# *Response to reviews and comments on the paper* "A monthly tidal envelope classification approach for semi-diurnal regimes with variability in $S_2$ and $N_2$ tidal amplitude ratios"

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**Introduction** We are very grateful for the reviews and comments received on this paper as collectively they has been very useful in helping to improve the paper. Below we have copied each individual reviewer comment, written below it a response in blue font, and then copied any insertions or modifications to the text. Almost all suggested changes have been adopted wholesale, but discussion and a couple of the points remain below regarding the link made to flooding hazard. Following our responses and changes made sections, we include in this file a revised version of the full paper with track changes. We will submit the revised paper file separately as well, according to the Copernicus instructions.

## *1.* Reply to *Interactive comment by Philip Woodworth, received and published 22 Dec. 2019*

***Abstract** - if I had written this abstract I would have used the useful words on lines 206-214 of the Discussion. For example, I can see that the new form factor could inform about shoreline ecology as ecology depends on the tidal climatology. However, I cannot see that it is much use in discussion of inundation hazards and climate change; for that one would be interested primarily in the character of sea level extremes and not just on simple descriptions of the tide.*

- **Response:** Thank you for this suggestion regards the discussion text – we have used some of this text to replace the original opening sentence of the abstract. Regards the inundation hazards and climate change link here with perigean-spring tides, this comment relates our experiences in Christchurch (e.g. Allen et al., 2014; Hart et al., 2018). This city (marked by the Sumner gauge site in Fig. 2) experienced up to 1 m relative sea level rise in coastal and river proximal suburbs due to subsidence during the Canterbury Earthquake Sequence (CES, 2010-2011). This instantaneous sea level change was equivalent in magnitude to that which had been predicted (in absolute as opposed to relative terms) for the next 50 to 100 years due to anthropogenic climate change and accelerated sea level rise. We thus use Christchurch as a 'laboratory' to consider what 1 m of sea level rise might look and feel like in a delta city (of which there are many similar settings in seismically active areas worldwide), albeit with process-response timescales being rather different to those under climate change scenarios. One of the greatest effects has been enhanced flooding issues, much more so than other coastline hazards such as erosion. Since the city relies on river and estuary drainage conduits, in particular, when pronounced perigean-spring tides occur in combination with sustained rainfall events, inland riverside and low-lying coastal suburb flooding is widespread, deep and persistent. It would seem that around half of the city had little freeboard, and that buffer has been significantly reduced with the CES such that monthly high tides pose issues for the lowest lying areas nowadays. The backwater effects of high tides combine with atmospheric low pressure and sustained precipitation events to extend the reach of flooding. We suspect that the latter will continue to be enhanced as the baseline mean sea level rises with climate change, meaning less ability to cope with perigean-spring tides. Since the CES, high tide alerts have become of wider public interest as they are now commonly associated with flooding. Understanding the frequency of such tidal alert days has been of use to those at the coal face of flooding, in terms of emergency responses, as well as in making decisions about whether to stay or retreat from subsidence affected areas. We therefore see monthly tidal height patterns as intricately linked to questions of initial sea level rise effects in our city.

- **The altered text now reads:** "**Abstract.** Daily tidal water level variations are a key control on shore ecology; access to marine environments via boat and shipping infrastructure such as ports, jetties and wharves; drainage links between the ocean and coastal hydrosystems such as lagoons and estuaries; and the duration and frequency of opportunities to access the intertidal zone for recreation and food harvesting purposes. Further, high perigean-spring tides interact with extreme weather events to produce significant coastal inundation in low-lying coastal settlements such as on deltas. Thus an understanding of daily through to monthly tidal envelope characteristics is fundamental to resilient coastal management and development practices".

***12 -*** *remove 'database'. 'theoretical experiments' –> 'theoretical arguments' maybe.*

- **Response:** Both 'database' and 'theoretical experiments' have been removed (see also this reviewer's comment on paper line 139 below, and our response).
- **The altered text now reads:** "Analyses of tidal records from 27 stations are used alongside data from the FES2014 tide model in order to find the key characteristics and constituent ratios of tides that can be used to classify monthly tidal envelopes".

***14 -*** *the symbol Fsm is a clunky one and even impossible to write on an ascii keyboard. What is it supposed to mean? A form factor showing S2's influence on M2? But what about N2 i.e. Fnm? I would have invented a simpler symbol such as F-prime or maybe E for envelope?*

- **Response:** As suggested, we have changed $F_M^S$ throughout the paper to the much simpler notation of *E*.

***20 -*** *I don't see that the first two references are really relevant to this sentence. Cartwright is a history of tidal science. D'Onofrio discusses Buenos Aires only and not spatial variation. The Nicholls reference is ok.*

- **Response:** The first two references have been removed from the sentence: "*Successful human-coast interactions in the world's low-lying areas are predicated upon understanding the temporal and spatial variability of sea levels*". Please note that we meant the phrase 'temporal and spatial variability in sea levels' to encompass a wide range of processes including cyclical tidal height variations, and were not meaning mean sea level variations alone, a topic best highlighted using the third reference. We have added the reference Woodworth et al. (2019) to emphasise this wider meaning.
- **The altered text now reads:** "Successful human-coast interactions in the world's low-lying areas are predicated upon understanding the temporal and spatial variability of sea levels (Nicholls et al., 2007; Woodworth et al., 2019)".

***24 -*** *'and gravimetry'. What does that refer to? Space gravimetry by missions such as GRACE? I would drop that. Then again the references are apparently random – Egbert et al. describes one particular model, while Stammer et al. describes many including Egbert. So why is Egbert here and not all the others?*

- **Response:** We have removed "*and gravimetry*" and the Egbert et al. (1994) reference. Stammer et al. (2014, p243) stated the point, which we repeated in shorter form, that "*An especially important application for accurate tide models is providing tide "corrections" to various measurements so that smaller nontidal signals may be studied. For example, barotropic tide models are used regularly to remove tidal variability from space geodetic observations; this is a critical necessity for successful satellite altimetry [e.g., Fu and Cazenave, 2001] and satellite gravimetry [Seeber, 2003; Visser et al., 2010], and in both cases improved tidal corrections lead to a reduction of aliased tidal "noise" in nontidal signals of interest*". We have made our use of the Stammer et al. point clearer by repositioning the reference, as below.
- **The altered text now reads:** "An understanding of tidal water level variations is fundamental to resilient inundation management and coastal development practices in such places (Cartwright, 1999; Masselink et al., 2014; Olson, 2012; Pugh, 1996), as well as to accurately resolving non-tidal signals of global interest (Stammer et al., 2014), such as in studies of sea level change".

***26 -*** *I would have the equation here i.e. F=(K1+O1)/(M2+S2) and not just words, like your equation (1) below which would become (2)*

- **Response:** We have added this equation explicitly, as suggested, and renumbered the other equation.

- **The altered text now reads:** "Originally developed by van der Stok (1897) based on three regime types, with a fourth type added by Courtier (1938), this simple and useful daily form factor comprises the ratio between the combined $K_1$ and $O_1$ diurnal amplitudes versus the combined $M_2$ and $S_2$ semi-diurnal amplitudes via the equation:

$$F = \frac{K_1+O_1}{M_2+S_2} \qquad (1)".$$

***26-27** - if you have four you can't add a fourth?*

- **Response:** This has been clarified in the text. Originally van der Stok (1897) divided tidal regimes into three types using the *F* equation, while Courtier (1938) added a fourth (daily) tidal regime type.
- **For altered text:** please refer to the altered text in the response immediately above this one.

***28** - aren't they the same form factor (singular)?*

- **Response:** This has been corrected in the text.

*I am not familiar with the van der Stok and Courtier references which are very old and I don't think many other readers will be either. How did you come across them? If in a more recent history of tides or a text book on tides then please add that.*

- **Response:** Van der Stok (1897) was available to us via interlibrary loan. We borrowed an original 1897 large format book from California through the UC library – see available copies here: https://www.worldcat.org/title/wind-and-weather-currents-tides-and-tidal-streams-in-the-east-indian-archipelago/oclc/488220907. It is an interesting piece of work as it clearly outlines the *F* equation and three of the four tidal regime types in common usage today, in a work dating back over 120 years. We feel that it is best to leave this reference in our paper discussion of the origins and history of use of *F*, not least to give credit to this early author. We found out about van der Stok's work from its citation in Courtier (1938), which is available online, in a PDF English translation, from: https://journals.lib.unb.ca/index.php/ihr/article/download/27428/1882520184. We have added this web link in our reference list entry for Courtier (1938) to make it more accessible to readers. Both of these references were located via a Google search (in contrast our university library multi-search returned no useful results).
- **The altered text now reads:** "Courtier, A.: Marées. Service Hydrographique de la Marine, Paris (English translation available from: https://journals.lib.unb.ca/index.php/ihr/article/download/27428/1882520184), 1938".

***34-36** this is a garbled sentence. Could you please reword?*

- **Response:** We have reworded this sentence into two shorter, clearer sentences as follows.
- **The altered text now reads:** "The daily tidal form factor identifies the typical number (1 or 2) and form (equal or unequal tidal ranges) of tidal cycles within a lunar day (i.e. 24 hours and 48 minutes) at a particular site. In contrast, the term 'tidal envelope' describes a smooth curve outlining the extremes (maxima and minima) of the oscillating daily tidal cycles occurring at a particular site through a specified time period".

***45-47** This isn't right. You say yourself that NZ tides are unusual so the reviews of Andersen etc. cannot be blamed for focusing on the main constituents relevant to global studies. However, that does not mean those authors were disinterested in other constitents. In fact one main aim of such studies was to determine how well the total tide could be determined which necessitates accuracy in N2 etc.*

- **Response:** We have deleted these lines.

***56** - as mentioned above I can't see form factors (of whatever kind) being directly relevent to coastal flooding hazards work, but if I am wrong please give references.*

- **Response:** You are absolutely reasonable to question the unusual link drawn in our paper between form factors and coastal flooding hazards work. However, we would like here to offer explanation for why we think this link exists for some places (delta cities) and is relevant. Again using Christchurch as an example - this city is situated towards the centre of NZ's east coast region of strongly perigean-apogean influenced tides. The city is constructed (like Tokyo, Jakarta, Charleston NC, and many other delta cities) on a low-lying, formerly swampy, coastal progradation and river delta plain in a seismically active area. This physical setting, combined with imprudent development, has influenced the flood hazard: major flooding occurs when periods of sustained heavy (as opposed to high intensity) rainfall produce river and overland flows which fail to drain efficiently through the city's distributed, gravity-based and sea level connected drainage network (Hart et al., 2018). One of the key factors that determines whether or not a sustained rainfall event will result in widespread and severe flooding, or not, is the tides. Flooding is more likely during perigean tides, since these times feature periods of more than a week with particularly high tidal ranges. As illustrated in the Fig. R1 (top), unlike in spring-neap dominated areas, periods of high tidal ranges in Christchurch can last for well over a week with short duration periods of smaller range tides between, when flooding is less likely. This means that high tide 'red alert' days (Fig. R1 (below)) can last for more than a week, and there is an increased chance that these might coincide with sustained rainfall events, than in more spring-neap dominated regions which feature the distinct and regular punctuations of the lower range neap tides. This is a subtle but genuine reason why we believe it is important for 'delta cities' like Christchurch to consider their monthly tidal pattern when considering the multiple factors that influence flooding. An additional aspect of this idea relates to how we quantify future flood risks and return periods under changing climate (not to mention in the multi-hazard context of future seismic activity, e.g. Allen et al., 2014). The tidal height patterns will not be hugely influenced by climate change, so we can already produce accurate frequency histograms and probability distributions for future high tide levels, like that conducted by D'Onofrio et al. (1999) for Buenos Aries. Future rainfall and storm surge statistics are harder to predict under changing climate and need to be combined with the more predictable tidal water level contributions to establish accurate flooding and inundation risk predictions. In the past we in NZ focussed on flood return periods established using historical water level records, but this is no longer a robust practice since the more predictable tidal water level probabilities need to be combined with the changing atmospheric components to produce altered flood risk estimates for the future. All this is in a relatively newly colonised country where hydrological data records are short. Our point is partly that amongst all this uncertainty, at least the tidal pattern component of these hazards is nicely predictable, so we encourage colleagues to take tidal patterns into account in their flood hazard analyses (something that has been lacking in past flood analyses). We hope to make the case for the connection between tidal envelope pattern and flood hazards in an upcoming ASCE (2020) monograph paper on flooding and inundation multi-hazards, but realise that this idea is only hinted at in our current paper. Please do recommend if we should delete text making this link in our current paper, or if we should leave it in, albeit as a fleeting mention, or some other suggestion.

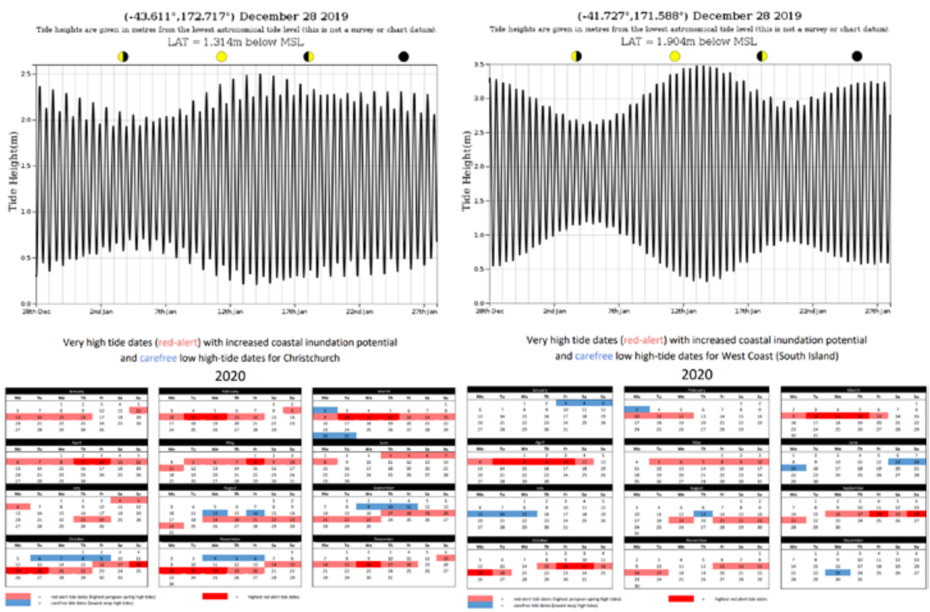



Figure R1. (Top) One month of tidal heights for Christchurch on the South Island's east coast (left) versus Westport on the South Island's west coast (right); and (Below) 2020 predicted tidal 'red alert' days for Christchurch (left) and the South Island West Coast (right), New Zealand (generated using NIWA, 2019).

***61 -** why don't you just have a simple map here for the reader to refer to i.e. Figure 2, and not wording such as 'latitudinal gradient' - you mean range of latitude. Having the Type information in the figure is ok but you have to return to that later (see below about that)*

- **Response:** We have corrected the word 'gradient' to 'range' and added a citation pointing the reader to Fig. 2 at this point in the text, as suggested. Also, in Results section 3.1 we have added another mention of Fig. 2, highlighting at this stage the observation station colour coding of their identified monthly tidal envelope types.
- **The Section 2.1 altered text now reads:** "New Zealand (Fig. 2) is a long (1600 km), narrow (≤400 km) country situated in the south-western Pacific Ocean and straddling the boundary between the Indo-Australian and Pacific plates. Its three main islands, the North Island, the South Island, and Stewart Island/ Rakiura, span a latitudinal range from about 34° to 47° South".
- **The Section 3.1 altered text now reads:** "Figure 5 illustrates the four types of monthly tidal envelope found around NZ as idealized types, two with stronger spring-neap signals (Types 1 and 2, see Fig. 5 a-b) and two with stronger fortnightly perigean-apogean signals (Types 3 and 4, see Fig. 5 c-d) while Fig. 2 includes a colour coded classification of the observation stations into the four tidal envelope types".

***62 -** what are 'absolute tides'?*

- **Response:** We have amended the sentence to read "*…micro through to macro tidal ranges*".

***68-69*** *- this business of a pair of amphidromes to the NW and SE is not easy for the reader to appreciate from your wording alone, and the amphidromes are in fact a long way NW and SE and off the maps of Figure 3. So you have to point the reader to where he can see a map of M2 in the SW Pacific - ideally a map from FES2014 as you have focused on that. Or see Fig 5.1 of Pugh and Woodworth (2014) which was provided by Richard Ray - i.e. a wider area than you have used for Fig.3. Anyway I don't think it is right to say S2 has a single wavefront and amphidrome in the SE. Take a look at Figure 4 of Walters et al. (2001) and you will see a pair of them close together in the SE. And I would drop mention of the Coriolis effect and simply say that they rotate anticlockwise.*

- **Response:** Regards the description of the $M_2$, we have added a citation Pugh and Woodworth (2014) Fig. 5.1 – thank you for this suggestion. We have amended our description of the $S_2$ and $K_1$ tide amphidromes in line with Walters et al. (2001; 2010). Mention of the Coriolis Force has been removed as suggested.
- **The altered text now reads:** "Highly complex tidal propagation patterns occur around NZ, including a complete semi-diurnal tide rotation, with tides generally circulating around the country in an anti-clockwise direction. This occurs due to the forcing of $M_2$ and $N_2$ tides by their respective amphidromes, situated northwest and southeast of the country respectively, producing trapped Kelvin waves (for a map of the $K_1$ and $M_2$ amphidromes see Fig. 5.1 in Pugh and Woodworth, 2014). The $S_2$ and $K_1$ tides propagate northeast to southwest around NZ. This results in a southward travelling Kelvin wave along the west coast, and small $S_2$ and $K_1$ amplitudes along the east coast, with amphidromes occurring southeast of New Zealand (Walters et al. 2001; 2010)".

***77*** *- 'years' is misleading as it suggests you have used many years per station whereas Table A1 shows you used only one year for each. Have the amplitudes and phase lags in Table A1 been adjusted for nodal variations according to equilibrium relationships? Or are they the observed amplitudes for the years shown? See below for other comments on this table. I would have prioritised the FES2014 model over the tide gauge data as the main aspects of what you are trying to show are best done with the model. Then at the end of the paper you can show your findings from FES2014 are consistent with those from the tide gauge positions.*

***80*** *- you mean 'in comparison with values obtained from the tidal potential or Equilibrium Tide'*

- **Response to 77:** We have added the adjective "individual" to highlight that an individual year was analysed for each of the 27 observation stations. In our paper we have chosen to initially employ the analysis of observational data, later on using the FES2014 model data to check our findings and extend our spatial coverage. Although the observational data does not have the same uniform coverage of the FES214 data, we prefer to initially use the observational data since it represents real in situ records that are accurate at the coast, while the FES2014 data is helpful for our final classification around the whole country (i.e. Figure 7).
- **Response to 80:** Yes, thank you – we have used your suggested (clearer) wording.
- **The altered text now reads:** "For both the LINZ and NIWA data, an individual year of good quality hourly data was selected for analysis per site from amongst the multi-year records. The 27 individual year sea level records were then harmonically analyzed using T_Tide (Pawlowicz et al., 2002) with the nodal modulation correction option, to examine spatial variation in the main tidal constituents' amplitudes, phase-lags, and amplitude ratios between regions (see Table A1 for raw results) and to compare them with values obtained from the tidal potential or Equilibrium Tide".

***81*** *- 'amplitude data' –> 'amplitudes'. 'was sourced' –> 'was obtained'*
***82*** *- days' length or days in length*
***83*** *- tides are the strongest*
***85, 242 and 268*** *- Carrere has an accent over the first e*
***86*** *- dataset –> model. experimental plots –> studies (maybe)*
***88*** *- siderial –> diurnal.*
***92-93*** *- mapped spatial variability*

- **Response:** All changes made exactly as suggested. The accent has been added everywhere that Carrère's work is cited.

***94-95*** *- .. those from the Equilibrium Tide (Defant, 1958). It was not Defant's theory. Anyway you might better refer to Cartwight and Tayler (1971) for example.*

- **Response:** We have altered the misplaced reference to Defant (1958) to indicate that this was the source from which we obtained the Equilibrium Tide data, and not the source of Newton's Theory itself, and we have also deleted the reference to Defant (1958) from the table (now numbered Table 1) since it is now clearer in the text.
- **The altered text now reads:** "Table 1 summarizes these data, and contrasts them with those from Equilibrium Theory (values obtained from Defant, 1958), while Table A1 catalogues the detailed results".

***95*** *- 'data results' –> results*
***98*** *- reinforces –> shows*
***101*** *- .. amplitude (Figure 3c).*
***102*** *- in the text and tables and figures it would be much simpler if you dropped the 'a' and have M2 for example to refer to its amplitude. All the a's make things messy. You would have to say you were doing that of course.*
***103*** *- drop relatively The two bullets below. Could you mention them as determining Type 1 and Type 4.*
***109*** *- surely that is not referring to Figure 1, you can't see Cook Strait in that at all*
***110*** *- 75 to 90% of what? What are the adjacent coasts?*
***114*** *- 'anomalistic timeframes' –> 'a month' and drop the 27.5546 four decimals –> 27.6 will do*

- **Response:** All changes made exactly as suggested. Figure 1 has been corrected to Fig. 2. For 110, see new text below.
- **The altered text now reads:** "Type 1 regimes occur on the Kapiti and Cook Strait area (Fig. 2), where the $N_2$ and $M_2$ amplitudes reduce by 75 to 90%, but the $S_2$ amplitude reduces by only about 30%, compared to on the western coasts both north and south of this central NZ area".

***116*** *Chatham Rise and Castle Point are not in Figure 2.*

- **Response:** The text read: "*This type of regime occurs, for example, around the northern Chatham Rise near Kaikoura, and as far north as Castlepoint on the east coast of the South Island*". We have left this text and the Fig. 2 map unchanged regards these labels as both Castlepoint and Kaikoura were on this figure (see north and south of Cook Strait on the central east coast). Other labels that were missing from Fig. 2 as pointed out below (e.g. North/ South/ Stewart Island) have been now added though, and the Castlepoint dot has been shifted ~3 mm north, and the spelling corrected from Castel Point to Castlepoint, in response to the Glen Rowe review comment (below).

***121 sentence*** *'By examining'. I would drop this sentence. You repeat yourself a lot.*

- **Response:** Deleted – thank you, we really appreciated all of your suggestions for shortening our text and removing repetition. The paper is now much tighter as a result.

***126*** *- I would say spring-neap and then perigean-apogean as that is the order else- where Two bullets. Can you mention them as Type 2 and 3*
***133*** *- amplitudes being only*

- **Response:** All changes made exactly as suggested.
- **The altered text now reads:** "The variability in these two ratios means that, except where we find 'spring-neap' or 'perigean-apogean' monthly tidal envelope types, spring-neap tides do occur but the overall monthly envelope shape is fundamentally altered (asymmetrically) due to the perigean-apogean influence".

***139*** *- Sumner not in Figure 2 Equations 1 - drop the a's (see above). Also drop the 'more stable' words. I guess you mean similar locally? But the same situation would apply if the constituents varied a lot spatially. These are just simple algebraic relationships at a particular position – they have nothing to do with spatial scale or 'stability'.*
*161 Table 4 should be 3?*

- **Response:** For 139, Sumner is/was in Fig. 2, on the central east coast of the south island (just above the peninsula – this is a gauge site for Christchurch city). For Eqs. 2, 2a and 2b (formerly 1, 1a and 1b), all 'a's have been deleted and it has been specified in the text that these ratios refer to amplitudes. All references to stability have been dropped. Re '161', both Tables 3 and 4 now seemed superfluous after re-arranging Table 1 and with removal of the

- experiments, so these two tables (3 and 4) have been deleted, as has all mention of them, shortening our paper nicely (thank you for those useful suggestions).
- **The altered text now reads:**

"Thus, in a similar manner to van der Stok's (1897) method for calculating *daily* tidal form factors, a *monthly* tidal envelope factor ($E$) may be calculated for semi-diurnal tidal regions, including that of NZ, according to:

$$E = \frac{\mathrm{M_2+N_2}}{\mathrm{M_2+S_2}}\,, \qquad (2)$$

where $M_2$, $N_2$ and $S_2$ refer to the constituent amplitudes. This equation can be further expressed as:

$$E = \frac{1+\frac{\mathrm{S_2}}{\mathrm{M_2}}x}{1+\frac{\mathrm{S_2}}{\mathrm{M_2}}}, \qquad \text{with } x = \frac{\mathrm{N_2}}{\mathrm{S_2}} \qquad (2a)$$

$$E = \frac{1+\frac{\mathrm{N_2}}{\mathrm{M_2}}}{1+\frac{\mathrm{N_2}}{\mathrm{M_2}}y}, \qquad \text{with } y = \frac{\mathrm{S_2}}{\mathrm{N_2}} \qquad (2b)\text{''.}$$

***173** - it is strange to read of M2, which is the largest, moderating something smaller. I think this paragraph needs rewording. Also I don't understand (i) and (ii). What are the 'annual' and 'subsequent' things? I guess the R in MTR is ratio? Not clear. But note that MTR stands for Mean Tidal Range in usual tidal studies. Anyway I found these experiments at lines 180-204 somewhat unconvincing, although I do understand why you felt the need to inject some rigour into the choice of boundary values between Types. But the experiments do not cover the whole space of possibilities for amplitude and phase lag of all constituents concerned. The main thing to me is Figure 6 which shows nicely how Fsm varies with x and y. Why don't you then just define the boundaries between Type 1 etc. in an ad hoc way, similar to the way as F is divided in an ad hoc way for 'semidiurnal' etc. After all, in the end all these form factors are just handy coarse descriptive subdivisions for the tide. Anyway lines 180-204 need rewriting - see my comment at line 173 also. It is just not clear what you are doing.*

- **Response:** Thank you for this simplifying comment. The "moderating influence of" has been replaced by "strong influence of". The whole section on the experiments, including Figure A1, has been deleted. As suggested, simplified ad hoc (and less repetitive) explanations for selecting the boundaries between the different *E* types has been used instead as follows.
- **The altered text now reads:**

"Below we explain how we set boundaries between the different E types around NZ, using our case study data, and as summarised in Fig. 6.

Firstly, in any semi-diurnal tidal regime (F<0.25) anywhere in the world where the amplitude ratio $\frac{\mathrm{N_2}}{\mathrm{S_2}} < 1$, spring-neap cycles will feature clearly in the tidal height records. Thus, the boundary separating Types 1 and 2 from Types 3 and 4 occurs at $\frac{\mathrm{N_2}}{\mathrm{S_2}} = 1$. Type 1 and 2 areas of the NZ coast are characterized by relatively larger $S_2$ amplitudes (19-40 cm) than areas with stronger perigean-apogean influences (2-18 cm) (Table 1). Secondly, tidal regimes with stronger spring-neap signals include places where spring-neap cycles occur as consecutive fortnightly cycles of similar magnitude (Type 1 or 'spring-neap' type regimes), and places where spring-neap signals dominate but with noticeable variability in the magnitudes of consecutive cycles due to subordinate perigean-apogean influences (Type 2 or 'intermediate, spring-neap' regimes). In NZ the strongest spring-neap influence occurs in the Cook Strait to Kapiti area, where harmonic analysis revealed an amplitude ratio of $\frac{\mathrm{N_2}}{\mathrm{S_2}} = 0.35$ and an E value of 0.79 (Table 1). Examining the shapes of tidal height plots showed that Kapiti had the only completely spring-neap dominated tidal envelope amongst the case study sites. Hence the boundary between Type 1 versus 2 was set as E = 0.8 for NZ, just greater than that of Kapiti and below the next strongest spring-neap influenced site, Nelson, where E = 0.9 (Fig. 6). Lastly, to set a boundary between 'perigean-apogean' and 'intermediate, perigean-apogean dominant' regimes (i.e. Types 3 versus 4), we again examined tidal height plots to determine a boundary value of E = 1.15, between the 'intermediate, perigean-apogean dominated' type regime of Napier (E = 1.147) and the 'perigean-apogean' type regime of Kaikoura (E = 1.162) (Table A1; Fig. 6)".

***203** - see below. mention the other red blob.*

- **Response:** The following text has been added:

- **The altered text now reads:** "As shown in Fig. 1c, such regimes unusual internationally, also occurring in limited areas of the Cook Islands and northeast of Pitcairn Islands in the Southwest Pacific Ocean; in Alaska's Bristol Bay, Canada's Hudson Bay and offshore of the North Carolina to Virginia coast in North America; on the north coast of the Bahamas in Central America; and in the Gulf of Ob in Russia".

***217** - if you agree then drop 'theoretical experiments' here.*

- **Response:** Yes – all mention of the experiments, and the experiments themselves, have been dropped completely from the paper.

***220** - these three do not all operate at 'synodic anomalistic timescales'. Why not just '..three key constituents (M2, S2 and N2).' At this point it occurred to me that a similar exercise could be conducted for areas of predominantly diurnal (but a bit mixed) tides. Could you speculate in this Discussion which parts of the world could benefit that way?*

- **Response:** The 3 key constituents change has been made. Using the FES2014 model for a similar exercise, we explored predominantly diurnal tidal regimes and found a possible area, the Ross Sea, Antarctica, where there are extremely weak (F>15), very weak (F>8) and weak (F>5) $M_2$ and $S_2$ amplitudes along with the areas of $M_2$>$S_2$, $S_2$>$M_2$, $N_2$>$S_2$ and $S_2$>$N_2$ amplitudes. Thus, our approach to classifying monthly tidal patterns can be applied to the Ross Sea diurnal tide area, but it is not as simple as the application in this paper to semi-diurnal NZ regimes, so we have left this exercise for another paper. We are thankful for this suggestion though.
- **The altered text now reads:** "The result is a widely applicable monthly tidal envelope factor, *E*, for classifying semi-diurnal regimes based on the amplitudes and amplitude ratios of three key constituents: $M_2$, $S_2$, and $N_2$".

***230** - this isn't necessarily true. Figure 1c shows where S2 is small compared to M2. It doesn't necessarily follow that perigean influences dominate.*

- **Response:** We checked the results for all 'red blob' areas, and in all of these the $N_2$ is at least five times greater than the $S_2$, hence we remain confident in this point. We did, however substitute the word 'paramount' with 'stronger' and 'minor with 'very weak'.
- **The altered text now reads:** "Figure 1b illustrates the division of the semi-diurnal areas of the world's oceans into those where spring-neap cycles are the main monthly tidal envelope influence versus those where the perigean-apogean signal is stronger, while Fig. 1c illustrates areas of the world's oceans where spring-neap signals are very weak compared to 'perigean-apogean' influences in the monthly tidal envelope".

***239** - what is 'low-frequency coastal flooding'?*

- **Response:** This unhelpful descriptor has been deleted.
- **The altered text now reads:** "We hope that our work inspires other efforts to study tidal height variations at timescales greater than daily, work which could draw renewed attention to the fundamental role of tidal water levels in shaping coastal environments, including in hazards such as coastal flooding".

***Table A1. Line 1** - you don't show tidal ranges, this will be confusing for most people. What you show on the last line are ranges of amplitudes and phase lags in your data set. Also the 'ranges' shown are crazy for some as shown e.g. see 6-360 for K1. But 360 degrees is the same as 0 degrees! Line 2 - values. Also the header should mention you show Types. Say if the phase lags shown are in Greenwich Mean Time or local time? if Greenwich then they are usually denoted by G.*

- **Response:** Corrections to caption and number values (360 –> 0) made exactly as suggested, and line 2 deleted. Phase lag reference added and notation amended to *G*. Also the columns in this table have been re-ordered in line with the suggested re-ordering of the Table 2 (now Table 1) columns.
- **The altered caption now reads:** "Table A1. Monthly tidal envelope (*E*) types and values, daily form factors (*F*), and data on the amplitude and phase lag (relative to Greenwich) values of 5 tidal harmonic constants at 27 sea level stations around New Zealand".

***Figure A1.** I don't understand the 'under conditions summarised in Table A1'. Surely all one needs to know is which stations were used for these 3 examples.*

- **Response:** Since the experiments have been deleted, this figure has also now been removed.

***261** - doesn't matter much but Figure 2 looks like a simple coastline map to me that one could make with GMT or Matlab, so where do the fancy 'map layers' come in? And with an undesirable national coordinate system to boot instead of lat/lon?*

- **Response:** The coordinate system and map outline were supplied by Mr Thyne as CorelDraw map layers (plural) – they were not particularly complicated layers but this is just a software difference where CorelDraw is set up to separate diagrams into component part layers. The coordinate system has been amended to internationally understandable Lat/Long, and the Acknowledgement note has been simplified to 'outline map to avoid queries from readers unfamiliar with CorelDraw.
- **The altered acknowledgement now reads:** "Thank you to …. John Thyne for supplying the Fig. 2 outline map".
- **The altered Fig. 2 now looks like:**

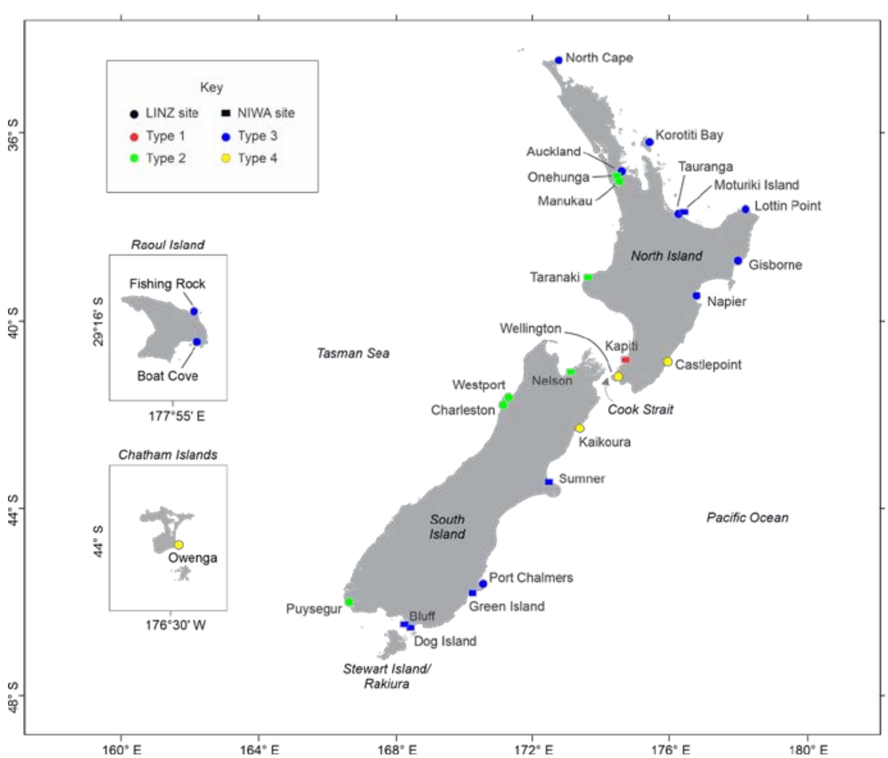



**Figure 2. Location of New Zealand sea level observation stations investigated in this research: circles indicate LINZ sites, rectangles indicate NIWA sites; each site is colored according to monthly tidal envelope type. Offshore islands are not shown to scale (Raoul and Chatham Islands).**

***Table 1. Line 1.*** *The word 'interval' in tides refers to the times of high tide since passage of the moon. What you are showing here are not intervals but the periods of beating of the shown pairs of constituents. And personally I would abandon columns 3 and 4 - you are not writing a text book here - certainly drop column 3 (and in M2/S2 – drop 'axial'. M2/N2 - drop 'relative'. line 3 'during the siderial month' –> during a month). And I would drop the Note which doesn't add anything.*

- **Response:** Fully taking on board your comments and acknowledging the level of the journal audience, we have completely deleted Table 1 (and also Tables 3 and 4, as per your additional comments below) and re-ordered the remaining table (previously Table 2, but now labelled Table 1).

***Table 2. I*** *would have a column 1 showing Type. And I would move Example Sites to be a column 2. First line of that: Equilibrium Theory (no footnote and no Note – you have already mentioned Defant in the text).*

- **Response:** Table columns re-ordered and changes made as suggested (note – now this original Table 2 is called Table 1, as per the table deletion changes in the point above).
- **The altered Table 1 (formerly Table 2) now looks like:**

**Table 1. Comparison of tidal constituent amplitudes, amplitude ratios (including daily tidal form factor, *F*, and monthly tidal envelope factor, *E*) and ranges between the four distinct types of monthly tidal envelope (*E* types) found in the 27 case study semi-diurnal tide regimes of New Zealand, and compared to Equilibrium Theory amplitude ratios**

| *E* type | Example sites | Amplitude (cm) | | | | | Amplitude ratio | | | | | | | *F* value range, description | *E* value range, description |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $M_2$ | $S_2$ | $N_2$ | $K_1$ | $O_1$ | $\frac{S_2}{M_2}$ | $\frac{N_2}{M_2}$ | $\frac{N_2}{S_2}$ | $\frac{S_2}{N_2}$ | $\frac{S_2+N_2}{M_2}$ | $\frac{K_1}{M_2}$ | $\frac{O_1}{M_2}$ | | |
| n/a | Equilibrium Theory | - | - | - | - | - | 0.47 | 0.19 | 0.41 | 2.44 | 0.66 | 0.584 | 0.415 | 0.68 mixed, mainly semi- diurnal | n/a |
| 1 | Kapiti | 55 | 26 | 9 | 2 | 2 | 0.47 | 0.16 | 0.35 | 2.89 | 0.64 | 0.04 | 0.04 | 0.05 semi-diurnal | 0.79 spring-neap |
| 2 | Nelson, Manukau, Taranaki, Onehunga, Westport, Charleston, Pusegur Point | 78 to 133 | 19 to 40 | 17 to 25 | 2 to 6 | 1 to 4 | 0.24 to 0.3 | 0.18 to 0.22 | 0.58 to 0.89 | 1.12 to 1.74 | 0.45 to 0.48 | 0.02 to 0.06 | 0.01 to 0.05 | 0.04 to 0.07 semi-diurnal | 0.90 to 0.98 intermediate, spring-neap dominant |
| 3 | North Cape, Boat Cove and Fishing Rock (Raoul Island), Dog Island, Auckland, Bluff, Lottin Point, Tauranga, Korotiti Bay, Moturiki, Green Island, Port Chalmers, Sumner, Gisborne, Napier | 50 to 112 | 4 to 18 | 10 to 22 | 2 to 8 | 1 to 4 | 0.06 to 0.2 | 0.2 to 0.23 | 1.07 to 3.5 | 0.29 to 0.94 | 0.28 to 0.43 | 0.02 to 0.10 | 0.01 to 0.06 | 0.05 to 0.14 semi-diurnal | 1.01 to 1.15 intermediate, perigean-apogean dominant |
| 4 | Kaikoura, Owenga, Castlepoint, Wellington | 48 to 65 | 2 to 3 | 10 to 14 | 2 to 4 | 2 to 4 | 0.04 to 0.05 | 0.21 to 0.22 | 4.67 to 5.50 | 0.18 to 0.21 | 0.25 to 0.27 | 0.04 to 0.06 | 0.04 to 0.06 | 0.08 to 0.12 semi-diurnal | 1.16 to 1.18 perigean-apogean |

***Table 3*** *- I guess this does no harm but it just repeats what has been given in the text. I would drop it.*

- **Response:** This table is now deleted – with clearer formatting of Table 2 (now Table 1) and this comment in mind we found that it was now superfluous.

***Table 4*** *- I don't understand this table. It is tied up with mention of the experiments, see comments above. I would drop this table as well.*

- **Response:** This table is now deleted, in line with removal of the experiments as commented on above.

***Figure 1*** *- just a suggestion but perhaps all panels could be made the same size. You have (a) large but that is for the normal F which is not the subject of this paper and can be found in many text books. Also for this, and also for the other colour maps in Figs 3,4 etc. could you have an arrow on the max colour as you have points on the maps with values which are in overflow. As for Figure 1 (c), you should mention somewhere in the text where the other red blob is. Near Tahiti? line 4 of caption '.... monthly tidal envelope using criteria described in section 3.' Then for (c) see my comment for line 230.*

- **Response:** All 3 maps are now the same size. The overflow issue has been eliminated from this figure. The red blobs in 1 c have now been described in the text more fully, as indicated in a point above. For Fig. 1c, see reply above. The caption for 1c has also been adjusted.
- **The altered Fig. 1 and caption are now as follows:**

**Formatted:** Section start: New page

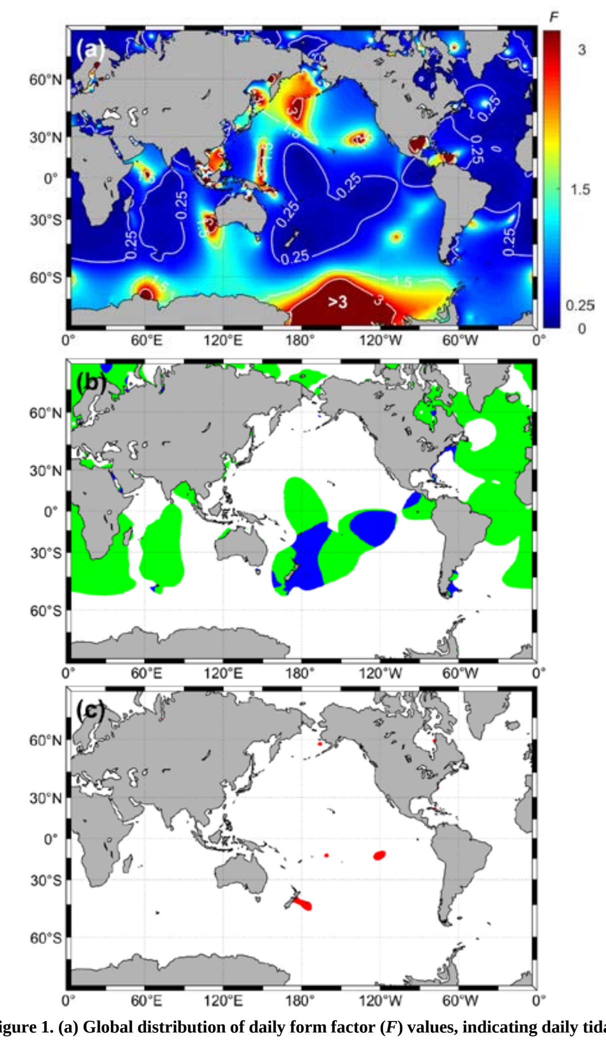


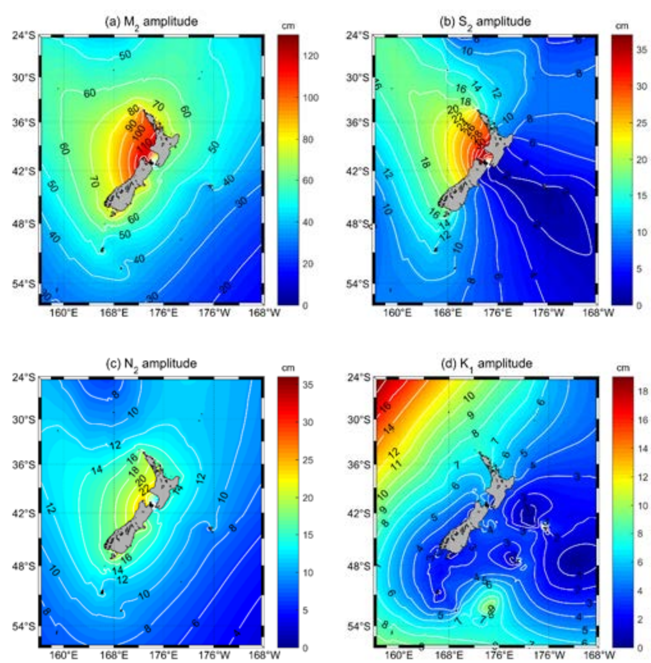

**Figure 1. (a) Global distribution of daily form factor (*F*) values, indicating daily tidal regime types (*F*<0.25: semi-diurnal; *F*>0.25 to *F*<1.5 mixed-mainly semi-diurnal; *F*>1.5 to *F*<3: mixed-mainly diurnal; and *F*>3: diurnal, according to the classification of van der Stok 1897, and Courtier 1938); (b) the world's semi-diurnal tidal areas (*F*<0.25) divided into those where spring-neap (green) versus perigean-apogean (blue) signals are the main influence on the monthly tidal envelope; and (c) semi-diurnal tidal regimes (in red) where the $S_2/M_2$ constituent amplitude ratio is <0.04 and the spring-neap tidal signals are very weak as compared to perigean-apogean signals, derived from FES2014 tidal harmonic constants.**

*Figure 2 - please use conventional lat/lon and not a national coordinate system no-one else will understand. As mentioned above there are places in the text (e.g. Stewart Is.) not shown. '&' –> 'and'. When Figure 2 is first mentioned in the text there is no mention of the Type 1, 2 etc. So you have to returrn to this figure after you discuss Figures 6 and 7 and mention the Types in Fig.2, and then please also use the same colours for the Types here as in Fig 6.*

- **Response:** All changes made as suggested. Please see new Fig. 2 above.

*Fig 3 - arrows needed on colour scales e.g. for the overflow top-left of 3(d). The contour annotation bottom right of 3(f) is messy, please thin out the annotations. Also drop 'Unit' in 'Unit mm'. line 1 of caption - 'Amplitudes for'. Drop 'horizontal'. Line 2 - drop 'derived and'. Drop 'database'. 'at a scale of' –> 'on a grid of'*

- **Response:** The scale of 3f has been changed to eliminate the overflow issue (we had previously mapped all the constituents using the same color scale but have now decided to alter colour scales to suit each plot better). The contours have also been thinned out as recommended. 'Unit' has been deleted from the scale bar. All caption changes have been made as suggested.
- **The altered Fig. 3 and caption are now as follows:**



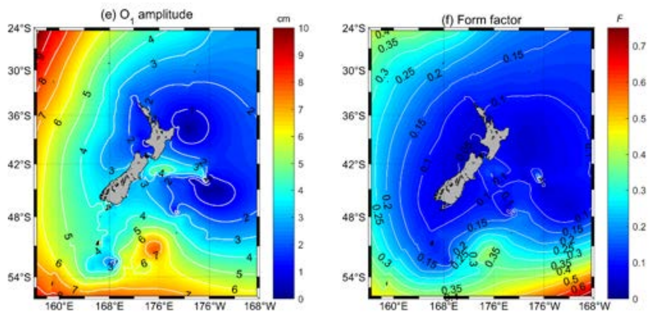
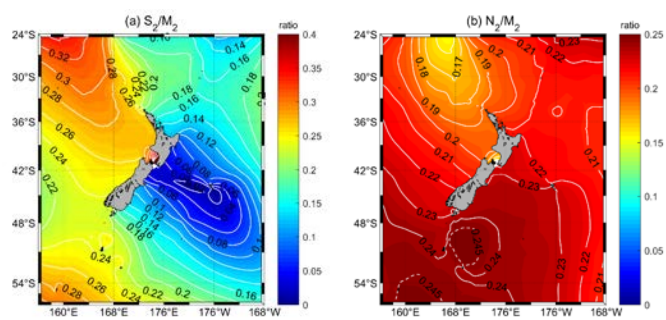



**Figure 3. Horizontal distribution of amplitudes for the (a) $M_2$, (b) $S_2$, (c) $N_2$, (d) $K_1$, and (e) $O_1$ tides around NZ, and (f) the resultant distribution of *F*, daily tidal form factor values, as calculated from the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude color scales vary between plots a and e.**

*Fig 4 - as mentioned I would drop the a's in the headers and captions. Arrows on colour scales. line 1 of caption - drop 'horizontal'. Line 2 - drop 'database'. 'at a scale of' –> 'on a grid of'*
*Fig 5 - drop a's*

- **Response:** The overflow area in Fig. 4c has been clearly delineated and labelled, and the suggested caption changes are made, including removal of 'a's.
- **The altered Fig. 4 and caption are now as follows:**



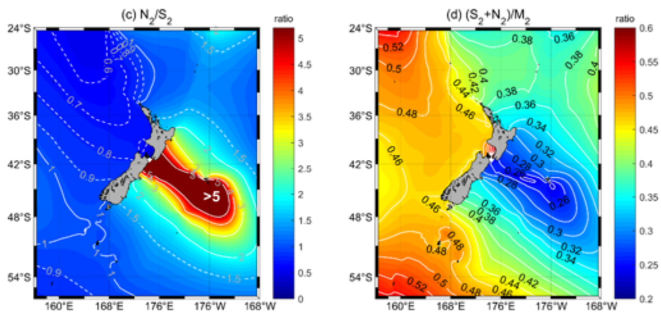



**Figure 4. Distributions of tidal constituent amplitude ratios around NZ for: (a) $\frac{S_2}{M_2}$; (b) $\frac{N_2}{M_2}$; (c) $\frac{N_2}{S_2}$ and (d) $\frac{S_2+N_2}{M_2}$; as calculated using the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude color scales vary between plots a and d.**

*Fig 6 - this is actually a useful plot. Use another colour instead of pink which is too much like red. drop a's. Use same colours for the Types as in Fig 2. Add dotted or dashed lines also for the Fsm boundary values chosen to define Types 1-4. Also what would be useful also would be to have values from FES2014 for the whole NZ coastline - that might be a fiddly computing exercise but is obviously possible.*

- **Response:** Color, dashed line boundary, and 'a' changes made as suggested. We decided not to make a FES2014 model based version of this diagram for the whole NZ coast due to our focus on observational data here (including the Walters et al. data comparison) and also since we use the FES2014 data to do this task (albeit in map rather than plot form), classifying the whole NZ coast into E type categories, in our newly expanded Figure 7.
- **The altered Fig. 6 and caption are now as follows:**

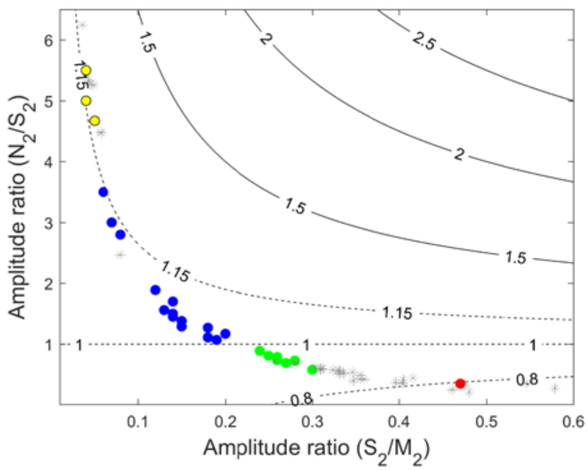



**Figure 6. Plot of the relationship between the $\frac{N_2}{S_2}$ and $\frac{S_2}{M_2}$ amplitude ratios (y and x axes respectively) versus *E* values (shown as plot contours), with data points corresponding to New Zealand waters Type 1 sites (red dots); Type 2 sites (green dots); Type 3 sites (blue dots); and Type 4 sites (yellow dots), all from Table A1; and tidal data representative of the greater Cook Strait area (grey crosses) from Walters et al. (2010, Tables 1 and 3).**

*Fig 7 - overflow arrow. could roughly the same colours be used as for Fig 6 as far as possible? That has red-green-blue-pink for types 1-4 whereas this has green-yellowred more or less (the blue is not used). line 2 - .. see Figure 5 for definitions and examples of ..*

- **Response:** All colour and caption changes made as suggested. Figures 2, 5, 6 and 7 now have the same colours for all *E* types.
- **The altered Fig. 7 and caption are now as follows:**

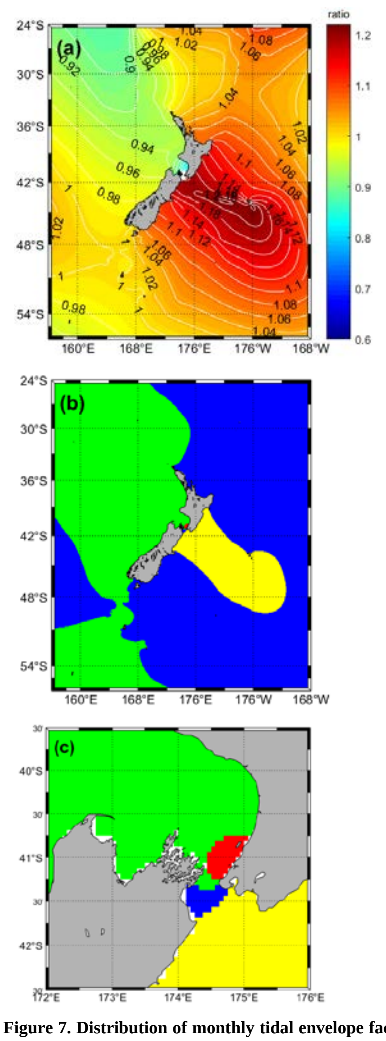



**Figure 7. Distribution of monthly tidal envelope factor (*E*) values (a); and types (b); in the waters around New Zealand, including in the Cook Strait area between the two main islands (c); calculated using FES2014 data. In (b), *E* type 1 areas are shown in red; type 2 in blue; type 3 in green; and type 4 in yellow. See Figure 5 for definitions and examples of monthly tidal envelope factor classes and patterns.**

## References

Allen J., Davis C., Giovinazzi S., Hart DE.: Geotechnical and flooding reconnaissance of the 2014 March flood event post 2010-2011 Canterbury Earthquake Sequence, New Zealand, Report No. GEER035, commissioned by the Geotechnical Extreme Events Reconnaissance Association, 134 pp, http://dx.doi.org/10.18118/G6001Z, 2014.

D'Onofrio, E. E., Fiore, M. M., and Romero, S. I.: Return periods of extreme water levels estimated for some vulnerable areas of Buenos Aires, Cont. Shelf Res., 19(13), 1681-1693, 1999.

Hart, D. E., Giovinazzi, S., Byun, D.-S., Davis, C., Ko, S.-Y., Gomez, C., Hawke, K., and Todd, D.: Enhancing resilience by altering our approach to earthquake and flooding assessment: multi-hazards, 16th European Conference on Earthquake Engineering, 18 to 21 Jun, 2018, Thessaloniki, (12164) 13 pp, 2018.

NIWA, National Institute of Water and Atmospheric Research.: Tide Forecaster, accessed 28 December 2019 from: https://tides.niwa.co.nz/, 2019.

## 2. Reply to: *Interactive comment by Glen Rowe, received and published 20 Jan. 2020*

*Place names: There is some inconsistency in the place names used in the paper. For example, Cook Strait is referred to as 'Cook Strait' (line 73 and others) and 'Te Moanao-Raukawa Cook Strait' (line 70 and Figure 2). Lines 60 and 61 give both alternative names for the North Island and South Island. The English and MaÅ ri names are alternatives; it is not necessary to use both - choose one form and use it consistently.*
*The official name for Stewart Island is 'Stewart Island / Rakiura', not 'Rakiura or Stewart Island' as shown in line 61.*
*It is recommended that place names used are as shown in the NZ Place Names Gazetteer. Cook Strait is just 'Cook Strait' (not an official names but a recorded one), 'Castle Point' (line 117) is 'Castlepoint' (official). 'Aotearoa New Zealand' has been used for the name of the country (and abbreviated to ANZ) but until an Act of Parliament is passed the country is 'New Zealand'.*

- **Response**: The approach taken was: at first mention of a name we used use both Te Reo Maori and English names, thereafter referring to each place by which of these two is the most commonly used name today. This was combined with including both languages on the map. The reason for including both official written language names at first mention/ on the map was to recognise, with equivalence, both types of official language name. This was also pragmatic, to try to give our paper some time-proofing, since it is not uncommon today for place names in our country to revert officially from their English to their Maori version. By including both, we thought our paper might withstand such changes and still be readable in the future. However in recognition of the direction to use only one form for each place name, and recognising that Copernicus has an international audience, we have selected one name for each place and used that consistently. On the other hand, the case of the Castlepoint typo (Castle Point on line 117) was an error and we have fixed this now.
- **Please see the new Fig. 2** above in the reply to the Woodworth review.

*Line 82: It would be helpful to point out that the results of the analysis of the records from the additional 33 locations are presented in Figure 6, and a sentence or two summarising those results would be appropriate.*

- **Response**: Yes, we have made this change as suggested.
- **The revised text now reads:** "The Cook Strait's tides were explored in detail by Walters et al. (2010): our Fig. 6 includes a re-analysis of their data using the E ratios. Note that the Cook Strait data includes 4 sites in the Type 1 category, as well as a number of Type 2 and Type 4 sites, and one Type 3 site, revealing this small Strait to be a concentrated area of monthly tidal envelope diversity".

*Line 83: What does 'reach the strongest' mean?*

- **Response**: Reach has been changed to "are"
- **The revised text now reads**: "*where spring-neap tides are the strongest in the country*".

*Line 93 and 94: The text here states that Figures 3 and 4 map the constituent amplitudes and ratios listed in Table 1, but surely the figures are derived from the FES2014 model as stated in the captions for Figures 3 and 4.*

- **Response**: Table 1 has now been deleted from our paper, according to the Woodworth review suggestion, so any confusion created by our reference to this table is also now now deleted.

*Line 117: Castlepoint is on the east coast of the North Island.*

- **Response**: Thank you for picking up this typo – "South" has been corrected to "North".

*Line 125: What does 'combined variability' mean? The rest of this sentence is difficult to follow - a diagram might help?*

- **Response**: We have deleted "combined" and altered this paragraph to make the meaning clearer.

- **The revised text now reads**: "We distinguished these two envelope types via the tides generated by variability in the amplitude ratios of $\frac{S_2}{M_2}$ and $\frac{N_2}{M_2}$ (i.e. of the spring-neap cycle, and perigean-apogean cycle, forming tides, respectively). In brief, the $\frac{S_2}{M_2}$ and $\frac{N_2}{S_2}$ amplitude ratios vary widely around NZ, with highest values in the west, lowest values in the east, and intermediate values to the north and south (Fig. 4). By comparison, the $\frac{N_2}{M_2}$ amplitude ratios are relatively stable and high, except in a relatively small area of Cook Strait to the Kapiti coast, where this ratio drops and thus spring-neap cycles predominate (see 'spring-neap' Type 1 regimes above). The variability in these two ratios means that, except where we find 'spring-neap' or 'perigean-apogean' monthly tidal envelopes types, spring-neap tides do occur but the overall monthly envelope shape is fundamentally altered (asymmetrically) due to the perigean-apogean influence".

*Figure 2: Castlepoint is shown out of its true position.*

- **Response**: Thank you – the map has been adjusted. See the adjusted position in Fig. 2, in the reply to Woodworth.

# *3.* Reply to: *Interactive comment by Anonymous Referee #2, received and published 5 February 2020*

*Reviewer introduction: The paper is basically acceptable, and Figures 1b, 1c, and 6 are useful. Most of the paper is devoted to trying to find the numerical delineations between spring-neap and perigean regimes, and that is a little tedious, as the boundaries are bound to be fuzzy and perhaps not applicable everywhere, even in purely semidiurnal regimes. (For example, the moderating role of K2, which likely causes variations throughout the year, isn't brought up. This, however, isn't fatal, since this whole exercise is merely to produce rough rules of thumb.) I didn't spot anything that is clearly in error, just minor issues, listed below. Some of these issues involve odd, almost off-the-cuff remarks in the introductory material rather than in the technical material. Numbers below refer to Line Numbers in the paper.*

- **Response**: Thank you for taking the time to review our paper. We feel we have been able to very significantly improve our paper based on the 3 sets of feedback provided. Please see below responses to the individual comments relevant to this review.

*24 - Neither the Egbert nor Stammer papers have anything to do with sea level change or gravimetry.*

- **Response**: The Egbert et al. (1994) reference has been deleted from here (details in our response to the Woodworth review). Stammer et al. (2014, p243) state as a justification for their accuracy assessment paper that "*An especially important application for accurate tide models is providing tide "corrections" to various measurements so that smaller nontidal signals may be studied. For example, barotropic tide models are used regularly to remove tidal variability from space geodetic observations; this is a critical necessity for successful satellite altimetry [e.g., Fu and Cazenave, 2001] and satellite gravimetry [Seeber, 2003; Visser et al., 2010], and in both cases improved tidal corrections lead to a reduction of aliased tidal "noise" in nontidal signals of interest*". It is this point from Stammer et al. (2014) that we wished to point our readers to. Our revised text now makes this clearer by the repositioning of this reference.
- **The revised text now reads**: **"**An understanding of tidal water level variations is fundamental to…. accurately resolving non-tidal signals of global interest (Stammer et al., 2014), such as in studies of sea level change".

*41 (also Table 1): Is it a sidereal month or a tropical month?*

- **Response**: This table has been deleted (see response to Woodworth review).

*47: "Far less attention" - There is a good reason for that, as the major tides are obviously most important for prediction. And why specify "modern" in this context? It's always been the case.*

- **Response**: Yes, thank you for your comment – we have removed this text and recalibrated the tone of remaining text.
- **The revised text now reads:** "Tidal envelopes at monthly scales depend on tidal regime. In general, semi-diurnal tidal regimes often feature two spring-neap tidal cycles per synodic (lunar) month. These two spring-neap tidal cycles are usually of unequal magnitude, due to the effect of the moon's perigee and apogee, which cycle over the period of the anomalistic month. In contrast, diurnal tidal regimes exhibit two pseudo spring-neap tides per sidereal month. For semi-diurnal regions where the $N_2$ constituent contributes significantly to tidal ranges, tidal envelope classification should consider relationships between the $M_2$, $S_2$, and $N_2$ amplitudes. The waters around NZ represent one such region: here the daily tidal form is consistently semi-diurnal, but large differences occur between sites within this region in terms of their typical tidal envelope types over fortnightly to monthly timescales. More than eighty years after the development of the ever-useful daily tidal form factors, attention to the regional distinction between different tidal envelope types within the semi-diurnal category forms the motivation for this paper".

*216 "having common ways of describing different types of tidal envelope is essential for living safely and productively..." – ESSENTIAL, really? That seems overblown. In fact, I consider a full-up tide prediction to be far more essential. Along the same lines, is it really necessary to have similar statements in the Abstract? The first and last sentences of the Abstract seem to me to be quite a stretch in trying to justify the work.*

- **Response**: We have deleted ‘essential’ from our text here and replaced it with ‘helpful’. The term in our revised abstract reads ‘of use’, which is a much milder claim than previously written. The abstract has been much modified in response to a similar point made in the Woodworth review, also improving it in terms of the comment made here. Please refer to the response to the Woodworth review above for the revised text.

*60: what plates NZ sits on is rather irrelevant to the subject.*

- **Response**: The names of the plates are not essential to our core paper topic but are useful in the context of explaining the long narrow shape of the chain of islands that make up New Zealand, and this shape plays a role in interacting with our ocean tides.
- **The revised text now reads:** “New Zealand (Fig. 2) is a long (1600 km), narrow (≤400 km) country situated in the south-western Pacific Ocean and straddling the boundary between the Indo-Australian and Pacific plates. Its three main islands, the North Island, the South Island, and Stewart Island/ Rakiura, span a latitudinal range from about 34° to 47° South”.

*88: I’m not sure why "sidereal" is used in reference to K1 and O1. "Declinational" or just "diurnal" seems more apt.*

- **Response**: Yes thank you - we have replaced ‘sidereal’ with ‘diurnal’ in our revised text.

*173: "moderating" is an odd way to refer to M2. Table A1. It should state these are Greenwich phase lags (which I believe to be the case), since lower-case "g" is often used to denote a local phase. One could also argue that the F value based on "Equilibrium Theory" ought to be a function of latitude.*

- **Response**: Thank you for these comments – we have addressed all of them. Table A1 now has correct reference to Greenwich phase lags in the caption and the corrected capital G parameter label in the table proper. Regards line 173, we removed the sentence with “moderating” in it (see details in the reply to the Woodworth review).
- **The revised text now reads:** “We distinguished these two envelope types via the tides generated by variability in the amplitude ratios of $\frac{S_2}{M_2}$ and $\frac{N_2}{M_2}$ (i.e. of the spring-neap cycle, and perigean-apogean cycle, forming tides, respectively). In brief, the $\frac{S_2}{M_2}$ and $\frac{N_2}{S_2}$ amplitude ratios vary widely around NZ, with highest values in the west, lowest values in the east, and intermediate values to the north and south (Fig. 4)”.

*Is Table 4 really necessary? Aren’t Tables 2 and 3 and Figure 6 sufficient?*

- **Response**: Thank you and yes, Table 4 was unnecessary, so we have deleted this table (see response to Woodworth review where we expand on our table deletions and adjustments). Basically only a revised version of the original Table 2 remains (now re-labelled Table 1), with the original Tables 1, 3 and 4 deleted.

*And finally a point on names. Presumably the government of New Zealand has not (yet?) changed the country name to Aotearoa. Is there a reason to use (what I assume is) Maori throughout this paper – including even for the Pacific Ocean and Tasman Sea? I suspect that indigenous Australians have a different name for these. Why not use those? Why not use Korean as well? I don’t really see the point of using an obscure indigenous name for the Pacific Ocean.*

- **Response**: Recognising that Copernicus has an international audience we have selected only one name for each place within the country now, called the country ‘New Zealand’, and used English ocean names consistently throughout the paper and in a revised version of Figure 2 (also see response to the Rowe comment for more details, and the Woodworth review response for the new Fig. 2).

# A monthly tidal envelope classification approach for semi-diurnal regimes with variability in $S_2$ and $N_2$ tidal amplitude ratios

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**Abstract.** Daily tidal water level variations are a key control on shore ecology; access to marine environments via boat and shipping infrastructure such as ports, jetties and wharves; drainage links between the ocean and coastal hydrosystems such as lagoons and estuaries; and the duration and frequency of opportunities to access the intertidal zone for recreation and food harvesting purposes. Further, high perigean-spring tides interact with extreme weather events to produce significant coastal inundation in low-lying coastal settlements such as on deltas. Thus an understanding of daily through to monthly tidal envelope characteristics is fundamental to resilient coastal management and development practices. For decades, scientists have described and compared daily tidal forms around the world's coasts based on the four main tidal amplitudes. Our paper builds on this 'daily' method by adjusting the constituent analysis to distinguish the different monthly types of tidal envelope occurring in the semi-diurnal coastal waters around New Zealand. Analyses of tidal records from 27 stations are used alongside data from the FES2014 tide model in order to find the key characteristics and constituent ratios of tides that can be used to classify monthly tidal envelopes. The resulting monthly tidal envelope classification approach described (*E*) is simple, complementary to the successful and much used daily tidal form factor (*F*), and of use for coastal flooding and maritime operation management and planning applications, in areas with semi-diurnal regimes.

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## 1 Introduction

Successful human-coast interactions in the world's low-lying areas are predicated upon understanding the temporal and spatial variability of sea levels (Nicholls et al., 2007; Woodworth et al., 2019). This is particularly the case in island nations like New Zealand (NZ), where over 70% of the population reside in coastal settlements (Stephens, 2015). An understanding of tidal water level variations is fundamental to resilient inundation management and coastal development practices in such places (Cartwright, 1999; Masselink et al., 2014; Olson, 2012; Pugh, 1996), as well as to accurately resolving non-tidal signals of global interest (Stammer et al., 2014), such as in studies of sea level change.

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In terms of daily cycles, tidal form factors or form numbers (*F*) based on the amplitudes of the four main tidal constituents ($K_1$, $O_1$, $M_2$, $S_2$) have been successfully used to classify tidal observations from the world's coasts into four types of tidal regime for nearly a century (Fig. 1a). Originally developed by van der Stok (1897) based on three regime types, with a fourth type added by Courtier (1938), this simple and useful daily form factor comprises the ratio between the combined $K_1$ and $O_1$ diurnal amplitudes versus the combined $M_2$ and $S_2$ semi-diurnal amplitudes via the equation:

$$F = \frac{K_1+O_1}{M_2+S_2} \qquad (1)$$

The results classify tides into those which roughly experience one high and one low tide per day (diurnal regimes); or two approximately equivalent high and low tides per day (semi-diurnal regimes); or two unequal high and low tides per day (mixed semi-diurnal dominant or mixed diurnal dominant regimes) (e.g. Defant 1958).

Albeit not part of their original design, some interpretation of the tidal envelope types observed at fortnightly and monthly timescales has accompanied use of daily tidal form classifications (e.g. Pugh, 1996; Pugh & Woodworth, 2014). The daily tidal form factor identifies the typical number (1 or 2) and form (equal or unequal tidal ranges) of tidal cycles within a lunar day (i.e. 24 hours and 48 minutes) at a particular site. In contrast, the term ‘tidal envelope’ describes a smooth curve outlining the extremes (maxima and minima) of the oscillating daily tidal cycles occurring at a particular site through a specified time period. The envelope time period of interest in this paper is monthly.

Tidal envelopes at monthly scales depend on tidal regime. In general, semi-diurnal tidal regimes often feature two spring-neap tidal cycles per synodic (lunar) month. These two spring-neap tidal cycles are usually of unequal magnitude, due to the effect of the moon’s perigee and apogee, which cycle over the period of the anomalistic month. In contrast, diurnal tidal regimes exhibit two pseudo spring-neap tides per sidereal month. For semi-diurnal regions where the $N_2$ constituent contributes significantly to tidal ranges, tidal envelope classification should consider relationships between the $M_2$, $S_2$, and $N_2$ amplitudes. The waters around NZ represent one such region: here the daily tidal form is consistently semi-diurnal, but large differences occur between sites within this region in terms of their typical tidal envelope types over fortnightly to monthly timescales.

More than eighty years after the development of the ever-useful daily tidal form factors, attention to the regional distinction between different tidal envelope types within the semi-diurnal category forms the motivation for this paper. In this first explicit attempt to classify monthly tidal envelope types, we examined the waters around NZ, a strong semi-diurnal regime with relatively weak diurnal tides (daily form factor $F$ <0.15) and variation in the importance of the $S_2$ and $N_2$ amplitude ratios. The result is an approach for classifying monthly tidal envelope types that is transferable to any semi-diurnal regime. As well as providing greater understanding of the tidal regimes of NZ, we hope that our paper opens the door for new international interest in classifying tidal envelope variability at multiple timescales, work which would have direct coastal and maritime management application including contributing to explanations of the processes behind delta city coastal flooding hazards and their regional spatial variability.

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**Deleted:** Whereas the daily tidal form factor identifies the number and form (equal or mixed) of tidal height cycles typical within a lunar day (i.e. 24 hours and 48 minutes) at a particular site, a tidal envelope describes the maximum and minimum boundaries of tidal height cycles occurring across a specified timescale at that site.
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The primacy placed on the four main amplitudes used in daily tidal form calculations has influenced the constituents examined in comparisons between global tide models and satellite altimeter data (e.g. Andersen, 1995; Stammer et al., 2014), emphasizing the importance of daily and spring-neap constituents. Far less attention has been paid to of the importance of other constituents in modern tidal research.
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## 2 Methodology

### 2.1 Study area

New Zealand (Fig. 2) is a long (1600 km), narrow (≤400 km) country situated in the south-western Pacific Ocean and straddling the boundary between the Indo-Australian and Pacific plates. Its three main islands, the North Island, the South Island, and Stewart Island/ Rakiura, span a latitudinal range from about 34° to 47° South. The tidal regimes in the surrounding coastal waters are semi-diurnal, with variable diurnal inequalities, and feature micro through to macro tidal ranges. Classic spring-neap cycles are present in western areas of NZ, while eastern areas feature distinct perigean-apogean influences (Byun and Hart, 2015; Heath, 1977, 1985; LINZ, 2017b; Walters et al., 2001).

Highly complex tidal propagation patterns occur around NZ, including a complete semi-diurnal tide rotation, with tides generally circulating around the country in an anti-clockwise direction. This occurs due to the forcing of $M_2$ and $N_2$ tides by their respective amphidromes, situated northwest and southeast of the country respectively, producing trapped Kelvin waves (for a map of the $K_1$ and $M_2$ amphidromes see Fig. 5.1 in Pugh and Woodworth, 2014). The $S_2$ and $K_1$ tides propagate northeast to southwest around NZ. This results in a southward travelling Kelvin wave along the west coast, and small $S_2$ and $K_1$ amplitudes along the east coast, with amphidromes occurring southeast of New Zealand (Walters et al. 2001; 2010). Around Cook Strait, the waterway between the two main islands, tides travelling north along the east coast run parallel to tides travelling south along the west coast. The pronounced differences between these east/west tidal states, combined with their tidal range differences, together produce marked differences in amplitude and strong current flows through Cook Strait (Heath, 1985; Walters et al., 2001, 2010).

### 2.2 Data analysis approach

Year-long sea level records were sourced from a total of 27 stations spread around NZ (Fig. 2): eighteen 1 minute-interval records from Land Information New Zealand (LINZ, 2017a); and nine 1 hour-interval records from the National Institute of Water and Atmospheric Research (NIWA, 2017). For both the LINZ and NIWA data, an individual year of good quality hourly data was selected for analysis per site from amongst the multi-year records. The 27 individual year sea level records were then harmonically analyzed using T_Tide (Pawlowicz et al., 2002) with the nodal modulation correction option, to examine spatial variation in the main tidal constituents' amplitudes, phase-lags, and amplitude ratios between regions (see Table A1 for raw results) and to compare them with values obtained from the tidal potential or Equilibrium Tide. An additional set of tidal constituent amplitudes was obtained from Tables 1 and 3 of Walters et al. (2010), derived from 33 records of between 14 and 1900 days in length, from around the greater Cook Strait area between NZ's two main islands, where spring-neap tides are the strongest in the country.

We then classified the monthly tidal envelope types found around NZ based on examination of constituent ratios produced from the tidal harmonic analysis results, data from the FES2014 tide model (see Carrère et al., 2016 for a full description of this model), and examination of tidal envelope plots. Due to the strong semi-diurnal tidal regimes in the study area, and similar

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to the approach of Walters et al. (2010), we were able to ignore diurnal ($K_1$, $O_1$) effects and simply consider the effects of spring-neap ($M_2$, $S_2$) and perigean-apogean cycles ($M_2$, $N_2$) in our monthly tidal envelope type characterization.

## 3 Results

### 3.1 Key tidal constituent amplitudes and amplitude ratios

In order to better understand the key constituents responsible for shaping tidal height forms around NZ, we first mapped spatial variability in the amplitudes of the $M_2$, $S_2$, $N_2$ $K_1$, and $O_1$ constituents and *F* (Fig 3), and in the ratio values of the semi-diurnal constituent amplitudes (Fig 4). Table 1 summarizes these data, and contrasts them with those from Equilibrium Theory (values obtained from Defant, 1958), while Table A1 catalogues the detailed results.

Tidal amplitude ratio comparisons confirmed that the waters around NZ are dominated by the three astronomical semi-diurnal tides: $M_2$, $S_2$ and $N_2$ (Table 1), the combination of which can generate fortnightly spring-neap tides ($M_2$ and $S_2$) and monthly perigean-apogean tides ($M_2$ and $N_2$). Figure 3 shows the relatively minor magnitudes of diurnal constituent amplitudes ($O_1$, $K_1$), as well as revealing the stronger west coast amplitudes of the spring-neap cycle generating constituents ($M_2$ and $S_2$), the relatively weak $S_2$ amplitudes overall (half that of Equilibrium Theory), and the more concentric pattern around NZ of the perigean-apogean cycle generating $N_2$ amplitude (Fig. 3c).

In terms of the semi-diurnal constituent amplitude ratios, Fig. 4 and Table 1 show that $\frac{S_2}{M_2}$ values cover a broad range around NZ (0.04 to 0.47), with most sites exhibiting smaller values (<0.3 at 26 out of 27 sites) than that of Equilibrium Theory (0.466).

In contrast, $\frac{N_2}{M_2}$ amplitude ratios were found to be more stable around NZ (values ranging from 0.16 to 0.23) and similar in magnitude to Equilibrium Theory (i.e. 0.191). By grouping the constituent amplitude and amplitude ratio results (Fig 3 to 4), we were able to differentiate four distinct monthly tidal envelope regimes around NZ (Table 1), with Types 1 and 4 distinguished as follows:

- Firstly, '*spring-neap*' type tidal regimes (Type 1) occur where the $S_2$ tide amplitude is large compared to that of the $N_2$ (Table 1, Fig 3). In these areas there are two spring-neap tides per month with similar ranges, and negligible influence of perigean-apogean cycles. Type 1 regimes occur on the Kapiti and Cook Strait area (Fig 2), where the $N_2$ and $M_2$ amplitudes reduce by 75 to 90%, but the $S_2$ amplitude reduces by only about 30%, compared to on the western coasts both north and south of this central NZ area.

- In direct contrast, there are '*perigean-apogean*' type tidal regimes (Type 4), in areas where the $N_2$ amplitude strongly dominates over the $S_2$ (Table 1, Fig. 3). In Type 4 regimes the $M_2$ and the $N_2$ tides combine to produce strong signals over monthly timeframes (27.6 days). Hence the highest tidal ranges in any given month occur in relation to the perigee, when the moon's orbit brings it close to Earth, rather than in line with the moon's phase, as is typical in

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spring-neap regimes. Type 4 regimes occur, for example, around the northern Chatham Rise near Kaikoura, and as far north as Castlepoint on the east coast of the North Island.

The remaining coastal waters around NZ can be separated into two tidal sub-regions, one with strong spring-neap signals (Type 2) and the other with strong perigean-apogean signals (Type 3), but both with overall mixed or *intermediate* monthly tidal envelope types (Table 1). We distinguished these two envelope types via the tides generated by variability in the amplitude ratios of $\frac{S_2}{M_2}$ and $\frac{N_2}{M_2}$ (i.e. of the spring-neap cycle, and perigean-apogean cycle, forming tides, respectively). In brief, the $\frac{S_2}{M_2}$ and $\frac{N_2}{S_2}$ amplitude ratios vary widely around NZ, with highest values in the west, lowest values in the east, and intermediate values to the north and south (Fig. 4). By comparison, the $\frac{N_2}{M_2}$ amplitude ratios are relatively stable and high, except in a relatively small area of Cook Strait to the Kapiti coast, where this ratio drops and thus spring-neap cycles predominate (see 'spring-neap' Type 1 regimes above). The variability in these two ratios means that, except where we find 'spring-neap' or 'perigean-apogean' monthly tidal envelope types, spring-neap tides do occur but the overall monthly envelope shape is fundamentally altered (asymmetrically) due to the perigean-apogean influence.

- In the first of the 'intermediate' monthly envelope sub-regions, tides exhibit two dominant, but unequal, spring-neap cycles per month due to a subordinate perigean-apogean effect. We term this type of monthly tidal envelope an '*intermediate, predominantly spring-neap*' type regime (Type 2). Here values of the $\frac{N_2}{S_2}$ amplitude ratio are $<1$, with $S_2$ amplitudes being only around 24 to 30% those of the $M_2$ constituent (Fig. 3 to 4; Table 1). Also in these areas, values of the $\frac{S_2+N_2}{M_2}$ amplitude ratio are ≥0.45. Type 2 tides occur, for example, at Westport and Puysegur.

- In the other 'intermediate' monthly envelope sub-region, tides exhibit a mainly perigean-apogean form with a weaker, but noticeable, spring-neap signal: we term this envelope type as '*intermediate, predominantly perigean-apogean*' (Type 3). Here values of the $\frac{N_2}{S_2}$ amplitude ratio sit between 1.07 and 3.5, while values of the $\frac{S_2+N_2}{M_2}$ amplitude ratio are 0.28 to 0.43 (Fig. 4, Table 1). Type 3 tides occur, for example, at Auckland and Sumner.

Figure 5 illustrates the four types of monthly tidal envelope found around NZ as idealized types, two with stronger spring-neap signals (Types 1 and 2, see Fig. 5 a-b) and two with stronger fortnightly perigean-apogean signals (Types 3 and 4, see Fig. 5 c-d) while Fig. 2 includes a colour coded classification of the observation stations into the four tidal envelope types.

### 3.2 A monthly tidal envelope factor (*E*) for semi-diurnal regimes

The four types of monthly tidal envelope types found around NZ are essentially different combinations of spring-neap and perigean-apogean signals. Thus, in a similar manner to van der Stok's (1897) method for calculating *daily* tidal form factors, a *monthly* tidal envelope factor (*E*) may be calculated for semi-diurnal tidal regions, including that of NZ, according to:

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$$E = \frac{M_2+N_2}{M_2+S_2}, \qquad (2)$$

where $M_2$, $N_2$ and $S_2$ refer to the constituent amplitudes. This equation can be further expressed as:

$$E = \frac{1+\frac{S_2}{M_2}x}{1+\frac{S_2}{M_2}}, \quad \text{with } x = \frac{N_2}{S_2} \qquad (2a)$$

$$E = \frac{1+\frac{N_2}{M_2}}{1+\frac{N_2}{M_2}y}, \quad \text{with } y = \frac{S_2}{N_2} \qquad (2b)$$

*E* takes into account the roles of the $S_2$ and $N_2$ tides in spring-neap and perigean-apogean cycles, while also factoring in the strong $M_2$ tide influence in both types of cycle. *E* may be used to classify the monthly tidal envelope types of any semi-diurnal region (i.e. where $F$<0.25) based on the analysis of constituent amplitudes and ratios from local data. Below we explain how we set boundaries between the different *E* types around NZ using our case study data and as summarised in Fig. 6.

Firstly, in any semi-diurnal tidal regime ($F$<0.25) anywhere in the world where the amplitude ratio $\frac{N_2}{S_2} < 1$, spring-neap cycles will feature clearly in the tidal height records. Thus, the boundary separating Types 1 and 2 from Types 3 and 4 occurs at $\frac{N_2}{S_2} = 1$. Type 1 and 2 areas of the NZ coast are characterized by relatively larger $S_2$ amplitudes (19-40 cm) than areas with stronger perigean-apogean influences (2-18 cm) (Table 1). Secondly, tidal regimes with stronger spring-neap signals include places where spring-neap cycles occur as consecutive fortnightly cycles of similar magnitude (Type 1 or 'spring-neap' type regimes), and places where spring-neap signals dominate but with noticeable variability in the magnitudes of consecutive cycles due to subordinate perigean-apogean influences (Type 2 or 'intermediate, spring-neap' regimes). In NZ the strongest spring-neap influence occurs in the Cook Strait to Kapiti area, where harmonic analysis revealed an amplitude ratio of $\frac{N_2}{S_2}$ = 0.35 and an *E* value of 0.79 (Table 1). Examining the shapes of tidal height plots showed that Kapiti had the only completely spring-neap dominated tidal envelope amongst the case study sites. Hence the boundary between Type 1 versus 2 was set as $E$ = 0.8 for NZ, just greater than that of Kapiti and below the next strongest spring-neap influenced site, Nelson, where $E$ = 0.9 (Fig. 6). Lastly, to set a boundary between 'perigean-apogean' and 'intermediate, perigean-apogean dominant' regimes (i.e. Types 3 versus 4), we again examined tidal height plots to determine a boundary value of $E$ = 1.15, between the 'intermediate, perigean-apogean dominated' type regime of Napier ($E$ = 1.147) and the 'perigean-apogean' type regime of Kaikoura ($E$ = 1.162) (Table A1; Fig. 6).

In summary, Fig. 7 illustrates the monthly tidal envelope values and types in the waters around NZ using *E*. The west coast is characterized by Type 2 monthly tidal envelopes, with two unequal spring-neap cycles per month. As mentioned above, Type 1 monthly tidal envelopes, with their defined spring-neap tides, are only found in the western Cook Strait to Kapiti coast area. The Cook Strait's tides were explored in detail by Walters et al. (2010): our Fig. 6 includes a re-analysis of their data using the *E* ratios. Note that the Cook Strait data includes 4 sites in the Type 1 category, as well as a number of Type 2 and Type 4 sites, and one Type 3 site, revealing this small Strait to be a concentrated area of monthly tidal envelope diversity. In contrast, the

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central eastern coasts show Type 4 'perigean-apogean' tidal envelopes. As shown in Fig. 1c, such regimes are unusual internationally, also occurring in limited areas of the Cook Islands and northeast of Pitcairn Islands in the Southwest Pacific Ocean; in Alaska's Bristol Bay, Canada's Hudson Bay and offshore of the North Carolina to Virginia coast in North America; on the north coast of the Bahamas in Central America; and in the Gulf of Ob in Russia. Type 3 'intermediate, perigean-apogean dominated' monthly tidal envelopes are found in the rest of the waters surrounding NZ.

## 4 Discussion and conclusion

Daily tidal water level variations are a key control on shore ecology; access to marine environments via boat and shipping infrastructure such as ports, jetties and wharves; drainage links between the ocean and coastal hydrosystems such as lagoons and estuaries; and the duration and frequency of opportunities to access the intertidal zone for recreation and food harvesting purposes. Fortnightly and monthly tidal envelope variations, such as those associated with spring-neap and perigean-apogean cycles, have similar moderating roles on human usage of intertidal and shoreline environments, and additionally these medium term variations in tide levels are important factors in coastal inundation risks (Menéndez & Woodworth, 2010; Stephens 2015; Stephens et al., 2014; Wood, 1978, 1986;). High perigean-spring tides, for example, interact with extreme weather events (including low pressures, strong winds and extreme rainfall) to produce significant coastal inundation in low-lying coastal settlements such as in the 'delta city' of Christchurch (Hart et al., 2015).

In a world of rising sea levels, and coastal inundation hazard cascades (Menéndez and Woodworth, 2010), having common ways of describing different types of tidal envelope is helpful for living safely and productively in coastal cities. This paper has employed observations from NZ and FES2014 tidal data to demonstrate a simple approach to classifying different monthly tidal envelope types, applicable to semi-diurnal regions anywhere. The result is a widely applicable monthly tidal envelope factor, *E*, for classifying semi-diurnal regimes based on the amplitudes and amplitude ratios of three key constituents: $M_2$, $S_2$, and $N_2$.

At a very basic level, in any semi-diurnal tidal regime anywhere in the world where the amplitude ratio of $\frac{N_2}{S_2}$ <1, then spring-neap cycles will be clearly visible in tidal height records, either as consecutive fortnightly cycles of similar magnitude (Type 1), or as a dominant signal with noticeable variability in the magnitudes of consecutive fortnightly cycles, due to a subordinate perigean-apogean influence (Type 2). Conversely, in semi-diurnal areas of the world's oceans where the amplitude ratio of $\frac{N_2}{S_2}$ >1, then perigean-apogean cycles will be visible, either as singularly evident monthly cycles (Type 4), or as a dominant influence with subordinate spring-neap signals (Type 3). Determining the actual boundaries between monthly tidal envelope Types 1 versus 2, and Types 3 versus 4 regimes at a local scale involves analysis of observational records, taking into account the important influence of the $M_2$ amplitude compared to that of the $S_2$ and $N_2$ amplitudes.

Figure 1b illustrates the division of the semi-diurnal areas of the world's oceans into those where spring-neap cycles are the main monthly tidal envelope influence versus those where the perigean-apogean signal is stronger, while Fig. 1c illustrates

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areas of the world's oceans where spring-neap signals are very weak compared to 'perigean-apogean' influences in the monthly tidal envelope. The predictable tidal water level fluctuations such as those in our perigean-apogean monthly envelope classes are an important influence in coastal inundation hazards in different locations around the world (e.g. Wood 1978, 1986; Stephens 2015).

Our simple approach to classifying *E*, monthly tidal envelope types in semi-diurnal regions, complements the existing, commonly used way of describing daily tidal forms, *F*, based on the amplitudes of the key diurnal ($K_1$, $O_1$) and semi-diurnal ($M_2$, $S_2$) constituents. We hope that our work inspires other efforts to study tidal height variations at timescales greater than daily, work which could draw renewed attention to the fundamental role of tidal water levels in shaping coastal environments, including in hazards such as coastal flooding.

**Data Availability**

The tidal data used in this paper are available from LINZ (2017a; 2017b), NIWA (2017) and Walters et al. (2010). Details of the FES2014 tide model database are found via https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html) and in Carrère et al. (2016). Appendix 1 contains the data produced from analysis of these primary resources in this paper.

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## Appendix 1

**Table A1.** Monthly tidal envelope ($E$) types and values, daily form factors ($F$), and data on the amplitude and phase lag (relative to Greenwich) values of 5 tidal harmonic constants at 27 sea level stations around New Zealand.

| Station name (record used) | $E$ type | $E$ value | $F$ value | $M_2$ | | $S_2$ | | $N_2$ | | $K_1$ | | $O_1$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | $a_i$ (cm) | $G_i$ (deg.) | $a_i$ (cm) | $G_i$ (deg.) | $a_i$ (cm) | $G_i$ (deg.) | $a_i$ (cm) | $G_i$ (deg.) | $a_i$ (cm) | $G_i$ (deg.) |
| Kapiti (2011) | 1 | 0.79 | 0.05 | 55 | 280 | 26 | 336 | 9 | 277 | 2 | 195 | 2 | 18 |
| Nelson (2015) | 2 | 0.90 | 0.04 | 133 | 276 | 40 | 329 | 23 | 254 | 6 | 187 | 1 | 80 |
| Manukau (2011) | 2 | 0.93 | 0.05 | 109 | 297 | 29 | 332 | 20 | 287 | 6 | 17 | 1 | 287 |
| Taranaki (2016) | 2 | 0.94 | 0.05 | 119 | 278 | 33 | 319 | 24 | 257 | 6 | 192 | 2 | 90 |
| Onehunga (2016) | 2 | 0.95 | 0.05 | 131 | 304 | 34 | 359 | 25 | 288 | 6 | 205 | 2 | 118 |
| Westport (2015) | 2 | 0.96 | 0.04 | 113 | 309 | 29 | 348 | 23 | 287 | 2 | 198 | 3 | 40 |
| Charleston (2015/2016) | 2 | 0.96 | 0.05 | 106 | 319 | 27 | 344 | 22 | 304 | 3 | 6 | 3 | 243 |
| Puysegur Point (2012) | 2 | 0.98 | 0.07 | 78 | 350 | 19 | 13 | 17 | 335 | 3 | 316 | 4 | 245 |
| North Cape (2010) | 3 | 1.01 | 0.11 | 80 | 230 | 15 | 279 | 16 | 209 | 8 | 10 | 2 | 351 |
| Boat Cove, Rauol Island (2012) | 3 | 1.02 | 0.14 | 50 | 208 | 9 | 287 | 10 | 176 | 5 | 43 | 3 | 44 |
| Dog Island (2011) | 3 | 1.03 | 0.06 | 91 | 33 | 18 | 57 | 21 | 6 | 2 | 119 | 4 | 60 |
| Auckland (2011) | 3 | 1.04 | 0.07 | 112 | 216 | 17 | 275 | 22 | 192 | 7 | 356 | 2 | 324 |
| Bluff (2016) | 3 | 1.04 | 0.05 | 84 | 48 | 15 | 75 | 19 | 23 | 2 | 133 | 3 | 71 |
| Fishing Rock, Raoul Island (2011) | 3 | 1.05 | 0.12 | 52 | 206 | 8 | 283 | 11 | 178 | 5 | 35 | 2 | 41 |
| Lottin Point (2011) | 3 | 1.06 | 0.1 | 70 | 195 | 9 | 262 | 14 | 168 | 6 | 352 | 2 | 328 |
| Tauranga (2011) | 3 | 1.06 | 0.08 | 70 | 211 | 9 | 277 | 14 | 186 | 5 | 0 | 1 | 330 |
| Korotiti Bay (2011) | 3 | 1.06 | 0.08 | 78 | 207 | 11 | 265 | 16 | 181 | 6 | 349 | 1 | 317 |
| Moturiki (2011) | 3 | 1.06 | 0.07 | 73 | 189 | 10 | 265 | 15 | 156 | 5 | 173 | 1 | 136 |
| Green Island (2011) | 3 | 1.08 | 0.08 | 73 | 81 | 10 | 91 | 17 | 50 | 3 | 93 | 4 | 44 |
| Port Chalmers (2011) | 3 | 1.09 | 0.07 | 77 | 112 | 9 | 112 | 17 | 89 | 3 | 270 | 3 | 247 |
| Sumner (2011) | 3 | 1.13 | 0.09 | 84 | 136 | 6 | 151 | 18 | 109 | 5 | 273 | 3 | 245 |
| Gisborne (2010) | 3 | 1.13 | 0.07 | 64 | 176 | 5 | 251 | 14 | 148 | 4 | 336 | 1 | 275 |
| Napier (2011) | 3 | 1.15 | 0.07 | 64 | 167 | 4 | 240 | 14 | 138 | 3 | 298 | 2 | 221 |
| Kaikoura (2011) | 4 | 1.16 | 0.12 | 65 | 146 | 3 | 171 | 14 | 117 | 4 | 275 | 4 | 233 |
| Owenga, Chatham Islands (2011) | 4 | 1.16 | 0.08 | 48 | 149 | 2 | 224 | 10 | 119 | 2 | 246 | 2 | 179 |
| Castlepoint (2011) | 4 | 1.17 | 0.09 | 63 | 159 | 3 | 225 | 14 | 129 | 3 | 280 | 3 | 219 |
| Wellington (2011) | 4 | 1.18 | 0.1 | 49 | 148 | 2 | 352 | 11 | 116 | 2 | 268 | 3 | 219 |
| Overall range | 1-4 | 0.79-1.18 | 0.04-0.14 | 48-133 | 33-350 | 2-40 | 13-359 | 9-25 | 6-335 | 2-8 | 0-356 | 1-4 | 40-351 |

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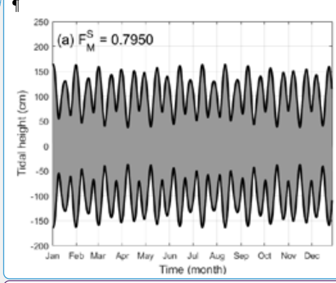


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## Author contribution

Both authors conceived of the idea behind this paper. DH produced the initial manuscript draft. D-SB analyzed the tidal data and wrote the results sections. Both authors worked on and finalized the full manuscript.

## Competing interests

The authors declare that they have no conflict of interest.

## Special issue statement (will be included by Copernicus)

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**Table 1. Comparison of tidal constituent amplitudes, amplitude ratios (including daily tidal form factor, *F*, and monthly tidal envelope factor, *E*) and ranges between the four distinct types of monthly tidal envelope (*E* types) found in the 27 case study semi-diurnal tide regimes of New Zealand, and compared to Equilibrium Theory amplitude ratios**

| *E* type | Example sites | Amplitude (cm) | | | | | Amplitude ratio | | | | | | | *F* value range, description | *E* value range, description |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $M_2$ | $S_2$ | $N_2$ | $K_1$ | $O_1$ | $\frac{S_2}{M_2}$ | $\frac{N_2}{M_2}$ | $\frac{N_2}{S_2}$ | $\frac{S_2}{N_2}$ | $\frac{S_2+N_2}{M_2}$ | $\frac{K_1}{M_2}$ | $\frac{O_1}{M_2}$ | | |
| n/a | Equilibrium Theory | - | - | - | - | - | 0.47 | 0.19 | 0.41 | 2.44 | 0.66 | 0.584 | 0.415 | 0.68 mixed, mainly semi- diurnal | n/a |
| 1 | Kapiti | 55 | 26 | 9 | 2 | 2 | 0.47 | 0.16 | 0.35 | 2.89 | 0.64 | 0.04 | 0.04 | 0.05 semi-diurnal | 0.79 spring-neap |
| 2 | Nelson, Manukau, Taranaki, Onehunga, Westport, Charleston, Pusegur Point | 78 to 133 | 19 to 40 | 17 to 25 | 2 to 6 | 1 to 4 | 0.24 to 0.3 | 0.18 to 0.22 | 0.58 to 0.89 | 1.12 to 1.74 | 0.45 to 0.48 | 0.02 to 0.06 | 0.01 to 0.05 | 0.04 to 0.07 semi-diurnal | 0.90 to 0.98 intermediate, spring-neap dominant |
| 3 | North Cape, Boat Cove and Fishing Rock (Raoul Island), Dog Island, Auckland, Bluff, Lottin Point, Tauranga, Korotiti Bay, Moturiki, Green Island, Port Chalmers, Sumner, Gisborne, Napier | 50 to 112 | 4 to 18 | 10 to 22 | 2 to 8 | 1 to 4 | 0.06 to 0.2 | 0.2 to 0.23 | 1.07 to 3.5 | 0.29 to 0.94 | 0.28 to 0.43 | 0.02 to 0.10 | 0.01 to 0.06 | 0.05 to 0.14 semi-diurnal | 1.01 to 1.15 intermediate, perigean-apogean dominant |
| 4 | Kaikoura, Owenga, Castlepoint, Wellington | 48 to 65 | 2 to 3 | 10 to 14 | 2 to 4 | 2 to 4 | 0.04 to 0.05 | 0.21 to 0.22 | 4.67 to 5.50 | 0.18 to 0.21 | 0.25 to 0.27 | 0.04 to 0.06 | 0.04 to 0.06 | 0.08 to 0.12 semi-diurnal | 1.16 to 1.18 perigean-apogean |

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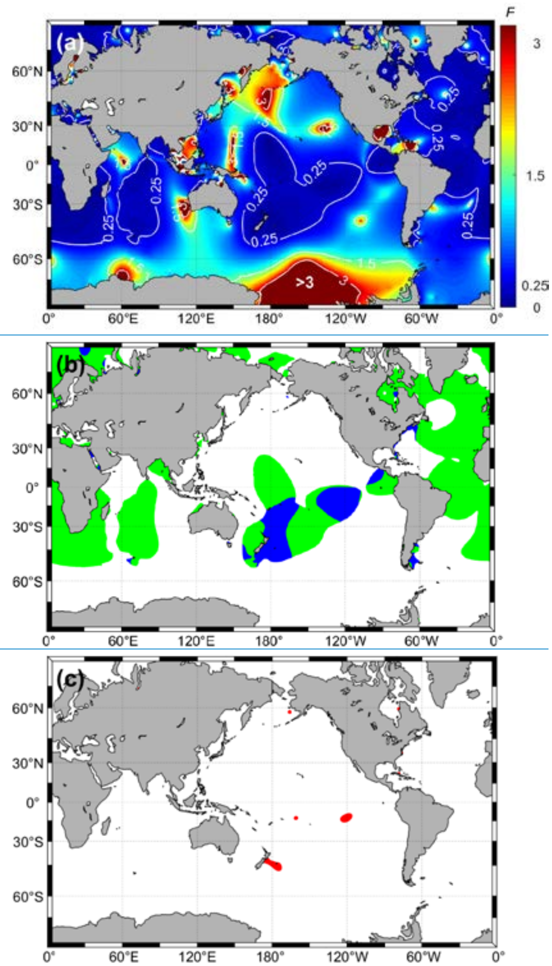


**Figure 1. (a) Global distribution of daily form factor (*F*) values, indicating daily tidal regime types (*F*<0.25: semi-diurnal; *F*>0.25 to *F*<1.5 mixed-mainly semi-diurnal; *F*>1.5 to *F*<3: mixed-mainly diurnal; and *F*>3: diurnal, according to the classification of van der Stok 1897, and Courtier 1938); (b) the world's semi-diurnal tidal areas (*F*<0.25) divided into those where spring-neap (green) versus perigean-apogean (blue) signals are the main influence on the monthly tidal envelope; and (c) semi-diurnal tidal regimes (in red) where the $S_2/M_2$ constituent amplitude ratio is <0.04 and the spring-neap tidal signals are very weak as compared to perigean-apogean signals, derived from FES2014 tidal harmonic constants.**

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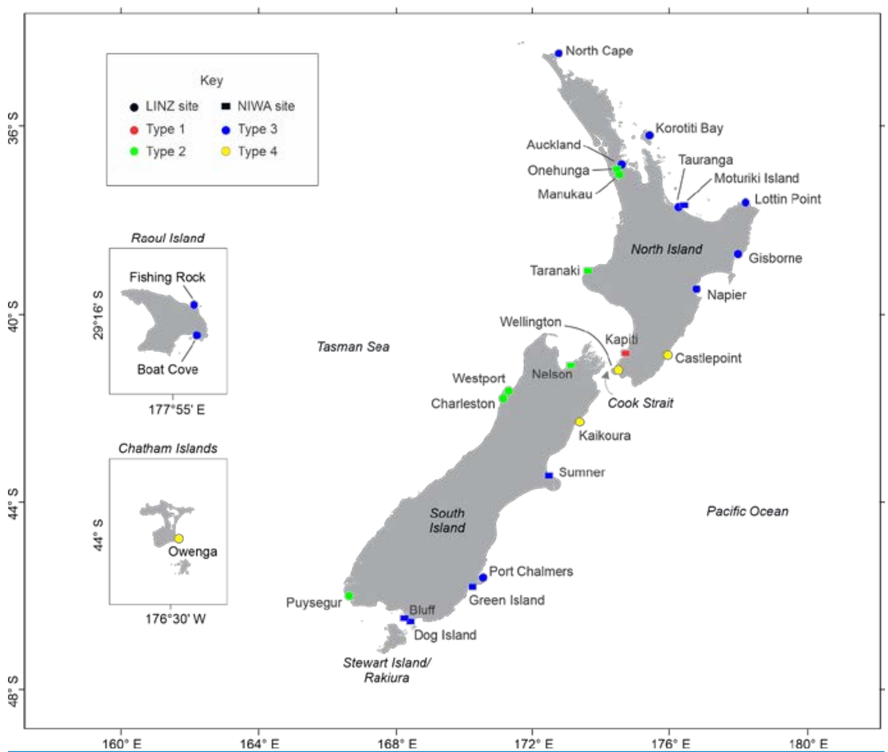


**Figure 2. Location of New Zealand sea level observation stations investigated in this research: circles indicate LINZ sites, rectangles indicate NIWA sites; each site is colored according to monthly tidal envelope type. Offshore islands are not shown to scale (Raoul and Chatham Islands).**

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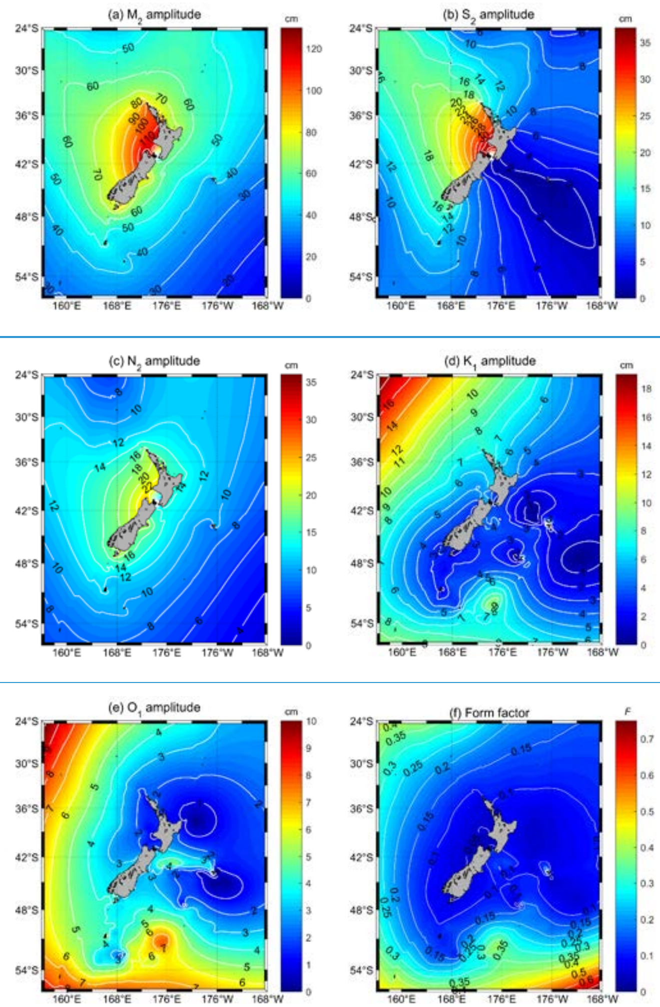


**Figure 3. Horizontal distribution of amplitudes for the (a) $M_2$, (b) $S_2$, (c) $N_2$, (d) $K_1$, and (e) $O_1$ tides around NZ, and (f) the resultant distribution of *F*, daily tidal form factor values, as calculated from the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude color scales vary between plots a and e.**

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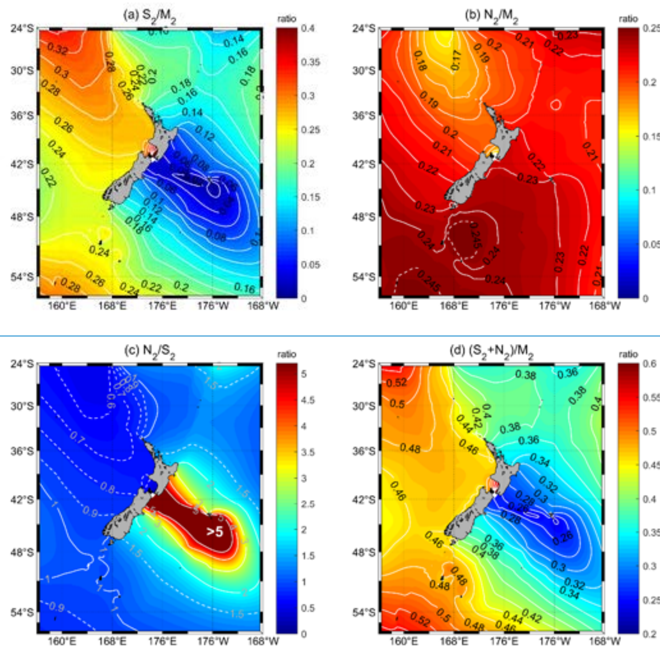


**Figure 4. Distributions of tidal constituent amplitude ratios around NZ for: (a) $\frac{S_2}{M_2}$; (b) $\frac{N_2}{M_2}$; (c) $\frac{N_2}{S_2}$ and (d) $\frac{S_2+N_2}{M_2}$; as calculated using the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude color scales vary between plots a and d.**

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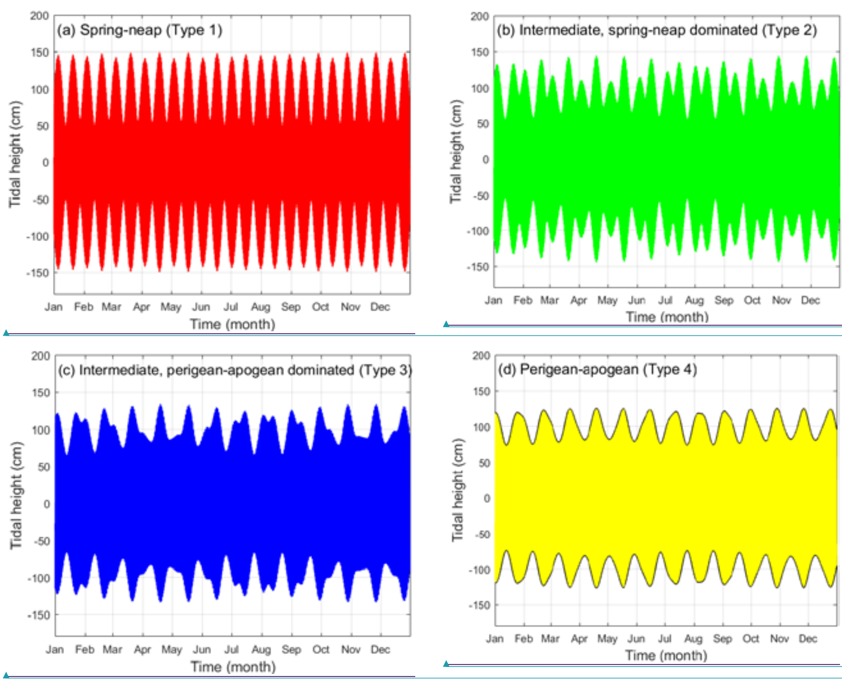


**Figure 5. Idealized examples of four different monthly tidal envelopes over one year, calculated using the amplitude value $M_2 = 100$ cm and the amplitude ratio values of: (a) $\frac{S_2}{M_2} = 0.46$, $\frac{S_2}{N_2} = 11.5$, $\frac{N_2}{M_2} = 0.04$; (b) $\frac{S_2}{M_2} = 0.27$, $\frac{S_2}{N_2} = 1.5$, $\frac{N_2}{M_2} = 0.18$; (c) $\frac{S_2}{M_2} = 0.12$, $\frac{S_2}{N_2} = 0.5455$, $\frac{N_2}{M_2} = 0.22$; and (d) $\frac{S_2}{M_2} = 0.04$, $\frac{S_2}{N_2} = 0.1818$, $\frac{N_2}{M_2} = 0.22$. Note that the $E$ values of these plots are: (a) 0.71; (b) 0.93; (c) 1.09; and (d) 1.17.**

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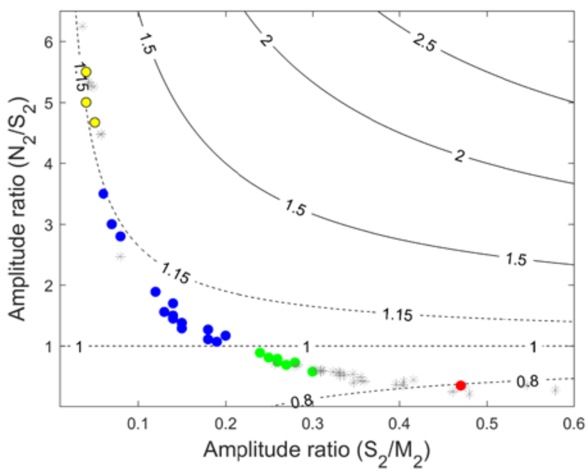


**Figure 6. Plot of the relationship between the $\frac{N_2}{S_2}$ and $\frac{S_2}{M_2}$ amplitude ratios (y and x axes respectively) versus $E$ values (shown as plot contours), with data points corresponding to New Zealand waters Type 1 sites (red dots); Type 2 sites (green dots); Type 3 sites (blue dots); and Type 4 sites (yellow dots), all from Table A1; and tidal data representative of the greater Cook Strait area (grey crosses) from Walters et al. (2010, Tables 1 and 3).**

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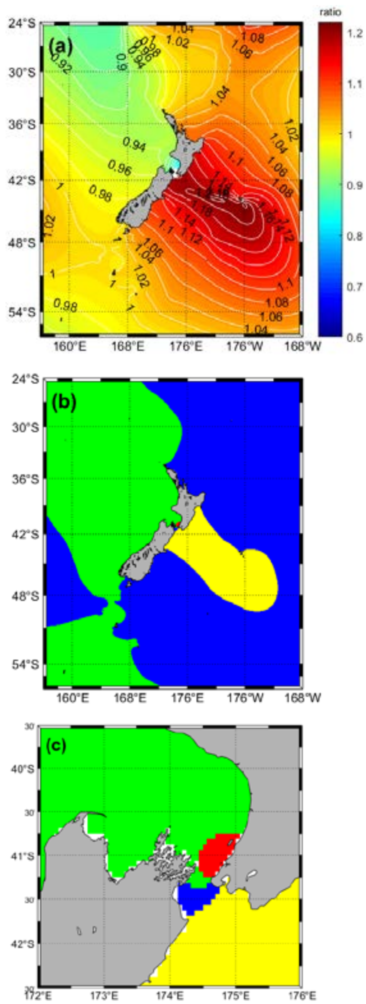


**Figure 7. Distribution of monthly tidal envelope factor (*E*) values (a); and types (b); in the waters around New Zealand, including in the Cook Strait area between the two main islands (c); calculated using FES2014 data. In (b), *E* type 1 areas are shown in red; type 2 in blue; type 3 in green; and type 4 in yellow. See Figure 5 for definitions and examples of monthly tidal envelope factor classes and patterns.**

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