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1 **Coastal flood: a composite method for past events**
2 **characterisation providing insights in past, present**
3 **and future hazards**
4 **Joining historical, statistical and modeling approaches**

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10 **Abstract** The characterisation of past coastal flood events is crucial for risk
11 prevention. However, it is limited by the partial nature of historical informa-
12 tion on flood events and the lack or limited quality of past hydro-meteorological
13 data. In addition coastal flood processes are complex, driven by many hydro-
14 meteorological processes, making mechanisms and probability analysis challeng-
15 ing. Here, we tackle these issues by joining historical, statistical and modelling
16 approaches. We focus on a macrotidal site (Gâvres, France) subject to overtopping
17 and investigate the 1900-2010 period. We build a continuous hydro-meteorological
18 database and a damage event database using archives, newspapers, maps and
19 aerial photographs. Using together these historic information, hindcasts and hy-
20 drodynamic models, we identify 9 flood events, among which 5 are significant flood
21 events (4 with high confidence: 1924, 1978, 2001, 2008; 1 with a lower confidence:
22 1904). These flood events are driven by the combination of sea-level rise, tide,
23 atmospheric surge, offshore wave conditions and local wind. We further analyse
24 the critical conditions leading to flood, including the effect of coastal defences,
25 showing, for instance, that the present coastal defences would not have allowed to
26 face the hydro-meteorological conditions of 09/02/1924, whose bi-variate return
27 periods of exceedance T_R (still water level relative to the mean sea level and sig-
28 nificant wave height) is larger than 1000 y. In the coming decades, T_R is expected
29 to significantly decrease with sea-level rise, reaching values smaller than 1 y, for

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30 8 of the 9 historical events, for a sea-level rise of 0.63 m, which is equal to the
31 median sea-level rise projected by the 5th Assessment Report of the IPCC in this
32 region for RCP8.5 in 2100.

33 **Keywords** overtopping · historical events · sea-level rise · SWASH · joint
34 probabilities · sensitivity analysis

35 1 Introduction

36 The characterisation (occurrence, mechanisms, probability) of past coastal flood
37 events is crucial for risk prevention (see e.g. *Dangendorf et al.* 2016). However,
38 it is not a trivial task, especially when considering events that occurred several
39 decades ago. Most of the time, the historical information is very partial, with
40 for instance mention of water invading docks or of damages on a given asset.
41 Even partial, this information remains very useful to improve the quantification of
42 extreme water levels, to better estimate potential flood hazards or to understand
43 the impacts of contemporary climate change (*Zong and Tooley* 2003; *Needham and*
44 *Keim* 2012; *Breilh et al.* 2014; *Jeffers* 2014; *Bulteau et al.* 2015; *Fortunato et al.*
45 2017; *Wadey et al.* 2017; *Haigh et al.* 2017; *Hénaff et al.* 2018; *Giloy et al.* 2018;
46 *Hamdi et al.* 2018; *Garnier et al.* 2018). However, historical information on flood
47 events is subject to uncertainties: while there is high confidence that reported flood
48 events really occurred, the absence of report does not necessarily mean that there
49 was no flood. This is especially the case on coastal sites with few or no assets until
50 the last decades, and thus where nobody reported the flood event or had reasons
51 to do so.

52 One key issue in the characterisation of the driving factors of historical flood
53 events and their probability is the availability of past hydro-meteorological data.
54 Flood often results from the combination of several conditions (e.g. tide, atmo-
55 spheric surge, waves), so that all these conditions must be characterised for ac-
56 curate assessment. There are two approaches to estimate these conditions: using
57 measurements or modelling. However, the spatial coverage of measurements is
58 limited, and their temporal coverage ranges from about a century (the longest
59 available tide gauge data, as in Brest, France) to few years only. While modelling
60 requires significant effort, many retrospective simulations (hereafter: hindcasts)
61 have been produced over the last decade and deliver reconstructions of pressures,
62 winds, waves or atmospheric storm surges. Some hindcasts go back to the end of
63 the 19th century (see e.g. 20CR for meteorological hindcasts, from *Compo et al.*
64 2015), opening the perspective of better characterising events that occurred sev-
65 eral decades ago. However, their quality is still lower than the one of hindcasts
66 limited to shorter and recent period (see e.g. CFSR, from *Dee et al.* 2014). As a
67 consequence, the characterisation of the driving factors of such historical event is
68 rarely done and their probability is not estimated.

69 In practice, when a coastal flood model is validated in a given area, it is most of
70 the time on a single (recent) event (see e.g. *Wadey et al.* 2013; *Bertin et al.* 2014;
71 *Le Roy et al.* 2015), and more rarely on several events (see e.g. *Gallien et al.* 2018,
72 for a discussion on coastal flood modelling challenges). This is even more true
73 for overtopping flood events, which are more difficult to model. In addition, the
74 limited knowledge of past hydro-meteorological conditions challenges our ability

75 to identify the critical hydro-meteorological conditions, which can led to flood.
76 However, such knowledge is crucial not only for early-warning systems but also to
77 anticipate the potential effect of sea-level rise in the future.

78 The present paper aims at demonstrating how knowledge of past event occur-
79 rence, their driving conditions and probability can be improved by joining histor-
80 ical, statistical and modelling approaches. We focus on a macrotidal site (Gâvres,
81 France) subject to overtopping and investigate the 1900-2010 period. First, the
82 site, method and flood model are described (Section 2). Section 3 describes the
83 databases and the added value of the model simulations to identify past flood
84 events. Section 4 describes the main flood events, identifies hydro-meteorological
85 conditions leading to flood events, estimates their probabilities, analyses the sensi-
86 tivity of flood event to changing forcing conditions and evolving coastal defences,
87 and investigates the effect of sea-level rise. The method, results, limits, and impli-
88 cations for local risk prevention and early warning systems are discussed (Sect. 5)
89 before drawing the conclusion.

90 2 Site, methodology and model

91 2.1 Gâvres

92 Gâvres is located on the French Atlantic coast (Figure 1a), in a macro-tidal envi-
93 ronment (mean spring tidal range: 4.2 m). This site is mainly subject to overtop-
94 ping, as illustrated for instance by the past flood event of the 10th of March 2008
95 (Cariolet 2011; André 2014; Le Roy et al. 2015). Its surface area is smaller than
96 2 km². In 2015 there were 695 inhabitants (and 752 in 2009), after the national
97 French statistics (INSEE). This population is multiplied by 5 in summer. During
98 the 2008 flood events, about 120 houses were flooded, after the data provided
99 by the town hall (Figure 1b). As a preliminary analysis of critical water levels
100 (including still water levels and waves) for flood, a bathtub method accounting
101 for the connectivity (see e.g. Poulter and Halpin 2008) was applied to a Digital
102 Elevation Model (DEM₂₀₀₈) representative of the 2008 topo-bathymetry (Figure
103 1a; see section 2.3). We find that land is flooded for nearshore water levels larger
104 than 3.77 m IGN69 (national vertical datum).

105 Local waves are affected by the presence of an offshore island (Groix) located
106 at the West of the study site (Figure 1c), such that the offshore wave conditions
107 between the site and Groix are strongly non-uniform. This local non-uniformity
108 makes the identification of the wave conditions leading to flood events not straight-
109 forward. To tackle this issue, offshore wave conditions need to be considered. Here,
110 after some wave modelling tests (not shown), the local non uniform wave condi-
111 tions can be satisfactorily modelled by propagating waves observed south of Groix
112 (Figure 1c, grey star).

113 Since more than 10 years, a lot of knowledge has been gained on the time
114 evolution of the territory of Gâvres, its coastal defences and past flood events.
115 The first key study was performed by Le Cornec and Schoorens (2007) as part
116 of a flood hazard assessment for regulatory coastal risk prevention plans. Since
117 1900, there have been many modifications of the territory. First, about half of the
118 buildings were built after 1950 (Figure 2 ; see also Le Cornec and Ferrand 2009;
119 Le Berre et al. 2012). Before 1915, there were no coastal defences, except along the

120 narrow part of the site and the east part of the tombolo (the so-called "polygone"
121 area). However, at that time, there were large coastal dunes. But in the early 1940's
122 (second world war), significant volume of sediment has been extracted from these
123 dunes for construction purposes (*Le Cornec et al. 2012*). After the local authorities,
124 this extraction weakened the capacity of the dunes to protect the land from floods
125 (for further details see *Le Cornec et al. 2012*). The urban development started in
126 the 1950's (most of the area flooded in 2008 was a lagoon in the 1900's), and coastal
127 defences have been progressively built along the coast, to fix the shoreline, with
128 the aim of protecting inland assets from flood and erosion. These coastal defences
129 were damaged and consolidated many times (*Le Cornec and Peeters 2010*). Hence,
130 a recent upgrade of coastal defences was implemented after the 2008 flood event.

131 In addition to land cover and coastal defences changes, the analysis of aerial
132 photographs shows that rocky outcrops that were not visible in 1932 appear now
133 on recent images in front of the Grande Plage beach, and that the overall surface of
134 visible rock outcrops is increasing with the time (Figure 2; see also *Le Cornec and*
135 *Peeters 2010*). This suggests a general trend toward a decrease of the intertidal
136 sediment volumes and a lowering of the intertidal topography. Consistently, two
137 groins were built in 2012 just at the east of the study site, along the south beach
138 of the tombolo, in order to prevent erosion and potential subsequent flood. Since
139 then, the beach was nourished several times.

140 2.2 Method

141 To investigate the past flood events and the conditions leading to flooding, we
142 follow the method summarised in Figure 3.

143 The first step consists in collecting all the information available on the study
144 site: in addition to scientific literature, this includes technical reports, coastal haz-
145 ards studies, local events knowledge, risk management practices, historical evolu-
146 tion of coastal defences and assets, etc. This allows drawing a first overall picture
147 of the main past flood events and factors causing flood. Then, two databases
148 are built: a damage events database (DED) and a hydro-meteorological database
149 (HMD). DED contains damage events resulting either from flood or from other
150 drivers (wind, erosion, etc.), and, for each event, a flood occurrence indicator and
151 its confidence indicator. The hydro-meteorological database contains continuous
152 time series, at least for water levels (including sea-level rise, tide and atmospheric
153 storm surge) and wave conditions. Locally the wind can also be a key driver, so
154 that the local wind conditions needs also to be estimated over the study period
155 (here, this is case, as it will be shown in the present paper).

156 Then, a preliminary comparison of DED and HMD is performed, in order to
157 identify if there are extreme hydro-meteorological conditions corresponding to no
158 flood events. If this happens, then further research of historical archives describing
159 the damages is required to reduce the uncertainties on these suspicious events.
160 This analysis potentially allows improving the quality of the DED database. A
161 numerical model relevant for the study site can be used optionally (this is the
162 case in the present study) to comfort the quality of the damage events database
163 and to help guiding the historical information survey. First, the model is used to
164 compute the flood or flood occurrence indicator (e.g. water volume invading the
165 land) related to the events of the DED database. This step leads to the creation

166 of a coastal flood model database (CFD). Then, the DED and CFD databases
167 can be compared to refine the confidence in the identified flood events of the
168 DED database, and to identify potential events for which both databases disagree.
169 If the model results suggest a significant flood whereas historical information is
170 uncertain, or if the event is known as a “no flood” event, then further research on
171 historical information (archives) is pursued. If additional historical information is
172 found, the DED database is updated.

173 After this loop, we assume that the DED database is the best that could be
174 achieved. Then a deeper analysis of the datasets is performed, for instance by char-
175 acterising the critical hydro-meteorological conditions leading to flood, estimating
176 their probability of exceedance and the potential changes with sea-level rise. In the
177 present study, the model is also used to better understand the flood occurrence
178 sensitivity to the hydro-meteorological forcing parameters.

179 2.3 The coastal flood modelling: models, set up, and flood indicator

180 To support the flood event analysis, a numerical model is set up with the objective
181 to provide indicator of flood events (in terms of occurrence and even in terms of
182 relative intensity), with a good accuracy, but with an affordable computation time.

183 To ensure the accuracy, we use the non-hydrostatic phase-resolving model
184 SWASH (*Zijlema et al.* 2011), which allows simulating wave overtopping and
185 wave overflow. The computational domain is shown in Figure 1a. The space and
186 time resolution are respectively 3 m and more than 10 Hz. The topography and
187 bathymetry are based on bathymetric surveys (SHOM, DHI), lidar (public RGE-
188 Alti@1m product) and GPS survey on coastal defences. In addition we propagate
189 the offshore wave conditions (south of Groix) to the boundaries of the SWASH
190 model using the spectral wave model WW3 (*Ardhuin et al.* 2010), taking into ac-
191 count the local wind (computation domain shown in Figure 1c). To summarize:
192 WW3 propagates the offshore wave conditions, taking into account the local wind
193 and still water level; wave parameters (H_s, T_p, D_p) are extracted along the bound-
194 aries of the SWASH computational domain; SWASH is run with the non-uniform
195 wave boundary conditions, the still water level and the local wind.

196 This model chain has been validated in terms of flooded area on the 10/03/2008
197 flood event (called Johanna) (see *Le Roy et al.* 2015, for more details on the flood
198 event). The Digital Elevation Model (called DEM₂₀₀₈) used as input of SWASH is
199 representative of this Johanna event (see *Le Roy et al.* 2015). For this validation,
200 the model has been run for an event that lasts over 6 hours, centred on the high tide
201 (i.e., starting 3 h before high tide and ending 3 h after), using the best available
202 forcing conditions: still water level modelled in (*Le Roy et al.* 2015), wave and
203 wind extracted from the HMD database (see section 3.1). Figure 1b shows that
204 there is a reasonable agreement between the modelled maximal high water during
205 the event and the observed flood extension (flooded houses).

206 One key issue for the simulation of past flood events is the availability of topo-
207 bathymetric data that prevailed at that time. Here, there is no precise topographic
208 data covering the entire study area and the study period prior to the LiDAR
209 data’s (i.e., here, prior to 2008). Thus, we cannot rigorously reproduce the actual
210 flood extension of past events, but we can investigate flood event occurrence by
211 focusing on water volume entering inland, keeping in mind the uncertainty related

212 to temporal changes of the topo-bathymetry. Modelling events that last 6 hours
213 is time consuming (60 hours on 48 cores). Thus, to provide flood indicators, but
214 with a reduced computation time, we focus on the water volume entering inland
215 (Vol) at high tide, over a 15 minutes time lapse. We estimate this water volume by
216 running the WW3 model first (over 2h to reach steady wave conditions), and then
217 the SWASH model over a 20 minutes window. Such simulation costs 1h30min
218 of time computation on 48 cores approximately. Considering that the spin-up
219 of the SWASH simulations can take a few minutes (but is always smaller than
220 5 min), the flood indicator (Vol) is computed by estimating the inland water
221 volume at the time steps $t=5$ and $t=20$ min, and then computing the difference.
222 Atmospheric surge, wave and wind conditions exhibit small changes at hourly time
223 scales (this has been checked also on the HMD data), so that the selected indicator
224 is representative of the flood event intensity, and thus can be used to rank the flood
225 events according to their severity.

226 3 The databases

227 3.1 The hydro-meteorological database (HMD)

228 The HMD database includes reconstructed time series of the hydro-meteorological
229 parameters, which can potentially control the flood on Gâvres, from 1900 to 2010.

230 Based on the preliminary site analysis and modelling tests, we identify that
231 the following hydro-meteorological factors are those affecting coastal flood: the still
232 water level (mean sea-level, tide and atmospheric storm surge), the wave conditions
233 (height, period, direction) and the local wind conditions (speed and direction). In
234 addition, preliminary modelling tests allow defining relevant geographical locations
235 of extraction for each of these parameters. The still water level is estimated close
236 to the site (black star in Figure 4b). Wave characteristics South of Groix are shown
237 representative of offshore wave conditions (grey star in Figure 4b; see section 2.1),
238 the modelling allowing to propagate these offshore conditions to Gâvres. Finally,
239 the local wind between Groix and Gâvres (black box in Figure 4b) is needed.

240 There is no tide gauge measurement close enough to the site and covering the
241 entire study period to estimate still water levels (ξ): for example, the tide gauge
242 located in Port Tudy (located approximately 10 km away from the study site)
243 has records back to 1975 only. Thus, we reconstruct each component of ξ (mean
244 sea level, tide, atmospheric storm surge) over the 1900-2010 period, such that ξ is
245 the sum of the 3 components. This approach implicitly assumes that there is no
246 interaction between sea-level rise, tide and surge, an assumption which is justified
247 on this site after the studies of *Idier et al.* (2012, 2017).

248 For the mean sea level (relative to the land), we first reconstruct mean sea level
249 changes following the procedure of *Rohmer and Le Cozannet* (2019) (see Appendix
250 A). Then, we reference the sea level time series to the vertical datum IGN69,
251 based on the vertical reference data provided in (*SHOM* 2014). To transform
252 these absolute values to values relative to the ground, the data is corrected from
253 the vertical land movement using the 3 nearest GPS stations data provided by
254 the SONEL network (*Santamaría-Gómez et al.* 2017). As shown in Appendix A,
255 the vertical land motion trend at these 3 stations is negative (subsidence). The
256 mean (computed with the least mean square method) provides a vertical land

257 movement of -0.33 ± 0.15 mm/y. The final relative mean sea level time series
258 (*MSL*) at Gâvres is plotted in Figure 5.

259 We use the tidal component database FES2014 ($1/16^\circ$ resolution ; *Carrere*
260 *et al.* 2016) to reconstruct the tide. To assess the FES2014 quality, we com-
261 pare predictions at Port-Tudy (Groix) with the tide gauge based tidal predictions
262 (SHOMAR). The correlation coefficient (r) is equal to 0.999.

263 For the atmospheric storm surge, waves and wind, we rely on hindcasts. Several
264 datasets are available, but none of them covers the entire period with a sufficient
265 quality. Thus we combine datasets of different qualities and reduce bias between
266 them by using a non-parametric quantile mapping using empirical quantiles (re-
267 ferred to as quantile-quantile (QQ) method in the following; see e.g. *Gudmundsson*
268 *et al.* 2012, for a review on the methods). These biases can be due to either the
269 intrinsic quality of the dataset, or an insufficient spatial resolution (such that the
270 point at which the data are extracted is different from the relevant location of
271 extraction). Table 1 contains the sources of each datasets. Figure 4a illustrates
272 the periods covered by each dataset and the method we used to set up continuous
273 time series over the study period.

274 For the storm surges, we selected three datasets. For the most recent period,
275 we use the 250 m resolution MARC hindcast (2006-2016), whose quality has been
276 proven (see e.g. *Muller et al.* 2014). The two other datasets are based on atmo-
277 spheric pressure hindcasts (CFSR, 20CR), from which the surge is estimated using
278 the inverse barometer (IB) approach. Because such estimated surge does not ac-
279 count for the wind induced storm surge, the resulting estimate is not expected to
280 be accurate. However, using the QQ correction of these datasets allows to indi-
281 rectly account for this wind-induced surge (as the MARC hindcast accounts for
282 the pressure and wind induced storm surge). The CFSR-IB dataset is corrected
283 with the QQ method using the MARC dataset on the overlapping period. Then, a
284 QQ correction is done on the 20CR-IB dataset relying on the corrected CFSR-IB
285 dataset. In both cases (see Figure 15a,b in Appendix B), this leads to an increase
286 of the under-estimated surge values of about 0.10 m for the largest surge values
287 (above quantile level of 99.9%, i.e. above ~ 0.50 m). It should be noted that due
288 to the resolution of 20CR, the extraction point is far from the location of interest
289 (200 km, Figure 4c), but the QQ correction contributes to indirectly propagate
290 this surge to the location of interest. At the end, we concatenate the datasets, such
291 that on overlapping periods, the best quality dataset is always selected. Figure 4a
292 shows the period for which we extract each dataset.

293 For the waves, the highest resolution hindcast available on the study area are
294 Homere and Norgasug (*Boudiere et al.* 2013). These hindcasts have a spatial res-
295 olution of a few hundred meters close to the coast. A comparison of the dataset
296 with measurements (on overlapping dates) is done at the closest wave buoy (Cand-
297 his network, buoy n°05602 located further South, $47^\circ 17.1'N$, $3^\circ 17.1'W$). Norgasug
298 provides the best correlation coefficients ($r=0.98, 0.79, 0.61$, for H_s, T_p, D_p , re-
299 spectively), so that it is selected in priority. Then, the dataset is built backward as
300 follows: Homere, BoBWA (10 km resolution), Sonel-waves (based on 20CR wind
301 forcing). As for the surges, we apply QQ corrections to improve the quality of the
302 wave data. First, we correct the local Homere data using the Norgasug hindcast
303 over the 2008-2016 period. As highlighted by Figure 16a,b,c in Appendix B, the
304 distributions (before correction) are quite close. The QQ correction leads to H_s
305 changes smaller than 0.50m for the highest waves (above the 99.9% quantile level,

i.e. above 6.20 m), T_p changes of about 1s for T_p values above 16 s, and a clockwise correction of a few degrees for the main mode (with a shift from 262°N to 265°N).

Then, Bobwa and Sonel-waves are corrected using the corrected Homere hindcast, as they do not overlap the Norgasug hindcast. The resulting correction of Bobwa (Figure 16d,e,f in Appendix B) compares well with the one of Homere (Figure 16a,b,c) with a small decrease of H_s (~ 0.40 to 0.50 m) for the highest waves (H_s larger than the 99.9% quantile level of ~ 7 m), a slight decrease (in average) in T_p and a few degrees of counter-clockwise correction in D_p for the main mode (with a shift from 267°N to 265°N). The corrections of the Sonel data are much larger (see Figure 16g,h,i), which is expected because the Sonel wave extraction point is located much more offshore (Figure 4b).

Regarding the wind, we first use the CFSR (1979-2010) hindcast to provide wind speed and directions for the most recent period. To complete the time series, we use the 20CR hindcast and correct it with the QQ correction method, using the CFSR data (Figure 17 in Appendix B). This leads to decreasing the 20CR wind speed of up to almost 7 m/s for quantile levels above 99.9% (i.e. $U > 20$ m/s), and to a clockwise rotation of about 15° for the main mode (with a shift from 245°N to 260°N), which is also the one corresponding to the largest wind speeds.

Finally, the HMD database covers the 1900-2010 period with a 10 min time step (linear interpolation). Figure 5 shows the distribution of each hydro-meteorological variable. The maximum values of the relative mean sea level, tide, surge, significant wave height, wave peak period and wind velocity are 0.52 m IGN69, 2.63 m, 0.83 m, 9.18 m, 25.20 s and 27.67 m/s respectively. The dominant wave direction is 265°N (i.e. from W-SW), while the wind direction is bimodal with a dominant mode at 260°N .

3.2 The historical damage events database (DED)

3.2.1 Initial set up

To set up the damage event database, we start from the study of *Le Cornec et al.* (2012), which referenced 44 damage events between 1900 and 2010 based on the Gâvres municipal archives, State Department archives (Bridges and Highways, Maritime Services), military archives and newspaper articles. This first dataset was completed with further research revisiting newspapers dated back up to 1900 (*Lambert* 2017), which led to identify 4 additional damage events (13-15/02/1900; 7-9/12/1911; 11/04/1922; 13-14/03/1937), and provided complementary information on 4 events (02/02/1904; 09/01/1924; 26-27/11/1924; 27/01/1936). This additional information also includes some reports on storm impacts in Port-Louis and Lorient (close to Gâvres). Then we classify each event in terms of flood event (F): 0 (no flood), 1 (moderate flood; e.g. few waves overtopping coastal defences), 2 (massive flood). In addition, we assess the uncertainty (C) of this classification (1: medium confidence, 2: high confidence). As a general rule, for every certain flood event, a confidence indicator of 2 is given. For all the other events, a confidence value of 1 is used in the first version of the database, before critical review with respect to numerical and statistical modelling. Indeed, the historical information available on these medium confidence events concerns mainly shipwrecks or coastal defence damages (erosion), and inland damages, but which seem related

351 to the direct effect of wind, rather than flood. For all these events, there is no
352 information on potential flood or waves overtopping the defences. However, this
353 does not guarantee that no waves overtopped the defences at that time. The list,
354 dates and classification of the identified events are given in Appendix C (Table
355 5, *F1* and *C1* indicators). Some events, especially the oldest ones, are not always
356 well identified in time (in Appendix C, see e.g. the event Nd=6 which is referenced
357 between the 12 and 20th of October 1922), while the damage event is identified
358 with an half-day resolution on the last decades.

359 The DED database includes 48 damage events between 1900 and 2010. Among
360 them, 9 correspond to a flood event. Among these flood events, 5 seem to be char-
361 acterised by moderate overtopping or moderate flood (02/02/1904, 07/02/2001,
362 27/10/2004, 10/02/2009, 28/02/2010), while the 4 others definitively correspond
363 to significant flood events (09/01/1924, 26/02/1978, 10/01/2001, 08/03/2008).
364 Especially for the first half of the XXth century, the absence of information indi-
365 cating a flood does not mean that there was no flood. Indeed, the urbanisation has
366 strongly increased after 1950 (most of the areas flooded during the Johanna event
367 (2008) were not built in 1950, see Figure 2). This implies that moderate flood
368 events have not necessarily been observed, and this could explain why the mod-
369 erate overtopping events have been mainly identified over the last decades. Thus,
370 the 9 flood events should be considered as a low bound of what really happened
371 between 1900 and 2010. This is an inherent limitation of any historical database.
372 Regarding the 1904 damage event, there was no clear indication of local flood.
373 However, one of the available archive (SHM1 in Table 1) stated that "lors du raz
374 de marée . . . les parapets de sable sans soutien intérieur ont été absolument im-
375 pressionnant à arrêter l'invasion de l'eau" (translation: *During the tidal wave ...*
376 *the parapets of sand without inner support were absolutely impressive in stopping*
377 *the invasion of the water*), suggesting that a massive flood event ("raz de marée")
378 occurred at least in the surrounding, but that the land behind the parapets (here,
379 the tombolo at the east of the study area) were not flooded. Based on this infor-
380 mation, we cannot ensure there was no flooding anywhere on the Gâvres land. In
381 addition, at Lorient (city located at about 5 km at the North of Gâvres) the 1904
382 event was considered at that time as a storm which would remain in memories as
383 one of the most damaging event in the region (see the article entitled "Un raz de
384 marée" from the "Courrier des Campagnes" journal of the 7th of February 1904).
385 Thus, we classify the 1904 event as a moderate flood with a medium confidence
386 index. Following our approach (Figure 3), this first version is refined in the next
387 paragraph.

388 3.2.2 Validation, modelling contribution and update

389 For each damage event of the database, we extract the hydro-meteorological condi-
390 tions at high tide (see Appendix C). When extreme hydro-meteorological condi-
391 tions are identified in the HMD but can not be associated to any flood event in the
392 DED, we seek clues in new complementary historical information, and eventually
393 use them to re-evaluate the flood and confidence indicators. In our case, the model
394 presented in section 2 can be used to identify such events. To do so, we compute
395 the flood indicator (*Vol*) on each hydro-meteorological conditions associated to
396 the damage events, for the DEM₂₀₀₈, keeping in mind that the coastal defences
397 and the nearshore bathymetry (upper part of the beach) changed significantly over

the time, so that the model results should be used as an indicator, rather than an accurate reconstruction of what actually happened during the event. Then:

- For damage events such that $F = 0$ and $C = 1$, if $Vol > 0$, then we keep the initial value of F and C ; else if $Vol = 0$, the model results and partial historical knowledge agree such that the confidence is increased and C is equal to 2.
- For damage events such that $F = 1$ and $C = 1$, if $Vol > 0$ and additional historical information indicates a significant flood, then $F = 2$ and either $C = 2$ (if the historical information are precise and local) or $C = 1$.

First, for 17 of the 39 "no flood" events of the initial version ($F1 = 0$) of the database, the model predicts that no flood occurs ($Vol = 0$). Thus, the confidence is increased to $C = 2$ for these 17 events. Second, the model predicts the 9 flood events ($F1 > 0$) identified in the initial version of the DED database (Figure 6). This reinforces the confidence in the model skills. However, ranking events according to their intensity using the modelling results and the DED leads to different results for the events of 1904, 2001, 2009 and 2010.

The largest volume is obtained for the 1904 event, suggesting that a massive flood occurred at that time. Thus, further newspaper research has been pursued. We found one reference (*Le Matin*, 05/02/1904, see Table 2) stating that "Mais sur toute la côte, à [...] Gâvres [...], tous ces petits ports où la mer bat au pied des maisons, furent balayés en partie par les lames qui arrachaient des maisons" (translation: *But all along the coast, at [...] Gâvres [...], all these small harbours where the sea beats at the foot of the houses were swept by the sea which tear off the houses*). The 1904 event is one of the events characterised by the largest still water level, wave height, wave period and wind (it can be seen by comparing the 1904 values of Table 3 with the distribution of the HMD database shown in Figure 5). In addition, in 1904, all the area flooded during the Johanna event was uninhabited and still connected to the sea (Figure 2). This could explain why this event did not appear as a drastic flood in the contemporary newspapers. However, the topo-bathymetry probably changed significantly between 1904 and 2008 (there were large dunes and probably a higher intertidal beach, see section 2). In addition, if a massive flood really occurred in Gâvres in 1904, it is still a bit surprising to find so few proofs of floods, in particular considering the significant amount of information found for the older flood events on the Gâvres tombolo (e.g. in 1866 or 1896) or for the same 1904 events but on the surrounding towns (*Le Cornec et al.* 2012). Based on these elements, the DED database is updated for the 1904 event by setting $F2 = 2$ (massive flood) but with $C2 = 1$ (medium confidence), as there are still doubts on the massive character of this historical flood event in Gâvres.

During the January 2001 event, coastal defences fully collapsed along the southern beach. Because our digital elevation model (DEM_{2008}) does not account for this collapse, we obtain a low flood indicator value using the model. After the 2008 flood event, the coastal defences were raised. To account for this upgrade of coastal defences, we set up a second DEM ($DEM_{upgrade}$) based on the DEM_{2008} but including higher coastal defences. Specifically, we use GPS and theodolite surveys to determine the new coastal defence height. These surveys were performed in 2017, but still reflect the current status of coastal defences as they were not upgraded after the beginning of 2009. Taking into account this upgrade leads to $Vol = 0$ and $\sim 35 \text{ m}^3$ for the 2009 and 2010 events respectively. This is consistent

446 with observations, as few overtopping were reported in 2009 and 2010. In addition,
447 these values are much smaller than for the 1904, 1924, 1978 and 2008 events
448 (considering the DEM_{2008} for these 4 events). This hierarchy in the intensity of
449 flood events is consistent with the DED database.

450 The cross-fertilization of historical information and the model results leads to
451 changing 18 events in the damage database, mainly their confidence indicator (17
452 events over 18). Appendix C includes the final version of the database ($F2, C2$),
453 and Table 2 provides the newspapers and archives considered for the 9 flood events.

454 4 Analysis

455 4.1 Flood events characteristics

456 Significant and moderate (overtopping) flood events are indicated in Table 3, together
457 with their hydro-meteorological conditions.

458 Figure 7 shows the storm tracks of these 9 flood events. They exhibit very
459 different patterns, with for instance the 2010 storm coming from SW and the
460 2008 storm coming from NW (Greenland). The travel speeds of these storms also
461 display significant differences, with the 1904 storm being the slowest one (see how
462 close the dark blue dots are in the Celtic Sea and English Channel), meaning that
463 this storm affected the surrounding of Gâvres during a long time. The 2001 event
464 includes two storm tracks, while the 2010 storm moved very quickly.

465 In the present study, we consider the 8 following forcing conditions: mean sea
466 level, tide, surge, wave height, wave period, wave direction, wind intensity and wind
467 direction. This 8 dimension problem can be reduced to a 6 dimension problem by
468 replacing the three first components by the resulting still water level ξ . Figure 8
469 shows all the damage events in this 6 dimension hydro-meteorological domain. The
470 5 main flood events correspond to different settings. The 1924 and 1978 events are
471 characterised by high still water level (3.14 and 3.06 m IGN69), high ($H_s = 8.5$ and
472 5.6 m) and long waves ($T_p = 21.2$ and 18.8 s), and moderate winds ($U = 7.2$ and
473 10.5 m/s) from NW and SW. The 2001 flood event is characterised by a lower still
474 water level of 2.97 m IGN69, smaller ($H_s = 3.5$ m) and shorter waves ($T_p = 11.2$
475 s), and stronger winds (13.5 m/s) from SW, but we should keep in mind the 2001
476 collapse of coastal defences along the South beach (Grande Plage). The 2008 flood
477 event is characterised by a much larger still water level of 3.42 m IGN69, large wave
478 height ($H_s = 5.53$ m) and moderate period ($T_p = 11$ s), for even stronger winds
479 (18.2 m/s) coming from W. The characteristics of the 1904 event look similar to
480 the 2008 event (large water level, large wave height) but with a larger wave period
481 ($T_p = 15.1$ s). Finally, the damage event associated with the highest still water
482 level ($\xi = 3.47$ m IGN69) corresponds to the 2010 Xynthia storm, but this event
483 is identified as a moderate flood event, since overtopping only was observed. The
484 corresponding hydro-meteorological conditions are quite similar to the one of the
485 2008 flood event, but with a significant wave height twice as small. This suggests
486 (and is confirmed by the model simulation) that without coastal defences upgrade
487 early 2009, the Xynthia storm would have led to a much larger flood event.

488 After the testimonies (*Le Cornec et al.* 2012), the recent flood events (February
489 2001, 2004, 2008, 2009, 2010) were induced by wave overtopping. After the model
490 results, the flood is mainly induced by wave overtopping for the 9 flood events,

491 whatever the DEM considered (DEM_{2008} , $DEM_{upgrade}$). This suggests that the
 492 main flood regime since 110 years is overtopping.

493 4.2 Critical hydro-meteorological forcing conditions

494 4.2.1 Based on databases

495 The cross-analysis of the Hydro-Meteorological and Damage Events Databases
 496 provides indications on the critical forcing conditions leading to flood (Figure
 497 8). First, the minimal still water level above which flood occurred is estimated
 498 to be $\xi_c = 2.77$ m IGN69. Second, from the scatter plot (ξ, H_s) we can draw
 499 a critical contour above which all the flood events occurred (red dotted line).
 500 The minimal peak period above which all significant flood occurred is $T_{pc} \sim 11$ s
 501 (scatter (ξ, T_p)). The minimal wind speed above which all significant flood occurred
 502 is $U_c \sim 7$ m/s (scatter plot (ξ, U) in Figure 8). This analysis suggests that the
 503 main drivers are the still water level and wave height, the effect of these drivers
 504 being modulated by the wave period and wind velocity.

505 In the above analysis we considered the still water level ξ , which includes the
 506 mean sea level, tide, and surge. Figure 9 shows the contribution of each of these
 507 three water level components. Comparing the first (1904) and last event (2010,
 508 corresponding to the largest still water level), we find that mean sea-level rise
 509 (~ 21 cm) contributes to 87% of the difference in ξ (24 cm). This difference in
 510 mean sea levels is comparable to the variability of the surges associated to the flood
 511 events. This highlights that past sea-level rise has already significantly altered the
 512 hydrodynamic forcing in Gâvres. Such increasing effect is not directly visible in
 513 the simulated floods over the 1900-2010 period (Figure 6), as flood is driven not
 514 only by the still water level, but also by the waves. However, we could wonder
 515 how a flood induced by the 1904 forcing conditions would look like for the present
 516 mean sea-level (see section 4.4).

517 4.2.2 Based on numerical simulations

518 The damage database contains "only" 48 events. Characterising the flood sen-
 519 sitivity to the 6 hydro-meteorological components based on information on 48
 520 events only is challenging. In addition, as discussed above, the topo-bathymetry
 521 has evolved over time. Thus, to further explore the flood sensitivity to the forcing
 522 conditions, we use the model simulations, considering a fixed topo-bathymetry
 523 (here, the DEM_{2008} configuration). In addition to the 48 simulated historical
 524 events (section 3.2.2) we made many other simulations (300) that we use here
 525 to identify the critical hydro-meteorological conditions leading to flooding. This
 526 represents 348 simulations, which are distributed as follows: : (i) 78 corresponding
 527 to the hydro-meteorological conditions listed in Figure 14, (ii) 90 corresponding to
 528 a sensitivity study to the wind direction for the hydro-meteorological conditions
 529 associated to the 1904, 1924, 1978, 2008 and 2010 flood events ; 20 corresponding
 530 to the historical conditions of the HMD database characterised by the largest still
 531 water levels (but not corresponding to events of the Damage Event Database),
 532 (iv) 160 focusing on the Johanna event and varying each parameter, keeping the
 533 others fixed. However, this dataset explores conditions around those related to

534 events listed in the damage database. To complete this dataset in a larger domain,
 535 we set up 100 additional scenarios. For this purpose, we followed the methodology
 536 described by *Gouldby et al.* (2014) to select a limited number of extreme, but re-
 537 alistic, forcing conditions to be used as inputs of the simulation model. This task
 538 was conducted by combining two methods. First, a multivariate extreme value
 539 analysis was conducted to randomly generate via a Monte-Carlo procedure a large
 540 number of offshore conditions (here chosen as 150,000 realizations), namely ξ ,
 541 H_s , T_p , D_p , U , D_u , by taking into account extreme values (and their dependence
 542 structure) based on the method described in Appendix D (but applied to events
 543 with high tide amplitude larger than 2.342 m and surge peak larger than 0 m).
 544 Second, 100 scenarios are selected from this dataset by means of a clustering al-
 545 gorithm based on maximum dissimilarity (MDA algorithm *Willett* 1999), and 100
 546 additional simulations are done.

547 We analyse the results of these 448 simulations in each of the bivariate input
 548 space (Figure 10) as follows. The bivariate space is discretized in regular cells.
 549 Then, in each cell, we compute the ratio r between the number of simulations
 550 leading to $Vol > 0$ and the total number of simulations done in this cell. First,
 551 critical contours can be identified in the (ξ, H_s) and (ξ, T_p) spaces, as in the analysis
 552 of the hydro-meteorological conditions related to the damage event database. For
 553 D_p , a critical contour below which flood is favoured can also be seen. This critical
 554 contour is such that D_p increases with ξ . Regarding the wind speed, r is increasing
 555 with increasing U , and for $U > 20$ m/s, all the simulations lead to flood event.
 556 Regarding the effect of D_u , the pattern is less clear, but it seems there is a range
 557 of direction (from about 90 to 240 °) favouring flood events.

558 To better assess the sensitivity to the wind direction, we investigate the ef-
 559 fect of D_u for the three past flood events subject to the largest local wind speed
 560 (Figure 8), i.e. the 1904, 2008 and 2010 events, with D_u ranging between 0 to
 561 340°, and $\Delta D_u = 20^\circ$. Figure 11 shows that whatever the wind direction, Vol is
 562 always larger than 0, such that the flood occurrence is not sensitive to D_u for these
 563 events, contrary to the Vol intensity which is very sensitive to the wind direction,
 564 reaching its maximum for $D_u \sim 230 - 240^\circ$. For the 1904, 2008 and 2010 events,
 565 the volume is increased by 17%, 256 %, and 466 % respectively, between its mini-
 566 mum and maximum values ($(\max(Vol) - \min(Vol)) / \min(Vol)$). On such a small
 567 domain (about 10 km between the offshore wave conditions and the study site), a
 568 so significant effect of local wind direction was not expected. The fact that wind
 569 direction of 230-240° are favouring flood can be physically interpreted as follows:
 570 the wind not only generates local waves, but also modifies the swells, in such a way
 571 that deep water swells coming from a given direction D_p are amplified by winds
 572 coming from a similar direction ($D_p \pm 30^\circ$), after *Aarnes and Krogstad* (2001). At
 573 the scale of the computational domain, the analysis of the spectral wave model
 574 (WW3) outcomes (see the black contour on Figure 1c) shows indeed that the
 575 largest regional scale wave height is obtained for simulations with a wind direction
 576 close to the wave direction. This explains the bump observed on the curves. The
 577 bumps are not exactly centred on the wave direction (248, 256 and 190 ° respec-
 578 tively) because of the local nearshore wave refraction. As an illustration, Figure
 579 12 shows the regional wave propagation for the hydro-meteorological conditions
 580 corresponding to the Johanna event (panel b) and how the wave pattern changes
 581 with the direction of the wind acting on the computational domain (panel a): (i)
 582 winds coming from 240° leads to the largest waves at the regional scale (panel a),

(ii) at the more local scale, H_s (extracted at the location indicated by the black dot on panel b) is also maximum for the 240° wind direction (panel a, polar plot) with $H_s = 2.9$ m to compare to $H_s = 2.3$ m for northern winds. Thus, local winds from SW direction appear as the most dangerous in terms of flood occurrence. Figure 11 also shows that the wind direction of the 2008 and 2010 flood events (black diamonds) falls outside the most unfavourable range, while the direction corresponding to the 1904 event corresponds to the most adverse direction.

The above critical conditions have been obtained considering a given topobathymetry and coastal defence scheme (DEM_{2008}). However, as suggested in section 3.2.2, coastal defences play a significant role on the flood intensity. For instance, the Vol indicator is divided by 8 for the Johanna event with the upgraded coastal defences compared to its reference value obtained for the 2008 coastal defence scheme (Figure 6). However, Vol is still not null, so that (moderate) flood is still expected even with upgraded coastal defences. For the 2009 and 2010 events, our results show that the coastal defence upgrade significantly reduced the flood. Thus, the critical hydro-meteorological conditions identified above should be considered as a secure estimation, as they assume lower coastal defences than those currently in place.

4.3 Hydro-meteorological conditions and flood events: occurrence probability

Over 110 years, at least 4 significant flood events occurred. This suggests an empirical return period of significant flood on Gâvres area of about 25 years. However, due to the uncertain significant flood event of 1904, there could have been a maximum of 5 significant flood events, such that 20 years could be considered as a low bound for the return period of significant flood events, keeping in mind that this is only an empirical estimation, which should be considered with caution. However, the topography and coastal defences have strongly evolved over the century and these 10 last years after the Johanna event, which led to increase the coastal defence height. In addition, no reliable estimate of the return period of floods (whether significant or not) can be provided using the present database, as events with moderate overtopping have probably not been reported during the first half of the century (see section 3.2).

However, using the continuous HMD database which covers 116 years (Figure 4), we can characterise the probability of occurrence of offshore conditions that led, in the past, to significant or moderate flood. For this purpose, bivariate extreme value analysis (bEVA) is performed by focusing on the still water level relative to the mean sea-level ($\xi_{/MSL} = \xi - MSL$) and wave height (H_s), which appeared as the main drivers (see section 4.2.1). The objective of bEVA is to extrapolate the joint probability density of the offshore sea condition variables to extreme values with appropriate consideration of the dependence structure. Using the HMD database, we follow a similar procedure as the one described by *Nicolae-Lerma et al.* (2018). The details on the procedure and application to our datasets are provided in Appendix D. Figure 13 shows the return periods of exceedance (T_R) obtained with this method. Amongst the 5 significant flood events, the offshore conditions ($\xi_{/MSL}; H_s$) of the significant flood of the 10^{th} of January 2001 have the smallest return period of exceedance. This suggests a significant role of the coastal defence failure that took place during this event. The 1924 event offshore

629 conditions exhibit the largest return period ($> 1,000$ y), while $T_R \in [100 - 200]$
630 y and $T_R \sim 100$ y for the 1904 and 2008 events conditions, respectively. We can
631 also notice that the 2010 event offshore conditions had a return period ($T_R \sim 20$
632 y) larger than the one of 1978 ($T_R \sim 10$ y).

633 4.4 Impact of sea-level rise

634 As highlighted in section 4.2.1 and in a number of other locations (*Haigh et al.*
635 2011; *Hallegatte et al.* 2013; *Arns et al.* 2015; *Le Cozannet et al.* 2015; *Haigh*
636 *et al.* 2016), past and future sea-level rise (SLR) should significantly alter flood-
637 ing. In the previous paragraph, the joint return period of water level and wave
638 height was estimated considering the reconstructed mean sea level (Figure 13).
639 This result allows discussing the impact of sea-level rise on return periods. For
640 instance, assuming that the water level ξ_{1904} of the 1904 flood event is reached
641 in 2017, the corresponding tide and surge contribution ($\xi_{/MSL}$) would be smaller,
642 and the return period of exceedance T_R would be decreased by a factor
643 larger than 5 (for the 1904 event: $\xi_{/MSL_{2017}} = 20$ y, to be compared to 100 y
644 $< \xi_{/MSL_{1904}} < 200$ y ; see e.g. the black bar and point of the 1904 event in Fig-
645 ure 13). This analysis is extended to a large range of sea-level rise values (-0.4
646 to 1 m) and to the 9 flood events. Figure 14 shows the variations of T_R with
647 SLR for each event conditions (as a reference, $SLR=0$ corresponds to the 2017
648 year). First, for all events except that of 1924, T_R decreases to values smaller
649 than 1 year for $SLR \leq 0.63$ m. Such SLR value is equal to the median regional
650 mean sea-level rise at the 2100 horizon provided by the 5th assessment report
651 of the IPCC for the RCP8.5 scenario (data provided by the Integrated Climate
652 Data Center of the Hambourg University, available online: [http://icdc.cen.uni-](http://icdc.cen.uni-hamburg.de/daten/ocean/ar5-slr.html)
653 [hamburg.de/daten/ocean/ar5-slr.html](http://icdc.cen.uni-hamburg.de/daten/ocean/ar5-slr.html); *Church et al.* 2013; *Carson et al.* 2016).
654 This suggests that by 2100, the joint conditions (ξ, H_s) corresponding to the past
655 flood events would statistically occur at least once a year.

656 5 Discussion

657 5.1 Limitations and perspectives

658 The present work contains residual uncertainties. First, the damage event database
659 probably lacks small events in the first half century (among the "no flood" events,
660 there could be some moderate flooding events, but which were not reported at
661 that time). For the simulations on past events, we considered the 2008 bathymetry.
662 However, topographic changes are also expected to take place in intertidal area.
663 In particular, we noticed in section 2.1 that, at least between 1932 and 2008,
664 the intertidal beach was lowered by more than 1 m in about 75 y (see Figure
665 2). In addition, we considered 2 coastal defences configurations only (2008 and
666 an upgraded version representative of the configuration since 2009), although we
667 know that there were massive dunes along the coast one century ago. For these old
668 configurations (coastal defences and bathymetry), the lack of topo-bathymetric
669 data accounts i.a. for the limited confidence in the 1904 event. Regarding the
670 hydro-meteorological database, we used a quantile-quantile correction method to

671 build consistent long enough time series of hydro-meteorological conditions. Even
 672 with this correction, the accuracy of the obtained forcing data is expected to
 673 decrease backwards in time. Due to the lack of local measurements, it was not
 674 possible to estimate the quality of the database for old events as for instance those
 675 of February 1904 and January 1924. Despite these uncertainties, the occurrence
 676 and severity of flood events as obtained from the HMD, DED and simulations still
 677 agree relatively well. This suggests that the databases and modelling experiments
 678 are of sufficient quality to investigate past flood conditions. At least, they allow to
 679 identify past hydro-meteorological events which could lead to massive flood under
 680 the present-day topo-bathymetry.

681 Based on this conclusion, we could consider several implications of this work,
 682 for instance in terms of extreme value analysis. First, at a regional scale, coastal
 683 flood hazard assessment relies on extreme value analysis of offshore hydrodynamic
 684 conditions to define scenarios for flood modelling. One key issue when perform-
 685 ing extreme value analysis is the availability of long enough data to estimate the
 686 return period of interest (*Bulteau et al. 2015; Wahl et al. 2017*). A first approach
 687 to tackle this issue is to perform a hindcast (*Muis et al. 2016*). This approach re-
 688 quires a significant computational effort. In addition, the quality of meteorological
 689 reanalyses is better for the last decades than in the early XXth century, so that
 690 high quality hindcast can be obtained only for the last decades. As a consequence,
 691 extreme value analysis are rarely done on more than 50 years of data. Then, be-
 692 cause our approach based on standard statistical methods and existing hindcasts
 693 allows building hydro-meteorological time series over more than 100 years, it ap-
 694 pears as an alternative solution when high-quality hindcast cannot be generated
 695 on a long enough period (for the return period's estimation). Second, at a more
 696 local scale, specific statistical method to account for partial historical information
 697 of extreme coastal water levels have been developed (*Bulteau et al. 2015; Hamdi*
 698 *et al. 2018*). These methods combine tide gauge measurements and historical in-
 699 formation. They are only applicable when historical information can be related to
 700 a vertical landmark. This is rare in practice, so that this method has not been
 701 used extensively so far. In addition, tide gauge water level observations include
 702 the relative sea-level rise, tides, atmospheric surges, but can also include the wave
 703 setup. In the present work, we rebuild a 1900-2100 relative mean sea-level, tide
 704 and atmospheric storm surge, such that standard extreme value methods can be
 705 used.

706 In future work, it would be interesting to evaluate how tide gauge measure-
 707 ments, corrected hindcasts (back to 1900, following our method), and partial his-
 708 torical information (older than 1900) could be used together to provide extreme
 709 value either of the still water level or of the storm tide level (i.e., including still
 710 water and wave setup). In addition, it would be interesting to explore other cor-
 711 rections methods (see *Gudmundsson et al. 2012*).

712 5.2 Local risk prevention and early-warning system implications

713 Assuming no coastal defence failure (and a fixed topo-bathymetry), the joint prob-
 714 ability analysis (Figure 13) highlights that the conditions leading to the largest
 715 modelled flood (1904) are not necessary the ones of largest joint return period of
 716 exceedance: $T_R \in [100 - 200]$ y for the 1904 event, while $T_R > 1000$ y for the 1924

717 event. First, it should be kept in mind that we focused on the joint probability
 718 of the two main driving variables to determine return periods. However, other
 719 parameters like the wave period or local wind also influence the flood. Second, as
 720 illustrated in (Garrity *et al.* 2007; Idier *et al.* 2013; Sanuy *et al.* 2019), as long as
 721 forcing conditions have a dimension D larger than 1, offshore conditions of return
 722 period T_{R1} induce water level at the coast (or flood) whose return period is not
 723 equal to T_{R1} . This highlights that the probability of flood, which is the relevant
 724 metrics for coastal risk management, can differ significantly from the probability
 725 of flood scenarios identified on T_R isocontours. Where $D > 1$, the probability of
 726 exceedance of a water level at the coast (or a given flood intensity), called Z_c ,
 727 requires identifying all the combinations of forcing conditions leading to exceed
 728 Z_c , i.e. locating the critical contour or frontier $Z = Z_c$ in the input space. It
 729 is noticeable that the black contour of Figure 8 (scatter plot $(H_s; \xi)$) exhibits a
 730 similar shape to the critical contour of water level at the coast obtained by (Idier
 731 *et al.* 2013) in a simpler case ($D = 2$).

732 The knowledge of critical contour or threshold values of hydro-meteorological
 733 conditions for flood occurrence is a key information for flood prevention, adapta-
 734 tion and early-warning system. Flood risk management and prevention practition-
 735 ers in Gâvres already know reasonably well which conditions favour flood. In addi-
 736 tion to the regulatory risk prevention plan (2011, available on <http://www.morbihan.gouv.fr/>),
 737 which includes a flood hazard assessment (Le Cornec and Schoorens 2007; Le
 738 Cornec and Peeters 2008), they know for instance that there is a risk of flood-
 739 ing when a storm is coming with strong local south wind together with a spring
 740 tide. In this case, they monitor several critical locations, mainly along the south
 741 beach (Grande Plage), 1 or 2 hours before the high tide of storm arrival. As
 742 practical results of our study, we refine this knowledge by estimating the main
 743 critical patterns on one hand, based on the DED and HMD databases, on the
 744 other hand, based on modelling (for the DEM₂₀₀₈ configuration). The analyses
 745 of the DED and HMD database provide some values which can be considered
 746 as secure ones (since the coastal defences are currently upgraded): $\xi_c = 2.77$ m
 747 IGN69, $H_{sc} = 2.6$ m, $T_{pc} = 9$ s, $U_c = 4$ m/s (Figure 8). Similar critical values are
 748 found when analysing the model results (ratio r introduced in section 4.2.2, Fig-
 749 ure 10): $\xi_c = 2.5$ m IGN69, $H_{sc} = 2$ m, $T_{pc} = 9$ s, $U_c = 5$ m/s. These thresholds
 750 are slightly different from those obtained using the DED and HMD databases,
 751 keeping in mind that: (1) the discretisation used to compute the ratio r in the
 752 forcing parameter space was limited by the number of simulations ($\Delta\xi = 0.25$
 753 m, $\Delta H_s = 1$ m, $\Delta T_p = 1$ s, $\Delta U = 5$ m/s), (2) the simulations used for the
 754 analyses were done with a single DEM (2008), (3) the 48 damage events of the
 755 database do not cover all the possible hydro-meteorological conditions. First, such
 756 similar results imply that knowing only the past hydro-meteorological conditions
 757 corresponding to the 48 damage events allows to already tackle the main critical
 758 conditions. The additional simulations allow to better capture the joint contours.
 759 Second, the model-based estimation of the critical conditions and contours were
 760 obtained for the DEM₂₀₀₈ configuration, and thus, should be considered as safety
 761 conditions. Such estimation could be further refined to better capture the present
 762 day contours by: (1) considering the upgraded coastal defences and present topo-
 763 bathymetry, (2) increasing the number of simulations. To properly cover the input
 764 space, assuming a regular computation grid experiment, a minimum of 10^6 sim-
 765 ulations (considering the 6 parameters and 10 values per parameters) would be

766 needed to estimate the probability of flood in each bivariate space. This would be
767 far too computationally expensive. Therefore, it could be worthwhile to set up a
768 meta-model to better assess the critical contours (see e.g. *Rohmer and Idier* 2012).
769 Such a meta-model could either focus on flood/no flood occurrence, or on the flood
770 indicator Vol . The work of *Azzimonti et al.* (2019) could also be used to visualize
771 such 6D contours. In addition, it would be needed to regularly update the r plots
772 with the evolution of the topo-bathymetry (including coastal defence evolution).

773 As highlighted by the simulations and the historical 2001 flood event, coastal
774 defences have a significant effect in Gâvres. However, even with the upgraded
775 coastal defences ($DEM_{upgrade}$), the hydro-meteorological conditions which led to
776 the 1904 and 1924 flood events are associated to flood indicator of the same order
777 of magnitude as the one computed for the Johanna event with the DEM_{2008} con-
778 figuration (Figure 6). This gives an indication of the minimal potential intensity of
779 flood that could still occur on Gâvres. In addition, these two large events occurred
780 at the beginning of the century, for a lower mean sea level (Figure 9). If such event
781 occurred in 2017 (in 2017, $MSL = 0.53$ m IGN69, after *SHOM* (2017)), their
782 expected impact would be even worse, with a still water level (3.45 and 3.31 m
783 IGN69, respectively) closer to the largest value of the HMD database (Xynthia,
784 3.47 m IGN69), but with much more energetic wave conditions. The analysis of
785 the changes in joint return period of the water level and the wave height induced
786 by sea-level rise suggests that by 2100, these joint conditions would statistically
787 occur at least once a year. The induced flood will then strongly depend on the
788 risk prevention measures applied in Gâvres. This type of analysis assumes that cli-
789 mate change has a negligible effect on tide (on the study site) and meteorological
790 conditions (which induces atmospheric surge and wave), in comparison with the
791 effect of mean sea-level rise. This assumption seems to be valid at the first order
792 for large enough sea-level rise, based on the work of *Idier et al.* (2017) and *Vous-*
793 *doukas et al.* (2018). A full integration of the nonstationary character of extreme
794 marine variables is identified as a perspective of the present work and can build on
795 recent advances in multivariate extreme value analysis under nonstationary (see
796 e.g. *Davies et al.* 2017; *Galiatsatou et al.* 2019).

797 6 Conclusion

798 In this study, we provide a pluri-disciplinary method relying on history, statistics
799 and modelling to improve our knowledge of past flood events and their driving fac-
800 tors. We apply this approach on the macro-tidal site of Gâvres (French Atlantic
801 coast). Using together historic information (archives, newspapers), hindcasts, hy-
802 drodynamic models and local knowledge on the evolution of the territory, we iden-
803 tify 9 flood events on the 1900-2010 period, amongst which 5 significant flood
804 events (4 with high confidence: 1924, 1978, 2001, 2008; 1 with a lower confidence:
805 1904). The 1904 event was clearly identified owing to the cross-fertilization of the
806 damage and hydro-meteorological databases and the flood simulations. These flood
807 events are driven by the combination of sea-level rise, tide, atmospheric surge, off-
808 shore wave conditions and local wind. The patterns of the 1904 and 2008 events
809 significantly differ from those of the 1924 and 1978 events: larger still water level,
810 less energetic waves, and stronger local wind.

811 The analysis of the hydro-meteorological conditions allows driving the main
812 patterns of the critical contours separating no flood and flood conditions. The
813 analysis of the databases and modelling results lead to very similar conclusions,
814 with the following critical conditions guaranteeing safety against flooding assuming
815 no failure of coastal defences: still water level of ~ 2.5 m IGN69, significant wave
816 height of ~ 2 m, peak period ~ 9 s, wind of ~ 4 m/s. For the events characterised
817 by strong local winds, the local wind direction has a significant effect on the flood
818 intensity. Strictly speaking, these critical conditions apply to the bathymetry and
819 coastal defences up to 2008.

820 An estimated low bound of return period of significant flood event is estimated
821 to be about 20 years, while the return period of exceedance of the associated still
822 water level (relative to mean sea level) and wave height is ranging between less
823 than 1 y (2001 event) to more than 1000 y (1924 event). However, these return
824 periods are changing due to ongoing sea-level rise. They will fall to values smaller
825 than 1 y for all historical flood events, except that of 1924, under the median
826 sea-level projection of the 5th assessment report of the IPCC. Even if this return
827 period represents the probability of a part of the forcing parameters, this illustrates
828 how the future local coastal defence strategy will be crucial for the study site.

829 The present analysis is based on 48 damage events, 9 observed flood and about
830 448 numerical simulations. To really assess flood probability (rather than the prob-
831 ability of forcing conditions) and to improve early-warning systems, more simula-
832 tions would be needed. Furthermore, accounting for the evolving topo-bathymetry
833 and coastal defences would be necessary. A promising way forward could be the
834 development and use of the meta-model approach (*Rohmer and Idier 2012; Rueda*
835 *et al. 2016*). Finally, accounting for the evolving topo-bathymetry and coastal de-
836 fences would be necessary to progress in the area of detection and attribution of
837 coastal flood changes.

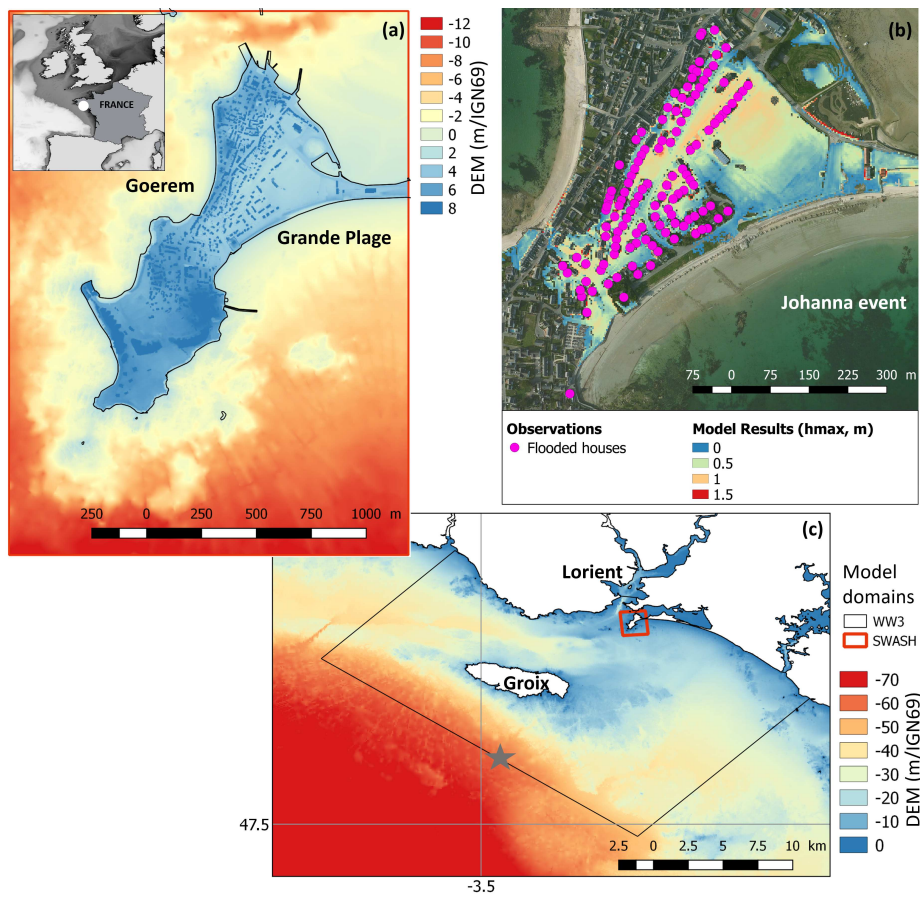


Fig. 1 (a) location of the site and topo-bathymetry; (b) observed and modelled flood for the Johanna event (10th March 2018); (c) surrounding of the study site, computational domains of the hydrodynamics models (WGS84) and location of the offshore forcing wave conditions (grey star).

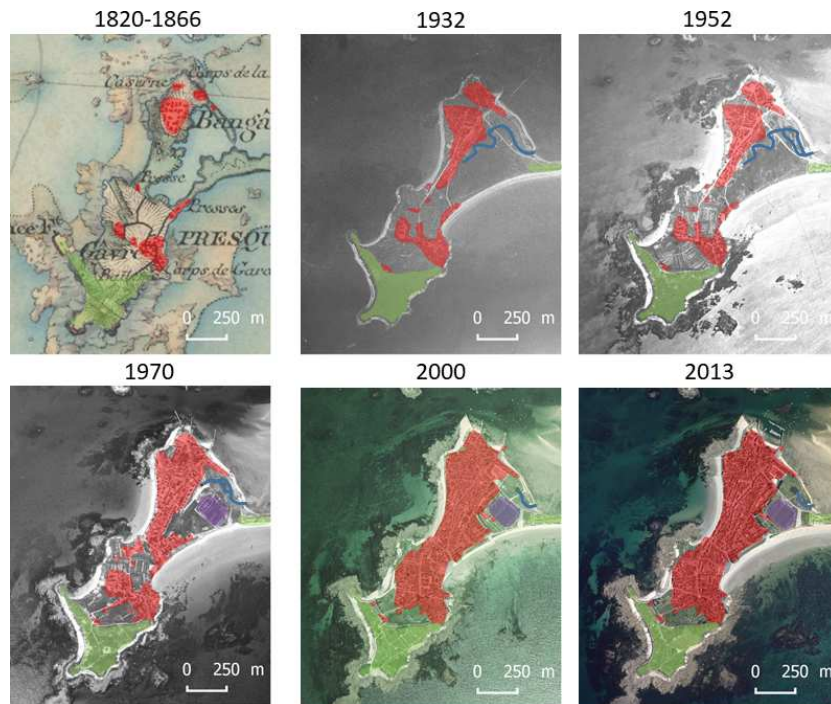


Fig. 2 Time evolution of the land cover: the top-left figure is extracted from the 1820-1866 Etat Major map (the red color indicates buildings). The other aerial photos are provided by IGN (Institut National de l'Information Géographique et Forestière). Green: historical military area, red: civil buildings, purple: sports field.

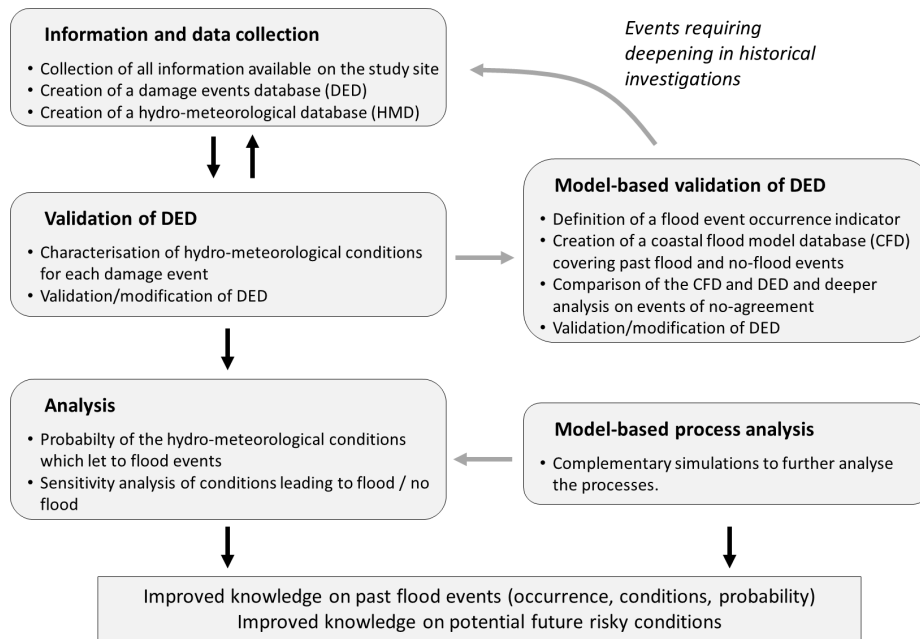


Fig. 3 Flowchart of the method used in the present paper.

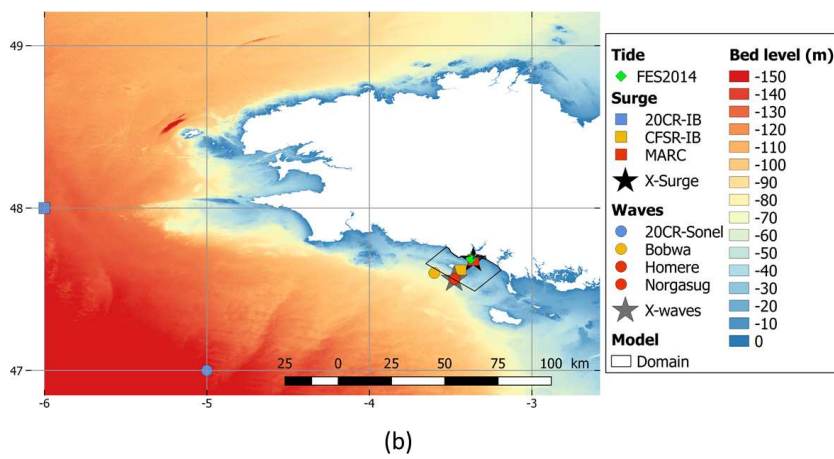
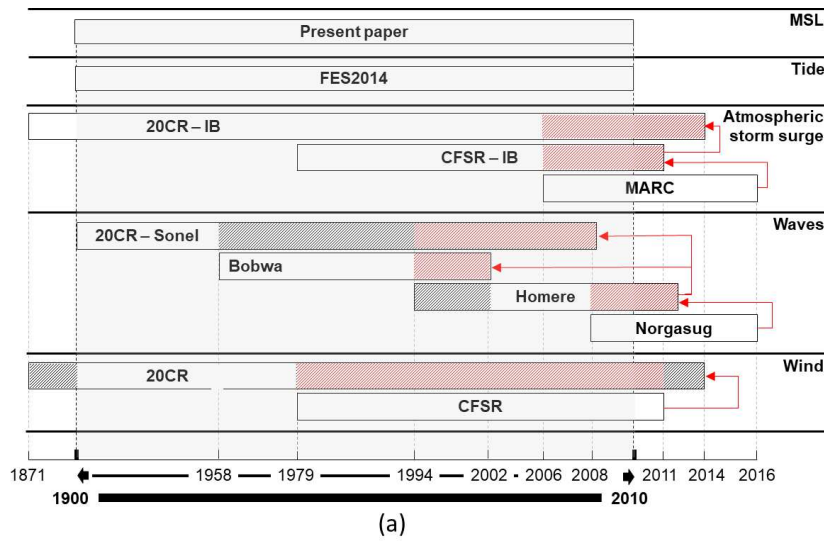


Fig. 4 Hydro-Meteorological Database: (a) data sources (extraction date: 2017), dataset period used to learn the QQ-corrections (in red), final selected dataset (in white). (b) Location of the tide, surge and wave datasets. X-Surge and X-waves indicate the location of the final composite data of surge and waves, respectively, in the Hydro-Meteorological Database. Source of bathymetric data: (*SHOM* 2015).

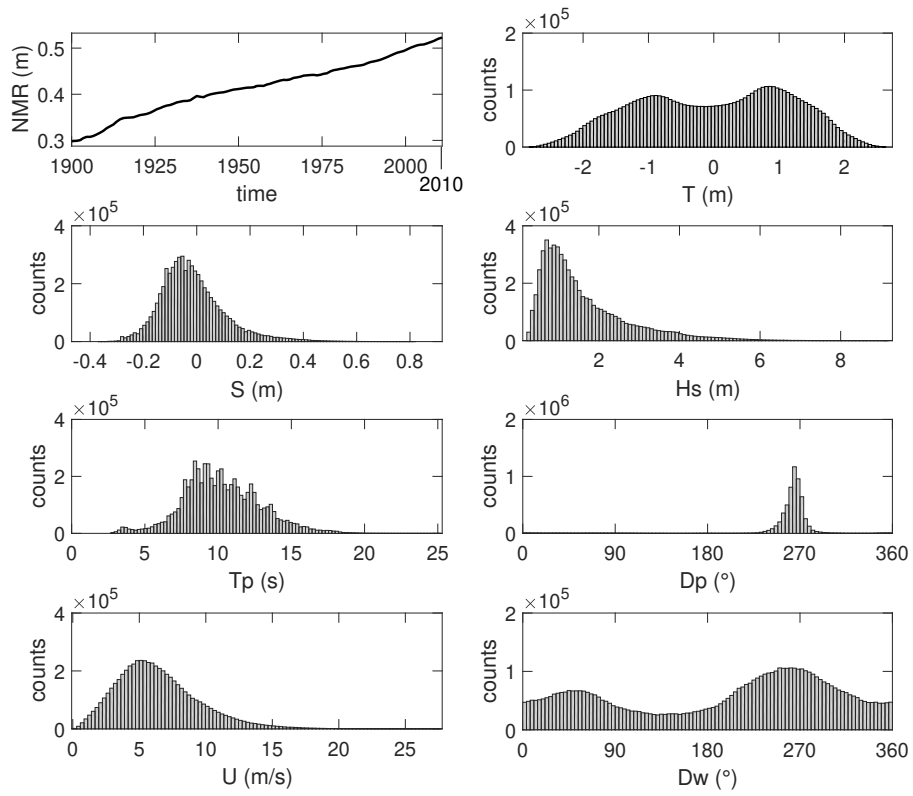


Fig. 5 Hydro-meteorological database: time series of the relative mean sea level (*MSL*) and distribution of the other hydro-meteorological variables: tide (*T*), surge (*S*), significant wave height (*H_s*), peak period (*T_p*), peak direction (*D_p*), wind velocity (*U*), wind direction (*D_w*).

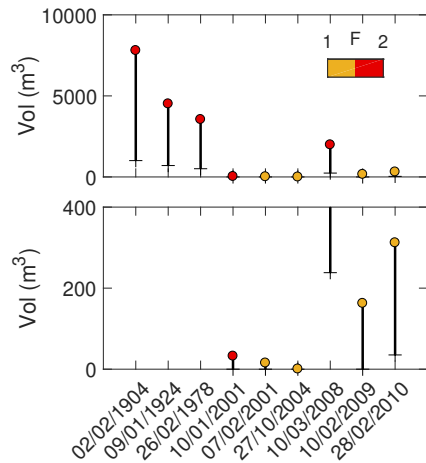


Fig. 6 Simulated flood indicator (Vol) for the 2008 topography (coloured points, DEM_{2008}) and the upgraded coastal defence case (+, $DEM_{upgrade}$), considering the events with $F \geq 1$. The colors refer to the Flood value of the Damage database. The bottom panel is a zoom of the upper panel for Vol values close to zero.

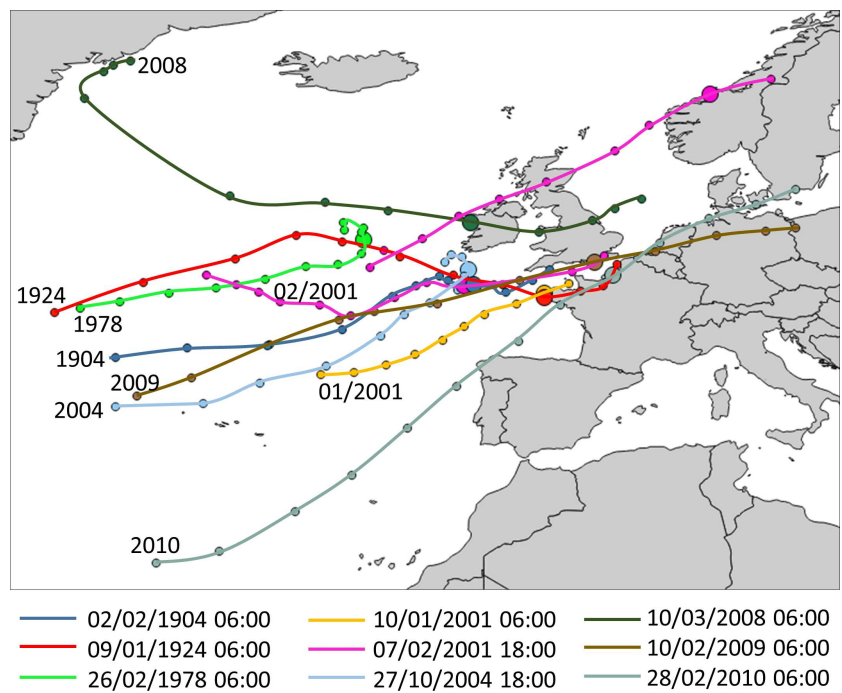


Fig. 7 Storm tracks associated with the 9 flood events, based on the 500hPa geopotential pressure, extracted from the 20CR data (until 1978), and CFSR data (after 1978), every 6 hours. Dates in caption indicate the reference time (large size circle).

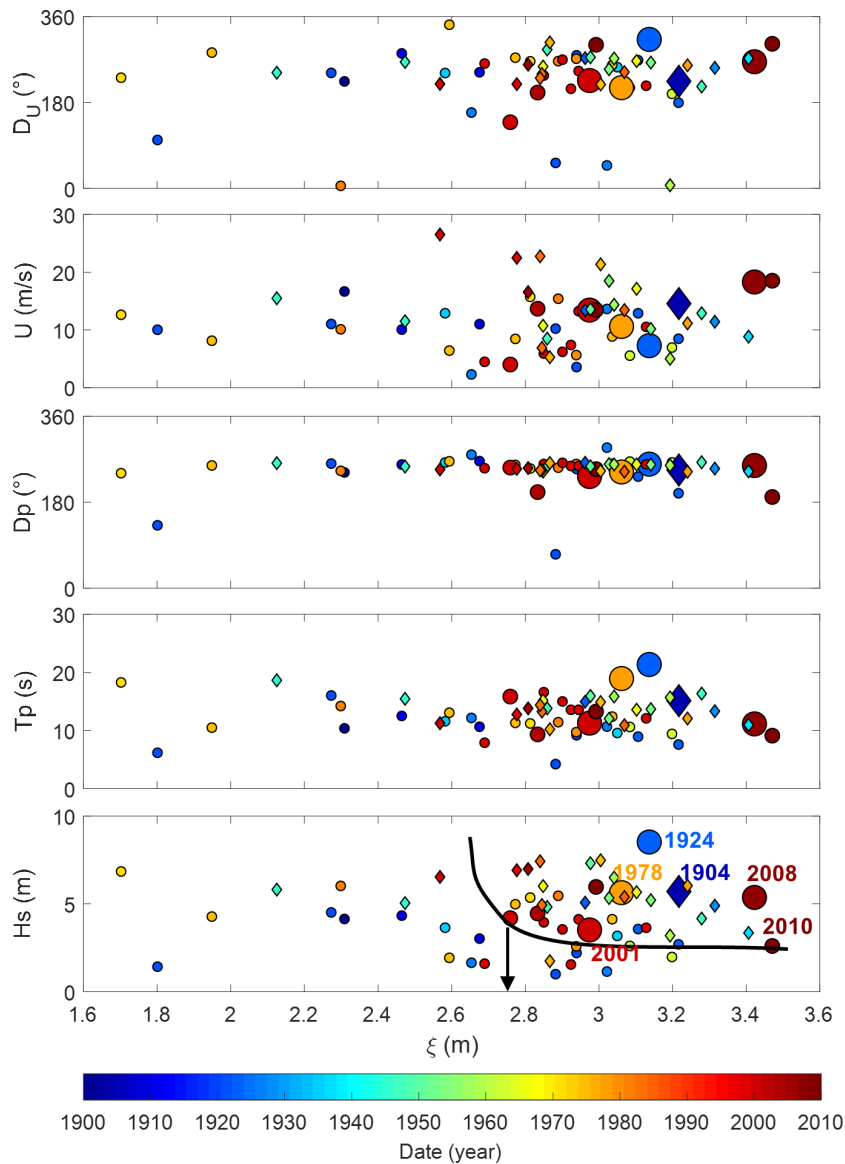


Fig. 8 Scatter plot of the Hydro-Meteorological conditions of the events of the Damage Event Database. The black arrow (bottom panel) indicates the smallest still water level ($\xi_c=2.77$ m IGN69) among the flood events ($F \geq 1$). The marker size indicates the *Flood* value (0-no flood: small size, 1-moderate flood: medium size, 2-significant flood: large size). The symbols indicate the confidence indicator value (1-medium confidence: diamond, 2-high confidence: circle). Years of the 5 main flood events are indicated. The grey areas indicate cluster of main flood ($F = 2$) event types. The black contour indicates an approximation of the critical contour so that an event can cause flooding only if it is associated with values above this contour.

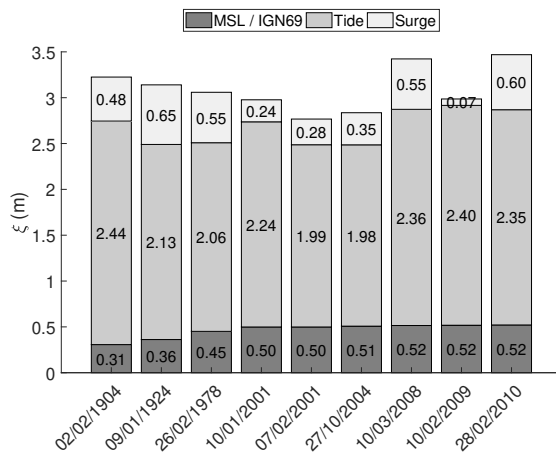


Fig. 9 Contribution of each water level component to the still water level (ξ), for the 9 flood events.

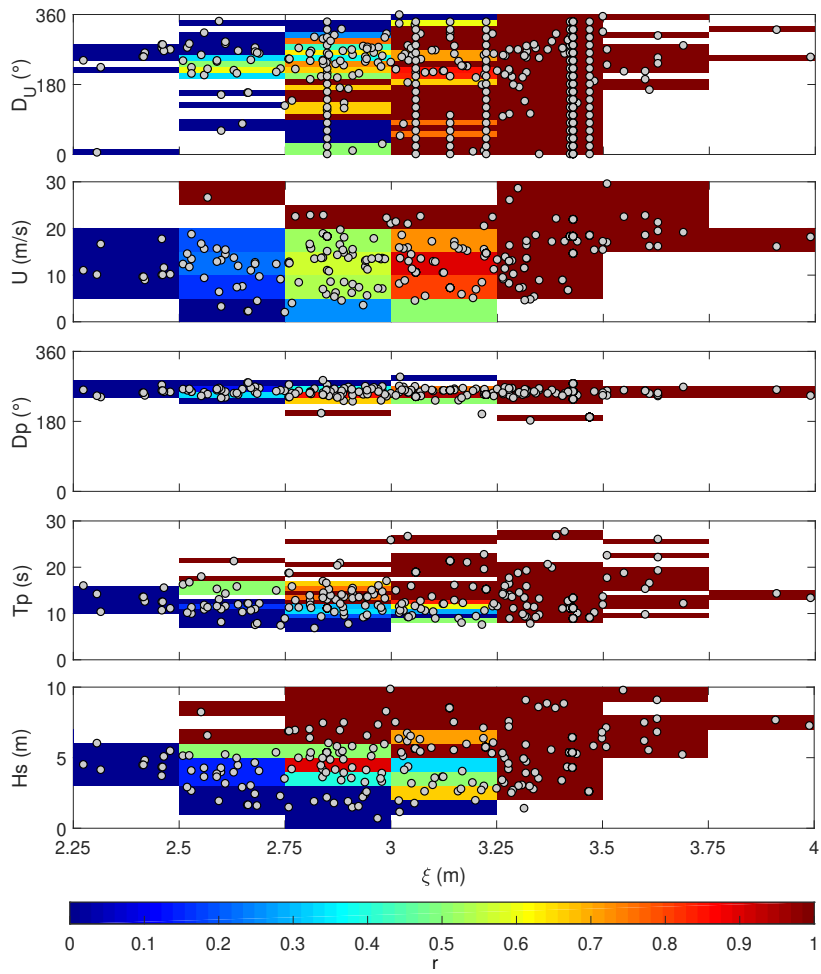


Fig. 10 Identification of conditions leading to flooding, based on the numerical flood simulations. The color scale indicates the value of the ratio r between the number of simulations providing $Vol > 0$ and the total number of computations for in each cell. Dots: simulation points. Based on simulations done with the DEM₂₀₀₈.

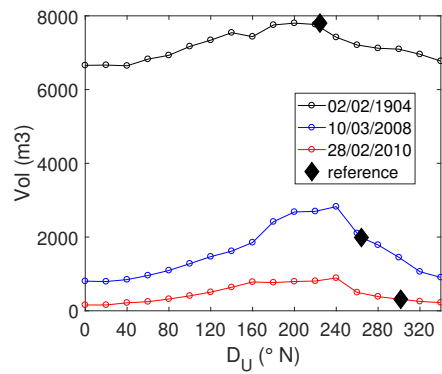


Fig. 11 Sensitivity of the flood indicator Vol to the wind direction D_u for the 3 flood events of largest wind speed, for the DEM₂₀₀₈ configuration.

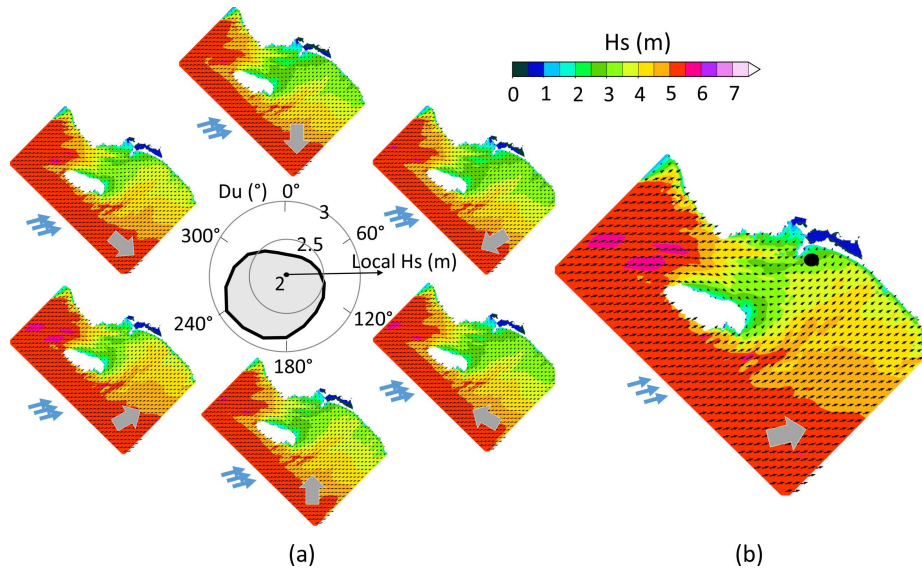


Fig. 12 WW3 model results (H_s) for the hydro-meteorological conditions corresponding to the Johanna event (b, $D_u = 264^\circ$), and for the same event, but for different wind directions (a, $D_u = 0, 60, 120, 180, 240, 300^\circ$). The polar plot indicates the significant wave height close to Gâvres (black dot on the right panel) for $D_u = 0:20:340^\circ$. Grey arrows indicate the wind direction and blue arrows the offshore wave direction ($D_p = 255^\circ$ for the Johanna event).

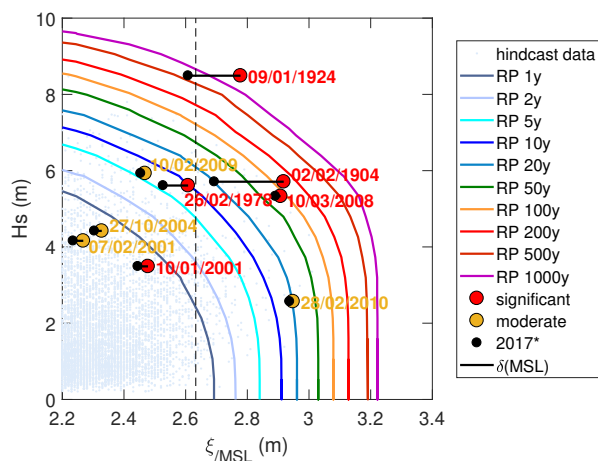


Fig. 13 Joint exceedance contours within the space (ξ_{MSL}, H_S) for return period values ranging from 10 to 1000 years together with the nine historical events. Note that the still water level ξ_{MSL} is expressed with respect to the mean sea level, i.e. $\xi_{MSL} = \xi - MSL$. The flood events of the damage database are indicated with coloured markers. The 2017* markers indicate the value of ξ_{MSL} of each event in case the same total still water level would occur in 2017 (i.e. $\xi_{MSL_{2017}} = \xi_{MSL_{event}} - \delta(MSL)$ with $\delta(MSL) = MSL_{2017} - MSL_{event}$ and *event* refers to the selected event).

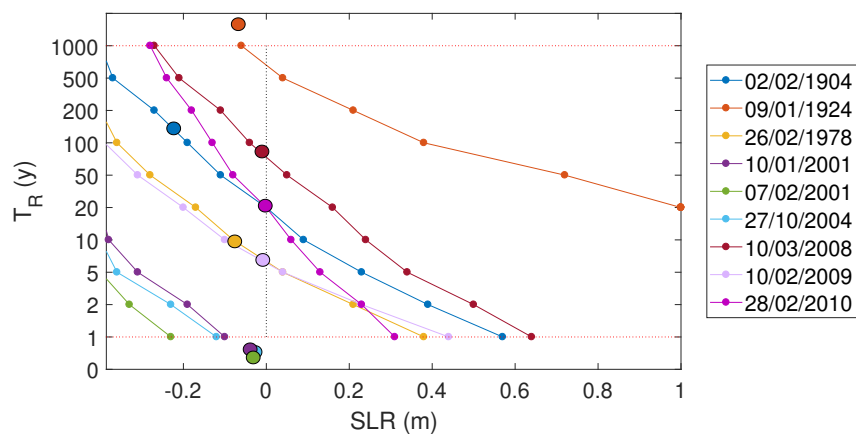


Fig. 14 Return periods T_R of the 9 flood events as a function of the mean sea-level rise (SLR). $SLR = 0$ corresponds to the year 2017 (vertical dotted line). The large circles indicate the return period T_R corresponding to the past events.

Table 1 Original datasets of tide, surge, waves and winds for the hydro-meteorological database. The asterisk (*) indicates that there is a data transformation (in the present case, sea surface pressure data are extracted and converted in storm surges using the inverse barometer computation). Websites: 1 (<https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2014.html>), 2 (<https://reanalyses.org/atmosphere>), 3 (<https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr>), 4 (<http://marc.ifremer.fr/>), 5 (<http://www.sonel.org/-Waves-.html?lang=en>), 6 (<http://bobwa.brgm.fr/>), 7 (http://marc.ifremer.fr/en/produits/rejeu_d_etats_de_mer_homere), 8 (<https://wwz.ifremer.fr/iowaga/Products>)

Parameter	Name	Source		
		Provider	Reference	Website
Tide (T)	FES2014	LEGOS	Carrere et al. (2016)	1
	20CR*	NOAA	Compo et al. (2015)	2
Storm surge (S)	CFSR*	NOAA	Dee et al. (2014)	3
	MARC	Ifremer-LOPS	Muller et al. (2014)	4
	Sonel (waves)	Liens	Bertin et al. (2013)	5
Waves (Hs, Tp, Dp)	BoBWA	BRGM	Charles et al. (2012)	6
	Homere	Ifremer-LOPS	Bouidière et al. (2013)	7
	Norgasug	Ifremer-LOPS	Bouidière et al. (2013)	8
	20CR	NOAA	Compo et al. (2015)	2
Wind (U, Dw)	CFSR	NOAA	Dee et al. (2014)	3

Table 2 Sources for the 9 flood events of the final Damage Database (after update). For the First half century, all the newspaper are available in the "Archives Départementales du Morbihan". Most of them have been gathered in (*Lambert 2017*). The newspaper articles used in this study after 1950 come from (*Le Cornec et al. 2012*). In what follows, the following specific archives also used (extracted from (*Le Cornec et al. 2012*)): ADM1 (Archives Départementales du Morbihan / rapport du Subdivisionnaire, pour la demande de crédit pour les réparations des avaries causées aux cales de Larmor et de Gâvres par la tempête du 27 Novembre 1924, 15 décembre 1924), CELM1 (Centre d'Essai de Lancement de Missiles / Relevé des tempêtes majeures sur le polygone de Gâvres), Cetmef1 (Cetmef Février 2001), GT (Gâvres town hall / Délibération du Conseil Municipal du 24 janvier 2001), SHM1 (Service Historique de La Marine / courrier du Président de la Commission de Gâvres au Préfet maritime de Lorient, 09/05/1904), SHM2 (Service Historique de La Marine / Consolidation de l'ouvrage de protection du rivage, Tranche 1978, Notice explicative).

Damage Event Nd (date)	Sources
2 (02/02/1904)	Courrier Morbihannais 7/02/1904 ; Le Matin 05/02/1904 Courrier des Campagnes 7/02/1904 ; L'Arvor 05/02/1904 La Croix du Morbihan 14/02/1904 ; SHM1
7 (09/01/1924)	Nouvelles de Lorient 29/11/1924 Le Nouvelliste du Morbihan 30/11/1924 L'ouest Républicain 30/11/1924 and 04/12/1924 ; ADM1
29 (26/02/1978)	CELM1 ; SHM2
42 (10/01/2001)	Le Télégramme 11 and 12/01/2001 Ouest France 11/01/2001 ; GT1
43 (07/02/2001)	Cetmef1
44 (27/10/2004)	Le Télégramme 29/10/2004
46 (10/03/2008)	Le Télégramme 11/03/2008 ; Ouest France 11/03/2008 <i>Le Cornec et al. (2012)</i>
47 (10/02/2009)	Ouest France 11/02/2009 ; <i>Le Cornec et al. (2012)</i>
48 (28/02/2010)	<i>Le Cornec et al. (2012)</i>

Table 3 List of the 9 flood events of the damage database, the corresponding Hight Tide time (Universal Time) and the corresponding hydro-meteorological conditions extracted (at high tide) from the HMD database (*MSL*: mean sea level, *T*: tide, *S*: atmospheric storm surge, *H_s*: significant wave height, *T_p*: wave peak period, *D_p*: wave peak direction, *U*: wind speed, *Du*: wind direction). The significant flood events and the maximum values (among the 9 events) of intensity parameters (i.e. *MSL*, *T*, *S*, *H_s* and *U*) are given in bold.

Event	HT	MSL (m)	T (m)	S (m)	H _s (m)	T _p (s)	D _p (°)	U (m/s)	Du (°)
02/02/1904	04:00	0.307	2.438	0.48	5.71	15.1	247.6	14.6	224.4
09/01/1924	05:30	0.362	2.128	0.65	8.49	21.3	258.5	7.8	310.8
26/02/1978	05:30	0.451	2.058	0.55	5.61	18.8	242.0	10.5	209.7
10/01/2001	03:40	0.499	2.238	0.24	3.49	11.2	232.6	13.3	224.7
07/02/2001	15:20	0.499	1.988	0.28	4.16	15.7	251.3	3.9	137.4
27/10/2004	15:20	0.508	1.978	0.35	4.42	9.23	199.9	13.6	199.6
10/03/2008	05:20	0.515	2.358	0.55	5.33	11.0	255.7	18.2	264.1
10/02/2009	04:00	0.518	2.398	0.07	5.93	13.2	248.0	13.4	299.6
28/02/2010	03:10	0.521	2.348	0.60	2.57	9.0	189.7	18.4	301.7

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 846 strengthened this paper.

847 References

- 848 Arnes J.E., Krogstad H.E. (2001) Partitioning sequences for the dissection of directional ocean
 849 wave spectra: A review. Part of work package 4 (Wp4) of the EnviWave (EVG-2001-00017)
 850 research programme under the EU Energy, Environment and Sustainable Development
 851 programme.
- 852 André C. (2014) Analyse des dommages liés aux submersions marines et évaluation des coûts
 853 induits aux habitations à partir de données d'assurance : perspectives apportées par les
 854 tempêtes Johanna (2008) et Xynthia (2010). PhD Manuscript. Géographie. Université de
 855 Bretagne occidentale - Brest, 2013. Français.
- 856 Arduin F., Rogers W.E., Babanin A.V., Filipot J., Magne R., Roland A., Van der Westhuysen
 857 A., Queffeuilou P., Lefevre J., Aouf L., Collard F. (2010) Semiempirical dissipation source
 858 functions for ocean waves. Part I: Definition, calibration, and validation. *J. Phys. Oceanogr.*
 859 *40*(1), 917– 1,941.
- 860 Arns A., Wahl T., Dangendorf S., Jensen J. (2015) The impact of sea level rise on storm surge
 861 water levels in the northern part of the German Bight. *Coastal Engineering*, *96*, 118-131.
- 862 Azzimonti D., Ginsbourger D., Rohmer J., Idier D. (2019) Profile extrema for visualizing and
 863 quantifying uncertainties on excursion regions. Application to coastal flooding. *Techno-*
 864 *metrics*, 1-26.
- 865 Bertin, X., E. Prouteau, and C. Letetrel (2013) A significant increase in wave height in the
 866 North Atlantic Ocean over the 20th century. *Global and Planetary Change* *106*, 77-83.
- 867 Bertin X., Li K., Roland A., Zhang Y. J., Breilh J.F., Chaumillon E. (2014) A modeling-
 868 based analysis of the flooding associated with Xynthia, central Bay of Biscay. *Coastal*
 869 *Engineering* *94*, 80-89.
- 870 Boudiere E., Maisondieu C., Arduin F., Accensi M., Pineau-Guillou L., Lepesqueur J. (2013)
 871 A suitable metocean hindcast database for the design of Marine energy converters. *Inter-*
 872 *national Journal of Marine Energy*, 3-4, e40-e52. doi:j.ijome.2013.11.010.
- 873 Breilh J.F., Bertin X., Chaumillon E., Giloy N., Sauzeau T. (2014) How frequent is storm-
 874 induced flooding in the central part of the Bay of Biscay?, *Global and Planetary Change*,
 875 *122*, 161–175.
- 876 Bulteau T., Idier D., Lambert J., Garcin M. (2015) How historical information can improve
 877 estimation and prediction of extreme coastal water levels: application to the Xynthia event
 878 at La Rochelle (France), *Nat. Hazards Earth Syst. Sci.*, *15*, 1135–1147.
- 879 Cariolet J.M. (2011) Inondation des côtes basses et risques associés en Bretagne : vers une
 880 redéfinition des processus hydrodynamiques liés aux conditions météo-océaniques et des
 881 paramètres morphosédimentaires. *Océan, Atmosphère*. Université de Bretagne occidentale
 882 - Brest, 2011. Français. <tel-00596426>.
- 883 Carrere L., F. Lyard, M. Cancet, A. Guillot, N. Picot (2016) FES 2014, a new tidal model -
 884 Validation results and perspectives for improvements, presentation to ESA Living Planet
 885 Conference, Prague.
- 886 Carson M., Köhl A., Stammer D., Slangen A.B.A., Katsman C.A., Van de Wal R.S.W., Church
 887 J., White N. (2016) Coastal sea level changes, observed and projected during the 20th and
 888 21st century. *Climatic Change*, *134*(1-2), 269-281.
- 889 Church J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merri-
 890 field, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S.
 891 Unnikrishnan (2013) Sea Level Change. In: *Climate Change 2013: The Physical Science*
 892 *Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergov-*
 893 *ernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor,

- 894 S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)). Cambridge
895 University Press, Cambridge, United Kingdom and New York, NY, USA.
- 896 Coles S.G., Tawn J.A. (1991) Modelling extreme multivariate events. *J. R. Stat. Soc. Ser. B*
897 *Methodol.* 53 (2), 377–392.
- 898 Coles S. (2001). *An Introduction to Statistical Modelling of Extreme Values*. Springer series in
899 statistics.
- 900 Compo G.P., Whitaker J.S., Sardeshmukh P.D., Allan R.J., McColl C., Yin X., Giese B.S.,
901 Vose R.S., Matsui N., Ashcroft L., Auchmann R., Benoy M., Bessemoulin P., Brandsma T.,
902 Brohan P., Brunet M., Comeaux J., Cram T., Crouthamel R., Groisman P.Y., Hersbach
903 H., Jones P.D., Jonsson T., Jourdain S., Kelly G., Knapp K.R., Kruger A., Kubota H.,
904 Lentini G., Lorrey A., Lott N., Lubker S.J., Luterbacher J., Marshall G.J., Maugeri M.,
905 Mock C.J., Mok H.Y., Nordli O., Przybylak R., Rodwell M.J., Ross T.F., Schuster D.,
906 Srncic L., Valente M.A., Vizi Z., Wang X.L., Westcott N., Woollen J.S., Worley S.J. (2015)
907 NOAA/CIRES Twentieth Century Global Reanalysis Version 2c. Research Data Archive
908 at the National Center for Atmospheric Research, Computational and Information Systems
909 Laboratory. <https://doi.org/10.5065/D6N877TW>. Accessed 28 feb 2017.
- 910 Corriou J.P. (2012) *Commande des procédés*, 1–766, Lavoisier, Tec& Doc.
- 911 Dangendorf S., Arns A., Pinto J.G., Ludwig P., Jensen J. (2016) The exceptional influence
912 of storm ‘Xaver’ on design water levels in the German Bight. *Environmental Research*
913 *Letters*, 11(5), p.054001.
- 914 Davies G., Callaghan D. P., Gravois U., Jiang W., Hanslow D., Nichol S., Baldock T. (2017)
915 Improved treatment of non-stationary conditions and uncertainties in probabilistic models
916 of storm wave climate. *Coastal Engineering*, 127, 1-19.
- 917 Dee D.P., Balmaseda M., Balsamo G., Engelen R., Simmons A.J., Thépaut J.-N. (2014) Toward
918 a Consistent Reanalysis of the Climate System. *Bull. Amer. Meteor. Soc.*, 95, 1235–1248.
- 919 Fortunato A.B., Freire P., Bertin X., Rodrigues M., Ferreira J., Liberato M.L. (2017) A numerical
920 study of the February 15, 1941 storm in the Tagus estuary. *Continental Shelf Research*
921 144, 50-64.
- 922 Galiatsatou P., Makris C., Prinos P., Kokkinos D. (2019) Nonstationary joint probability
923 analysis of extreme marine variables to assess design water levels at the shoreline in a
924 changing climate. *Natural Hazards*, 98(3), 1051-1089.
- 925 Gallien T.W., Kalligeris N., Delisle M.P.C., Tang B.X., Lucey J.T.D., Winters M.A. (2018)
926 Coastal Flood Modeling Challenges in Defended Urban Backshores. *Geosciences* 8, 450,
927 10.3390/geosciences8120450.
- 928 Garnier E., Ciavola P., Spencer T., Ferreira O. Armaroli C., Mc Ivor A. (2018) Historical
929 analysis of storm events: Case studies in France, England, Portugal and Italy. *Coastal*
930 *Engineering*, 134, 0-23.
- 931 Garrity N. J., Battalio R., Hawkes P. J., Roupe D. (2007) Evaluation of event and response
932 approaches to estimate the 100-year coastal flood for Pacific coast sheltered waters. *Coastal*
933 *Engineering*, 1651-1663.
- 934 Giloy N., Hamdi Y., Bardet L., Garnier E., Duluc C. M. (2018) Quantifying historic skew
935 surges: an example for the Dunkirk Area, France. *Natural Hazards*, 1-25.
- 936 Gouldby B., Méndez F.J., Guanache Y., Rueda A., Mínguez R. (2014). A methodology for
937 deriving extreme nearshore sea conditions for structural design and flood risk analysis.
938 *Coastal Engineering*, 88, 15-26.
- 939 Gudmundsson L., Bremnes J. B., Haugen J. E., Engen-Skaugen T. (2012) Technical Note:
940 Downscaling RCM precipitation to the station scale using statistical transformations - a
941 comparison of methods. *Hydrology and Earth System Sciences*, 16, 3383-3390.
- 942 Haigh I.D., Nicholls R.J., Wells N. (2011) Rising sea levels in the English Channel 1900 to
943 2100. *Proceedings of the Institution of Civil Engineers - Maritime Engineering*, 164(2),
944 81-92.
- 945 Haigh I., Wadey M.P., Wahl T., Ozsoy O., Nicholls R.J., Brown J.M., Horsburgh K., Gouldby
946 B. (2016) Spatial and temporal analysis of extreme sea level and storm surge events around
947 the coastline of the UK. *Scientific Data*, 3, 160107.
- 948 Haigh I.D., Ozsoy O., Wadey M.P., Nicholls R.J., Gallop S.L., Wahl T., Brown, J.M. (2017)
949 An improved database of coastal flooding in the United Kingdom from 1915 to 2016.
950 *Scientific data*, 4, 170100.
- 951 Hallegatte S., Green C., Nicholls R.J., Corfee-Morlot, J. (2013) Future flood losses in major
952 coastal cities. *Nature climate change*, 3(9), 802.

- 953 Hamdi Y., Garnier E., Giloy N., Duluc C. M., Rebour V. (2018) Analysis of the risk associated
954 with coastal flooding hazards: a new historical extreme storm surges dataset for Dunkirk,
955 France. *Natural Hazards and Earth System Sciences*, 18(12), 3383-3402.
- 956 Hawkes P. J., Gouldby B. P., Tawn J. A., Owen M. W. (2002) The joint probability of waves
957 and water levels in coastal engineering design, *J. Hydraul. Res.*, 40, 241-251.
- 958 Heffernan J.E., Tawn J.A. (2004) A conditional approach for multivariate extreme values (with
959 discussion). *J. R. Stat. Soc. Ser. B Stat Methodol.* 66 (3), 497-546.
- 960 Hénaff A., Le Cornec E., Jabbar M., Pétré A., Corfou J., Le Drezen Y., Van Vliët-Lanoë
961 B. (2018) Caractérisation des aléas littoraux d'érosion et de submersion en Bretagne par
962 l'approche historique, *Cybergeo: European Journal of Geography*, 847.
- 963 Jevrejeva S., Moore J.C., Grinsted A., Matthews A.P., Spada G. (2014) Trends and acceleration
964 in global and regional sea levels since 1807. *Global and Planetary Change*, 113, 11-22.
- 965 Idier D., Muller H., Pedreros R., Thiébot J., Yates M., avec la collaboration de Créach R.,
966 Voineson G., Dumas F., Lecornu F., Pineau-Guillou L., Ohl P., Paradis D. (2012) Système
967 de prévision de surcotes en Manche/Atlantique et Méditerranée : Amélioration du système
968 existant sur la façade Manche/Gascogne [D4]. Rapport final. BRGM/RP-61019-FR, 165
969 p., 71 fig., 11 tabl., 9 ann.
- 970 Idier D., Rohmer J., Bulteau T., and Delvallée E. (2013) Development of an inverse method for
971 coastal risk management, *Nat. Hazards Earth Syst. Sci.*, doi:10.5194/nhess-13-999-2013,
972 13, 999-1013.
- 973 Idier D., Paris F., Le Cozannet G., Boulahya F., Dumas F. (2017) Sea-level rise impacts on
974 the tides of the European Shelf, *Continental Shelf Research*.
- 975 Jeffers J.M. (2014) Environmental knowledge and human experience: using a historical analysis
976 of flooding in Ireland to challenge contemporary risk narratives and develop creative policy
977 alternatives. *Environmental Hazards*, 13(3), 229-247.
- 978 Lambert J. (2017) Contribution au recensement des effets de tempêtes historiques dans la
979 région de Gâvres-Lorient (Morbihan). Technical report BRGM_DRP-RSV 17-NT-058.
- 980 Le Berre I., David L., Henaff A., Meur-Ferec C., Cuq V., Lageat Y. (2012) Atlas des risques
981 d'érosion - submersion; contribution à l'étude de la vulnérabilité côtière des communes de
982 Gâvres et Guissény. Rapport final Adaptalitt, GICC, LETG-Geomer, UBO, 55 pp.
- 983 Le Cornec E., Ferrand J.P. (2009) Etude de protection du littoral de Gâvres. Phase 1 : Analyse
984 des données existantes. GEOS-AEL, Ferrand and DHI report. Lorient-Agglomération, 62
985 pp.
- 986 Le Cornec E., Schoorens G. (2007) Etude de l'aléa submersion marine sur le site de la Grande
987 Plage de Gâvres, Rapport d'étude GEOS-DHI, DDE du Morbihan, 102 pp.
- 988 Le Cornec E., Peeters P. (2008) Simulation de la tempête du 10 mars 2008 sur le site de la
989 Grande Plage de Gâvres, Rapport d'étude GEOS-DHI, DDE du Morbihan.
- 990 Le Cornec E. and Peeters P. (2010) Etude de l'aléa submersion à Gâvres, in "La gestion du
991 trait de côte", Ministère de l'Ecologie, de l'Energie, du Développement Durable et de la
992 Mer, Editions Quae, pp 238-244. ISBN: 978-2-7592-0360-4.
- 993 Le Cornec E., Le Bris E., Van Lierde M. (2012) Atlas des risques littoraux sur le département du
994 Morbihan. Phase 1 : Recensement et conséquences des tempêtes et coups de vent majeurs.
995 Rapport d'étude GEOS-DHI. Direction Départementales des Territoires et de la Mer du
996 Morbihan, 476 pp.
- 997 Le Cozannet G., Rohmer J., Cazenave A., Idier D., van De Wal R., De Winter R., Pedreros
998 R., Balouin Y., Vinchon C., Oliveros C. (2015) Evaluating uncertainties of future marine
999 flooding occurrence as sea-level rises. *Environmental Modelling and Software*, 73, 44-56.
- 1000 Le Roy S., Pedreros R., André C., Paris F., Lecacheux S., Marche F., Vinchon C. (2015)
1001 Coastal flooding of urban areas by overtopping: dynamic modelling application to the
1002 Johanna storm (2008) in Gâvres (France), *Nat. Hazards Earth Syst. Sci.*, 15, 2497-2510,
1003 <https://doi.org/10.5194/nhess-15-2497-2015>.
- 1004 Meyssignac B., Becker M., Llovel W., Cazenave A. (2012) An assessment of two-dimensional
1005 past sea level reconstructions over 1950-2009 based on tide-gauge data and different input
1006 sea level grids. *Surveys in Geophysics*, 33(5), 945-972.
- 1007 Muis S., Verlaan M., Winsemius H.C., Aerts J.C.J.H., Ward P.J. (2016) A global reanalysis of
1008 storm surges and extreme sea levels. *Nature Communications* 7, 11969.
- 1009 Muller H. Pineau-Guillou L., Idier D., Arduin F. (2014) Atmospheric storm surge modeling
1010 along the French (Atlantic and English Channel). *Ocean Dynamics* 64(11):1671-1692.
- 1011 Needham H.F., Keim B.D. (2012) A storm surge database for the US Gulf Coast. *International
1012 Journal of Climatology*, 32(14), 2108-2123.

- 1013 Nicolae-Lerma A., Bulteau T., Elineau S., Paris F., Durand P., Anselm, B., Pedreros, R. (2018)
1014 High-resolution marine flood modelling coupling overflow and overtopping processes: fram-
1015 ing the hazard based on historical and statistical approaches, *Nat. Hazards Earth Syst.*
1016 *Sci.*, 18, 207-229.
- 1017 Poitevin C., Wöppelmann G., Raucoules D., Le Cozannet G., Marcos M., Testut L. (2019)
1018 Vertical land motion and relative sea level changes along the coastline of Brest (France)
1019 from combined space-borne geodetic methods. *Remote Sensing of Environment*, 222, 275-
1020 285.
- 1021 Poulter B., Halpin P.N. (2008) Raster modelling of coastal flooding from sea-level rise. *Inter-*
1022 *national Journal of Geographical Information Science*, 22(2), 167-182.
- 1023 Rohmer J., Idier D (2012) A meta-modelling strategy to identify the critical off-
1024 shore conditions for coastal flooding, *Nat. Hazards Earth Syst. Sci.*, 12, 2943-2955,
1025 <https://doi.org/10.5194/nhess-12-2943-2012>.
- 1026 Rohmer J., Le Cozannet G. (2019) Dominance of the mean sea level in the high-percentile sea
1027 levels time evolution with respect to large-scale climate variability: a Bayesian statistical
1028 approach, *Environmental Research Letters*, 10.1088/1748-9326/aaf0cd.
- 1029 Rueda A., Gouldby B., Méndez F. J., Tomás A., Losada I. J., Lara J. L., Díaz-Simal P. (2016)
1030 The use of wave propagation and reduced complexity inundation models and metamodels
1031 for coastal flood risk assessment. *Journal of Flood Risk Management*, 9(4), 390-401.
- 1032 Santamaría-Gómez A., Gravelle M., Collilieux X., Guichard M., Martin-Miguez B., Tiphaneau
1033 P., Wöppelmann G. (2012) Mitigating the effects of vertical land motion in tide gauge
1034 records using a state-of-the-art GPS velocity field. *Global and Planetary Change*, 98-99,
1035 6-17.
- 1036 Santamaría-Gómez A., Gravelle M., Dangendorf S., Marcos M., Spada G., Wöppelmann G.
1037 (2017) Uncertainty of the 20th century sea-level rise due to vertical land motion errors.
1038 *Earth and Planetary Science Letters*, 473, 24-32.
- 1039 Sanuy M., Jiménez J. A., Ortego M. I., Toimil A. (2019) Differences in assigning probabilities
1040 to coastal inundation hazard estimators: Event versus response approaches. *Journal of*
1041 *Flood Risk Management*, e12557.
- 1042 SHOM (2014) *Références Altimétriques Maritimes - édition 2014*. ISBN 0180-989X.
- 1043 SHOM (2015) *MNT Bathymétrie de façade Atlantique (Projet Homonim)*.
1044 <http://dx.doi.org/10.17183/MNT-ATL100m-HOMONIM-WGS84>.
- 1045 SHOM (2017) *Références Altimétriques Maritimes - édition 2017*. ISBN 978-2-11-139469-8.
- 1046 Simon B. (1994) *Statistique des niveaux marins extrêmes le long des côtes de France*, SHOM
1047 Rapport no. 001/94.
- 1048 Visser H., Dangendorf S., Petersen A.C. (2015) A review of trend models applied to sea level
1049 data with reference to the “acceleration-deceleration debate”. *Journal of Geophysical Re-*
1050 *search: Oceans*, 120(6), 3873-3895.
- 1051 Vousdoukas M.I., Mentaschi L., Voukouvalas E., Verlaan M., Jevrejeva S., Jackson L.P., Feyen
1052 L. (2018) Global probabilistic projections of extreme sea levels show intensification of
1053 coastal flood hazard, *Nature Communications* 9, 2360.
- 1054 Wadey M.P., Nicholls R.J., Haigh, I (2013) Understanding a coastal flood event: the 10th
1055 March 2008 storm surge event in the Solent, UK. *Natural Hazards* 67, 829-854.
- 1056 Wadey M., Brown S., Nicholls R.J., Haigh I. (2017) Coastal flooding in the Maldives: an
1057 assessment of historic events and their implications. *Natural Hazards*, 89(1), 131-159.
- 1058 Wahl T., Haigh I.D., Nicholls R.J., Arns A., Dangendorf S., Hinkel J., Slangen A.B. (2017)
1059 Understanding extreme sea levels for broad-scale coastal impact and adaptation analysis.
1060 *Nature communications*, 8, 16075.
- 1061 Willett P. (1999) Dissimilarity-based algorithms for selecting structurally diverse sets of com-
1062 pounds. *J. Comput. Biol.* 6 (3-4), 447-457.
- 1063 Wöppelmann G., Marcos M. (2016) Vertical land motion as a key to understanding sea level
1064 change and variability. *Reviews of Geophysics*, 54(1), 64-92.
- 1065 Zijlema M., Stelling G., Smit P. (2011) SWASH: An operational public domain code for sim-
1066 ulating wave fields and rapidly varied flows in coastal waters. *Coast. Eng.* 58:992-1012.
- 1067 Zong Y., Tooley M.J. (2003) A Historical Record of Coastal Floods in Britain: Frequencies
1068 and Associated Storm Tracks, *Natural Hazards*, 29, 13-36.

A Reconstruction of past sea-level changes in the Bay of Biscay and Gâvres

A.1 Reconstruction of past sea-level changes in the Bay of Biscay

We follow the approach of *Rohmer and Le Cozannet (2019)* to reconstruct past geocentric mean sea-level changes in the Bay of Biscay. This approach assumes that once vertical ground motions are removed, all tide gauge measure the same geocentric mean sea-level changes along the coasts of the Bay of Biscay. The approach uses data from PSMSL (Permanent Service for Mean Sea-Level) and SONEL (*Santamaría-Gómez et al. 2012*, www.sonel.org) and proceeds as follows:

- First, we compute relative mean sea-level changes and their uncertainties using a forward-backward Kalman filter (*Corriou 2012; Visser et al. 2015*) at the following tide gauge: Devonsport, Newlyn, St Mary, Roscoff Le Conquet, Brest, St Nazaire, Les Sables D'Olonne, La Rochelle, Port Bloc, Boucau, St Jean de Luz, Bilbao, Santander 1 and 3. We exclude five tide gauges in the Bay of Biscay with too short or with too many gaps: Pointe Saint Gildas, Le Verdon, Pasajes, Santander 2 and Gijon 2. This step allows to complete mean-sea level records that display gaps and to compute the associated uncertainties.
- Second, we estimate vertical ground motions at each tide gauge either using a GNSS station (*Santamaría-Gómez et al. 2012*) or an estimate of the GIA effect (*Jevrejeva et al. 2014*). In the first case, the uncertainties are based on the analysis of the GNSS time series. In the second case, an uncertainty of $\pm 2\text{mm/y}$ is assigned, which is the standard deviation of the empirical distribution of the difference between vertical motion trends from GNSS records in the Sonel database and the GIA (*Wöppelmann and Marcos 2006*).
- Third, using the local vertical ground motions and past mean sea-level changes obtained at the two previous steps, we compute local geocentric mean sea-level changes and their uncertainties, assuming they are Gaussian.
- Finally, we use a weighted least square model to reconstruct a yearly time series of the regional geocentric mean sea-level changes curve.

Because the Bay of Biscay includes many high-quality tide gauge records and GNSS stations (e.g., Brest, Newlyn), our reconstructed curve compares well with other sea-level reconstructions based on tide gauge records, ocean models and altimetric measurements (*Meysignac et al. 2012*), as well as to the records in Brest, which is the longest tide gauge in the region and where vertical motions are small (*Poitevin et al. 2019*).

A.2 Reconstruction of relative past sea-level changes in Gâvres

To transform the absolute mean-sea level reconstruction obtained above to values relative to the ground in Gâvres, we use an estimation of the local vertical land movement (VLM) in Gâvres based on the 3 nearest GPS stations provided by the SONEL network (*Santamaría-Gómez et al. 2017*). Table 4 shows the station information and VLM trend extracted from the SONEL platform. The 3 stations exhibit a slightly negative vertical land motion (subsidence). The mean of the trends (computed with the least mean square method) provides a vertical land movement of $-0.33 \pm 0.15 \text{ mm/y}$. The final relative mean sea level time series (*MSL*) is plotted in Figure 5.

Table 4 GPS station information and velocity of the vertical land motion, extracted from SONEL platform the 29th of October 2019, for the 3 nearest stations to Gâvres.

Name	Lat ($^{\circ}$)	Lon ($^{\circ}$)	Time period	Velocity (mm/y)
Kone	47.866	-3.902	11/2007 - 10/2019	$-0.46 \text{ m} \pm 0.32$
GROI	47.648	-3.508	10/2002 - 03/2015	$-0.10 \text{ m} \pm 0.33$
SARZ	47.524	-2.770	05/2007 - 10/2019	$-0.36 \text{ m} \pm 0.20$

1110 B Quantile-Quantile corrections for the hydro-meteorological database

1111 The figures below show the initial and corrected distribution of the surge, wave, and wind
1112 datasets used to build the hydro-meteorological database. These figures are plotted for the
1113 calibration periods (i.e. for the periods corresponding to the red areas in Figure 4a). For each
1114 dataset, this correction is then applied for the rest of the period (in white in Figure 4a).

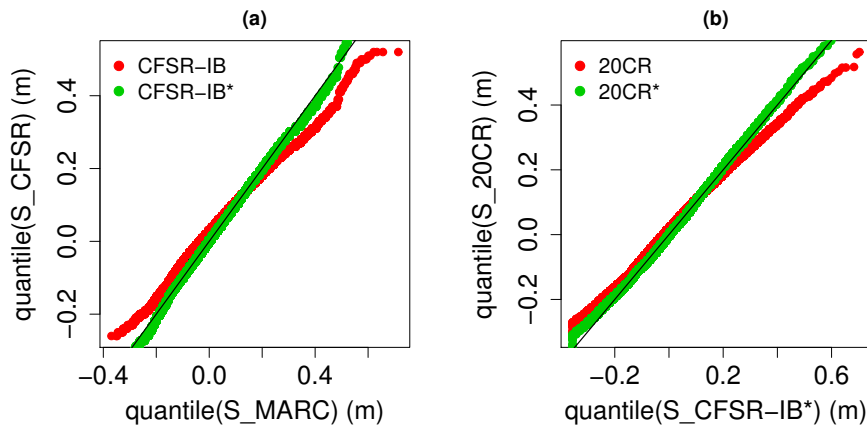


Fig. 15 Quantile-quantile corrections of surge data. QQ plots of the reference (MARC), data to correct and corrected data. (a) CFSR-IB data corrected with MARC data, (b) 20CR-IB data corrected with MARC data.

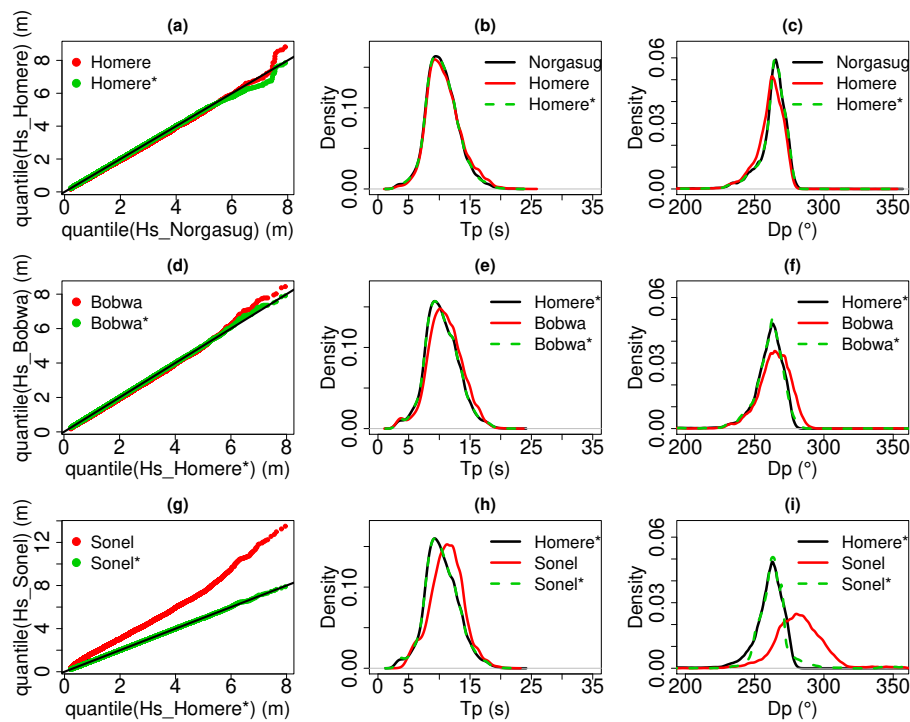


Fig. 16 Quantile-quantile corrections of wave data. QQ plots of wave height, probability density function (smoothed) of wave peak period and peak direction. (a,b,c) Homere data corrected with Norgasug data, (c,d,e) BOBWA data corrected with the corrected Norgasug data, (c,d,e) Sonel-waves data corrected with the corrected Norgasug data.

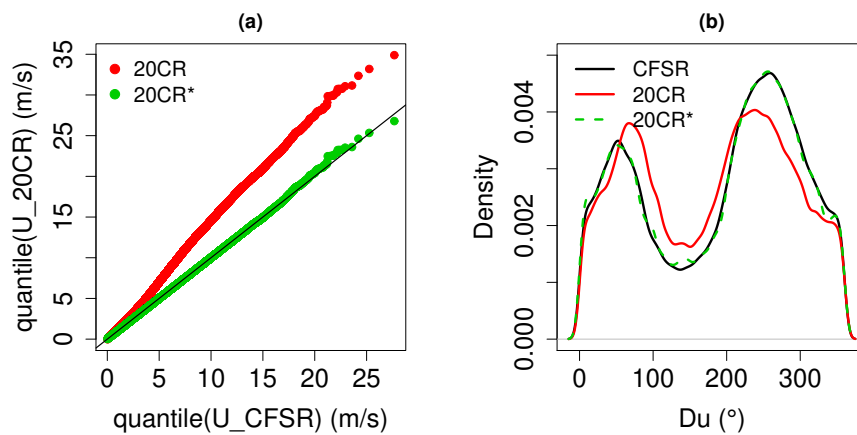


Fig. 17 Quantile-quantile corrections of the 20CR wind data using the CFSR wind data. QQ plots of wind speed (a) and probability density function (smoothed) of wind direction (b).

1115 C Damage events and associated hydro-meteorological conditions

1116 Table 5 shows an extract of the damage events, containing all the events, the dates, and
1117 the flood and confidence information. The corresponding hydro-meteorological conditions ex-
1118 tracted from the HMD are given in Figure 18. The begin and end dates of (old) damage events
1119 are sometimes not very precise due to the lack of historical information. In these cases, the
1120 hydro-meteorological conditions selection method consists in selecting the highest tide during
1121 the period, as well as the high tide which is the closest to the highest wave height. This im-
1122 plies that for some events, two dataset of hydro-meteorological conditions can be selected (see
1123 e.g. the damage event n°40 for instance in the following table). When two dataset of hydro-
1124 meteorological conditions are associated to a flood event, we consider the most penalising
1125 conditions (based on flood simulations). Among the flood events, there is only one (Nd n°29)
1126 which corresponds to two hydro-meteorological scenarios. The analysis of the values suggests
1127 that the event occurs for the most penalising scenario, i.e. hydro-meteorological conditions
1128 dataset numbered Nhm=49. See Table 3 for the selected hydro-meteorological conditions of
1129 each flood event.

Table 5 Damage events, estimated flood (F, with the classification: 0 for no flood, 1 for moderate flood event, 2 for significant flood event) and confidence (C, with the classification: 1 for medium confidence, 2 for high confidence) indicators. Nd is the numbering in the damage events. F1 and C1 refer to the first version of the database. F2 and C2 refer to the second version, after the use of the numerical model.

Nd	Date(begin)	Date(end)	F1	C1	F2	C2
1	13/02/1900	15/02/1900	0	1	0	2
2	01/02/1904	02/02/1904	1	1	2	1
3	07/12/1911	09/12/1911	0	1	0	2
4	27/01/1922	29/01/1922	0	1	0	2
5	11/04/1922	11/04/1922	0	1	0	2
6	12/10/1922	20/10/1922	0	1	0	2
7	09/01/1924	09/01/1924	2	2	2	2
8	26/11/1924	27/11/1924	0	1	0	2
9	28/12/1924	29/12/1924	0	1	0	1
10	08/11/1927	09/11/1927	0	1	0	2
11	22/03/1928	23/03/1928	0	1	0	1
12	27/01/1936	27/01/1936	0	1	0	2
13	14/03/1937	14/03/1937	0	1	0	1
14	23/12/1945	23/12/1945	0	1	0	1
15	24/03/1947	24/03/1947	0	1	0	1
16	01/01/1948	28/02/1948	0	1	0	1
17	05/02/1950	06/02/1950	0	1	0	1
18	08/12/1954	09/12/1954	0	1	0	1
19	14/02/1957	15/02/1957	0	1	0	1
20	01/12/1959	01/12/1959	0	1	0	1
21	02/11/1963	03/11/1963	0	1	0	2
22	21/02/1966	22/02/1966	0	1	0	1
23	01/11/1967	04/11/1967	0	1	0	1
24	01/11/1972	31/12/1972	0	1	0	2
25	16/01/1974	11/02/1974	0	1	0	1
26	28/01/1975	29/01/1975	0	1	0	2
27	01/11/1975	30/11/1975	0	1	0	2
28	25/10/1976	25/10/1976	0	1	0	1
29	26/02/1978	26/02/1978	2	2	2	2
30	01/12/1978	31/12/1978	0	1	0	1
31	20/01/1980	20/01/1980	0	1	0	2
32	13/12/1981	13/12/1981	0	1	0	2
33	24/12/1981	24/12/1981	0	1	0	2
34	21/12/1983	21/12/1983	0	1	0	1
35	22/11/1984	23/11/1984	0	1	0	1
36	07/04/1985	08/04/1985	0	1	0	1
37	26/09/1999	26/09/1999	0	1	0	2
38	24/10/1999	24/10/1999	0	1	0	1
39	24/12/1999	29/12/1999	0	1	0	1
40	29/09/2000	29/09/2000	0	1	0	2
41	30/10/2000	30/10/2000	0	1	0	1
42	10/01/2001	10/01/2001	2	2	2	2
43	07/02/2001	07/02/2001	1	2	1	2
44	27/10/2004	27/10/2004	1	2	1	2
45	02/12/2005	02/12/2005	0	1	0	1
46	10/03/2008	10/03/2008	2	2	2	2
47	10/02/2009	10/02/2009	1	2	1	2
48	28/02/2010	28/02/2010	1	2	1	2

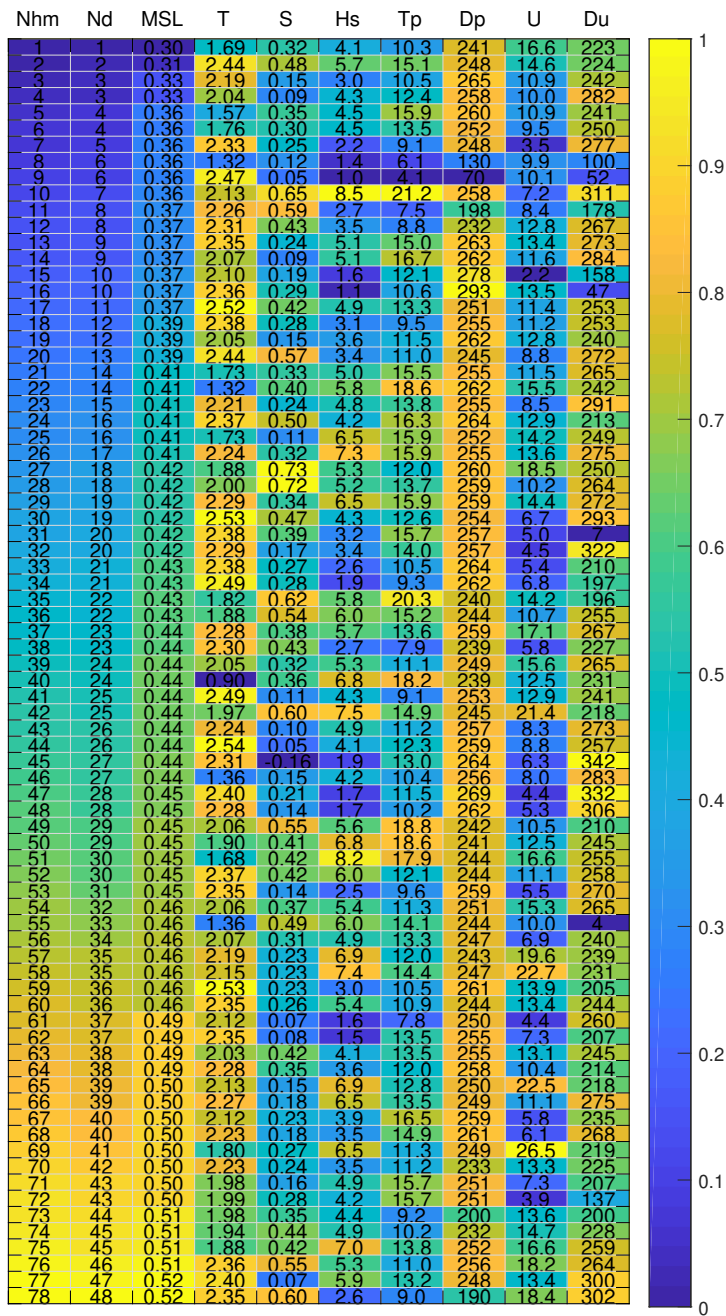


Fig. 18 Hydro-meteorological conditions extracted from the database for each damage events of table 5 with a rescaled colorbar. Nd and Nhm are the numbering in the damage events and hydro-meteorological events database, respectively. The other columns indicate the values of the following hydro-meteorological parameters: mean sea level (MSL, in meter referenced to IGN69 system), tide (T, in meter), atmospheric storm surge (S, in meter), significant wave height (H_s , in meter), wave peak period (T_p , in second), wave peak direction (D_p , in degree, nautical convention), wind speed (U , in meter per second), wind direction (D_u , in degree, nautical convention).

1130 D Bivariate extreme value analysis

1131 Bivariate extreme value analysis (bEVA) is performed focusing on the still water level relative
 1132 to the mean sea-level ($\xi_{/MSL} = \xi - MSL$) and wave height (Hs).

1133 The objective of bEVA is to extrapolate the joint probability density of the offshore sea
 1134 condition variables to extreme values with appropriate consideration of the dependence struc-
 1135 ture. We follow a similar procedure as the one described by *Nicolae-Lerma et al.* (2018), which
 1136 holds as follows:

- 1137 – We use the 1900-2016 HMD to extract the values of wave height (Hs) and of skew surge
 1138 (SS) at each high tide, using the reconstructed tide (T) and surge (S) time series;
- 1139 – The marginals of Hs and SS are modelled by the combination of the empirical distribution,
 1140 below a suitable high threshold u , with the Generalised Pareto distribution (GPD), above
 1141 the selected threshold u (*Coles and Tawn* 1991) using the method of moments. The thresh-
 1142 old value is selected by a combination of methods (visual inspection of quantile–quantile
 1143 graphs, “mean residual life plots”, “modified scale and shape parameters plots” ; see *Coles*
 1144 2001), which yield $u_{Hs} = 6.2\text{m}$ and $u_S = 0.48\text{m}$. The marginal of $\xi_{/MSL}$ is estimated by
 1145 combining the marginal of the skew surge (SS) with the empirical probability distribution
 1146 of tides (T) by following the convolution approach of *Simon* (1994). This approach implic-
 1147 itly assumes that there is no interaction between tide and surge, an assumption which is
 1148 justified on the study site of Gâvres after the study of *Idier et al.* (2012);
- 1149 – The dependence structure of the variables ($\xi_{/MSL}; Hs$) (with prior transformation into
 1150 common standard Gumbel margins) is modelled by following the approach by *Heffernan*
 1151 *and Tawn* (2004). This is based on a non-linear regression model that is fitted above a
 1152 given threshold; hereby selected at 0.95 (expressed as a probability of non-exceedance) by
 1153 using the diagnostic tools described in *Heffernan and Tawn* (2004);
- 1154 – Once fitted, a Monte Carlo simulation procedure is used to randomly generate realiza-
 1155 tions of the variables ($\xi_{/MSL}; Hs$). A total number of more than 6 millions of events are
 1156 generated, which virtually represent a 100,000 year-period;
- 1157 – Finally, the joint exceedance contour (*Hawkes et al.* 2002) is estimated, i.e. the contour
 1158 (x, y) within the space ($\xi_{/MSL}; Hs$) whereby the joint exceedance probability $Pr(\xi_{/MSL} >$
 1159 $x, Hs > y)$ is constant (and equal to the probability associated to the return period of
 1160 interest) at every point around the contour.