Response to final review of the paper* "A monthly tidal envelope classification approach for semi-diurnal regimes with variability in S_2 and N_2 tidal amplitude ratios" *by Philip Woodworth, submitted 21 April 2020

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Introduction We are grateful for the final Woodworth review on this paper (received via the Editor's letter) as it has been useful in helping with a final polish and improvement of 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, with the exception of redefining the monthly tidal envelope types based on one instead of two ratios (please see below where we explain that we added your idea but also kept the two ratios). 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 final paper file separately as well, according to the Copernicus instructions.

Comments on resubmission of 'A monthly tidal envelope classification approach for semi-diurnal regimes with variability in S2 and N2 tidal amplitude ratios' by Byun and Hart (OS special issue)
I didn't look back in great detail on my comments on the first version and the replies of the authors, I decided to just read it afresh. I think it now reads much better than it did before, although it is still a bit repetitive.
I list below some things that I noticed with the new version but couple of main things:

- **Response:** Thank you for this additional, careful review.

One thing that looks wrong is sentence lines 126-128. This sentence is ok for S2/M2 but the ratio variation is the opposite for N2/S2. Just look at Figure 4(a,c). Rewording needed.

- **Response:** Thank you for pointing this out: we have fixed the wording of this sentence.
- **The altered 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 $\frac{S_2}{M_2}$ amplitude ratio varies widely around NZ, with highest values in the west, lowest values in the east, and intermediate values to the north and south, while variation in the $\frac{N_2}{S_2}$ amplitude ratio exhibits an opposite pattern (compare Fig. 4a to 4c).

The other is that, as I mentioned last time, the most interesting figure to me is the present Figure 7 which made me wonder at the value of the new E. Forget Type 1 for the moment which has only one red dot. You can see that using E to decide between types 3 and 4 at 1.15 is problematical - the curve just scrapes the blue and yellow dots. A more efficient selection would be simply by N2/S2 ratio at 4.0, as for the division between types 2 and 3 at 1.0. I hope you see what I mean and can put in a sentence along these lines in the Discussion.

- **Response:** We understand you mean Figure 6 (the E type separating plot that you identified as most interesting in your first review). Thank you for this suggestion. Upon careful consideration and understanding of your idea, we are still using both ratios in defining our boundaries but we also accommodated your point in new section 3.2 text (see yellow highlight below) that spells out the boundaries including comment regarding how our Type 3 and Type 4 dots are separated by distinct N2/S2 ratios boundaries (though so too are the two type 3 clusters – read on). We have also minimised the size of the dots to improve the appearance of dots skimming the boundary lines, but cannot make the dots too small or their colour distinction disappears. We put back a third decimal place in the E ratio data in Table 1 and A1 as we realised, thanks to your comment, that rounding to 2 decimal places obscured the actual point locations relative to the boundary lines.

As you see in Fig. 7, the distinction between types 2 and 3 (green and blue dots) at N2/S2 = 1.0 is as close to the line as the Type 3 and 4 distinction that you highlight as a problem (yellow and blue dots either side of the E=1.15 line). Despite the proximity of dots to the N2/S2 = 1.0, we are confident that this is a proper boundary since it denotes where perigean/apogean influences dominate over spring/neap influences, and vice versa. There is some separation between the green Type 2 cluster and start of the blue Type 3 cluster on the S2/M2 x-axis, making this axis relevant to this boundary.

As you point out, there is a y-axis gap (around N2/S2 = 4) between the yellow and blue dots. But there is another gap on the y-axis, in the middle of the blue dots, at around N2/S2=2. When we plot these monthly tidal envelope types out, the blue dot sites all have mixed perigean/apogean and spring/neap influences, but all with perigean/apogean being the dominant influence.

We therefore feel that the combination of the two ratios is a better way to separate out the types overall, compared to using the N2/S2 alone, acknowledging the gaps on both ratio axes.

- **The altered text now reads:**

"The boundaries between our different NZ monthly tidal envelope types were as follows:

- *E* < 0.8 indicates a Type 1 'spring-neap' regime;
- *E* between 0.8 and 1.0 indicates a Type 2 'intermediate, predominantly spring-neap' regime (with the upper bound also corresponding to an amplitude ratio of $\frac{N_2}{S_2} < 1$ in semidiurnal regimes);
- *E* between 1.0 and 1.15 indicates a Type 3 'intermediate, predominantly perigean-apogean' regime (with the lower bound also corresponding to an amplitude ratio of $\frac{N_2}{S_2} > 1$ in semidiurnal regimes); and
- *E* > 1.5 indicates a Type 4 'perigean-apogean' regime (with the lower bound also corresponding to an amplitude ratio of $\frac{N_2}{S_2} > 4$ in our NZ regimes)".

- **The altered Fig. 6 now looks like:**

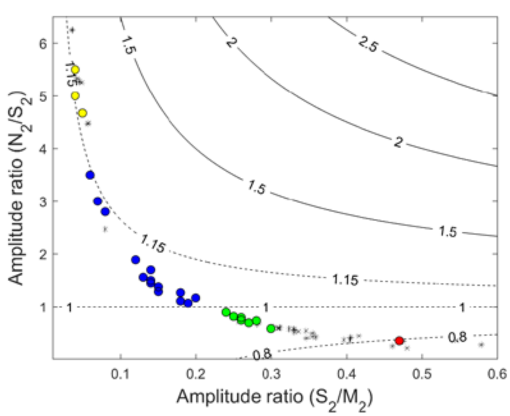

Figure 6. Plot of the relationship between the $\frac{N_2}{S_2}$ and $\frac{S_2}{M_2}$ amplitude ratios (y and x axes respectively) versus *E* values (shown as plot contours), with data points corresponding to New Zealand waters Type 1 sites (red dots); Type 2 sites (green dots); Type 3 sites (blue dots); 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).

Other things in line order:
title - I wondered if the title would be better as 'A monthly tidal envelope classification for semi-diurnal tidal regimes in terms of the relative proportions of the S2, N2 and M2 constituents'. Or something like that, it is your paper so up to you.

- **Response:** We have altered the title as suggested.
- **The altered text now reads:** "A monthly tidal envelope classification for semi-diurnal regimes in terms of the relative proportions of S_2, N_2 and M_2 constituents".

7-8 and 187-189 - I didn't understand 'access .. wharves'. What are you saying? That access to marine environments by boat is difficult and/or to infrastructure? Needs rewording.

- **Response:** Yes, we meant that the tide controls our access to marine environments when we need to use fixed infrastructure like jetties to access the water by boat. It was a bit wordy so we simplified this text.
- **These two altered sections of text now read:**
  "Daily tidal water level variations are a key control on shore ecology; on access to marine environments via ports, jetties and wharves; on drainage links between the ocean and coastal hydrosystems such as lagoons and estuaries; and on the duration and frequency of opportunities to access the intertidal zone for recreation and food harvesting purposes".
  "The daily water level variations wrought by the tides are a key control on shore ecology and on the accessibility of marine environments via fixed port, jetty and wharf infrastructure. These variations also moderate the functioning of drainage links between the ocean and coastal hydrosystems; and determine the duration and frequency of opportunities to access the intertidal zone for recreation and food harvesting purposes".

26-27 - as I mentioned before these references are all about tides rather than non-tidal signals. But ok. But I would add Stammer et al to the others - there is no reason to separate it.

- **Response:** We have placed all the references together at the end of this sentence again.
- **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, as well as to accurately resolving non-tidal signals of global interest such as in studies of sea level change (Cartwright, 1999; Masselink et al., 2014; Olson, 2012; Pugh, 1996, Stammer et al., 2014)".

137 - Fig 3 and 4

- **Response:** This change has been made as suggested.
- **The altered text now reads:** "…(Fig. 3 and 4…".

142 .. ratio are between ..

- **Response:** This change has been made.
- **The altered text now reads:** "Here values of the $\frac{N_2}{S_2}$ amplitude ratio are between 1.07 and 3.5, while values of the $\frac{S_2+N_2}{M_2}$ amplitude ratio are between 0.28 and 0.43 (Fig. 4, Table 1)".

146 - you have UK spelling here (colour) and US (color) in the figure captions. I suggest you use UK spelling throughout as Copernicus is a European journal.

- **Response:** The spelling has been changed to UK throughout. Color, analyzed and characterized have been replaced with colour, analysed and characterised, in particular.

162 - please add '.. occurs at N2/S2 =1 when also E = 1.'

- **Response:** Change made as suggested.
- **The altered text now reads:** "Thus, the boundary separating Types 1 and 2 from Types 3 and 4 occurs at $\frac{N_2}{S_2} = 1$, when also $E = 1$".

You need to spell out what the divisions between types are.

- **Response:** Thank you for this prompt. Yes, we have added a clear statement spelling out the boundaries in list form as follows.
- **The altered text now reads:**

"The boundaries between our different NZ monthly tidal envelope types in NZ waters were as follows:

- $E < 0.8$ indicates a Type 1 'spring-neap' type regime;
- E between 0.8 and 1.0 indicates a Type 2 'intermediate, predominantly spring-neap' type regime (with the upper bound also corresponding to an amplitude ratio of $\frac{N_2}{S_2} < 1$ in semidiurnal regimes);
- E between 1.0 and 1.15 indicates a Type 3 'intermediate, predominantly perigean-apogean' type regime (with the lower bound also corresponding to an amplitude ratio of $\frac{N_2}{S_2} > 1$ in semidiurnal regimes); and
- $E > 1.5$ indicates a Type 4 'perigean-apogean' type regime (with the lower bound also corresponding to an amplitude ratio of $\frac{N_2}{S_2} > 4$ in our NZ regimes)".

This is also a point to mention that you call these things Types here, but in the tables you call them E-Types. Because I think they can just as easily be defined by N2/S2 (see the second of my main points above) I think they would be better as Types throughout.

- **Response:** We have changed all table and text mentions of "E types" to read "envelope types" for consistency.
- **The altered text now reads:** "envelope types".

lines 181-185. There are several problems here:
- one is the last sentence returns to mention of NZ after you have digressed to the rest of the world. Could you somehow work the last sentence after line 180 probably, then go onto other places.

- **Response:** We have reworded this paragraph to position the non-NZ places after all of the NZ place descriptions. We have also reworded the list of international (non-NZ) places and deleted reference to 'North America'.
- **The altered text now reads:** "In summary, Fig. 7 illustrates the monthly tidal envelope values and types in the waters around NZ using E. The west coast is characterised 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. Extensive areas of Type 3 'intermediate, perigean-apogean dominated' monthly tidal envelope are found along the northeast and southeast coasts of NZ, while the central east 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; northeast of the Pitcairn Islands; in Canada's Hudson Bay; in Alaska's Bristol Bay; offshore of the North Carolina to Virginia coast in the Unites States of America; on the north coast of the Bahamas; and in the Gulf of Ob in Russia".

Another problem with your lists in this paper is you seem to use semicolons and commas randomly. In lists one starts with a colon, with semicolons between items (or some people have commas). Please can you go through and tidy that up?

- **Response:** Yes – the reason why it seemed that we mixed commas and semi-colons in the above list of places was that there was a regional groupings separated by semi-colons with countries separated by commas within the regional groups. However we simplified this, as above, to remove the regional groupings and just use semicolons. We have checked the lists throughout the rest of the paper text and use semicolons throughout now, except in the Fig. 6 caption alone, where there are types separated by commas and data groupings separated by semicolons. We hope that you can suggest if you would prefer some other pattern to this one figure caption punctuation during the proofing stage.

- then a couple of these examples such as N Carolina/Virginia or Gulf of Ob just don't appear on Fig 1c, no doubt because the dots are so small. So you should say that to save people wasting time looking for them. Where is the Gulf of Ob anyway?

- **Response:** As stated in the text above, the Gulf of Ob is in Russia. All of the places mentioned are marked by red blobs in Fig. 1c though some are indeed small – they should be readily visible if people view the electronic version of the paper figure but perhaps not easily seen on a printed copy if this figure is reproduced at column instead of page width. If possible we recommend that this Fig.1 is reproduced at page width.

187-189 copies verbatim from the abstract. Could you maybe change the wording a little to show willing?

- **Response:** Yes – we have altered this text so it is now different, not verbatim. Please see the new text for both section in response to the comment on lines 7-8 and 187 to 189 earlier in this document.

228 - reword something like: Monthly tidal envelope types and values of monthly (E) and daily (F) form factors ... of 5 tidal constituents ...

- **Response:** This has been reworded as suggested.
- **The altered text now reads:** "Table A1. Monthly tidal envelope types and values of monthly (*E*) and daily (*F*) form factors, and data on the amplitude (a_i) and phase lag (G_i, relative to Greenwich) values of 5 tidal constituents' (subscript *i*) harmonic constants at 27 sea level stations around New Zealand".

column 2 - Type

- **Response:** This has been modified to envelope type instead of *E* type.
- **The altered text now reads:** "Envelope type".

As I mentioned before, in the last line you don't seem to realise that 0 and 360 deg is the same thing. This range is not a very useful anyway when you have shown there are amphidromes all over the place. I would either not include that whole line or just show the ranges of amplitude.

- **Response:** We have deleted the phase lag ranges from this table, as recommended.

279 - Chichester

- **Response:** This typo has been fixed.
- **The altered text now reads:** "Chichester".

Table 1, line 300 - E types --> types

- **Response:** This has been modified to envelope types instead of *E* types.
- **The altered text now reads:** "the four distinct monthly tidal envelope types found in the 27 case study semi-diurnal tide regimes of New Zealand".

column 1 - Type

- **Response:** This has been modified to eliminate "E" type.
- **The altered text now reads:** "Envelope type".

Figure 2 is fine but it will probably be printed at half this size so I would make all the fonts larger. Also when it is smaller you won't be able to tell circles from rectangles so they should be larger also. colored - see above

- **Response:** We have redrawn this figure with larger font and larger dots as recommended. We realised, thanks to your comment, that the circles and rectangles differentiating the NIWA and LINZ data sources was an unnecessary complication, so we changed them all to be the same circular form and have deleted reference to these two different data providers. We also changed the language to UK English.
- **The altered Fig. 2 now looks like:**

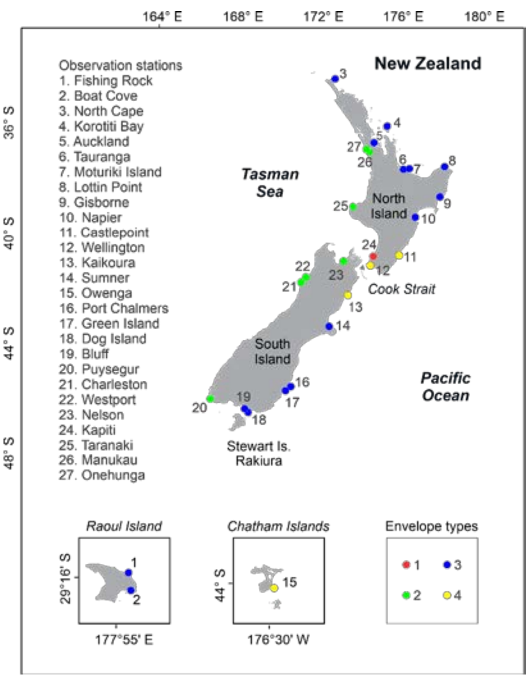

Figure 2. Location of New Zealand sea level observation stations investigated in this research. Each site is coloured according to monthly tidal envelope type. Offshore islands are not shown to scale (Raoul and Chatham Islands).

Fig 3 caption - drop Horizontal

- **Response:** This has been deleted.
- **The altered text now reads:** "Figure 3. Distribution of amplitudes for the (a) M2, (b) S2, (c) N2, (d) K1, and (e) O1 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 colour scales vary between plots a and e".

Fig 5 - it doesn't matter much but looks a bit odd to show one ratio like 0.46 to 2 decimals and one like S2/N2 to four

- **Response:** Yes, we have rounded the two 4 decimal place numbers to 2 decimal place numbers for consistency.
- **The altered caption now reads:** "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) $\frac{S_2}{M_2} = \mathbf{0.46}$, $\frac{S_2}{N_2} = \mathbf{11.5}$, $\frac{N_2}{M_2} = \mathbf{0.04}$; (b) $\frac{S_2}{M_2} = \mathbf{0.27}$, $\frac{S_2}{N_2} = \mathbf{1.5}$, $\frac{N_2}{M_2} = \mathbf{0.18}$; (c) $\frac{S_2}{M_2} = \mathbf{0.12}$, $\frac{S_2}{N_2} = \mathbf{0.54}$, $\frac{N_2}{M_2} = \mathbf{0.22}$; and (d) $\frac{S_2}{M_2} = \mathbf{0.04}$, $\frac{S_2}{N_2} = \mathbf{0.18}$, $\frac{N_2}{M_2} = \mathbf{0.22}$. Note that the *E* values of these plots are: (a) 0.71; (b) 0.93; (c) 1.09; and (d) 1.17".

Fig 6, line 1 - versus E values --> and E values. It is not versus which is when you have y vs. x.

I looked at this draft on paper and I couldn't see the grey points at all - I could on the pdf - so I would make them a bit darker. Also they are stars (or asterisks) and not crosses.

- **Response:** We have changed ‘versus’ to ‘and’. We have re-drawn the figure with the ‘grey crosses’ (which, yes, were actually stars) as black stars and fixed the caption to reflect this.
- **The altered caption now reads:** “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) and *E* values (shown as plot contours), with data points corresponding to New Zealand waters monthly tidal envelope 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 (black stars) from Walters et al. (2010, Tables 1 and 3)”.

Fig 7 caption - (a) Distribution ... values and (b)tidal types in .. including (c) in the . islands, all calculated using .. In (b) and (c) ..

- **Response:** Changes made exactly as recommended.
- **The altered caption now reads:** “Figure 7. (a) Distribution of monthly tidal envelope factor (*E*) values; and (b) monthly tidal envelope types; in the waters around New Zealand, including (c) in the Cook Strait area between the two main islands; all calculated using FES2014 data. In (b) and (c), envelope 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”.

A monthly tidal envelope classification for semidiurnal regimes in terms of the relative proportions of the S_2, N_2, and M_2 constituents

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Abstract. Daily tidal water level variations are a key control on shore ecology; on access to marine environments via ports, jetties and wharves; on drainage links between the ocean and coastal hydrosystems such as lagoons and estuaries; and on 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 semidiurnal 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 semidiurnal 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, as well as to accurately resolving non-tidal signals of global interest such as in studies of sea level change (Cartwright, 1999; Masselink et al., 2014; Olson, 2012; Pugh, 1996, Stammer et al., 2014).

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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 a ratio between diurnal and semidiurnal tide amplitudes via the equation:

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

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 (semidiurnal regimes); or two unequal high and low tides per day (mixed semidiurnal 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, semidiurnal 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 semidiurnal 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 semidiurnal, 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 semidiurnal 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 semidiurnal 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 semidiurnal 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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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 semidiurnal, 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 semidiurnal tide rotation, with tides generally circulating around the country in an anticlockwise 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 NZ (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 the 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 analysed using T_Tide (Pawlowicz et al., 2002) with the nodal (satellite) 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 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 semidiurnal 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 characterisation.

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 semidiurnal constituent amplitudes (Fig. 4). Table 1 summarises 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 semidiurnal 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 semidiurnal 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 (0.47). 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. 0.19). 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 $\frac{S_2}{M_2}$ amplitude ratio varies widely around NZ, with highest values in the west, lowest values in the east, and intermediate values to the north and south, while variation in the $\frac{N_2}{S_2}$ amplitude ratio exhibits an opposite pattern (compare Fig. 4a to 4c). 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' sub-regions, tides exhibit two dominant, but unequal, spring-neap cycles per month due to subordinate perigean-apogean effects. 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 and 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' 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 are between 1.07 and 3.5, while values of the $\frac{S_2+N_2}{M_2}$ amplitude ratio are between 0.28 and 0.43 (Fig. 3 and 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 idealised types, two with stronger spring-neap signals (Types 1 and 2, see Fig. 5 a-b) and two with stronger 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.

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3.2 A monthly tidal envelope factor (*E*) for semidiurnal regimes

The four types of monthly tidal envelope 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 semidiurnal 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:

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

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

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 semidiurnal region (i.e. where F<0.25) based on the analysis of constituent amplitudes and ratios from local data. The boundaries between our different NZ monthly tidal envelope types were as follows:

- E < 0.8 indicates a Type 1 'spring-neap' regime;
- E between 0.8 and 1.0 indicates a Type 2 'intermediate, predominantly spring-neap' regime (with the upper bound also corresponding to an amplitude ratio of $\frac{\mathrm{N_2}}{\mathrm{S_2}}$ < 1 in semidiurnal regimes);
- E between 1.0 and 1.15 indicates a Type 3 'intermediate, predominantly perigean-apogean' regime (with the lower bound also corresponding to an amplitude ratio of $\frac{\mathrm{N_2}}{\mathrm{S_2}}$ > 1 in semidiurnal regimes); and
- E > 1.5 indicates a Type 4 'perigean-apogean' regime (with the lower bound also corresponding to an amplitude ratio of $\frac{\mathrm{N_2}}{\mathrm{S_2}}$ > 4 in our NZ regimes).

Here we explain how we set boundaries between the different envelope types around NZ using case study data and as summarised in Fig. 6. Firstly, in any semidiurnal 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, when also E = 1. Type 1 and 2 areas of the NZ coast are characterised 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'

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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* = 0.790 for NZ, just greater than that of Kapiti and below the next strongest spring-neap influenced site, Nelson, where *E* = 0.902 (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 characterised 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. Extensive areas of Type 3 'intermediate, perigean-apogean dominated' regimes are found along the northeast and southeast coasts of NZ, while the 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; northeast of the Pitcairn Islands; in Canada's Hudson Bay; in Alaska's Bristol Bay; offshore of the North Carolina to Virginia coast in the Unites States of America; on the north coast of the Bahamas; and in the Gulf of Ob in Russia.

4 Discussion and conclusion

The daily water level variations wrought by the tides are a key control on shore ecology and on the accessibility of marine environments via fixed port, jetty and wharf infrastructure. These variations also moderate the functioning of drainage links between the ocean and coastal hydrosystems; and determine 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 risk (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 model data to demonstrate a simple approach to classifying different

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monthly tidal envelope types, applicable to semidiurnal regions anywhere. The result is a widely applicable monthly tidal envelope factor, *E*, for classifying semidiurnal 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 semidiurnal 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 semidiurnal 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 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 semidiurnal 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. 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 semidiurnal 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 semidiurnal (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 types and values of monthly (*E*) and daily (*F*) form factors, and data on the amplitude (a_i) and phase lag (G_i, relative to Greenwich) values of 5 tidal constituents' (subscript *i*) harmonic constants at 27 sea level stations around New Zealand.

Station name (record used)	Envelope 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	0.790	0.05	55	280	26	336	9	277	2	195	2	18
Nelson (2015)	2	0.902	0.04	133	276	40	329	23	254	6	187	1	80
Manukau (2011)	2	0.935	0.05	109	297	29	332	20	287	6	17	1	287
Taranaki (2016)	2	0.941	0.05	119	278	33	319	24	257	6	192	2	90
Onehunga (2016)	2	0.945	0.05	131	304	34	359	25	288	6	205	2	118
Westport (2015)	2	0.958	0.04	113	309	29	348	23	287	2	198	3	40
Charleston (2015/2016)	2	0.962	0.05	106	319	27	344	22	304	3	6	3	243
Puysegur Point (2012)	2	0.979	0.07	78	350	19	13	17	335	3	316	4	245
North Cape (2010)	3	1.011	0.11	80	230	15	279	16	209	8	10	2	351
Boat Cove, Rauol Island (2012)	3	1.017	0.14	50	208	9	287	10	176	5	43	3	44
Dog Island (2011)	3	1.028	0.06	91	33	18	57	21	6	2	119	4	60
Auckland (2011)	3	1.039	0.07	112	216	17	275	22	192	7	356	2	324
Bluff (2016)	3	1.040	0.05	84	48	15	75	19	23	2	133	3	71
Fishing Rock, Raoul Island (2011)	3	1.050	0.12	52	206	8	283	11	178	5	35	2	41
Lottin Point (2011)	3	1.063	0.1	70	195	9	262	14	168	6	352	2	328
Tauranga (2011)	3	1.063	0.08	70	211	9	277	14	186	5	0	1	330
Korotiti Bay (2011)	3	1.056	0.08	78	207	11	265	16	181	6	349	1	317
Moturiki (2011)	3	1.060	0.07	73	189	10	265	15	156	5	173	1	136
Green Island (2011)	3	1.084	0.08	73	81	10	91	17	50	3	93	4	44
Port Chalmers (2011)	3	1.093	0.07	77	112	9	112	17	89	3	270	3	247
Sumner (2011)	3	1.133	0.09	84	136	6	151	18	109	5	273	3	245
Gisborne (2010)	3	1.130	0.07	64	176	5	251	14	148	4	336	1	275
Napier (2011)	3	1.147	0.07	64	167	4	240	14	138	3	298	2	221
Kaikoura (2011)	4	1.162	0.12	65	146	3	171	14	117	4	275	4	233
Owenga, Chatham Islands (2011)	4	1.160	0.08	48	149	2	224	10	119	2	246	2	179
Castlepoint (2011)	4	1.167	0.09	63	159	3	225	14	129	3	280	3	219
Wellington (2011)	4	1.176	0.1	49	148	2	352	11	116	2	268	3	219
Overall range	1-4	0.79-1.176	0.04-0.14	48-133		2-40		9-25		2-8		1-4	

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Author contribution

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

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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 monthly tidal envelope types found in the 27 case study semidiurnal tide regimes of New Zealand, and compared to Equilibrium Theory amplitude ratios

Envelope 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	0.58	0.42	0.68 mixed, mainly semidiurnal	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 semidiurnal	0.790 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 semidiurnal	0.902 to 0.979 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 semidiurnal	1.011 to 1.147 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 semidiurnal	1.162 to 1.176 perigean-apogean

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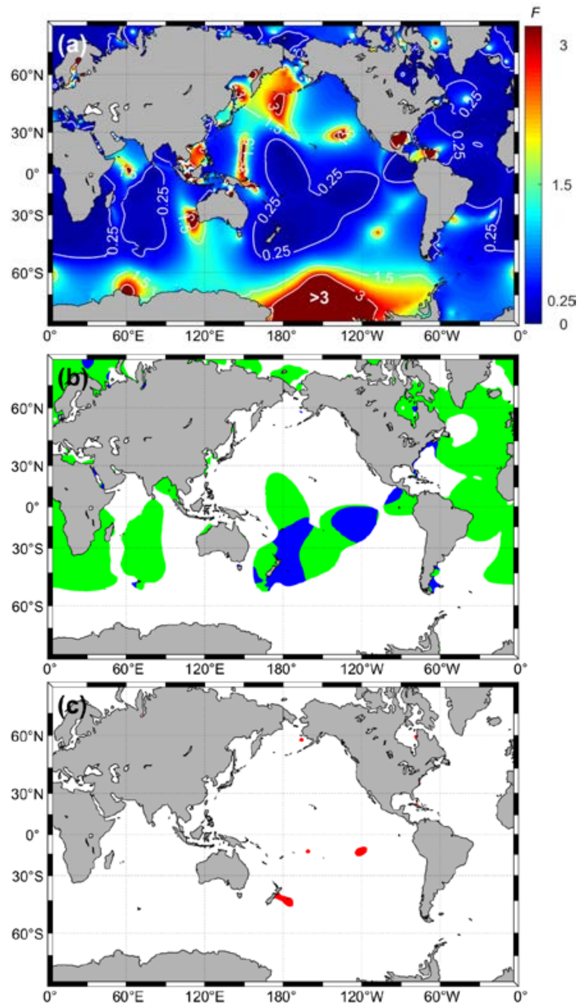

Figure 1. (a) Global distribution of daily form factor (*F*) values, indicating daily tidal regime types (*F*<0.25: semidiurnal; *F*>0.25 to *F*<1.5 mixed-mainly semidiurnal; *F*>1.5 to *F*<3: mixed-mainly diurnal; and *F*>3: diurnal, according to the classification of van der Stok 1897, and Courtier 1938); (b) the world's semidiurnal 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) semidiurnal 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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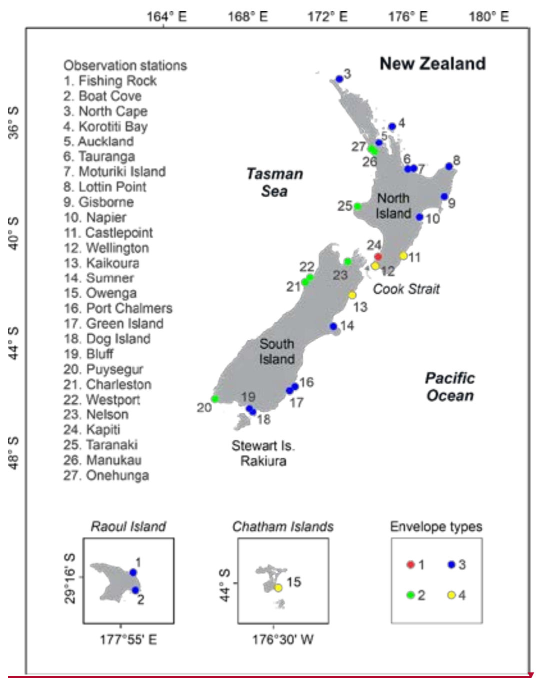

Figure 2. Location of New Zealand sea level observation stations investigated in this research. Each site is coloured according to monthly tidal envelope type. Offshore islands are not shown to scale (Raoul and Chatham Islands).

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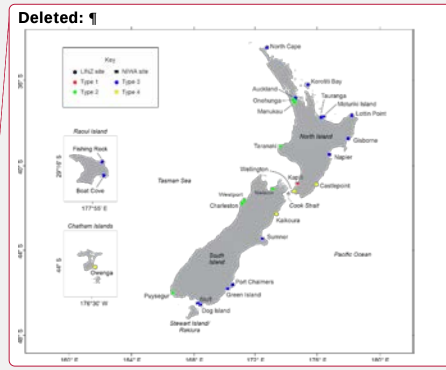

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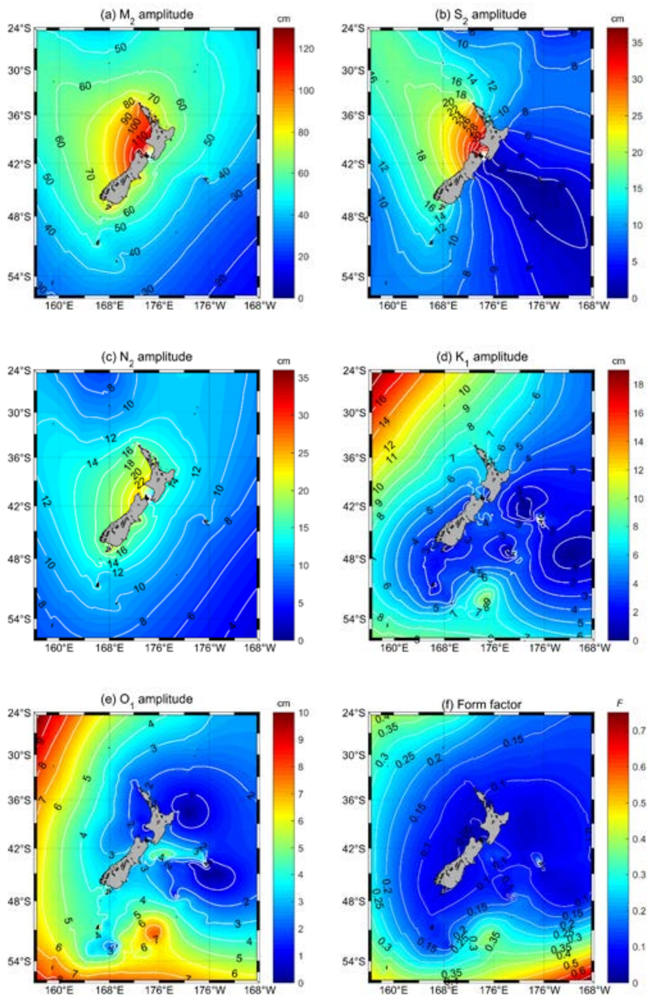

Figure 3. Distribution of amplitudes for the (a) M_2, (b) S_2, (c) N_2, (d) K_1, and (e) O_1 tides around NZ, and (f) the resultant distribution of *F*, daily tidal form factor values, as calculated from the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude colour scales vary between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

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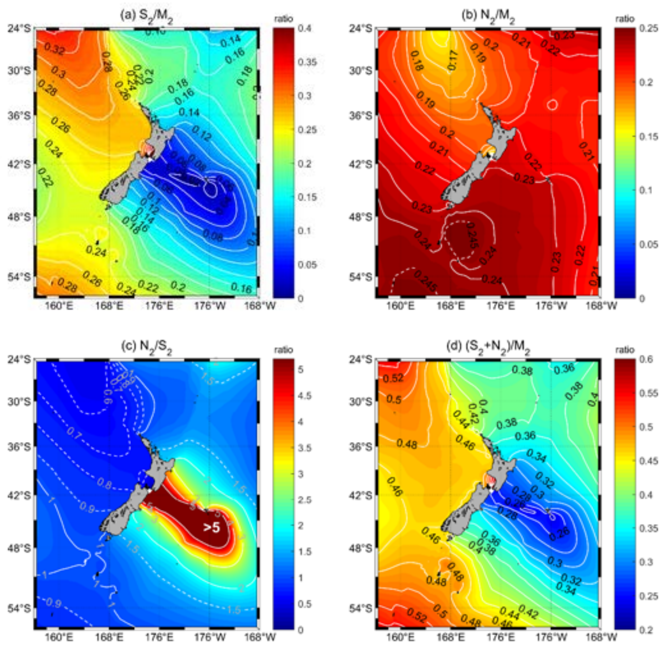

Figure 4. Distributions of tidal constituent amplitude ratios around NZ for: (a) $\frac{S_2}{M_2}$; (b) $\frac{N_2}{M_2}$; (c) $\frac{N_2}{S_2}$ and (d) $\frac{S_2+N_2}{M_2}$; as calculated using the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude colour scales vary between plots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

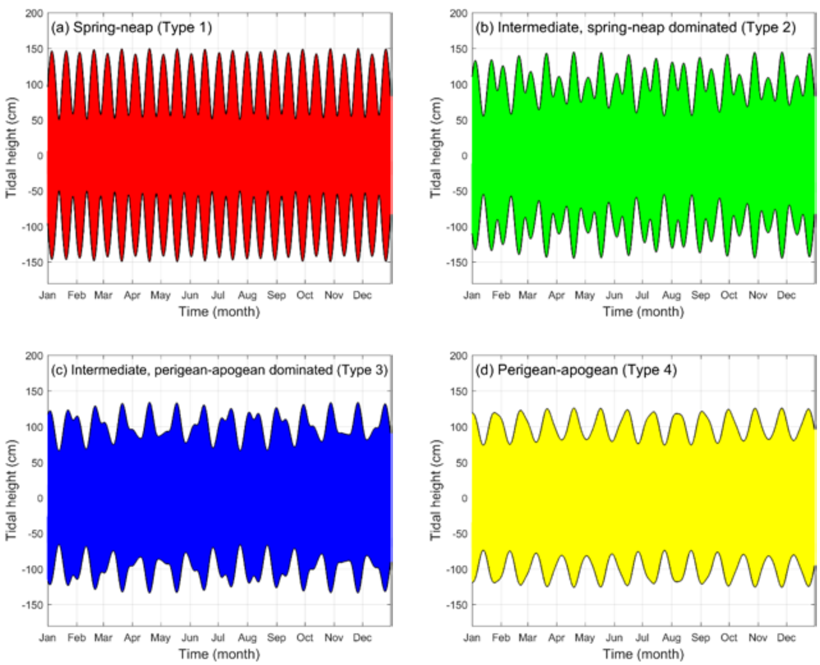

Figure 5. Idealised examples of four different monthly tidal envelopes over one year, calculated using the amplitude value M_2 = 100 cm and the amplitude ratio values of: (a) $\frac{S_2}{M_2} = 0.46$, $\frac{S_2}{N_2} = 11.5$, $\frac{N_2}{M_2} = 0.04$; (b) $\frac{S_2}{M_2} = 0.27$, $\frac{S_2}{N_2} = 1.5$, $\frac{N_2}{M_2} = 0.18$; (c) $\frac{S_2}{M_2} = 0.12$, $\frac{S_2}{N_2} = 0.54$, $\frac{N_2}{M_2} = 0.22$; and (d) $\frac{S_2}{M_2} = 0.04$, $\frac{S_2}{N_2} = 0.18$, $\frac{N_2}{M_2} = 0.22$. 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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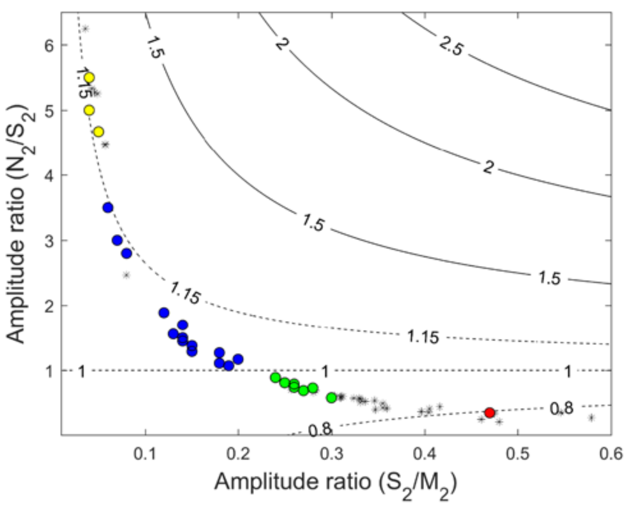

Figure 6. Plot of the relationship between the $\frac{N_2}{S_2}$ and $\frac{S_2}{M_2}$ amplitude ratios (y and x axes respectively) and *E* values (shown as plot contours), with data points corresponding to New Zealand waters monthly tidal envelope Type 1 sites (red dots), Type 2 sites (green dots), 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 (black stars) from Walters et al. (2010, Tables 1 and 3).

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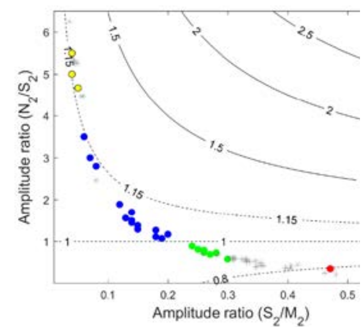

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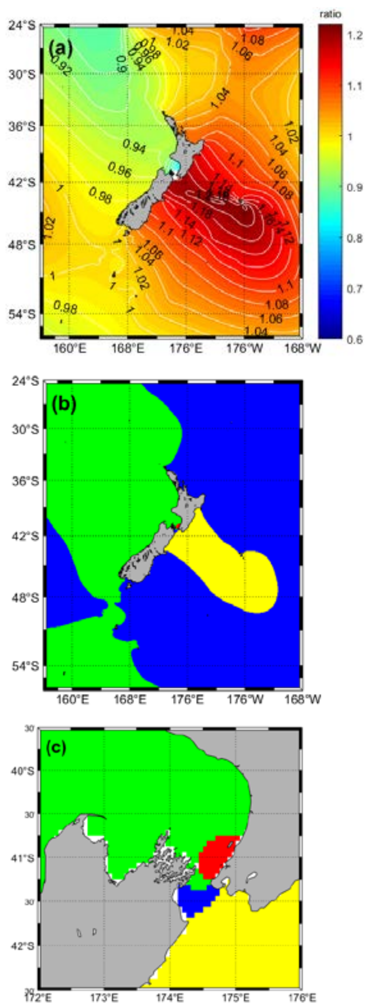

Figure 7. (a) Distribution of monthly tidal envelope factor (*E*) values; and (b) monthly tidal envelope types; in the waters around New Zealand, including (c) in the Cook Strait area between the two main islands; all calculated using FES2014 data. In (b) and (c), envelope type 1 areas are shown in red;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

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