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1 # A mechanistic classification of double tides

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6

7 **Abstract**
8 Double high or low tides are usually explained by adding a higher harmonic to the dominating tide. In its simplest form, the
9 criterion for a double tide is that the amplitude ratio between the higher harmonic and the dominating constituent is larger than
10 $1/n^2$ where n is the ratio of their periods. However, it is not always clear how the higher harmonic becomes large enough to
11 generate the double tide. This is rectified here by identifying three possible ways to enhance the higher harmonic enough to
12 produce a double tide. Using TPXO9, the latest version of the altimetry constrained global tide database, potential locations
13 for all three classes are identified and the existence of double tides are then evaluated using historic long-term tide gauge data
14 from nearby locations. Thirteen locations with double tides were identified this way across the classes, of which seven are
15 discussed further and shown to fit the classification scheme. The search criterion for classes 1 and 2, based on the amplitudes
16 of M2, S2, and M4, work well with TPXO9 and suggests over 400 locations with double tides. The main reason we cannot
17 identify more double tide locations is a lack of TG data, especially in the polar areas. Class 3, which requires an embayment
18 resonant for the higher harmonic initially provided over 8000 potential locations, but only a few of these were in embayments.
19 This class thus requires more manual work to identify the locations. It is concluded that the mechanism behind double tides in
20 most textbooks needs to be revised because they are far more frequent in both space and time than previously thought.
21

Introduction

22 **Introduction**

23 Double tides (DT in the following) are a quite rare but interesting feature of coastal tidal observations. In a double high the
24 tide rises to a first maximum, followed by a short dip in water level, before it rises again to a second maximum and then falls
25 towards the subsequent low water (Bowers et al., 2013; Byrne et al., 2017; Godin, 1993), whereas in a double low tide the ebb
26 tide starts to rise, only to drop back down before the rise starts anew. Double tides are usually not generated by the lunar or
27 solar astronomic forcing but rather by the addition of locally generated higher harmonics to the dominating tide. Furthermore,
28 DTs can only be generated if the phasing between the higher harmonic and the lower frequency tide (henceforth called the
29 parent constituent) is correct and the higher harmonic has a large enough amplitude (Byrne et al., 2017). We therefore expect
30 to find DTs only in shallow water, where higher harmonics can be generated due to frictional effects and the reduced depth
31 (Godin, 1993), or by a transient seiche set up by the tide (Bowers et al., 2013). The DT can be generated this way because the
32 wavelength, L, of a higher harmonics of the tide is shorter than that of a constituent with a lower frequency (i.e., $L_{M4}<L_{M2}<L_{K1}$).
33 This means that any location with a double high tide has a nearby location with a double low tide as well. Arguably, the best-
34 known double tide occurs in Southampton (UK), where the prolonged high water associated with the double low tide provided
35 the port with a commercial advantage. An example of a location with a double low tide is Providence in Narragansett Bay,
36 USA (Redfield, 1980). DTs have also been described in Den Helder in the Netherlands, Woods Hole, USA, Port Ellen, UK

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37 (see Byrne et al., 2017, for the analysis of the latter), and in Daya Bay, China, where M6 is the responsible constituent (Song
38 et al., 2016).
39
40 Doodson proposed a minimum criterion to predict the occurrence of DTs tides when a higher-frequency tidal harmonic
41 (normally M4) is added to the semi-diurnal tide (M2):

42 $$\frac{b}{a} > \frac{1}{n^2}$$ (1)

43 Here, b (a) is the amplitude of the higher (parent) harmonic, and n is the frequency ratio between the two (i.e., for M2 and M4,
44 $n = 2$). Byrne et al. (2017) expanded this criterion to include the phase difference between the two harmonics. The revised
45 parameter is $B = br^2/a$, where r is a number generally less than n. They applied the new theory to data from Port Ellen in
46 Scotland and found that For Port Ellen, $B > 1$ and $n = 3$ (i.e., M6 is the source of the DT) when DTs occur. Note that throughout
47 most of the ocean, the ratio of amplitudes b/a is small – typically less than 1% - and special conditions are needed to increase
48 the ratio above the critical value.
49
50 A fundamental question is how are the right conditions for double tides created? What is needed is to increase the size of the
51 higher harmonics or reduce the size of the lower, or both. Based on the recent investigations into DTs, we now have ability to
52 propose classifications for DTs based on different forming mechanisms. We have identified three possible mechanisms:
53 1. The DT will occur close to a node in M2 and an antinode in M4, giving M4 the possibility to set up a DT by itself. This is
54   referred to a class 1 DT in the following, and it is the textbook mechanism behind the DT in Southampton.
55 2. In the case of Port Ellen, the semi-diurnal tide is reduced at neaps because M2 and S2 are about the same size (Byrne et
56   al., 2017). If M4 is large, it can flatten out the ebb tide during neaps, giving higher harmonics the opportunity to set up a
57   double low tide, or M4 can do it by itself. We call this a class 2 DT in the following.
58 3. In the third class, M4 is amplified more than M2 inside an embayment and cant therefore generate a DT. This can happen
59   if the bay is near-resonant for the higher harmonic. An example of a class 3 tide occurs in Providence, at the head of
60   Narragansett Bay (Redfield, 1980), and is analysed further below.
61
62 Double tides are rare but more are being discovered, e.g., Port Ellen and Daya Bay. The aim of this paper is therefore to carry
63 out a global search for the conditions likely to create a double tide. The criteria we use for this search are those that we would
64 expect for the three classes of double tide that we have described (see below for details). We use the latest altimetry constrained
65 tidal elevation database (TPXO9) in combination with historic tide-gauge data to locate and classify locations with double
66 tides. Potential locations for class 1 and 2 DTs can be directly identified in the altimetry data (see below for details). Class 3
67 double tides are more difficult to locate in this way because they depend on the characteristics (size and depth) of a coastal
68 embayment in which the port is located. Suggested locations can still be found in the altimetry data, but most will have to be
69 discarded and we will therefore deal with class 3 double tides on a case-by-case basis.

70 **Data and analysis**

71 To pinpoint possible locations of DTs we use TPXO9 (see http://volkov.oce.orst.edu/tides/global.html and Egbert and
72 Erofeeva, 2002) to map where we may expect DTs based on the classifications above. TPXO9 is the latest version in the
73 TPXO-series, which consists of global tidal solutions that fit, in a least-squares sense, both Laplace's tidal equations and
74 altimetry data. In the version used here, the data comes at a horizontal resolution of 1/6° in both latitude and longitude. The
75 criteria used for each class in the search were
76 Class 1: The ratio between the M4 and M2 amplitudes are larger than 1 and M2 is smaller than 0.025m.
77 Class 2: The ratio between M2 and S2 is larger than 0.9, and M2 is larger than 0.1m and M4 is larger than 0.025m,

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78   Class 3: The ration between M4 and M2 is larger than 0.1 at the mouth to a bay or gulf. Note that from the TPXO data we have
79   a lot of points where this is fulfilled, but along coastlines and this class require substantial manual identification of
80   locations.
81   For all classes we also required that the local water depth, at the TPXO9 resolution of 1/6º, was shallower than 500m. This
82   made sure that amphidromic points in the open ocean were excluded.
83
84   We then used the GESLA tide gauge data set (see Woodworth et al., 2017 and http://gesla.org for details) to compute the
85   amplitudes and phases of the K1, O1, M2, S2, M4, M6, and M8 constituents for the TG station nearest to the potential DT-
86   locations identified in the TPXO-data. Note that in some areas, e.g., in Antarctica, along the Siberian coast, and in Hudson
87   Bay, there are potential DTs, but no suitable TG stations nearby. The TG data was analysed using t_tide (Pawlowicz et al.,
88   2002). In the case of multi-year data sets, the harmonic analysis (HA) was done on a selected year, preferably towards the end
89   of the series, where DT were found through visual inspection. For clarity, we only show data from a single 2-day period, during
90   which DTs were found, in the following. Further analysis of specific periods took place for class 3 DTs and are described
91   below.
92
93
94   **Results**
95   **TPXO results**
96   We identified 219 class 1 locations (see Figure 1a), 140 potential class 2 locations (Figure 1b), and over 8000 class 3 points
97   (Figure 1c). The latter could quickly be whittled down to about 100 locations because the initial criteria stipulates that we
98   should be in an embayment – something we didn't take into account when doing the initial search in Figure 1c. The locations
99   of potential DTs where then reduced further by our requirement that there must be a GESLA TG within 20km (corresponding
100   roughly to the width of one TPXO9 gridcell) from the TPXO9 DT point. This led us to finally process data from 30 TG, and
101   we found double tides at 13 locations, including the 4 previously reported on. From these, we opted to further discuss seven:
102   Den Helder, Providence (and Newport, although there is no DT there – see the section on class 3 DTs for details), Thevenard,
103   Victor harbour, Rio Grande, and Imituba. The results of the HA is summarised in Table 2, and the locations of these gauges
104   are marked in Figure 1b
105

106   **Class 1**

107   Class 1 DTs, i.e., when the higher harmonic is larger than the parent because of an amphidromie of the parent is located nearby,
108   were found at two new locations: Pari in Indonesia and Rio Grande in Brazil, along with the previously reported double high
109   tide in Den Helder in the Netherlands (see Figure 2). Rio Grande is a special case, where the double tide, and on occasion triple
110   highs, occur on the dominating diurnal tide. Because of this uniqueness we discuss it separately later. The DT at Pari is quite
111   small, and instead we choose to discuss Den Helder.
112
113   This location experiences a double high tide because it is close to an M4 antinode and an M2 node. In fact, we are between to
114   M2 amphidromes, but because of the nature of the tide in the North Sea, that corresponds to a tidal minimum (Figure 2a). This
115   local minimum in M2 tidal amplitudes allows the relatively large M4 in the region to set up the double high tide seen in Figure
116   2c (see also Figure 2b).
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118   **Class 2**

119   Class 2 DTs appeared in 7 locations, including the previously described Port Ellen. Note that Rio Grande may be either a class
120   1 or class 2, or both, and is discussed further below). At these locations there is a large spring-neap cycle and the overtides,
121   sometime multiple constituents in partnership, can generate DTs. Two clear examples can be found on Australia's south coast,
122   where double low tides are found at the data from Thevenard and Victor Harbour (Figure 3a and b, respectively).
123
124   The data from Thevenard shows a flattened high tide during neaps, which M4 is able to modulate into the double low tide (M6
125   and M8 are both negligible at this location). Victor Harbor is more complicated, because we find the double low tide on the
126   diurnal tide (dominated by K1). The mechanism is the same, however: there is a diurnal spring-neap cycle, the semi-diurnal
127   tide, strongly modulated by the semi-diurnal spring neap cycle because S2 is larger than M2, can set up double low tides on
128   the dominating diurnal tide. Note that K1 and S2 alone cannot generate a double low tide here; combined they give a very
129   large daily inequality in the tide – and having the spring-neap modulation is a necessity to generate a genuine double low tide.
130

131   **Class 3**

132   Narragansett Bay in New England USA provides an excellent example of a class 3 double low tide. The mechanism proposed
133   for this class is that the M4 tidal amplitude is amplified more in the bay than M2. In Narragansett Bay this happens because
134   the natural resonant period is ~4 hours (L~35 km, H~8m, giving quarter-wavelength resonance at 4.4 hours). Using GESLA
135   data from Newport (at the mouth) and Providence (at the head; see Figure 5) from 2014, we find that there is indeed
136   amplification at the head of the bay: b/a=0.18 compared to 0.11 at the mouth. However, this is not enough to produce a double
137   low tide, yet one is seen in the record at numerous times. This is because the annual fits are not necessarily representative of
138   the conditions when the double lows occur – not all low tides have a double low in the Bay.
139
140   Instead, we focus our attention on the neap period around year day 44.2 shown in Figure 5, when we have an observed double
141   low. Redoing the fit on a 25-hour part of record, between days 43.50-44.535, we find that the reduced semi-diurnal constituent
142   indeed does allow for a double low: b/a = 0.26 at Providence, whereas it is 0.14 at Newport for this period, i.e., an amplification
143   of ~85%. There are two conclusions to draw from this analysis: first, the mechanism suggested – M4 amplification - is the true
144   one in this instance, and second that using long-term records to locate DTs, may be dubious because the annual fits may not
145   necessarily capture the needed signals. Rather, looking at the semidiurnal neap amplitude (i.e., M2-S2) may be a better measure
146   in that case. Indeed, the annual fit gives *b/a* = 0.23 at Providence if the M2-S2 amplitudes are used for a. This further stress
147   that it is at neap tides M4 can act in Providence and set up a double low tide.
148
149   Of course, Narragansett Bay is not unique in amplifying M4 more than M2 - any coastal bay with a natural period closer to 6
150   hours than 12 will do this (e.g., Song et al., 2016). What is special about Narragansett Bay is that the *b/a* ratio at the mouth is
151   so large and the phase is often just right for producing a flattening at low water. An amplification of *b/a* by 50% then turns the
152   flattened low water at Newport into a double low water at Providence. There is, however, more to the story in Narragansett
153   Bay. Of the 673 tidal cycles in 2014 that we have analysed, 196 fulfil the Doodson criterion of b/a>0.25, but only 43 exhibit a
154   double low water at Providence that would satisfy a visual inspection. Of these, 23 are produced by M2 and M4 alone, i.e., by
155   the *b/a* amplification larger than 50% between Newport and Providence. In the remaining 20 cases of a double tide in this
156   period, the *b/a* amplification serves to increase the duration of low-water flattening at Providence and then M6 acts on the
157   flattened low tide to create a double low water. An example of this is shown in Figure 5 at day 327.8. In this case, there is only
158   a 22% *b/a* amplification, and although the ratio is supercritical at Providence, the *phase* is not right between the M2 low tide

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159 and the M4 high tide. Consequently, we instead see an extended period of flattening of the low tide, on which the small 5cm
160 M6 tide can set up a small double tide. This is why the Doodson criterion is not always correct, and the phasing should be
161 taken into account as well (Byrne et al., 2017).

163 Note that there is no M6 tide at Newport (not shown). The M6 constituent at Providence must therefore be created within the
164 Bay. This happens because the resonance period of the Bay is about 4 hours, so any small forcing with this period is likely to
165 produce an amplified response in the Bay. The mechanism is known as a compound tide. When a shallow bay is forced with
166 a mixture of semi-diurnal and quarter diurnal tides, shallow water effects create tides with a frequency equal to the sum and
167 the difference of the frequencies of the two constituents: the compound tides thus have frequencies of $2\omega-\omega=\omega$ (which enhances
168 the semi-diurnal tide) and $2\omega+\omega=3\omega$, which is the M6 tide in this case. The amplitude of this new M6 tide is expected,
169 theoretically, to be proportional to the product ab of M2 and M4 tides. This seems to be true in Narragansett Bay (not shown;
170 the M6 amplitude in providence is ~0.3ab) and is likely the mechanism in Daya Bay, China (Song et al., 2016).

172 To summarise, there are two ways of creating a class 3 DT. The first is by selective amplification of the M4 tide to the point
173 where the sum M4+M2 at the head is alone sufficient to make a DT. Here, this happens when the b/a ratio at the mouth
174 (Newport in Narragansett Bay) reaches its largest values, which are then amplified at the head.. This mechanism is seen at
175 small neap tides. Alternatively, a lower value of b/a at the mouth can be amplified to produce a low tide at the head with an
176 extended period of flattening. A small high frequency (M6) oscillation added to this will then produce a double-dip low tide.
177 This oscillation is likely to have a period of 4 hours, since that is the resonant period of the bay, and can have a variety of
178 causes.

180 Because the DTs here are more prominent during neaps than springs, we also asked if the 18.6-year lunar nodal cycle influence
181 the occurrence of DTs at Providence. This could be the case here because S2 does not have a nodal cycle so one could expect
182 that there would be a further potential for DTs during the nodal minimum in M2 tides, because the tidal range at neaps would
183 then be smaller. The results, which are not shown, suggest that there is no difference in the number of DTs occurring. The
184 reason is quite simply that because M2 is reduced, so are the overtides M4 and M6 and there is no net gain in the potential to
185 generate DTs.

Diurnal multiple high- and low tides

188 The data from Rio Grande shows pronounced double low tides, and there are triple high tides on occasion (Figure 6a). This is
189 an exciting location, because S2 is larger than M2 and O1 is the dominating signal (see Table 2 for a summary). The variance
190 capture of the harmonic analysis is quite low - about 20% of the variability with the 7 constituents – mainly because the TG is
191 near the mouth of the river, and freshwater fluxes are affecting the time-series. In fact, on at least one occasion the TG actually
192 dries out.

194 The large O1 and K1 constituents lead to a diurnal spring-neap cycle with a 13.4-day beat. The semi-diurnal tide, dominated
195 by S2 but with a large semi-diurnal spring-neap cycle as well, can then set up a double low tide in the diurnal tide ($b/a>0.25$
196 for both M2 and S2 over O1). However, M4 is actually larger than M2 at the location, so it can generate a double low tide on
197 the semi-diurnal tide. Combined, these double DT lead to a triple high/low in the diurnal tide, as seen between days 210-210.5
198 in Figure 7. This is not a one-off occurrence of a THT in the series; the triple occur on most high waters during diurnal neap
199 tides. Note that the reconstruction of the fit (the red line) has a damped down version of the THT in it, so the THT must come
200 from the constituents under investigation. The timing is crucial here: we need a diurnal neap in combination with a semi-

201 diurnal spring with M4 timed right. The beat between the diurnal spring-neap and the semi-diurnal spring-neap cycle is 6.1
202 hours, which is very close to the period of M4, so this may exaggerate the M4 signal and allow setting up the THT.
203
204 Interestingly, the TG at Imituba, further north along the Brazil coast, also have triple highs (Figure 6). There is, however, a
205 different mechanism at play here: M2 is now the dominating tidal constituent, but the station sees a large daily inequality
206 generated by O1 and a large spring-neap cycle due to a large S2 constituent. This allows M4 and M6 together to generate
207 double and triple highs on the semi-diurnal tide.
208
209
210 **Discussion**
211 Most textbooks on oceanography state that DTs are set up by a combination of M2 and M4, with a DT generated if Doodson's
212 criterion is fulfilled. There is, however, usually very little discussion about *how* M4 becomes large enough to fulfil the Doodson
213 criterion. Here, we suggest three potential mechanisms responsible for this amplification, and show that even higher harmonics
214 may be needed to get the desired results. We also argue that in the search for DTs, visual inspection of the TG data is crucial,
215 and that fits must be done on short periods of data to capture the correct dynamics; annual fits are not necessarily 100% relevant
216 for short periods of data. Furthermore, global altimetry products, e.g., TPXO9, are helpful to identify potential locations of
217 DTs, but at the end of the day, it is necessary to have high temporal resolution TG data to identify and quantify the DT.
218
219 Whilst we identified a large number of locations with potential DTs in TPXO9, we were limited in the areas we could analyse
220 because of limited TG coverage, especially in the Polar Regions, including Hudson Bay. However, we feel that we have had
221 good enough coverage to show that our classification works, and leave further analysis and searches for TG data for future
222 publications. Another future prospect is to investigate if DTs will become more frequent during future change due to sea-level
223 and warming. This has implications for mitigation purposes, because a prolonged high tide due to higher harmonics has the
224 potential to increase flood risk due to storm surges. From the most recent simulations of the effect of sea-level rise on tides
225 (Schindelegger et al., 2018) it appears that there are no changes in the number of potential locations fulfilling Doodson's
226 criterion, but the resolution of the model prevents any further detailed simulations. Instead, we argue that it be worthwhile to
227 do regional high-resolution simulations of the Patagonian Shelf and Gulf of Maine to see how the DTs there may be affected
228 in the future.
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258 Tables

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260 **Table 1: Results from the HA for the respective station. "Variance" refers to the variance captured by the harmonic analysis, using**
261 **O1, K1, M2, S2, M4, M6, and M8. "amp" refers tot the constituent's amplitude (in meters), whereas "pha" is the phase (in degrees),**
262 **measured relative to the starting point of the time series.**

	Den Helder Netherlands		Providence USA		Newport USA		Thevenard Australia		Victor Harbor Australia		Rio Grande Brazil		Imituba Brazil	
tide	amp	pha	amp	pha	amp	pha	amp	pha	amp	pha	amp	pha	amp	pha
O1	0.12	169.8	0.04	351.9	0.04	351.0	0.14	55.7	0.16	122.1	0.12	66.6	0.12	121.2
K1	0.07	59.1	0.06	169.3	0.06	167.6	0.20	302.5	0.22	262.8	0.04	300.0	0.07	58.5
M2	0.64	210.5	0.62	157.0	0.53	151.2	0.30	337.3	0.13	341.5	0.03	33.0	0.15	39.8
S2	0.19	344.6	0.13	62.9	0.11	55.0	0.36	207.8	0.15	150.3	0.04	103.2	0.11	162.3
M4	0.10	263.2	0.11	356.0	0.06	332.7	0.02	285.7	0.03	339.0	0.03	86.4	0.03	308.4
M6	0.05	48.0	0.03	30.5	0.01	298.1	0.00	126.6	0.00	349.0	0.00	348.7	0.00	180.8
Variance	63.7%		85.8%		85.1%		70.9%		61.5%		19.3%		41.1%	

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265 **Table 2: Results from the HA on the data from Narragansett Bay. "Full year" refers to analysis of the whole 2014-record, "25-**
266 **hours" to the analysis of data from day 39-40.035, and "Annual Neap" to the results based on M2-S2 from the Full Year HA (see**
267 **the text for details).**

|	Newport	Providence	Amplification
Full year			
M2	0.53	0.62	1.17
M4	0.06	0.11	1.83
b/a	0.11	0.18	1.64
25 hours			
M2	0.36	0.42	1.16
M4	0.06	0.11	1.83
b/a	0.17	0.26	1.52
Annual neap			
M2-S2	0.42	0.49	1.16
M4	0.06	0.11	1.83
b/a	0.14	0.23	1.65

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274   Figures
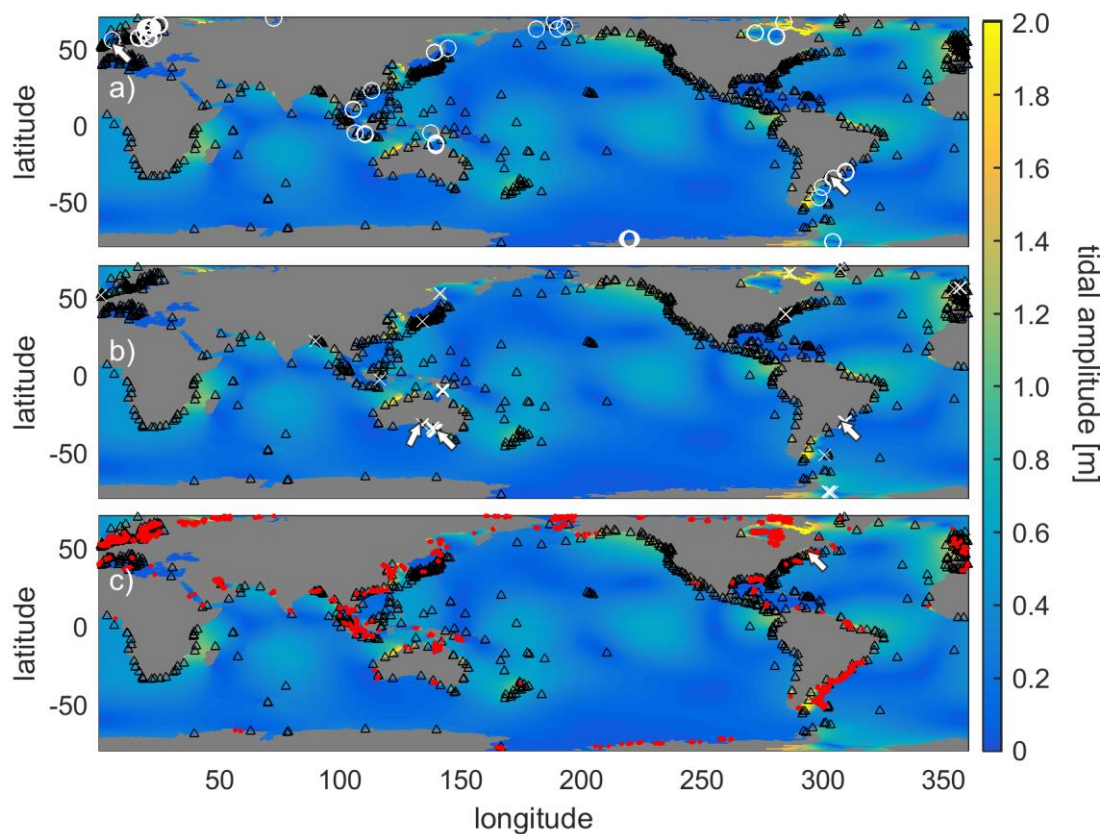
Figure 1: M2 amplitudes (colour – note that the scale bar saturates at 2m) from TPXO and potential locations for DTs using the three classes (panel a)=class one, b)=class 2, c) = class 3). The TG locations in the GESLA database, in water shallower than 500m in the TPOX9 grid, are marked as black triangles. The filled white arrows point tow the location of stations analysed further in this paper.

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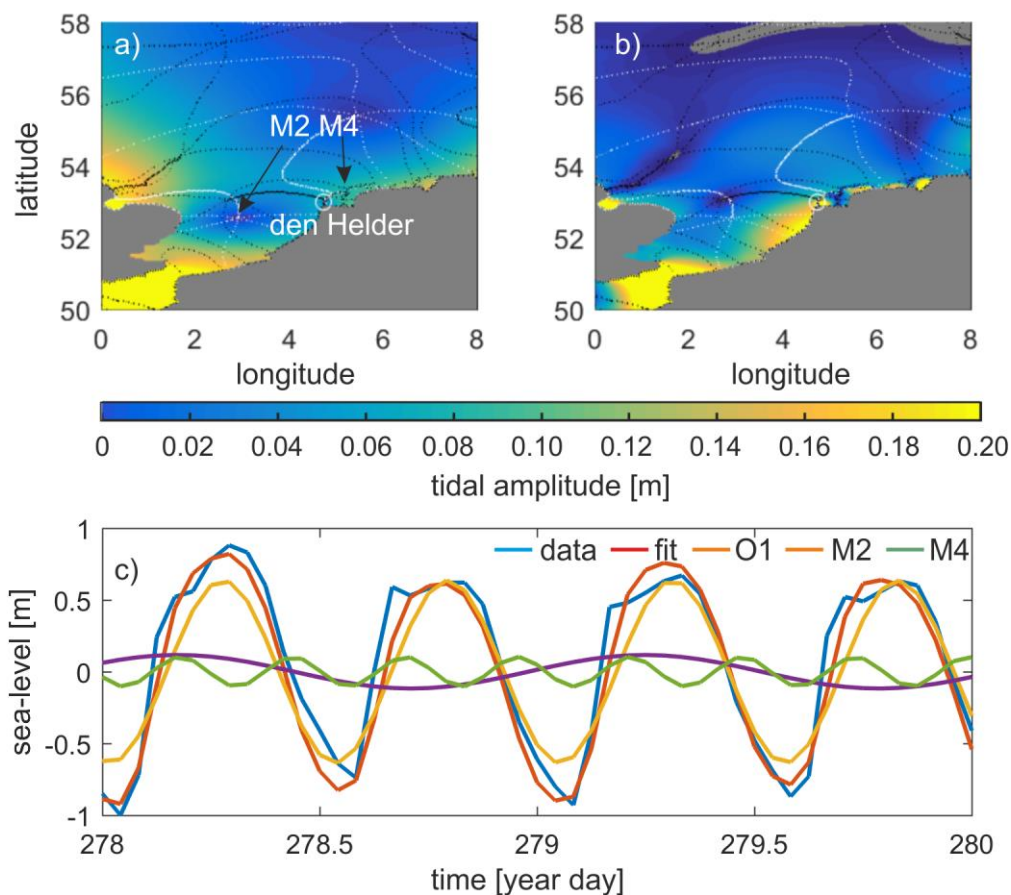
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Figure 2: a) A blow-up of Figure 1 showing the English Channel and the North Sea with Den Helder marked with a white circle. The colours show M2 (M4) amplitudes from TPXO9 in the left (right) panel, whereas the white (black) lines are M2 (M4) phases separated every 60°. The amphidromic points closest to the TG station are marked by the arrows.

b) As in a) but showing the M4 field.

c) Shown is an example of a class 1 DT in the TG data from Den Helder. The blue line shows hourly observations from 1986, and the red line the reconstruction after fitting O1, K1, M2, S2, M4, M6, and M8 to the data. The yellow, purple, and green lines are the fitted O1, M2 and M4 curves (see Table NN for a summary of the fit).
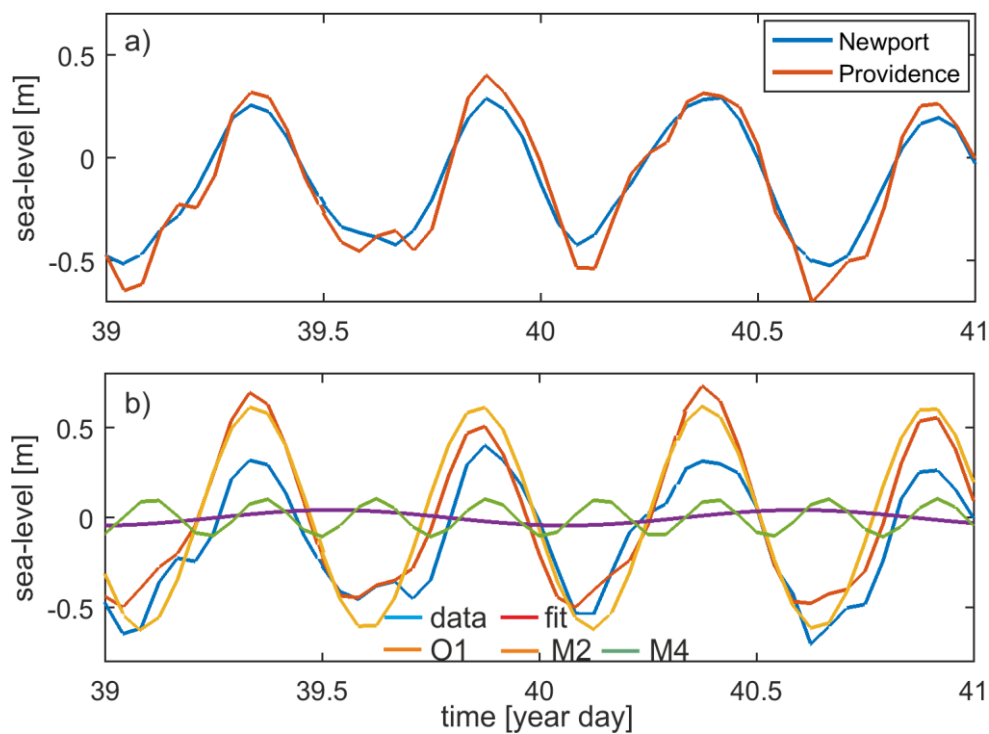
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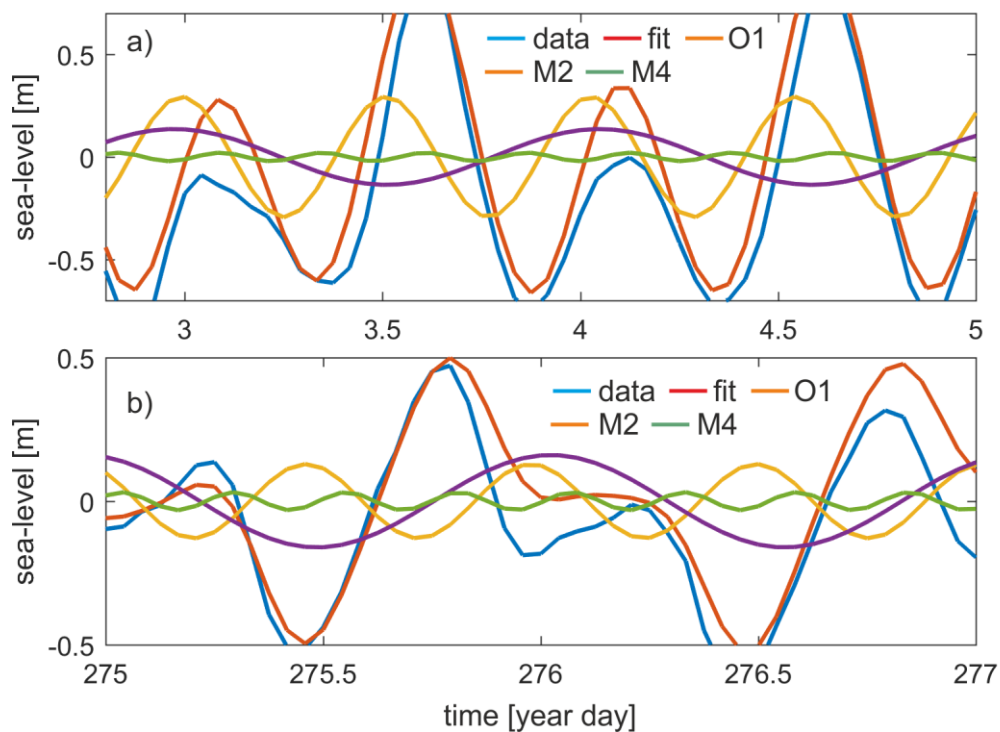
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Figure 3: As in Figure 2c but showing examples of Class 2 double tides from Thevenard (a) data from 2011) and Victor Harbor (b) data from 2004), both on the south coast of Australia.
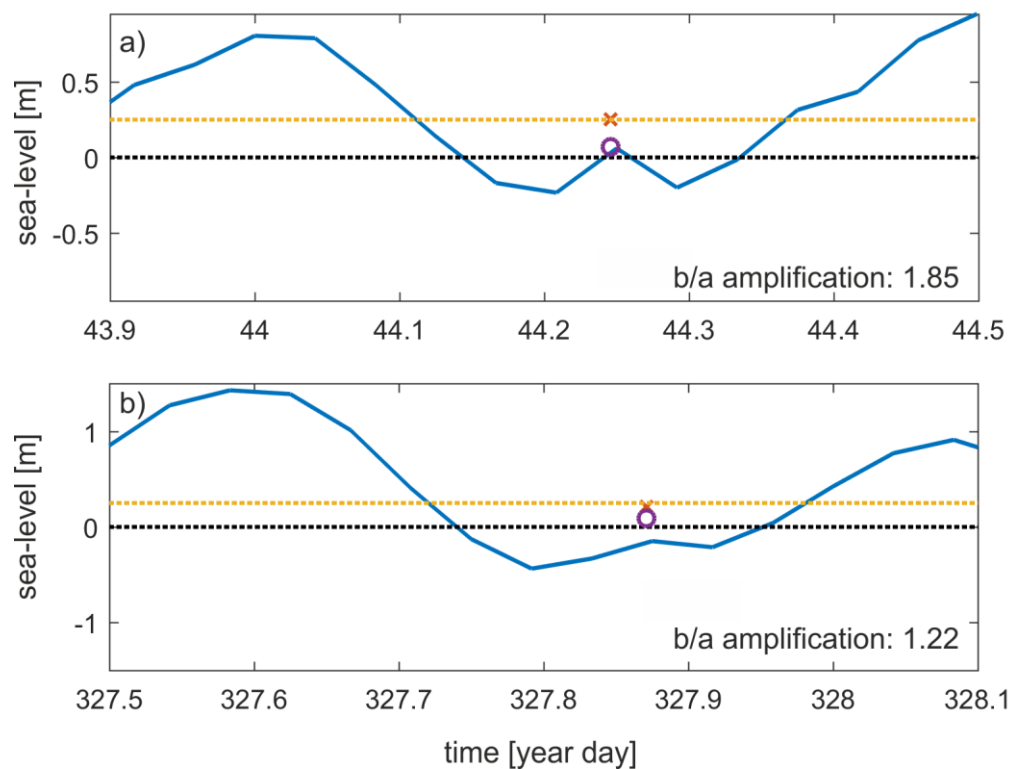
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Figure 4: A 2-day example of the sea-level record from Newport (blue) and Providence (red), USA, from 2014 (panel a). Panel b)
**shows the Providence data and reconstructed results from the HA for the whole of 2014, i.e., as in Figure 2c.**

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Figure 5: Blow up of 13 hours of data from Providence for two different dates. The b/a ratio is plotted with an orange x; the orange dotted line marking he critical value form Doodson's criterion. The black circle and line mark the M6 amplitude at Providence and the 0 line. The text is the amplification of the b/a ratio between Newport and Providence based on a tidal fit to the period of data shown.

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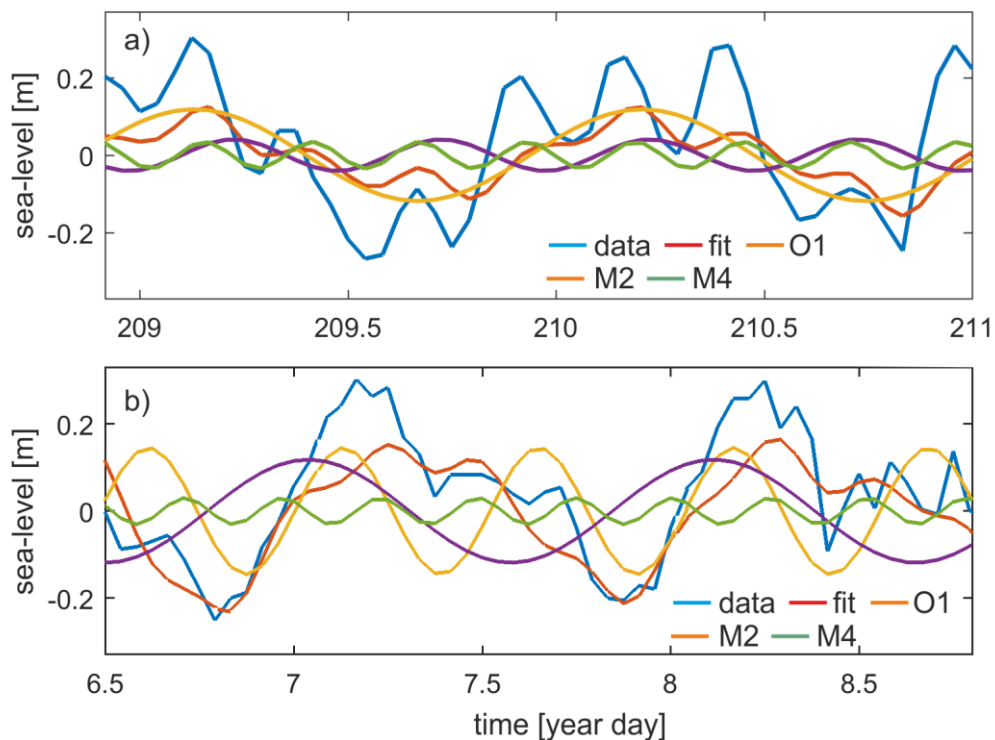
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Figure 6: Shown are two days of data from Rio Grande (panel a) and Imituba (panel b). Note the triple high in the Rio Grande series.

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