Journal of Coastal Research	SI	88	89–109	Coconut Creek, Florida	2019

Long, Medium, and Short-term Shoreline Dynamics of the Brittany Coast (Western France)

Pierre Stéphan[†*], Emmanuel Blaise[‡], Serge Suanez[∞], Bernard Fichaut[∞], Ronan Autret[∞], France Floc'h[§], Véronique Cuq[∞], Nicolas Le Dantec[§#], Jérôme Ammann[§], Laurence David[†], Marion Jaud[§] and Christophe Delacourt[§]

[†]CNRS, Université de Bretagne Occidentale
UMR LETG 6554, IUEM
Plouzané, France

[‡]Université de La Rochelle
UMR 7266 CNRS LIENSs
La Rochelle, France

[∞]Université de Bretagne Occidentale, CNRS
UMR LETG 6554, IUEM
Plouzané, France

[§]Université de Bretagne Occidentale, CNRS
UMR 6538 LGO, IUEM
Plouzané, France

[#]CEREMA/EMF/ER
Plouzané, France

www.cerf-jcr.org

www.JCRonline.org

ABSTRACT

Stéphan, P.; Blaise, E.; Suanez, S.; Fichaut, B.; Autret, R.; Floc'h, F.; Cuq, V.; Le Dantec, N.; Ammann, J.; David, L.; Jaud, M., and Delacourt, C., 2019. Long, medium, and short-term shoreline dynamics of the Brittany Coast (western France). *In:* Castelle, B. and Chaumillon, E. (eds.), *Coastal Evolution under Climate Change along the Tropical Overseas and Temperate Metropolitan France*. *Journal of Coastal Research*, Special Issue No. 88, pp. 89–109. Coconut Creek (Florida), ISSN 0749-0208.

This paper aims to analyze the shoreline changes of coastal accumulations (sandy and gravel beaches/barriers) of Brittany (Western France). Three long, medium, and short term spatio-temporal scale observations are taken into consideration for the assessment of shoreline dynamics at this regional scale. Firstly, the long-term shoreline position evolution is based on a comparison of two sets of aerial orthophotos (1949-1952 and 2006-2009). A total of 652 beaches were analyzed in order to map and quantify erosion (35% of the total studied coastline), stability (38%), and accretion (27%) over the last 60 years. In detail, these percentages vary significantly according to the beach/barrier morphologies (spits vs pocket beaches), sediment composition (sandy vs gravelly), and hydrodynamic context (exposed vs sheltered). Secondly, a pluri-annual (*i.e*., medium-term) shoreline change analysis based on five representative beaches was conducted. This analysis was also based on image processing using sets of aerial photos taken every five years over the last 60 years (1948-2013). Results show an alternation of significant erosion- and accretion-dominated periods (respectively EDP and ADP), with six main EDP (*i.e*., periods 1962-1968, 1977-1978, 1980-1985, 1987-1990, 1993-1997, and 2013-2014) related to an increase in the frequency of extreme water levels associated with storm events. Finally, the short-term change analysis based on high-frequency monitoring of 11 sites was carried out over the period 1998-2017. These surveys, based on field topo-morphological measurements, highlight the impact of five morphogenetic events associated with significant storm events: 1998-2000 (storms Lothar and Martin in December 1999), 2008 (storm Johanna on March 10, 2008), the winter of 2013-2014 (a cluster of storms in January, February, and March 2014), 2016 (storm Ruzica/Imogen on February 8, 2016) and 2018 (storm Eleanor on January 2, 2018). A relevant recovery phase, which took place between 2008 and 2012 due to the calm and cold winters, was also recognized. The identification of parameters involved in shoreline variations at these three timescales is important for future management options of the Brittany coast.

ADDITIONAL INDEX WORDS: *Shoreline, Brittany, storms, erosion, recovery, beach, barrier.*

INTRODUCTION

The study of the dynamic processes that govern the evolution of coastal shoreline accumulations is largely dependent on the spatio-temporal scales at which they operate (Fenster and Dolan, 1993, Short, 1999). Processes acting at very large scales (multi-millennia) will affect areas extending into the oceanic domain, while seasonal processes and short-term events (*i.e.*, storms) will more likely impact the coastal fringe. From the beginning of the 1980's, the use of predictive numerical models has produced a terminology allowing for the formalization of this spatio-temporal notion. The term LSCB (for *Large-Scale Coastal Behavior*) is employed by many authors to illustrate morphodynamic changes observed at pluri-decadal timescales (de Vriend, 1991; de Vriend *et al.*, 1993; Fisher, Dolan, and Hayden, 1984; List *et al.*, 1997; Stive, Roelvink, and de Vriend, 1990; Terwindt and Battjes, 1991). The terms "*mesoscale*" (Kana, 1995), and "*medium-term*" (Jimenez and Sánchez-Arcilla, 1993) are used to define morphodynamic variations operating at decadal to pluri-annual time-scales, while "*short-term*" is employed to characterize seasonal variations (Aubrey, 1979; Davidson-Arnott and Law, 1990; Moreira, 1988; Winant, Inman, and Nordstrom, 1975). Finally, the terms "*instantaneous or event scale*", or "*episodic-scale*" define morphodynamic processes generally related to storm events with a duration of a few hours (Guillen

DOI: 10.2112/ SI88-008.1 received 9 November 2018; accepted in revision 29 March 2019.
*Corresponding author: pierre.stephan@univ-brest.fr

and Palanques, 1994; Jimenez *et al*., 1997). Many authors have noted the difficulty in describing morphological changes where processes operating at different timescales interact with each other. For instance, very short-term high-intensity storm events lead to a more chaotic evolution which may deviate from the long-term linear trend of shoreline changes (Cowell and Thom, 1994). The survey of Moruya beach (Sydney, Australia) undertaken between 1972 and 1988 showed a strong 1974-1978 erosion-dominated period (EDP) inducing a significant discontinuity in the long-term accretion dominated period (ADP). While the beach experienced a slight and gradual increase of the sediment budget over the entire studied period, the few years from 1974 to 1978 were characterized by a rapid erosion caused by a succession of storm events (Thom and Hall, 1991). Therefore, the problem is how to evaluate long-term trends that can effectively illustrate the evolution of a shoreline without this evolution being disturbed by the impact of very short-term changes (Douglas, Crowell, and Leatherman, 1998; Fenster, Dolan, and Elder, 1993; Zuzek *et al.*, 2003). Eliot and Clarke (1989) indicated that a 10 year-long survey based on monthly measurements is required to minimize seasonal effects and/or very short-term changes due to storm events. Regarding the methodological aspect, statistical approaches based on linear-regression have been used as these best fit the data according to the Minimum Description Length or for predicting future shoreline positions which behave in a nonlinear, cyclic, or chaotic manner (Dolan, Fenster, and Holme, 1991; Douglas, Crowell, and Leatherman, 1998; Eliot and Clarke, 1982; Fenster, Dolan, and Elder, 1993; Honeycutt, Crowell, and Douglas, 2001). Similarly, either factor analysis (*i.e.,* ACP) (Cuadrado and Perillo, 1997; Fisher, Dolan, and Hayden, 1984), Empirical Orthogonal Function (*i.e.*, EOF) (Eliot and Clarke, 1982; Maron, Rihouey, and Dubranna, 2004), or Empirical Eigenfunctions" (Aubrey 1979; Larson and Kraus, 1994; Winant, Inman, and Nordstrom, 1975) are also used to analyze the spatiotemporal variations of a beach sediment budget. Notwithstanding the difficulties involved in disentangling the impact of these spatio-temporal scales, their consideration is important, since the understanding of observed processes associated with each scale has become essential for coastal management, and in predicting the morphosedimentary evolution of the coastal domain (*e.g.,* Castelle *et al*., 2018; Evans, 1992; Fleming, 1992; Masselink *et al.*, 2016).

This paper aims to estimate the shoreline dynamics of the coastal accumulations of Brittany, western France (Figure 1),

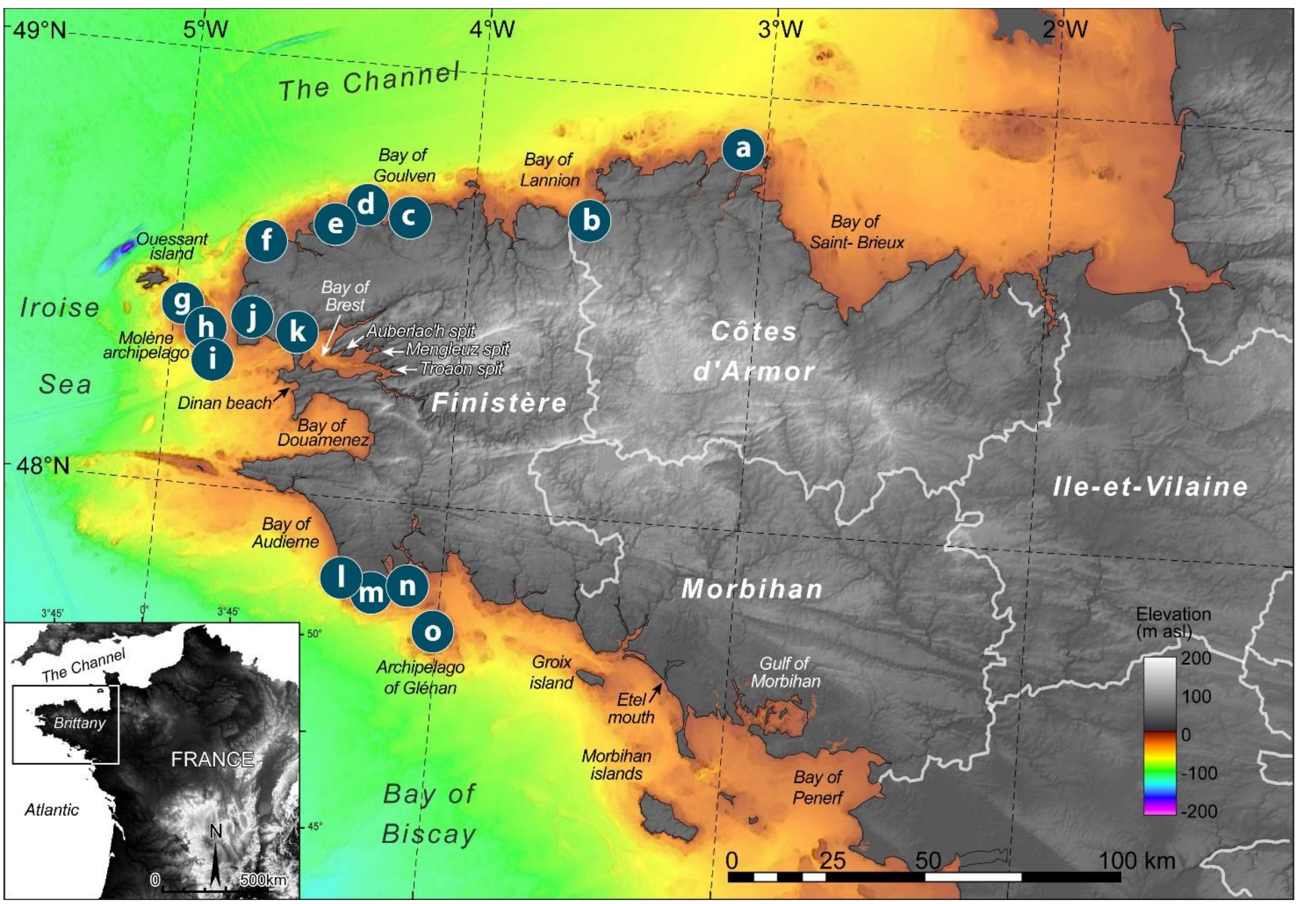

Figure 1. Location maps of the Brittany coast. The letters (a) to (o) correspond to the location of the beaches studied at medium and short-term timescales (see Figure 4).

Table 1. *Some wave statistics from simulation points of the ANEMOC numerical model (see Figure 3 for location) over the period of 1979-2002 (source: Laboratoire 186 National d'Hydraulique et d'Environnement, LNHE-EDF Chatou, and Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement, CEREMA Brest).*

				Hs (m)		Tp (s)	
ANEMOC Point	Latitude	Longitude	Depth (m)	0.5% exceedance	0.1% exceedance	0.5% exceedance	0.1% exceedance
COAST-3668	48°47.220'N	1°42.420'W	15.50	2.65	3.13	18.3	19.6
COAST-2893	48°46.620'N	2°1.020'W	25.20	3.21	3.83	18.1	19.6
COAST-3611	48°45.180'N	2°20.340'W	16.10	3.28	3.92	18.5	19.7
COAST-2991	48°47.640'N	2°47.040'W	23.90	2.88	3.46	18.4	19.7
COAST-2193	48°56.280'N	3°12.660'W	36.10	5.02	5.95	18.3	19.6
COAST-4171	48°50.640'N	3°39.960'W	10.50	4.27	4.32	18.7	19.7
COAST-1004	48°46.020'N	4°10.440'W	68.80	6.89	8.07	17.9	19.3
COAST-1178	48°39.420'N	4°40.860'W	62.80	7.82	9.37	18.1	19.4
COAST-0730	48°29.880'N	4°58.140'W	80.20	5.51	6.26	15.3	15.5
COAST-3343	48°14.160'N	4°39.480'W	19.20	7.02	7.68	18.3	19.5
COAST-2867	48°8.760'N	4°26.220'W	25.60	3.49	3.59	18.2	19.5
COAST-1662	48°5.400'N	4°50.280'W	48.80	8.67	10.51	18	19.3
COAST-2511	47°54.660'N	4°30.900'W	30.70	7.66	8.98	17.8	19
COAST-2409	47°43.560'N	4°7.500'W	32.40	6.63	8.16	17.7	19
COAST-3898	47°44.340'N	3°41.460'W	12.90	4.98	5.21	17.7	18.9
COAST-3036	47°29.220'N	3°10.020'W	23.40	5.58	6.59	17.8	19.2
COAST-3197	47°23.220'N	3°2.400'W	21.30	3.3	4.02	17.7	19.4
COAST-3281	47°25.920'N	2°52.080'W	20.20	3.55	3.85	18.6	19.8
COAST-3521	47°23.640'N	2°35.460'W	17.00	3.58	4.46	18.5	19.8

such as beach/dune systems, sandy-gravel beaches, and gravel barriers. Rocky or soft-material cliffs are not included. Three spatiotemporal scales are considered successively in order to provide quantitative data needed for a better management of the shoreline changes. The long-term analysis covers the last 60 years and more than 650 study sites located all around the Brittany coast. It is based on the analysis of two sets of aerial photographs taken in 1948-1952 and 2006-2009, providing a global trend of shoreline recession or accretion. The second spatiotemporal scale deals with the medium-term analysis of five study sites situated in north, west, and south Brittany. It is also based on the treatment of aerial photographs and/or field measurements covering the last 70 years (1948-2018) but with a higher frequency (3 to 5 years) depending on the periods and studied sites. The higher frequency of observations allows us to identify pluri-annual phases of shoreline erosion and accretion as medium-term changes in the long-term trend. Finally, the short-term to event-scale analysis of shoreline changes is discussed. It is based on monitoring programmes carried out for several years on sandy beaches and gravel barriers located in the departments of Finistère and Côtes-d'Armor. These monitoring programmes include the "*Observatoire du Domaine Côtier* – ODC" of the *Institut Universitaire Européen de la Mer* (https://www-iuem.univ-brest.fr/observatoire/observation-109 cotiere/suivi-geomorphologique), which started in 2002. The "*Service National d'Observation – SNO DYNALIT*" is also one of the major survey programmes of shoreline dynamics for the French coastline (https://www.dynalit.fr/). It is funded by the "*Institut National des Sciences de l'Univers - INSU*" of the CNRS, and was started in 2010. Lastly, some data were acquired through non-permanent monitoring carried out as part of scientific projects and/or doctoral research. These very short-term observations are based on topo-morphological field measurements and allow us to identify and quantify the impact of extreme events (storms) on shoreline recession.

STUDY SITES

The Brittany Coast

Coastal Morphology

The 2.470 km long Brittany coast stretches over the four departments of Ile-et-Vilaine (north Brittany), Côtes-d'Armor (north Brittany), Finistère (north, west, and south Brittany), and Morbihan (south Brittany) (Figure 1). It is an extremely rugged coastline, where rocky promontories alternate with embayments consisting of beach/dunes or gravel beaches. Consequently, the number of sediment cells is very important. For just the Bay of Brest, Stéphan (2011b) identified more than 95 sediment cells along the 250 km-long coast, which highlights the high diversity of environmental conditions, especially in terms of lithology, morphology, hydrodynamism, and sedimentology. The coastal accumulations corresponding to beach/dunes, sandy and gravel beaches or barriers (clay and silt environments are not considered in this study) amount to 630 km (*i.e.*, 25.5% of the whole Brittany coastline) (Blaise, 2017). These coastal accumulations show a large proportion of sandy coasts, up to 453 km (*i.e.*, 71% of the studied coastline), mainly composed of dunes, *i.e.*, 308 km of the total sandy coastline (Guilcher and Hallégouët, 1991). They are mainly located in the departments of Finistère and Morbihan (Figure 2). Gravel beaches represent about 17% of the Brittany coastline (*i.e.*, 109 km), and they are largely located in the departments of Côtes-d'Armor (*i.e.*, 37.5% of the department coastline) and Finistère (*i.e.*, 22.5% of the department coastline representing 54 km). Finally, 65 km of the Brittany coast are a mixture of sandy-gravel accumulations, representing 10.5% of the total coastline. They form small beaches backed by coastal defense structures and/or barriers enclosing saltmarsh estuaries or embayments.

Tides, Waves, and Mean Sea-level

The Brittany coast is a meso- to macrotidal environment. The tidal range is highly variable from the NE to the W (Figure 3). The maximum tidal range reaches up to 14 m during spring tides in Mont-Saint-Michel Bay. It gradually decreases westward with a maximum ranging from 6.9 m to 7.6 m in the Iroise Sea. Along the southern coast of Brittany, the tidal range goes from 6.1 m in the Bay of Penerf to a minimum value of 3.3 m in the Gulf of Morbihan. The wave climate is energetic and strongly seasonally modulated, especially in western Brittany where high-energy winter swells and storm waves come from the W-NW with significant wave height Hs frequently exceeding 5 m (Table 1). In northern Brittany, the direction of incident waves ranges from 300° N to 310° N with Hs values exceeding 3 m only 6% of the time. Wave refraction and diffraction are significant near the coast due to the presence of numerous islands and reefs. Consequently, wave conditions are highly variable alongshore and are very site-specific. Along the south Brittany coastline, incident waves generally arrive from the SW with Hs reaching up 3 m only 3% of the time. The coast between Quiberon and the Bay of Penerf is sheltered by a set of islands (the Belle-île-en Mer, Houat, and Hoëdic islands) and Tertiary rocky shoals, leading to significant refraction of waves approaching the beaches. Finally, the Bay of Brest and the Gulf of Morbihan are very sheltered environments where the wave climate is highly controlled by local wind. Here, because of the fetch-limited conditions, significant wave heights are <1 m most of the time. In Brittany, the mean sea-level trend is estimated at +1.26 $mm.yr^{-1}$ in the Brest harbor (W Brittany) for the period of 1900-1990 (Dodet *et al.*, this issue). The rates of mean sea-level rise increased over the more recent period of 1990-2018 with values ranging from +2.03 $mm.yr^{-1}$ in south Brittany to +2.86 $mm.yr^{-1}$ in west Brittany and +1.8 $mm.yr^{-1}$ in north-west Brittany (Dodet *et al.*, this issue).

Impact of human activity on the coast of Brittany

Over the last centuries and decades, the influence of human activity on shoreline changes in Brittany can be summarized as follows. During the 18th and 19th centuries, a large number of back-barrier salt-marshes were empoldered for economic (agricultural development) and sanitary reasons (to eradicate mosquitoes and malaria). Seawalls were constructed in the inner part of numerous embayments and coastal valleys, resulting in major changes in tidal, wave, and current conditions. These

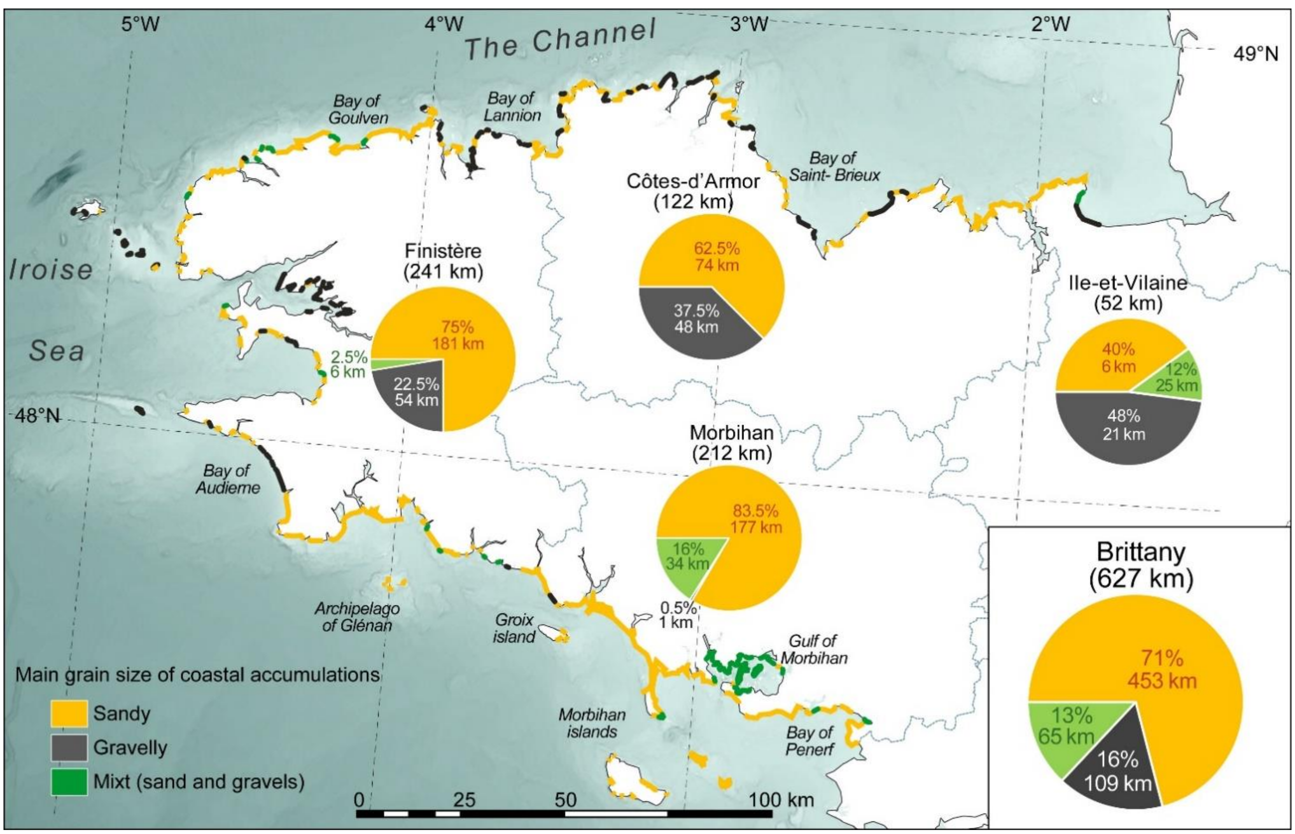

Figure 2. Location of the coastal accumulations along the Brittany coast, according to the grain size (sandy, gravelly, and mixed sands and gravels). The shoreline length covered by each grain-size class and the corresponding percentages are given for each of the Brittany departments.

anthropogenic changes strongly modified sediment transfers along many sandy spits initially located in front of low-elevation polders.

During the 20th century, the intensification of human activity along the coast of Brittany led to a large range of morphogenetic impacts on sandy and gravelly beaches and barriers. During WW2, massive extractions of gravels were carried out on several gravel barriers by the German army for the construction of fortifications forming the Atlantic Wall (Chanson, 2004). The most important gravel extractions occurred in the Bay of Audierne, with an estimated volume of around 1.10^6 m^3 (Morel, 1995). In other coastal areas, farmers massively exploited calcareous beach sand for soil enhancement (Guilcher and Hallégouët, 1991; Hallégouët and Hénaff, 1995; Yoni and Hallégouët, 1998). During the 1970s and 1980s, the rapid extension of urbanized areas in the coastal zone (mainly residential housing and associated infrastructure and facilities) (Le Berre *et al.*, 2017) also led to the installation of numerous hard defense structures along the shoreline in order to prevent erosion. Between the 1960s and the 1980s, the huge increase in the number of tourists on beaches led to a strong degradation of dune vegetation and a remobilization of the sand, caused by trampling, camping, riding, driving, motorcycling, etc. Numerous dunes in Brittany suffered severe erosion (Guilcher and Hallégouët, 1991). Finally, several marinas and jetties were constructed in estuaries, especially in southern Brittany, with an impact on the hydrodynamic processes and sediment transfers along the beaches located in the vicinity of these estuaries (Hénaff and Jegu, 1995).

From the 1980s onward, soft management of dunes and beaches was adopted with the creation of the Coastal Conservancy (*Conservatoire du Littoral*) in 1975, patterned on the National Trust of Britain. This public agency bought or received coastal lands and delegated their management to public councils or private societies for nature conservation. Marram grass plantations and wooden fences were installed on the most degraded dunes. These soft solutions were very efficient in preventing aeolian erosion and blowouts and in channeling

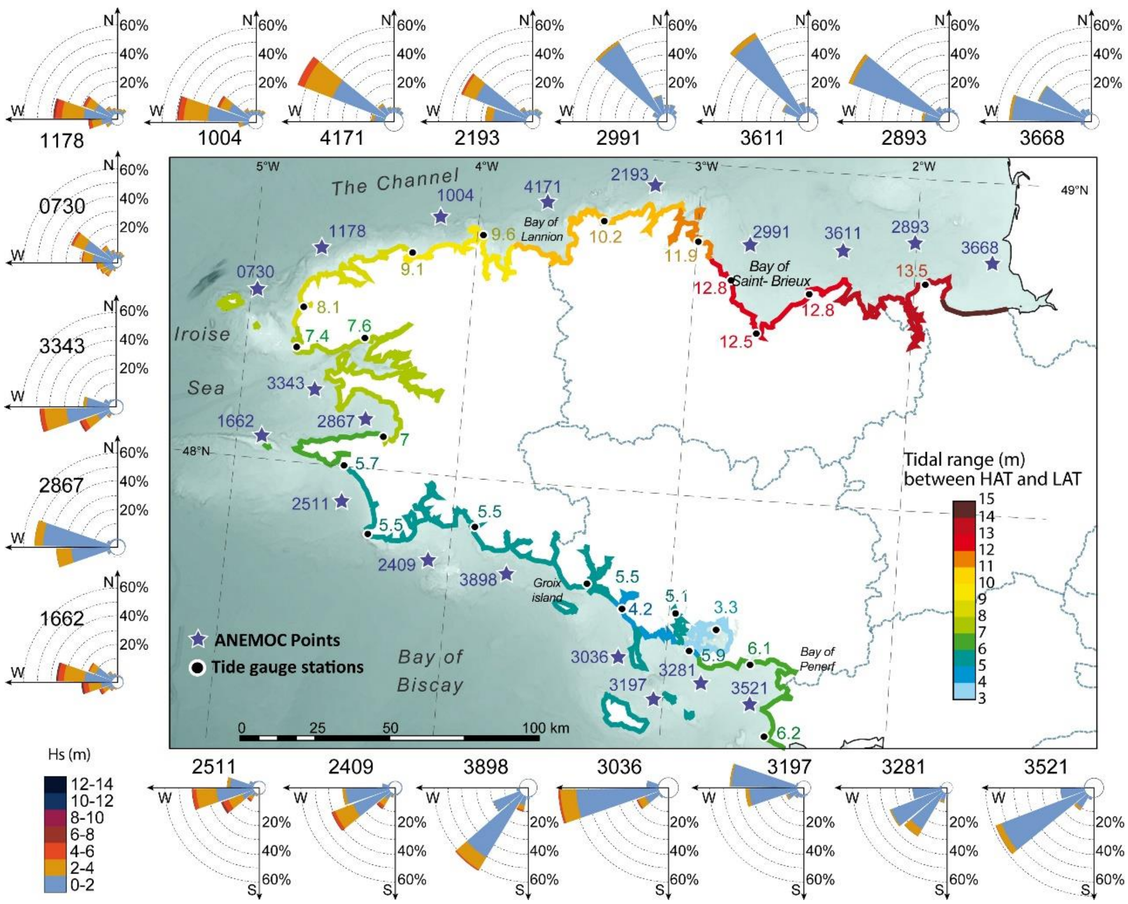

Figure 3. Tide and wave conditions along the Brittany coast. Offshore wave data were obtained from the numerical model ANEMOC over the period of 1979-2002 (source: *Laboratoire* 186 *National d'Hydraulique et d'Environnement, LNHE-EDF Chatou*, and *Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement, CEREMA Brest*). Tide data are provided by the *Service Hydrographique et Océanographique de la Marine*, SHOM-Brest).

pedestrian flows through the coastal dunes. Several back-barrier marshes were relinquished back to the sea. Very few hard defense structures were removed where considered as ineffective (*e.g.*, on the Sillon de Talbert in 2004).

Morphology of Beaches and Barriers

According to the morphological and sedimentary characteristics, beaches and barriers of Brittany can be classified into four different types: *(i)* sandy beach/high dune systems; *(ii)* low-lying aeolian accumulations; *(iii)* shingle beaches and gravel barriers; *(iv)* small embayed beaches (Figure 4).

Sandy Beach/High Dune Complex

This type of morphology is characterized by a sandy beach backed by high dunes that culminate between 5 and 6 m above the highest astronomical tide level (HAT). This is the case for the beach/dune systems of Tréompan (Figure 4f), Vougot (Figure 4e), Boutrouilles (Figure 4d), Keremma (Figure 4c), Kerrity (Figure 4l), Kersauz (Figures 4m), and Lehan (Figure 4n). The Tréompan, Vougot, Boutrouilles, and Keremma beaches are located on the northern coast of Brittany (Figure 1). The mean grain size is ranged from 200 to 315 µm. They correspond to a Holocene beach/dune system fronted by a rocky platform (Guilcher and

Figure 4. Aerial photos of the studied beaches. a: Sillon de Talbert. b: Saint-Michel-en-Grève Bay. c: Keremma beach (Bay of Goulven). d: Boutrouilles beach. e: Vougot beach. f: Tréompan beach. g: Lez ar C'hrizienn Island. h: Trielen Island. i: Béniguet Island. j: Blancs-Sabons beach. k: Porsmilin beach. l: Kerrity beach. m: Kersauz beach. n: Lehan beach. o: Saint-Nicolas island (archipelago of Glénan). (see Figure 1 for location). (Photo credit: L. Brigand, D. Halleux, 244 CEVA-Pleubian, CCPBS-Pont-L'Abbé).

Hallégouët, 1991). The astronomical tidal range (*i.e.,* between HAT and LAT) reaches about 8.20 m at Tréompan, 8.40 m at Vougot and Boutrouilles, and 9 m at Keremma beach (Bay of Goulven) further east (Figure 3), while the dunes culminate at highest elevations of between 11 and 13 m asl. Blancs-Sablons beach is a 1300 m long end-cove beach situated on the western coast of Brittany. The beach is backed by a massive perched dune system up to 10 to 12 m high. The astronomical tidal range reaches about 7.5 m. Kerrity, Lehan, and Kersauz beaches are situated in the south of Brittany (Figure 1). The mean grain size is ranged from 500 to 700 µm. They correspond to long sandy barriers stretching west-east that protect low-lying back-barrier wetlands against flooding. The elevation of the dunes reaches about 11 m asl at Kersauz and 7 m asl at Kerrity. The astronomical tidal range is about 5.5 m (Figure 3).

Low-lying Aeolian Accumulations

This morphology describes beaches where the dunes have a low altitude (1 to 2 m above HAT) and are of limited extension. Therefore, they may be considered to be low-lying aeolian accumulations rather than true established foredunes. This is the case for Saint-Michel-en-Grève Bay located in northern Brittany (Figure 4b), and the E-NE coast of Béniguet Island (Figure 4i), situated on the archipelago of Molène off the western Brittany coast (Figure 1). Saint-Michel-en-Grève Bay is a wide sheltered sandy beach (mean grain size of 155 µm) surrounded by rip-raps. The low-lying aeolian accumulations are divided into the three small dunes of Saint-Efflam, Treduder, and Saint-Michel-en-Grève. The astronomical tidal range is about 9.70 m (Figure 3). Béniguet Island is mainly composed of an accumulation of pebbles forming a huge comet tail on the lee side of a rocky headland (Guilcher, 1950). Nevertheless, the north-east coast is formed by a sandy beach backed by a small dune ridge stretching over 800 m that culminates between 6 and 7 m asl. The astronomical tidal range is about 5.5 m (Figure 3).

Shingle Beaches and Gravel Barriers

This type of morphology corresponds to accumulations composed of coarse sediments such as gravels and pebbles. They may correspond to a gravel barrier spit such as the Sillon de Talbert located in northern Brittany (Figure 4a), or gravel beaches such as those on the islands of the Molène archipelago off west Brittany, *i.e.*, Trielen island (Figure 4h), and Lez ar C'hrizienn (Figure 4g). The Sillon de Talbert is a 3.5 km long swash-aligned gravel barrier spit (mean grain size ranged from 25 to 40 mm) that culminates between 6 to 8.5 m asl (Stéphan, Suanez, and Fichaut, 2012). The astronomical tidal range is about 11 m (Figure 3). The gravel beaches of the Trielen and Lez ar C'hrizienn Islands form comet tails on the lee side of the island enclosing a back-barrier brackish pond (Guilcher, 1959; Suanez *et al.*, 2011). They culminate between 6 to 8.5 m asl depending on the ridges, while the astronomical tidal range is about 7.9 m (Figure 3). The mean grain size is ranged from 20 to 50 mm.

Small Embayed Beaches

Porsmilin beach is a small embayed beach located on the western part of the Brittany coast, in a sheltered south-facing orientation (Figure 4k). The mean grain size is about 320 µm (Dehouck, Dupuis, and Sénéchal, 2009). Originally it was a small embayed welded barrier beach flanked by cliffs (east and west) and backed by a brackish water marsh to the north. However, the mid-bay gravel spit was turned into an artificial embankment covered by a narrow dune ridge which culminates at 6.2 m asl (Lemos *et al.*, 2018). The astronomical tidal range is 7.2 m (Figure 3).

METHODS AND DATA

Shoreline Indicator Features

Boak and Turner (2005) identified more than forty shoreline reference features which can be classified into three different groups using morphological, biological, and hydrological limits. Therefore, depending on the morphology, different shoreline limits were used in this paper.

For the beach/high dune complex and the low-lying aeolian accumulations, either the seaward dune vegetation line or the erosion scarp (corresponding more often to the top of the bluff cut by erosion process) was adopted as the limit. This shoreline reference feature is highly relevant because it clearly demarcates the dune vegetation from the loose sand of the backshore (Crowell, Leatherman, and Buckley, 1991; Zuzeck *et al.*, 2003). Therefore, this limit was straightforward to extract from aerial photography using tonal differences (brightness) between the vegetated and non-vegetated beach areas. The seaward edge of the dune vegetation, primarily *Elymus farctus,* was adopted as the limit measured in the field.

In some cases, for the shingle beaches and the gravel barriers, the supratidal vegetation line was used as the shoreline proxy when the accumulation crest was vegetated. Topographic breaks or scarps corresponding to the top crest edge were also used when they could be clearly identified. Finally, the base of the rear edge was automatically selected for gravel barriers because its landward displacement due to rollover processes can be interpreted as a relevant proxy of shoreline changes (Stéphan, 2011b; 2018a; Stéphan, Suanez, and Fichaut, 2012). This limit was also straightforward to extract from aerial photography using tonal differences between the bright and dark colour of gravel sediment and back-barrier muddy salt-marsh. This limit was also easy to measure inasmuch as it corresponds to a pertinent topographic break.

Aerial Photography Processing for Long and Medium-term Analysis

The analysis of the long-term and medium-term shoreline changes was carried out from the processing of vertical aerial photographs (Figure 5). These photographs were produced by the *Institut Géographique National* (IGN) (*i.e.,* French National Geographic Institute) and scanned with a resolution of about 0.5 m. The set of images was geometrically corrected using second-order polynomial geo-correction, and georeferenced according to a well-known procedure described by many authors (Crowell, Leatherman, and Buckley, 1991; Douglas and Crowell, 2000; Moore, 2000). Georeferencing errors were estimated to ±2.5 m from a set of ground control points distributed on the geoprocessed images. The long-term shoreline change analysis of Brittany at the regional scale (*i.e.,* 652 beaches were studied representing a coastline length of 335 km) was based on two periods of aerial photographs corresponding to the "*BD ORTHO® Historique"* of 1948 or 1952, and the "*BD ORTHO®*

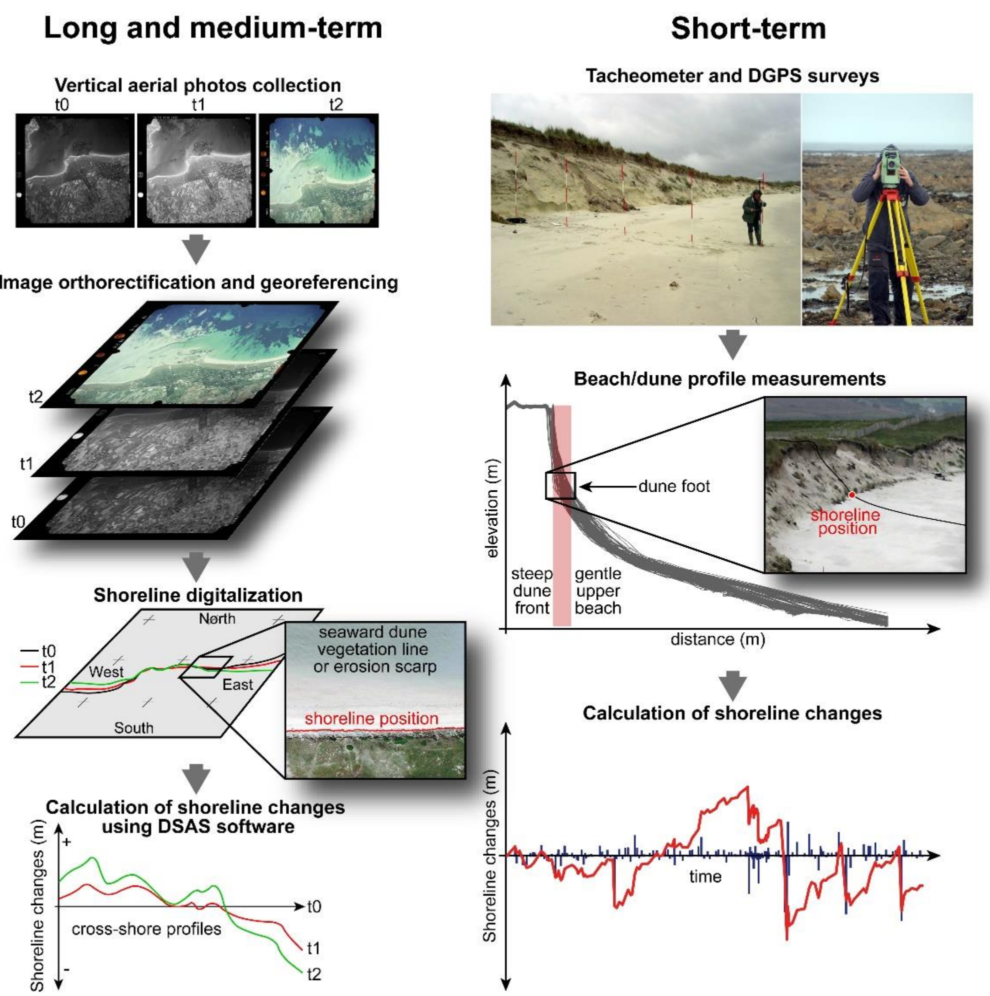

Figure 5. Workflows for shoreline change analyses at long, medium and short-term.

2010" of 2006 or 2009. Therefore, the long-term analysis covered a maximum period of 60 years. The medium-term shoreline change analysis was achieved using five representative beaches situated in north, west and south Brittany (Figure 1). It was based on a larger set of the "*BD ORTHO® Historique"* and the "*BD ORTHO® 2010*" vertical aerial photographs taken with a time-period frequency of four to six years over a period of about 70 years, *i.e.,* 1948 to 2015.

Field Measurements for Short-term Analysis

The short-term analysis (*i.e.,* the last 15 to 20 years) was based on topo-morphological field measurements such as beach profiles, identification of shoreline and dune front limits (Figure 5 and Table 2). As Vougot beach is experiencing a rotation process (Dodet *et al.*, 2019), two beach profiles have been monitored; profile 1 is located on the eastern part of the beach which is in erosion, and profile 2 on the western part which is in accretion (Figure 4e). For the Sillon de Talbert, two profiles located on the two most retreating sections (Stéphan *et al*., 2018b) have been monitored (Figure 4a). Different techniques, such as a tacheometer (*i.e.,* Nikon DTM300® and Leica TCR303®) and DGPS (*i.e.*, Trimble 5700/5880® and Topcon HyperV®), were used. Each measurement was calibrated using the geodesic marker from the French datum and the geodesic network provided by the IGN (*Institut Géographique National*). For each measurement campaign in all the study sites, the position of the control points was measured and the margin of error for the three dimensions (*x, y*, and *z*) was calculated using standard deviation. The estimated margin of error reached respectively ±5 to 7 cm for *x* and *y,* and ±2 cm for *z*. These values were used to estimate the margin of error associated with the results.

Data Analysis and Proxies of Shoreline Dynamics

Regarding vertical aerial photograph processing, measurement of shoreline change was automatically performed using Digital Shoreline Analysis (DSA) Arcview GIS tools. The process automates the drawing of a baseline and the corresponding perpendicular transects with a constant spacing varying from 50 to 5 m (depending on the study site) from which erosion and accretion are measured (Moore, 2000). In this case, the proxy of shoreline dynamics corresponds to an erosion/accretion distance in metres (Table 2). The shoreline indicator used from the beach/dune profile measurements corresponds to the foredune foot, *i.e.*, the sharp break in slope from the gentle upper beach to the steep dune front, or the dune erosion scarp (Boak and Turner, 2005). The shoreline position was obtained by the intersection of the coastal profiles with the vertical elevation of this topo-morphological feature, carefully defined for each study site from a visualization of profile changes.

RESULTS

Data obtained from aerial photography processing and field measurements were used to analyze the shoreline changes of the Brittany coast at the long, medium, and short timescales.

An Overview of Long-term Shoreline Changes in Brittany

Figure 5 shows the shoreline changes between 1949-1952 and 2006-2009 on 652 beaches distributed along the coast of Brittany. The data reveal the alongshore variability of shoreline change over the last ≈60 years. A large number of beaches (n=326) experienced no significant shoreline change (Table 3), with advance or retreat values of less than 2.5 m, which remains below the margin of error associated with aerial image processing (see section 3.2). Therefore, these beaches are considered to be stable in terms of shoreline change. This group represents a shoreline length of 127.4 km, *i.e.*, 38% of the total regional shoreline length. Most of these beaches are located in sheltered zones such as the Bay of Brest and the Gulf of Morbihan. In more energetic environments, beaches with minimal shoreline changes are small-sized pocket beaches, with limited sediment transfers. Beaches with significant retreat (>–2.5 m) represent a total length of 118.7 km, *i.e.*, 35%. Most of these retreating beaches are located in north Brittany, notably in the departments of Côtes-d'Armor and Ile-et-Vilaine, where minimal shoreline changes total 47% and 50% of their coastlines, respectively. The most significant changes concern sandy and gravelly spits, and the large open-coast beach/dune systems. The maximum values of retreat concern the gravel spit of Sillon de Talbert (north Brittany), and Tronoën beach (Bay of Audierne, south-west Brittany) with values of –50 m and –63 m, respectively (Figure 6). Conversely, a large number of beaches show significant advance (>+2.5 m). A total of 135 beaches experienced progradation over the last ≈60 yrs. In north Brittany, the sandy spits of Ile Blanche, Dossen, and Pen ar C'hleuz experienced high progradation rates in their distal part, with values up to +30 m from 1952 to 2009 (Figure 6). In south Brittany, a significant accreting process (up to +20 m) affects beaches located around the Etel river mouth. The beaches in progradation represent a length of 88.9 km, *i.e.*, 27% of the total regional shoreline.

Medium-term Shoreline Change Variability along Five Representative Beaches

The medium-term shoreline change analysis is based on five beaches located in north, west and south Brittany (Figures 1 and 7). These beaches have not been impacted by anthropogenic forcing, therefore the medium-term shoreline changes are

Table 2. *Inventory of the beach surveys carried out for the short-term shoreline dynamic analysis (see Figures 1 and 4 for the location of the studied sites). NB and WB stand for Norther Brittany and Western Brittany, respectively, N is the number of measurements available.*

Study sites	Location	Measurement	Period surveyed	N	Frequency	Long-term trend (EPR)
1 - Spit of Sillon de Talbert – Pleubian (Côtes d'Armor)	NB	shoreline	08/10/2002 to 07/09/2017	19	semi-annually to annually	-28 m
		beach profiles 1 & 2	18/09/2012 to 13/09/2018	76	bimonthly to monthly	-23 to -31 m
2 - dune of Plestin-les-Grèves (Saint-Michel-en-Grève Bay)	NB	shoreline	24/07/1998 to 28/06/2017	20	annually	-1.7 m
3 – dune of Saint-Michel-en-Grève (Saint-Michel-en-Grève Bay)	NB	shoreline	24/07/1998 to 28/06/2017	20	annually	-2.9 m
4 - Boutrouilles beach – Kerlouan (North Finistère)	NB	beach profile	28/11/2006 to 13/06/2017	30	quartely to annually	-6 to -8 m
5 - Vougot beach – Guissény (North Finistère)	NB	beach profile 2 (west)	17/06/2011 to 29/08/2018	65	monthly	+3 m
		beach profile 1 (east)	05/07/2004 to 29/08/2018	190	weekely to monthly	-2 m
6 - Blancs-Sablons beach – Le Conquet (West Finistère)	WB	beach profile	12/07/2006 to 16/07/2018	31	quartely to annually	-1.1 m
7 – Lez ar C'hrizienn Island (Archipelago of Molène)	WB	shoreline	22/08/2005 to 17/04/2014	10	annually	-5.2 m
8 – Porz beach - Trielen Island (Archipelago of Molène)	WB	shoreline	23/09/2002 to 17/04/2014	13	annually	-5.3 m
9 - Porsmilin beach (West Finistère)	WB	beach profile	08/01/2003 to 05/12/2017	216	bimonthly to monthly	-7.8 m
10 - Lehan beach – Treffiagat (South Finistère)	WB	beach profile	24/01/2012 to 07/04/2015	20	quartely to semi-annual	-5.9 m
11 - Kersauz beach – Treffiagat (South Finistère)	WB	beach profile	08/07/2011 to 11/03/2016	23	quartely to semi-annual	-4 m

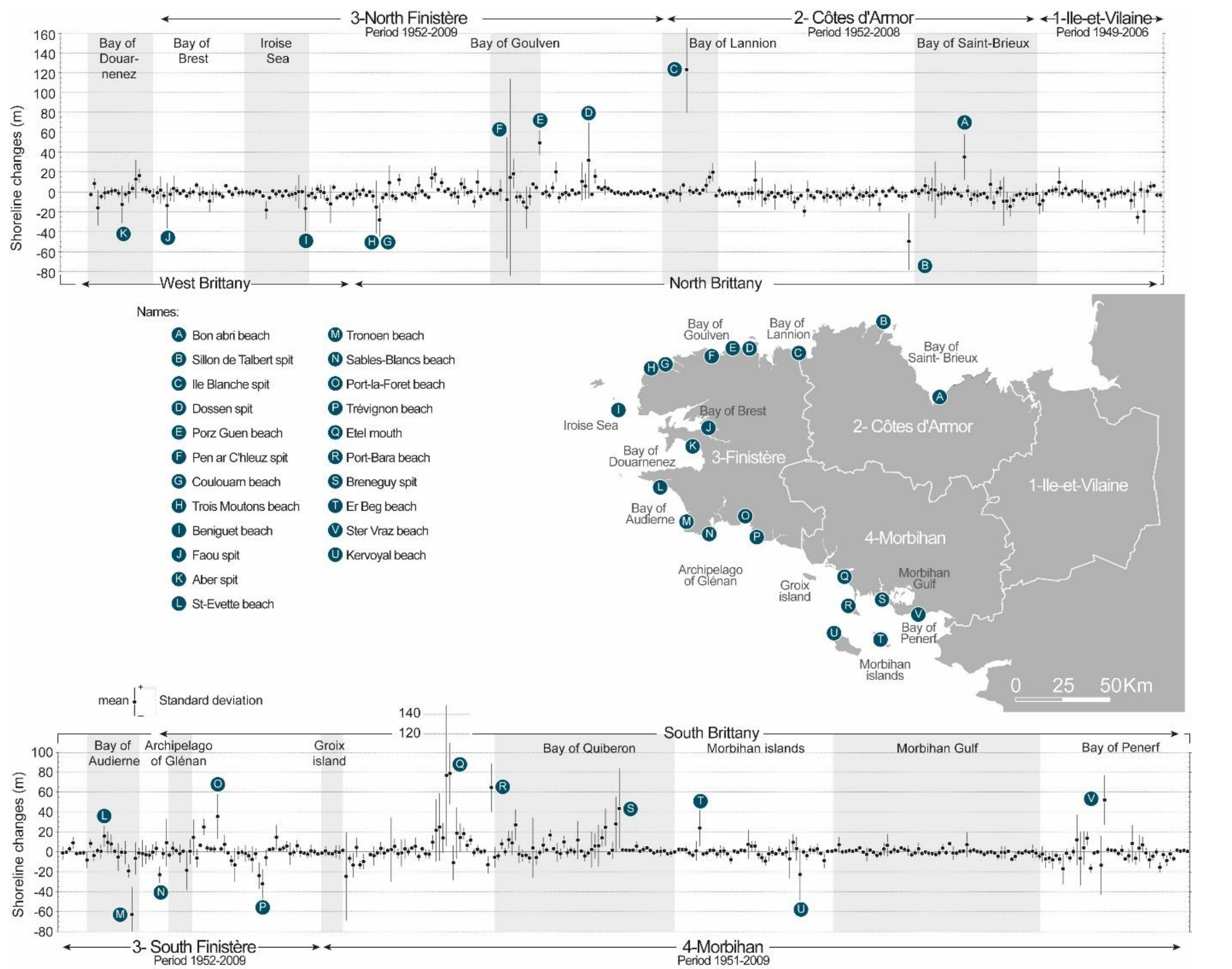

Figure 6. Shoreline changes of the Brittany coast based on the analysis of 652 beaches and barriers (black dots on the graphs) between 1949-1952 and 2006-2009 (after Blaise, 2017, modified). The letters on the map correspond to beaches where shoreline changes (erosion or accretion) are highly significant.

attributed solely to meteo-oceanic forcing. A high variability of shoreline change is observed over the last decades (Figure 7). Two main temporal patterns can be depicted. The first pattern is a quasi-steady erosion trend interrupted by several periods of stability or minor advance. This pattern is noted on Keremma and Béniguet beaches, where the net retreat from 1952 to 2016 is about –20 m and –30 m, respectively. The retreat happened in three main erosion phases, from 1961 to 1968, from 1978 to 1990, and a third one mainly related to the winter of 2013-2014. These three erosion periods alternate with three periods of stability (Figure 7). The second, more complex, temporal pattern of change is characterized by a succession of significant retreat and advance reflecting the alternation of a larger number of short erosion and recovery periods of the beach/dune systems. For instance, eight periods of erosion were identified on Tréompan beach between 1952 and 2018, systematically followed by an almost equivalent progradation. On Kerrity and Squividan beaches, the same shoreline dynamic is observed with more limited values of change. By compiling all the erosion-dominated periods (EDP) and accretion-dominated periods (ADP) identified in the five study sites, a regional pattern of the shoreline dynamic is observed. Six EDPs were identified in Brittany from 1952 to 2016: 1962-1968, 1977-1978, 1980-1985, 1987-1990, 1993-1997, and 2013-2014.

Short-term Shoreline Changes

From the topo-morpholocial surveys, three main patterns of short-term shoreline changes were observed: *(i)* an erosion trend over the studied period (*i.e.*, for the beaches of Boutrouilles, Trielen, Lez ar C'hrizienn, and Sillon de Talbert), *(ii)* an alternation of erosional and accretion periods, with a net shoreline stability (*i.e.*, for Saint-Michel-en-Grève Bay and the eastern part of Vougot beach), *(iii)* a continuous accretion (as for the western part of Vougot beach) (Table 2). The analysis of the short-term time series shows that whatever the pattern of shoreline change, all the studied beaches exhibit a succession of EDPs, especially during significant storm events, and ADPs or SDPs associated with relatively calm periods of low morphogenetic activity (Figure 8).

Five EDPs were recognized from 1998 to 2017. The dunes of Saint-Michel-en-Grève Bay (*i.e.*, the Plestin-les-Grèves and Saint-Michel-en-Grève dunes) show an initial (EDP) from 1998 to the beginning of the 2000s. As indicated by Suanez and Stéphan (2011), this phase can be related to the significant impact of storms Lothar and Martin in December 26-27, 1999. This erosion phase is followed by a period of slight stability that can be related to low morphogenetic conditions, except on Lez ar C'hriziénn and Trielen beaches affected by minor erosion processes (Suanez *et al.*, 2011).

The second EDP is related to storm Johanna on March 10, 2008 (Figure 8). This event was characterized by energetic north-west waves associated with a high spring tide level (Cariolet *et al.*, 2010) which induced severe erosion in most of the studied sites (Figure 8). For instance, on the gravel spit of Sillon de Talbert, the maximum retreat reached –22 m during this event (Stéphan, Suanez, and Fichaut, 2012), while on Vougot and Boutrouilles beaches, the retreat was –6 m and –3 m, respectively (Suanez and Cariolet, 2010). Storm Johanna also strongly eroded the dunes of Saint-Michel-en-Grève, inducing a significant loss of their surface areas (Suanez and Stéphan, 2011). The storm also impacted the islands of Trielen and Lez ar C'hriziénn, where the mean shoreline retreat was –4 m and –3 m, respectively (Suanez *et al.*, 2011). Conversely, erosion was not significant on Porsmilin beach, due to its sheltered position with respect to the NW orientation of the storm waves.

This second EDP was followed by a long ADP/SDP from 2008 to 2013. During this period, significant recovery of the beach/dune systems occured, as shown by the increase of the dune sediment budget on Vougot (Suanez *et al.*, 2012) and Porsmilin beaches, and the increase in the Plestin-les-Grèves and Saint-Michel-en-Grève dune surface areas (Suanez and Stéphan, 2011) (Figure 8). For the other studied sites, such as the Sillon de Talbert, Lez ar C'hriziénn, Trielen, Kersauz, Léhan, and Blancs-Sablons beaches, no significant changes were observed (Stéphan *et al.*, 2018; Suanez *et al.*, 2011).

This ADP/SDP ended during the winter of 2013-2014, which was characterized by a series of severe storms (Masselink *et al.*, 2016). The morphogenetic impact of these storms was strong shoreline retreat all around the Brittany coast (Blaise *et al.*, 2015). Between December 2013 and March 2014, the maximum shoreline retreat reached –30 m on the Sillon de Talbert (Stéphan *et al.*, 2018b); –14 m and –9 m on Vougot (Figure 9) and Boutrouilles beaches, respectively; –13 m and –19 m on Kersauz and Porsmilin beaches, respectively (Figure 10); –7 m on Blancs-Sablons beach (Figure 11); and –4 m and –12.5 m on the islands of Lez ar C'hriziénn and Trielen, respectively. Similarly, the dune surface areas of Saint-Michel-en-Grève Bay significantly decreased due to the severe retreat of the dune front (Figure 12). As shown in Figure 8, this erosive phase was characterized by three major storms that occurred during spring tide conditions in the beginning of January, February, and March 2014. The impact of this cluster of storms was observed on all studied sites and remains the most important EDP of the entire period concerning the short-term shoreline dynamic.

Since the winter of 2013-2014, the situation has been dominated by ADP and/or SDP. However, two storm events occurring on February 8, 2016 (storm Ruzica/Imogen), and January 2, 2018 (storm Eleanor) impacted some sites, with different spatio-temporal shoreline responses. As shown by the survey of Vougot (P1), Lehan, and Boutrouilles beaches, storm Ruzica led to a strong shoreline retreat (Figure 8). This retreat was less intense on the Sillon de Talbert and on Porsmilin beach; and was not observed on the other sites. Similarly, storm Eleanor only significantly impacted the Sillon de Talbert and the eastern part of Vougot beach, while the other sites were not eroded (Figure 8).

DISCUSSION

The Long-term Trends at a Regional Scale

The analysis of the long-term shoreline changes in Brittany shows that a large proportion of sandy and gravel beaches (about 38% of the total coastline length studied which represents 127.4

Table 3. *Statistics of long-term shoreline changes in Brittany (after Blaise, 2017, modified).*

		Total	stability no significant (< ±2,5 m)	erosion significant retreat (> -2,5 m)	accretion significant advance (> +2,5 m)
Department of Ile-et-Vilaine (North Brittany)	Number of beaches:	38	20	14	4
	Shoreline lenght (km):	12.9	5.7	6.1	1.1
	%	100	44	47	9
Department of Côtes d'Armor (North Brittany)	Number of beaches:	107	50	46	11
	Shoreline lenght (km):	56.6	21.5	28.4	6.7
	%	100	38	50	12
Department of Finistere (North, West and South Brittany)	Number of beaches:	256	120	77	59
	Shoreline lenght (km):	140.4	51.6	54.0	34.8
	%	100	37	38	25
Department of Morbihan (South Brittany)	Number of beaches:	251	136	54	61
	Shoreline lenght (km):	125.1	48.7	30.1	46.3
	%	100	39	24	37
TOTAL	Number of beaches:	652	326	191	135
	Shoreline lenght (km):	335.0	127.4	118.7	88.9
	%	100	38	35	27

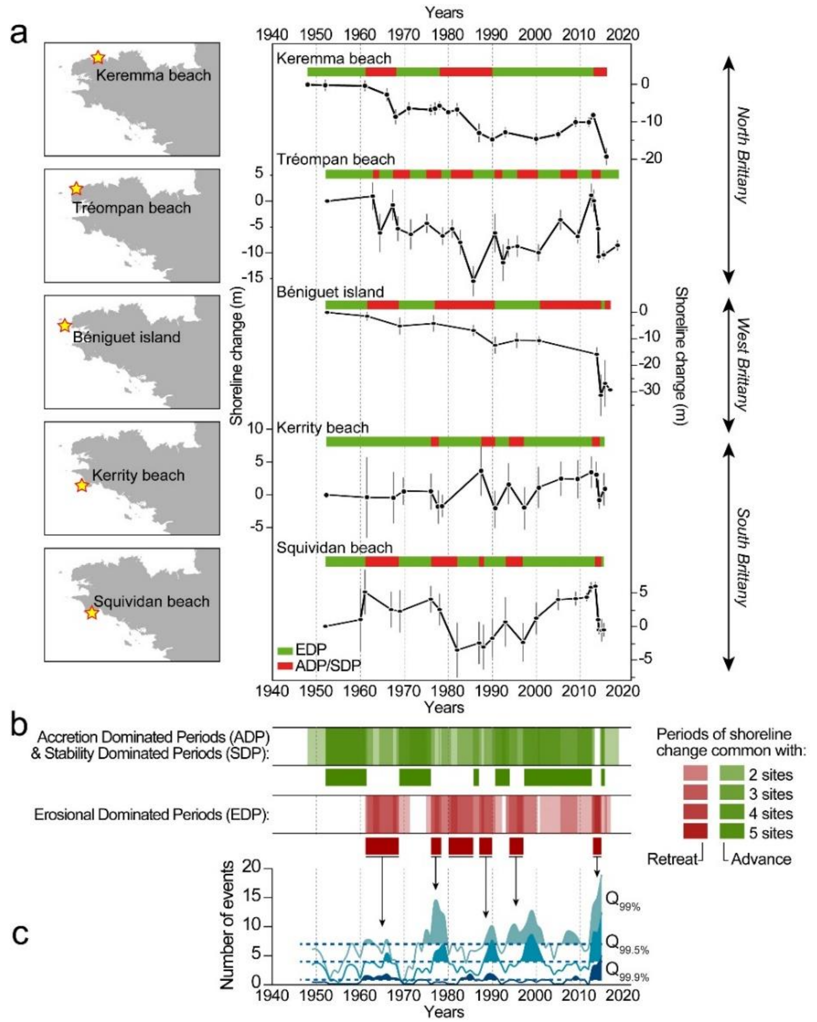

Figure 7. Medium-term shoreline changes along the Brittany coast. (a) Temporal variability over the last decades for the five representative beaches of Keremma beach, Tréompan beach, Béniguet island, Kerrity beach, and Squividan beach. (b) accretion-/stability-dominated periods (ADP/SDP) and erosion-dominated periods (EDP) depicted from the compilation of shoreline dynamics for the five studied beaches. (c) Annual frequency (three-year moving average) of water levels exceeding the 99th (Q99%), 99.5th (Q99.5%) and 99.9th (Q99.9%) percentiles between 1948 and 2016 in north-west Brittany (from Stéphan *et al.*, 2018a). Horizontal dotted lines correspond to the mean annual frequency over the entire period.

km) are stable or have experienced no significant changes in last decades. These results do not take into account the total coastline length that has been artificially stabilized since the 1950s. Blaise (2017) estimates that this corresponds to about 200 beaches totaling 133.7 km. In addition, beaches and barriers that have only short sections artificially stabilized (with rip-rap and seawalls) represent an additional length of about 82.9 km. On these beaches, hard defense structures were most often built in response to erosion processes. Consequently, the statistics of the long-term shoreline changes produced in this study (Table 3) likely underestimate the erosion of the Brittany coast. Another bias regarding the long-term shoreline analysis concerns the dates of aerial photographs. For instance, the "*BD ORTHO®2010*" provides aerial photographs taken in 2006 for the department of Ile-et-Vilaine, in 2008 for the department of Côtes-d'Armor, and in 2009 for the departments of Finistère and Morbihan. Considering the significant shoreline retreat induced by storm Johanna on March 10, 2008 on several beaches (Stéphan, Suanez, and Fichaut, 2010; Suanez and Cariolet, 2010; Suanez *et al.*, 2011; Suanez and Stéphan, 2011), the erosion dynamic is more or less well-identified depending on whether the aerial photographs were taken before and after the storm. Such a bias may lead to underestimated statistics produced for the department of Ile-et-Vilaine, where the impact of this event was not visible on the aerial photos, and for the departments of Finistère and Morbihan where recovery processes between 2008 and 2009 may have compensated for the shoreline erosion (Suanez and Stéphan, 2011; Suanez *et al.*, 2012).

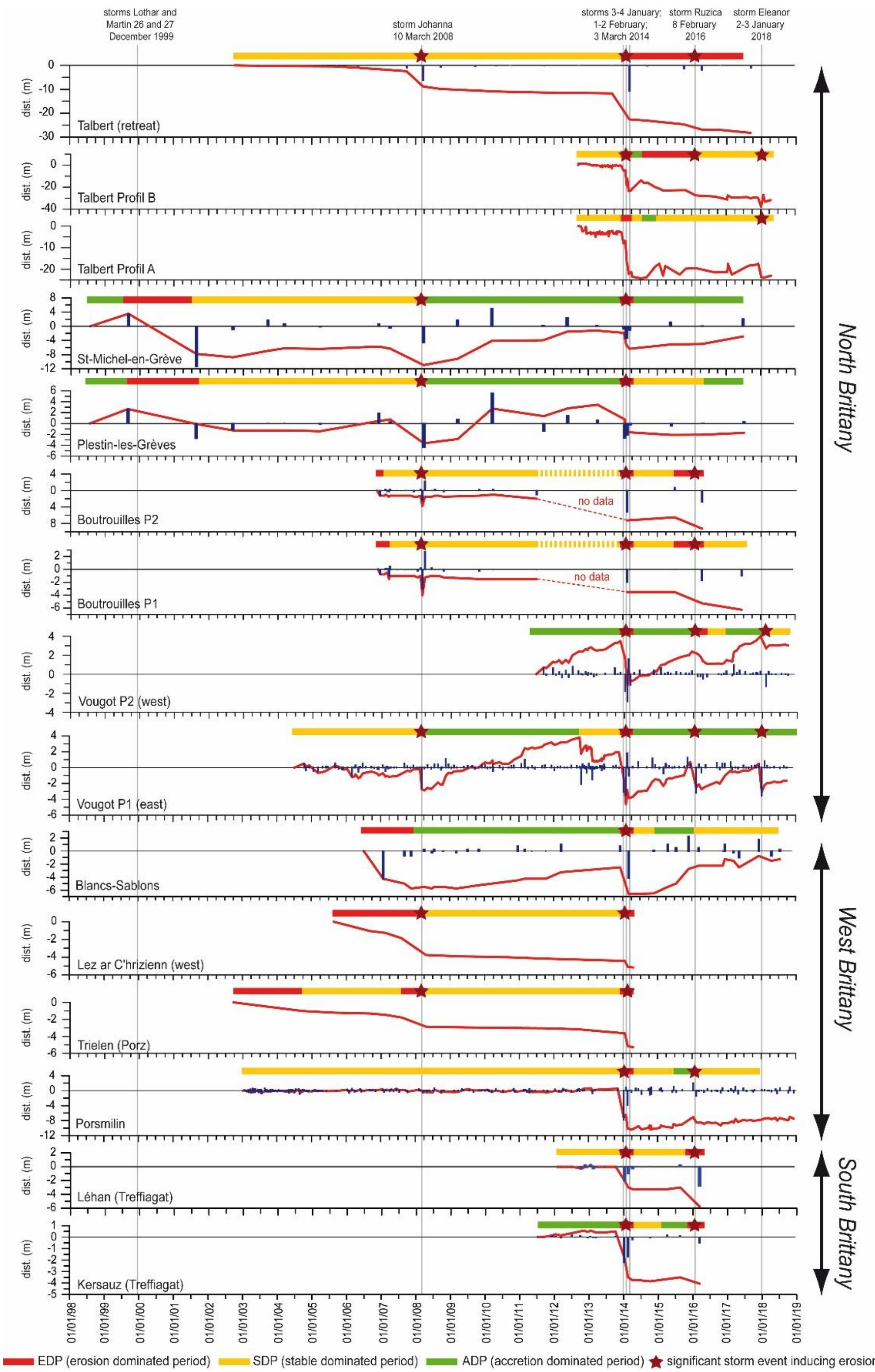

Figure 8. Short-term shoreline changes along the Brittany coast based on the topo-morphological monitoring of 11 sites (see Figures 1 and 4 for location).

Only a small number of beaches experienced high rates of shoreline retreat (<–2.5 m) between 1948-1952 and 2006-2009. Especially effected were the sandy and gravel spits dominated by longshore sediment transfers (Stéphan, 2011b; Stéphan, Suanez, and Fichaut, 2015; Stéphan *et al.*, 2018a, 2018b). In the western part of the Bay of Goulven, changes along the Pen Ar Ch'leuz spit clearly reflect a process of alongshore sediment reworking (Stéphan *et al.*, 2018a). While the proximal part of the spit experienced a maximum retreat of –77m from 1948 to 2016 with rates of –1.22 m.yr^{-1}, the distal part exhibited an exceptional progradation of +330 m with rates of +4.6 m.yr^{-1}.

In the Bay of Brest, a large number of gravel spits were also affected by these alongshore reworking processes over the last decades (Stéphan, 2011b), with, however, lower rates of shoreline changes. The variability of the responses in terms of shoreline changes along the spits can be attributed to numerous site-specific factors such as barrier sediment grain-size and morphology (sandy or gravel), hydrodynamic conditions, and/or the accommodation space available on the distal parts of the spits. For instance, in the Bay of Goulven, large sandflats occupy the lower part of the intertidal zone and provide a large surface area for sediment accumulation, favouring the rapid accretion of multiple low-elevated dune ridges with very high rates of progradation (Hallégouët, 1981). Conversely, the reworking of the gravel spits in the Bay of Brest led to lower rates of shoreline change due to limited alongshore sediment transfers and a reduced extension (in plan-view) of the gravel ridges that accumulated in the distal parts of the spits (Stéphan, 2011b). These components explain the differences in terms of shoreline changes at the regional scale.

The human impact on shoreline change remains difficult to establish at the regional scale because of the long history of anthropogenic actions along the coast and the very site-specific nature of these impacts (Hénaff and Jegu, 1995). In many cases, anthropogenic actions have only locally increased the rates of shoreline retreat (Suanez, Cariolet, and Fichaut, 2010). For instance, Hallégouët and Bodéré (1993) showed from a set of historical maps and vertical photographs that Tronoën beach experienced retreat well before the sediment extractions undertaken during WW2 by the German Army. The mean rate of shoreline retreat was estimated at around –0.6 m.yr^{-1} from 1780 to 1943, and reached –1.1 m.yr^{-1} in the following decades from 1966 to 1990. In this case, it is clearly demonstrated that erosion predated human actions, which only exacerbated this retreat for the recent period. In other cases, the erosion observed over the last decades is the result of pluri-centennial human-induced coastal changes, as shown by the mobility of the Pen ar C'hleuz spit, in the Bay of Goulven. The erosion of this spit was induced by the building of a dyke in the 1820s (Yoni and Hallégouët, 1998). This dynamic was only exacerbated more recently by sand mining operated by farmers from the 1970s to the 1990s (Stéphan *et al.*, 2018a). Finally, anthropogenic forcing partially explains the erosion of only a minority of beaches and barriers in Brittany. Stéphan (2011b) detailed the impact of some jetties that have led

Figure 9. Shoreline retreat on Vougot beach during the stormy winter of 2013-2014. Pre-storm situation (a), post-storm situation (b) and after the storm of February 1-2, 2014 (c).

Figure 10. Retreat of Kersauz beach (south Brittany, left-hand panels) and Porsmilin beach (west Brittany, right-hand panels) during the stormy winter of 2013-2014. (a,d) Pre-storm situation; (b,e): after the storm of January 3-4, 2014; (c,f) after the storm of February 1-2, 2014.

Figure 11. Shoreline retreat on Blancs-Sablons beach (west Brittany) during the stormy winter of 2013-2014. Pre-storm situation (a,c), post-storm situation (b) after the storm of January 3-4, 2014), and (d) after the storm of February 1-2, 2014.

to a reduction of downdrift longshore supply towards several spits in the Bay of Brest. These coastal structures triggered the reworking of the Troaon and Auberlac'h spits and the erosion observed on the spit of Mengleuz (Figure 1) (Stéphan, Suanez, and Fichaut, 2005).

The long-term trend of shoreline erosion raises the question of coastal sediment depletion at the regional scale. Stéphan, Suanez, and Fichaut (2015) pointed out the erosional trend of the gravel spits during the last decades and hypothesized the scarcity of coarse sediment supply for the Brittany coast as a potential cause. The gravel beaches and barriers of Brittany were constructed by the shoreward remobilisation of periglacial deposits that accumulated on the inner shelf during the post-glacial marine transgression. Nowadays, unconsolidated cliffs formed of Pleistocene deposits (head) are considered to be the most significant sources of coarse sediments in Brittany (Guilcher, Adrian, and Blanquart, 1959; Guilcher, Bodéré, and Hallégouët, 1990). In some sites (*e.g.*, the Bay of Brest), the highly weathered shale cliffs also locally contribute to feed the gravel barriers. However, the present volumes provided by their erosion are not sufficient enough to prevent reworking of the drift-aligned spits and the retreat of the swash-aligned barriers (Stéphan, Suanez, and Fichaut, 2015). Furthermore, gravel barriers are formed by fossil deposits that accumulated within a context of sediment abundance and a decrease of Holocene sea-level rise around 6,000 cal.yr BP (García-Artola *et al.*, 2018; Stéphan *et al.*, 2015). This sediment source was gradually depleted during the last few millennia because of the decrease of relative sea-level rise. On the coast of Nova Scotia (Canada), researchers have explained the erosion of gravel barriers and spits by the absence of major sea-level fluctuations during the past millennia (Forbes *et al.*, 1995; Orford, Forbes, and Jennings, 2002). In that context, cliffs do not provide any sediment supply. In Brittany, the present-day sea-level rise is not sufficient to provide significant amounts of sediment. Field observations indicate that the bases of unconsolidated cliffs are nowadays rarely reached by incident waves (Stéphan, 2011a). Moreover, large platforms in front of the current cliffs dissipate wave energy before it reaches the foot of these cliffs (Suanez *et al.*, 2011).

Concerning the sandy beaches and barriers, the situation of the sediment budget is divided, with some beaches suffering significant scarcity, *e.g.*, the Bay of Audierne (Faye, Hénaff, and Hallégouët, 2007), while other beaches are characterized by substantial sediment input, *e.g.*, Dinan beach (Hallégouët and Hénaff, 1995). These different contexts are mainly due to the heterogeneous distribution of available sand in the nearshore areas. The long-term changes from the 1950s to the 2000s show that most beaches that have experienced significant shoreline advance are located in the vicinity of estuary mouths, *e.g.*, the beaches around the Etel estuary (Figures 1 and 6). This progradation is probably related to the supply of sediment to nearby beaches. In the Glénans archipelago (south Brittany, see Figure 1), Hénaff *et al.* (2015) highlighted the link between shoreline change and the mobility of subtidal sandbanks between 1927 and 2012. On the north and south coasts of Saint-Nicolas Island (Figure 4o), numerous sandbanks and submarine dunes migrate eastward and contribute episodically to the sediment supply to beaches. The availability of sandy material in the subtidal zone is also integral to the post-storm response of beaches, as it controls the efficiency of beach/dune recovery processes at the medium timescale (Suanez and Stéphan, 2011; Suanez *et al.*, 2012). The significant advance observed on some beaches in north Brittany only a few months after storm events may be partly attributed to the large volumes of sand on the shorefaces of the English Channel that supply the beach/dune systems during periods characterized by low energy winter-waves (Pinot, 1995; Suanez and Stéphan, 2011; Suanez *et al.*, 2012). However, the sediment supply is particularly relevant after severe

Figure 12. Dune front evolution (as a shoreline dynamic) on Plestin-les-Grèves and Saint-Michel-en-Grève beaches respectively, before (a,c) and after (b,d) the severe storm of February 1-2, 2014.

storm events, first inducing a net retreat of the dune, but also generating onshore sediment transfers from the shoreface to the intertidal zone. Following this, sediment transfers from the beach to the dune contribute to the recovery process (Suanez *et al.*, 2012). Similar processes have been reported along the coast of the North Sea where barrier dynamics are largely related to the onshore supply of sand from the shore-parallel to sub-shore-parallel shoreface banks (Anthony, 2013; Héquette and Aernouts, 2010; Sedrati and Anthony, 2008). These banks modulate the delivery of storm wave energy to the coast, redirect currents alongshore, and are the sand sources for the accretion of coastal dunes.

Conversely, numerous sandy beaches and barriers in Brittany exhibit large areas of shallow rocky platforms devoid of a significant sedimentary cover. Around Kerrity and Lehan beaches, a recent LiDAR survey carried out on the sub- and intertidal zones emphasizes the significant lack of sediment on the shoreface, thus enabling easy identification of the highly fractured and sharp morpho-bathymetry of the offshore rocky platform (Duperret *et al.*, 2016). A recent study conducted by Jabbar, Hénaff, and Deschamps (2015) on the sandy shoreface of the Combrit beach/dune barrier shows that rapid erosion has taken place over the last 40 years. The sediment loss between depths of 0 and –13 m was estimated at about 5.4 M m^3 between 1971 and 2012. This sediment depletion in the nearshore zone can favour significant shoreline erosion, inasmuch as sediment is no longer supplied to the beach/dune system.

The Impact of Meteo-oceanic Forcing over the Last Decades

The analysis of the medium-term shoreline changes carried out on five beaches shows relevant variations with an alternation of EDP and ADP in the last decades (Figure 7). The recognition of common erosion phases on several beaches along the three facades (north, west and south) of Brittany suggests the impact of morphogenetic events at a regional scale (Figure 7b). These EDP are compared with the chronology of morphogenetic phases reconstructed in NW Brittany from the joint analysis of wave and tidal conditions over the period 1948-2015 (Stéphan *et al.*, 2018a). The annual frequency of extreme water levels exceeding the 99^{th}, 99.5^{th}, and 99.9^{th} percentiles, was used to quantify meteo-oceanic forcing over the last 67 years (Figure 7c). This comparison suggests that EDP are strongly associated with the frequency of extreme water levels. The EDP observed from 1962 to 1968 corresponds to a high number of morphogenetically significant events. The high frequency of storms during this period has been documented by Cariolet (2011) from the study of local journalistic archives which describe significant damage along the Brittany coast. Other coastal barriers experienced erosion during the mid-1960s, attributed to severe storms, such as the episode of April 5, 1962 on the Sillon de Talbert (Stéphan, Suanez, and Fichaut, 2012), the storm of January 17-20, 1965 on the south-west coast of Brittany (Cariolet, 2011), and the storm of November 1967 in the Bay of Brest (Berthois and Auffret, 1969; Stéphan and Laforge, 2013). The EDP highlighted from 1977 to 1978 corresponds to a very high frequency of extreme water levels. A total of 18 episodes of water levels exceeding the 99.5^{th} percentile is inventoried between 1977 and 1979 (Stéphan *et al.*, 2018b). Furthermore, a very high magnitude event with water levels exceeding the 99.9^{th} percentile occurred in February 1978. The EDP of the 1980-1985 period is probably related to a single extreme water level event exceeding the 99.9^{th} percentile on November 22-23, 1984. This event is associated with one of the strongest storms recorded along the French coast in recent decades (Bessemoulin, 2002) during a high astronomical tide. The atmospheric conditions of the event were described by Roche *et al.* (2014). Several marine floods occurred in northern Finistère (Cariolet, 2011). In the Bay of Brest, this storm is one of the most morphogenetically significant events recorded in the last 60 years. It led to the complete overwash of many gravel barriers (Stéphan, 2011b). The morphogenic impact was also recorded as far as the coast of Belgium (Haerens *et al.*, 2012). The EDP recognized between 1989 and 1991 is clearly related to a significant increase of the extreme water level frequency and magnitude, particularly during the winter of 1989-1990. This winter was characterized by a cluster of severe storms that hit the entire Western European coast (Betts *et al.*, 2004; Caspar, Costa, and Jakob, 2007; McCallum and Norris, 1990). Many studies reported large morphological impacts along the Brittany coast (Fichaut and Hallégouët, 1989; Guilcher and Hallégouët, 1991; Hallégouët and Hénaff, 1993, 2006). Three storms occurred during high astronomical tides and generated extremely high water levels exceeding the 99.9^{th} percentile in the Bay of Goulven. The event of December 16, 1989 caused flooding in several localities of Brittany (Cariolet, 2011). The storm of February 12, 1990 is mentioned by Haerens *et al.* (2012) as being one of the most morphogenic events experienced on the Belgian coast during the period 1983-2007. The EDP identified from 1993 to 1997 coincided with a period of high frequency of extreme water levels exceeding the 99^{th} percentile, but with few very high magnitude episodes (> 99.9^{th} percentile) identified in the Bay of Goulven. Surprisingly, no EDP was observed between 2008 and 2010 despite the high number of extreme water levels reached during storm Johanna on March 10, 2008 and storm Becky on November 2010, and during which much coastal flooding and shoreline erosion occurred in Brittany (Cariolet, 2011; Cariolet *et al.*, 2010; Fichaut and Suanez, 2010, 2011; Regnauld *et al.*, 2010; Stéphan and Laforge, 2013; Stéphan, Suanez, and Fichaut, 2010; Suanez and Cariolet, 2010; Suanez, Cariolet, and Fichaut, 2010; Suanez *et al*., 2011). Finally, the EDP of 2013-2014 is clearly identified as the most erosive one in Brittany. The severe coastal erosion is related to three main storm events that occurred between January and March of 2014, reported along the Atlantic and English Channel coasts of France (Blaise *et al.*, 2015; Castelle *et al.*, 2015; Crapoulet *et al.*, 2015; Masselink *et al.*, 2016b).

Medium-term Shoreline Changes and Climatic Indexes

Several studies undertaken on the Brittany coast have explored the relationship between medium-term morphological changes (*i.e.*, alternation of accretion and erosion phases) and the variability of climatic indexes, such as the North Atlantic Oscillation (NAO) index (Stéphan, Suanez, and Fichaut, 2010; Suanez and Stéphan, 2011; Suanez *et al.*, 2011, 2015) and the West Europe Pressure Anomaly (WEPA) index (Autret *et al.*, 2018; Dodet *et al.*, 2019; Stéphan *et al.*, 2018a). The positive NAO (NAO+) phase represents a stronger than usual difference in pressure between the Azores and Iceland. In that case, western winds dominate, bringing with them warm air, while the position of the jet stream enables stronger and more frequent storms traveling across the Atlantic to Western Europe at the latitude of England and Brittany (Donat *et al.,* 2010; Gómara *et al.,* 2014; Lau, 1988). In such circumstances, the coastal erosion dynamic becomes effective, particularly when storm events are combined with high spring tides. The NAO– phase represents the reverse with a weaker than usual difference in pressure between the Azores and Iceland. Winds from the east and north-east are more frequent, bringing with them cold air, while the adjusted position of the jet stream leads to weaker and less frequent storms. This situation is notably associated with dune/beach accretion (*i.e.*, recovery processes). Stéphan, Suanez, and Fichaut (2010) demonstrated a sound relationship between morphogenetic events and a positive NAO+ on the gravel spit of Sillon de Talbert over the last six decades. Suanez *et al.* (2015) suggested that the pluri-annual variability in dune erosion and accretion on Vougot beach between 2004 and 2014 was also related to the NAO index. However, Castelle *et al.* (2017) produced a new index, the Western Europe Pressure Anomaly (WEPA), based on the sea level pressure (SLP) gradient between monitoring stations in Valentia (Ireland) and Santa Cruz de Tenerife (Canary Islands). A positive WEPA phase reflects an intensified and southward-shifted SLP difference between the Icelandic low and the Azores high, driving severe storms that funnel high-energy waves toward Western Europe southward of 52°N. For instance, the authors indicated that the WEPA better captured the 2013/2014 extreme winter that caused widespread coastal erosion and flooding in Western Europe (Brittany and southern England) than the NAO index. Based on the same approach comparing the NAO and WEPA index, Stéphan *et al.* (2018a) indicated a better relationship between the positive WEPA index and the high frequency of storm-induced extreme water levels favouring shoreline retreat in the Bay of Goulven over the period of 1948-2015. Autret *et al.* (2018) came to the same conclusion regarding the long–term variability of supratidal coastal boulder activation on the Brittany coast.

Short-term Shoreline Changes: Acceleration of the Erosion Rates?

The detailed study of shoreline changes on several coastal barriers of Brittany suggests an increase in retreat rates over the last few years. For instance, the Sillon de Talbert experienced high landward migration rates by rollover over the last decades. From 1930 to 2010, Stéphan *et al.* (2012) estimated the maximum rates of retreat to around –1.5 to –2 $m.y^{-1}$. However, if we only consider the recent years (the period 2002-2017) the rates of retreat have increased twofold, with maximum values ranging from –3 to –4 $m.y^{-1}$ (Stéphan *et al.*, 2018b; Suanez *et al.*, 2018). This acceleration was attributed to more energetic offshore wave conditions, associated with an increase in the frequency of overwash events from 2002 to 2017 (Suanez *et al.*, 2018). Four significant storms (storm Johanna storm in March, 2008, the winter 2013-2014 storm cluster, storm Ruzica/Imogen in February, 2016, and storm Eleanor in January, 2018) were responsible for the spit's erosion by causing sluicing overwash and lowering of the crest. In the absence of such morphogenetic events, Stéphan *et al.* (2018b) estimated that around a four year time-span would be needed for the complete reconstruction of the crest of the Sillon de Talbert by overtopping processes. However, the continual storms since the winter of 2013-2014 have shortened the recovery period. Similarly, beach profile measurements on the eastern part of Vougot beach showed that the significant erosion caused by storm Johanna was followed by a long period of dune recovery (up to November 2013), inducing a large increase of the dune sediment budget (Figure 8). However, as indicated by Suanez *et al.* (2012), this recovery was related to cross-shore sediment transfers from the intertidal beach which experienced strong erosion. Therefore, the net sediment budget of the dune/beach system was in deficit. As shown on Figure 8, the strong erosion of Vougot beach/dune during the winter of 2013-2014 has not yet been annulled four years after this event, notably on the eastern part of the beach (see, profile 1). This indicates that sediment transfers between the intertidal beach and the dune are no longer as effective as they were after storm Johanna storm in March, 2008. Therefore, the enhanced storminess of the recent years raises the question of the resilience of the coastal accumulations in Brittany, especially in areas where sediment stocks in shallow waters have disappeared (Hénaff *et al.*, 2015; Jabbar, Hénaff, and Deschamps, 2015). Further work on sediment dynamics between offshore – shallow zones and the shoreline must be carried out for the entire Brittany coast.

CONCLUSIONS

This paper presents for the first time a general overview of the shoreline changes of the Brittany coast over the last 60 years. Based on the analysis of 335 km of coastline (corresponding to natural sandy and gravel beaches), stable, retreating, and prograding shorelines represent respectively 38%, 35%, and 27% of the total studied shoreline length. The most significant changes were measured on gravel or sandy spits dominated by longshore sediment transfers. The erosion dynamic, particularly significant on gravel barriers, is interpreted to be a consequence of a scarcity of coarse material along the Brittany coast. The long-term changes of sandy beaches are more contrasted, suggesting that in some cases sandy deposits offshore can still supply the beaches. Anthropogenic impacts have locally accentuated (and more rarely triggered) coastal erosion or accretion; however, these impacts remain difficult to quantify at the regional scale. The medium-term analysis of the shoreline changes on five representative beaches reveals two main temporal patterns of change, *i.e*., (i) a quasi-steady shoreline retreat interrupted by periods of stability and (ii) an alternation of significant EDP and ADP which lead to net shoreline stability. Six common EDPs were identified over the last 60 years: 1962-1968, 1977-1978, 1980-1985, 1987-1990, 1993-1997, and 2013-2014. These erosional periods are associated with an increase in the frequency of extreme water levels. The EDP and ADP indicate that the medium-term evolution of coastal accumulations in Brittany is controlled by meteo-oceanic variability, which is related to the WEPA index. The analysis of the short-term time series conducted between 1998 and 2018 also showed a shorter alternation of EDP, clearly related to significant storm events, and ADP or stability-dominated periods associated with low morphogenetic activity. Five main storm events/periods, *i.e*., 1998-2000 (storms Lothar and Martin in December 1999), 2008 (Johanna), the 2013-2014 winter storm cluster, 2016 (Ruzica/Imogen), and 2018 (Eleanor), were identified as the most erosive. The series of severe storms that occurred during the winter of 2013-2014 generated the most significant EDP of the entire period regarding the short-term shoreline dynamic of all studied sites. The identification of the parameters driving shoreline variations at the three considered timescales is an important contribution to future management options on the Brittany coast, especially in a time of climate change associated with sea-level rise and more morphogenetically active storms.

ACKNOWLEDGMENTS

This work was supported by ISblue project, Interdisciplinary graduate school for the blue planet (ANR-17-EURE-0015) and co-funded by a grant from the French government under the program "Investissements d'Avenir" and ANR 850 COCORISCO by means of the "*Changements Environnementaux Planétaires & Sociétés* (CEP&S) 2010" (ANR-10-CEPL-0001) research programme. It was also supported by the French "*Institut National des Sciences de l'Univers*" (INSU) satellite programme, SNO-DYNALIT.

LITERATURE CITED

Anthony, E.J., 2013. Storms, shoreface morphodynamics, sand supply, and the accretion and erosion of coastal dune barriers in the southern North Sea. *Geomorphology*, 199, 8–21.

Aubrey, D.G., 1979. Seasonal patterns of onshore/offshore sediment movement. *Journal of Geophysical Research*, 84(C10), 6347–6354.

Autret, R.; Dodet, G.; Suanez, S.; Roudaut, G., and Fichaut, B., 2018. Long–term variability of supratidal coastal boulders activation in Brittany (France). *Geomorphology*, 304, 184–200.

Berthois, L. and Auffret, G., 1969. Contribution à l'étude des conditions de sédimentation dans la rade de Brest. *Cahiers Océanographiques*, 5, 469–485.

Bessemoulin, P., 2002. Les tempêtes en France. *Annales des Mines*, 9–14.

Betts, N.L.; Orford, J.D.; White, D., and Graham, C.J., 2004. Storminess and surges in the South-Western Approaches of the eastern North Atlantic: the synoptic climatology of recent extreme coastal storms. *Marine Geology*, 210(1-4), 227–246.

Blaise, E., 2017. Etude des dynamiques du trait de côte de la région Bretagne à différentes échelles spatio-temporelles. Brest, France: Université de Bretagne occidentale, Ph.D. dissertation, 285p.

Blaise, E. ; Suanez, S.; Stéphan, P.; Fichaut, B.; David, L.; Cuq, V.; Autret, R.; Houron, J.; Rouan, M.; Floc'h, F.; Ardhuin, F.; Cancouët, R.; Davidson, R.; Costa, S., and Delacourt, C., 2015. Bilan des tempêtes de l'hiver 2013-2014 sur la dynamique de recul du trait de côte en Bretagne. *Géomorphologie : Relief, Processus, Environnement*, 21(3), 267–292.

Boak, E.H. and Turner, I.L., 2005. Shoreline Definition and Detection: A Review. *Journal of Coastal Research*, 21(4), 688–703.

Cariolet, J.M., 2011. Inondation des côtes basses et risques associés en Bretagne : vers une redéfinition des processus hydrodynamiques liés aux conditions météo-océaniques et des paramètres morpho-sédimentaires. Brest, France: Université de Bretagne occidentale, Ph.D. dissertation, 348p.

Cariolet, J.; Costa, S., Caspar, R., Ardhuin, F., Magne, R., and Goasguen, G., 2010. Aspects météo-marins de la tempête du 10 mars 2008 en Atlantique et en Manche. *Norois*, 215, 11–31.

Caspar, R.; Costa, S., and Jakob, E., 2007. Fronts froids et submersions de tempête dans le nord-ouest de la France : Le cas des inondations par la mer entre l'estuaire de la Seine et la baie de Somme. *La Météorologie*, 57, 37–47.

Castelle, B.; Dodet, G.; Masselink, G., and Scott, T., 2017. A new climate index controlling winter wave activity along the Atlantic coast of Europe: The West Europe Pressure Anomaly. *Geophysical Research Letters*, 44(3), 1384–1392.

Castelle, B.; Guillot, B.; Marieu, V.; Chaumillon, E.; Hanquiez, V.; Bujan, S., and Poppeschi, C. 2018. Spatial and temporal patterns of shoreline change of a 280-km high-energy disrupted sandy coast from 1950 to 2014: SW France. *Estuarine, Coastal and Shelf Science*, 200, 212–223

Castelle, B.; Marieu, V.; Bujan, S.; Splinter, K.D.; Robinet, A.; Sénéchal, N., and Ferreira, S., 2015. Impact of the winter 2013–2014 series of severe Western Europe storms on a double-barred sandy coast: Beach and dune erosion and megacusp embayments. *Geomorphology*, 238, 135–148.

Chanson, H., 2004. The Atlantic Wall in North Brittany (Bretagne Nord), France. *Shore & Beach*, 72(4), 10–12.

Cowell, P.J. and Thom, B.G., 1994. Morphodynamic of coastal evolution. In: Carter, R.W.G., and Woodroffe, C.D., (eds.), *Coastal evolution: late quaternary shoreline*. Cambridge: Cambridge University Press, pp. 33–86.

Crapoulet, A.; Héquette, A.; Levoy, F., and Bretel, P., 2015. Évaluation de l'évolution du trait de côte et du bilan sédimentaire littoral en baie de Wissant (nord de la France) par LiDAR aéroporté. *Géomorphologie : Relief, Processus, Environnement*, 21(4), 313–330.

Crowell, M.; Leatherman, S.P., and Buckley, M.K., 1991. Historical shoreline change: error analysis and mapping accuracy. *Journal of Coastal Research*, 7(3), 839–852.

Cuadrado, D.G. and Perillo, G.M.E., 1997. Migration of Intertidal Sandbanks, Bahía Blanca Estuary, Argentina. *Journal of Coastal Research*, 13(1), 155–163.

Davidson-Arnott, R.G.D. and Law, M.N., 1990. Seasonal patterns and controls on sediment supply to coastal foredunes, Long Point, Lake Erie. In: Nordstrom, K.; Psuty, N., and Carter, B., (eds.), *Coastal dunes. Form and process*. England: John Wiley & Sons, pp. 177–200.

Dehouck, A.; Dupuis, H., and Sénéchal, N., 2009. Pocket beach hydrodynamics: The example of four macrotidal beaches, Brittany, France. *Marine Geology*, 266, 1–17.

de Vriend, H.J., 1991. Mathematical modelling and large scale coastal behavior. *Journal of Hydraulic Research*, 29(6), 727-753.

de Vriend, H.J.; Capobianco, M.; Chesher, T.; De Swart, H.E.; Latteux, B., and Stive, M.J.F., 1993. Approaches to long-term modelling of coastal morphology: a review. *Coastal Engineering*, 21(1–3), 225–269.

Dodet, G.; Bertin, X.; Bouchette, F.; Gravelle, M.; Testut, L., and Wöppelmann, G., 2019. Characterization of sea-level variations along the metropolitan coasts of France: waves, tides, storm surges and long-term changes. *Journal of Coastal Research,* Special Issue No. 88, ??-??.

Dodet, G.; Castelle, B.; Masselink, G.; Scott, T.; Davidson, M.; Floc'h, F.; Jackson, D., and Suanez, S., 2019. Beach recovery from extreme storm activity during the 2013/14 winter along the Atlantic coast of Europe. *Earth Surface Processes and Landforms*, 44, 393–401.

Dolan, R.; Fenster, M.S., and Holme, S.J., 1991. Temporal analysis of shoreline recession and accretion. *Journal of Coastal Research*, 7(3), 723–744.

Donat, M.G.; Leckebusch, G.C.; Pinto, J.G., and Ulbrich, U., 2010. Examination of wind storms over Central Europe with respect to circulation weather types and NAO phases. *International Journal of Climatology*, 30, 1289–1300.

Douglas, B.C. and Crowell, M., 2000. Long-term shoreline position prediction and error propagation. *Journal of Coastal Research,* 16(1), 145–152

Douglas, B.C.; Crowell, M., and Leatherman, S.P., 1998. Considerations for shoreline position prediction. *Journal of Coastal Research*, 14(3), 1025–1033.

Duperret, A.; Raimbault, C.; Le Gall, B.; Authemayou, C.; van Vliet-Lanoë, B.; Regard, V.; Dromelet, E., and Vandycke, S., 2016. High-resolution onshore–offshore morpho-bathymetric records of modern chalk and granitic shore platforms in NW France. *Comptes Rendus Geoscience*, 348, 422–431.

Eliot, I.G. and Clarke, D.J., 1982. Temporal and spatial variability of the sediments budget of the subaerial beach at Warilla, New South Wales. *Australian Journal of Marine and Freshwater Research*, 33(6) 945–969.

Eliot, I.G. and Clarke, D.J., 1989. Temporal and spatial bias in the estimation of shoreline rate-of-change statistics from beach survey information. *Coastal Management*, 17(2), 129–156.

Evans, A.W., 1992. The application of geomorphology in coastal management studies. *Ocean and Coastal Management*, 17(1), 47–55.

Faye I.; Hénaff A., and Hallégouët, B., 2007. Évolution récente de la ligne de rivage en baie d'Audierne : de Penhors à la pointe de la Torche. *Pen Ar Bed*, 199-200, 50–61.

Fenster, M.S. and Dolan, R., 1993. Historical shoreline trends along the outer banks, North Carolina: processes and responses. *Journal of Coastal Research*, 9(1), 172–188.

Fenster, M.S.; Dolan, R., and Elder, J.F., 1993. A new method for predicting shoreline positions from historical data. *Journal of Coastal Research*, 9(1), 147–171.

Fichaut, B. and Hallégouët, B., 1989. Banneg : une île dans la tempête. *Penn ar Bed*, 135, 36–43.

Fichaut, B. and Suanez, S., 2010. Dynamiques d'arrachement, de transport et de dépôt de blocs cyclopéens par les tempêtes. Exemple de la tempête du 10 mars 2008 sur l'île de Banneg (archipel de Molène, Finistère). *Norois*, 215, 33–58.

Fichaut, B. and Suanez, S., 2011. Quarrying, transport and deposition of cliff-top storm deposits during extreme events: Banneg Island, Brittany. *Marine Geology*, 283(1-4), 36–55.

Fisher, N.; Dolan, R., and Hayden, B.P., 1984. Variations in large-scale beach amplitude along the coast. *Journal of Sedimentary Petrology*, 54(1), 73–85.

Fleming, C.A., 1992. The development of coastal engineering. In: Barrett, M.G., (ed.), *Coastal Zone Planning and Management*. London, UK: Thomas Telford, pp. 5–20.

Forbes, D.L.; Orford, J.D.; Carter, R.W.G.; Shaw, J., and Jennings, S.C., 1995. Morphodynamic evolution, self-organisation, and instability of coarse-clastic barriers on paraglacial coast. *Marine Geology*, 126(1–4), 63–85.

García-Artola, A.; Stéphan, P.; Cearreta, A.; Kopp, R.E.; Khan, N.S., and Horton, B.P., 2018. Holocene sea-level database from the Atlantic coast of Europe. *Quaternary Science Reviews*, 196, 177–192.

Guilcher, A., 1950. L'île de Béniguet (Finistère), exemple d'accumulation en queue de comète. *Bulletin d'Information du Comité Central d'Océanographie et d'Etude des Côtes*, II(7), 243–250.

Guilcher, A., 1959. L'archipel de Molène (Finistère). Etude morphologique. *Revue de Géographie Physique et de Géologie Dynamique*, II(2), 81–96.

Guilcher, A.; Adrian, B., and Blanquart, A., 1959. Les « queues de comète » de galets et de blocs derrière des roches isolés sur les côtes Nord-Ouest et Ouest de Bretagne. *Norois*, 22, 125–145.

Guilcher, A.; Bodéré, J.-C., and Hallégouët, B. 1990. Coastal evolution in western, southestern and northern Brittany as a regional test of impact of sea level rise. *Journal of Coastal Research*, Special Issue No. 9, 67–90.

Guilcher, A. and Hallégouët, B., 1991. Coastal dunes in Brittany and their management. *Journal of Coastal Research*, 7, 517–533.

Guillen, J. and Palanques, A., 1994. Short-time evolution of a micro-tidal barrier-lagoon system affected by storm overwashing: the Trabucador bar (Ebro delta, NW Mediterranean). *Zeitschrift fur Geomorphie*, 8(3), 267–281.

Gómara, I.; Rodríguez-Fonseca, B.; Zurita-Gotor, P., and Pinto, J.G., 2014. On the relation between explosive cyclones affecting Europe and the North Atlantic Oscillation. *Geophysical Research Letters*, 41, 2182–2190.

Haerens, P.; Bolle, A.; Trouw, K., and Houthuys, R., 2012. Definition of storm thresholds for significant morphological change of the sandy beaches along the Belgian coastline. *Geomorphology*, 143–144, 104–117.

Hallégouët, B., 1981. Les crêtes littorales dunifiées du massif Armoricain, France : formation et évolution. *Géographie Physique Quaternaire*, 35, 205–218.

Hallégouët, B. and Bodéré J.-C., 1993. Un littoral fragilisé: le sud de la baie d'Audierne. *Proceedings of « Le Pays Bigouden. A La Croisée Des Chemins »* (Pont l'Abbé, France), pp. 263–271.

Hallégouët, B. and Hénaff, A., 1993. Evolution du littoral septentrional du pays bigouden entre Penhors et Pors Poulhan. *Proceedings of « Le Pays Bigouden. A La Croisée Des Chemins »* (Pont l'Abbé, France), pp. 273–280.

Hallégouët, B. and Hénaff, A., 1995. L'engraissement des plages de l'anse de Dinan à l'ouest de la presqu'île de Crozon en Bretagne occidentale. *Norois*, 165, 131–152.

Hallégouët, B. and Hénaff, A., 2006. Evolution récente et gestion des espaces littoraux de l'ouest Cornouaille. *Proceedings of rencontres de L'ouest Cornouaille « Quelles Pistes de*

Développement Pour Le Territoire ? » (Pont l'Abbé, France), pp. 20–34.

Hénaff, A. and Jegu, O., 1995. Conséquences des aménagements portuaires sur la sédimentation dans l'avant-port d'Audierne. *Norois*, 165, 119–129.

Hénaff, A.; Lageat, Y.; Hallégouët, B.; Jabbar, M.; Delliou, N., and Diard, M., 2015. Évolutions des accumulations littorales et relations avec les dynamiques d'avant-plage dans l'archipel des Glénan (Sud-Finistère, France). *Géomorphologie : Relief, Processus, Environnement*, 21(4), 359–384.

Héquette, A. and Aernouts, D., 2010. The influence of nearshore sand bank dynamics on shoreline evolution in a macrotidal coastal environment, Calais, northern France. *Continental Shelf Research*, 30(12), 1349–1361.

Honeycutt, M.G.; Crowell, M., and Douglas, B.C., 2001. Shoreline-Position Forecasting: Impact of Storms, Rate-Calculation Methodologies, and Temporal Scales. *Journal of Coastal Research*, 17(3), 721–730.

Jabbar, M.; Hénaff, A., and Deschamps, A., 2015. Dynamiques et évolutions morpho-sédimentaires de l'avant-plage du secteur littoral de Combrit – Île-Tudy entre le XIXe et le XXIe siècle. *Géomorphologie : Relief, Processus, Environnement*, 21(1), 45–56.

Jimenez, J.A. and Sánchez-Arcilla, A., 1993. Medium-term coastal response at the Ebro delta, Spain. *Marine Geology*, 114(1–2), 105–118.

Jimenez, J.A., Sánchez-Arcilla, A., Bou, J., and Ortiz, M.A., 1997. Analysing short-term shoreline changes along the Ebro delta using aerial photographs. *Journal of Coastal Research*, 13(4), 1256–1266.

Kana, T.W., 1995. A mesoscale sediment budget for Long Island, New York. *Marine Geology*, 126(1–4), 87–110.

Larson, M., and Kraus, N.-C., 1994. Temporal and spatial scales of beach profil change, Duck, North Carolina. *Marine Geology*, 117(1–4), 75–94.

Lau, N.-C., 1988. Variability of the Observed Midlatitude Storm Tracks in Relation to Low-Frequency Changes in the Circulation Pattern. *Journal of the Atmospheric Sciences*, 45, 2718–2743.

Le Berre, I. ; Thériault, M. ; Maulpoix, A., and Gourmelon, F., 2017. Moderation effect of planning on housing development along the French Atlantic coast: findings from an event history hazard model. *Journal of Land Use Science*, 12(4), 271-291.

Lemos, C.; Floc'h, F.; Yates, M.; Le Dantec, N.; Marieu, V.; Hamon, K.; Cuq, V.; Suanez, S., and Delacourt, C., 2018. Equilibrium modeling of the beach profile on a macrotidal embayed beach. *Ocean Dynamics*, 68(9), 1207–1220.

List, J.H.; Jaffe B.E.; Sallenger Jr.; A.H., and Hansen, M.E., 1997. Bathymetric Comparisons Adjacent to the Louisiana Barrier Islands: Processes of Large-Scale Change. *Journal of Coastal Research*, 13(3), 670–678.

Maron, P.; Rihouey, D., and Dubranna, J., 2004. Méthode d'analyse factorielle appliquée au suivi bathymétrique de l'embouchure de l'Adour. In: Levacher, D.; Sergent, P., and Ouahsine, A., (eds.), *Actes des VIIIèmes Journées Nationales Génie Civil – Génie Côtier*. Paralia, pp. 261–271.

Masselink, G.; Castelle, B.; Scott, T.; Dodet, G.; Suanez, S.; Jackson, D., and Floc'h, F., 2016. Extreme wave activity during 2013/2014 winter and morphological impacts along the Atlantic coast of Europe. *Geophysical Research Letters*, 43, 1–9.

McCallum, E. and Norris, W.J.T., 1990. The storms of January and February 1990. *Meteorological Magazine*, 119, 201–210.

Moore, L.J., 2000. Shoreline mapping techniques. *Journal of Coastal Research*, 16(1), 111–124.

Moreira, M.E.S.A., 1988. Seasonal processes of the beach-dune system on the western coast of Portugal. *Journal of Coastal Research*, Special Issue No. 3, 47–51.

Morel, V., 1995. Impacts des actions anthropiques sur les cordons de galets. *Hommes et Terres du Nord*, 1–2, 58–64.

Orford, J.D.; Forbes, D.L., and Jennings, S.C., 2002. Organisational controls, typologies and time scales of paraglacial gravel-dominated coastal systems. *Geomorphology*, 48, 51–85.

Pinot, J.-P., 1995. Quelques plages en voie d d'engraissement dans la région de Lannion. *Norois*, 165, 99–117.

Regnauld, H.; Mahmoud, H.; Oswald, J.; Planchon, O., and Musereau, J., 2010. Tempêtes, rythme de fonctionnement d'une cellule sédimentaire et « espace d'accueil » : exemple sur l'Anse du Verger, Bretagne Nord. *Norois*, 215, 133–146.

Roche, A.; Baraer, F.; Cam, H.L.E., and Madec, T., 2014. Projet VIMERS : une typologie des tempêtes bretonnes pour prévoir l'impact des tempêtes à venir et mieux s'y préparer. In: Levacher, D. ; Sanchez, M. ; Héquette, A., and Lalaut, Y. (eds.), *Actes des XIIIèmes Journées Nationales Génie Côtier-Génie Civil* (Dunkerque), pp. 925–932.

Sedrati, M. and Anthony, E.J., 2008. Sediment dynamics and morphological change on the upper beach of a multi-barred macrotidal foreshore, and implications for mesoscale shoreline retreat: Wissant Bay, northern France. *Zeitschrift für Geomorphologie*, 52, Suppl. 3, 91–106.

Short, A.D., 1999. Handbook of beach and shoreface morphodynamics. Chichester, UK: Wiley, 379 p.

Stéphan, P., 2011a. *Les flèches de galets de Bretagne : évolution passée, présente et future*. Paris: L'Harmattan, 263p.

Stéphan, P., 2011b. Quelques données nouvelles sur la mobilité récente et le bilan sédimentaire des flèches de galets de Bretagne. *Géomorphologie : Relief, Processus, Environnement*, 17(2), 205–232.

Stéphan, P.; Dodet, G.; Tardieu, I.; Suanez, S., and David, L., 2018a. Dynamique pluri-décennale du trait de côte en lien avec les variations des forçages météo-océaniques au nord de la Bretagne (baie de Goulven, France). *Géomorphologie : Relief, Processus, Environnement*, 24(1), 79–102.

Stéphan, P.; Goslin, J.; Pailler, Y.; Manceau, R.; Suanez, S.; Van Vliet-Lanoë, B.; Hénaff, A., and Delacourt, C., 2015. Holocene salt-marsh sedimentary infillings and relative sea-level changes in West Brittany (France) from foraminifera-based transfer functions. *Boreas*, 44(1), 153–177.

Stéphan, P. and Laforge, M., 2013. Mise au point sur l'évolution géomorphologique et le devenir des flèches de galets du Loc'h de Landévennec (Bretagne, France). *Géomorphologie : Relief, Processus, Environnement*, 19(2), 191–208.

Stéphan, P.; Suanez, S., and Fichaut, B., 2005. Impacts de l'anthropisation sur l'évolution morphosédimentaire d'un système littoral de flèches en chicane : le sillon de Mengleuz à Logonna-Daoulas en rade de Brest (Finistère). In: Durand, P., and Goeldner-Gianella, L., (eds.), *Milieux littoraux, nouvelles perspectives d'étude*. Paris: L'Harmattan, pp. 95–114.

Stéphan, P.; Suanez, S., and Fichaut, B., 2010. Franchissement et recul des cordons de galets par rollover, impact de la tempête du 10 mars 2008 dans l'évolution récente du Sillon de Talbert (Côte d'Armor, Bretagne). *Norois*, 215, 52–58.

Stéphan, P.; Suanez, S., and Fichaut, B., 2012. Long-term morphodynamic evolution of the Sillon de Talbert gravel barrier spit, Brittany, France. *Shore & Beach*, 80(1), 19–36.

Stéphan, P.; Suanez, S., and Fichaut, B., 2015. Long-, Mid- and Short-Term Evolution of Coastal Gravel Spits of Brittany, France. In: Randazzo, N.; Jackson, D., and Cooper, A., (eds.), *Sand and Gravel Spits*. Springer, pp. 275–288.

Stéphan, P.; Suanez, S.; Fichaut, B.; Autret, R.; Blaise, E.; Houron, J.; Ammann, J., and Grandjean, P., 2018b. Monitoring the medium-term retreat of a gravel spit barrier and management strategies, Sillon de Talbert (North Brittany, France). *Ocean & Coastal Management*, 158, 64–82.

Stive, M.J.F.; Roelvink, J.A., and de Vriend, H.J., 1990. Large-scale coastal evolution concept. In: Edge, W., (ed.), *Proceeding 22nd International Conference on Coastal Engineering* (New-York), pp. 1962–1974.

Suanez, S.; Cancouët, R.; Floc'h, F.; Blaise, E.; Ardhuin, F.; Filipot, J.-F.; Cariolet, J.-M., and Delacourt, C., 2015. Observations and predictions of wave runup, extreme water levels, and medium-term dune erosion during storm conditions. *Journal of Marine Science and Engineering*, 3(3), 674–698

Suanez, S. and Cariolet, J.-M., 2010. L'action des tempêtes sur l'érosion des dunes : les enseignements de la tempête du 10 mars 2008. *Norois*, 215, 77–99.

Suanez, S.; Cariolet, J.-M.; Cancouët, R.; Ardhuin, F., and Delacourt, C., 2012. Dune recovery after storm erosion on a high-energy beach : Vougot Beach, Brittany (France). *Geomorphology*, 139–140, 16–33.

Suanez, S., Cariolet, J.-M., and Fichaut, B., 2010. Monitoring of recent morphological changes of the dune of Vougot beach (Brittany, France) using differential GPS. *Shore & Beach*, 78(1), 37–47.

Suanez, S.; Fichaut, B.; Magne, R.; Ardhuin, F.; Corman, D.; Stéphan, P., and Cariolet, J.-M., 2011. Changements morphologiques et bilan sédimentaire des formes fuyantes en queues de comète de l'archipel de Molène (Bretagne France). *Géomorphologie : Relief, Processus, Environnement*, 17(2), 187–204.

Suanez, S. and Stéphan, P., 2011. Effects of natural and human forcing on mesoscale shoreline dynamics of Saint-Michel-en-Grève Bay (Brittany, France). *Shore & Beach*, 79(2), 19–38.

Suanez, S.; Stéphan, P.; Floc'h, F., Autret, R., Fichaut, B., Blaise, E., Houron, J., Ammann, J., Grandjean, P., Accensi, M., André, G., and Ardhuin F., 2018. Fifteen years of hydrodynamic forcing and morphological change leading to breaching of a gravel spit, Sillon de Talbert (Brittany, France). *Géomorphologie : Relief, Processus, Environnement*, 24(4), 403–428.

Terwindt, J.H.J. and Battjes, J.A., 1991. Research on large-scale coastal behavior. *Proceeding 22nd International Conference on Coastal Engineering* (New York), pp. 1975–1982.

Thom, B.G. and Hall, W., 1991. Behaviour of beach profiles during accretion and erosion dominated periods. *Earth Surface, Processes and Landforms*, 16(2), 113–127.

Winant, C.D., Inman, D.L., and Nordstrom, C.E., 1975. Description of seasonal beach changes using empirical eigenfunctions. *Journal of Geophysical Research*, 80(15), 1979–1986.

Yoni, C. and Hallégouët, B., 1998. Extractions d'amendements marins et recul de la ligne de rivage en baie de Goulven (Finistère). Les paradoxes de la gestion d'un site. *Norois*, 177, 63–73.

Zuzek, P.J.; Nairn, R.B., and Thieme, S.J., 2003. Spatial and Temporal Considerations for Calculating Shoreline Change Rates in the Great Lakes Basin. *Journal of Coastal Research*, Special Issue No. 38, 125–146.