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## Coastal flood: a composite method for past events characterisation providing insights in past, present and future hazards-joining historical, statistical and modelling approaches

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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 km<sup>2</sup>. 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 (DEM<sub>2008</sub>) 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 DEM<sub>2008</sub>) 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 ( $\xi$ ): 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  $\xi$  (mean  
244 sea level, tide, atmospheric storm surge) over the 1900-2010 period, such that  $\xi$  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  $-0.33 \pm 0.15$  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  $\sim 0.50$  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  $262^\circ\text{N}$  to  $265^\circ\text{N}$ ).

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  $H_s$  ( $\sim 0.40$  to  $0.50$  m) for the highest waves ( $H_s$  larger than the 99.9% quantile level of  $\sim 7$  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  $267^\circ\text{N}$  to  $265^\circ\text{N}$ ). 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  $15^\circ$  for the main mode (with a shift from  $245^\circ\text{N}$  to  $260^\circ\text{N}$ ), 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  $265^\circ\text{N}$  (i.e. from W-SW), while the wind direction is bimodal with a dominant mode at  $260^\circ\text{N}$ .

## 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 20<sup>th</sup> 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 XX<sup>th</sup> 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 7<sup>th</sup> 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 DEM<sub>2008</sub>, 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

with observations, as few overtopping were reported in 2009 and 2010. In addition, these values are much smaller than for the 1904, 1924, 1978 and 2008 events (considering the DEM<sub>2008</sub> for these 4 events). This hierarchy in the intensity of flood events is consistent with the DED database.

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

## 4 Analysis

### 4.1 Flood events characteristics

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

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

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

After the testimonies (*Le Cornec et al.* 2012), the recent flood events (February 2001, 2004, 2008, 2009, 2010) were induced by wave overtopping. After the model 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  $(\xi, H_s)$  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  $(\xi, T_p)$ ). The minimal wind speed above which all significant flood occurred  
 502 is  $U_c \sim 7$  m/s (scatter plot  $(\xi, U)$  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  $\xi$ , 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 ( $\sim 21$  cm) contributes to 87% of the difference in  $\xi$  (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  $\xi$ ,  
 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  $(\xi, H_s)$  and  $(\xi, T_p)$  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  $\xi$ . 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  $240^\circ$  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  $\xi_{1904}$  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 5<sup>th</sup> 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 ( $\xi, H_s$ ) 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 XX<sup>th</sup> 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 DEM<sub>2008</sub> 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 DEM<sub>2008</sub> 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).

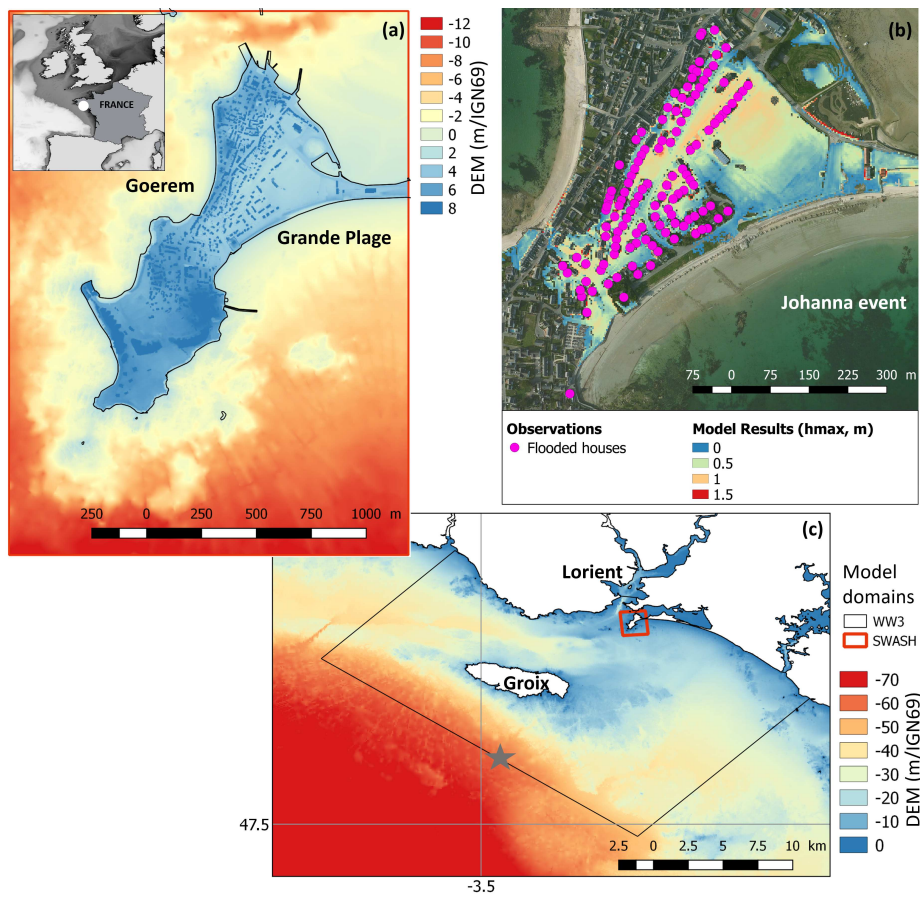
## 797 6 Conclusion

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.

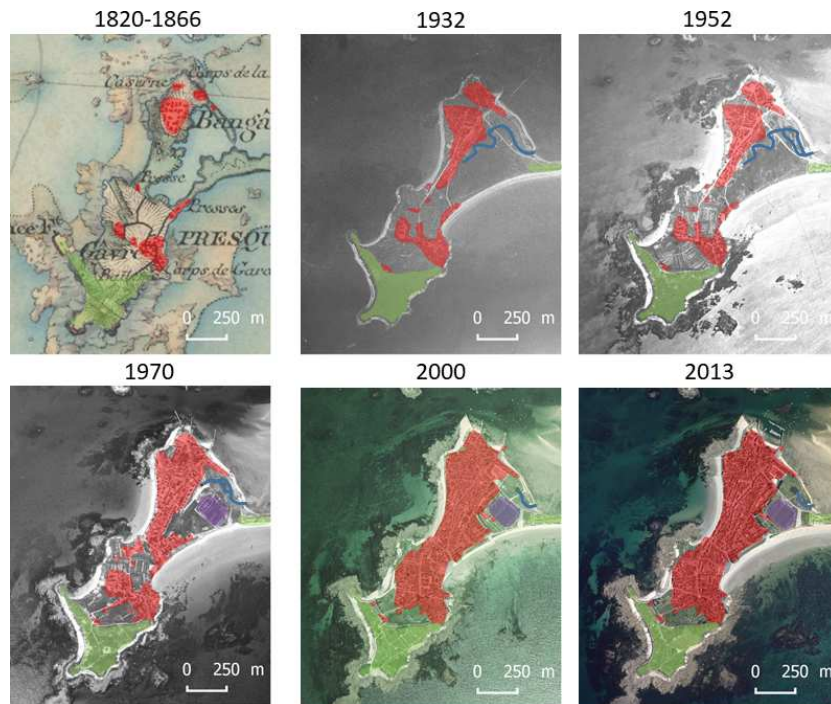
811 The analysis of the hydro-meteorological conditions allows driving the main  
812 patterns of the critical contours separating no flood and flood conditions. The  
813 analysis of the databases and modelling results lead to very similar conclusions,  
814 with the following critical conditions guaranteeing safety against flooding assuming  
815 no failure of coastal defences: still water level of  $\sim 2.5$  m IGN69, significant wave  
816 height of  $\sim 2$  m, peak period  $\sim 9$  s, wind of  $\sim 4$  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 5<sup>th</sup> 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.

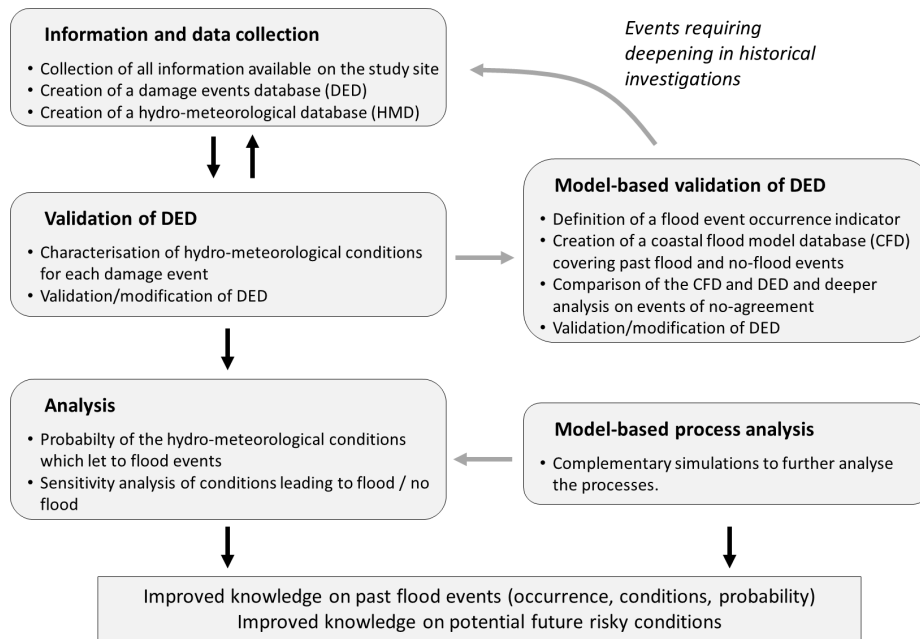
829 The present analysis is based on 48 damage events, 9 observed flood and about  
830 448 numerical simulations. To really assess flood probability (rather than the prob-  
831 ability of forcing conditions) and to improve early-warning systems, more simula-  
832 tions would be needed. Furthermore, 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.



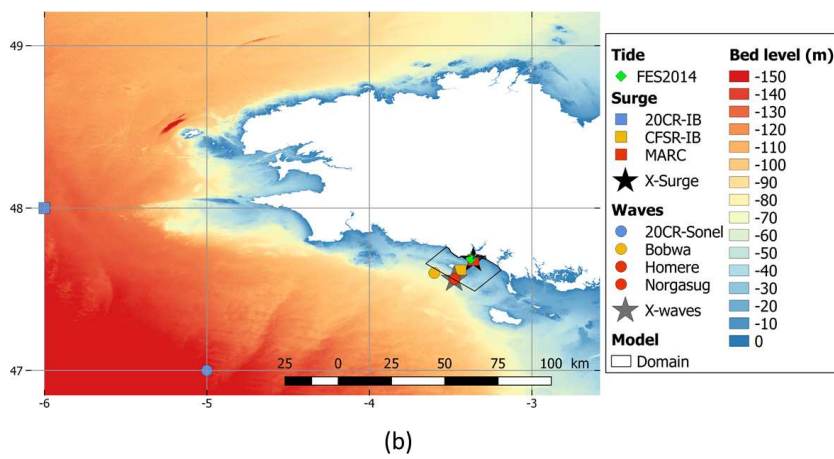
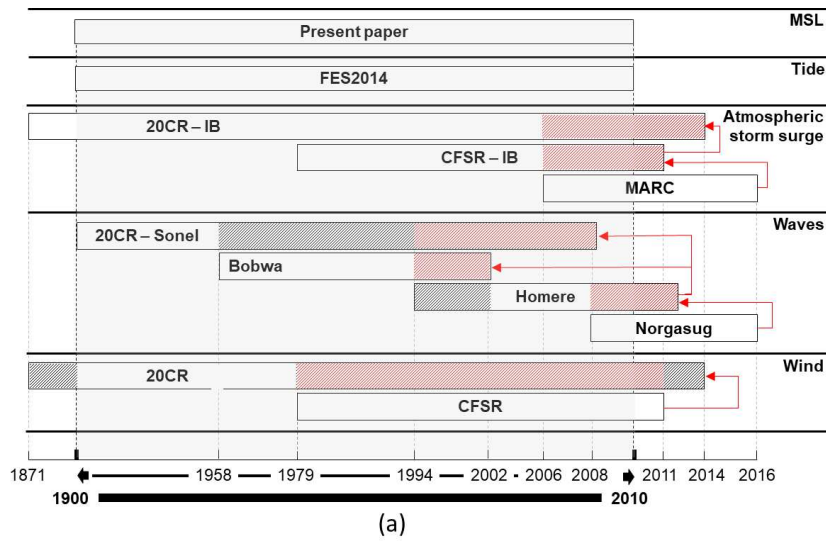
**Fig. 1** (a) location of the site and topo-bathymetry; (b) observed and modelled flood for the Johann event (10th March 2018); (c) surrounding of the study site, computational domains of the hydrodynamics models (WGS84) and location of the offshore forcing wave conditions (grey star).



**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.

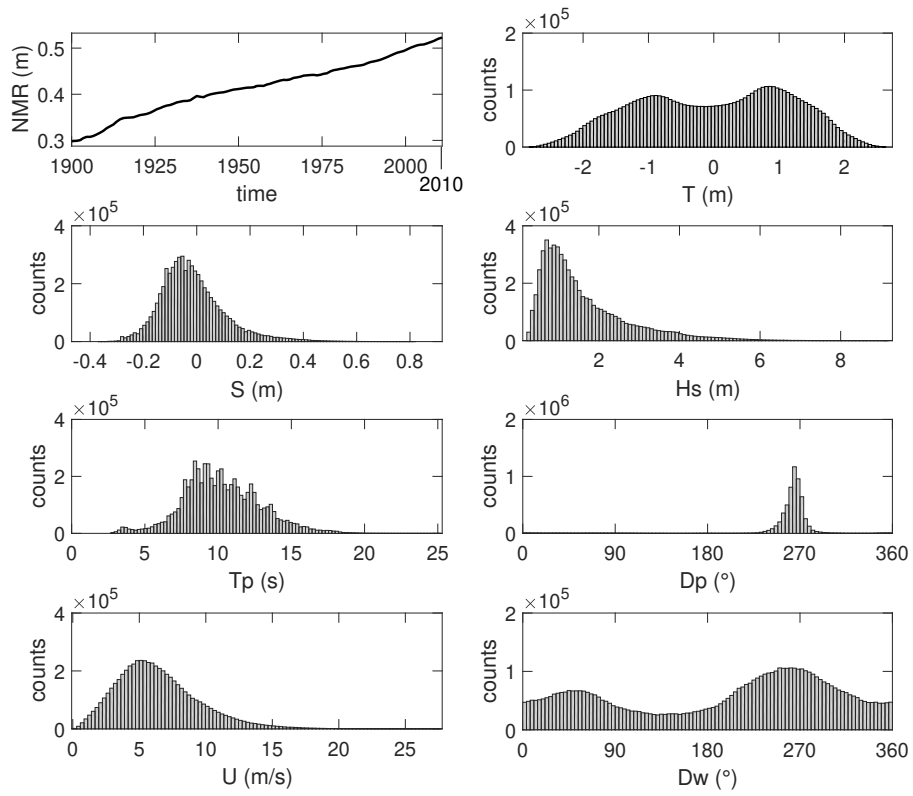


**Fig. 3** Flowchart of the method used in the present paper.

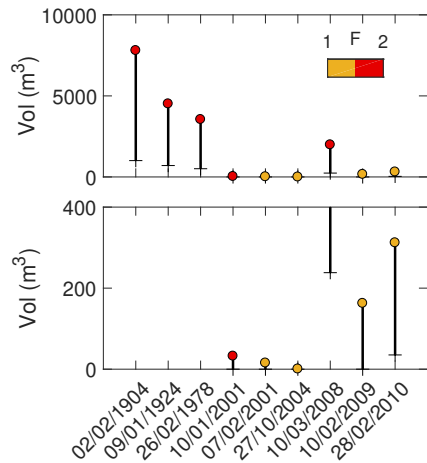


**Fig. 4** Hydro-Meteorological Database: (a) data sources (extraction date: 2017), dataset period used to learn the QQ-corrections (in red), final selected dataset (in white). (b) Location of the tide, surge and wave datasets. X-Surge and X-waves indicate the location of the final composite data of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

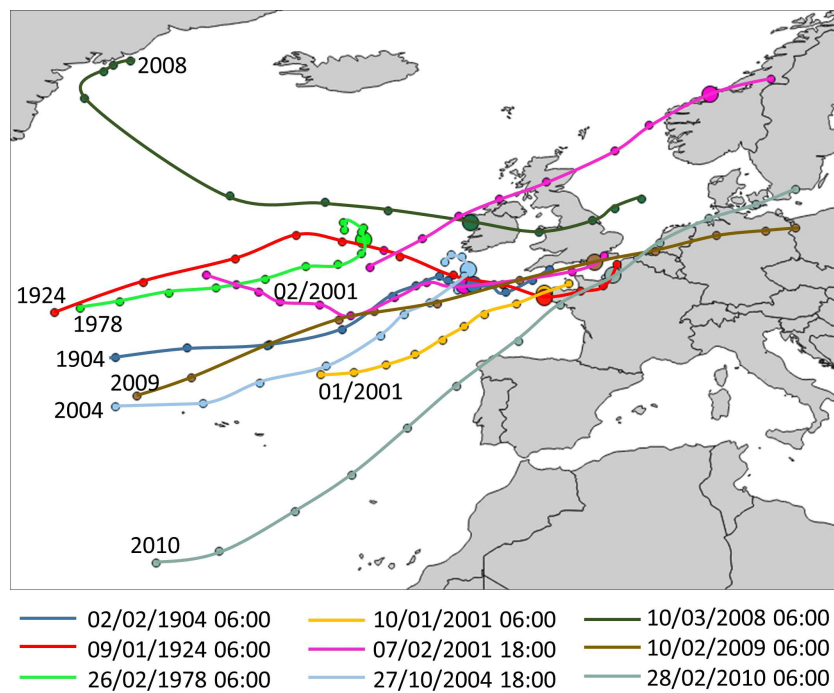




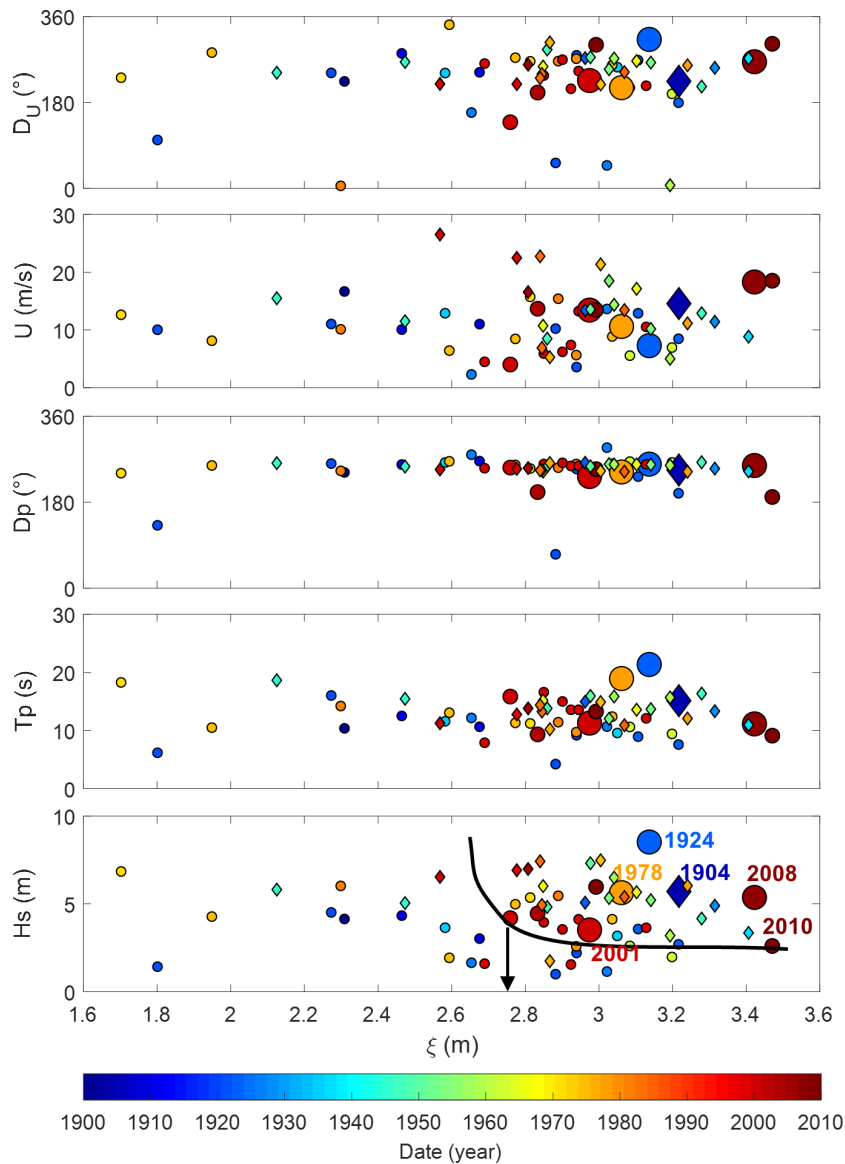
**Fig. 5** Hydro-meteorological database: time series of the relative mean sea level ( $MSL$ ) and distribution of the other hydro-meteorological variables: tide ( $T$ ), surge ( $S$ ), significant wave height ( $H_s$ ), peak period ( $T_p$ ), peak direction ( $D_p$ ), wind velocity ( $U$ ), wind direction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



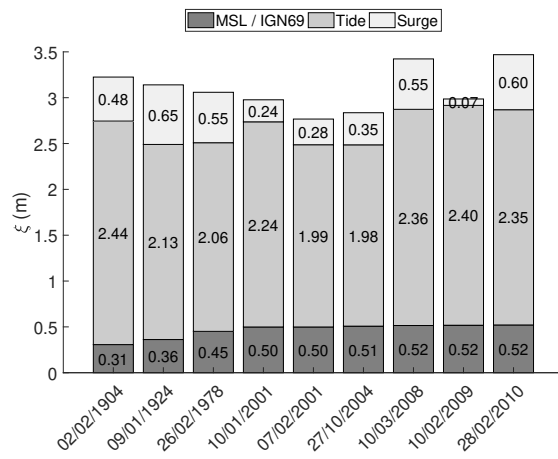
**Fig. 6** Simulated flood indicator ( $Vol$ ) for the 2008 topography (coloured points,  $DEM_{2008}$ ) and the upgraded coastal defence case (+,  $DEM_{upgrade}$ ), considering the events with  $F \geq 1$ . The colors refer to the Flood value of the Damage database. The bottom panel is a zoom of the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



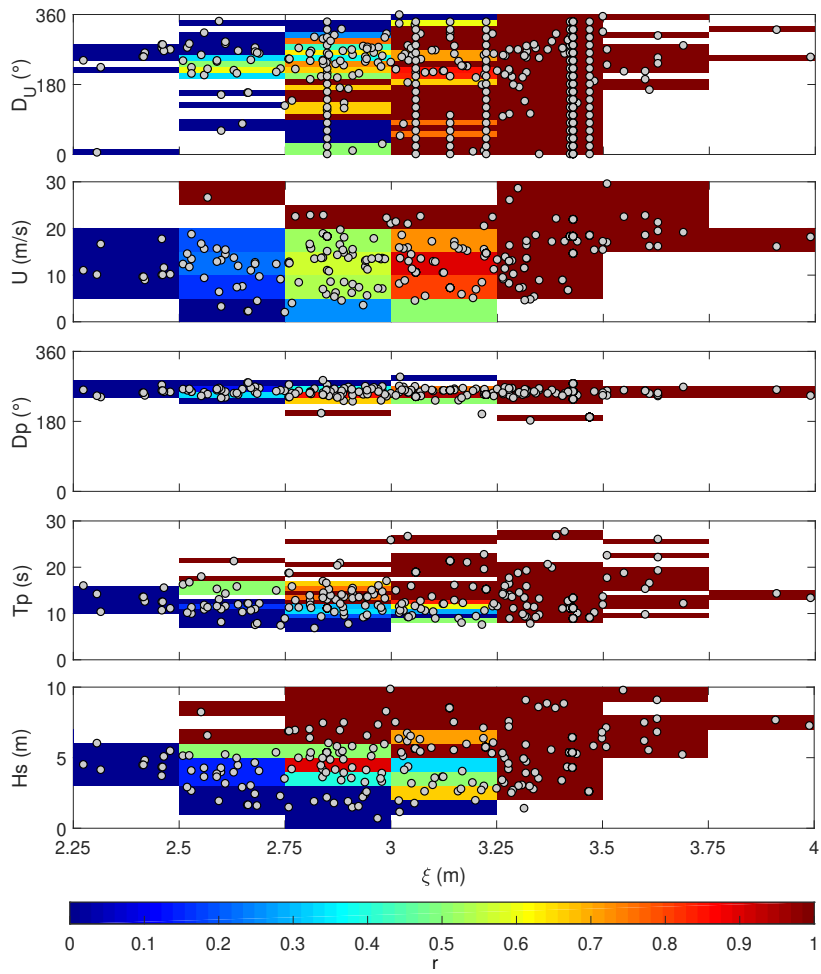
**Fig. 7** Storm tracks associated with the 9 flood events, based on the 500hPa geopotential pressure, extracted from the 20CR data (until 1978), and CFSR data (after 1978), every 6 hours. Dates in caption indicate the reference time (large size circle).



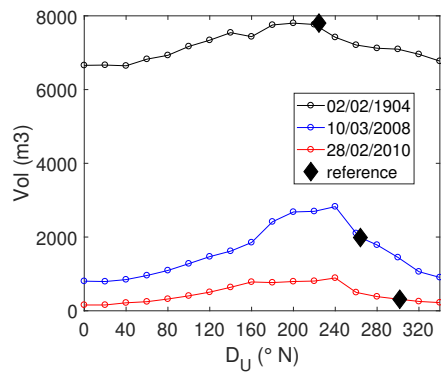
**Fig. 8** Scatter plot of the Hydro-Meteorological conditions of the events of the Damage Event Database. The black arrow (bottom panel) indicates the smallest still water level ( $\xi_c=2.77$  m IGN69) among the flood events ( $F \geq 1$ ). The marker size indicates the *Flood* value (0-no flood: small 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.



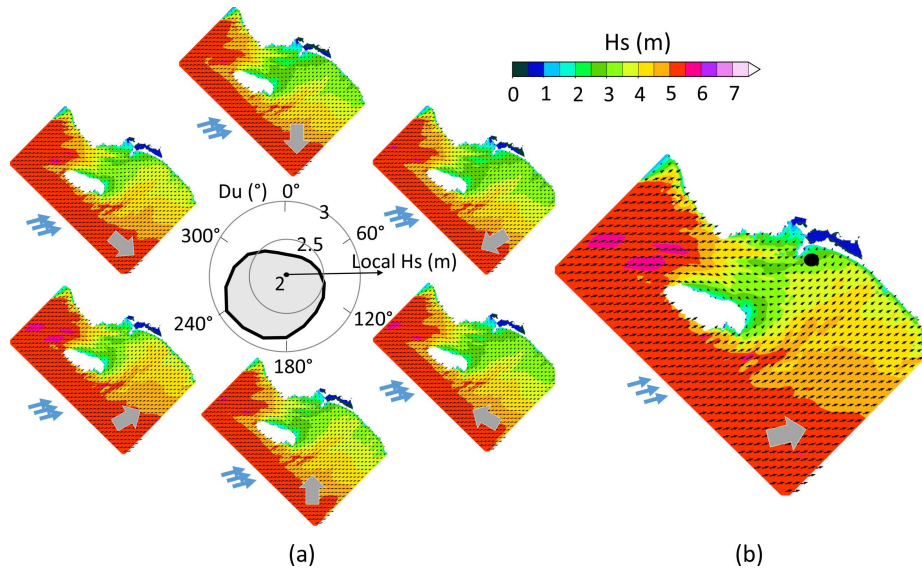
**Fig. 9** Contribution of each water level component to the still water level ( $\xi$ ), for the 9 flood events.



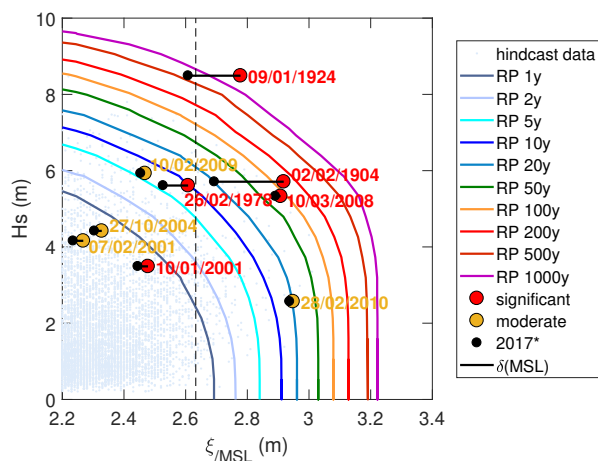
**Fig. 10** Identification of conditions leading to flooding, based on the numerical flood simulations. The color scale indicates the value of the ratio  $r$  between the number of simulations providing  $Vol > 0$  and the total number of computations for in each cell. Dots: simulation points. Based on simulations done with the DEM<sub>2008</sub>.



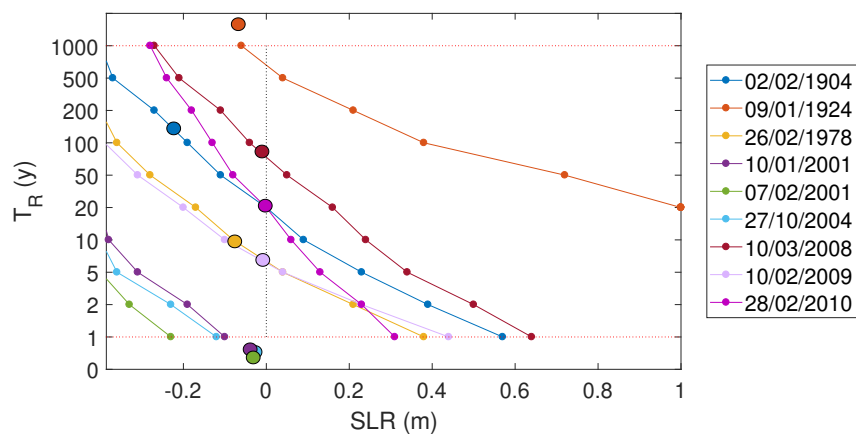
**Fig. 11** Sensitivity of the flood indicator  $Vol$  to the wind direction  $D_u$  for the 3 flood events of largest wind speed, for the DEM<sub>2008</sub> configuration.



**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  $(\xi_{MSL}, H_S)$  for return period values ranging from 10 to 1000 years together with the nine historical events. Note that the still water level  $\xi_{MSL}$  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  $\xi_{MSL}$  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](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<sub>s</sub>*: significant wave height, *T<sub>p</sub>*: wave peak period, *D<sub>p</sub>*: 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<sub>s</sub>* and *U*) are given in bold.

Event	HT	MSL (m)	T (m)	S (m)	H <sub>s</sub> (m)	T <sub>p</sub> (s)	D <sub>p</sub> (°)	U (m/s)	Du (°)
<b>02/02/1904</b>	04:00	0.307	2.438	0.48	5.71	15.1	247.6	14.6	224.4
<b>09/01/1924</b>	05:30	0.362	2.128	<b>0.65</b>	<b>8.49</b>	<b>21.3</b>	258.5	7.8	310.8
<b>26/02/1978</b>	05:30	0.451	2.058	0.55	5.61	18.8	242.0	10.5	209.7
<b>10/01/2001</b>	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
<b>10/03/2008</b>	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	<b>2.398</b>	0.07	5.93	13.2	248.0	13.4	299.6
28/02/2010	03:10	<b>0.521</b>	2.348	0.60	2.57	9.0	189.7	<b>18.4</b>	301.7

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 840 LOPS-IFREMER, SHOM. X. Bertin is also acknowledged for having running and provided  
 841 the Sonel-waves data. T. Bulteau is acknowledged for discussions on the implementation of  
 842 the method of *Heffernan and Tawn* (2004). The authors are also grateful to local stakehold-  
 843 ers comity of the RISCOPE project which provided useful informal knowledge and some key  
 844 reports and data (D. Le Vouédec, M.O. Botti-Le-Formal), to L. Pineau-Guillou and C. Meur-  
 845 Ferec for fruitful discussions, and to the anonymous referee for his insightful comments that  
 846 strengthened this paper.

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## 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](http://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

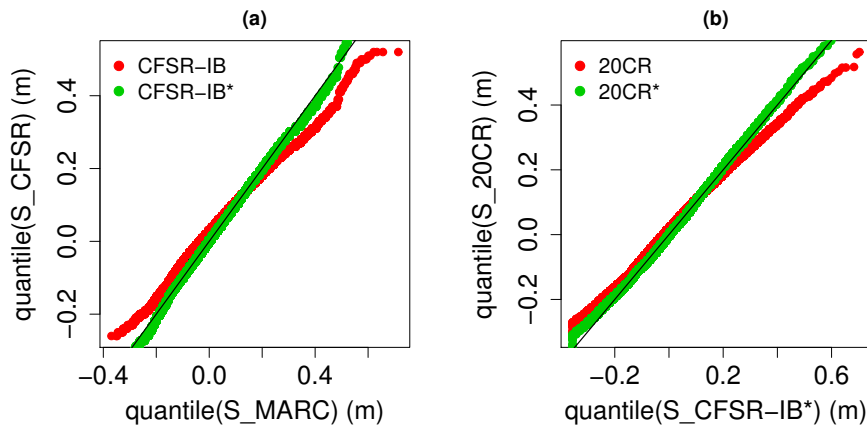
To transform the absolute mean-sea level reconstruction obtained above to values relative to the ground in Gâvres, we use an estimation of the local vertical land movement (VLM) in Gâvres based on the 3 nearest GPS stations provided by the SONEL network (*Santamaría-Gómez et al. 2017*). Table 4 shows 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	$-0.36 \text{ m} \pm 0.20$

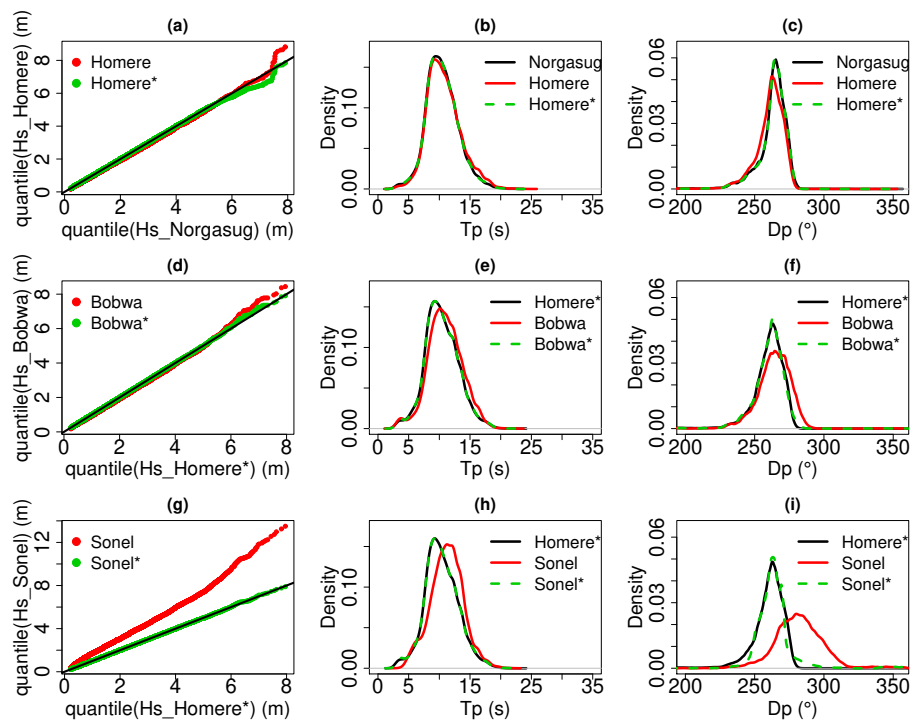
1110 **B Quantile-Quantile corrections for the hydro-meteorological database**

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).

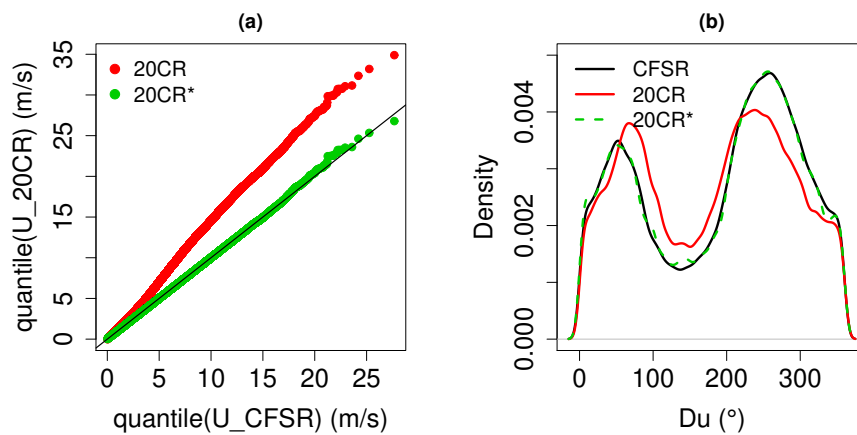


**Fig. 15** Quantile-quantile corrections of surge data. QQ plots of the reference (MARC), data to correct and corrected data. (a) CFSR-IB data corrected with MARC data, (b) 20CR-IB data corrected with MARC data.





**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).

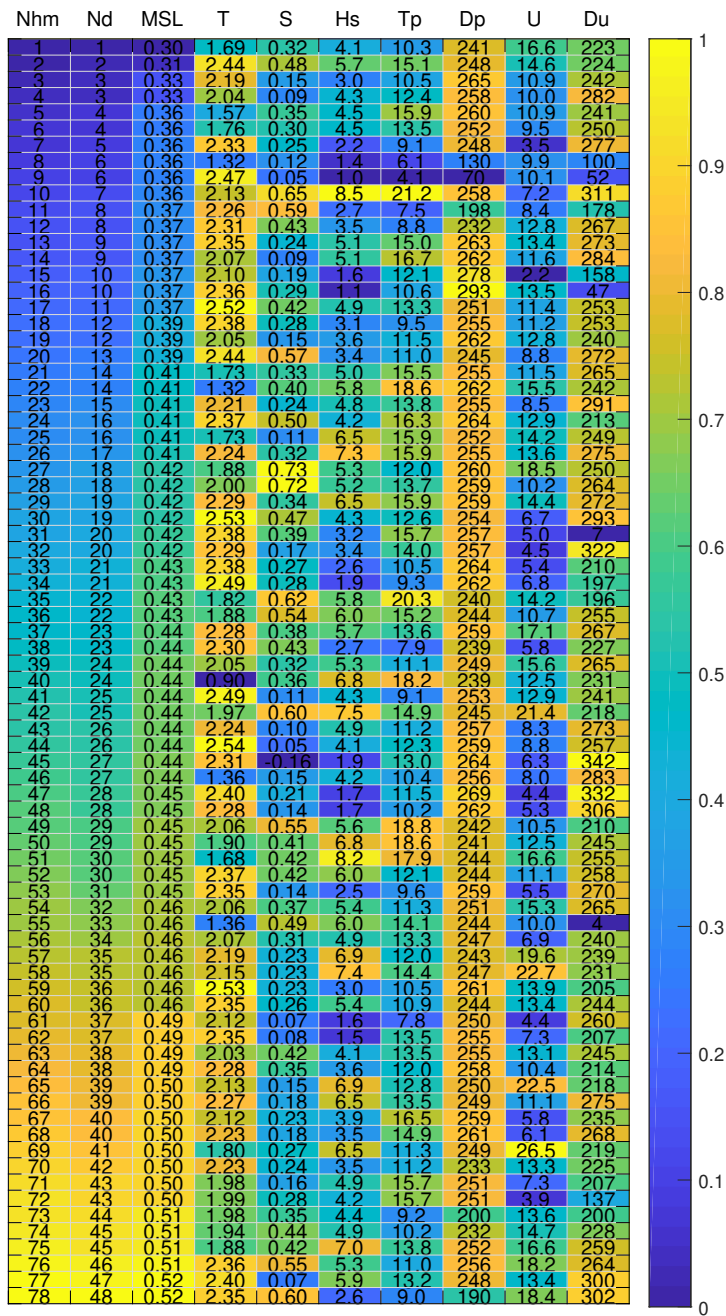
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**1115 C Damage events and associated hydro-meteorological conditions**

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.