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# Influence of shoreface morphological changes since the 19th century on nearshore hydrodynamics and shoreline evolution in Wissant bay (northern France)

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## Abstract

Located at the southern approaches to the North Sea, the Wissant bay has had the most rapidly eroding shoreline in mainland France in recent decades. Using historical bathymetries spanning the second half of the 19th century to the present, an analysis of the long-term coastal morphological changes and evolution of a prominent sand bank (Line bank) extending across the bay was carried out. A period of overall seabed erosion with a width-reduction of the Line bank; a deepening of the channel between the Line bank and the coast; and a lowering of the foreshore have been ongoing since the middle of the 20th century. This phase followed a period of channel infill in the western part of Wissant bay in the early 20th century. Numerical modelling of wave propagation and tidal circulation was performed using the TELEMAC suite of models to get some insights into the influence of these bathymetry changes on coastal hydrodynamics. Two seabed configurations were identified revealing a contrasting hydrodynamic circulation. An erosional one induces an acceleration of tidal currents and an increase in wave height. Conversely, accumulation leads to an hydrodynamic regime weakening with a decrease in current velocity and to

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more wave energy dissipation in the nearshore. This study highlights the role of morphological feedbacks between nearshore morphology and coastal hydrodynamics. The identification of these feedbacks mechanisms at a historical time scale is important to assess potential drivers of coastal changes.

*Keywords:* Sand banks, North Sea, France, Hydrodynamic, Tidal currents, Waves, Wissant bay

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## 1. Introduction

Sand banks are large sedimentary features that occur in many coastal and shelf seas where there is a large amount of sediment and strong enough currents to transport this sediment (Caston, 1972; Kenyon et al., 1981; Dyer & Huntley, 1999; Deleu et al., 2004; Pan et al., 2007). There is a complex interaction between hydrodynamic and seabed leading to a variety of shapes and sizes, classified according to their formation and hydrodynamic settings (Huthnance, 1982; Dyer & Huntley, 1999; de Swart & Yuan, 2018). These sand banks are controlled either by storms (storm-generated ridges) or by tidal currents (tide-dominated banks) (Belderson, 1986)

The southern North Sea is characterized by a large number of tidal sand banks and has been extensively studied (Houbolt, 1968; Caston, 1972; Davies, 1980; Lanckneus et al., 1992; Berné et al., 1994; Lanckneus et al., 1994; Tessier et al., 1999) Sand banks play an important role in influencing shoreline evolution by attenuating the incident wave energy through wave breaking and bed friction processes (MacDonald & O'Connor, 1996; Héquette & Aernouts, 2010). Erosion is widespread along the central and southern part of the North Sea coastline, in France 20% of the coasts are under erosion (Hédou et al., 2018). In Wissant bay (northern France) the average shoreline retreat can exceed  $5 \text{ m.an}^{-1}$  (Aernouts & Héquette, 2006; CEREMA, 2018). Previous studies have suggested strong interactions between shoreline evolution and associated nearshore due to cross-shore and long-shore sediment transfers (Carter et al., 1982; Hanna & Cooper, 2002; Shaw et al., 2008; Héquette et al., 2009; Héquette & Aernouts, 2010;

24 Thomas et al., 2011; Héquette et al., 2013; Sedrati & Anthony, 2014).

25 Long bathymetric time series (several decades to centuries) are rare and gen-  
26 erally localised in the vicinity of ports or in the context of dredging and aggregate  
27 extraction operations. In northern France, topographic and hydrographic sur-  
28 veys of coastal and nearshore morphologies have been conducted since the begin-  
29 ning of the 19th century and provide a direct source of data for assessing coastal  
30 and nearshore environments evolution (Latapy et al., 2019). Understanding the  
31 long-term characteristics of the morphology and the association with natural  
32 and anthropogenic forcing factors are important for coastal management. His-  
33 torical bathymetries have already been used to investigate coastal morphology  
34 and hydrodynamic interactions (Cooper & Navas, 2004; Bertin, 2005; Bertin  
35 & Chaumillon, 2005; Aernouts & Héquette, 2006; Horrillo-Caraballo & Reeve,  
36 2008; Héquette & Aernouts, 2010). For example, Horrillo-Caraballo & Reeve  
37 (2008) demonstrated that the 150 year-long changes in UK's eastern sand bank  
38 morphology can be largely explained by changes in its tidal residual currents.  
39 Cooper & Navas (2004) simulated wave propagation across the southeast coast  
40 of Northern Ireland and found a marked change in nearshore patterns of energy  
41 dispersal and related sediment transport pathways in one century. Neverthe-  
42 less, these investigations generally focused on wave or tide-induced processes  
43 whereas natural systems are subjected to a combination of waves and tides. In-  
44 deed, tides change the mean water depth, which affects wave propagation over  
45 the inner shelf and the shoreface (Wolf & Prandle, 1999; Osuna & Monbaliu,  
46 2004). Tides are also responsible for variations in the nearshore flow field which  
47 in turn modifies wave-current interaction (Wolf & Prandle, 1999), especially in  
48 a macrotidal environment. In addition, interactions between wave generated  
49 currents and tidal currents lead to an increase of bottom shear stress, particu-  
50 larly at the sand bank crests that can intensify sediment transport (Villaret &  
51 Davies, 2004; Giardino et al., 2010; Brown et al., 2015).

52 The present investigation tries to quantify the relative importance of nearshore  
53 morphology changes on wave and tide interactions and analyzes the possible im-  
54 pacts on shoreline evolution since the 19th century. First, the coastal evolution

55 of Wissant bay was assessed using historical bathymetry by comparison of dig-  
56 ital bathymetric data. Then, effects of the tide-induced time-varying water  
57 depths and currents on wave height, and their possible changes depending of  
58 the sea bed evolution, were investigated. Finally, the links between documented  
59 shoreline changes and modelled modifications in tidal currents and wave regime  
60 in the coastal zone are also discussed.

## 61 **2. Study area**

### 62 *2.1. Wissant bay's shoreface morphology*

63 The North Sea coast of France generally consists of wide, gently sloping,  
64 sandy barred beaches (Reichmüth & Anthony, 2007). Sand banks are particu-  
65 larly widespread in this area, where they form linear shore-parallel or slightly  
66 oblique sand bodies about 10–30 km long and 1–3 km wide. These banks belong  
67 to the Flemish Banks (Houbolt, 1968) and generally occur as groups of banks  
68 from shallow coastal areas near beaches to depths of several tens of meters (Vi-  
69 caire, 1991; Anthony & Orford, 2002). Previous studies have revealed a strong  
70 variability in nearshore evolution along large parts of the northern France's  
71 coastal zone since the last few decades (Aernouts & Héquette, 2006; Héquette  
72 et al., 2013) but also over a larger time-scale (Aernouts, 2005; Ruz et al., 2017;  
73 Latapy et al., 2019).

74 Wissant bay is 8 km-long and located on the westernmost part of the French  
75 North Sea coast (Figure 1). It forms a well defined, single longshore sediment  
76 cell between Capes Gris Nez and Blanc Nez (Dewez et al., 1989; Beck et al.,  
77 1991; Anthony, 2000; Anthony et al., 2006). It is characterized by a 300 to 600  
78 m-wide intertidal bar-trough beach dissected by drainage channels (Sedrati &  
79 Anthony, 2007). The gently sloping shallow shoreface extending seaward of the  
80 beach bars and trough is characterized by a prominent tidal sand bank named  
81 the Line bank (Figure 1), oriented WSW-ENE, roughly parallel to the coastline.  
82 The Line bank belongs to headlands banks based on the categorization by Dyer  
83 & Huntley (1999) and particularly banner banks formed where the coast changes

84 direction and where headland are resistant to erosion. The sediment distribution  
85 consists of a remarkably homogeneous sand, with median diameter ( $D_{50}$ ) ranging  
86 from 0.17 to 0.21 mm (Anthony & Héquette, 2007; Sedrati & Anthony, 2007).

87 Massive aggregate extraction has been carried out in the past, especially  
88 in the western sector of the Line bank, closest to the shore. A Senate report  
89 mentions that during the 1970s, about 600 000 m<sup>3</sup> of sediment was extracted  
90 (Pintat, 1975). This practice was prohibited in 1983, but the damages caused  
91 by this extraction, added to other anthropogenic causes such as the expansion of  
92 the port of Boulogne-sur-mer in the 1930s, has resulted in a significant sediment  
93 deficit in the bay. This recurrent sediment deficit now affects the beach which  
94 contributes to the shoreline retreat (Crapoulet et al., 2017). Indeed Wissant bay  
95 is presently one of the most strongly eroded coasts in mainland France, erosion  
96 is strongest in the southwestern and central parts of the bay while the northeast  
97 was characterized by a significant foredune growth during the second part of  
98 the 20th century (Aernouts & Héquette, 2006; Chaverot et al., 2008; Sedrati &  
99 Anthony, 2014) (Figure 1a).

## 100 *2.2. Hydrodynamic context*

101 As with adjacent coastal area, the Wissant bay is a typical mixed storm-wave  
102 and tide-dominated environment. This bay is subject to a complex pattern of  
103 time-varying influences of both tides and storms and even to wind forced flows  
104 (Héquette et al., 2008). Winds are generally from southwest and northeast,  
105 but the strongest winds mostly originate from west to southwest. Based on the  
106 HOMERE wave hindcast database (Accensi & Maisondieu, 2015), offshore waves  
107 are commonly less than 1 m (mean  $H_s = 0.87$  m) but may exceed 3 m during  
108 extreme events (max  $H_s = 4.5$  m). Wave periods mostly range from 5 to 7  
109 seconds (mean period 6.14 s) and the dominant waves are from the south-west  
110 to west (from the English Channel) followed by waves from the northeast to  
111 north (originated from the North Sea) (Figure 1b). Because depth-induced re-  
112 fraction and dissipation of waves occurs over the shoreface and over the Line  
113 bank, at the coast waves are usually reduced and from a NW to NNE window.

114 The tidal regime is semi-diurnal and macrotidal (tidal range about 7 m during  
115 spring tides (Shom, 2017)). The nearshore circulation during fair-weather con-  
116 ditions is characterized by a flood-dominated asymmetry responsible for strong  
117 northeastward-directed currents (Héquette et al., 2008) (Figure 1c). Longshore  
118 currents can become particularly strong during storms as a result of direct wind  
119 and wave stress (Sedrati & Anthony, 2007). The net regional sediment trans-  
120 port in the coastal zone is directed eastward in response to the easterly-directed,  
121 flood-dominated tidal circulation (Augris et al., 1990) but locally counter-drift  
122 currents toward the west-southwest are also observed (EGIS, 2014).

### 123 **3. Methodology**

#### 124 *3.1. Bathymetry changes*

125 Several bathymetry datasets covering the northern France coastline and ad-  
126 joining seabed are available dating back to the mid-19th century. Most surveys  
127 were carried out over 2-3 years given the limited resources available at the time  
128 and the extent of the area covered (Table 1). Historic hydrographic field sheets  
129 from the French Hydrographic Service (SHOM) were scanned, digitized and  
130 then interpolated using the "kriging" method to produce Digital Elevation  
131 Models (DEMs). The coordinate system is the WGS84, and elevations are in  
132 meters below chart datum (lowest low-water spring level). The uncertainty as-  
133 sociated with each survey was calculated by taking into account the sounding  
134 tool and the positioning technique (Table 1). To quantify bathymetry changes,  
135 differential DEMs, along-shore and cross-shore transects and sediment volume  
136 calculation were made (more details on interpolation and computing methods  
137 can be found in Latapy et al. (2019)). Morphological changes and computed  
138 volumes are considered significant when they are not within the error margin.

#### 139 *3.2. Numerical model*

140 To investigate the influence of seabed morphological changes on coastal  
141 hydrodynamic, a numerical approach was developed. This study used the

142 TELEMAC suite of models, consisting of TELEMAC-2D (Hervouet, 2007) and  
143 TOMAWAC to simulate tides and waves respectively. As a first step, TELEMAC-  
144 2D and TOMAWAC were run separately to study individually the impact of  
145 bathymetric changes on tidal circulation and on wave propagation.

146 Subsequently, TELEMAC-2D and TOMAWAC were run in fully coupled  
147 mode so that the wave propagation module integrates the effects of the time-  
148 varying water depth and currents computed by the circulation modules. TELEMAC  
149 transfers to TOMAWAC values of current velocities and water depths, while  
150 TOMAWAC solves the wave action density conservation equation with reference  
151 to those current and water depth values and returns to TELEMAC the updated  
152 values of the wave driving forces  $F_X$  and  $F_Y$  (including surface, bottom and  
153 radiation stresses) acting on the current. Water-depths variation modulates the  
154 dissipation of waves energy by bottom friction and wave breaking. Opposing  
155 tidal flows induce a steepening of the incident wave field thus increasing wave  
156 height. Finally, the combination of the time-varying water depths and currents  
157 leads to wave refraction and to a variability of the incident wave energy at  
158 specific coastal locations.

159 TELEMAC-2D and TOMAWAC were set up on a domain covering northern  
160 France's coastal zone - from the Belgium border to the Dover Strait (Figure  
161 9). The first three bathymetry surveys extended over sufficiently large areas  
162 were used for numerical modelling (2016 survey was restricted to Wissant bay)  
163 (Table 1). DEMs generated from the selected bathymetry surveys were used  
164 to obtain three grids (Table 2) with a mesh resolution ranging from 250 m at  
165 the coast and over sand banks, increasing to 2.5 km offshore (Figure 9).

166 We forced our model to simulate the most powerful currents and waves  
167 possible in each mesh in order to identify high energy areas and those that have  
168 potentially undergone the most significant changes. We focussed our analysis on  
169 extreme events because coastal changes (such as beach and coastal dune erosion)  
170 are largely due to high-energy processes (Masselink et al., 2014; Castelle et al.,  
171 2015). Forcing conditions are described in the following sections.



172 *3.2.1. TELEMAC forcing*

173 The model is forced at the offshore open boundary with specified elevation  
174 for 143 tidal harmonics from the tidal model cstFRANCE developed and used  
175 by the SHOM (Le Roy & Simon, 2003). The validation of the models was  
176 carried out with tidal observations and predictions at the ports of Calais and  
177 Dunkirk. Current observations also allowed the model to be adjusted and cal-  
178 ibrated (see the Appendix A for a detailed overview of the validation of the  
179 model). The time step is set to 10 seconds and the bottom friction coefficient is  
180 computed with Chezy’s law. As the modelled area was spatially restricted, and  
181 is composed of quasi-homogeneous sea-bed sediment (sandy-gravelly) (Anthony  
182 & Héquette, 2007) a uniform friction coefficient was applied to the entire mesh  
183 ( $64 \text{ m}^{1/2} \cdot \text{s}$ ). This coefficient is consistent with those obtained for equivalent  
184 surficial sediment (Soulsby, 1983, 1997; Cooper et al., 2004).

185 The model was run for a period of 30 days during the highest astronomical  
186 tides of 2015 (03/01/2015 to 03/30/2015) with sea-level elevation over the whole  
187 domain at 10 min intervals. Residual tidal currents are computed over the  
188 whole simulated period, these maps were used to identify possible transport  
189 pathways. Since the maps represent flow and not sediment transport they are  
190 only indicative of the likely direction of sediment transport and should not be  
191 interpreted quantitatively.

192 *3.2.2. TOMAWAC parametrization*

193 TOMAWAC model enables us to evaluate the effects of changing seabed  
194 morphology on wave refraction and on the pattern of wave energy distribution  
195 at the coast (see the Appendix B for a detailed overview of the validation of  
196 the model). Significant wave height ( $H_s$ ), peak wave period ( $T_{\text{peak}}$ ) and wave  
197 direction ( $\text{Dir}$ ) were calculated using TOMAWAC spectral wave model run on  
198 the same mesh as the hydrodynamic calculation (Figure 9) with a time step of  
199 10 seconds, 20 frequency bins and 20 wave directions. Observations from a wave  
200 buoy located offshore (CEREMA, 1985) and analysis of hindcase database in this  
201 area (Boudière et al., 2013; Accensi & Maisondieu, 2015) showed a strongly bi-

202 model distribution of wave direction grouped around north-easterly and westerly  
203 directions (Figure1b). A set of two wave model runs were created by applying  
204 constant wave height, peak period and directions boundary forcing using the  
205 99th percentile of wave height calculated from HOMERE database (Hs99%) for  
206 each of the two dominant wave directions. The model was run for these two  
207 wave conditions representative of the extreme wave regime of the region. (see  
208 Table 3).

## 209 4. Results

### 210 4.1. Evolution of the Wissant bay seabed

211 The bathymetric differential maps between 1878 and 2016 allowed us to  
212 examine the evolution of the seabed morphology in the Wissant bay (Figure 2).  
213 Significant bathymetry changes have occurred all over the study area since the  
214 end of the 19th century. An extended seafloor lowering of more than 7 m has  
215 taken place on both sides of the Line bank and also in the westernmost part  
216 of the foreshore. Moreover, an erosion pattern is clearly identified offshore of  
217 the Line bank in the northern part of the bay. Conversely, significant sediment  
218 accumulation has only been observed on the NE of the Line bank. Based on the  
219 bathymetry change observed and the error margin of  $\pm 2.7$  m between these two  
220 dates, an estimate of the volume change was computed showing a significant  
221 loss of more than  $28 \times 10^6 \text{ m}^3$  of sediment throughout the bay. Considering  
222 only the Line bank, this loss is estimated at  $14 \times 10^6 \text{ m}^3$ . In order to analyze  
223 the Line bank and nearby morphological evolution, cross-shore and long-shore  
224 profiles were derived from DEMs (Figure 3), which revealed two distinct periods  
225 of evolution:

- 226 • Between 1878 and 1910: on the westernmost and central part of the bay,  
227 the Line bank underwent a lowering of its crest and a simultaneous widen-  
228 ing (Profile A and B on Figure 3), especially towards the coast. This  
229 coastward migration led to a infill of the channel between the coast and  
230 the sand bank, which is well-identified on Profile A. On Profile C, the

231 onshore migration of the Line bank is visible, although the channel re-  
232 mained unchanged in the easternmost part of the Wissant bay. Profile D  
233 confirms the lowering of the crest over almost the total bank area. The  
234 foreshore rose (Profile A) or remained stable (Profiles B and C) between  
235 the end of the 19th and the beginning of the 20th century. The associated  
236 bathymetric differential map (Figure 2 inset map) shows that over almost  
237 the whole bay, morphological changes were relatively minor. It indicates  
238 a stability of the coastal zone to the east and sediment accumulation to  
239 the west during this period.

240 • Between 1910 and 2016: the channel between the coast and the Line bank  
241 was subject to significant erosion, with more than 5 m lowering on Profile  
242 A. Conjointly, the Line bank experienced a decrease of its width of about  
243 500-600 m (Profile B) and up to 700 m locally (Profile A). The most  
244 remarkable changes are visible on Profile B, in 1974 the Line bank did  
245 not exceed a width of 200 m. In 1974, the height of the bank was at its  
246 lowest level (Profile A and D) while the eastern part of the bay was more  
247 stable. Over the 1974-2016 period, even though the Line bank experienced  
248 a slight increase of its width (Profile B), in most part of the Wissant bay,  
249 the channel continued to deepen and reached the -5 m isobath on Profile  
250 A and -12 m on Profile C. This had an impact on the foreshore which  
251 lowered significantly during the 20th century in the western and central  
252 part of the bay (Profile A and B) while Profile C indicates a more stable  
253 morphology.

254 Therefore, until the beginning of the 20th century, Wissant bay had experi-  
255 enced an infilling of coastal channel, mostly due to the widening and the onshore  
256 migration of the Line bank in the western and central part of the bay. It was  
257 during the 20th century that a widespread erosion of the bay can be observed.  
258 It not only impacts on the Line bank's morphology, but also the channel and the  
259 foreshore - leading to a net landward retreat of the shoreline observed during  
260 the second half of the 20th century (Aernouts & Héquette, 2006; CEREMA,

261 2018).

262 Because wave energy distribution at the coast strongly depends on wave  
263 refraction and dissipation over the shoreface, any change in the nearshore mor-  
264 phology is expected to modify wave propagation patterns and therefore induce  
265 changes in wave height. In this macrotidal environment, tide must be taken into  
266 account in the model in order to also study the effects of water level variation on  
267 wave energy. Results of these simulations are presented in the following sections  
268 (Section 4.2 and 4.3).

#### 269 *4.2. Tidal residual currents changes*

270 Figure 4 shows the computed tidally induced residual currents for Wissant  
271 bay over a 30-day simulation for three bathymetry configurations (1878, 1910,  
272 1974). In Figure 5 the model integrates the wave propagation module suggesting  
273 a complex residual current flow field that is partly controlled by wave direction.

##### 274 *4.2.1. 1878*

275 Considering the no-waves configuration, tidal residual currents are essentially  
276 directed to the NE which correspond to the flood-dominated direction and can  
277 reach  $0.3 \text{ m.s}^{-1}$  on the seaward side of the Line bank (Figure 4a).

278 With waves from the N-NE direction, the intensity of residual currents is  
279 generally of the same amplitude as that of the no-waves configuration, although  
280 the distribution of these velocities changes: with weaker currents on the offshore  
281 side and more intense to the interior of the bay (Figure 5a). Locally, and mostly  
282 on the east of the bay, current direction is also reversed, with residual currents  
283 towards the SW, which correspond to a predominance of the ebb.

284 WSW waves tend to induce much stronger residual currents (Figure 5d) with  
285 speeds ranging from 0 to  $0.9 \text{ m.s}^{-1}$ ; the maximum residual currents being located  
286 on the seaward flank of the Line bank (residual current peak at  $0.9 \text{ m.s}^{-1}$ ). In  
287 this configuration, currents are mainly directed towards the NE, which would  
288 be expected given the initial wave direction that would drive and intensify the  
289 currents in Wissant bay.

290 *4.2.2. 1910*

291 By not taking into account any waves, an area of high current velocities  
292 (about  $0.5 \text{ m.s}^{-1}$ ) is noticeable on the western border of the model, probably due  
293 to boundary effect in the model (Figure 4b). Across Wissant bay, tidal residual  
294 currents are directed towards the NE, except in the westernmost part where  
295 onshore currents are apparent. Throughout the foreshore, residual currents are  
296 weaker than those computed in the 1878 mesh. In the NE part of the Line bank,  
297 there is also a decrease in the velocity of residual currents.

298 When waves are from the NE sector, as in the 1878 model, there is a residual  
299 current direction reversal in the eastern part of the foreshore leading to a local  
300 predominance of the ebb (Figure 5b). On the SW part of Wissant bay, currents  
301 are weaker, not only at the foreshore, but also at or near the crest of the Line  
302 bank ( $0.12 \text{ m.s}^{-1}$ ).

303 For westerly waves, over the whole bay, currents are stronger than the two  
304 previous set-ups. However, residual currents are lower over the 1910 bathymetry  
305 compared to currents velocities observed with westerly waves over the 1878  
306 bathymetry. This is clearly observable, even on the seaward side of the sand  
307 bank where currents are usually more intense, they do not exceed  $0.75 \text{ m.s}^{-1}$   
308 against  $0.9 \text{ m.s}^{-1}$  in 1878 (Figure 5e).

309 *4.2.3. 1974*

310 With the no-waves set-up, residual currents mostly flow toward the NE  
311 (flood-direction) (Figure 4c). Weakest currents are located on the central part  
312 of the Line bank ( $\approx 0.05 \text{ m.s}^{-1}$ ), while strongest ones, are located in the SW  
313 part of the bay, particularly on the seaward side of the bank ( $\approx 0.3 \text{ m.s}^{-1}$ ).

314 For northeasterly waves, residual currents speeds are lower at the sand bank  
315 margins ( $< 0.1 \text{ m.s}^{-1}$ ) but they increase on the Line bank crest. At the shoreline,  
316 the linear area where currents are directed towards the SW is extended north-  
317 eastward and now reaches the town of Wissant. Facing the hamlet of Wissant,  
318 these SW residual currents are opposed to those in the channel and may create  
319 shearing zones (Figure 5c).

320 With westerly waves, residual current are still stronger than those obtained  
321 with the no-waves and NE-waves configurations (Figure 5f). However, compared  
322 to the 1910-W set-up, areas where currents exceed  $0.4 \text{ m}\cdot\text{s}^{-1}$  are more extensive,  
323 especially in the western part of the bay (on the top of the Line bank and also  
324 in the channel). Likewise, there is an increase in velocities on the Line bank  
325 seaward flank and at the shoreline in the central part of the bay.

#### 326 *4.3. Impact on waves propagation*

327 Wave height transects from the 1878, 1910 and 1974 models are presented  
328 in Figures 6 for northeasterly waves and in Figure 7 for westerly waves (the  
329 location of the wave height transects is the same as the bathymetric ones). In  
330 each transect, for same wave conditions, the wave heights obtained during high  
331 water springs and without considering tides are plotted in order to compare the  
332 effect of tides on wave height distribution and in turn energy dissipation in the  
333 nearshore.

334 Figures 6 and 7 clearly show the effect of tides on wave height with higher  
335 wave heights occurring during high water springs. These results are consistent  
336 with previous studies that investigated the contribution of tidal modulation on  
337 incident wave power (Peregrine, 1976; Lugo-Fernández et al., 1998; Masselink,  
338 1998; Davidson et al., 2008; Hedges, 2015). There is a strong wave energy  
339 dissipation over the sand bank for both westerly and northeasterly waves, which  
340 results in a similar  $H_s$  distribution from one configuration to another as shown  
341 on Profile A, B and C (Figures 6 and 7).

342 On the top of the Line bank, wave height changed significantly between 1878  
343 and 1974 (Profile D Figures 6 and 7). Without tides, in the 1878 model, there  
344 is already a strong gradient, with an  $H_s$  of 1.5 m in the NE part of the bay  
345 decreasing until 0 m to the SW. However, from 1878 onwards, waves exceed 0.5  
346 m on the Profile D over a length of 4 km in 1878, increasing to 6 km in 1910,  
347 and finally 7.5 km in 1975, which corresponds approximately to the length of  
348 the Line bank (Profile D Figures 6 and 7). At the end of the 19th century,  
349 the Line bank was locally above the hydrographic datum (Profile A Figure 3)

350 so it was often emerged inducing wave dissipation and breaking. This explain  
351 why, without tides, in the 1878 and even in the 1910 model,  $H_s$  is equal to 0  
352 m from the top of the bank to the coast (Profile A Figures 6 and 7). However,  
353 during high water springs, the water depth is high enough to cover the Line  
354 bank and waves can break farther landward (Profile A Figures 6 and 7). When  
355 high water springs are considered, on the NE part of the Profile D,  $H_s$  slightly  
356 increases in time but remained mostly stable for both western and northeastern  
357 waves. However, significant changes occurred in the western and central part of  
358 the Line bank where, for both waves direction, an increase  $H_s$  of around 0.5 m  
359 is observed between the 1878 and the 1974 models (Profiles A and B Figures 6  
360 and 7).

361 From 1878 to 1974, waves do not only become higher on the top of the sand  
362 bank, but also in most part of the coastal channel. This increase is well-identified  
363 in Profiles D and E (Figures 6 and 7) where  $H_s$  become larger particularly in  
364 the central part of the profiles. At the end, in 1974, without tides, more than 4  
365 km of channel recorded a wave height greater than 0.5 m (against 2 km in 1878  
366 and 3 km in 1910). During high water springs, for all models,  $H_s$  exceeds 0.5  
367 m over the whole channel. In the same way, the portion of the profile greater  
368 than 1 m represents 66% for 1878, 60% for 1910 and 83% for 1974 revealing a  
369 small decrease of wave energy in the channel in 1910 and a strong rise in 1974  
370 (Profile E Figures 6 and 7).

371 From 1878 to 1974, in the western and central part of Wissant bay, there is  
372 an increase in wave height at the coast of 0.2-0.4 m for W waves and of 0.3-0.6 m  
373 for NE waves for both non-tidal and high water springs configurations (Profile  
374 A et B Figures 6 and 7). The highest wave heights are logically observed during  
375 high water springs due to higher water levels over the bank and shoreface, this  
376 being particularly visible on Profile B. With a lower water depth (no tide) the  
377 wave height strongly decrease landward in 1878 and 1910 but when the water  
378 level is higher (high water springs), wave height decreases gradually (Figures  
379 6 and 7). On Profile B, this results in a strong reduction of  $H_s$  between the  
380 channel and the coast (over less than 500 m) highlighting strong wave energy

381 dissipation at the coast.

382 The easternmost part of Wissant bay is characterized by different wave  
383 height changes, becoming more stable and even reducing locally between the  
384 1878, 1910, and 1974 models (Profile C Figures 6 and 7). In Profile C, wave  
385 height changes are less significant. It should be noted, that for the 1974 model,  
386 with or without tides, the wave height is always lower than the ones obtained  
387 with the 1878 and 1910 models. Considering the tide, however, in 1974, waves  
388 are higher offshore up to  $X=2000$  (isobath -5 m) and only lower from the fore-  
389 shore to the shoreline (Profile C Figures 6 and 7)

390 In summary, the results of our numerical modeling wave height over succes-  
391 sive bathymetries since 1878 suggest that morphological changes and Line bank  
392 positions, have induced significant changes in wave height distribution (Table 7)  
393 along Wissant's coast. Accordingly, we can divide Wissant bay into three main  
394 areas (Table 7):

- 395 • The eastern part of the bay, characterized by a stability in wave heights  
396 through time, and even a decreasing trend in some areas.
- 397 • The central part of the bay where our results show a generally increased  
398 wave heights between the Line bank and the coast from 1878 to 1974.
- 399 • The western part of the bay, with a more complex evolution: between  
400 1878 and 1910, wave height increased on the Line bank, but decreased on  
401 the foreshore and the shoreline, while an overall increasing trend of wave  
402 height is observed all along the nearshore for the period 1910-1974.

## 403 5. Discussion

404 Based on historical bathymetric surveys, our study reveals a high variability  
405 in the Wissant bay seabed morphology. Using ancient nautical charts, Briquet's  
406 work (Briquet, 1930) pointed out that the Line bank was once located more  
407 offshore from Wissant Bay and has experienced a gradually on-shore migration  
408 since 1640 (Figure 8). In 1776, the bank was located 800 m seaward of the Gris



409 Nez Cape at low tide, but was at only 200 m from the cape in 1810. In 1835, the  
410 area between the bank and the coast was largely exposed at low tide, although  
411 a deep channel was still present. Briquet's work highlighted that the trough  
412 was gradually filled in the 1870s, and in 1910 the Line bank was almost welded  
413 to the beach, which is confirmed in the western part of the Wissant bay by our  
414 DEMs (Profile A Figure 3). Previous studies and our historical bathymetry sets  
415 enable us to assess the complex morphological evolution of this area:

- 416 • During the end of the 19th and the beginning of the 20th century, the  
417 Line bank experienced a widening and a coastward migration resulting in  
418 a gentler beach and foreshore profile in 1910;
- 419 • Since the 1970s, Wissant bay underwent a thinning of the Line bank, a  
420 deepening of the coastal channel and a lowering of the foreshore associated  
421 with an overall erosion of the seabed. It appears that the lowering of the  
422 seabed in Wissant Bay is a fairly recent phenomenon following a phase of  
423 sediment accumulation and coastward migration of the bank.

424 Nearshore changes are strongly linked to shoreline evolution as shown by sev-  
425 eral other studies carried out in a variety of coastal settings (Corbau et al., 1999;  
426 McNinch, 2004; Aernouts & Héquette, 2006; Backstrom et al., 2007; Houser  
427 et al., 2008) and the recent shoreline retreat observed in the western and cen-  
428 tral part of the bay and the shoreline advance in the eastern part can be partially  
429 explained by this interaction (Aernouts & Héquette, 2006).

430 With a similar approach, Bertin (2005); Horrillo-Caraballo & Reeve (2008)  
431 found that the pattern of residual currents is strongly linked to the configuration  
432 of sand banks. In addition, observations and numerical results on sandy coast  
433 revealed the essential role of wave energy dispersal in the nearshore sediment  
434 distribution (Morton et al., 1995; Sedrati & Anthony, 2007) and its contribution  
435 for controlling the development of erosion or accretion hot spots.(Barnard &  
436 Hanes, 2006; Héquette & Aernouts, 2010)

437 The results of our numerical modeling highlight two types of shoreface/nearshore

438 configurations leading to two different types of hydrodynamic circulation pre-  
439 sented below.

#### 440 *5.1. The eroding-configuration*

441 The 1974 model can be assimilated as the **eroding-configuration**. For  
442 this bathymetric configuration, stronger residual tidal currents, and higher wave  
443 heights are observed in the western and central part of the Line bank, compared  
444 to the two preceding seabed morphologies. This occurs for waves either from the  
445 W or NE (Figures 5, 6 and 7). The last DEMs highlight a significant thinning of  
446 the Line bank and an extensive lowering of the seabed in Wissant Bay between  
447 1910 and 1974 (Figure 2). This contributes to increase the foreshore's exposure  
448 to high energy waves by reducing the effects of wave dissipation and refraction  
449 on the sea bed (Barnard & Hanes, 2006). This may have also modified wave-  
450 induced sand dynamics (due to wave-current interaction) and thus sand bank  
451 equilibrium. Sediment transported from the nearshore to the upper shoreface is  
452 more likely to be remobilized and distributed northeastward by currents than  
453 to accumulate on the beach. This combined phenomenon may have induced  
454 an increase in longshore sediment transport that could explain the pervasive  
455 shoreline retreat observed in the second half of the 20th century (Aernouts &  
456 Héquette, 2006; Sedrati & Anthony, 2014). Moreover, the wave-current shear-  
457 ing zones in front of Wissant town obtained with the NE-waves configuration  
458 (Figure 5c) could accentuate the erosion of the channel and the beach in this  
459 area (Jing & Ridd, 1996). In the eastern part of Wissant bay, the foreshore  
460 experienced a decrease of  $H_s$  and also a reduction of the strength of residual  
461 currents directed to the SW. This reduction in current speeds may result in less  
462 sediment transport to the western and central parts of the Wissant bay that  
463 could enhance the sediment deficit in these parts of the bay. On the other hand,  
464 it may also result in more sediment deposition in the eastern part of the bay  
465 and therefore generate the shoreline advance observed in this part of the bay  
466 during the second half of the 20th century.

467 *5.2. The accumulation-configuration*

468 The **accumulation-configuration** (corresponding to the 1910 bathymetric  
469 configuration), reveals significant changes in the central and western parts of the  
470 bay. First, during NE-waves events, residual currents are weaker than in 1878  
471 between the Line bank and the coast where current speeds do not exceed  $0.15$   
472  $\text{m}\cdot\text{s}^{-1}$  (Figure 5b). For western waves, residual currents remain strong on the  
473 seaward side of the Line bank, but have decreased in the channel and on the  
474 foreshore compared to 1878 (Figure 5e). Secondly, the increasing wave height  
475 between 1878 and 1910 on the top of the Line bank (Profile D Figures 6 and  
476 7) and the following decrease of  $H_s$  in the channel (Profile E Figures 6 and  
477 7) indicate wave energy dissipation. As shown in several studies, gently slop-  
478 ing dissipative profiles favor onshore-directed transport (Hesp, 1988; Davidson-  
479 Arnott & N. Law, 1996; Aagaard et al., 2004; Cooper & Navas, 2004; Héquette  
480 & Aernouts, 2010). Modelling of wave propagation revealed that the widen-  
481 ing and the onshore movement of the Line bank between 1878 and 1910 was  
482 responsible for a decrease in wave energy associated with more dissipative con-  
483 ditions in the nearshore zone, which may have resulted in a net, wave-induced  
484 shoreward sediment transport. In this configuration, as residual currents speeds  
485 are particularly lower in the western and central part of the bay, this may have  
486 favored sediment accumulation and channel infill.

487 Beach and nearshore morphologies are the result of the interaction between  
488 physical processes controlling the cross-shore and longshore transport that even-  
489 tually cause morphological changes. The present study highlights positive feed-  
490 backs between hydrodynamic and coastal morphology. Indeed, both bathymet-  
491 ric configurations (eroding and accumulation) affect the hydrodynamic circula-  
492 tion in such a way that the morphodynamic response may be reinforced. How-  
493 ever, our analysis do not identify processes that can induce a switch between  
494 both regimes. According to their dynamic and morphological characteristics,  
495 sandy beaches can be classified into several morphodynamic types (Wright &  
496 Short, 1984; Short, 1999). Scott et al. (2011) expanded this classification to  
497 take into account the influence of tidal range. In their classification, Wissant

498 bay belongs to the MITB beach type (Multiple inter-tidal barred). Investigation  
499 made on MITB beaches suggest that these beaches have a rapid morphologi-  
500 cal response under increasing energy conditions, while under decreasing energy  
501 the adjustment is slower. Owever, because our study is essentially focussed on  
502 extreme events, it does not examine relaxation time effects. Nevertheless, a  
503 decrease or increase in storms frequency, variations in large-scale hydrodynamic  
504 circulation and/or changes in sediment supply through time may have affected  
505 the nearshore-shoreface equilibrium and then induced a morphodynamic rever-  
506 sal.

### 507 *5.3. Combined effects of waves and tides*

508 It appears from these different simulation runs that, residual currents ob-  
509 tained do not exceed  $0.40 \text{ m.s}^{-1}$  and are mostly directed in the flood-direction  
510 (*i.e.* to the NE) when tides only are considered. The interaction with the waves,  
511 on the contrary, accelerate these currents (up to  $0.9 \text{ m.s}^{-1}$  locally for western  
512 waves) and sometimes even reverse their direction (with NE waves). These re-  
513 sults are consistent with King et al. (2019) study which investigate the relative  
514 influence of tidal and wave forcing on potential sand transport in analogous  
515 macrotidal environment (South West UK). Similarly, they found that extreme  
516 waves are able to induce directional shifts and even full reversals which strongly  
517 influence sand transport direction. Likewise, although the direction of the wave  
518 has only a limited influence on the wave height at the coast, taking into ac-  
519 count the tides affects the water elevation and therefore, in the case of high  
520 water springs, nearshore wave height may double or even triple. This shows the  
521 potential importance and influence of these processes on shoreline dynamic. In-  
522 dividually, they already provide some preliminary explanations for the observed  
523 shoreline changes, but when coupled together, a very energetic hydrodynamism  
524 emerges in this sector, which has evolved considerably over the past century.

### 525 *5.4. Limitations of the results and perspectives for future research*

526 In this study, one of the main assumptions made was that past and present  
527 hydrodynamics remained the same. Accordingly, the only variable would be the

528 seabed morphology as the main task of this study was to highlight the influence  
529 of nearshore morphology changes on wave and tide interactions. In fact, wave  
530 climate has potentially changed since the beginning of the 20th century. Using a  
531 100-year numerical wind-wave hindcast, Dodet et al. (2010); Bertin et al. (2013)  
532 found an increase of wave height of  $0.01 \text{ m}\cdot\text{year}^{-1}$  in the North-East Atlantic  
533 Ocean since 1900 due to a rise in wind speed of more than 20%. At a global  
534 scale, with a 23-year database of altimeter measurements (1985-2009), Young  
535 et al. (2011) investigated global changes in wave height. They suggested an  
536 increase of more than  $1\%\cdot\text{year}^{-1}$  in the 99th-percentile wave height trends over  
537 this period at high latitudes. The rate of increase is greater for extreme events  
538 as compared to the mean condition. Moreover, MacDonald & O'Connor (1996)  
539 predicted an average wave energy increasing by the order of 10% by 2130 under  
540 a sea level rise scenario. On European shelf, Idier et al. (2017) investigated  
541 the effect of sea level rise on tidal dynamics and observed a notable increase in  
542 high tide levels in the Southern part of the North Sea. All these studies suggest  
543 significant changes in hydrodynamic circulation. Sea level rise was not taken  
544 into account in our numerical models, but added to the increase in wave height  
545 during the 20th century, one can imagine that the hydrodynamic context at  
546 the end of the 19th century was weaker and therefore that our 1878 and 1910  
547 models partially overestimate currents and waves. Potentially, it is possible that  
548 the differences in energy levels between the end of the 19th century and 1974  
549 may be even greater than expected. Finally, in the present context of climate  
550 change, even if coastal morphology remained hypothetically unchanged in the  
551 following decades, it can be expected that there will be significant changes in  
552 coastal hydrodynamics in this area with the increase in wave height with sea  
553 level rise.

554 Hydrodynamic circulation changes have an important role in the coastal  
555 systems equilibrium. However, it is also important to assess the sediment in  
556 transit through this system, which should be included in any further work. It  
557 is frequently suggested that the recent trend reversal is not only due to natural  
558 causes but also to local factors related to anthropogenic development or con-

559 struction (Mattheus et al., 2018; Li et al., 2019), such as the expansion of the  
560 port of Boulogne-sur-mer in the 1930s and the massive aggregate extraction in  
561 the 1960s-1970s. The construction of the Boulogne-sur-mer dikes may have re-  
562 duced or even blocked the sedimentary transit from the English Channel coasts  
563 to the North Sea, thus reducing the supply to the Bay of Wissant. In addition,  
564 the extraction of marine aggregate in the western of the bay and on the Line  
565 Bank, the sediment budget being in deficit, may have triggered a process of ero-  
566 sion that became self-maintained even following the interruption of extraction  
567 (Sedrati & Anthony, 2014).

568 Other studies carried out in the northern France's coastal zone have revealed  
569 that sand banks are actively migrating alongshore and onshore as a result of  
570 shore-parallel tidal currents and onshore storm waves (Garlan, 1990; Corbau,  
571 1995; Tessier et al., 1999; Héquette et al., 2009; Héquette & Aernouts, 2010;  
572 Héquette et al., 2013) . Other studies carried out in the inner part of some con-  
573 tinental shelves have highlighted significant variations in nearshore morpholo-  
574 gies due to sand banks dynamics (Parker et al., 1982; De Moor, 2002; Hanna  
575 & Cooper, 2002; Schmitt & Mitchell, 2014). This numerical approach, being  
576 based upon general principle of hydrodynamics is anticipated to have wider ap-  
577 plicability to others nearshore sandbank systems, as those previously mentioned.  
578 This will contribute to a better understanding of the long-term dynamics of this  
579 coastal zones, characterized by the presence of mobile sand banks, and provide  
580 a better insight into the mechanisms involved in their evolution.

## 581 **6. Conclusion**

582 Changes in the Wissant bay nearshore have been investigated directly from  
583 a comparison of historical hydrographic surveys determined from seabed sound-  
584 ings as well as with the results from an hydrodynamic model. This model,  
585 coupling both tides and waves, for the northern France area (between the Dover  
586 Strait and the Belgium border) has been calibrated and validated. In the second  
587 half of the 20th century, the nearshore experienced a thinning of the Line bank,

588 a deepening of the coastal channel and a lowering of the foreshore leading to an  
589 overall erosion of the seabed. This phase followed a period of channel infill in  
590 the western part of the bay in the early 1910s.

591 These recent morphological changes led to significant hydrodynamic shift  
592 with residual tidal currents acceleration in most parts of the nearshore zone and  
593 an increase of wave height in the western and central parts of Wissant bay where  
594 one of the most rapid shoreline retreats has been recorded in France since the  
595 1950s. However, at the beginning of the 20th century, seabed morphology led to  
596 more dissipative conditions: it resulted in an overall decrease in wave height and  
597 to lower residual currents speeds that could favor sediment deposition on the  
598 foreshore and eventually on the beach. As the seabed morphology changes, this  
599 affects tidal currents and wave dissipation; so there is a complex interaction  
600 and feedback between hydrodynamic circulation and the seabed. Using his-  
601 torical bathymetry coupling with numerical models has provided a qualitative  
602 explanation of observed bathymetry changes and shoreline evolution during the  
603 last decades. This approach involves wave-current interactions and brings new  
604 insight into the long-term coastal dynamics of this area and on the processes  
605 controlling erosion and accumulation along shorelines affected by the movement  
606 of nearshore sand banks.

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622 alexa.latapy@gmail.com



623 **Appendix A. TELEMAC-2D validation**

624 TELEMAC-2D (v6p3) solve the non-conservative form of the shallow water  
 625 equations (Equations A.1, A.2 and A.3):

$$\frac{\partial h}{\partial t} + \mathbf{U} \cdot \nabla(h) + h \cdot \text{div}(\mathbf{U}) = S_h \quad (\text{A.1})$$

$$\frac{\partial U}{\partial t} + \mathbf{U} \cdot \nabla(U) = -g \frac{\partial h}{\partial x} + S_x + \frac{1}{h} \text{div}(h\nu_t \nabla U) \quad (\text{A.2})$$

$$\frac{\partial V}{\partial t} + \mathbf{U} \cdot \nabla(V) = -g \frac{\partial h}{\partial y} + S_y + \frac{1}{h} \text{div}(h\nu_t \nabla V) \quad (\text{A.3})$$

626 where  $h$  is the water depth,  $t$  is the time,  $\mathbf{U}$  is the depth-averaged velocity  
 627 vector with components  $U$  and  $V$  in the  $x$  and  $y$  Cartesian coordinate respec-  
 628 tively.  $\nu_t$  is the diffusion coefficient (considered as constant),  $g$  is the gravity  
 629 acceleration,  $S_h$  is a source or sink term in the continuity equation. The source  
 630 or sink term  $S_x$  and  $S_y$  in the dynamic equations represent the wind and the  
 631 atmospheric pressure, the Coriolis force, the bottom friction and additional  
 632 sources or sink of momentum within the domain in the two directions  $x$  and  
 633  $y$ . Model domains are shown in Figure 9 and integrate historical bathymetry  
 634 (1878-79, 1910-11, 1930-32 and 1974-76). To validate the tidal model, a range  
 635 of cases were studied. A set of tests was performed in which the bottom friction  
 636 coefficient was changed by varying the Chezy's law coefficient between 50 and  
 637 70  $\text{m}^{1/2} \cdot \text{s}$ . The influence of the bottom friction coefficient on the models ability  
 638 to reproduce observed data was examined first. A set of tidal height observa-  
 639 tions are available for Dunkirk and Calais harbors at each date and are used to  
 640 compare with outputs of our 4 models (Figure10b). Tidal height predictions are  
 641 also compared with results from numerical models to only evaluate astronomical  
 642 tides. Bests results are obtained using a coefficient of 64  $\text{m}^{1/2} \cdot \text{s}$ . Soulsby (1983,  
 643 1997)'s works on dynamics of marine sands linked the Chezy coefficient to the  
 644 nature of the seabed. For sandy-gravelly seabed(Anthony & Héquette, 2007),  
 645 Chezy coefficient ranges between 57 and 65 which is consistent with our results.

646 The Table 5 shows tidal height comparison at Calais and Dunkirk (tidal ob-  
 647 servation are only available in 1878 and 1930); it appears that for each models,  
 648 simulated results and tide predictions give a good correlation ( $R^2 > 0.85$ ). By  
 649 analysing observations and models,  $R^2$  obtained are also statistically signifi-  
 650 cant even if these values are lower than those computed with predictions. This  
 651 deviation is probably due to meteorological phenomena (atmospheric pressure,  
 652 wind effect) recorded in water levels but not taken into account in the model  
 653 parametrization. Only a few tidal current records are available in model areas  
 654 before the 1970s, however, in 1935, current observations were made at Calais  
 655 and are then used to improve the calibration our models. It appears that with  
 656 a coefficient of  $64 \text{ m}^{1/2} \cdot \text{s}$ , model currents amplitude and phase are consistent  
 657 with observations made in 1935 (Figure 10a). A statistically significant corre-  
 658 lation is obtained with a  $R^2=0.95$ . Simulations were carried out over a winter  
 659 period (March 2015), *i.e.* when the water-column is well mixed, no thermocline  
 660 is present and therefore no vertical stratification is required.

## 661 Appendix B. TOMAWAC validation

662 TOMAWAC models the changes, both in time and in the spatial domain, of  
 663 the power spectrum of wind-driven waves and wave agitation. The directional  
 664 spectrum of wave action density is considered as a function of five variables  
 665 (Marcos, 2003):

$$N(\vec{x}, \vec{k}, t) = N(x, y, k_x, k_y, t) \quad (\text{B.1})$$

666 Where  $\vec{x} = (x, y)$  is the spatial location in a Cartesian coordinate sys-  
 667 tem,  $\vec{k} = (k_x, k_y) = (k \cdot \sin\Theta, k \cdot \cos\Theta)$  is the wave number vector for directional  
 668 spectrum discretization,  $\Theta$  is the wave propagation direction and  $t$  the time. Hy-  
 669 potheses made on the wave representation, on the model application domain and  
 670 on modelled physical processes enable to write the evolution of the directional  
 671 spectrum of wave action as followed:

$$N(k_x, k_y, x, y, t) = \frac{CCg}{2\pi\sigma} \tilde{N}(x, y, f_r, \Theta, t) \quad (\text{B.2})$$

672  $Cg$  and  $C$  are respectively the group velocity and the phase velocity of waves  
673 and  $\sigma$  is the angular frequency. The equation expresses that, in the general case  
674 of waves propagating in a non-homogeneous, unsteady environment (currents  
675 and/or sea levels varying in time and space), the wave action is preserved to  
676 within the source and sink terms (designated by the term  $Q$ )(Marcos, 2003).  
677 Our study area is mainly located in the coastal zone, so we configured our  
678 model for the coastal domain. For shallow areas, some physical processes must  
679 be included and specified in our parameter file such as:

- 680 • Bottom friction-induced dissipation ( $Q_{bf}$ ), with  $Q_{bf}=0.038 \text{ m}^2 \cdot \text{s}^{-3}$  which  
681 improves the estimation of wave growth in shallow water (Zijlema et al.,  
682 2012).
- 683 • Non-linear triad interactions between waves, considering the LTA (Lumped  
684 Triad Approximation) which improves the computation time.
- 685 • Bathymetric breaking-induced dissipation ( $Q_{br}$ ) where we have chosen the  
686 Battjes and Janssen's model (1978) after performing a sensitivity test be-  
687 tween the 4 proposed models in TOMAWAC (Battjes and Janssen, Thorn-  
688 ton and Guya, Roelvink, and Izumiya and Horikawa).

689 The TOMAWAC wave model was first run independently. In the absence of  
690 wave observations before the 1970s, the model was validated from another wave  
691 model (WaveWatchIII). WaveWatchIII has been implemented on the MANGAS  
692 grid (created by Michaud et al. (2015)), which is an unstructured grid with a  
693 resolution ranging from 10 km at the open boundaries of the domain to about  
694 200 m resolution at the coast. The mesh is based on the HOMONIM digital  
695 elevation model (DEM) developed by SHOM as part of the HOMONIM project  
696 (Biscara et al., 2014). In order to compare the same bathymetry, we created  
697 a new grid based on the HOMONIM DEM and we simulated the two offshore  
698 waves configuration (Table 3). Then, results obtained with TOMAWAC are  
699 compared to those of Wavewatch with similar wave conditions (Table 6).

700 For westerly and northeasterly waves, Hs obtained with WaveWatchIII and  
701 TOMAWAC were extracted at each node (Figure 11a-b). The distribution of Hs  
702 was compared using Q-Q plot. Regression coefficient obtained are very close to 1  
703 and error terms are close to 0, which confirms the model's ability to reproduce Hs  
704 of WW3 (Figure 11c-d). Largest differences are observed for Hs between 0 and 1  
705 m. These differences are mainly due to the fact that WW3 considers additional  
706 forcing, such as wind, tide and currents in contrast to TOMAWAC. Overall, we  
707 obtain for both simulations an RMSE of less than 0.15 m corresponding to an  
708 error of less than 6% and an  $R^2$  of 0.96-0.97 which is statistically significant  
709 (Figure 11c-d).

710 **References**

- 711 Aagaard, T., Davidson-Arnott, R., Greenwood, B., & Nielsen, J. (2004).  
712 Sediment supply from shoreface to dunes: linking sediment transport  
713 measurements and long-term morphological evolution. *Geomorphology*,  
714 *60*, 205–224. URL: [http://www.sciencedirect.com/science/article/  
715 pii/S0169555X03003325](http://www.sciencedirect.com/science/article/pii/S0169555X03003325). doi:10.1016/j.geomorph.2003.08.002.
- 716 Accensi, M., & Maisondieu, C. (2015). HOMERE. Ifremer - Laboratoire  
717 Comportement des Structures en Mer. URL: [https://doi.org/10.12770/  
718 cf47e08d-1455-4254-955e-d66225c9dc](https://doi.org/10.12770/cf47e08d-1455-4254-955e-d66225c9dc).
- 719 Aernouts, D. (2005). *Le rôle des changements bathymétriques à l'avant-côte*  
720 *sur l'évolution des littoraux meubles du Cap Gris-Nez à Dunkerque, Côte*  
721 *d'Opale, Nord de la France*. Ph.D. thesis Université Littoral Côte d'Opale.  
722 URL: <http://www.theses.fr/2005DUNK0138>.
- 723 Aernouts, D., & Héquette, A. (2006). L'évolution du rivage et des petits-  
724 fonds en baie de Wissant pendant le XXe siècle (Pas-de-Calais, France).  
725 *Géomorphologie: relief, processus, environnement*, *12*, 49–64. URL: [https:  
726 //geomorphologie.revues.org/477](https://geomorphologie.revues.org/477). doi:10.4000/geomorphologie.477.
- 727 Anthony, E., & Orford, J. (2002). Between Wave- and Tide-Dominated Coasts:  
728 the Middle Ground Revisited. *Journal of Coastal Research Special Issue*, *36*,  
729 8–15. doi:10.2112/1551-5036-36.sp1.8.
- 730 Anthony, E. J. (2000). Marine sand supply and Holocene coastal sedimen-  
731 tation in northern France between the Somme estuary and Belgium. *Ge-*  
732 *ological Society, London, Special Publications*, *175*, 87–97. URL: [http://  
733 sp.lyellcollection.org/content/175/1/87](http://sp.lyellcollection.org/content/175/1/87). doi:10.1144/GSL.SP.2000.  
734 175.01.08.
- 735 Anthony, E. J., & Héquette, A. (2007). The grain-size characterisation of  
736 coastal sand from the Somme estuary to Belgium: Sediment sorting processes  
737 and mixing in a tide-and storm-dominated setting. *Sedimentary Geology*,

- 738 202, 369–382. URL: [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S0037073807001364)  
739 [pii/S0037073807001364](http://www.sciencedirect.com/science/article/pii/S0037073807001364). doi:10.1016/j.sedgeo.2007.03.022.
- 740 Anthony, E. J., Vanhee, S., & Ruz, M.-H. (2006). Short-term beach–dune  
741 sand budgets on the north sea coast of France: Sand supply from  
742 shoreface to dunes, and the role of wind and fetch. *Geomorphology*,  
743 81, 316–329. URL: [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/S0169555X06001577)  
744 [pii/S0169555X06001577](http://www.sciencedirect.com/science/article/pii/S0169555X06001577). doi:10.1016/j.sedgeo.2007.03.022.
- 745 Augris, C., Clabaut, P., & Vicaire, O. (1990). Le domaine marin du Nord-Pas  
746 de Calais. Nature, morphologie et mobilité des fonds.
- 747 Backstrom, J. T., Jackson, D. W. T., & Cooper, J. A. G. (2007). Shoreface Dy-  
748 namics of Two High-Energy Beaches in Northern Ireland. *Journal of Coastal*  
749 *Research, ICS2007*, 5. URL: <https://www.jstor.org/stable/26481656>.
- 750 Barnard, P. L., & Hanes, D. M. (2006). Integrating field research, modeling and  
751 remote sensing to quantify morphodynamics in a high-energy coastal setting,  
752 ocean beach, San Francisco, California. URL: [https://pubs.er.usgs.gov/](https://pubs.er.usgs.gov/publication/70028957)  
753 [publication/70028957](https://pubs.er.usgs.gov/publication/70028957). doi:10.1061/40855(214)96.
- 754 Beck, C., Clabaut, P., Dewez, S., Vicaire, O., Chamley, H., Augris, C., Hoslin,  
755 R., & Caillot, A. (1991). Sand bodies and sand transport paths at the En-  
756 glish Channel-North Sea border: Morphology, hydrodynamics and radioac-  
757 tive tracing. *Oceanologica Acta, Special issue*, . URL: [http://archimer.](http://archimer.ifremer.fr/doc/00268/37887/)  
758 [ifremer.fr/doc/00268/37887/](http://archimer.ifremer.fr/doc/00268/37887/).
- 759 Belderson, R. H. (1986). Offshore Tidal and Non-Tidal Sand Ridges and  
760 Sheets: Differences in Morphology and Hydrodynamic Setting, . (pp. 293–  
761 301). URL: [http://archives.datapages.com/data/cspg\\_sp/data/011/](http://archives.datapages.com/data/cspg_sp/data/011/011001/293_cspgsp0110293.htm)  
762 [011001/293\\_cspgsp0110293.htm](http://archives.datapages.com/data/cspg_sp/data/011/011001/293_cspgsp0110293.htm).
- 763 Berné, S., Trentesaux, A., Stolk, A., Missiaen, T., & de Batist,  
764 M. (1994). Architecture and long term evolution of a tidal sand-  
765 bank: The Middelkerke Bank (southern North Sea). *Marine Geol-*

- 766 *ogy*, 121, 57–72. URL: [http://www.sciencedirect.com/science/article/  
767 pii/0025322794901562](http://www.sciencedirect.com/science/article/pii/S0025322794901562). doi:10.1016/0025-3227(94)90156-2.
- 768 Bertin, X. (2005). *Morphodynamique séculaire, modélisation et architecture*  
769 *interne d'un système baie-embouchure tidale: le Pertuis de Maumusson et la*  
770 *Baie de Marennes-Oléron*. Ph.D. thesis La Rochelle. URL: [http://www.  
771 theses.fr/2005LAROS140](http://www.theses.fr/2005LAROS140).
- 772 Bertin, X., & Chaumillon, r. (2005). Contribution of simulations on his-  
773 torical bathymetries to the understanding of evolutions of estuarine  
774 sand banks. *Comptes Rendus Geoscience*, 337, 1375–1383. URL: [http:  
775 //www.sciencedirect.com/science/article/pii/S1631071305001768](http://www.sciencedirect.com/science/article/pii/S1631071305001768).  
776 doi:10.1016/j.crte.2005.06.007.
- 777 Bertin, X., Prouteau, E., & Letetrel, C. (2013). A significant in-  
778 crease in wave height in the North Atlantic Ocean over the 20th  
779 century. *Global and Planetary Change*, 106, 77–83. URL: [http:  
780 //www.sciencedirect.com/science/article/pii/S092181811300088X](http://www.sciencedirect.com/science/article/pii/S092181811300088X).  
781 doi:10.1016/j.gloplacha.2013.03.009.
- 782 Biscara, L., Schmitt, T., Correard, S., & Creach, R. (2014). Modèles numériques  
783 de bathymétrie pour la prévision hydrodynamique du dispositif vigilance  
784 vagues-submersions. In *XIIIèmes JNGCGC Dunkerque* (pp. 547–556). Edi-  
785 tions Paralia. URL: [http://www.paralia.fr/jngcgc/13\\_60\\_biscara.pdf](http://www.paralia.fr/jngcgc/13_60_biscara.pdf).  
786 doi:10.5150/jngcgc.2014.060.
- 787 Boudière, E., Maisondieu, C., Ardhuin, F., Accensi, M., Pineau-Guillou, L., &  
788 Lepesqueur, J. (2013). A suitable metocean hindcast database for the design  
789 of Marine energy converters. *International Journal of Marine Energy*, 3-  
790 4, e40–e52. URL: [http://www.sciencedirect.com/science/article/pii/  
791 S2214166913000362](http://www.sciencedirect.com/science/article/pii/S2214166913000362). doi:10.1016/j.ijome.2013.11.010.
- 792 Briquet, A. (1930). *Le littoral du nord de la France et son évolution mor-*  
793 *phologique*. Thèse de doctorat Université de Paris (1896-1968). Faculté des  
794 lettres France.

- 795 Brown, J. M., Amoudry, L. O., Souza, A. J., & Plater, A. J. (2015). Resid-  
796 ual circulation modelled at national UK scale to identify sediment pathways  
797 to inform coastal evolution models. In *The Proceedings of the Coastal Sedi-*  
798 *ments 2015. The Proceedings of the Coastal Sediments 2015.* (p. 14). Wang,  
799 P.; Rosati, J.D.; Cheng, J.,. URL: <https://core.ac.uk/display/33454048>.
- 800 Carter, R. W. G., Lowry, P., & Stone, G. W. (1982). Sub-tidal ebb-  
801 shoal control of shoreline erosion via wave refraction, Magilligan fore-  
802 land, Northern Ireland. *Marine Geology*, 48, M17–M25. URL: <http://www.sciencedirect.com/science/article/pii/0025322782901268>.  
803 doi:10.1016/0025-3227(82)90126-8.
- 804
- 805 Castelle, B., Marieu, V., Bujan, S., Splinter, K. D., Robinet, A., Sénéchal,  
806 N., & Ferreira, S. (2015). Impact of the winter 2013-2014 series of severe  
807 Western Europe storms on a double-barred sandy coast: Beach and dune  
808 erosion and megacusp embayments. *Geomorphology*, 238, 135–148. URL:  
809 <http://adsabs.harvard.edu/abs/2015Geomo.238..135C>. doi:10.1016/j.  
810 [geomorph.2015.03.006](http://adsabs.harvard.edu/abs/2015Geomo.238..135C).
- 811 Caston, V. N. D. (1972). Linear sand banks in the Southern North Sea. *Sedi-*  
812 *mentology*, 18, 63–78. doi:10.1111/j.1365-3091.1972.tb00003.x.
- 813 CEREMA (1985). Centre d’Archivage National de Données de Houles In  
814 Situ Littoral de la France métropolitaine - CANDHIS 1985. URL: <http://candhis.cetmef.developpement-durable.gouv.fr/>.
- 815
- 816 CEREMA (2018). *Dynamiques et évolution du littoral Synthèse des*  
817 *connaissances de la frontière Belge à la pointe du Hourdel*. Fasci-  
818 cule 1. URL: [http://www.cerema.fr/fr/centre-ressources/boutique/](http://www.cerema.fr/fr/centre-ressources/boutique/dynamiques-evolution-du-littoral)  
819 [dynamiques-evolution-du-littoral](http://www.cerema.fr/fr/centre-ressources/boutique/dynamiques-evolution-du-littoral).
- 820 Chaverot, S. (2006). *Impact des variations récentes des conditions météo-*  
821 *marines sur les littoraux meubles du Nord-Pas-de-Calais*. thesis Université  
822 Littoral Côte d’Opale. URL: <http://www.theses.fr/2006DUNK0146>.



- 823 Chaverot, S., Héquette, A., & Cohen, O. (2008). Changes in storminess and  
824 shoreline evolution along the northern coast of France during the second half  
825 of the 20th century. *Annales de Géomorphologie / Annals of Geomorphology*  
826 / *Zeitschrift für Geomorphologie, Sup. Bd.,52*, Sup. Bd., 52 (3), p. 1–20.  
827 URL: [https://www.schweizerbart.de/papers/zfg\\_suppl/detail/52/  
828 65699/Changes\\_in\\_storminess\\_and\\_shoreline\\_evolution\\_along\\_the\\_  
829 northern\\_coast\\_of\\_France\\_during\\_the\\_second\\_half\\_of\\_the\\_20th\\_  
830 century](https://www.schweizerbart.de/papers/zfg_suppl/detail/52/65699/Changes_in_storminess_and_shoreline_evolution_along_the_northern_coast_of_France_during_the_second_half_of_the_20th_century). doi:10.1127/0372-8854/2008/0052S3-0001.
- 831 Cooper, J. A. G., Jackson, D. W. T., Navas, F., McKenna, J., & Mal-  
832 varez, G. (2004). Identifying storm impacts on an embayed, high-  
833 energy coastline: examples from western Ireland. *Marine Geology,*  
834 *210*, 261–280. URL: [http://www.sciencedirect.com/science/article/  
835 pii/S0025322704001409](http://www.sciencedirect.com/science/article/pii/S0025322704001409). doi:10.1016/j.margeo.2004.05.012.
- 836 Cooper, J. a. G., & Navas, F. (2004). Natural bathymetric change as a control  
837 on century-scale shoreline behavior. *Geology*, *32*, 513–516. URL: [https:  
838 //pubs.geoscienceworld.org/gsa/geology/article-abstract/32/6/  
839 513/29467/natural-bathymetric-change-as-a-control-on-century](https://pubs.geoscienceworld.org/gsa/geology/article-abstract/32/6/513/29467/natural-bathymetric-change-as-a-control-on-century).  
840 doi:10.1130/G20377.1.
- 841 Corbau, C. (1995). *Dynamique sédimentaire en domaine Macrotidale : exemple*  
842 *du littoral du Nord de la France (Dunkerque)*. Ph.D. thesis Université des  
843 Sciences et Technologiques de Lille 1.
- 844 Corbau, C., Tessier, B., & Chamley, H. (1999). Seasonal Evolution of Shoreface  
845 and Beach System Morphology in a Macrotidal Environment, Dunkerque  
846 Area, Northern France. *Journal of Coastal Research*, *15*. URL: [http:  
847 //journals.fcla.edu/jcr/article/view/80429](http://journals.fcla.edu/jcr/article/view/80429).
- 848 Crapoulet, A. (2015). *Evolution du trait de côte, bilan sédimentaire et évaluation*  
849 *des zones à risques sur le littoral du Nord-Pas-de-Calais : analyse multi-*  
850 *échelles par LiDAR aéroporté*. Ph.D. thesis Université du Littoral Côte  
851 d’Opale.

- 852 Crapoulet, A., Héquette, A., Marin, D., Levoy, F., & Bretel, P. (2017). Varia-  
853 tions in the response of the dune coast of northern France to major storms  
854 as a function of available beach sediment volume. *Earth Surface Processes*  
855 *and Landforms*, 42, 1603–1622. URL: [https://onlinelibrary.wiley.com/](https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4098)  
856 [doi/abs/10.1002/esp.4098](https://onlinelibrary.wiley.com/doi/abs/10.1002/esp.4098). doi:10.1002/esp.4098.
- 857 Davidson, M. A., O'Hare, T. J., & George, K. J. (2008). Tidal Modulation of  
858 Incident Wave Heights: Fact or Fiction? *Journal of Coastal Research*, 24,  
859 151–159. URL: <https://www.jcronline.org/doi/abs/10.2112/06-0754>.  
860 1. doi:10.2112/06-0754.1.
- 861 Davidson-Arnott, R., & N. Law, M. (1996). *Measurement and prediction of*  
862 *long-term sediment supply to Coastal Foredunes* volume 12.
- 863 Davies, J. L. (1980). *Geographical variation in coastal development*. Longman  
864 Sc & Tech.
- 865 De Moor, G. (2002). Evaluation of sea-floor sediment dynamics in the Flemish  
866 Banks (southern North Sea) between 1985 and 1995. *Géomorphologie : relief,*  
867 *processus, environnement*, 8, 135–150. URL: [https://www.persee.fr/doc/](https://www.persee.fr/doc/morfo_1266-5304_2002_num_8_2_1135)  
868 [morfo\\_1266-5304\\_2002\\_num\\_8\\_2\\_1135](https://www.persee.fr/doc/morfo_1266-5304_2002_num_8_2_1135). doi:10.3406/morfo.2002.1135.
- 869 Deleu, S., Van Lancker, V., Van den Eynde, D., & Moerkerke, G. (2004).  
870 Morphodynamic evolution of the kink of an offshore tidal sandbank: the  
871 Westhinder Bank (Southern North Sea). *Continental Shelf Research*, 24,  
872 1587–1610. URL: [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S027843430400161X)  
873 [S027843430400161X](http://www.sciencedirect.com/science/article/pii/S027843430400161X). doi:10.1016/j.csr.2004.07.001.
- 874 Dewez, S., Clabaut, P., Vicaire, O., Beck, C., Chamley, H., & Augris, C.  
875 (1989). Transits sédimentaires resultants aux confins Manche-mer du Nord.  
876 *Bulletin de la Société Géologique de France*, V, 1043–1053. URL: [https:](https://pubs-geoscienceworld-org.insu.bib.cnrs.fr/sgf/bsgf/article/V/5/1043/90299/transits-sedimentaires-resultants-aux-confins)  
877 [//pubs-geoscienceworld-org.insu.bib.cnrs.fr/sgf/bsgf/article/](https://pubs-geoscienceworld-org.insu.bib.cnrs.fr/sgf/bsgf/article/V/5/1043/90299/transits-sedimentaires-resultants-aux-confins)  
878 [V/5/1043/90299/transits-sedimentaires-resultants-aux-confins](https://pubs-geoscienceworld-org.insu.bib.cnrs.fr/sgf/bsgf/article/V/5/1043/90299/transits-sedimentaires-resultants-aux-confins).  
879 doi:10.2113/gssgfbull.V.5.1043.

- 880 Dodet, G., Bertin, X., & Taborda, R. (2010). Wave climate variability  
881 in the North-East Atlantic Ocean over the last six decades. *Ocean*  
882 *Modelling*, 31, 120–131. URL: [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S1463500309002066)  
883 [article/pii/S1463500309002066](http://www.sciencedirect.com/science/article/pii/S1463500309002066). doi:10.1016/j.ocemod.2009.10.010.
- 884 Dyer, K. R., & Huntley, D. A. (1999). The origin, classification and  
885 modelling of sand banks and ridges. *Continental Shelf Research*, 19,  
886 1285–1330. URL: [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S027843439900028X)  
887 [S027843439900028X](http://www.sciencedirect.com/science/article/pii/S027843439900028X). doi:10.1016/S0278-4343(99)00028-X.
- 888 EGIS (2014). *Etude de faisabilité pour le réensablement de la partie centrale*  
889 *de la baie de Wissant - Phase 1: Dimensionnement du réensablement -*  
890 *Elaboration de scénarios de réensablement*. Rapport définitif EP 132771M.  
891 URL: [https://www.hauts-de-france.developpement-durable.gouv.fr/](https://www.hauts-de-france.developpement-durable.gouv.fr/IMG/pdf/ep132771m_wissant_phase1_vfinale.pdf)  
892 [IMG/pdf/ep132771m\\_wissant\\_phase1\\_vfinale.pdf](https://www.hauts-de-france.developpement-durable.gouv.fr/IMG/pdf/ep132771m_wissant_phase1_vfinale.pdf).
- 893 Garlan, T. (1990). L'apport des levés bathymétriques pour la connaissance de  
894 la dynamique sédimentaire. L'exemple des Ridens de la Rade aux abords de  
895 Calais. (pp. 71–75). Marseille.
- 896 Giardino, A., Van den Eynde, D., & Monbaliu, J. (2010). Wave effects on  
897 the morphodynamic evolution of an offshore sand bank. *Journal of Coastal*  
898 *Research*, (pp. 127–140). URL: [http://agris.fao.org/agris-search/](http://agris.fao.org/agris-search/search.do?recordID=AV2012056824)  
899 [search.do?recordID=AV2012056824](http://agris.fao.org/agris-search/search.do?recordID=AV2012056824). doi:10.2307/40928825.
- 900 Hanna, J. E., & Cooper, J. (2002). Mesoscale Morphological Changes on  
901 Linear, Nearshore Sandbanks, Co.Wexford, SE Ireland. *Journal of Coastal*  
902 *Research*, (pp. 356–364). URL: [http://www.bioone.org/doi/abs/10.2112/](http://www.bioone.org/doi/abs/10.2112/1551-5036-36.sp1.356)  
903 [1551-5036-36.sp1.356](http://www.bioone.org/doi/abs/10.2112/1551-5036-36.sp1.356). doi:10.2112/1551-5036-36.sp1.356.
- 904 Hédou, F., Roche, A., Trmal, C., Moraud, S., & Deniaud, Y. (2018). Élaboration  
905 de l'indicateur national de l'érosion côtière. In *XVèmes Journées, La Rochelle*  
906 (pp. 647–654). Editions Paralia. URL: [http://www.paralia.fr/jngcgc/15\\_](http://www.paralia.fr/jngcgc/15_75_hedou.pdf)  
907 [75\\_hedou.pdf](http://www.paralia.fr/jngcgc/15_75_hedou.pdf). doi:10.5150/jngcgc.2018.075.

- 908 Hedges, T. (2015). Combinations of waves and currents: an introduction. *Pro-*  
909 *ceedings of the Institution of Civil Engineers, Part 1*, 567–585. doi:10.1680/  
910 *iicep.1987.319*.
- 911 Hervouet, J.-M. (2007). *Hydrodynamics of Free Surface Flows: Modelling With*  
912 *the Finite Element Method*. Wiley; 1 edition (May 29, 2007).
- 913 Hesp, P. (1988). *Surfzone, beach and fordune interactions on the Australian*  
914 *southeast coast* volume 3.
- 915 Horrillo-Caraballo, J. M., & Reeve, D. E. (2008). Morphodynamic behaviour of  
916 a nearshore sandbank system: The Great Yarmouth Sandbanks, U.K. *Marine*  
917 *Geology*, 254, 91–106. URL: [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S002532270800176X)  
918 [article/pii/S002532270800176X](http://www.sciencedirect.com/science/article/pii/S002532270800176X). doi:10.1016/j.margeo.2008.05.014.
- 919 Houbolt, J. (1968). Recent sediments in the Southern Bight of the North Sea.  
920 *Geologie en Mijnbouw* 47, .
- 921 Houser, C., Hapke, C., & Hamilton, S. (2008). Controls on coastal  
922 dune morphology, shoreline erosion and barrier island response to extreme  
923 storms. *Geomorphology*, (pp. 223–240). URL: [https://scholar.uwindsor.](https://scholar.uwindsor.ca/environmentalsciencepub/31)  
924 [ca/environmentalsciencepub/31](https://scholar.uwindsor.ca/environmentalsciencepub/31). doi:10.1016/j.geomorph.2007.12.007.
- 925 Héquette, A., & Aernouts, D. (2010). The influence of nearshore sand  
926 bank dynamics on shoreline evolution in a macrotidal coastal envi-  
927 ronment, Calais, Northern France. *Continental Shelf Research*, 30,  
928 1349–1361. URL: [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S0278434310001561)  
929 [S0278434310001561](http://www.sciencedirect.com/science/article/pii/S0278434310001561). doi:10.1016/j.csr.2010.04.017.
- 930 Héquette, A., Anthony, E. J., Ruz, M.-H., Maspataud, A., Aernouts, D., &  
931 Hemdane, Y. (2013). The influence of nearshore sand banks on coastal hy-  
932 drodynamics and sediment transport, northern coast of France. In *Proceedings*  
933 *Coastal Dynamics* (pp. 801–810).
- 934 Héquette, A., Hemdane, Y., & Anthony, E. J. (2008). Sedi-  
935 ment transport under wave and current combined flows on a tide-

936 dominated shoreface, northern coast of France. *Marine Geology*, 249,  
937 226–242. URL: [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S0025322707003027)  
938 [S0025322707003027](http://www.sciencedirect.com/science/article/pii/S0025322707003027). doi:10.1016/j.margeo.2007.12.003.

939 Héquette, A., Ruz, M. H., Maspataud, A., & Sipka, V. (2009). Effects of  
940 nearshore sand bank and associated channel on beach hydrodynamics: im-  
941 plications for beach and shoreline evolution. *Journal of Coastal Research*,  
942 *Special issue 56*, 59–63. URL: <http://www.jstor.org/stable/25737537>.

943 Huthnance, J. M. (1982). On one mechanism forming linear sand  
944 banks. *Estuarine, Coastal and Shelf Science*, 14, 79–99. URL: [http://](http://www.sciencedirect.com/science/article/pii/S0302352482800686)  
945 [www.sciencedirect.com/science/article/pii/S0302352482800686](http://www.sciencedirect.com/science/article/pii/S0302352482800686).  
946 doi:10.1016/S0302-3524(82)80068-6.

947 Idier, D., Paris, F., Cozannet, G. L., Boulahya, F., & Dumas, F. (2017). Sea-  
948 level rise impacts on the tides of the European Shelf. *Continental Shelf*  
949 *Research*, 137, 56–71. URL: [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S0278434317300250)  
950 [article/pii/S0278434317300250](http://www.sciencedirect.com/science/article/pii/S0278434317300250). doi:10.1016/j.csr.2017.01.007.

951 Jing, L., & Ridd, P. V. (1996). Wave-current bottom shear stresses and  
952 sediment resuspension in Cleveland Bay, Australia. *Coastal Engineering*,  
953 29, 169–186. URL: [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S0378383996000233)  
954 [pii/S0378383996000233](http://www.sciencedirect.com/science/article/pii/S0378383996000233). doi:10.1016/S0378-3839(96)00023-3.

955 Kenyon, N. H., Belderson, R. H., Stride, A. H., & Johnson, M. A. (1981). Off-  
956 shore Tidal Sand-Banks as Indicators of Net Sand Transport and as Potential  
957 Deposits. In *Holocene Marine Sedimentation in the North Sea Basin* (pp.  
958 257–268). Wiley-Blackwell. URL: [https://onlinelibrary.wiley.com/doi/](https://onlinelibrary.wiley.com/doi/abs/10.1002/9781444303759.ch20)  
959 [abs/10.1002/9781444303759.ch20](https://onlinelibrary.wiley.com/doi/abs/10.1002/9781444303759.ch20). doi:10.1002/9781444303759.ch20.

960 King, E. V., Conley, D. C., Masselink, G., Leonardi, N., McCarroll,  
961 R. J., & Scott, T. (2019). The Impact of Waves and Tides on  
962 Residual Sand Transport on a Sediment-Poor, Energetic, and Macroti-  
963 dal Continental Shelf. *Journal of Geophysical Research: Oceans*, 124,

964 4974–5002. URL: [https://agupubs.onlinelibrary.wiley.com/doi/abs/](https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2018JC014861)  
965 10.1029/2018JC014861. doi:10.1029/2018JC014861.

966 Lanckneus, J., De Moor, G., De Schaepmeester, G., De Winne, E., & Meyus,  
967 I. (1992). Monitoring of a tidal sandbank: evolution of bedforms, volumetric  
968 trends, sedimentological changes. *Special Publication (Hydrographic Society)*,  
969 .

970 Lanckneus, J., De Moor, G., & Stolk, A. (1994). Environmental set-  
971 ting, morphology and volumetric evolution of the Middelkerke Bank  
972 (southern North Sea). *Marine Geology*, 121, 1–21. URL: <http://www.sciencedirect.com/science/article/pii/0025322794901538>.  
973 doi:10.1016/0025-3227(94)90153-8.  
974

975 Latapy, A., Héquette, A., Pouvreau, N., Weber, N., & Robin-Chanteloup, J.-  
976 B. (2019). Mesoscale Morphological Changes of Nearshore Sand Banks since  
977 the Early 19th Century, and Their Influence on Coastal Dynamics, Northern  
978 France. *Journal of Marine Science and Engineering*, 7, 73. URL: <https://www.mdpi.com/2077-1312/7/3/73>. doi:10.3390/jmse7030073.  
979

980 Le Roy, R., & Simon, B. (2003). *Réalisation et validation d'un modèle de marée*  
981 *en Manche et dans le Golfe de Gascogne (application à la réalisation d'un*  
982 *nouveau programme de réduction des sondages bathymétriques)*. Technical  
983 Report 002/03 EPSHOM.

984 Li, D., Tang, C., Hou, X., & Zhang, H. (2019). Rapid Morphological Changes  
985 Caused by Intensive Coastal Development in Longkou Bay, China. *Journal of*  
986 *Coastal Research*, . URL: [http://www.jcronline.org/doi/abs/10.2112/](http://www.jcronline.org/doi/abs/10.2112/JCOASTRES-D-18-00095.1)  
987 [JCOASTRES-D-18-00095.1](http://www.jcronline.org/doi/abs/10.2112/JCOASTRES-D-18-00095.1). doi:10.2112/JCOASTRES-D-18-00095.1.

988 Lugo-Fernández, A., Roberts, H. H., & Wiseman, J., W. J. (1998). Tide Effects  
989 on Wave Attenuation and Wave Set-up on a Caribbean Coral Reef. *Estuarine,*  
990 *Coastal and Shelf Science*, 47, 385–393. URL: <http://www.sciencedirect.com/science/article/pii/S0272771498903651>. doi:10.1006/ecss.1998.  
991 0365.  
992

993 MacDonald, N. J., & O'Connor, B. A. (1996). Changes in wave impact  
994 on the Flemish coast due to increased mean sea level. *Journal of Ma-*  
995 *rine Systems*, 7, 133–144. URL: [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S0924796395000321)  
996 [article/pii/S0924796395000321](http://www.sciencedirect.com/science/article/pii/S0924796395000321). doi:10.1016/0924-7963(95)00032-1.

997 Marcos, F. (2003). Logiciel TOMAWAC de Propagation de Houle En Elements  
998 Finis. Notice D'utilisation, Version 5.2, .

999 Masselink, G. (1998). The effect of sea breeze on beach morphology,  
1000 surf zone hydrodynamics and sediment resuspension. *Marine Geology*,  
1001 146, 115–135. URL: [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S0025322797001217)  
1002 [article/pii/S0025322797001217](http://www.sciencedirect.com/science/article/pii/S0025322797001217). doi:10.1016/S0025-3227(97)00121-7.

1003 Masselink, G., Austin, M., Scott, T., Poate, T., & Russell, P. (2014).  
1004 Role of wave forcing, storms and NAO in outer bar dynamics on a high-  
1005 energy, macro-tidal beach. *Geomorphology*, 226, 76–93. URL: [https://](https://linkinghub.elsevier.com/retrieve/pii/S0169555X14003900)  
1006 [linkinghub.elsevier.com/retrieve/pii/S0169555X14003900](https://linkinghub.elsevier.com/retrieve/pii/S0169555X14003900). doi:10.  
1007 1016/j.geomorph.2014.07.025.

1008 Mattheus, C., Diggins, T., Boyce, C., Cockrell, J., Kruske, M., & VanWin-  
1009 kle, M. (2018). Geomorphology of a Harbor-Breakwater Beach along a  
1010 High Sand-Supply, Wave-Dominated Great Lakes Littoral Cell. *Journal of*  
1011 *Coastal Research*, . URL: [http://www.jcronline.org/doi/abs/10.2112/](http://www.jcronline.org/doi/abs/10.2112/JCOASTRES-D-17-00209.1)  
1012 [JCOASTRES-D-17-00209.1](http://www.jcronline.org/doi/abs/10.2112/JCOASTRES-D-17-00209.1). doi:10.2112/JCOASTRES-D-17-00209.1.

1013 McNinch, J. E. (2004). Geologic control in the nearshore: shore-oblique sand-  
1014 bars and shoreline erosional hotspots, Mid-Atlantic Bight, USA. *Marine*  
1015 *Geology*, 211, 121–141. URL: [http://www.sciencedirect.com/science/](http://www.sciencedirect.com/science/article/pii/S0025322704002075)  
1016 [article/pii/S0025322704002075](http://www.sciencedirect.com/science/article/pii/S0025322704002075). doi:10.1016/j.margeo.2004.07.006.

1017 Michaud, H., Pasquet, A., Baraille, R., Leckler, F., Aouf, L., Dalphinnet, A.,  
1018 Huchet, M., Roland, A., Dutour-Sikiric, M., Arduin, F., & Filipot, J. F.  
1019 (2015). Implementation of the new French operational coastal wave forecast-  
1020 ing system and application to a wave- current interaction study. (p. 10). Key  
1021 West, Florida.

- 1022 Morton, R. A., Gibeaut, J. C., & Paine, J. G. (1995). Meso-scale trans-  
1023 fer of sand during and after storms: implications for prediction of  
1024 shoreline movement. *Marine Geology*, *126*, 161–179. URL: <http://www.sciencedirect.com/science/article/pii/0025322795000716>.  
1025 doi:10.1016/0025-3227(95)00071-6.  
1026
- 1027 Osuna, P., & Monbaliu, J. (2004). Wave-current interaction in the Southern  
1028 North Sea. *Journal of marine systems*, *52*, 65–87. doi:10.1016/j.jmarsys.  
1029 2004.03.002.
- 1030 Pan, S., MacDonald, N., Williams, J., O'Connor, B. A., Nicholson, J., & Davies,  
1031 A. M. (2007). Modelling the hydrodynamics of offshore sandbanks. *Continental Shelf Research*, *27*, 1264–1286. URL: <http://www.sciencedirect.com/science/article/pii/S0278434307000337>. doi:10.1016/j.csr.2007.01.  
1032 007.  
1033  
1034
- 1035 Parker, G., Lanfredi, N. W., & Swift, D. J. P. (1982). Seafloor response to flow  
1036 in a southern hemisphere sand-ridge field: Argentine inner shelf. *Sedimentary Geology*, *33*, 195–216. URL: <http://www.sciencedirect.com/science/article/pii/0037073882900550>. doi:10.1016/0037-0738(82)90055-0.  
1037  
1038
- 1039 Peregrine, D. H. (1976). Interaction of Water Waves and Currents. In C.-  
1040 S. Yih (Ed.), *Advances in Applied Mechanics* (pp. 9–117). Elsevier vol-  
1041 ume 16. URL: <http://www.sciencedirect.com/science/article/pii/S0065215608700875>. doi:10.1016/S0065-2156(08)70087-5.  
1042
- 1043 Pintat, J.-F. (1975). *Projet de loi relatif à la prospection, à la recherche et*  
1044 *à l'exploitation des substances minérales non visées par l'article 2 du code*  
1045 *minier et contenues dans les fonds marins du domaine public métropolitain*.  
1046 Technical Report 381 Sénat.
- 1047 Reichmüth, B., & Anthony, E. J. (2007). Tidal influence on the inter-  
1048 tidal bar morphology of two contrasting macrotidal beaches. *Geomorphology*, *90*, 101–114. URL: <http://www.sciencedirect.com/science/article/pii/S0169555X0700030X>. doi:10.1016/j.geomorph.2007.01.015.  
1049  
1050



- 1051 Ruz, M.-H., Héquette, A., Marin, D., Sipka, V., Crapoulet, A., & Cartier,  
1052 A. (2017). Development of an incipient foredune field along a prograd-  
1053 ing macrotidal shoreline, northern France. *Géomorphologie : relief, proces-  
1054 sus, environnement*, 23, 37–50. URL: [http://journals.openedition.org/  
1055 geomorphologie/11638](http://journals.openedition.org/geomorphologie/11638). doi:10.4000/geomorphologie.11638.
- 1056 Schmitt, T., & Mitchell, N. C. (2014). Dune-associated sand fluxes at  
1057 the nearshore termination of a banner sand bank (Helwick Sands, Bris-  
1058 tol Channel). *Continental Shelf Research*, 76, 64–74. URL: [http:  
1059 //www.sciencedirect.com/science/article/pii/S0278434314000089](http://www.sciencedirect.com/science/article/pii/S0278434314000089).  
1060 doi:10.1016/j.csr.2014.01.003.
- 1061 Scott, T., Masselink, G., & Russell, P. (2011). Morphodynamic characteris-  
1062 tics and classification of beaches in England and Wales. *Marine Geology*,  
1063 286, 1–20. URL: [http://www.sciencedirect.com/science/article/pii/  
1064 S0025322711001095](http://www.sciencedirect.com/science/article/pii/S0025322711001095). doi:10.1016/j.margeo.2011.04.004.
- 1065 Sedrati, M., & Anthony, E. J. (2007). Storm-generated morphological  
1066 change and longshore sand transport in the intertidal zone of a multi-  
1067 barred macrotidal beach. *Marine Geology*, 244, 209–229. URL: [http:  
1068 //www.sciencedirect.com/science/article/pii/S0025322707001776](http://www.sciencedirect.com/science/article/pii/S0025322707001776).  
1069 doi:10.1016/j.margeo.2007.07.002.
- 1070 Sedrati, M., & Anthony, E. J. (2014). Confronting coastal morphodynamics  
1071 with counter-erosion engineering: the emblematic case of Wissant Bay, Dover  
1072 Strait. *Journal of Coastal Conservation*, 18, 483–494. URL: [https://doi.  
1073 org/10.1007/s11852-013-0300-1](https://doi.org/10.1007/s11852-013-0300-1). doi:10.1007/s11852-013-0300-1.
- 1074 Shaw, J., Duffy, G., Taylor, R. B., Chassé, J., & Frobel, D. (2008). Role  
1075 of a Submarine Bank in the Long-Term Evolution of the Northeast Coast of  
1076 Prince Edward Island, Canada. *Journal of Coastal Research*, (pp. 1249–1259).  
1077 URL: <http://www.jcronline.org/doi/abs/10.2112/07-08607.1>. doi:10.  
1078 2112/07-08607.1.

- 1079 Shom (2017). *Annuaire des Marées 2019, Ports de France Métropole, Tome 1*.
- 1080 Short, A. D. (Ed.) (1999). *Handbook of beach and shoreface morphodynamics*.  
1081 New York: John Wiley.
- 1082 Soulsby, R. (1997). *Dynamics of Marine Sands: A Manual for Practical Appli-*  
1083 *cations*. Thomas Telford.
- 1084 Soulsby, R. L. (1983). Chapter 5 The Bottom Boundary Layer of Shelf  
1085 Seas. In B. Johns (Ed.), *Elsevier Oceanography Series* (pp. 189–  
1086 266). Elsevier volume 35 of *Physical Oceanography of Coastal and*  
1087 *Shelf Seas*. URL: <http://www.sciencedirect.com/science/article/pii/S0422989408705038>. doi:10.1016/S0422-9894(08)70503-8.
- 1089 de Swart, H. E., & Yuan, B. (2018). Dynamics of offshore tidal sand ridges, a  
1090 review. *Environmental Fluid Mechanics*, . URL: <https://doi.org/10.1007/s10652-018-9630-8>. doi:10.1007/s10652-018-9630-8.
- 1092 Tessier, B., Corbau, C., Chamley, H., & Auffret, J.-P. (1999). Internal Struc-  
1093 ture of Shoreface Banks Revealed by High-Resolution Seismic Reflection in  
1094 a Macrotidal Environment (Dunkerque Area, Northern France). *Journal*  
1095 *of Coastal Research*, 15, 593–606. URL: <http://www.jstor.org/stable/4298976>.
- 1097 Thomas, T., Phillips, M. R., Williams, A. T., & Jenkins, R. E. (2011). A  
1098 multi-century record of linked nearshore and coastal change. *Earth Sur-*  
1099 *face Processes and Landforms*, 36, 995–1006. URL: <http://onlinelibrary.wiley.com/insu.bib.cnrs.fr/doi/10.1002/esp.2127/abstract>. doi:10.1002/esp.2127.
- 1102 Vicaire, O. (1991). *Dynamique hydro-sédimentaire en mer du Nord méridionale*  
1103 *(du Cap Blanc-Nez à la frontière Belge)*. Ph.D. thesis Université des Sciences  
1104 et Techniques de Lille 1.

- 1105 Villaret, C., & Davies, A. G. (2004). Numerical modelling of littoral sand  
1106 transport. In *Proceedings of the 29th International Conference on Coastal*  
1107 *Engineering* (pp. 1678–1689.). Lisbon: World Scientific.
- 1108 Wolf, J., & Prandle, D. (1999). Some observations of wave–current interaction.  
1109 *Coastal Engineering*, 37, 471–485. URL: [http://www.sciencedirect.com/](http://www.sciencedirect.com/science/article/pii/S0378383999000393)  
1110 [science/article/pii/S0378383999000393](http://www.sciencedirect.com/science/article/pii/S0378383999000393). doi:10.1016/S0378-3839(99)  
1111 00039-3.
- 1112 Wright, L. D., & Short, A. D. (1984). Morphodynamic variabil-  
1113 ity of surf zones and beaches: A synthesis. *Marine Geology*,  
1114 56, 93–118. URL: [http://www.sciencedirect.com/science/article/](http://www.sciencedirect.com/science/article/pii/0025322784900082)  
1115 [pii/0025322784900082](http://www.sciencedirect.com/science/article/pii/0025322784900082). doi:10.1016/0025-3227(84)90008-2.
- 1116 Young, I. R., Zieger, S., & Babanin, A. V. (2011). Global Trends in Wind  
1117 Speed and Wave Height. *Science*, 332, 451–455. URL: [https://science.](https://science.sciencemag.org/content/332/6028/451)  
1118 [sciencemag.org/content/332/6028/451](https://science.sciencemag.org/content/332/6028/451). doi:10.1126/science.1197219.
- 1119 Zijlema, M., van Vledder, G. P., & Holthuijsen, L. H. (2012). Bot-  
1120 tom friction and wind drag for wave models. *Coastal Engineering*,  
1121 65, 19–26. URL: [http://www.sciencedirect.com/science/article/pii/](http://www.sciencedirect.com/science/article/pii/S0378383912000440)  
1122 [S0378383912000440](http://www.sciencedirect.com/science/article/pii/S0378383912000440). doi:10.1016/j.coastaleng.2012.03.002.

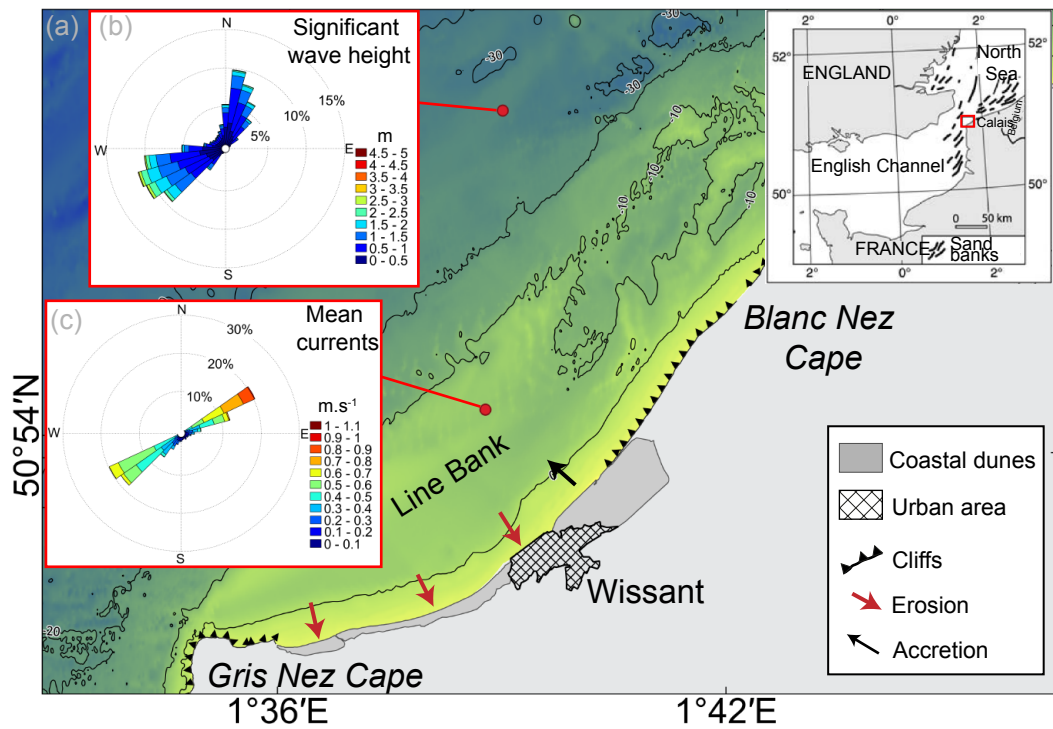


Figure 1: Wissant bay in the southern North Sea facing the Dover Strait (inset map) (a) Bathymetry from HOMONIM Digital Elevation Model ([http://dx.doi.org/10.17183/MNT\\_ATL100m\\_HOMONIM\\_WGS84](http://dx.doi.org/10.17183/MNT_ATL100m_HOMONIM_WGS84)) and synthesis of Wissant bay's shoreline evolution (Chaverot, 2006; Crapoulet, 2015), (b) Wave height from the HOMERE database (point E164N5094) and (c) direction and intensity of mean currents during the campaign between 05/17/2016 and 06/07/2016 (DDTM62)

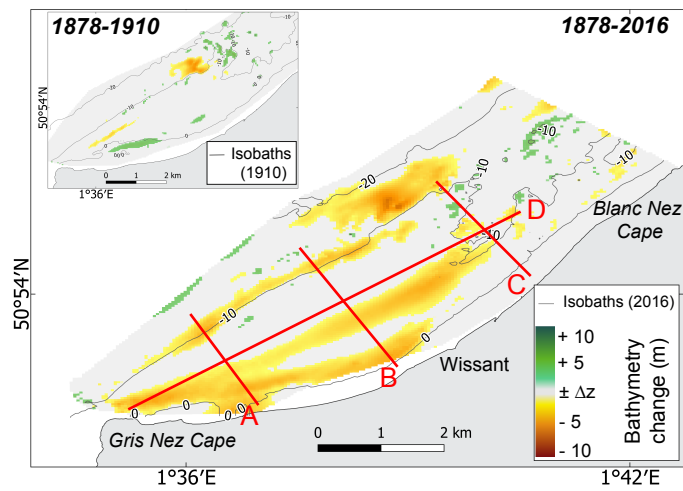


Figure 2: Bathymetric differential map of the Wissant bay between 1878 and 2016 and between 1878 and 1910 (inset map). Red-orange pattern indicates a seabed lowering; reciprocally blue-green areas correspond to vertical accretion; areas in grey correspond to the margin error ( $\pm\Delta z$ ) and are considered as stable over the study period. Transects A, B, C and D correspond to the location of bathymetric profiles in Figure 3.

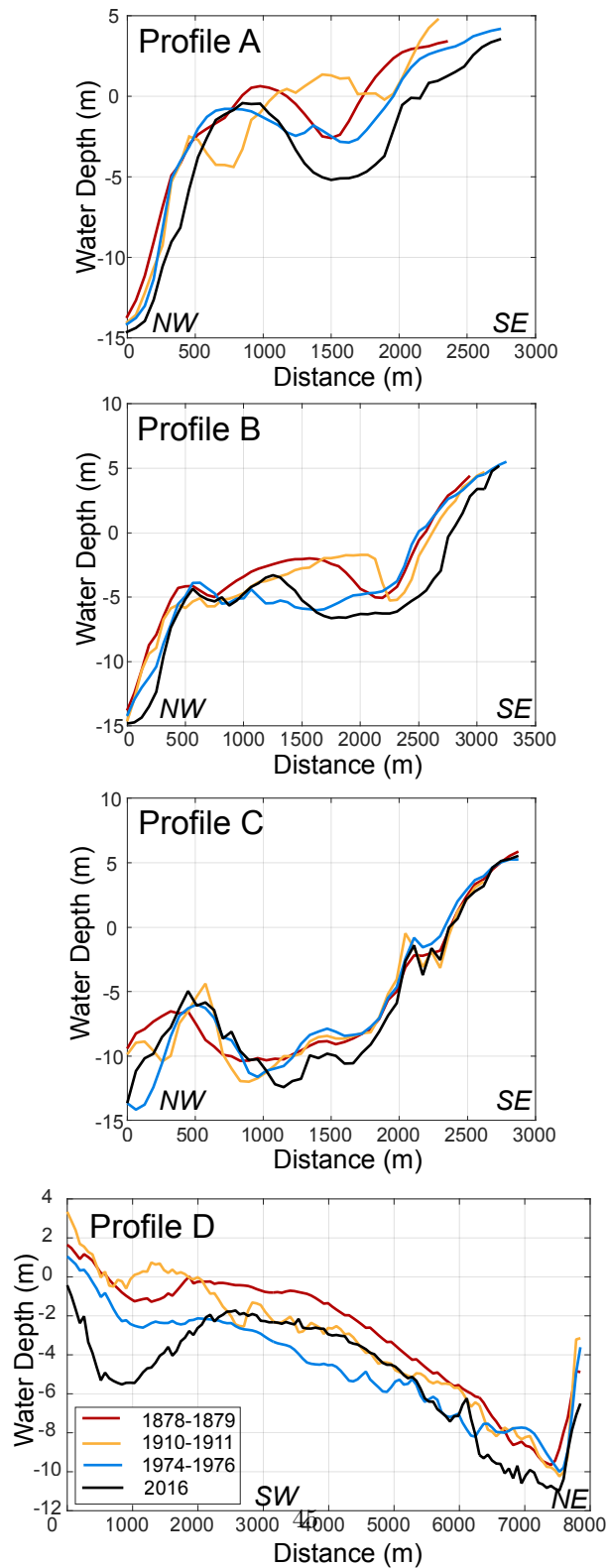


Figure 3: Bathymetry profiles evolution across the Wissant bay and the Line Bank from 1878 to 2016, (a-c) are cross-shore profiles and (d) is long-shore profile. See Figure 2 for profile location

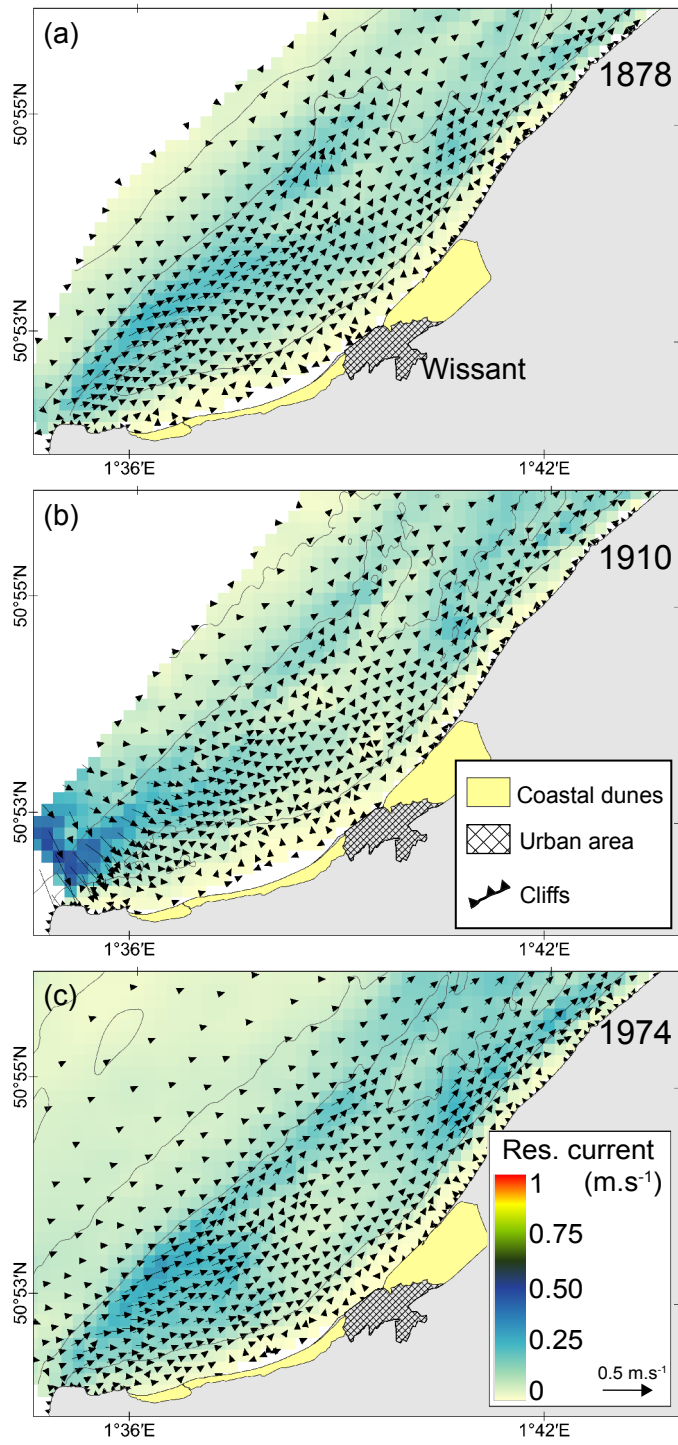


Figure 4: Simulations of changes in tidal residual current over 1878 (a), 1910 (b), and 1974 (c) bathymetries considering only the effect of tides.

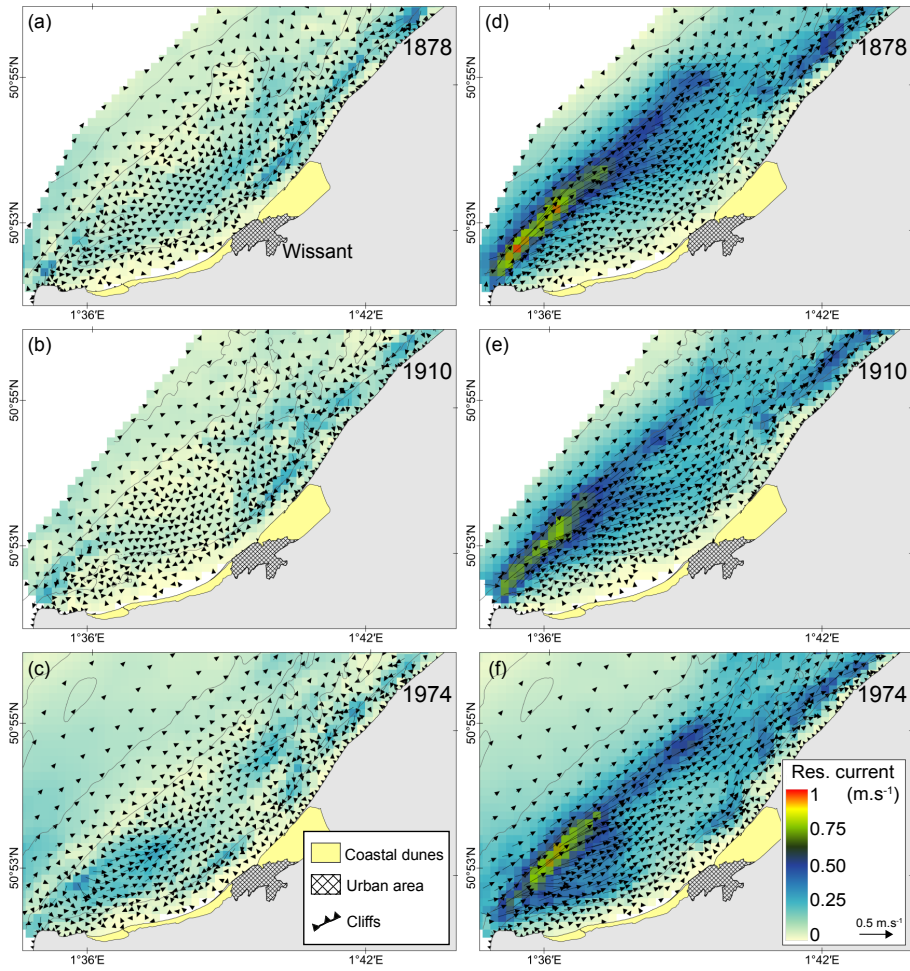


Figure 5: Simulations of changes in tidal residual current over 1878, 1910, and 1974 bathymetries considering the coupling effect of tides and waves: (a),(b), and (c) with north-easterly off-shore waves and (d), (e), and (f) with westerly off-shore waves



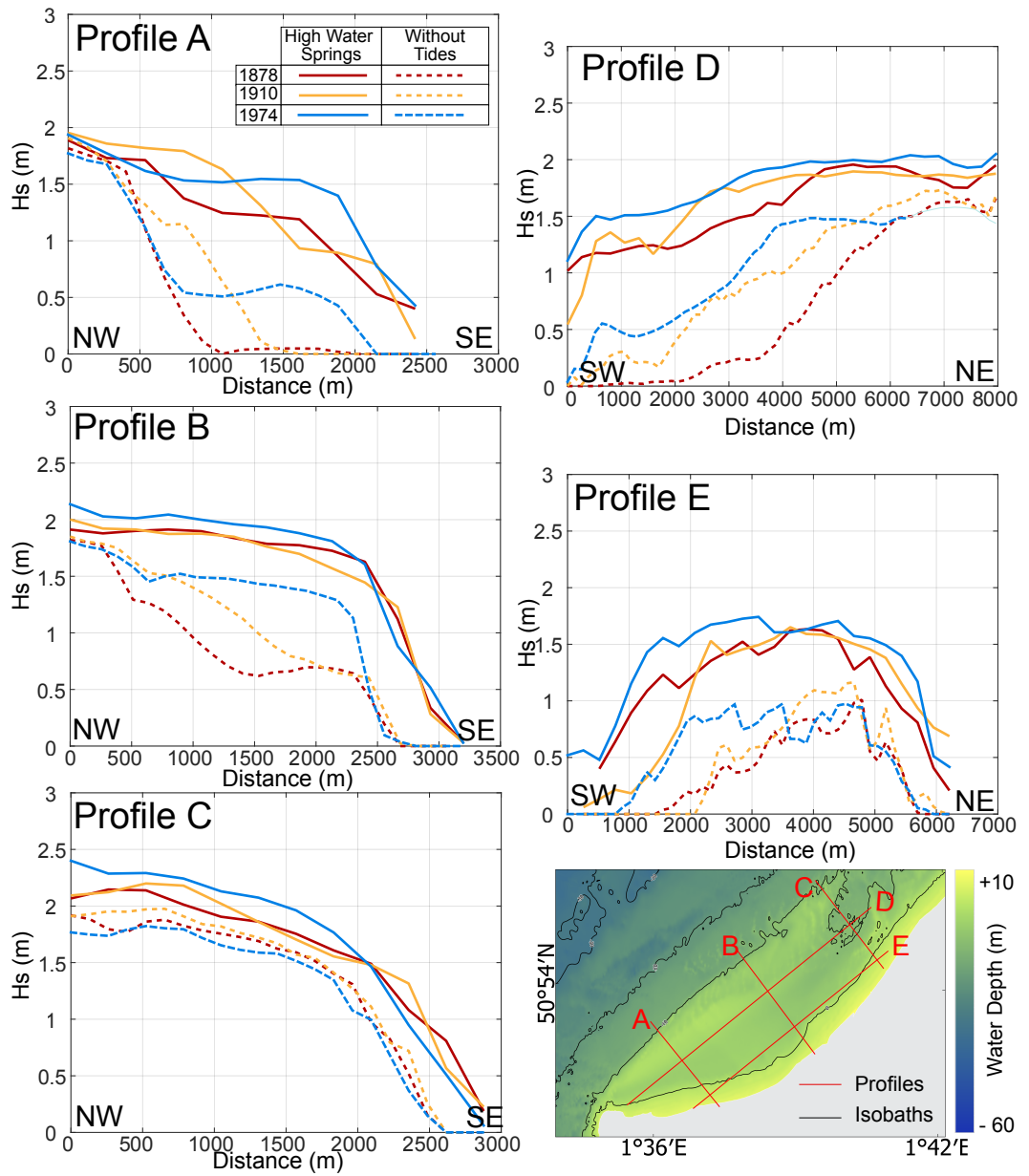


Figure 6: Significant wave height transects from the 1878, 1910 and 1974 models with north-easterly waves with and without considering tides

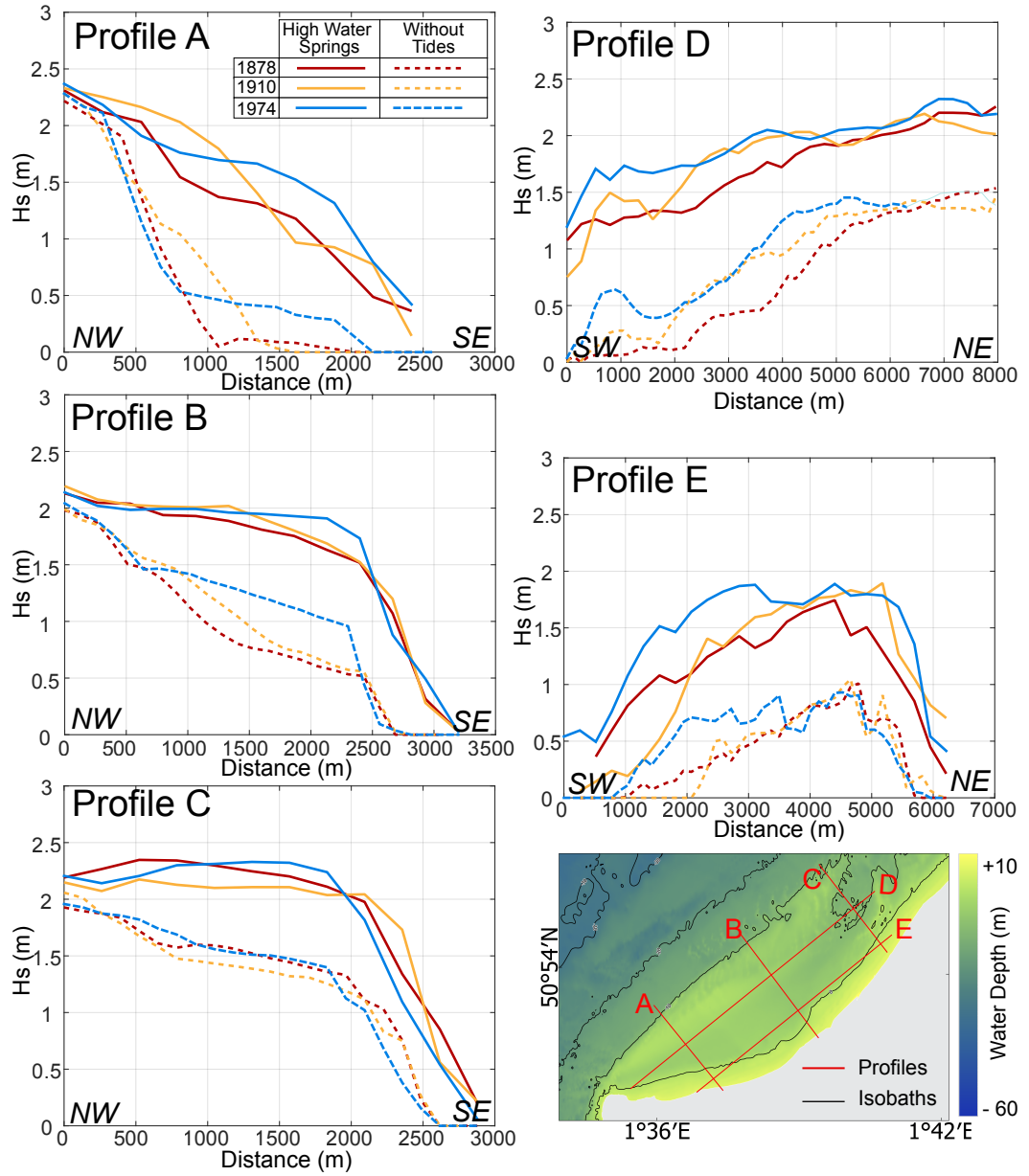


Figure 7: Significant wave height transects from the 1878, 1910 and 1974 models with westerly waves with and without considering tides

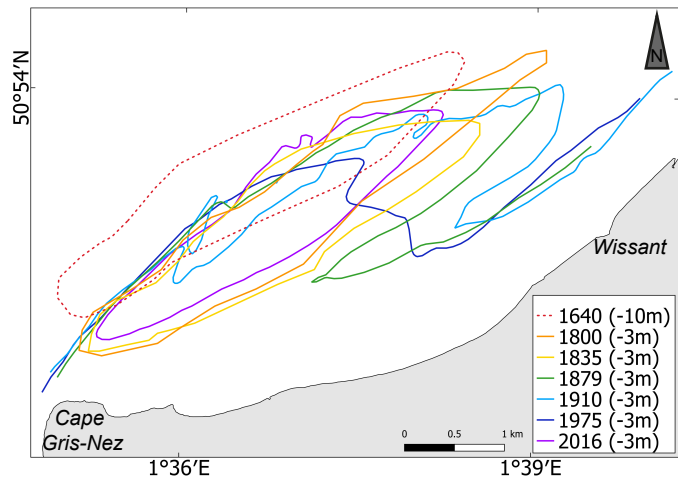


Figure 8: Evolution of the Line bank position and shape since 1640, adapted from the work of Briquet (1930) and completed with data digitized through this study. The -3m isobath was used as a reference for the position of the Line bank except for 1640 where the -10m isobath was chosen

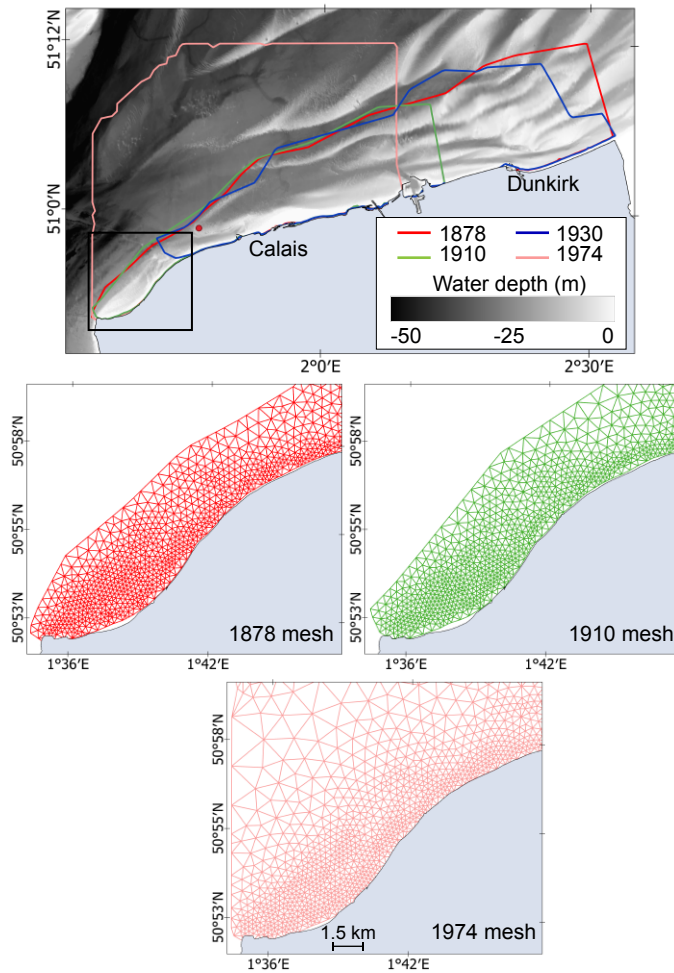


Figure 9: Above: Spatial extent of the 4 models used in this study on the HOMONIM Digital Elevation Model ([http://dx.doi.org/10.17183/MNT\\_ATL100m\\_HOMONIM\\_WGS84](http://dx.doi.org/10.17183/MNT_ATL100m_HOMONIM_WGS84)), the black box indicates the location of the Wissant bay and the red dot the position of the currentmeter used for current validation in the Figure 10 . Bottom: zoom on meshes covering Wissant Bay (1878, 1910, 1974)

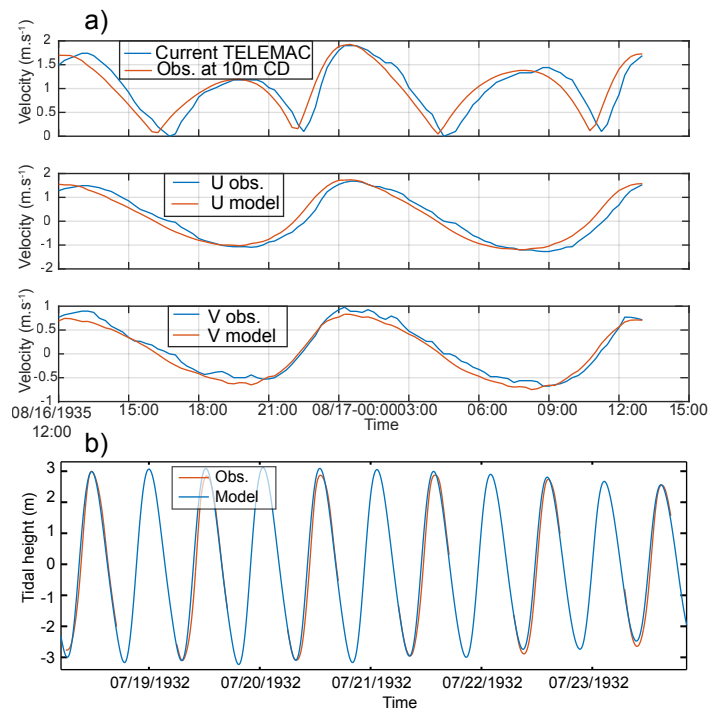


Figure 10: a) Tidal current observation made in 1935 and obtained with the 1930 model, offshore of Calais, at 10 m below Chart Datum (position of the currentmeter is indicated on the Figure 9). b) Comparison between tidal height observation at Calais in 1932 and tidal height obtained with the 1930 model at the same dates.

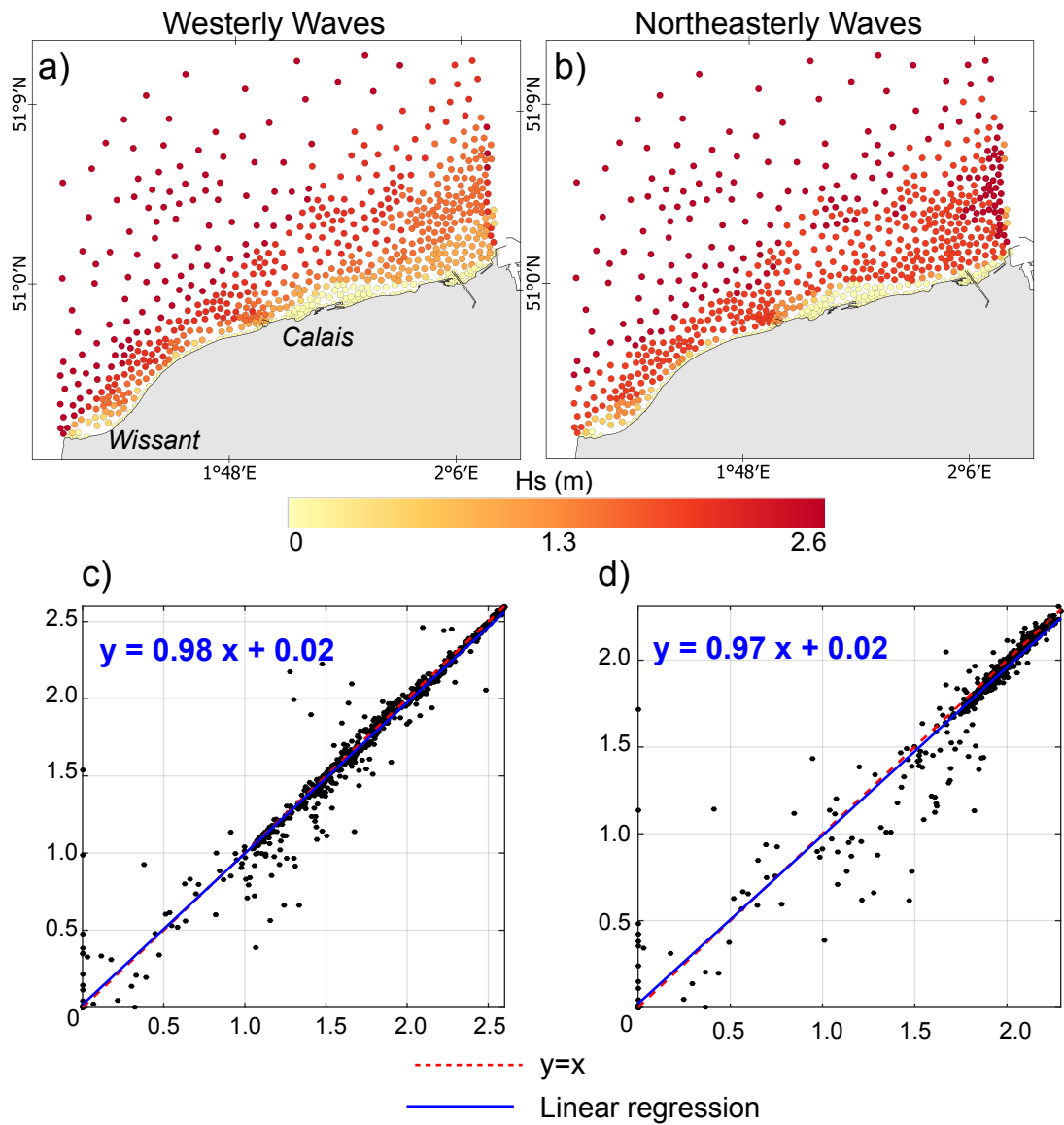


Figure 11: Wave height (Hs) obtained with the HOMONIM DEM with Tomawac for westerly (a) and northeasterly (b) off-shore waves. Q-Q plot comparing at each node Hs obtained with Tomawac and WaveWatch3 for westerly (c) et northeasterly waves (d). For both Q-Q plot linear regression (in blue) is plotted

<b>Year</b>	<b>1878-79</b>	<b>1910-11</b>	<b>1974-76</b>	<b>2016</b>
Surface (km <sup>2</sup> )	691	400	1025	41
MHE (m)	15.5	15.5	10	3
MVE (m)	2.0	2.0	1.2	0.6

Table 1: Bathymetry surveys used in this study (source: SHOM, except for 2016 made by DDTM). MHE: Maximum Horizontal Error; MVE: Maximum Vertical Error. These first three bathymetry surveys were used for numerical modelling

<b>Dates</b>	<b>Nodes</b>	<b>Finite elements</b>
<i>1878</i>	8,058	15,698
<i>1910</i>	5,690	10,961
<i>1974</i>	4,408	8,559

Table 2: Computational mesh characteristics. Note that the year of each grid corresponds to the first year of the bathymetry surveys



NNE waves (Dir=N10)	WSW waves (Dir=N250)
Hs99% = 2.25m Fpeak99%=0,1364 Hz (Tpeak=7.33s)	Hs99% = 2.62m Fpeak99%=0,1336Hz (Tpeak=7.33s)

Table 3: 99th percentile of Hs and fpeak for WSW and NNE waves calculated from the HOMERE database (<http://doi.org/10.12770/cf47e08d-1455-4254-955e-d66225c9dc90>)

	1878-1910	1910-1974	<b>1878-1974</b>
Western foreshore	Hs ↓	Hs ↑	<b>Overall increase</b>
Central foreshore	Hs ↑	Hs ↑	<b>Overall increase</b>
Eastern foreshore	Hs ↓ or remained stable	Hs ↓ or remained stable	<b>Stable</b>
Line bank	Hs ↑ or remained stable	Hs ↑	<b>Increase</b>
Coastal channel	Hs ↓ or remained stable	Hs ↑	<b>Increase</b>

Table 4: Synthesis of wave height evolution depending on the location in the bay and the period considered

		1878	1910	1930	1974
Calais	Obs	<b>0.87</b>	<b>0.92</b>	<b>0.92</b>	<b>0.83</b>
		0.67	0.51	0.51	0.79
	Pred	<b>0.92</b>	<b>0.92</b>	<b>0.93</b>	<b>0.88</b>
		0.50	0.54	0.48	0.68
Dunkirk	Obs	<b>0.91</b>	-	<b>0.88</b>	-
		0.43		0.54	
	Pred	<b>0.92</b>	-	<b>0.88</b>	-
		0.43		0.55	

Table 5: Statistic computed ( $R^2$  and RMSE) by comparing simulated tidal height at Calais and Dunkirk from each model with observations and predictions

NNE waves WW3 (Dir=10°N)	WSW waves WW3 (Dir=230°N)
<i>21/03/2015 22:00</i> Hs= 2.2 m Fpeak99%=0,14 Hz (Tpeak=7.14s)	<i>22/02/2015 23:00</i> Hs = 2.5 m Fpeak99%=0,14Hz (Tpeak=7.14s)

Table 6: WaveWatch3 outputs used to validate TOMAWAC runs