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.

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.

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:

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

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 (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.

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 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 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:

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

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

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

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

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 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 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.

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

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.

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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

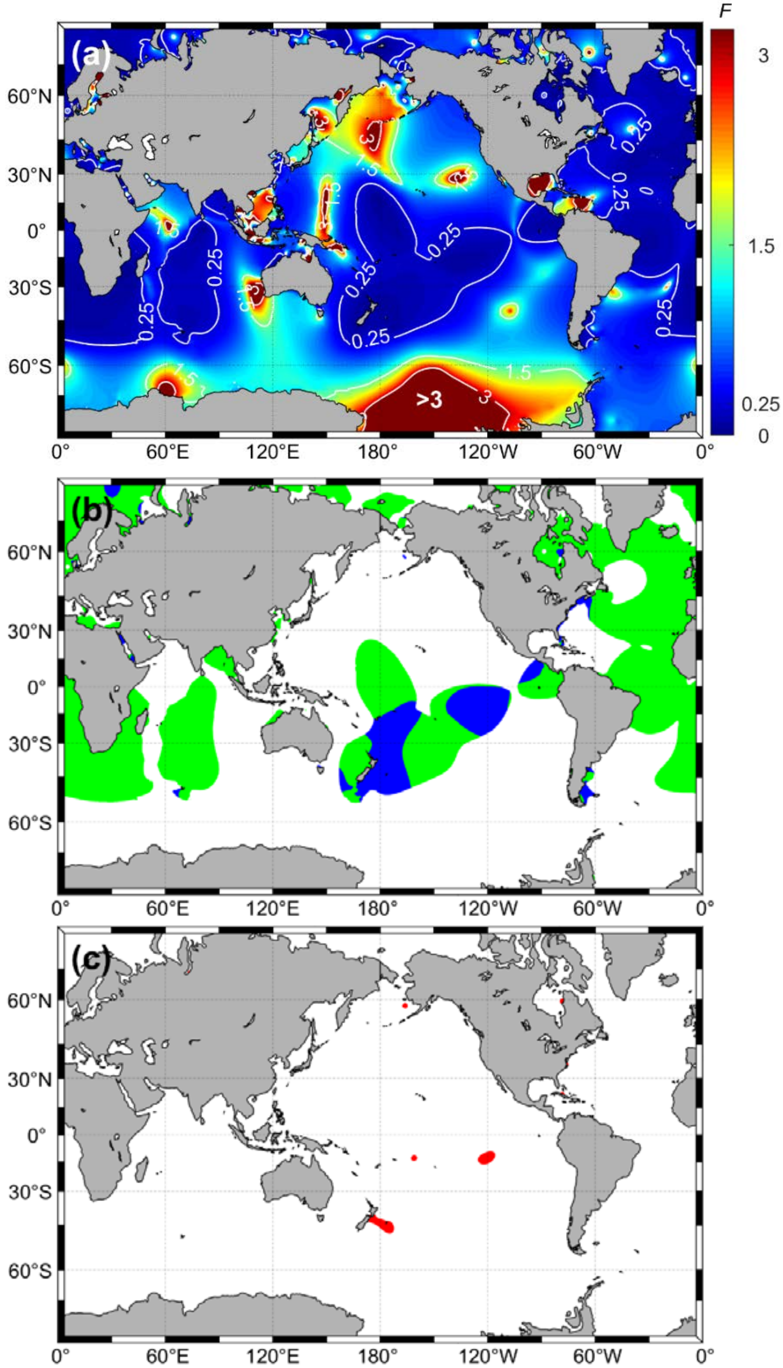

Figure 1. (a) Global distribution of daily form factor (*F*) values, indicating daily tidal regime types (*F*<0.25: semi-diurnal; *F*>0.25 to *F*<1.5 mixed-mainly semi-diurnal; *F*>1.5 to *F*<3: mixed-mainly diurnal; and *F*>3: diurnal, according to the classification of van der Stok 1897, and Courtier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

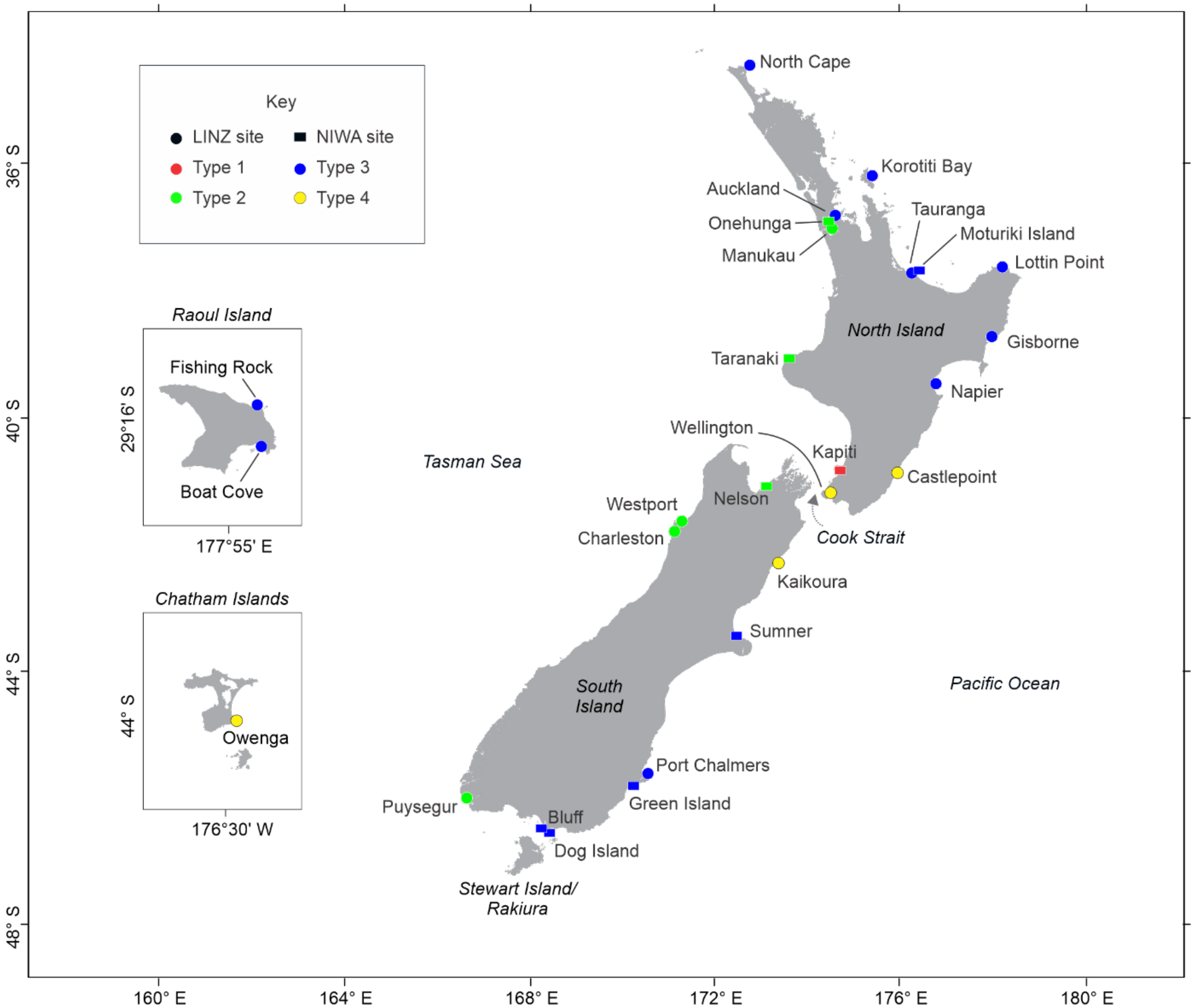

Figure 2. Location of New Zealand sea level observation stations investigated in this research: circles indicate LINZ sites, rectangles indicate NIWA sites; each site is colored according to monthly tidal envelope type. Offshore islands are not shown to scale (Raoul and Chatham Islands).

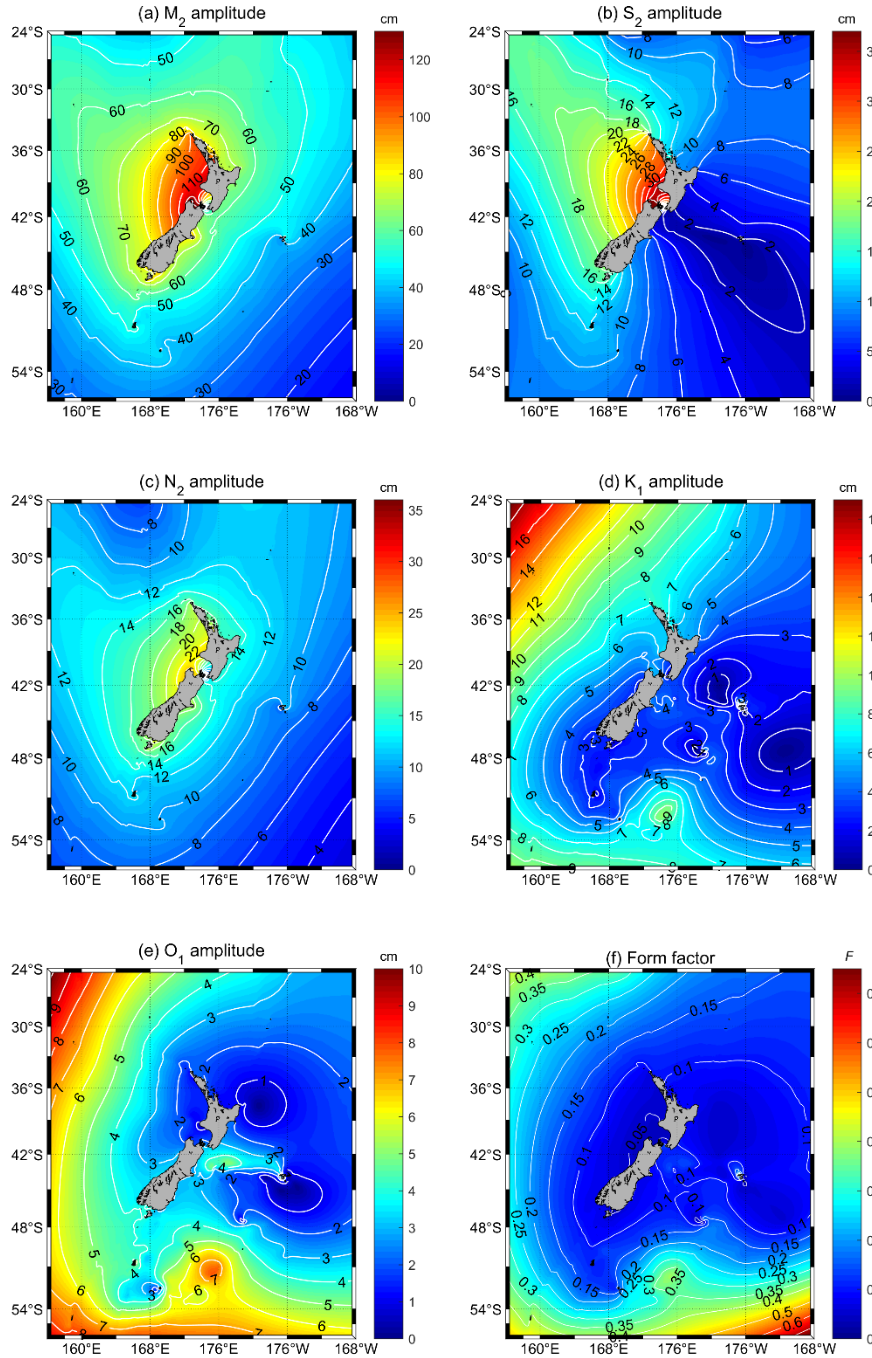

Figure 3. Horizontal distribution of amplitudes for the (a) M_2, (b) S_2, (c) N_2, (d) K_1, and (e) O_1 tides around NZ, and (f) the resultant distribution of *F*, daily tidal form factor values, as calculated from the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude color scales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

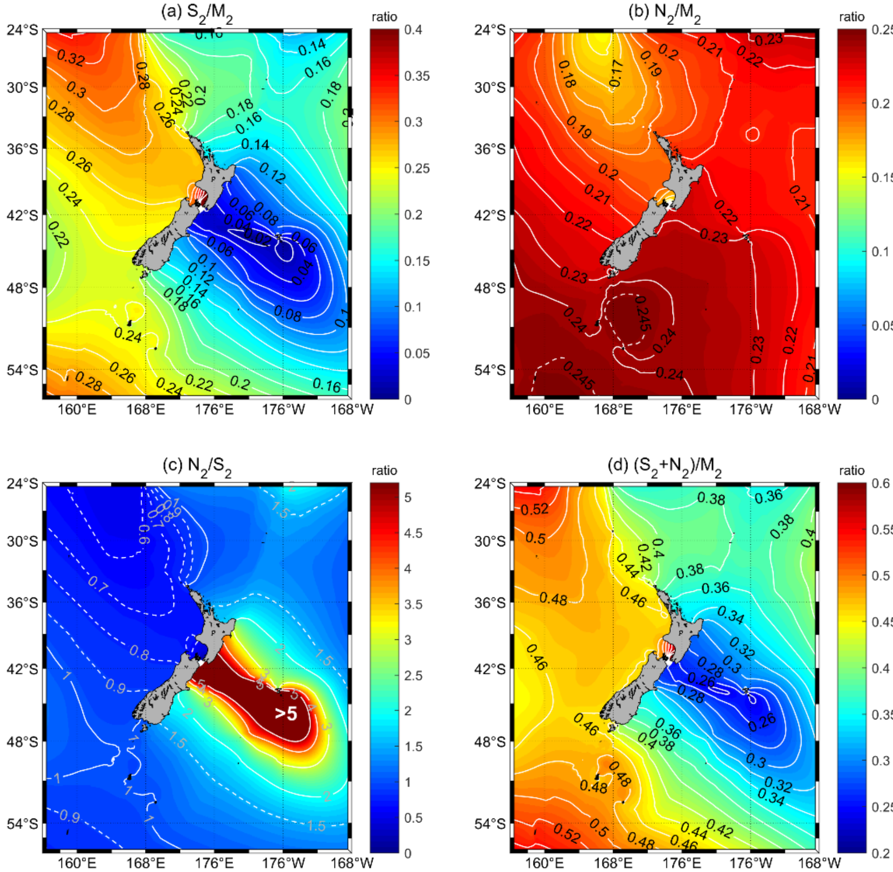

Figure 4. Distributions of tidal constituent amplitude ratios around NZ for: (a) $\frac{S_2}{M_2}$; (b) $\frac{N_2}{M_2}$; (c) $\frac{N_2}{S_2}$ and (d) $\frac{S_2+N_2}{M_2}$; as calculated using the FES2014 tide model on a grid of 1°/16×1°/16. Note that the amplitude color scales vary between plots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

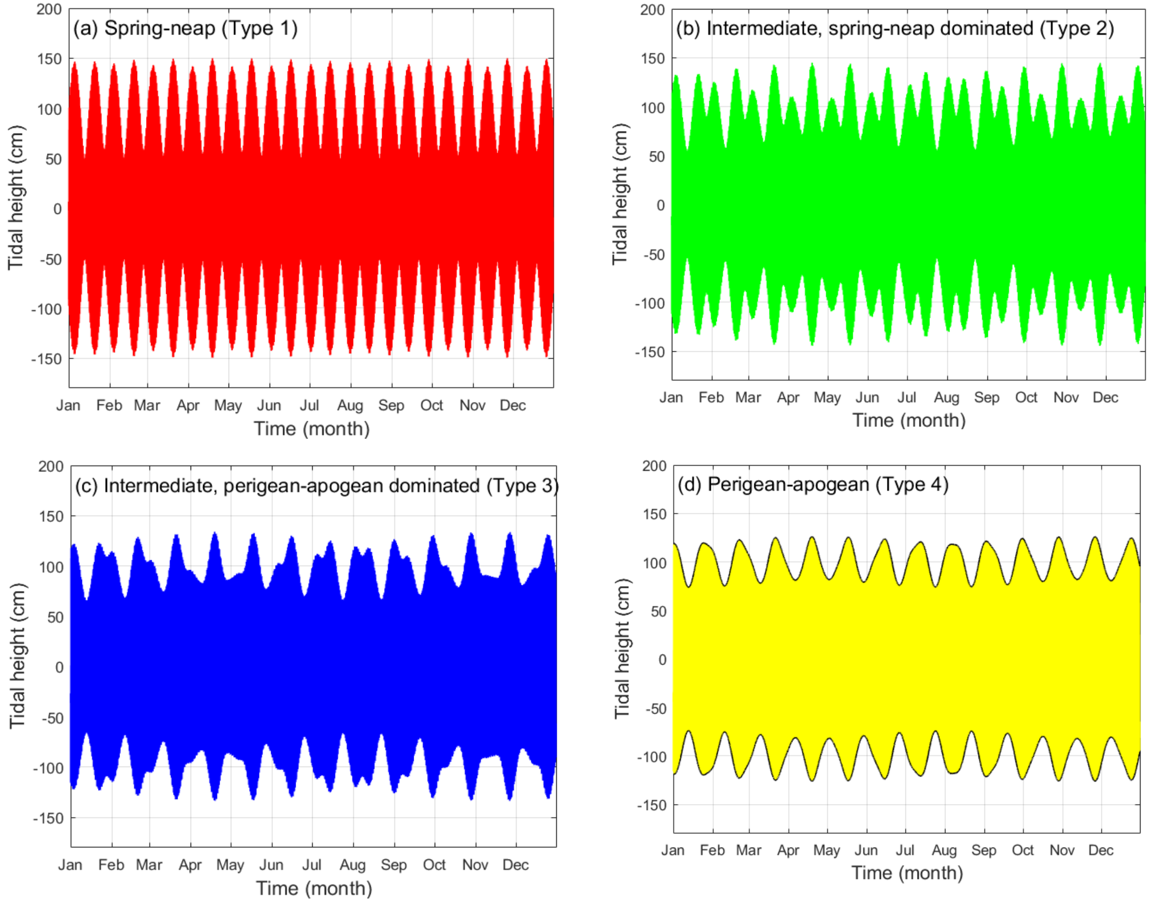

Figure 5. Idealized examples of four different monthly tidal envelopes over one year, calculated using the amplitude value M_2 = 100 cm and the amplitude ratio values of: (a) $\frac{S_2}{M_2} = 0.46$, $\frac{S_2}{N_2} = 11.5$, $\frac{N_2}{M_2} = 0.04$; (b) $\frac{S_2}{M_2} = 0.27$, $\frac{S_2}{N_2} =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

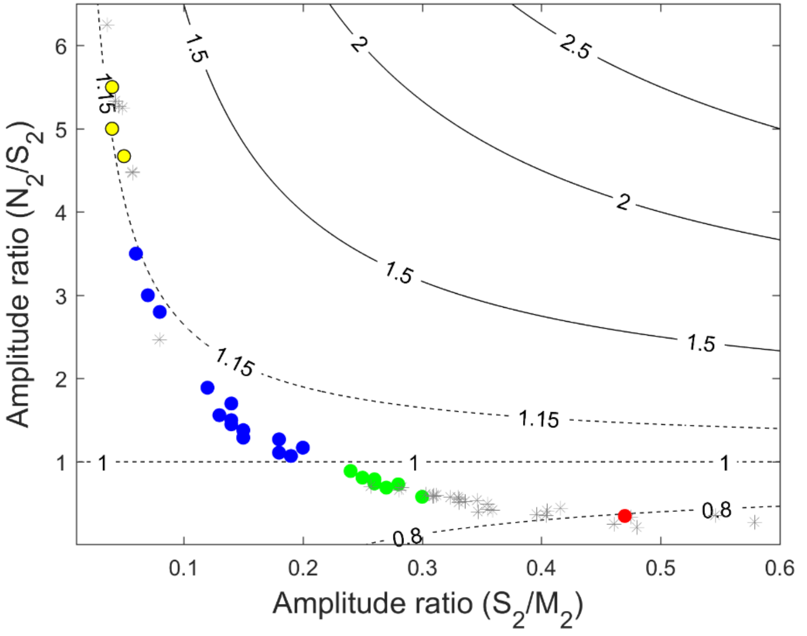

Figure 6. Plot of the relationship between the $\frac{N_2}{S_2}$ and $\frac{S_2}{M_2}$ amplitude ratios (y and x axes respectively) versus *E* values (shown as plot contours), with data points corresponding to New Zealand waters Type 1 sites (red dots); Type 2 sites (green dots); Type 3 sites (blue dots);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

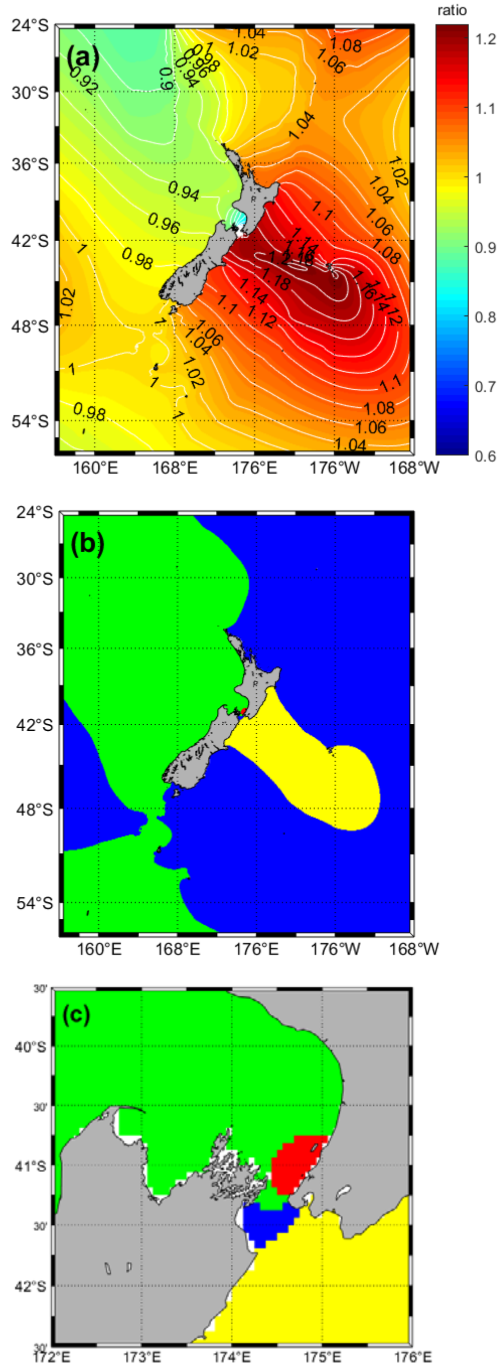

Figure 7. Distribution of monthly tidal envelope factor (*E*) values (a); and types (b); in the waters around New Zealand, including in the Cook Strait area between the two main islands (c); calculated using FES2014 data. In (b), *E* type 1 areas are shown in red; type 2 in blue; type 3 in green; and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