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

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

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Format We are very grateful for this editorial comment as it has been useful in helping to improve our paper. In this reply we copied each individual reviewer point, wrote below it a response, then pasted the modified text of the paper to show the changes made.

Individual review comments and our responses.

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 methodological communication based on your comments above. As a result we wrote a simpler explanation of the

approach for Section 3, and cut and pasted all of the original math parts into the new Appendix 1. In this new appendix we defined all undefined terms and fixed the issues you identify below. The newly focused Section 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 SHr; 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: "Having analysed the tidal harmonic constants at the two stations based on their concurrent short-term records, we then employed the CTSM+TCC method (Byun and Hart, 2015) to generate tidal height predictions for JBARS, our 'temporary' tidal observation station (subscript o), using ROBT as the 'reference' station (subscript r). This prediction approach (see Appendix 1 for the detailed calculations, and Byun and Hart (2015) for explanation of procedure development) is based on: using long-term ($\geq$183 days) reference station records (LHr) and CTSM calculations to make an initial anytime (τ) tidal prediction (η_r (τ)), which involves summing tidal species' heights for the reference station (Fig.3); comparing the tidal harmonic constants (amplitude ratios and phase lag differences) of representative tidal constituents (e.g., M2 and K1) for each tidal species between the temporary and reference stations, calculated using T_TIDE and concurrent short-term records ($\geq$25 hr duration, starting at midnight) from the temporary (SHo) and reference (SHr) stations; and using the step (ii) comparative data and the TCC calculations for each tidal species to adjust the η_r (τ) tidal species' heights in order to generate accurate, anytime tidal height predictions for the temporary tidal station (η_o (τ)). In this Ross Sea case study we used the 2017 austral summertime JBARS tidal observation records (i.e. 17.04 days from 00:00 29 January to 01:00 15 February) as a source of SHo, keeping the second 2019 JBARS 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. LHr must comprise high quality (e.g. few missing data) tidal height observations from anytime. For SHo and SHr, Byun and Hart (2015) employed observational data for both records, but as will be demonstrated in this paper, the method can also be applied using tidal predictions as a source of SHr. This slight adjustment in approach arose since for the 2017 JBARS observation time period, the concurrent 2017 ROBT records available online (LINZ, 2019) had multiple missing data. We solved this issue by producing a year-long synthetic 2017 record for ROBT using T_TIDE (Pawlowicz et al., 2002) and the 2013 (i.e. LHr) observational record as input data. The 17.04 days of predicted tides that were concurrent with the 2017 JBARS observation record were then used as our SHr source. While this CTSM+TCC 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 challenging to obtain 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 η_o (τ), each using different concurrent pairs of SHo and SHr daily data slices in step (ii) above to produce daily amplitude ratios and phase lag differences between the two stations for the diurnal K1 and semidiurnal M2 tidal constituents. Comparisons are then made between the different η_o (τ) data sets produced and the original temporary station observations, to determine the optimal 25 hr window to use in subsequent calculations of anytime η_o (τ). Once the optimal window is 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 summertime JBARS observation records and from the concurrent ROBT predictions, forming 17 pairs of SHo and SHr ‘daily’ slices. Each paired data set was then used with LHr to generate tidal height predictions for JBARS covering both the 2017 and 2019 KHOA temporary observation campaign time periods. Comparisons were made between the JBARS observations and the 17 prediction data sets generated for each observation campaign to identify which 25 hr short-term data window produces optimal η_o (τ) results".

And the new Appendix 1 (complimenting the new section 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 (SHo), our temporary tidal observation station (subscript o), and 2013 year-long observations (LHr) and 2017 short-term tidal predictions (SHr, concurrent with SHo) 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: calculating each tidal species' modulation at the reference tidal station; 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 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 (η_o (τ)) were initially derived from reference station predictions (η_r (τ)) 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 (φ_r^((s))) for each tidal species, this step is expressed as: η_r (τ)=∑_(s = 1)^k A_r^((s))(τ) cosâĄą(ω_R^((s)) t-φ_r^((s)) (τ)) ãĂŮ (A1) with A_r^((s)) (τ)=√(∑_(i = 1)^m[f(τ)ãĂŮ_i^((s)) a_i^((s))]^2+2∑_(i = 1)^($m-2$) ∑_($j = i + 1$)^m[f(τ)ãĂŮ_i^((s)) a_i^((s))][ãĂŰf(τ)ãĂŮ_j^((s)) a_j^((s))] cosâĄą{(ω_i^((s))-ω_j^((s)))t+[ãĂŰV(t_0)ãĂŮ_i^((s))+ãĂŰu(τ)ãĂŮ_i^((s))-G_i^((s))]-

[ãĂŰV(t_0)ãĂŮ_jˆ((s))+ãĂŰu(τ)ãĂŮ_jˆ((s))-G_jˆ((s))]} ãĂŮãĂŮ) (A2) and φ_rˆ((s))(τ)=ãĂŰtanãĂŮˆ(-1) (($\sum$_($i = 1$)ˆ$m a$_iˆ(s))sin[(ω_iˆ((s))-ω_Rˆ((s)))t+ ãĂŰV(t_0)ãĂŮ_iˆ((s))+ãĂŰu(τ)ãĂŮ_iˆ((s))-G_iˆ((s)) ãĂŮ]/($\sum$_($i = 1$)ˆ$m a$_iˆ(s))cos[(ω_iˆ((s))-ω_Rˆ((s)))t+ ãĂŰV(t_0)ãĂŮ_iˆ((s))+ãĂŰu(τ)ãĂŮ_iˆ((s))-G_iˆ((s)) ãĂŮ])) (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 ãĂŰτ= tãĂŮ_0+t; ω_iˆ((s)) are the angular frequencies of each tidal constituent (subscripts i and j), ω_Rˆ((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., K1 and M2 are used as representative of the diurnal and semidiurnal species, respectively). For each tidal constituent, a_iˆ((s)) and G_iˆ((s)) are the tidal harmonic amplitudes and phase lags (referenced to Greenwich), ãĂŰf(τ)ãĂŮ_iˆ((s)) is the nodal amplitude factor of each tidal constituent, ãĂŰu(τ)ãĂŮ_iˆ((s)) is the nodal angle and ãĂŰV(t_0)ãĂŮ_iˆ((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 tidal observation and reference tidal stations (i.e. from SHo and SHr). The process of selecting the optimal 25 hr window for these concurrent data slices from amongst the 17.04 days of available records is explained in Section 3 of this paper. Once the optimal 2017 short-term data window was selected, the third step involved adjusting the tidal predictions at the reference station calculated from Eq. (A1), to represent those for the temporary station (η_o (τ)), by substituting the daily (i.e. SHo and SHr) amplitude ratios ((a_oˆ((s)))/(a_rˆ((s)))) and phase lag differences (G_oˆ((s))-G_rˆ((s))) for the tidal constituents (K1 and M2) representing the diurnal and semidiurnal tidal species between the temporary and reference stations into Eq. (A1) as follows (Byun and Hart, 2015): η_o (τ)=$\sum$_($s = 1$)^k A_o^((s))(τ) cosâĄą(ω_Rˆ((s)) t-φ_oˆ((s)) (τ)) ãĂŮ (A4) with A_oˆ((s)) (τ)=A_rˆ((s)) (τ)((a_oˆ((s)))/(a_rˆ((s)))), and (A5) φ_oˆ((s)) (τ)=φ_rˆ((s)) (τ)+G_oˆ((s))-G_rˆ((s)) (A6) Substituting Eqs. (A5) and (A6) into Eq. (A4), η_o (τ) can be expressed as: η_o (τ)=$\sum$_($s = 1$)^k A_r^((s))(τ)((a_oˆ((s)))/(a_rˆ((s))))cosâĄą[ω_Rˆ((s)) t-(φ_rˆ((s)) (τ)+G_oˆ((s))-G_rˆ((s)))] ãĂŮ (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 agree so have reduced section 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 Ross Sea tidal predictions We have demonstrated that the CTSM+TCC approach can produce reasonably accurate tidal predictions (RMSE <5 cm, R2 >0.92) for a new site in the Ross Sea, Antarctica, based on 25 hr temporary observation records from periods with higher than 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 R2 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 tides. Table 2 summarises the characteristics of 6 long-period tides (Sa, Ssa, MSm, Mm, Mf, MSf) at the ROBT station, derived from tidal harmonic analysis of year-long (2013) in situ observation records. To verify the main cause of the apparent fortnightly prediction biases in results, in particular that in the 2019 predictions (Fig. 7b), we examined the effects of two fortnightly tidal constituents (Mf, and MSf) 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 Mf; and Run2 was based on Srun but also incorporated the Mf and MSf. Comparisons between Run1 and Srun predictions show that exclusion of the Mf tide (2.7 cm amplitude) can produce prediction biases during periods of lunar declination change (Fig. 9a), with comparisons between Run2 and Run1 results showing that the additional exclusion of the MSf tide (1.2 cm amplitude) intensifies the biases (Fig. 9b). Rosier and Gudmundsson (2018) found that ice flows are modulated at various tidal frequencies, including that of the MSf tide. 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. 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 section 4.1. The section 4.1 text now includes: "As illustrated in Fig.5, the RMSE and R2 results varied in relation to the JBARS tidal range (range being twice amplitude), with greater accuracy evident in predictions made using data derived from 25 hr periods when the tidal range was higher than average". Section 5.2 now reads: "Figure 11 illustrates the form factors of tidal regimes in the seas surrounding Antarctica, according to FES2014 model data. There are large areas characterised by 'diurnal' (F>3); 'mixed, mainly diurnal' (1.5<F<3); and 'mixed, mainly semidiurnal' (0.25<F<1.5) forms. Only in a small area half-way along the Weddell Sea coast of the Antarctic Peninsula (at 72°S) do tides exhibit a 'semidiurnal' form (F<0.25). Strong 'diurnal' tides predominate in the Ross Sea area of West Antarctica, around to the Amundsen Sea. In addition, a small area near Prydz Bay (Fig. 2) in East Antarctica exhibits diurnal and mixed mainly diurnal tides. The rest of the seas surrounding Antarctica, including the Weddell Sea, are predominantly characterised by 'mixed, mainly semidiurnal' tides. Since diurnal tides have larger nodal factor and nodal angle variations than semidiurnal tides (Pugh and Woodworth, 2014), areas like the Ross Sea will have larger variations in tidal height across the 18.61 yr lunar nodal cycle compared to areas like the Weddell Sea (see details for ROBT in Byun and Hart, 2019). As the nodal angle variations of the diurnal and semidiurnal tides are out of phase, this leads to differing tidal responses around Antarctica over 18.61 years, particularly between the Ross and Weddell Seas. Given that CTSM+TCC is based on modulated tidal constant corrections for each diurnal and semidiurnal species, it is applicable in studying a continent with such a diversity of tidal regime types. Accurate (cm scale) quantification of the contrasting tidal behaviours and environments around Antarctica's margins are not only of use for polar station maritime operations, they are essential for estimating ice flows to the sea. This paper has shown how the CTSM+TCC approach may be used to complement existing efforts to quantify variations in tidal processes around Antarctica, in particular for places with sparse in situ tidal monitoring, such as the Ross Sea".

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 Section 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 January 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 (K1, O1) and semidiurnal tides (M2, S2). Fig. 10a shows separately the resulting diurnal (with their period of 13.66 days) and semi-diurnal (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 semi-diurnal 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 semi-diurnal 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 has been uploaded and its full caption now reads: "Figure 10. Time series (29 December 2018 to 18 January 2019) of (a) predictions of the diurnal (K1+O1) tides (blue line) and the semidiurnal (M2+S2) 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 reviewer 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: Thank you, we have added the word "tidal". The text now ends: "...to accurately predict tides for a temporary tidal station in the Ross Sea, Antarctica using records from a neighbouring reference station charac-

terised 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 throughout the paper and replaced with "at high lunar declinations". For example, line 18 test 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 declinations and/or spring periods)".

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. 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 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. . ."

50 - transfers –> transfer Response: This has been changed as suggested. The text

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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 imagery 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 section 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 constituents".

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 the second (Rowe) review. 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. The inference method was used to separate out neighbouring diurnal (K1 and P1) and semidiurnal (S2 and K2) tide constituents, with their amplitude ratios and phase lag differences obtained from harmonic analysis of the long-term ROBT reference station records. Analysis revealed that the two main diurnal (O1 and K1) and semidiurnal (M2 and S2) tides had similar amplitudes at the two stations (Table 1), with the diurnal amplitudes being slightly larger at ROBT than at JBARS, the semidiurnal amplitudes being slightly smaller at ROBT than at JBARS, and the phase lags of all four tides having only slightly different values”.

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 comment in review 2). 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 from Reviewer 2 (Rowe).

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 the second (Rowe) review, before this section was rewritten, cutting and pasting the math into a new Appendix 1. Regarding the italics, we intended to highlight these terms but removed them in response to a similar comment in the Rowe review (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 re-write of section 3 (see comment explaining this towards the beginning of this reply). This particular part of the new section 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. LHr) 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 SHr source. While this CTSM+TCC 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 challenging to obtain 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 section 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: "...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 section 2.1 of the paper, in response to your query. We also hope that our clearer section 3 eliminates the confusion created here. The text of section 2.1 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 January and 16 February 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, starting from midnight, for each prediction experiment. That left us with 17 days and 1 hour of useable tidal observation data as the basis of the temporary tidal station's primary observation record in this study".

175 - where –> when Response: This change has been made. The text now reads: "As illustrated in Fig.5, the RMSE and R2 results varied in relation to the JBARS tidal range (range being twice amplitude), with greater accuracy evident in predictions made using data derived from 25 hr periods when the tidal range was higher than average".

227 - versus –> and day –> days add respectively at end of sentence Response: These changes have been made. The text now reads: "Results revealed that the ADI are very similar, and there is <1 day AT difference, between the two stations. The ADI values were 0.57 and 0.23 or 0.30 days, while the AT values were -2.30 and -1.44 or -2.87 days, for ROBT and JBARS respectively (Table 1)".

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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 JBARS tidal predictions, using concurrent 25 hr records from both stations and long-term reference records from ROBT”.

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 the shortening of section 5.1 while brief mention has been made of lunar declination changes. 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 Mf tide (2.7 cm amplitude) can produce prediction biases during periods of lunar declination change (Fig. 9a), with comparisons between Run2 and Run1 results showing that the additional exclusion of the MSf tide (1.2 cm amplitude) intensifies the biases (Fig. 9b)”.

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 the Rowe review, 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 MSf 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)”.

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 verify the main cause of the apparent fortnightly

prediction biases in results, in particular that in the 2019 predictions (Fig. 7b), we examined the effects of two fortnightly tidal constituents (Mf, and MSf) 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 Mf tide (2.7 cm amplitude) can produce prediction biases during periods of lunar declination change (Fig. 9a), with comparisons between Run2 and Run1 results showing that the additional exclusion of the MSf tide (1.2 cm amplitude) intensifies the biases (Fig. 9b)".

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 of Rowe, including deletion of almost all the digression into ice shelves. Please see the new text early in this reply, and the response to Rowe 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 patch 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 section 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 the Rowe review.

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 the Rowe review 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. The new Table 1 will be included in the merged ‘reply to all reviews’ file, and its caption now reads: “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 January to 15 February 2017) and 20.54 day records (29 December 2018 to 18 January 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 K1 (S2) and P1 (K2) tidal constituents, using inference parameters estimated from the ROBT 2013 harmonic analysis. Note that Amp. denotes amplitude; Pha. denotes phase lag, referenced to 0°, Greenwich; F is the ratio of the K1 and O1 diurnal tide amplitudes to the M2 and S2 semidiurnal tide amplitudes; 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. The new Table 2 will be included in the merged 'reply to all reviews' file, and its caption now reads: "Table 2. Harmonic constants for 6 long-period tidal constituents, derived from harmonic analyses of year-long observations (2013) measured at the Cape Roberts sea level gauge (ROBT), using T_Tide (Pawlowicz et al., 2002) Phase lags are referenced to 0°, Greenwich and SNR denotes the signal-to-noise ratios".

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 January 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 the Rowe review.

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 the Rowe review.

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 Figure 4 (formerly 5) changes in the response to the Rowe review.

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. Please see details of Figure 5 (formerly 6) changes in the response to the Rowe review.

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. Please see details of Figure 6 (formerly 7) changes in the response to the Rowe review.

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 R2 definitions have been added to the caption. We have also altered this figure to show observations minus predictions, as suggested. Please see details of Figure 7 (formerly 8) changes in the response to the Rowe review.

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 Figure 8 (formerly 9) changes in the response to the Rowe review.

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 Figure 9 (formerly 10) changes in the response to the Rowe review.

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 has been uploaded and its full 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 of fully semidiurnal tides (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.

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

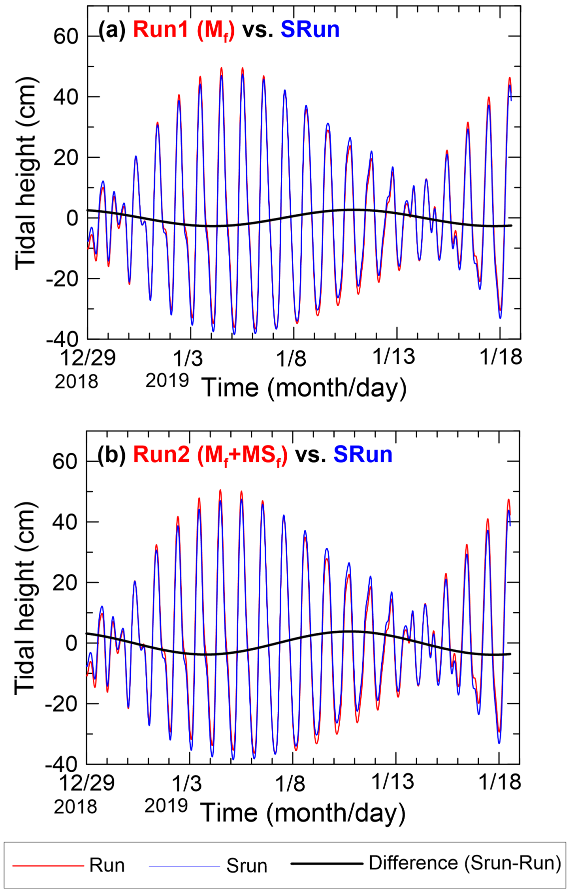

Fig. 1. Figure 9. Time series of ROBT tidal predictions (a) made without long-period constituents ('SRun', i.e. excluding the constituents listed in Table 2) versus with the Mf tide ('Exp1'); and (b) time ser

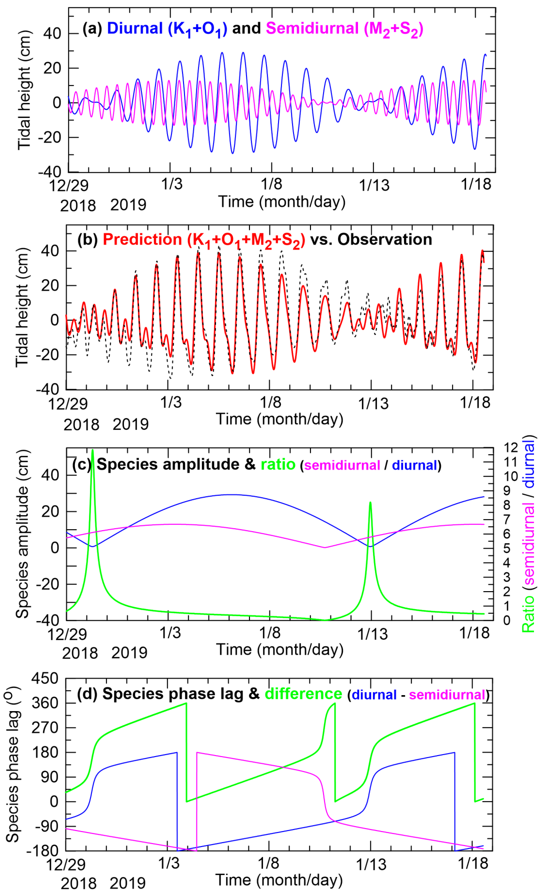

Fig. 2. Figure 10. Time series (29 December 2018 to 18 January 2019) of (a) predictions of the diurnal (K1+O1) tides (blue line) and the semidiurnal (M2+S2) tides (magenta line) for JBARS; (b) their combined

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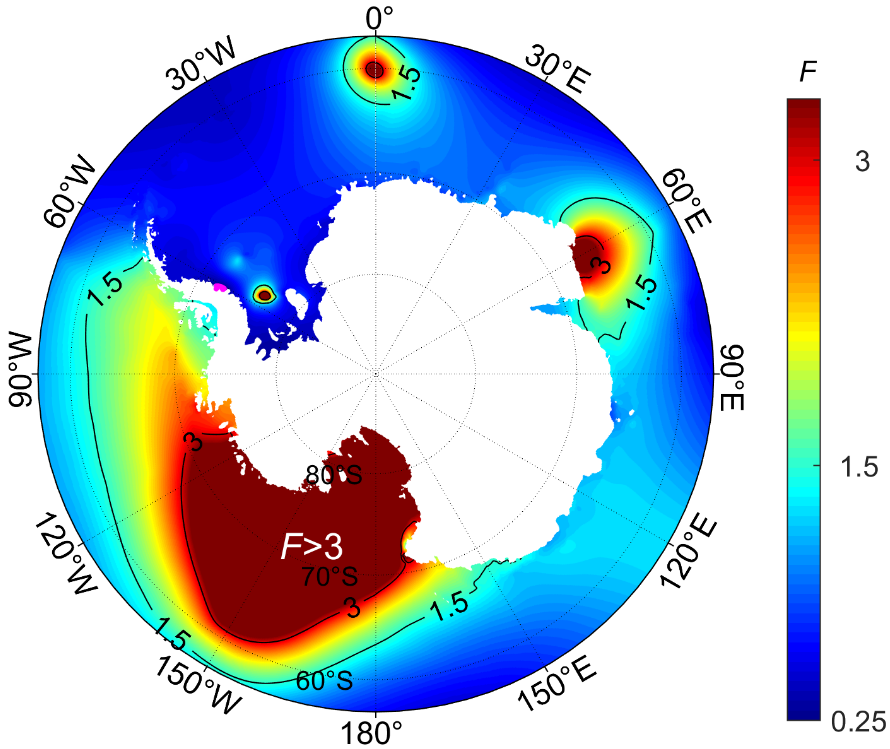

Fig. 3. Figure 11. Distribution of tidal form factor (F) values around Antarctica. Note the magenta area (72°S) on the Antarctic Peninsula's Weddell Sea coast denotes the only area with a properly semidiurnal

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