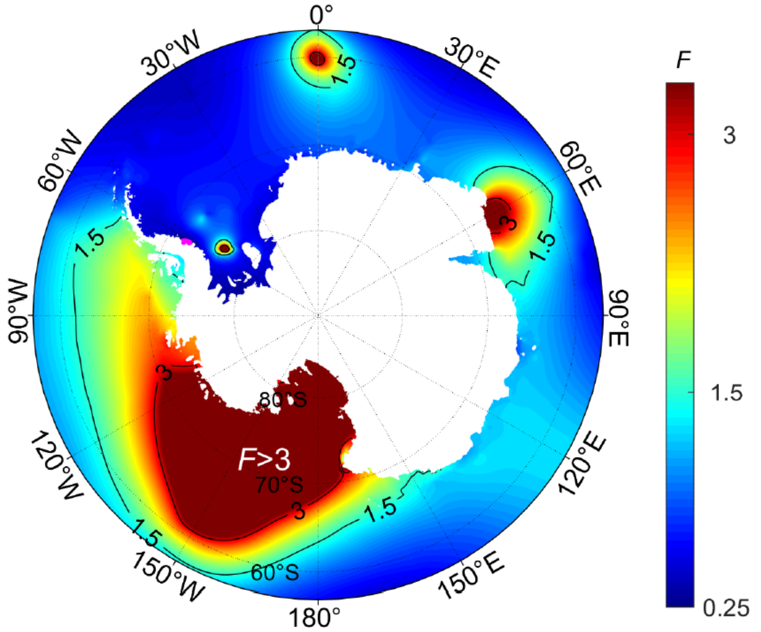


Figure 11. ~~Horizontal~~ Ddistribution of tidal form factor (*F*) values around Antarctica. Note the magenta area (72°S) on the Antarctic Peninsula's Weddell Sea coast denotes the only area with a~~of~~ properly semi-diurnal tide regimes (*F*<0.25) in the Antarctic region.