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► **To cite this version:**

Jerome Aucan, Terence Desclaux, Romain Le Gendre, Vetea Liao, Serge Andréfouët. Tide and wave driven flow across the rim reef of the atoll of Raroia (Tuamotu, French Polynesia). *Marine Pollution Bulletin*, 2021, 171, 112718 (10p.). 10.1016/j.marpolbul.2021.112718 . hal-04203542

HAL Id: hal-04203542

<https://hal.science/hal-04203542v1>

Submitted on 22 Jul 2024

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Tide and wave driven flow across the atoll rim reef of the atoll of Raroia (Tuamotu, French Polynesia)

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Abstract

The currents flowing across the rim of the atoll of Raroia were investigated with a 1 year-long dataset of wave, water level and currents. Offshore waves break on the edge of the reef outside the atoll's rim and drive current into the lagoon, through the shallow *hoa* that cut across the rim. The additional water volume generated by this wave driven flow induces an elevation of water level throughout the atoll's lagoon and is evacuated back into the open ocean through a deep reef pass. The water level inside the atoll is also driven by astronomical tides, which enter the lagoon through the reef pass, after undergoing a $\sim 50\%$ decrease in amplitude and a ~ 4 hours lag. Using a simple parametric model with three calibrated coefficients, we show that currents across the atoll's rim can be estimated as a function of the offshore wave conditions and the water level difference between the ocean and the lagoon.

Keywords: pearl farming; lagoon; coral reef; hydrodynamic

1. Introduction

2 The production of black pearls in the Central Pacific Ocean mostly takes
3 place in deep ($> 25m$) atoll lagoons. The hydrology and hydrodynamics of
4 these lagoons is an important factor for the successful farming of the black
5 lip pearl oyster *Pinctada margaritifera*, which produces the prized pearls after
6 the grafting in the oyster pearl sac of an artificial nucleus paired with a piece
7 of mantle from a donor. Beyond proper handling by farmers, oysters growth

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8 and survival at larval, juvenile and adult stages depend on adequate hydrologic
9 conditions, in particular trophic planktonic conditions and lagoon temperature
10 ranges (Sangare et al., 2020). These conditions are largely controlled by the
11 exchange of water between the ocean and the lagoon, through the atoll rim and
12 passes (Lowe and Falter, 2015).

13 Atoll lagoons are isolated from the nearby ocean by an atoll rim, which is
14 typically a kilometer wide, and can have emerged, intertidal and submerged
15 sections. In Tuamotu Archipelago (French Polynesia) the rim is typically com-
16 posed of shallow reef flat channels (*hoa*) that occur between sandy cays (*motu*).
17 The numbers of *hoa*, and their width can vary widely from one atoll to another
18 (Andréfouët et al., 2001a). The rim can also be cut by one or more deep passes.
19 In addition to the intrinsic rim structure, and its degree of openness to the
20 ocean, sea level, waves, tides and wind can have a strong influence on the la-
21 goon renewal and its physical and chemical properties, and its water circulation
22 (Tartinville and Rancher, 2000; Andréfouët et al., 2006; Dumas et al., 2012;
23 Charpy et al., 2012, among many others).

24 Wave driven flows over reefs have mostly been studied over "closed reefs" or
25 "fringing reef" on one hand, or on "open reefs" or "barrier reef" on the other
26 hand (Lindhart et al., 2021, as a recent example). A "closed reef" describes a
27 reef where the leeward water level is close to or as high as the water setup on the
28 reef (Lowe et al., 2009, for an example). An "open reef" describes a reef where
29 water level leeward of the reef return to a water level similar to the open ocean
30 (Monismith et al., 2013, for an example). Here we describe measurements over
31 an "atoll rim reef" where water level leeward of the reef (in the atoll lagoon)
32 is neither equal to the setup on the reef nor equal to the open ocean water
33 level. Instead, water level leeward of an "atoll rim reef" is a combination of
34 tidal elevation driven by ebb and constrained within reef passes that can be 10s
35 of km away, and wave driven flow occurring at many other places of the atoll
36 rim.

37 For the Tuamotu Archipelago atolls, where significant pearl farming takes
38 place, there has been limited work on the water fluxes through the *hoa*, and
39 in particular how it is related with waves in the ocean (generated by distant
40 swells and local winds), tides and sea level. To the best of our knowledge,
41 Lenhardt (1991); Tartinville and Rancher (2000); Dufour et al. (2001); Dumas
42 et al. (2012) have investigated this aspect, which is critical in order to achieve
43 the 3D numerical model of an atoll lagoon (Andréfouët et al., 2006). Specif-
44 ically, Lenhardt (1991) monitored current speed in one *hoa* of Tikehau atoll.
45 Tartinville and Rancher (2000) in Mururoa atoll, and Pagès and Andréfouët
46 (2001) and Andréfouët et al. (2001b) in several different atolls, could compare
47 empirically at day-scale the flows across several *hoa* with significant wave height
48 estimated by satellite altimetry. Andréfouët et al. (2001a) in particular con-
49 cluded that a linear relationship between flows and wave height could be found,
50 although the exact relationship differed between different types of atoll rims,
51 and possibly between atolls. Dumas et al. (2012) when developing a numerical
52 model of lagoon circulation for Ahe atoll confirmed the effect of local condi-
53 tions, as they could simply apply a constant flow in Ahe numerous, but narrow

54 *hoa*, considering how little this atoll was affected by waves most of the time,
55 due to its geographic position protected from the incoming distant swells by
56 nearby atolls (Andréfouët et al., 2012). However, these results generally used
57 short series of observations, except for Ahe, and they did not really disqualify
58 the possibility to infer a generic, rim-independent, relationship if long time se-
59 ries could be acquired for an atoll, or several atolls, presenting various type of
60 rims exposed to distant swells and to local wind-generated waves as well. Such
61 parameterization would be critical to continue developing lagoon hydrodynamic
62 models for a variety of atolls (Le Gendre et al. in prep.).

63 Raroia is a 40km long and 12km wide atoll of the Central Tuamotu, with
64 only one deep reef pass on its western side (Figure 1), numerous *hoa* on all
65 sides of the atoll’s diverse rim, and is believed to be flushed by both tide and
66 waves from different directions. Raroia is also an important pearl oyster farming
67 site, for both spat collecting and pearl production, although, like in many atolls,
68 several farms have recently closed due to the crisis of the pearl farming industry.
69 Raroia was therefore an ideal study site to develop a generic, multi-rim, model
70 of currents through the *hoa* based on wave and tide characteristics. This simple
71 relationship between wave height, water level and inbound current across the
72 rim, will allow the integration of this forcing into future lagoon 3D numerical
73 circulation models.

74 2. Material and methods

75 2.1. Study site

76 Raroia is a large (368km²), deep (maximum depth = 68m) atoll of the Cen-
77 tral Tuamotu. Its lagoon geomorphology is described in detail in Andréfouët
78 et al. (2020) from multibeam data set also acquired in preparation for the mod-
79 eling of the lagoon circulation. It is oriented along NE-SW direction, offering
80 a long stretch of rim directly exposed to the east tradewinds. This area cor-
81 responds best to the rim Type 7 described in Andréfouët et al. (2001a). This
82 rim is characterized by small elongated or circular motu bordered by wide ar-
83 eas of intertidal sand, and wide shallow *hoa*. Conversely the south side of the
84 atoll does not present any motu and corresponds to the rim type 4 (Andréfouët
85 et al., 2001a). The western side can be related to the rim type 5 with narrow
86 well defined sharply bounded *hoa* between wide motu that form on top of ele-
87 vated ($\sim 1m$) conglomerate. Hence, not all rim types are present in Raroia,
88 but there is a good variety of the semi-open (rim 5, 7) and the very open one is
89 present (rim 4).

90 2.2. Site description and instrumentation

91 In-situ data collection lasted for almost a year over three different legs (May-
92 Aug 2018, Aug-Dec 2018 and Jan-March 2019). We concentrated our efforts
93 around 3 *hoa* on the western (1, rim type 7), eastern (2, rim type 5) and southern
94 (3, rim type 4) facing sides of the atoll. Outside of each *hoa* (O1, O2, and O3), a
95 pressure sensor was deployed on the forereef at $\sim 10m$ depth to measure offshore

96 waves and water level outside the atoll. Within each *hoa*, an acoustic current
 97 meter was deployed in 1 – 3m depth to measure currents and water levels (H1,
 98 H2, and H3). This sampling strategy is illustrated on Figure 1 (middle). H1
 99 was deployed during leg 1, H3 was deployed during legs 2 and 3, and H2 was
 100 deployed on all 3 legs. Within the lagoon several pressure sensors were deployed
 101 on pinnacles at $\sim 8m$ depth to measure water level inside the atoll (L4,L5,L6,L7
 102 and L8). Instruments positions are shown on Figure 1 (top) and characteristics
 103 are summarized in Table 1.

104 *Water level*

105 At the ocean sites (O), *hoa* sites (H), and lagoon sites (L), pressure sensors
 106 sampled the in-situ water pressure continuously (no burst sampling), at 1Hz
 107 (see Table 1). The continuous 1Hz pressure record was divided into 1-hour-
 108 long bursts to calculate the mean hourly water level h_{ocean} or h_{lagoon} . Between
 109 each leg, each instrument was recovered, data was offloaded, batteries were
 110 changed and the instrument was deployed again. While water level from the
 111 uncorrected pressure record on all sites showed similar short term variability,
 112 they also showed trends relative to each others that could not have a physical
 113 explanation other than expected instrumental drift, that remained within the
 114 manufacturer’s specification of 1cm/year. We therefore corrected the raw pres-
 115 sure data for 1) individual pressure offsets due to a change in vertical position
 116 between leg or an instrumental bias, and 2) linear drift of individual instruments.
 117 The measured trend at each instrument during each leg is the combination of
 118 the instrument drift and the actual water level trend. We calculated an average
 119 trend across all sites for each leg, which we considered as the actual water level
 120 trend (assuming individual drifts would cancel each others). To correct each
 121 instrumental pressure records, for each leg, we therefore removed the individual
 122 trends at each instrument before adding back the common trend. The resulting
 123 corrected time-series are shown on (Figure 2).

124 Daily values of water level were subsequently obtained from the hourly water
 125 level values by applying a Demerliac filter (Bessero, 1985) to remove the effects
 126 of the astronomical tide and resampled to daily time-steps. Tidal phases and
 127 amplitudes were calculated using the Matlab Utide package (Codiga, 2011).

128 *Wave characteristics*

129 Each burst was subjected to a Fourier analysis to obtain pressure spectra
 130 $S_p(f)$ at frequency f in the 3 – 25s period band. The pressure spectra $S_p(f)$
 131 was converted into sea-surface elevation spectra $S(f)$ using linear wave theory
 132 after removal of a constant atmospheric pressure value of 1013 hPa. We then
 133 calculated significant wave height H_{sig} as $4 \times \sqrt{\sum S(f)df}$ and the mean period
 134 T_{m01} as $\frac{\sum f^{-1}S(f)}{\sum S(f)}$. Since we are interested in reef processes, we also calculated
 135 a breaking wave height equivalent $H_b = H_{sig}^{4/5} T_{m01}^{2/5}$ using a parameterization
 136 similar to that of Caldwell and Aucan (2007), Hench et al. (2008) or Merrifield
 137 et al. (2014), with a shore-normal propagation angle.

138 *Currents*

139 At the *hoa* sites (H) (see Table 1), current profilers measured current speed
 140 and direction in 12 vertical bins each 20cm high. The valid bins were selected
 141 based on the measured water depth above the instrument. We used a depth
 142 average over the valid vertical bins to calculate the mean current vector $\vec{U} =$
 143 $[u_1, v_1]$. We then calculated the principal direction θ of the current by solving
 144 in the least square sense $v_1 = a \times u_1 + b$ with $\theta = atan(a)$ (i.e., the yellow lines
 145 on Figure 5). The principal current direction should be predominantly along
 146 the axis of the *hoa*, perpendicular to the atoll rim (Figure 1 and Figure 5). For
 147 the rest of the paper, we only consider the current speed along the principal
 148 direction θ , where U refers to the current projected on this principal direction.
 149 Daily values of current speed were obtained from the hourly values by applying
 150 a Demerliac filter (Bessero, 1985) and a daily resampling, to remove the effects
 151 of the astronomical tide.

152 *Parametric model*

153 The aim of this study is to relate the current speed in the *hoa* to the wave
 154 and water level condition in a parametric, and generic sense, and for further
 155 inclusion into a lagoon circulation model (ie Le Gendre et al. in prep.). To
 156 guide us, there has been numerous previous studies on how to relate waves to
 157 across-reef flow (Symonds et al., 1995; Hearn, 1999; Gourlay and Colleter, 2005;
 158 Bonneton et al., 2007; Hench et al., 2008; Chevalier et al., 2015), although not
 159 specific to atoll rim environments. One of the key forcing parameters of across-
 160 reef flow is offshore wave conditions (wave height H_{sig} and wave period T_{m01}) or
 161 the breaking wave height (H_b), which drive wave setup in the breaking zone and
 162 across-reef flow downstream of the breaking zone. To simulate the water speed
 163 component in the *hoa* that is only due to the waves (e.g. the daily-averaged
 164 current), we can use a simple model based on equation 1, with the daily average
 165 (e.g. de-tided) values.

$$U_{daily} = AH_b + C \quad (1)$$

166 where U is the current, H_b is the breaking wave height equivalent, and A and C
 167 are constants. The breaking wave height equivalent $H_b = H_{sig}^{4/5} T_{m01}^{2/5}$, obtained
 168 by conserving the wave energy flux from offshore to the break point (Caldwell
 169 and Aucan, 2007; Hench et al., 2008) for a shore normal incoming wave. For
 170 each *hoa* and each leg, these constants were optimized in the least-square sense,
 171 in order to give the best fit to measured values of U_{daily} . We note that the
 172 dimensions in our equation 1 don't reflect the dimensions of the momentum
 173 equation normally used for "closed reefs" or "open reefs" as in Lindhart et al.
 174 (2021). In this case, our equation balances the wave forcing with the friction,
 175 averaging over the tidally driven pressure gradient.

176 Another key forcing parameter of across-reef flow is the water level down-
 177 stream of the surf zone which controls the flow of water across the reef. Symonds
 178 et al. (1995); Hearn (1999); Tartinville and Rancher (2000) make the hypothesis
 179 that water level within the lagoon, downstream of the surf zone is the same as

180 offshore (e.g. the outgoing flow through reef passes is unrestricted enough to
 181 compensate the incoming wave driven cross-reef flow). In Gourlay and Colleter
 182 (2005), there are no such hypothesis. In our case, the water level inside the
 183 lagoon is also tidally driven, with a phase lag of several hours compared to the
 184 open ocean (see Table 3 and section below). Hence, the water level downstream
 185 of the surf zone, across the *hoa* is controlled by the tide, and the lagoon wide
 186 return flow through the reef pass. To simulate hourly currents in the *hoa*, with
 187 a dependence on both tidal elevation changes and wave height, we included a
 188 pressure gradient term in equation 1 :

$$U_{hourly} = AH_b + B[(h_{ocean} - \overline{h_{ocean}}) - (h_{lagoon} - \overline{h_{lagoon}})] + C \quad (2)$$

189 where H_b is the breaking wave height equivalent, h_{ocean} is the sea-level height
 190 outside the reef, h_{lagoon} is the sea-level height inside the lagoon, the overbar
 191 designate time-averaged quantities and A, B and C are constants. The first
 192 term represents the effect of waves, the second term represents the effect of
 193 water level difference between ocean and lagoon, and the third is a constant.
 194 For each *hoa* and each leg, these constants were optimized in the least-square
 195 sense, in order to give the best fit to measured values of U_{hourly} . Similarly to the
 196 classic momentum balance equation Lindhart et al. (2021, for a recent study)
 197 equation 2 is simply balancing a pressure gradient, a radiation stress (the wave
 198 forcing), and a friction term (the velocity term).

199 3. Results

200 *Water level*

201 Outside the atoll, hourly sea level variations are predominantly tidal ($\sim 98\%$
 202 of the sea level variability explained by a tidal harmonic analysis), with a strong
 203 dominance of the semidiurnal components (Table 2). Daily water levels outside
 204 the atoll varied by a few cm over the course of the study (Figure 2 top), due
 205 to large scale ocean features, and are comparable to time-series of sea level
 206 anomalies products from satellite altimetry (not shown). Transient differences
 207 between water level among the ocean sites can be attributed to passing meso-
 208 scale eddies with horizontal length scales smaller than the atoll. We note that
 209 large scale currents could also cause such differences (Rogers et al., 2017).

210 Within the atoll, daily sea level variations were an order of magnitude higher
 211 than on the ocean side (Figure 2 bottom), and can vary by tens of cm during the
 212 course of a few days. Compared to the ocean sites, only 60 to 70% of the hourly
 213 sea level variability could be explained by a tidal harmonic analysis (Table 2).
 214 This higher variability and lesser tidal character of sea level inside the atoll
 215 compared to outside was attributed to wave events that drive water inside the
 216 atoll through the *hoa*.

217 We note that there was little geographical variation of daily sea level values
 218 within the atoll (Figure 2 bottom). There wasn't also any lag between tidal
 219 constituent within the atoll, indicating the sea level within the lagoon varies

220 uniformly at hourly and daily time scales. There was a factor ~ 2 attenuation
221 for all semidiurnal amplitudes (Table 2) and a lag of 3 – 4 hours between the
222 ocean tide and the lagoon tide (Table 3). This can be explained by the strong
223 flow restriction at the reef pass, which is the only unobstructed passage across
224 the atoll rim. These observations are comparable to those of Dumas et al. (2012)
225 in the nearby Ahe atoll in the Western Tuamotu.

226 3.1. Waves

227 Waves in Raroia atoll come from 3 main generation areas during the studied
228 period : low frequency waves from the NW (SW) are generated remotely by
229 mid to high latitude winter storms in the northern (southern) hemisphere, and
230 high frequency waves from the E are generated by the local trade wind (Dutheil
231 et al., 2020, and their Figure 5). Given the atoll rim orientation at each site,
232 low frequency waves from the NW were prevalent at O1/H1 during November
233 to April, where wave height could episodically reach $2m$. Low frequency SW
234 waves were prevalent at O3/H3 from June to October with wave heights up to
235 $3m$. Finally, high frequency trade wind seas were prevalent at O2/H2 nearly
236 year-round with heights also up to $3m$ (Figures 3 and 4).

237 3.2. Currents in the *hoa*

238 Daily averaged currents in the *hoa* were always lagoon-ward and could reach
239 0.5 to $0.6m.s^{-1}$ (Figures 5 and 6). We will show later that the daily current
240 is driven by waves. Hourly currents in the *hoa* exhibited a strong semidiurnal
241 variability due to the tide (not shown).

242 3.3. Parametric model

243 The modeled daily-averaged current was in good agreement with the obser-
244 vations (Figure 6). For each individual leg and site, the correlation between
245 observed and modeled current is above 0.95 except for one data set (leg 3 at
246 H2), and the range-normalized RMSE is always below 10% (Table 4). The val-
247 ues of the parameters A and C vary by a factor ~ 2 . If we use the mean values
248 of A and C and try to generalize our model, the correlation remains almost the
249 same as before, and the RMSE is increasing (Table 5), up to 32% at one site.

250 The modeled hourly-averaged current was in good agreement with the obser-
251 vations (example in Figure 7, top). For each individual leg and site, the
252 correlation between observed and modeled current is above 0.9 except for one
253 leg (leg 3 at H2), and the range-normalized RMSE is always below 10% (Table
254 6). The values of the parameters A, B and C vary by a factor ~ 2 . If we use the
255 mean values of A and B and C and try to generalize our model, the correlation
256 remains almost the same as before, and the RMSE is increasing (Table 5), but
257 less than for the daily model ($< 16.5\%$ at all sites and legs).

258 **4. Discussion**

259 The aim of this study was to provide a simple parameterization of currents
 260 in the *hoa*, so that these currents can be taken into account in a 3D circulation
 261 model of the atoll. Because this parameterization is to be included in a 3D
 262 circulation model, the model variables also need to be limited to those available
 263 from the 3D circulation model (e.g. water level inside or outside the lagoon) or
 264 through other readily available sources (offshore wave conditions from regional
 265 or global wave models such as Dutheil et al. (2020)). A high resolution 3D
 266 model resolving the driving process in play would require a high resolution
 267 digital elevation map. However, in our case, only bathymetric data in navigable
 268 areas (hence relatively deep) was available. Elevation and bathymetric data in
 269 the *hoa* and the reef crest were not available.

270 Furthermore, we used a very simple model because we had data only at a
 271 limited number of points (one offshore, one in the *hoa* and one in the lagoon,
 272 on each ocean-*hoa*-lagoon transect). With this limitation we could not study
 273 the processes more thoroughly (for example, we have no data in the surf zone).
 274 However, since we have data for a long period (1 year), we collected a wide
 275 range of conditions, allowing us to properly estimate the strength of our model,
 276 unlike shorter experiments.

277 We chose a formulation based on previous work (Gourlay and Colleter, 2005;
 278 Hench et al., 2008; Lindhart et al., 2021, etc...), but with some adaptations.
 279 The equation used balances a radiation stress gradient (the wave driven term),
 280 a pressure gradient (the water level term) and a friction term (the velocity).
 281 The wave-driven term (first term in equations 1 and 2) describes the process in
 282 which waves break, generate a wave setup which then drives a flow downstream
 283 in the lagoon through the *hoa*. It is always positive, directed toward the lagoon.
 284 It uses the formulation of the breaking wave height equivalent $H_b = H_{sig}^{4/5} T_{m01}^{2/5}$,
 285 obtained by conserving the wave energy flux from offshore to the break point
 286 (Caldwell and Aucan, 2007; Hench et al., 2008). More precisely, the exact for-
 287 mulation is $H_b = H_{sig}^{4/5} T_{m01}^{2/5} g^{1/5} \gamma^{1/5} (8\pi)^{-2/5} \cos(\theta)^{2/5}$, where γ is the breaking
 288 point parameter, θ is the propagation angle relative to the shore-normal, and
 289 g is the gravity constant (Hench et al., 2008). Here, a shore-normal propaga-
 290 tion is assumed at all times. It is a reasonable assumption since we measure
 291 wave height really close to shore (in $\sim 10m$ depth). In addition, we did not
 292 measure wave direction, so we could not test whether releasing this assumption
 293 would improve the model performance. For future usage, if wave conditions are
 294 obtained from further offshore, then one could use $H_b = H_{sig}^{4/5} T_{m01}^{2/5} \cos(\theta)^{2/5}$.
 295 The breaking parameter γ relates the water depth to the wave height at the
 296 breaking point. In our formulation, γ is considered constant with time, and is
 297 included in the constant A, along with the other fixed terms in the theoretical
 298 H_b formulation.

299
 300 The water level difference term describes the flow generated across the *hoa*
 301 by a difference in water level. We lack absolute measurements of the slope
 302 between ocean and lagoon because the bottom-mounted pressure sensors used

303 to measure water level in the ocean and the lagoon were too far apart (and
304 too deep) to be related to each other. Given the tidal regime in the atoll with
305 the phase lag between ocean and lagoon (discussed above), there are also no
306 time when we could make the assumption that water levels inside and outside
307 are equal (e.g when waves are small). In our formulation, we therefore used
308 the variations of water level around their respective time-average. The flow
309 predicted by this term can therefore be directed either way : a higher (lower)
310 water in the lagoon can drive flow out of (into) the lagoon. The constant term
311 B is equivalent to a friction coefficient. The constant term C in the equations
312 1 and 2 compensates the cases where waves are small (hence, not driving any
313 current), yet the formulation of equations 1 and 2 still predicts a wave-driven
314 current. Any time-averaged water level difference between ocean and lagoon
315 would also be represented by the constant term C. The respective contribution
316 of these 3 terms is illustrated on Figure 7, bottom.

317 The A, B and C parameters of the equations 1 and 2 were optimized for
318 each site and leg, and all values are within a factor 2 of each other, whether
319 comparing sites during the same leg, or during different leg for the same site.
320 We tested whether we could generalize our parametrization to all *hoa* sites and
321 leg with one set of parameters. To do so, values of the "optimized" constants
322 A, B and C were averaged, to provide a "mean" set of parameter. The currents
323 were simulated with these parameters in equations 1 and 2, and the quality of
324 the simulation was estimated (see Tables 5 and 7). This robustness analysis
325 showed good results. The performance remained very satisfactory in terms of
326 correlation, and the RMSE remained below 33% for daily simulations, and below
327 16% for hourly simulations. Small transient offsets appear between timeseries of
328 modeled and observed velocities (figures 6 and 7) that we could attribute to 1)
329 processes not included in the model (wind) 2) wave driven processes occurring
330 at other hoas around the atoll, or inherent limitations of our simple model.
331 Nonetheless, a very simple parametrization was found to be able to account
332 for the wide variety of wave and tide conditions that the *hoa* experienced, and
333 to simulate the speed of water passing through them. More precisely: the
334 parametrization provides very good timing of the events - as quantified by the
335 correlation coefficient - and a good estimate of their magnitude - as quantified
336 by the RMSE. This is a very noticeable result, as, to the best of our knowledge,
337 it had never been reported in the Tuamotu region. This implies that we have
338 good confidence with regard to the extension of the parametrization to other
339 periods of time or islands with similar geomorphology.

340 Our observations of dominant inflows through *hoa* match reports from other
341 atolls. Besides Ahe atoll already mentioned Dumas et al. (2012); Kench and
342 McLean (2004) observed in an atoll of the Indian Ocean, small outflowing hourly
343 currents in the *hoa*, but overall, the hourly currents were predominantly lagoon-
344 ward (figures 5 and 7). In Manihiki, a pearl farming atoll in the Cook Islands,
345 there is no deep pass Andréfouët et al. (2020), and the circulation across the
346 rim is different than atolls with passages. For this atoll, and Rakahanga as well,
347 inflows by waves fill the lagoon in the exposed part of the rim (as described for
348 Raroia), but *hoa* on the opposite side of the rim also drive by gravity the excess

349 amount of water outwards during the tidal cycle (Callaghan et al., 2006). These
350 outbound processes could also be simulated with our simple model : One the
351 wave exposed hoa , the wave term $A \times H_b$ is larger than the water level term
352 $B \times ((h_{ocean} - \overline{h_{ocean}}) - (h_{lagoon} - \overline{h_{lagoon}}))$ so the modeled flow is directed into
353 the lagoon, and on the non-exposed hoa , the wave term is zero, and the water
354 level term $B \times ((h_{ocean} - \overline{h_{ocean}}) - (h_{lagoon} - \overline{h_{lagoon}}))$ drives an outward flow.

355 5. Conclusion

356 We collected for the first time in a Tuamotu atoll environment, a nearly
357 1-year long dataset of oceanic wave, lagoon water level and currents across the
358 Raroia atoll rim. The data set allowed defining a multi-rim generic and simple
359 relationship between wave height and inbound current across the rim, in order
360 to integrate this forcing into future lagoon 3D numerical models. We found that
361 in Raroia Atoll, daily (hourly) currents in the hoa were always (predominantly)
362 flowing into the lagoon, and are dependent on both offshore wave conditions
363 and water level difference between ocean and lagoon.

364 Water level inside the atoll was driven 60 to 70% by the tide flowing in and
365 out. The remainder corresponded to water driven by waves through the hoa .
366 Tidal amplitude in the lagoon were 50% lower than in the ocean, and there was
367 a 4h lag between lagoon tides and ocean tides.

368 Based on this dataset, we successfully created a very simple parametric
369 model with three calibrated coefficients to estimate cross-rim currents using
370 only offshore wave conditions (Wave height and mean period), and the differ-
371 ence between offshore and lagoon water level. The model agrees well with the
372 observations with RMSEs below 10% on all legs, for daily (detided) or hourly
373 values. The model was able to simulate the currents with very good timing and
374 good magnitude.

375 Moreover, the cross-rim currents model we implemented for semi-open Tu-
376 amotu atoll like Raroia relies on very few variables, that are available in plethora
377 of water circulation models (e.g. water level inside or outside the lagoon) or
378 through other readily available sources (offshore wave conditions from regional
379 or global wave models). Therefore, it is now possible, if the three coefficients are
380 known, to correctly and generically parameterize the flow through atoll rim hoa ,
381 as one of the boundary component of 3D lagoon models. Future work should
382 include testing this parameterized model in other atoll settings and exploring if
383 the values of the three model coefficients are generalizable. This is a significant
384 step towards the development and use of numerical models for pearl farming
385 management in Tuamotu atolls.

386 Authorship contribution statement

387 Jérôme Aucan : Conceptualization, Methodology, Formal analysis, Writing
388 original draft

389 Romain Le Gendre : Conceptualization, Data curation, Writing, review and
390 editing.

391 Terence Desclaux : Methodology, Formal analysis, Writing, review and edit-
392 ing.

393 Vetea Liao : Conceptualization, Funding acquisition, Writing, review and
394 editing.

395 Serge Andréfouët : Conceptualization, Resources, Writing, review and edit-
396 ing, Supervision, Project administration, Funding acquisition.

397 **Acknowledgements**

398 This study was funded by the ANR-16-CE32-0004 MANA (Management of
399 Atolls) project. Two oceanographic cruises MALIS 1 and MALIS 2, on board
400 R/V Alis (<https://doi.org/10.17600/18000582>), also made this work possible.
401 We are grateful to the R/V Alis crew, as well as to IRD, Ifremer and DRM
402 electronicians and scientific divers: David Varillon, Bertrand Bourgeois, John
403 Butscher, Chloe Germain, Joseph Campanozzi-Tarahu and Fabien Tertre. The
404 study was co-funded by the DRM OTI project, Contrat de Projet France-French
405 Polynesia, Program 123, Action 2, 2015–2020. Facilities at Tahiti were offered
406 by IFREMER/CIP. We thank the 2 reviewers for their useful comments that
407 helped improve the manuscript. We are also extremely grateful to Raroia’s
408 inhabitants and their Mayor for their help during fieldwork.

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Table 1: Site instrumentation and positions

Site	Latitude (S)	longitude (W)	variable measured	Make and model	Sampling rate
H1	15.997	142.433	current and water level	Nortek Aquadopp	5 min bursts
H2	16.035	142.346	current and water level	Nortek Aquadopp	5 min bursts
H3	16.241	142.479	current and water level	Nortek Aquadopp	5 min bursts
H5	16.115	142.382	current and water level	Nortek Aquadopp	5 min bursts
L4	15.987	142.364	wave and water level	RBR Duet	continuous 1 second
L5	16.065	142.419	wave and water level	RBR Duet	continuous 1 second
L6	16.151	142.469	wave and water level	RBR Duet	continuous 1 second
L7	16.118	142.503	wave and water level	RBR Duet	continuous 1 second
L8	16.153	142.411	wave and water level	RBR Duet	continuous 1 second
O1	15.994	142.437	wave and water level	RBR Duet	continuous 1 second
O2	16.037	142.341	wave and water level	RBR Duet	continuous 1 second
O3	16.249	142.480	wave and water level	RBR Duet	continuous 1 second

Table 2: Total hourly sea level variance explained by the tidal analysis (in %) and tidal harmonics amplitude (cm) for the principal semidiurnal (M2, N2, S2 and K2) and diurnal (K1) tidal constituents at the different sites

	Ocean sites			Lagoon sites				
	O1	O2	O3	L4	L5	L6	L7	L8
Variance explained	98.3	98.3	97.9	70.5	70.3	70.9	70.3	70.5
M2	32.3	33.1	29.8	15.8	15.8	15.9	15.9	15.9
N2	7.1	7.5	6.7	3.3	3.3	3.3	3.3	3.3
S2	6.1	6.6	6.7	2.1	2.1	2.1	2.1	2.1
K1	2.5	1.8	2.1	1.7	1.7	1.8	1.7	1.8
K2	2.1	2.3	2.4	0.9	0.9	1.0	1.0	0.9

Table 3: Tidal phase lag (h) for the principal semidiurnal (M2, N2, S2 and K2) and diurnal (K1) tidal constituents at the different sites relative to tidal phase at O1

	Ocean sites			Lagoon sites				
	O1	O2	O3	L4	L5	L6	L7	L8
M2	0.0	-0.3	-0.4	4.4	4.4	4.4	4.4	4.4
N2	0.0	-0.4	-0.3	4.5	4.5	4.5	4.5	4.5
S2	0.0	-0.4	-0.4	6.2	6.2	6.1	6.1	6.2
K1	0.0	0.3	-0.0	3.6	3.6	3.7	3.6	3.6
K2	0.0	-0.2	-0.1	4.9	4.9	4.9	4.9	4.9

Table 4: A and C parameter values in equation 1 calculated for each leg , correlation and range-normalized RMSE (%) between modeled and daily-averaged observations.

	A	C	Correlation	RMSE(%)
H1 Leg3	0.178	-0.179	0.976	5.1
H2 Leg1	0.125	-0.195	0.987	3.6
H2 Leg2	0.110	-0.157	0.986	3.5
H2 Leg3	0.082	-0.079	0.857	9.7
H3 Leg1	0.099	-0.175	0.966	5.1
H3 Leg2	0.083	-0.124	0.959	6.7
Mean	0.113	-0.151		

Table 5: Correlation (r) and range-normalized RMSE (%) between modeled and daily-averaged observations when using equation 1 and mean values of A and C parameters, cf Table 4.

	Correlation	RMSE(%)
H1 Leg3	0.975	32.1
H2 Leg1	0.986	4.4
H2 Leg2	0.986	5.0
H2 Leg3	0.857	11.5
H3 Leg1	0.966	16.1
H3 Leg2	0.959	24.2

Table 6: A, B, and C parameter values in equation 2 calculated for each leg , correlation and range-normalized RMSE (%) between model and hourly observation.

	A	B	C	Correlation	RMSE(%)
H1 Leg3	0.191	0.584	-0.213	0.971	4.2
H2 Leg1	0.172	0.551	-0.343	0.911	8.1
H2 Leg2	0.148	0.450	-0.270	0.900	8.5
H2 Leg3	0.096	0.397	-0.114	0.832	8.8
H3 Leg1	0.115	0.291	-0.224	0.935	6.1
H3 Leg2	0.103	0.285	-0.183	0.916	7.9
Mean	0.138	0.427	-0.225		

Table 7: Correlation (r) and range-normalized RMSE (%) between model and observation when using equation 2 and mean values of A, B and C parameters, cf Table 6 .

	Correlation	RMSE(%)
H1 Leg3	0.971	16.5
H2 Leg1	0.911	9.1
H2 Leg2	0.900	8.7
H2 Leg3	0.825	9.3
H3 Leg1	0.929	11.9
H3 Leg2	0.914	15.9

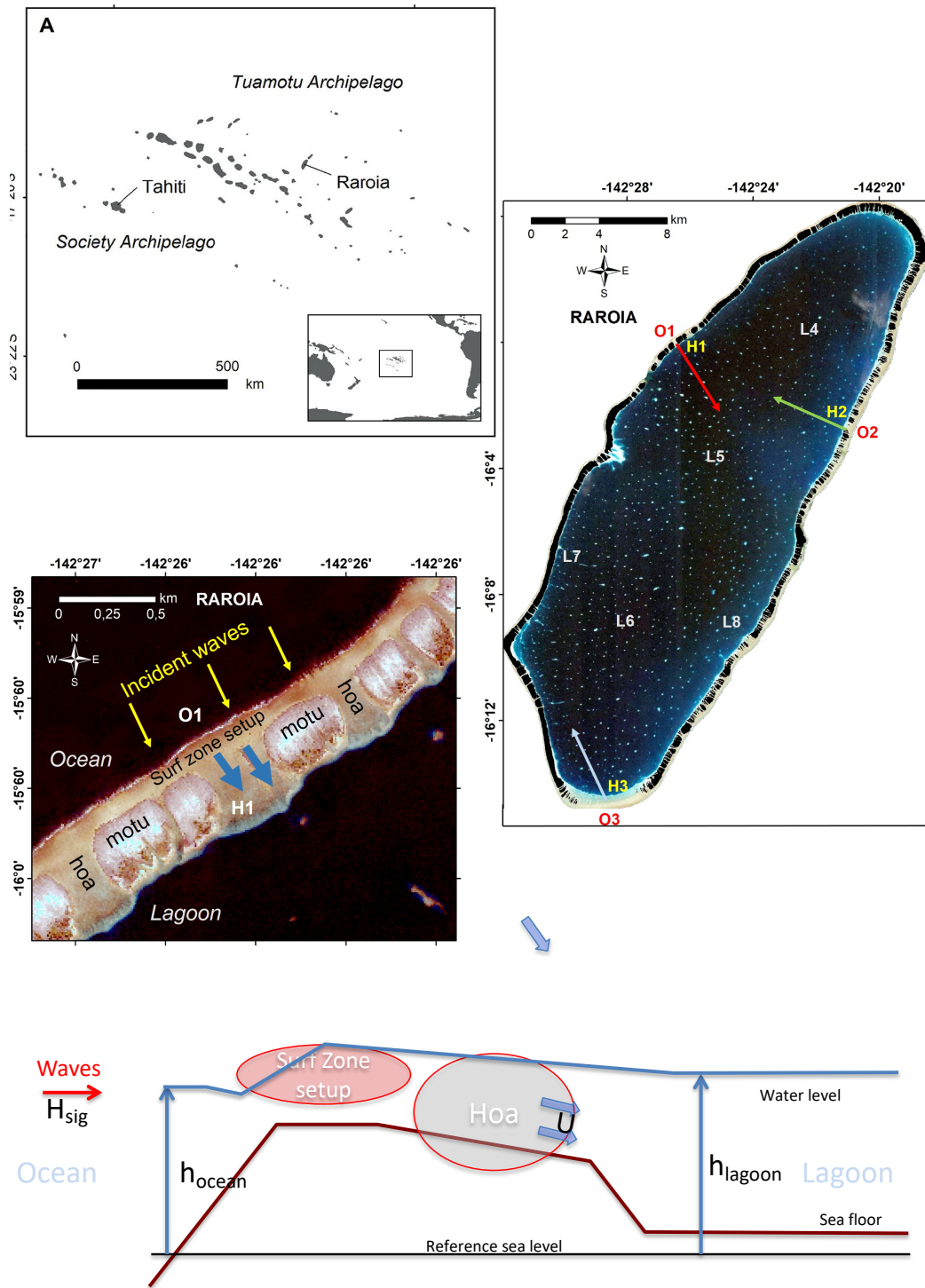


Figure 1: Top : Location map of the Raroia atoll, middle right, with location of the instruments. Arrows indicate principal direction of current discussed in section 2.2. middle left : Typical instrument configuration near site 1. Bottom : Schematics of site along with observed variables.

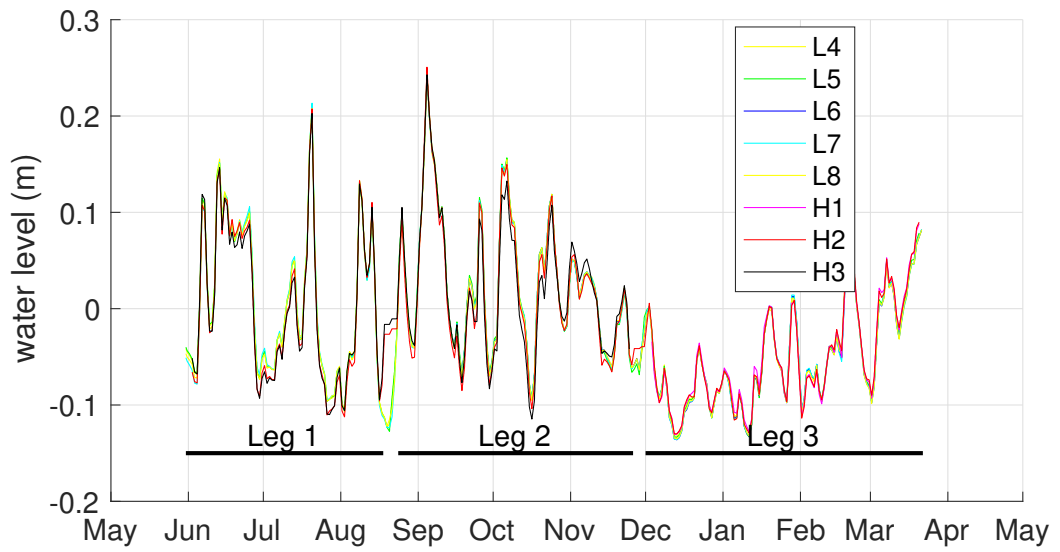
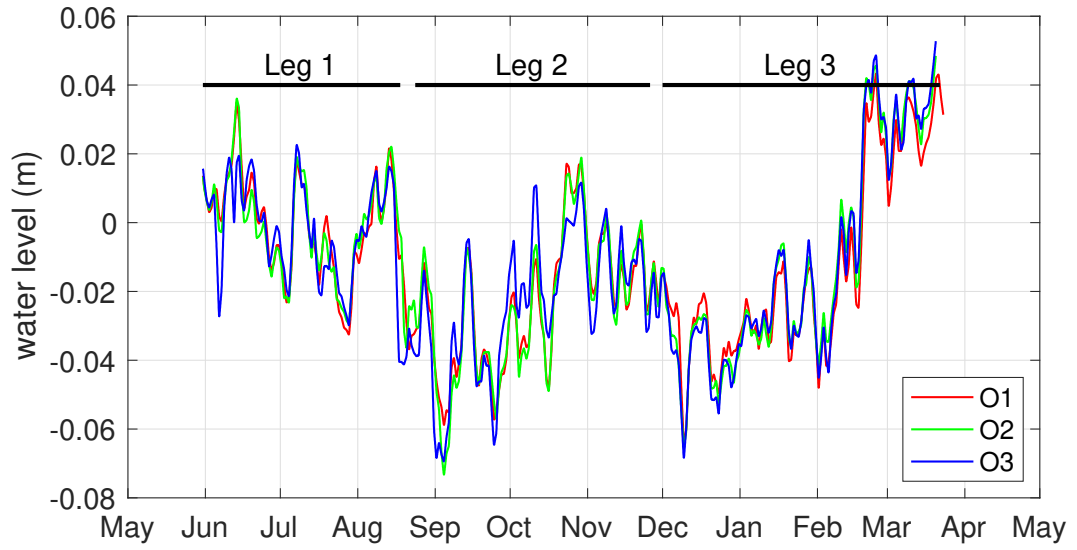


Figure 2: Water level at the 3 ocean sites (top) and at the 5 lagoon and 3 *hoa* sites (bottom). Water levels are shown relative to the time-average water level at each station. Leg durations are indicated in black.

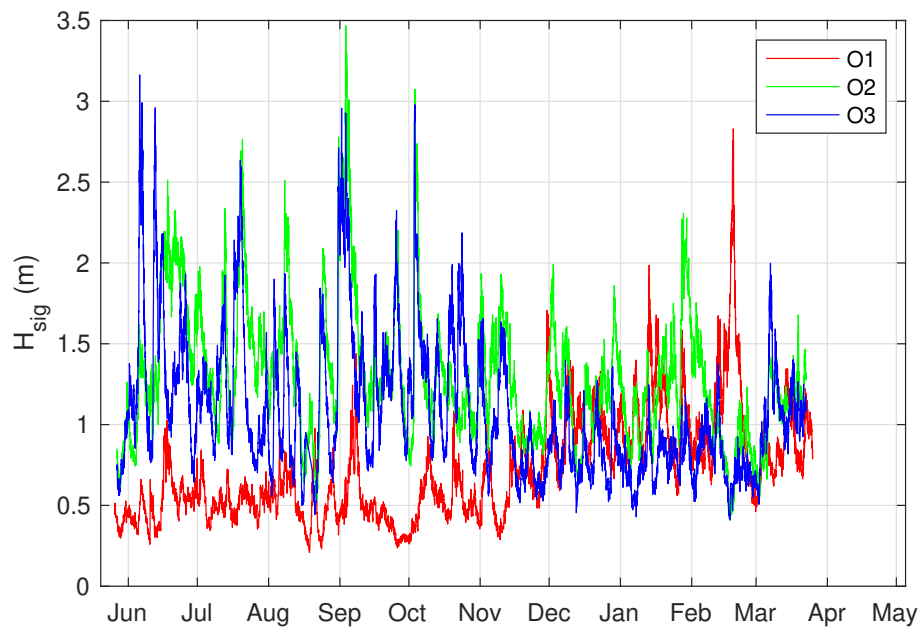


Figure 3: Wave height at the ocean sites O1 (red), O2 (green) and O3 (blue)

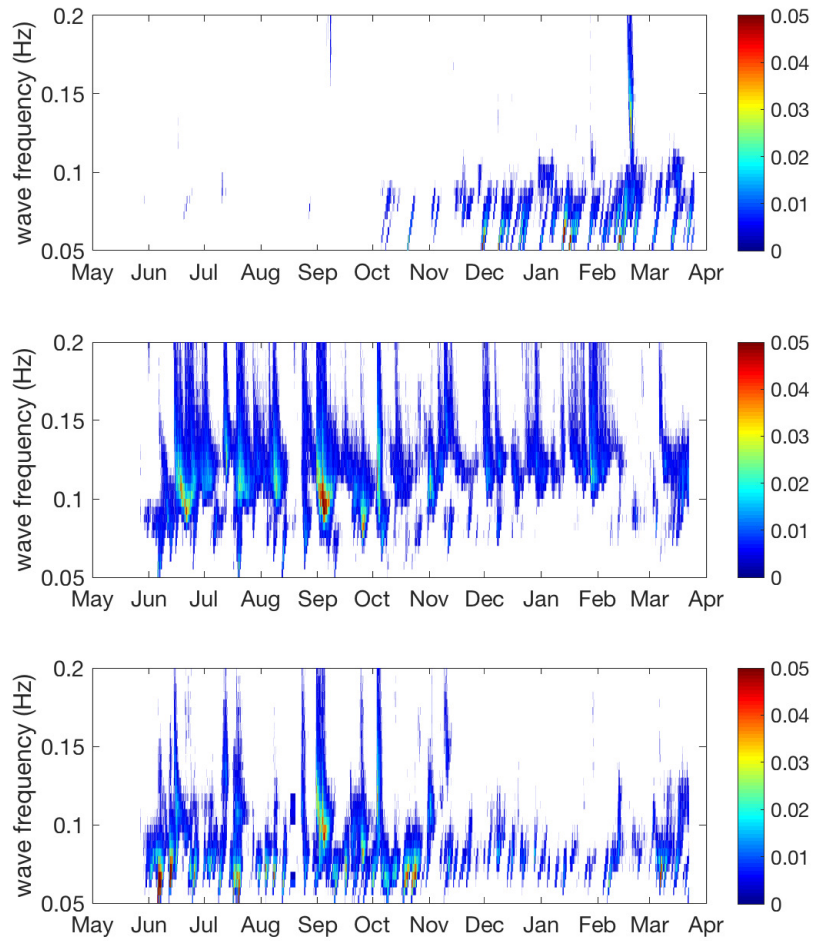


Figure 4: Water level spectrogram ($S(f)$, in m^2) at the ocean sites O1 (top), O2 (middle) and O3 (bottom).

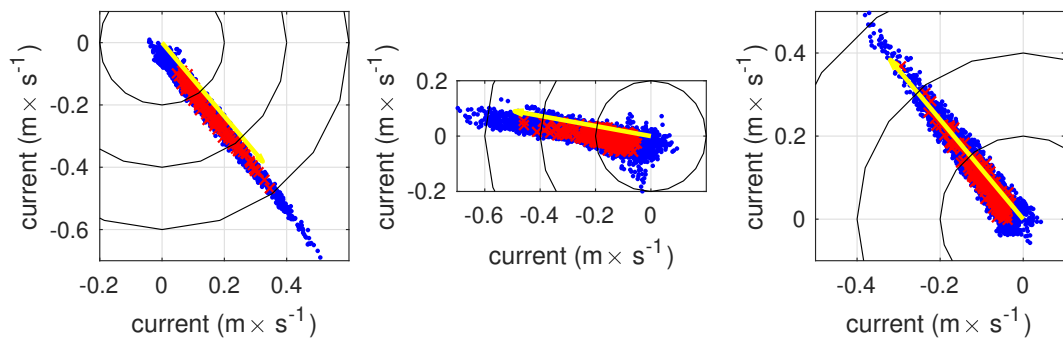


Figure 5: Hourly (blue) and daily (red) averaged E-N current vectors at site H1 (left), H2 (center) and H3 (right). Principal directions are indicated in yellow.

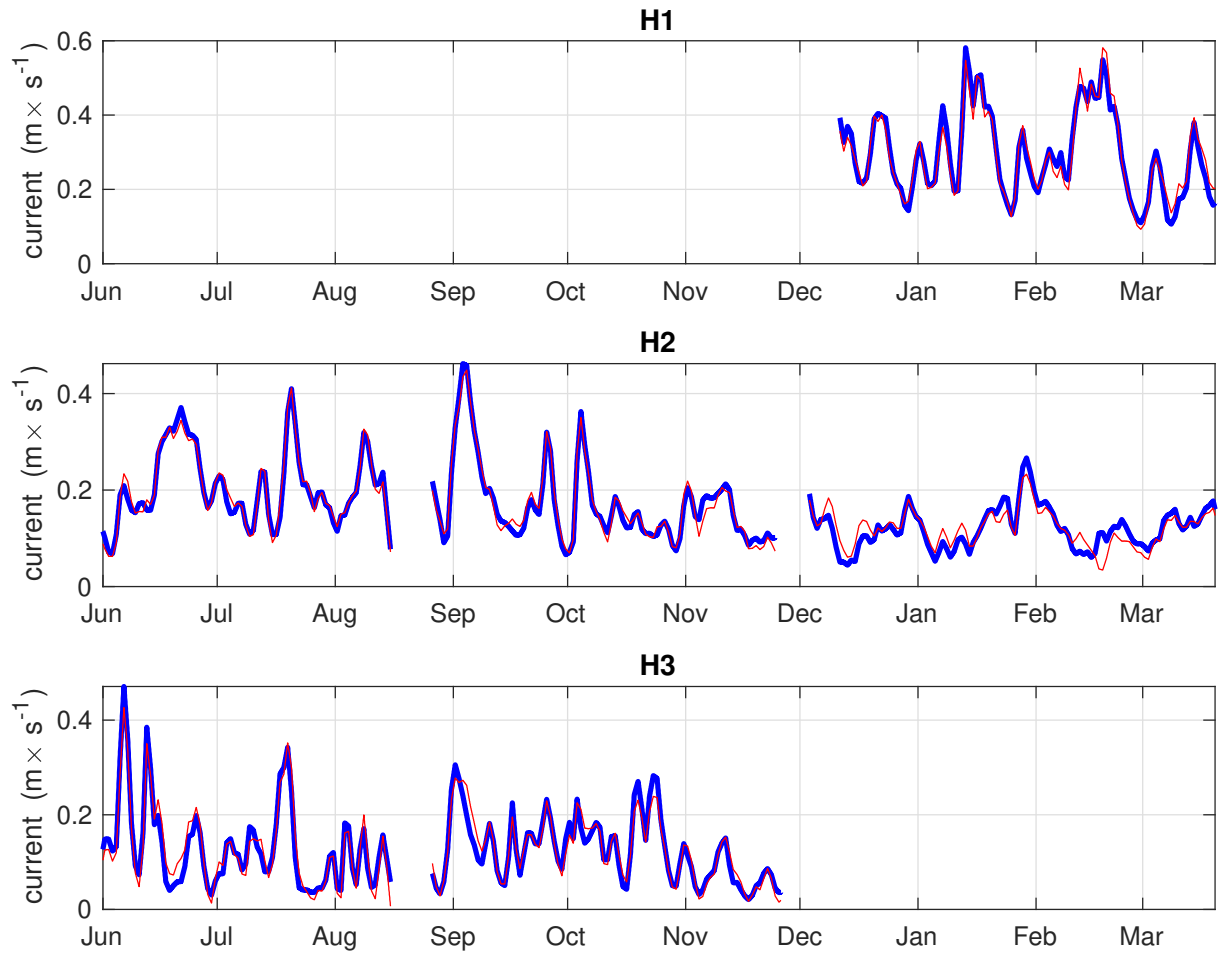


Figure 6: Daily average current speed in the hoar at the different legs and sites, measured (thick blue line), and modeled (thin red line) using equation 1 .

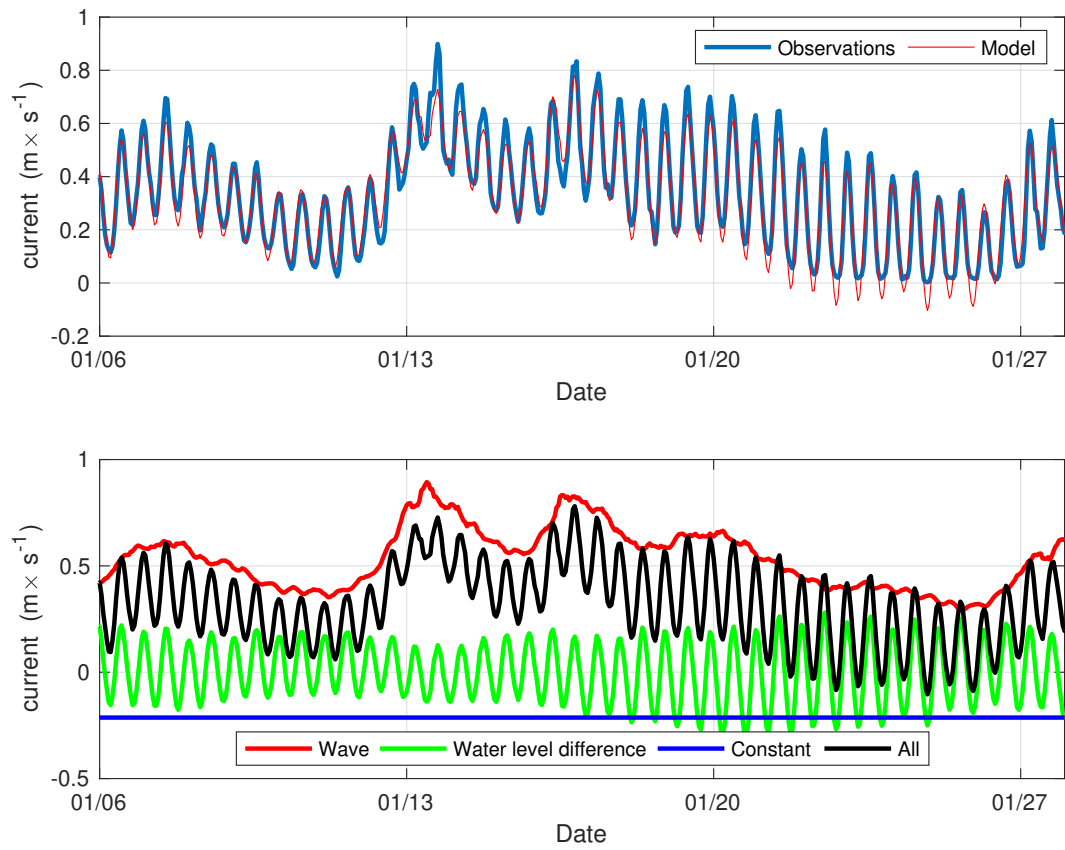


Figure 7: Example of hourly averaged speed in the hoa at H1 during leg 3, measured (thick blue line), and modeled (dashed red line) using equation 2. Example of individual contributions of terms in equation 2 .