COASTAL EVOLUTION DUE TO CLIMATE CHANGE AND THE IMPACT ON CABLES IN THE LANDFALL ZONE

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1. Introduction

In today's global context, climate change is one of the most pressing issues (Banno and Kuriyama, 2014). In response, many countries have set goals to reduce their ecological impact, such as France, which is seeking to reduce its production of CO_2 emissions (Paris Agreements - 2015). In recent years, to reduce these emissions, alternatives to fossil fuels have been sought. One renewable energy source is wind power, which produces energy from the wind via wind turbines.

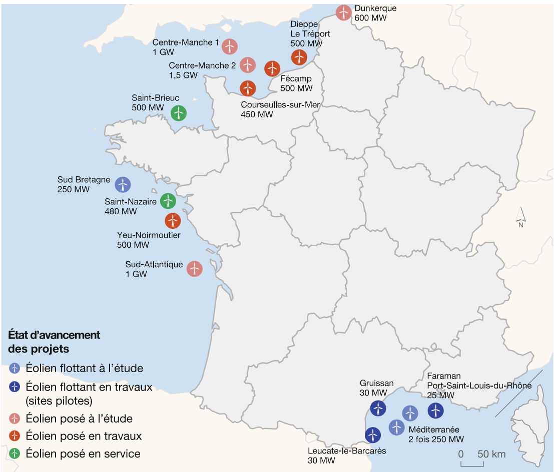

Fig. 1 : Map of French offshore wind farms installed and in the planning phase (© eoliennesenmer.fr)

Onshore wind farms have been in France since the early 1990s, and in recent years a new type of wind farm has been gaining ground in Europe: offshore wind farms. At sea, the wind is more stable and often more intense, and it enables the deployment of larger turbines. The potential wind resource in Europe is large (34 000 TWh/year, IFPEN), so the development of offshore wind farms is currently in expansion. In France, there are three operational offshore wind farms located in Saint-Brieuc (Côtes d'Armor), Fécamp (Seine Maritime), and Saint-Nazaire (Loire Atlantique) (Fig. 2). Five offshore wind farms (commercial or pilot sites) are under construction: 2 in the English Channel, one in the Atlantic Ocean, and 3 in the Mediterranean Sea. Additionally, 6 other wind farms are planned in these three coastal regions (Fig. 1).

Fig. 2: Offshore wind farm off Saint-Nazaire (© France Energies Marines)

However, with a lifespan of 40 years (Poppeschi *et al.*, 2024), climate change could have important impacts on offshore wind farms. Currently, climate change monitoring is being conducted by scientists worldwide, and the Intergovernmental Panel on Climate Change (IPCC) brings together these experts to compile reports and syntheses of the most recent scientific studies related to climate change (IPCC, 2023). In response to the IPCC report conclusions on climate change, a project focused on its impact on offshore wind farms was initiated by France Energies Marines, called the 2C NOW project, and this study is part of the 2C NOW project. The aim of 2C NOW is to understand the impacts of climate change on wind energy production, the longevity of wind turbine structures, and the design of all the elements of an offshore wind farm. One of the initial tasks of this project is to review the state of the art concerning current statistics and trends in atmospheric and hydrodynamic phenomena affecting the farms (e.g. wind, waves and water levels), and the impacts of climate change on their future evolution.

In addition to the direct impacts on wind farms, these hydrodynamic phenomena influence the morphological evolution of the seabed, including the nearshore zone and shoreline, and thus climate change impacts will likely cause changes in this area.

For offshore wind farms, morphological changes in the nearshore zone due to variations in hydrodynamic phenomena could pose a problem. The electricity produced at sea by wind turbines is transmitted to land via submarine cables laid on the seabed offshore and buried in the sand in the nearshore. This burial zone is called the cable landfall zone. To anticipate the problems that climate change could cause in the landfall zone, it is necessary to study the morphological evolution of the shoreline and nearshore beach profile.

A review of the evolution of the meteorological and hydrodynamical phenomena due to climate change was completed in the first work package of the 2C NOW project (Poppeschi *et al.*, 2024). The bibliographic study was carried out globally, with a specific focus on Europe and France. However, studying the morphological evolution of the coastline at these scales is not possible to allow considering the complex local hydrodynamical forcing and beach characteristics. Therefore, the objective here is to study these phenomena at local scales, demonstrating an approach that may be used to study the impacts of climate change on nearshore morphological changes for cable landfall site selection evaluation.

While few studies have been conducted on the specific issue of climate change impacts on morphological evolution in wind farm cable landfall zones, there are many studies on the broader issue of climate change impacts on nearshore beach profile and shoreline evolution. Notably, in France, the BRGM and Cerema published a joint report in 2022 entitled “Recommendations for the development of a local exposure map of shoreline retreat”, which summarizes the state of the art in the existing literature on methods used to estimate future shoreline changes. The report was published to serve as a guide for municipalities exposed to coastal erosion risks who need to evaluate shoreline changes at 30- and 100-year timescales in response to the French Climate and Resilience Law.

The goal of the current study is to analyse beach profile and shoreline evolution in the cable landfall zone of offshore wind farms, considering the impacts of climate change. To study shoreline evolution, the BRGM and Cerema report recommends understanding several key elements specific to the study site (Fig. 3), including the historical evolution of the coastline (retreat rate in meters/year), major retreat events (e.g. storm erosion), the presence of protective structures, sea level changes, and the uncertainties surrounding these data (BRGM and Cerema, 2022). With these elements and projections of future sea level changes, the report recommends defining and evaluating two scenarios:

- the “median scenario”, which considers median values and sea-level projections based on the IPCC SSP2-4.5,
- the “safety scenario”, which considers more extreme values and sea-level projections based on the IPCC SSP5-8.5,

where SSP stands for Shared Socio-economic Pathway, and the 4.5 and 8.5 pathways are middle and high-end scenarios.

The recommendations guide mentions two main approaches for quantifying shoreline retreat: the so-called “classical” and “expert” approaches. The classical approach involves extrapolating current shoreline change trends to calculate a retreat rate, considering the various specific characteristics of the coasts that could influence the retreat, and applying it to the shoreline in question. The expert approach is a numerical approach, where projections of extreme events and long-term changed are numerically modelled for a set of selected scenarios.

Projection: main elements	Methods	Main parameters	Median scenario	Safety scenario
1)Chronic evolution	2 approaches (§ 2.4)	Recoil rate Tx (m/yr)	Tx median	Tx (high margin)
2)Major event setbacks	2 approaches (§ 2.5)	Recoil Lmax (m)	Recoil Lmax (m)	Recoil Lmax (m)
3)Structures	2 approaches (§ 2.6)	Durability	Case by case	Non-perennial
4) Sea level rise	2 approaches (§ 3.3)	Sea level	Minimal values: 30 years: +20cm 100years: +60 cm or locals projections based on GIEC SSP2-4.5	Minimal values: 30 years: + 20cm 100 year: +100cm or local projections based on GIEC SSP5-8.5
5) Uncertainties over results	2 approaches (§ 2.7)	Margins of error	Median values	High margins

Fig. 3: Main elements to consider when building shoreline projection scenarios (© BRGM and Cerema, 2022)

2. General context

2.1 Presentation of cables and cable landfall zones

The objective of wind farms is to produce electricity, and once produced, it is transmitted to an onshore electrical station by a cable. The cables are composed of an electrical cable in the centre, surrounded by armour and sheaths (Fig. 4). There are two types of cables: submarine cables that bring electricity from the open sea to the coast, and underground cables that bring electricity from the coast to the inland power station. This transition between the two types of cables generally takes place at the top of the beach in a landfall chamber, where there is no seawater infiltration to affect the underground cable. The main difference between submarine and underground cables is the resistance and waterproofing of subsea cable sheaths.

Fig. 4: Subsea cable internal composition (© France Energies Marines)

For offshore submarine cables, the primary risk of damage comes from dragged anchors (ICPC, 2009). Several protection methods including burying the cables in the seabed or designing the cables with additional armour and then simply laying them on the seabed. The final protection options are tubular products (Fig. 5), mattresses (Fig. 6) and rock placement.

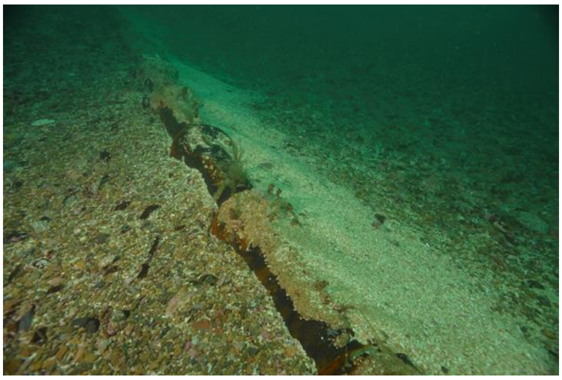

Fig. 5: Subsea cable laid on the seabed (© Olivier Dugornay, Ifremer)

Fig. 6 : Mattress protection (© Olivier Dugornay, Ifremer)

The cable is typically laid on the seafloor in the offshore zone but is buried when it reaches the upper shoreface.

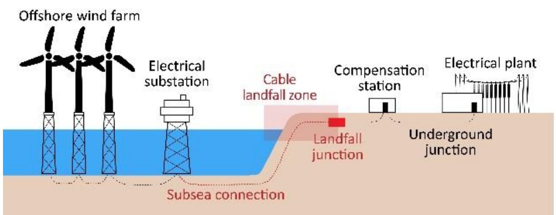

Fig. 7: Cable landfall zone of an offshore wind farm (© France Energies Marines)

The nearshore area where the cable is buried, up to the landfall chamber, is called the cable landfall zone (Fig. 7). Morphological changes on the seafloor may also be significant, in areas with submarine dunes, but this study is particularly focused on the impacts of climate change on shoreline and beach profile evolution. The landfall zone is a dynamic environment where sediment transport rates may be large, causing significant morphological changes (Vousdoukas *et al.*, 2020; Antolínez *et al.*, 2019). For more information about submarine dune evolution and their impacts on offshore wind farms, see two recent R&D projects led by France Energies Marines: DUNES (2019-2022) and MODULLES (2021-2024).

Submarine cables are buried in the cable landfall zone for protection because it is a high-risk area for cables. The cables are buried to protect them from both natural processes and anthropic activities (ex: fishing). There are two main burial methods: the Horizontal Directional Drilling (HDD) method and the open-cut trenching method. The HDD method involves drilling horizontally into the ground and then passing the cable through the borehole (Fig. 8 and 9). This method is thus suitable for beaches with high cliffs, hard rock or highly erosive character. It also allows passing under sea defence systems (e.g. sea walls, dikes, dunes) and has a low environmental impact by avoiding stirring up sediment and impacting the flora and fauna at the seabed along the cable's path in the zones where it is underground.

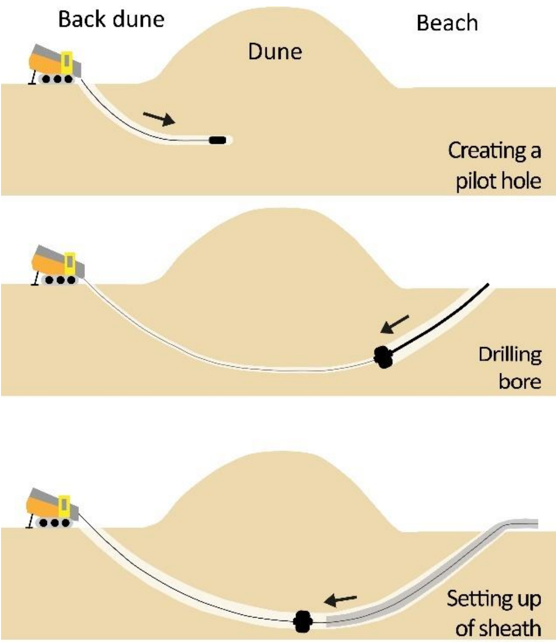

Fig. 8: HDD method diagram (© France Energies Marines)

Fig. 9: Drilling machine for HDD (© Ditch Witch)

The second method, open-cut trenching, consists of digging a trench in the sand, laying the cable and then backfilling the trench (Fig 10). This method is suitable for beaches that can be excavated, uses standard construction equipment, is relatively inexpensive and allows relatively easy access to the cable in case repairs are needed.

Fig. 10: Positioning the cable before digging, with the cable laying ship in the distance (© Sergio 77)

Before choosing the type of burial method, it is necessary to study the cable corridor and landfall zone to optimize the technical and economic aspects, including the expected risks. The cable landfall zone is an area particularly impacted by coastal evolution, which can cause risks to cables that may increase with future climate change impacts (ICPC, 2009).

2.2 Risks for submarine cables in the cable landfall zone

Power submarine cables are very sensitive to risks, since if they are exposed to hazards and suffer damage, this interrupts the transmission of electricity from the wind farm. Thus, the cable placement needs to be planned carefully to minimize risks, and the cables need to be protected, such as with armouring when they are laying on seabed or by burial in the cable landfall zone (as explained in Section 2.1). Despite these safeguards, there are still risks.

2.2.1 Current hazards

At present, cables in the landfall zone are exposed to many hazards, both natural and anthropic. Table 1 summarizes several types of hazards that affect cables in the nearshore zone: hydrodynamic, meteorological, morphological, and human. The main type of risks impacting the landfall zone are hydrodynamic risks, due to the following phenomena: waves, currents and water level changes, which cause morphological changes.

Hazards	Risks
Waves	Coastal erosion
Rising and falling sea levels	Impacts on navigation and cable burial in shallow water
Mobile sediments	Cable free spanning, or excessive burial and overheating
Sedimentary seabed movement	Exposure to mechanical forces/impacts, vibration and fatigue
Low temperature	Impact on cable handling activities on-site, cable load capacity
Precipitation (rain, snow)	Flooding of open trenches
Bad design	Limits the cooling and causes cable overloading and premature failure
Extreme events	Cable exposure and cable faults

Table 1. Present hazards and their consequences on cables in the cable landfall zone (source: DNV-RP-0360, 2021)

For submarine cables, the main risks caused by hydrodynamic hazards are excessive burial (leading to overheating) and cable exposure and free spanning due to erosion of the protective sand layer. Without this protective layer, submarine cables no longer have any protection against external events (storm wave energy, anthropic activities, etc.), and this can lead to cable failure. Thus, hydrodynamic phenomena causing morphological changes in the landfall zone are important to evaluate to avoid significant burial or exposure of cables, potentially causing damage.

Waves and water levels are phenomena that impact the landfall zone at a range of timescales. At short temporal scales, for example during storm events, large morphological changes may be observed notably due to cross-shore sediment transport. Changes in water levels (e.g. tide level, storm surge, mean sea level variability) also have significant impacts on morphological changes by changing the extent of the beach that may be impacted by waves.

During storms, water levels are often higher, and waves are more energetic, inducing rapid erosion along the upper beach around the shoreline. This eroded sediment is often transported offshore and may form a sand bar in the surf zone. The upper beach erosion can lead to the exposure of submarine cables. On the other hand, during periods of calm metocean conditions with low water levels and low-energy waves, sandbars tend to migrate toward the coast and can lead to accretion and potentially excessive burial and overheating of submarine cables (Fig. 11).

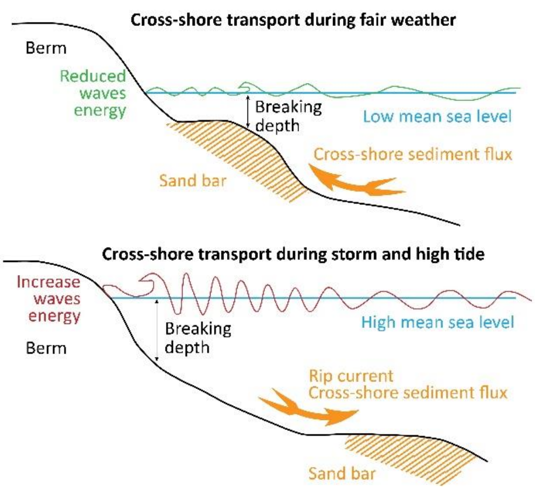

Fig. 11: Diagram of forcing factors (sea level and wave energy) and their impacts on cross-shore transport and sand bars movement (© France Energies Marines)

At longer temporal scales, ranging from years to decades, alongshore sediment transport, or slow changes in sea level or sediment supply may also generate significant morphological evolution. For example, longshore sediment transport is generated longshore currents, which may have an impact on the morphology of the landfall zone (see Section 3.1).

2.2.2 Future hazards

Future hazards for submarine cables in the cable landfall zone due to climate change are still a very recent and little-studied issue. There are very few in-depth scientific publications on this subject, except for Clare *et al.*, who published in 2023 a study about geomorphological evolution and the impacts of climate change in the cable landfall zone. In their study, they show that cable landfall zones will be exposed to climatic hazards to varying degrees depending on their location, emphasizing the necessity to conduct studies at local scales to understand the changes in risks to which cable landfall zones will be subjected. Thus, the first step is to identify the current hazards and then to evaluate the projected changes in these hazards.

During the 2C NOW project, a bibliographic study of the evolution of physical phenomena (wind, waves, and water levels) due to climate change was conducted, and Table 2 summarizes the results for water levels. Historical data in France indicates that the mean and extreme water levels (including storm surge) have increased by approximately 1.25 and 1.5 mm/year, respectively. Future projections at spatial scales of Europe estimate an increase in water levels ranging from 53 cm to 100 cm by 2100, depending on the chosen scenario (e.g. RCP/SSP 4.5 or 8.5) (IPCC, 2023).

One of the main consequences of climate change is an increase in the maximum level and frequency of high-water level events due to mean sea level rising. It can be observed (Fig. 12) that extreme water levels relating to mean sea level and storm surges show significant regional and local variability (Muis *et al.*, 2016). For example, according to Clare *et al.* in 2023, Northwestern Europe could be subjected to significantly higher water levels related to increases in storm surges, with the 100-year return period extreme water level reaching up to 9 meters.

However, this study was completed at a global scale, and it is important to conduct local studies at the specific sites of interest to quantify accurately the hazards and understand the risks for the given site. The direct consequence of storm surges on cables in the landfall zone is scouring and abrasion, as well as undermining of landfall stations and beach manholes. In addition to changes in the extreme water levels related to storm surge, sea-level rise (SLR) will also cause a greater number of landfall stations to be exposed to the effects of storm surges in the future. Since underground land cables do not have sheaths as impermeable and as protective as submarine cables, this would lead to significant deterioration of these cables if this is not considered in the design phase.

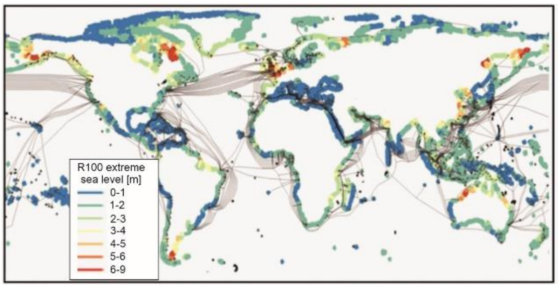

Fig. 12 : Global projection map of extreme water levels with a 100-year return period. High extreme water levels are observed in Northwest Europe, with heights ranging between 3 and 9 meters (from Clare et al., 2023).

Sea level	Mean conditions	Extreme conditions
Historical	France: Increase + 1.25 mm/year (Reinert *et al.*, 2021) Strong local differences: + 1.23mm/year Roscoff + 4.25 mm/year Nice Intensity increases stronger in the last 2 decades (+ 2.4 mm/year)	France: Increase + 1.5 mm/year (Reinert *et al.*, 2021)
Future	Europe: Increase 2050 => + 21 cm (RCP4.5) + 24 cm (RCP8.5) 2100 => + 53 cm (RCP4.5) + 77 cm (RCP8.5) (Vousdoukas *et al.*, 2017)	Europe: Increase 2100 => + 57 cm (RCP4.5) + 81 cm (RCP8.5) Up to 100 cm in the North Sea (Vousdoukas *et al.*, 2017) Increase slowing down over time (IPCC, 2023)

Table 2: Summary of historical observations and future projections of sea level changes for mean and extreme conditions (© 2CNOW Project, 2024)

Waves	Mean conditions	Extreme conditions
Historical	France: Increase of Hs and Tp in the Bay of Biscay (Dodet *et al.*, 2010; Charles *et al.*, 2012) 0.19 cm / 0.0051 s in winter 0.16 cm / 0.0034 s in summer. Changes of wave direction (Morim *et al.*, 2019) Strong seasonality of waves along French coasts (Dodet *et al.*, 2010; Charles *et al.*, 2012)	France: Increase of Hs: + 1 to 2 cm/year (Charles *et al.*, 2012; Wang *et al.*, 2012)
Future	North Atlantic: Decrease of Hs 2100 => - 6% (RCP4.5) - 10% (RCP8.5) (Aarnes *et al.*, 2017) Europe: Decrease 2100 => -0.2 m (RCP4.5 & 8.5) (Bricheno & Wolf, 2018) North Sea: Increase of Hs (Hemer *et al.*, 2013) Atlantic & Mediterranean: Decrease of Hs and Tp (Chaigneau *et al.*, 2023) Bay of Biscay: Decrease of Hs (Charles *et al.*, 2012)	Europe & France: No clear signal Increase of Hs (Bricheno and Wolf, 2018) Decrease of Hs (Aarnes *et al.*, 2017)

Table 3: Summary of historical observations and future projections of waves evolution for mean and extreme conditions of the significant wave height (Hs) and peak period (Tp) (© 2CNOW Project, 2024)

A second effect of climate change highlighted by Clare *et al.* in 2023 is the accentuation of coastal erosion and the increase in sediment mobility due to the increased intensity (measured as changes in the significant wave height Hs and peak wave period Tp) and frequency of extreme events (Table 3). Figure 13 presents a global projection map of shoreline changes by 2100 for the SSP5-8.5 scenario, based on the results of the study of Vousdoukas *et al.* in 2020, who estimated changes as the sum of extrapolated historical trends and a sea-level rise component (the Bruun Rule, see Section 3.3.1). Under this scenario, global shoreline retreat could range between 0 and 250 m, depending on the region. For Western Europe, significant retreat is anticipated; however, the map lacks precision at regional and local scales, neglecting local geomorphology, bathymetric effects, wave variability, and sediment characteristics and availability.

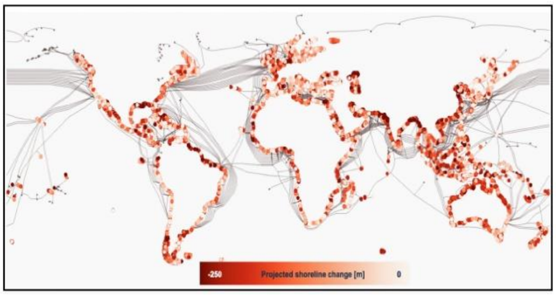

Fig. 13: Global projection map of shoreline changes by 2100 for the SSP5-8.5 scenario. The map was created using average data from Vousdoukas et al., 2020 (from Clare et al., 2023)

One additional effect of climate change on cable landfall zones is river flooding. Following the SSP5-8.5, river flooding events that currently have return periods of 100 years, are projected to have much shorter return periods (Clare *et al.*, 2023). The risk of river flooding can lead to slope failures and sediment run-off into the sea, causing cable exposure and potentially breakage. These events could occur in regions where rivers flow into submarine canyons.

In conclusion, Clare *et al.* in 2023 summarized the main effects of climate change on cables in the landfall zone, concluding that it is likely to be an increase in the frequency and intensity of existing risks. It is important to emphasize that there is high regional and local variability in these risks, which necessitates local-scale studies to be able to characterize them accurately at a specific study site.

2.3 Industry practices for assessing morphological evolution in the cable landfall zone

In this section, a review of the existing literature on industry practice for evaluating morphological evolution in the cable landfall zone (e.g. site selection, processes considered, timescales) will be presented. The DNV Recommended Practices are written to assist and guide industry in the study, creation, implementation, and maintenance of offshore wind farms. These guides are based on existing knowledge and technology, and while submarine cables have only been used for offshore wind farms in the last couple of decades, they have long since been used for telecommunication. The DNV-RP-0360 (2021) guide summarizes the important factors to consider for the design and installation of submarine cables in the nearshore zone. In this part, we will base our discussion on DNV-RP-0360 (2021), as well as on several studies at cable landfall sites (Repsol & EDP Renewables, 2018), (RTE, 2016), and an interview with members of the RTE - Réseau de Transport d'Electricité group specialized in cable landfall zone studies.

2.3.1 Cable landfall zone selection

The selection and design of the cable landfall site is an essential element in the planning phase of an offshore wind farm. To do this, criteria are established, based on economic, environmental, and technical factors that must be considered, and a range of preliminary studies are conducted to assess these different aspects. The goal is to optimize all three types of criteria: choosing a site that meets environmental criteria (with minimal impacts on the ecosystem, avoiding environmentally sensitive areas, preserving subaerial dunes, etc.), technical criteria (feasibility of burial techniques in the area and other engineering constraints), and, of course, cost considerations. To facilitate site selection, it is recommended to avoid as many potentially problematic areas as possible that may pose critical constraints on the project (Repsol & EDP Renewables, 2018), a point confirmed during an interview with a member of the RTE group, partner of the 2C NOW project.

The chosen site must also have a substantial amount of verified observational data. One of the first steps in assessing a cable landfall zone is a thorough bibliographic review of data available in the literature and in previous studies completed at the site, including geological, bathymetric, topographic, meteorological, metocean, environmental, and human activity data (DNV-RP-0360, 2021).

Once the cable corridor has been identified, technical studies are conducted, including geophysical studies of the superficial geology with seabed profiling and an unexploded ordnance (UXO) survey, as well as satellite imagery and GPS bathymetric and topographic surveys to obtain information on the morphodynamics of the area. Morphologically active zones are generally avoided, but if this is not possible, frequent monitoring is necessary.

Historical observations of the nearshore zone allow characterizing the observed maximum and minimum sediment depth, the existence of a seasonal cycle, and any interannual or long-term trends, depending on the data availability. Along with surveys characterizing the general sediment (e.g. grain size) and geological characteristics (e.g. boulders, rock platforms, cliffs, dunes, etc.) of the site, this data allows evaluating the current morphodynamics of the site. Depending on the available data, and if the study area proves to be highly variable morphologically, additional observations may be necessary to complete these evaluations.

To evaluate the morphological evolution of the cable landfall zone during the project lifetime, modelling studies are completed to estimate the expected morphological changes for a series of different scenarios. These studies are typically completed for a selection of potential cable route profiles to select the optimal cable route that is feasible for a given corridor.

To ensure the proper functioning of the cables during their lifetime, it is necessary to reduce the risk of erosion or accretion causing cable exposure or excessive burial. Thus, future beach profile changes must be evaluated, and it is recommended to estimate morphological changes at two different timescales:

- short timescale events causing rapid changes during storms, using storm events with return periods beyond the lifetime of the wind farm structures. Current industry practice is based on 50-to 100-year return period events.
- medium to long timescale changes causing seasonal to decadal and longer evolution of the profile related to alongshore sediment transport or changes in mean water levels, sediment supply, or the mean wave climate.

To consider fully the impacts of climate change, one must specifically consider both changes in mean sea levels and in the wave climate (i.e. evolution of the distribution of wave height, period, or direction). At this time, no single morphological change model is capable of accurately estimating beach profile changes across the wide range of spatial and temporal scales discussed here. Different types of models must be used to estimate changes at these two temporal scales (see Section 3.3), and observations of previous changes are necessary to calibrate these models using historical events before they can be used to make projections of future changes.

2.3.2 Existing recommendations regarding cable burial depth

As previously mentioned, cables are buried in the landfall zone to protect them from various external risks. The cable burial depth is a measure describing the thickness of the layer of sediment (typically sand) covering the cable. If the burial depth is not sufficient, the cable may become exposed, thus increasing the risk of damage. If the burial depth is excessive, this may lead to overheating and malfunction of the cable. Thus an optimal burial depth must be estimated. The different burial depths are represented in Fig. 14:

- **Depth of trench**: vertical distance between the bottom of the trench and the undisturbed (mean) seabed level.
- **Depth of lowering**: vertical distance between top of the cable and the undisturbed (mean) seabed level.
- **Depth** (height) **of cover**: vertical distance between the top of the cable and the average level of the backfill over the cable.

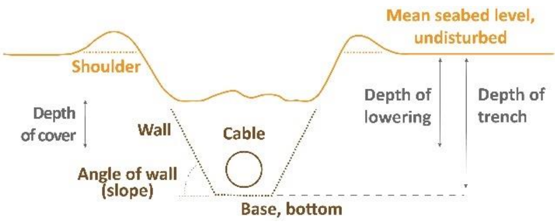

Fig. 14: Definition of the different burial depths (from DNV-RP-0360)

The main failures of this protection method are sediment depletion and sediment accretion (Fig. 15).

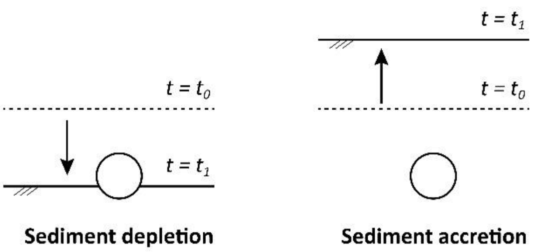

Fig. 15: Main burial failures (from DNV-RP-0360)

To avoid these difficulties, a burial depth assessment study is conducted based on the hazards the cable is exposed to (fishing gear, object drop, shipping, sediment depletion, accretion) and site conditions (soil properties and sediment movement). According to DNV-RP-0360 (2021), the optimal burial depth corresponds to the depth at which the cable is protected from risks. The depth must provide sufficient protection but also be economical, so it may vary along the cable's length. There are methods to determine this depth, based on the hazards the cables are exposed to. These methods involve identifying the various hazards that may impact the cable (e.g., dropped and/or dragged anchors, fishing gear), and assessing the soil composition to determine how deep these elements can penetrate.

The burial methods are:

- State of the art of past long-term experiences with similar structures such as pipelines or telecommunications cables (DNV-RP-0360, 2021). This quantitative study method is very informative, but it is generally not sufficient on its own for an offshore wind cable installation.
- The Burial Protection Index (BPI) method is a semi-quantitative method (Allan, 1998) that involves identifying potential anthropogenic and natural hazards, followed by studying the soil composition (Fig. 16). Based on this data, a protective cover is determined. A limitation of this method is that it has not been sufficiently validated, so the factor of safety achieved is uncertain.

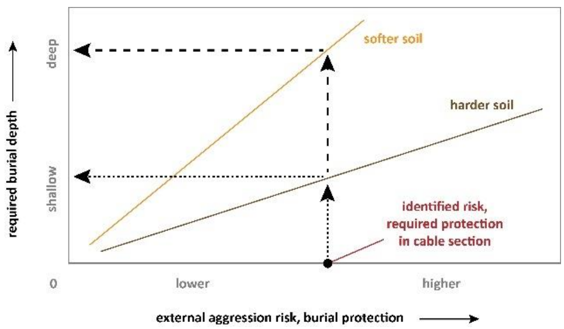

Fig. 16: Burial protection index (from DNV-RP-0360)

- The method of establishing a threat line involves determining a limit depth representing the maximum penetration of an anthropogenic hazard into the soil. This limit can be determined for each potential hazard. Once all risks are assessed, a limit depth is established that also meets the reliability objectives of the cable system (DNV-RP-0360, 2021). As shown in Fig. 17, this limit can vary in depth along the cable route depending on the soil composition. The cable is then buried slightly deeper than the threat line to ensure its protection. This method also adapts to the hazard of sediment movement.

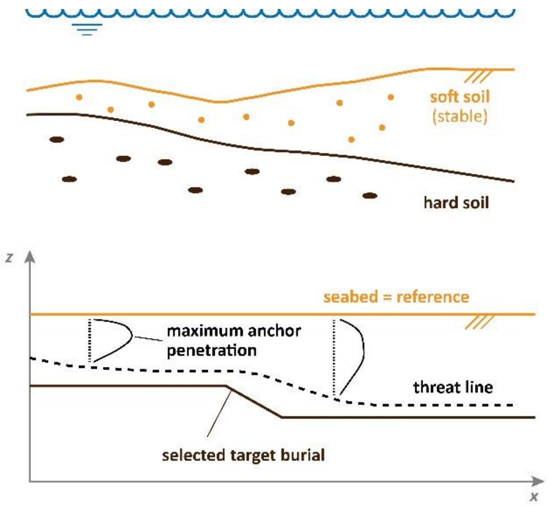

Fig. 17: Threat line (from DNV-RP-0360)

- The Cable Burial Risk Assessment (CBRA) method works in the opposite way to the BPI method. Initially, the soil composition is studied, and a register of all potential hazards is established. A proposed cable burial depth is then specified. To validate this depth, an assessment of all hazards that could affect the cable at this depth and their probability of occurrence is conducted. Subsequently, the results are discussed with the various stakeholders involved in deciding on the burial depth (Fig. 18).

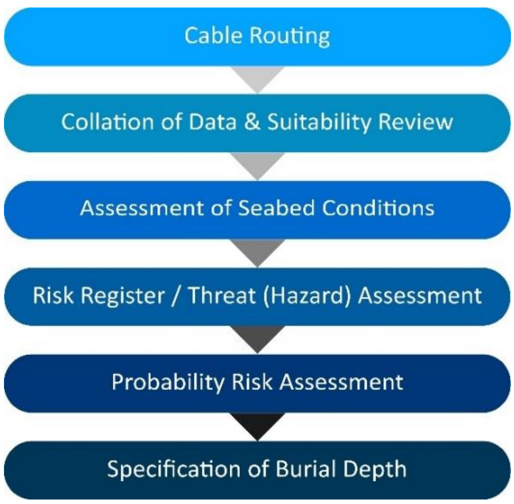

Fig. 18: CBRA method (from DNV-RP-0360)

Current practice in estimating the cable burial depth considering the impacts of climate change consists in combining different scenarios of sea-level rise (SLR) with storms with a specified return period. The typical design lifetime of a wind turbine is about 40 years; thus, sea level rise estimates are based on the expected value at the site in 40-50 years. For the choice of storm events, multiple storms will be chosen with different combinations of Hs, Tp, and incident wave direction to evaluate the storm that may cause the most significant morphological changes. The choice of the storm return period often exceeds the structure's expected lifetime because a storm with a return period of 100 years still has a small but non-negligeable probability of occurring in a 50-year period. Thus, data is acquired to estimate the projected SLR at the local site, and to complete an extreme value analysis to estimate the storm events with a 50 and 100-year return period. At medium to long temporal scales, both the effects of SLR and changes in the general wave climate must be considered. These longer-term simulations can thus be used to define the expected envelope of seasonal to decadal-scale erosion and accretion to assist in defining the threat line. In doing so, a series of simulations are often completed using different combinations of sea levels and wave conditions to consider the nonlinear interactions between changes in water level and wave conditions.

This study focuses on the risks of excessive cable burial or cable exposure to answer the following scientific question: What is the geomorphological evolution of the coastal area due to climate change, and its impact on wind cable landfall zones? To answer to this question, we must first understand the important physical processes to consider in the landfall area, through observations and/or appropriate models.

3. Coastal morphological evolution

3.1 Observations

Different types of data are needed to study coastal morphological evolution: topographic and bathymetric data, wave state and sea level data and granulometric data. These data are required to understand the morphodynamics of a site and to force and calibrate models. This section presents the different types of instruments that are used to measure the beach morphology, wave conditions, and sediment characteristics.

3.1.1 Topographic observations

A range of methods and measuring devices are available for acquiring topographic data. The first method is profile measurements, which may consist in making cross-shore or alongshore measurements. It is common to measure along cross-shore transects that extend from the top of the beach to the deepest accessible altimetric contour and are spaced along the beach in the alongshore direction. Subsequent profiles can then be compared to estimate the topographic evolution in time. This method only represents the individual beach profiles and depending on the profile spacing and alongshore variability at a site, this may lead to uncertainties.

The measuring devices that can be used for this technique are theodolites and optical levels, which are manual acquisition devices that can therefore be impacted by human error (Fig. 19). Topographic acquisitions with these types of equipment can be very time-consuming. These transects can also be surveyed using a mobile Global Navigation Satellite System (GNSS) station, a faster and less error-prone method.

Fig. 19: Total station (© Cafeymas/Pixabay)

A second method of acquiring topography/bathymetry is in-plane measurements using different types of equipment: electronic tacheometers, total stations, GNSS receivers and remote sensing (Fig. 20). Remote sensing is a measurement method that does not make invasive in situ measurements and can be used to monitor various physical metrics on different types of shorelines (radar interferometry, airborne or satellite photogrammetry, orthophotography, airborne or terrestrial lidar, photogrammetry).

Fig. 20: Mobile GNSS station (© Paulbr75/Pixabay)

Among these measurement methods, lidar and photogrammetry are the most accurate and dense, even over large areas (Fig. 21).

Fig. 21: Lidar scanning performed with a multicopter UAV (© Cargyrak)

3.1.2 Wave observations

The second type of data needed to study and model shoreline evolution is wave observations. The main method for acquiring this data is with wave buoys, which are used to obtain the physical parameters characterizing the sea state:

- H: Wave height (m)
- T: Wave period (s)
- D: Wave direction (s)

Wave buoys are typically used in deeper water conditions and may sometimes be far away from the study site (Fig. 22). To have accurate wave data at a study site, wave models may be used to estimate nearshore wave conditions.

Fig. 22: Wave buoy in situ (© France Energies Marines)

During individual measurement campaigns, in shallow water conditions, a range of other instruments may be used, such as (Acoustic Doppler Current Profilers (ADCP), pressure sensors, Acoustic Doppler Velocimeter (ADV), as well as video stations (which present higher uncertainties).

3.1.3 Sediment observations

The third type of data required to study shoreline evolution is the sediment granulometry of the sites of interest. In particular, the D50 and D90, which are commonly used descriptors of the sediment characteristics (Fig. 23). The D50 represents the particle diameter for which there are as many larger-diameter grains and as many smaller-diameter grains in the sample. The D90 represents the particle diameter for which only 10% of the volume of sediments in the sample have a larger diameter.

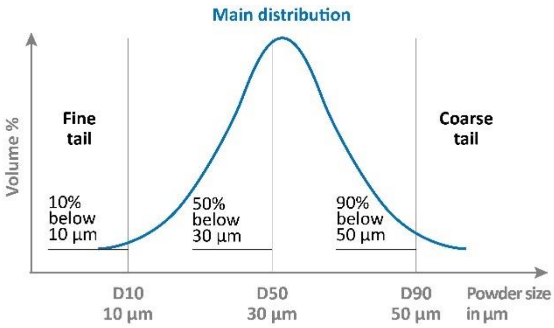

Fig. 23: Example article size distribution

There are several methods for observing particle size, the first of which is sieving. This method is the simplest to set up, and involves sieves with different mesh sizes, known as a sieve shaker (Fig. 24).

Fig. 24: Sieve shaker (© Bastien Taormina)

This sieve shaker is used to quantify the sample mass representative of each grain size. This makes it possible to estimate the distribution of grain diameters in the sample. A second method is the diffraction method, which involves observing particle size through the diffraction of light, using what is called a laser granulometer (Fig. 25). There also exist image analysis methods.

Fig. 25: Laser granulometer (© Christophe Anciaux)

Light microscopy and scanning electron microscopy can be used to acquire representative images of the samples, and, with the aid of image processing software, estimation the distribution of the samples. The last granulometric analysis method is the sedimentation and centrifugation method, for which Stokes' law is used to determine the sediment size.

3.2 Physical processes

This study focuses on the coastal area, which is composed of several elements extending along a beach profile. The coastal area is defined from the back beach (consisting of dunes, cliffs, seawalls, etc.) to the closure depth. The closure depth is the depth beyond which there is no significant impact of waves or currents on the seabed. At this depth, sediments are no longer suspended, resulting in little or no sediment transport due to waves and currents. This depth delineates the active coastal zone in which wave-induced sediment transport may cause morphological changes.

The coastal area is divided into several cross-shore zones (Fig. 26). The offshore-most zone is called the shoreface, where waves interact with the seabed. It is delimited by the closure depth and the mean water level, respectively, at the offshore and onshore extents. The shoreface can be divided into two areas: the lower shoreface, which is the shoaling zone, and the upper shoreface, where the most wave energy is dissipated due to wave breaking. Moving shoreward, the beach is defined until the coastline. The beach is divided in two areas, the lower part which is the 'wet area', called the beach face or foreshore and the upper part which is the 'dry area' (under normal conditions) called the backshore. And finally, the upper landward part of the beach profile more generally referred to as the coast.

The coastal area is impacted by numerous hydrodynamic phenomena, including waves, currents, and variations in water levels. All these phenomena influence the morphological evolution of the coastline and beach profiles. Waves and currents significantly impact morphological evolution by causing sediment suspension and transport along the beach. Variations in water levels also affect morphological evolution since these changes lead to the shifting of the breaking zone along a beach profile, thereby altering the beach profile's morphology.

In the coastal area, sediment transport is often separated into the cross-shore and longshore components, which together modulate the morphology of the shoreline and beach profile (Fig. 27). To study sediment transport and thus morphological evolution, these two main types of transport are generally distinguished: cross-shore transport and longshore transport. This distinction is particularly used in numerical models since different physical mechanisms cause cross-shore and longshore sediment transport.

This study will therefore focus on these two types of sediment transport. Cross-shore sediment transport is normal to the shoreline, while longshore sediment transport is parallel to the shoreline.

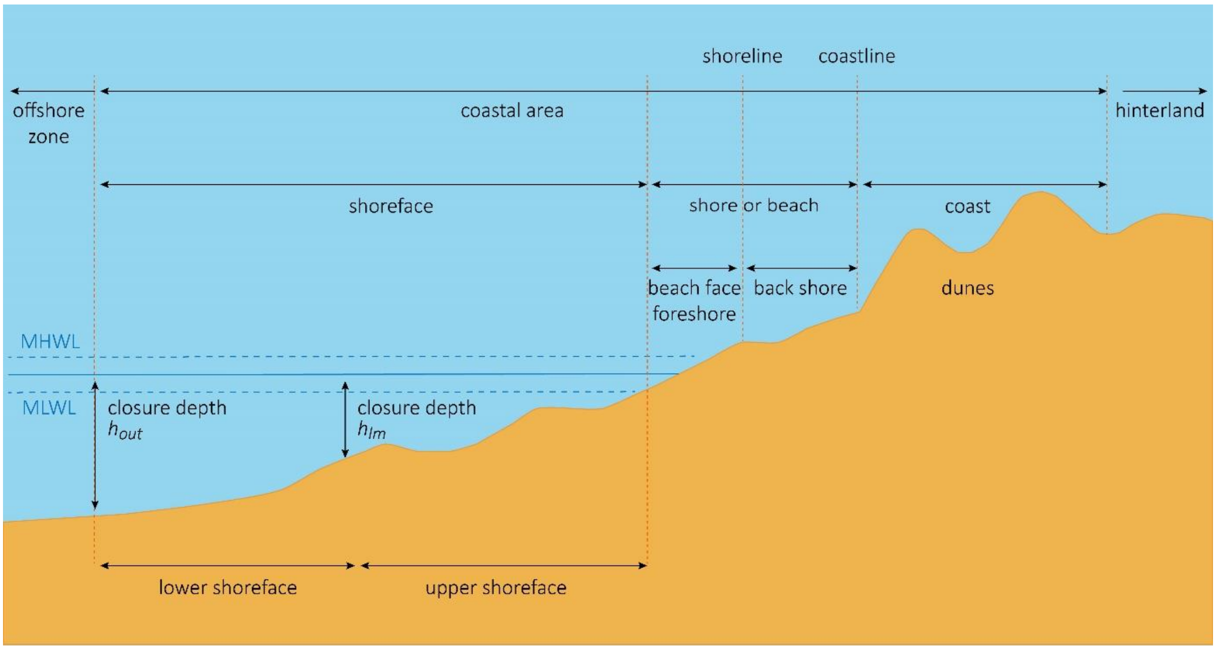

Fig. 26: Beach profile from the closure depth to the top of the back beach (adapted from US Army Corps Engineers, 1984)

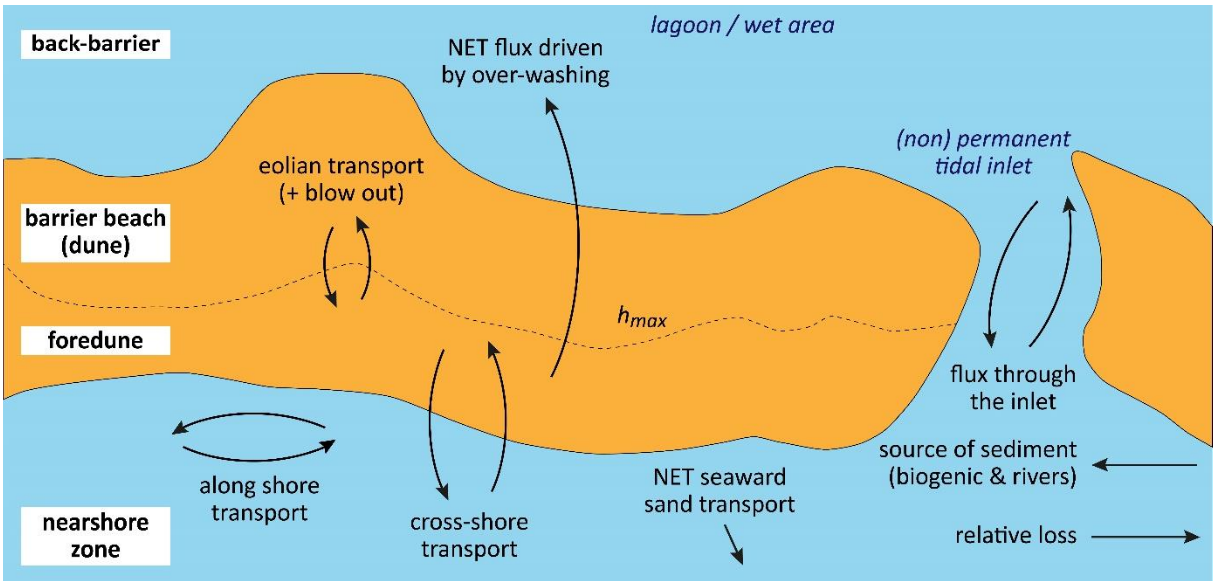

Fig. 27: Different sediment transport processes that impact the coastal area (from Frédéric Bouchette, personal communication)

Cross-shore processes

Cross-shore sediment transport occurs when the combined waves and currents acting on the seabed exceed a critical threshold (or critical Shield's number) allowing incipient particle motion. Sediments may then be transported by bedload (when the sediment particles move along the bed) or by suspended load (when the sediment particles are transported in suspension in the flow transport). The relative importance of bedload or suspended sediment transport depends on the hydrodynamic conditions (waves and currents) and on the sediment characteristics.

In a review about cross-shore sediment transport models, the authors conclude that the general state of knowledge concerning sediment transport in the nearshore zone is still incomplete due to the complex interactions between the hydrodynamic forcing and the sediments (Marin & Vah, 2024). Thus, many simplified models have also been proposed relying on the commonly known equilibrium beach profile theory. Beach profiles have long been thought to respond to a constant wave forcing by forming an equilibrium beach profile (Dean, 1977). According to this theory, a beach profile eventually reaches a state of equilibrium in response to a constant wave forcing, such that there is no longer significant morphological evolution (Fig. 28). If the incoming wave energy increases, this typically causes erosion near the shoreline, and the eroded sediment is transported offshore. Reciprocally, if the incoming wave energy decreases, sediment transport is typically in the shoreward direction, causing accretion near the shoreline. Cross-shore sediment transport is rapid and thus to occur on short timescales. This may result in beach profile changes in only a few hours (coastal erosion due to storm event), or over the span of a few days (period of fair-weather waves).

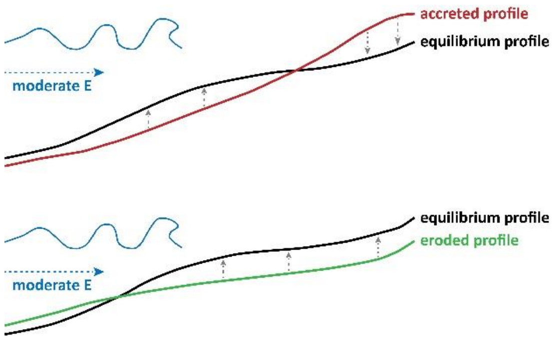

Fig. 28: Figure showing initially accreted (red) and eroded (blue) profiles, typical of common summer and winter profiles, respectively, returning to the same equilibrium profile (black) when exposed to the same constant moderate wave energy E. (from Yates, 2009).

Longshore transport

Longshore sediment transport also impacts beach profile and shoreline changes. Longshore transport is caused by differences between the wave incidence angle at the coast and the beach orientation, as well as alongshore gradients in the wave height and incidence angle. When the wave propagation direction is not perpendicular to the coast, longshore currents, and thus longshore sediment fluxes are generated in the surf zone. There is no longer significant longshore transport if the wave propagation direction is either perpendicular to the coast.

The longshore current is associated with the longshore energy flux, which is the propagation speed of the wave energy relative to the angle of wave incidence at the coast and it can vary along the coast depending on several parameters (wave energy, incidence angle, shoreline morphology). These variations are quantified by the energy flux gradient, which defines the spatial variations of sediment transport and, consequently, morphological changes along the shoreline and entire beach profile. When this gradient is positive, it indicates an increase in the energy flux and sediment transport, leading to coastal erosion. Conversely, when the gradient is negative, the energy flux decreases, reducing sediment transport and causing sediment deposition (Fig. 29). In comparison to rapid cross-shore sediment transport during storms, longshore sediment transport often becomes more dominant at longer time scales.

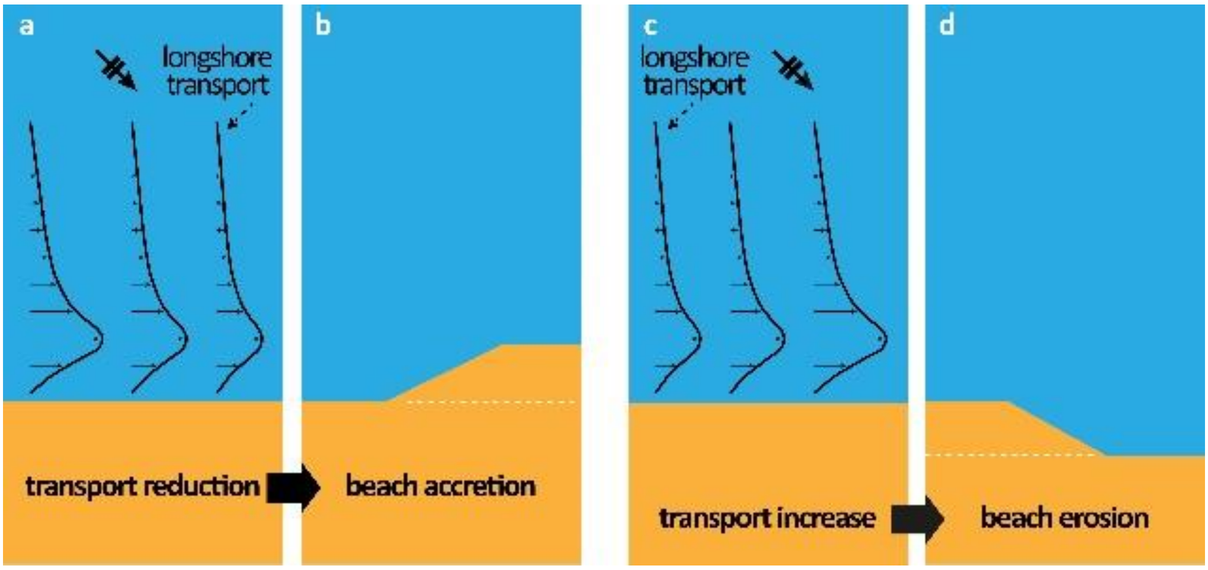

Fig. 29: Evolution of beach characteristics in response to a negative (a,b) and positive (c,d) longshore sediment transport gradient (from Cailler, 2019)

3.3 Modelling morphological changes

3.3.1 Model review

As summarized in section 2.3.1, to make projections of long-term coastline evolution and of the impacts of future extreme storm events, numerical models must be used (BRGM and CEREMA, 2022) to go beyond simple extrapolations of previously observed trends. This paragraph is therefore a state-of-the-art review of existing morphological evolution models.

First, the choice of model depends on the objective of the desired simulation, including the dominant spatial and temporal scales. There does not exist a single model that is able to accurately simulate morphological changes at all spatial and temporal scales. Thus, the dominant physical processes must be identified at a given study site to select the optimal model to be applied at the site. The physical processes are then categorized by the timescale of the beach morphological response.

Three broad types of time scales can be identified by Hunt *et al.* in 2023:

- Short term (hourly, daily), for modelling wave sequences and storms.
- Medium term (seasonal, annual), for modelling seasonal wave variability and the wave climate.
- Long term (decadal, centennial), for modelling wave climate evolution and sea-level impacts.

There are numerous models that vary in suitability depending on the process to be simulated. The shorter the time scale of the phenomenon to be modelled, the more complex and less efficient the model may be in terms of computational speed. Conversely, the longer the time scale of the processes to be represented, the more efficient the model must be, though it will make simplifications to represent or parameterize the dominant physical processes. Morphological change models can broadly be separated into two main families representing these two-time scales (short-term and long-term): *physics-based* (sometimes also called *process-based*) models for simulating short-term processes, and *behaviour-based* models for representing long-term processes (Fig. 30).

In the context of climate change and cable landfall zones, the objectives of estimating future beach profile and shoreline changes are twofold: estimate the maximum erosion that may be expected during a storm event, and estimate the long-term evolution of a site, considering sea-level rise projections and the evolution of the wave climate. It is necessary to estimate the vertical changes (losses or increases) in the sediment depth, since this criterion is used to determine the cable burial depth and the potential exposure to risks.

To fulfil these objectives, two different types of morphological change models need to be used: a physics/process-based model to estimate the beach profile changes during a short time scale event (e.g. storms with a 100-year return period), and a behaviour-based model that can estimate long-term (decadal to centennial) changes, including changes in the wave climate and sea level.

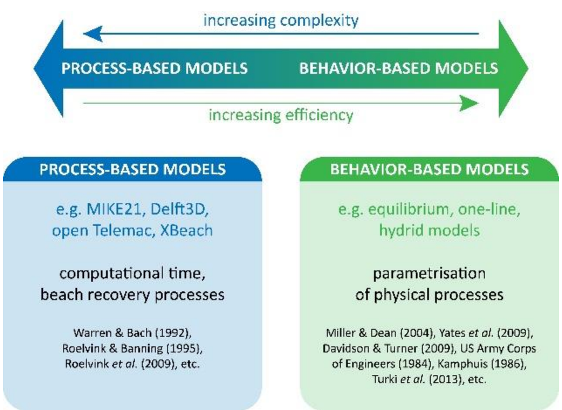

Fig. 30: The two main types of morphological change models: process-based and behaviour-based models, highlighting their advantage and limitations, and listing several examples (from Yates et al., 2022)

Process-based models are complex models that calculate directly the physical processes of sediment transport. First, the wave and current hydrodynamics are simulated by solving the hydrodynamical equations, and then they are coupled with a sediment transport module to estimate the resultant morphological evolution. Consequently, their computation time can be very long, and they are thus limited to small areas (beach profiles or beaches) and short time periods (hours to days). This type of model may be very successful in the short-term projection of nearshore phenomena. Many process-based models exist, and a couple of well-known examples are: MIKE21 (Warren & Bach, 1992), Delft3D (Roelvink & Banning, 1995) and XBeach (Roelvink *et al.*, 2009).

Behaviour-based models are simplified models that often simulate a single dominant physical process. They are frequently used to observe the long-term evolution of beaches (e.g. BRGM and CEREMA, 2022) since they are relatively easy to set up and use. However, as these models parameterize the dominant physical processes, there can be significant uncertainties. There are several families of behaviour-based models, depending on the process being modelled (Hoagland *et al.*, 2023):

- **Longshore models:** This type of model simulates shoreline evolution by calculating the longshore sediment transport gradient (e.g. GENESIS (Hanson & Kraus, 1989), the CERC equation (US Army Corps of Engineers, 1984), Coastline Evolution Model (Ashton *et al.*, 2001), Gencade (Frey *et al.*, 2012)).
- **Shoreface model:** These models represent the cross-shore evolution of a profile by calculating the morphological evolution of the shoreface (e.g. Hinged Panel Model - HPM (de Vriend *et al.*, 1993), Advection Diffusion Model ADM (Niedoroda *et al.*, 1995)).
- **Equilibrium profile model:** This type of model combines cross-shore evolution based on equilibrium theory (e.g. Miller & Dean, 2004, Yates *et al.*, 2009, Davidson *et al.*, 2013).
- **Translation models:** These models use the Bruun rule (see Section 3.2.1) to model the impact of rising sea levels on the beach profile and shoreline position (e.g. Pilkey *et al.*, 1993, Thieler *et al.*, 2000).

The most used method to estimate shoreline changes (i.e. retreat) due to sea level rise is the Bruun rule (Bruun, 1962). It considers a constant beach profile extending from the berm to the closure depth (Fig. 31). It's a simplified model that is based on two hypotheses: the sediment budget is fixed in this zone (conservation of sediment), and the wave climate remains constant. The Bruun rule only estimates the upward (with sea-level rise) and shoreward translation of an equilibrium profile as the wave action causes the beach to adjust to an increase in sea level (i.e. cross-shore changes only) and thus does not consider longshore transport.

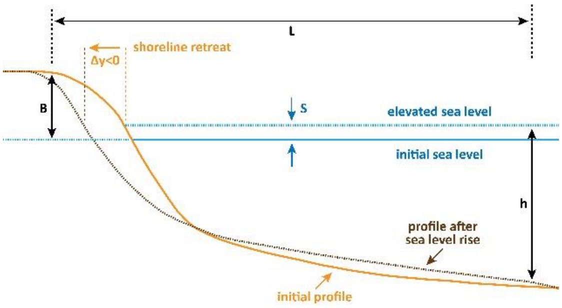

Fig. 31: Schematic diagram of the Bruun Rule (from Amer et al., 2023)

Bruun rule

$$R = S\left(\frac{L}{B+h}\right) = S\,(\frac{1}{tan\ \alpha})$$

with:

- *R*: shoreline recession
- *S*: sea level rise
- *L*: horizontal length of the bottom affected by sea level rise
- *B*: dune height above sea level
- *h*: depth of closure
- *tan α*: beach slope

More recent efforts have tried to achieve the goal of creating behaviour-based, efficient models that are applicable in more complex environments and thus that consider more of the physical processes. Thus, many coupled cross-shore - longshore models have been created in recent years (Hoagland *et al.*, 2023):

- Shoreline change and transgression models: CEM model (Ashton & Murray, 2006), BRIE model (Nienhuis & Lorenzo-Trueba, 2019), Palalane & Larson (2019) model.
- Cross-shore (equilibrium shoreline and dune-based models) and longshore (e.g. one-line formula) models: CoSMoS-COAST (Vitousek *et al.*, 2017), LX-Shore (Robinet *et al.*, 2018), COCOONED (Antolínez *et al.*, 2019).

A new category of models has also been developed recently: data-based models. With the significant increases in data availability from long-term in situ monitoring sites, remote sensing sources (e.g. lidar, drones), satellite observations, video monitoring, and citizen-based science programs, data-based approaches have expanded rapidly in recent years. These models use statistical principles and a range of machine learning modelling approaches to first train the model and then to run fast computations over large spatial and long temporal scales. These models require very large amounts of data but have recently been shown to be able to accurately simulate morphological changes (e.g. Hunt *et al.*, 2023; Calkoen *et al.*, 2021; Gomez-de La Pena *et al.*, 2023).

3.3.2 Modelling climate change impacts on morphological evolution

Marine inundation and coastal erosion risks impact coastal communities worldwide, and climate change is projected to increase these risks. The French State, with the Climate and Resilience Law, is one among many nations that has adopted public policies encouraging the estimation of future shoreline position changes to integrate this in coastal management, land use and/or urban development planning. There is a strong need worldwide for evaluating future shoreline and beach changes, which is also important in the context of offshore wind farms, concerning the location and design of the cable landfall zone. The most used approach for estimating the impacts of climate change is to apply the Bruun Rule, which estimates shoreline changes caused by sea-level rise (D'Anna *et al.*, 2021). While this simplistic approach is known to have high uncertainties (Cooper & Pilkey, 2004), no simple and viable alternative exists, and therefore, as shown in the Synthesis Report of the 6th Assessment Report of the IPCC, it continues to be the global reference (IPCC, 2023). However, it is important to keep in mind the high uncertainties associated with this approach.

As explained in this report, to evaluate the potential future wave-induced shoreline and beach profile changes, two different temporal scales need to be considered: short-term studies of event-based morphological changes, aiming to estimate the maximum changes expected during an extreme event, and medium-to-term studies that estimate the continuous morphological evolution on seasonal to decadal to centennial timescales. In a review paper, the author cites the common approach of using process-based models such as XBeach, Delft3D, Mike21, or SBEACH to evaluate expected storm-driven beach changes, emphasizing the importance of taking a probabilistic and not deterministic approach (e.g. Callaghan *et al.*, 2009; Callaghan *et al.*, 2013), suggesting the importance of running many Monte Carlo simulations of storm events to obtain, for example, the 100-year storm erosion volume, which is not necessarily associated with the 100-year storm wave conditions and water levels (Ranasinghe, 2016). Due to their simplicity and efficiency at large spatial and long temporal scales, additional approaches using equilibrium-based, reduced-complexity, and data-driven models are used more frequently to estimate the expected long-term evolution related to cross-shore and longshore processes, including sea level rise (e.g. Vitousek *et al.*, 2017; Antolinez *et al.*, 2019; Banno & Kuriyama, 2014; D'Anna *et al.*, 2021).

In 2020, Ranasinghe also emphasized the necessity of having sufficient hydrodynamical and morphological observations at a study site to be able to calibrate these different modeling approaches. In 2017, Vitousek *et al.* highlighted this point by presenting a comparison of different types of modeling approaches, ranging from what they called a "forward model", meaning that the model was run in a predictive mode only, to a probabilistic, data assimilation model that was calibrated and validated with hindcast data, including during a forward modelling period, with increasing "believability" in the obtained predictions (Fig. 32).

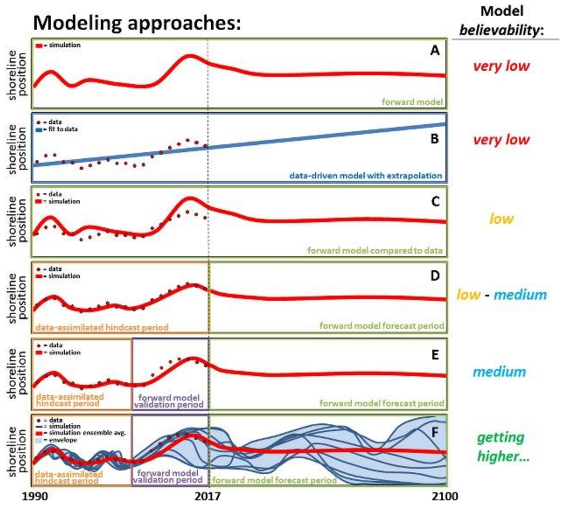

Fig. 32: A comparison of different broad types of modelling approaches integrating data, and the qualitative resultant model "believability" (from Vitousek et al. 2017)

In addition, to complete long-term simulations of beach morphological changes over the next ~50 years, it is thus necessary not only to have sufficient data for hindcast model calibration, but also to have continuous (probabilistic) projections of future wave and water level time series. In recent years, increases in the availability of wave projections and downscaling wave products has improved access to local-scale, probabilistic wave conditions, but more work is necessary to ensure accurate estimates of wave conditions in the nearshore environment to force morphological models.

4 Conclusion

With the increasing development of offshore wind farm projects with expected lifetimes of 30-40 years, it has become necessary to evaluate the impacts of climate change during the project design phase. This report is focused specifically on the impact of climate change on coastal morphological changes in the cable landfall zone to minimize the risks of cable damage or failure.

An extensive bibliographic review was first completed to present the context of submarine cables and the cable landfall zone, including the design constraints, burial methods, risks and current industry practices in the design phase. Then, the physical processes causing coastal evolution, and the different methods used to measure the beach topography, wave conditions, and sediment characteristics were described. Finally, the state of the art of current morphological change models, including approaches considering climate change impacts, was presented, with a focus on the two different types of models that are necessary to use to model beach morphological changes at short (storm event) and long (decadal and longer) timescales: physics/process-based and behaviour-based models.

Many studies conducted thus far have been at a global scale; however, for the issue at hand, local-scale studies are necessary. To carry out these studies, the acquisition of field data is necessary, including hydrodynamical (waves and water levels), morphological (topographic and bathymetric) and geological (e.g. sediment) observations. These data enable understanding the historical evolution of a site and calibrating numerical models. Obtaining long time series with high acquisition frequency improves the overall comprehension of the observed trends at a given site.

As summarized also in the Recommendations guide of the BRGM and Cerema (2021), estimated projections of future morphological evolution is achieved through the application of numerical models using two approaches: a short-term, storm event-based approach, and a medium to long-term evolution approach. The short-term approach allows observing the impact of the dominant hydrodynamic phenomena on beach morphological evolution over a short period, such as the study of the impacts of extreme wave and water level events. The medium to long-term approach allows observing the impact of dominant hydrodynamic phenomena on beach morphology over the medium to long time periods, such as longshore evolution or sea-level rise impacts due to climate change. At this time, there is no single morphological change model capable of reproducing beach changes at these two timescales, thus two different types of models are necessary: a behaviour model to quantify medium to long-term beach evolution, requiring long-term data acquisition to calibrate and validate the model in hindcast mode, and a physics-based model for short-term studies, requiring high-frequency data acquisition over a short period to calibrate the model with observations of historical storm events.

4. Bibliography

- Aarnes O.J., Reistad M., Breivik Ø., Bitner-Gregersen E., Ingolf Eide L., Gramstad O., Magnusson A.M., Natvig B., Vanem E. (2017) Projected changes in significant wave height toward the end of the 21st century: Northeast Atlantic. *Journal of Geophysical Research: Oceans*, Vol. 122, pp. 3394-3403
- Allan P.G. (1998) Geotechnical aspects of submarine cables. IBC Conference on Subsea Geotechnics, Aberdeen, Unted-Kingdom, November 1998
- Antolínez J.A.A., Méndez F.J., Anderson D., Ruggiero P., Kaminsky G.M. (2019) Predicting Climate-Driven Coastlines With a Simple and Efficient Multiscale Model. *Journal of Geophysical Research: Earth Surface*, Vol. 124, pp. 1596-1624, DOI:10.1029/2018JF004790
- Ashton A., Murray A.B., Arnault O. (2001) Formation of coastline features by large-scale instabilities induced by high-angle waves. *Nature*, Vol. 414, pp. 296-300
- Ashton A.D. & Murray A.B. (2006) High-angle wave instability and emergent shoreline shapes: 1. Modeling of sand waves, flying spits, and capes. *Journal of Geophysical Research: Earth Surface*, Vol. 111, F04011
- Banno M. & Kuriyama Y. (2014) Prediction of future shoreline change with sea-level rise and wave climate change at Hasaki, Japan. *Coastal Engineering Proceedings*, Vol. 34, 56
- BRGM & Cerema (2022) Recommandations pour l'élaboration de la carte locale d'exposition au recul du trait de côte. 96 p., ISBN 978-2-7159-2791-9 et 978-2-37180-566-8
- Bricheno L.M. & Wolf J. (2018) Future Wave Conditions of Europe, in Response to High-End Climate Change Scenarios. *Journal of Geophysical Research: Oceans*, Vol. 123, pp. 8762-8791
- Bruun P. (1962) Sea-level rise as a cause of shore erosion. *Journal of the Waterways and Harbors Division*, Vol. 88, pp. 117-130
- Calkoen F., Luijendijk A., Rivero C. R., Kras E., Baart F. (2021) Traditional vs. Machine-Learning Methods for Forecasting Sandy Shoreline Evolution Using Historic Satellite-Derived Shorelines. *Remote Sensing*, Vol. 13, 934, DOI:10.3390/rs13050934
- Callaghan D.P., Roshanka R., Andrew S. (2009) Quantifying the storm erosion hazard for coastal planning. *Coastal Engineering*, Vol. 56, pp. 90–93, https://doi.org/10.1016/j.coastaleng.2008.10.003
- Callaghan D.P., Ranasinghe R., Roelvink D. (2013) Probabilistic estimation of storm erosion using analytical, semi-empirical, and process-based storm erosion models. *Coastal Engineering*, Vol. 82, pp. 64-75
- Chaigneau A.A., Law-chune S., Melet A., Voldoire A., Reffray G. (2023) Impact of sea level changes on future wave conditions along the coasts of western Europe. *Ocean Science*, Vol. 19, pp. 1123–1143
- Charles E., Idier D., Delecluse P., Déqué M., Le G. (2012) Climate change impact on waves in the Bay of Biscay, France. *Ocean Dynamics,* Vol. 62, pp. 831–848, https://doi.org/10.1007/s10236-012-0534-8
- Clare M.A., Yeo I.A., Bricheno L., Aksenov Y., Brown J., Haigh I.D., Wahl T., Hunt J., Sams C., Chaytor J., Bett B.J., Carter L. (2023) Climate change hotspots and implications for the global subsea telecommunications network. *Earth-Science Reviews*, Vol. 237, 104296, https://doi.org/10.1016/j.earscirev.2022.104296
- Cooper J.A.G. & Pilkey O.H. (2004) Sea-level rise and shoreline retreat: time to abandon the Bruun Rule. *Global and Planetary Change*, Vol. 43, pp. 157–171
- D'Anna M., Idier D., Castelle B., Vitousek S., Le Cozannet G. (2021) Reinterpreting the Bruun Rule in the Context of Equilibrium Shoreline Models. *Journal of Marine Science and Engineering*, Vol. 9, 974, https://doi.org/10.3390/jmse9090974
- Davidson M.A., Splinter K.D., Turner I.L. (2013) A simple equilibrium model for predicting shoreline change. *Coastal Engineering*, 73: 191–202
- Davidson M.A. & Turner I.L. (2009) A behavioral template beach profile model for predicting seasonal to interannual shoreline evolution. *Journal of Geophysical Research Earth Surface*, Vol. 114, F01020
- Dean R.G. (1977) Equilibrium beach profiles: US Atlantic and Gulf Coasts - Ocean Engineering Report N° 12. Department of Civil Engineering, University of Delaware, USA, 51 p.
- de Vriend H.J., Capobianco M., Chesher T., de Swart H.E., Latteux B., Stive M.J.F. (1993) Approaches to long-term modelling of coastal morphology: A review. *Coastal Engineering*, Vol. 21, pp. 225-269
- DNV (2021) DNV-RP-0360 - Subsea power cables in shallow water. 187 p.
- Dodet G., Bertin X., Taborda R. (2010) Wave climate variability in the North-East Atlantic Ocean over the last six decades. *Ocean Modelling*, Vol. 31, pp. 120-131, https://doi.org/10.1016/j.ocemod.2009.10.010
- Frey A.E., Connell K.J., Hanson H., Larson M., Thomas R.C., Munger S., Zundel A.K. (2012) GenCade version 1 model theory and user's guide. US Army Corps of Engineers - Engineer Research and Development Center, USA, 187 p.
- Gomez-de La Pena E., Coco G., Whittaker C., Montano J. (2023) On the use of convolutional deep learning to predict shoreline change. *Earth Surface Dynamics*, Vol. 11, pp. 1145-1160, https://doi.org/10.5194/esurf-11-1145-2023
- Hanson H. & Kraus N.C. (1989) GENESIS: Generalized Model for Simulating Shoreline Change. Report 1. Technical Reference. Department of the Army - Corps of Engineers, Vicksburg, USA, 247 p.
- Hemer M.A., Katzfey J., Trenham C.E. (2013) Global dynamical projections of surface ocean wave climate for a future high greenhouse gas emission scenario. *Ocean Modelling*, Vol. 70, pp. 221-245,

https://doi.org/10.1016/j.ocemod.2012.09.008
- Hoagland S.W.H., Jeffries C.R., Irish J.L., Weiss R., Mandli K., Vitousek S., Johnson C.M., Cialone M.A. (2023) Advances in Morphodynamic Modeling of Coastal Barriers: A Review. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, Vol. 149: 03123001, https://doi.org/10.1061/JWPED5.WWENG-1825
- Hunt E., Davidson M., Steele E.C.C., Amies J.D., Scott T., Russell P. (2023) Shoreline modelling on timescales of days to decades. *Cambridge Prisms: Coastal Futures*, Vol. 1, e16, https://doi.org/10.1017/cft.2023.5
- ICPC (2009) Damage to Submarine Cables Caused by Anchors. *Loss Prevention Bulletin*, 18 March 2008, 4 p.
- IPCC (2023) Climate Change 2023, Synthesis Report, Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 184 p.
- IPCC (2022) Implementation of FAIR principles in the IPCC: the WGI AR6 Atlas repository. *Science Data*, Vol. 9, 629, https://doi.org/10.1038/s41597-022-01739-y
- Kamphuis J.W., Davies M.H., Nairn R.B., Sayao O.J. (1986) Calculation of littoral sand transport rate. *Coastal Engineering*, Vol. 10, pp. 1-21
- Marin F. & Vah M. (2024) Cross-Shore Sediment Transport in the Coastal Zone: A Review. *Water*, Vol. 16, 957, DOI:10.3390/w16070957
- Miller J.K. & Dean R.G. (2004) A simple new shoreline change model. *Coastal Engineering*, Vol. 51, pp. 531–556
- Morim J., Hemer M., Wang X.L., Cartwright N., Trenham C., Semedo A., Young I., Bricheno L., Camus P., Casas-Prat M., Erikson L., Wehner M., Wolf J., Kamranzad B., Webb A., Stopa J., Andutta F. (2019) Multivariate wind-wave climate projections. *Nature Climate Change*, Vol. 9., pp. 711–718, https://doi.org/10.1038/s41558-019-0542-5
- Muis S., Verlaan M., Winsemius H.C., Aerts J.C.J.H. Ward P.J. (2016) A global reanalysis of storm surges and extreme sea levels. *Nature Communications*, Vol. 7, 11969
- Niedoroda A.W., Reed C.W., Swift D.J.P., Arato H. Hoyanagi K. (1995) Modeling shore-normal large-scale coastal evolution. *Marine Geology*, Vol. 126, pp. 181–199
- Nienhuis J.H. & Lorenzo-Trueba J. (2019) Simulating barrier island response to sea level rise with the barrier island and inlet environment (BRIE) model v1.0. *Geoscientific Model Development*, Vol. 12, pp. 4013–4030, https://doi.org/10.5194/gmd-12-4013-2019
- Palalane J. & Larson M. (2019) A Long-Term Coastal Evolution Model with Longshore and Cross-Shore Transport. *Journal of Coastal Research*, Vol. 36, pp. 411–423, https://doi.org/10.2112/JCOASTRES-D-17-00020.1
- Pilkey O.H., Young R.S., Riggs S.R., Smith A.W.S., Wu H., Pilkey W.D. (1993) The Concept of Shoreface Profile of Equilibrium: A Critical Review. *Journal of Coastal Research*, Vol. 9, pp. 255-278
- Poppeschi C., Anindita P., Pimoult M. (2024). State of the Art of Climate Change Impact on Offshore Wind. 2C NOW Deliverable D2.1, 93 p.
- Ranasinghe R. (2016) Assessing climate change impacts on open sandy coasts: A review. *Earth-Science Reviews*, Vol. 160, pp. 320–332
- Reinert M., Pineau-Guillou L., Raillard N., Chapron B. (2021) Seasonal Shift in Storm Surges at Brest Revealed by Extreme Value Analysis. *Journal of Geophysical Research: Oceans*. Vol. 126, pp. 1-12, https://doi.org/10.1029/2021JC017794
- Repsol & EDP Renewables (2018) Inch Cap offshore wind farm - New energy for Scotland - Offshore environmental statement - Volume 2A - Appendix 6B - Landfall Feasibility Study, 24 p.
- Robinet A., Idier D., Castelle B., Marieu V. (2018) LX-Shore : Un nouveau modèle d'évolution du trait de côte pour les littoraux sableux dominés par l'action des vagues. *Actes des XVèmes Journées Nationales Génie Côtier - Génie Civil*, pp. 273–282, DOI:10.5150/jngcgc.2018.031
- Roelvink D., Reniers A., van Dongeren A., van Thiel de Vries J., McCall R., Lescinski J. (2009) Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, Vol. 56, pp. 1133–1152
- Roelvink J.A. & Banning G.K.F.M.V. (1995) Design and development of DELFT3D and application to coastal morphodynamics. *Oceanographic Literature Review*, Vol. 11, 925
- RTE (2016) Résumé non technique de l'étude d'impact de la partie anglaise du projet IFA2, 42 p.
- Thieler E.R., Pilkey O.H. Jr., Young R.S., Bush D.M., Chai F. (2000) The Use of Mathematical Models to Predict Beach Behavior for U.S. Coastal Engineering: A Critical Review. *Journal of Coastal Research*, Vol. 16, pp. 48–70
- Turki I., Medina R., Gonzalez M., Coco G. (2013) Natural variability of shoreline position: Observations at three pocket beaches. *Marine Geology*, Vol. 338, pp. 76-89
- US Army Corps of Engineers (1984) Shore Protection Manual. Coastal Engineer Research Center, Vicksburg, USA, 652 p.
- Vitousek S., Barnard P.L., Limber P. (2017) Can beaches survive climate change? *Journal of Geophysical Research: Earth Surface*, Vol. 122, pp. 1060-1067
- Vitousek S., Barnard P.L., Limber P., Erikson L., Cole B. (2017) A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate climat change: CoSMoS-COAST. *Journal of Geophysical Research: Earth Surface*, Vol. 122, pp. 782–806
- Vousdoukas M.I., Mentaschi L., Voukouvalas E., Verlaan M., Feyen L. (2017) Extreme sea levels on the rise along Europe's coasts. *Earth's Future*, Vol. 5, pp. 304–323
- Vousdoukas M.I., Ranasinghe R., Mentaschi L., Plomaritis T.A., Athanasiou P., Luijendijk A., Feyen L. (2020) Sandy coastlines under threat of erosion. *Nature Climate Change*, Vol. 10, pp. 260–263

- Wang X.L., Feng Y., Swail V.R. (2012) North Atlantic wave height trends as reconstructed from the 20th century reanalysis. *Geophysical Research Letters*, Vol 39, L18705, https://doi.org/10.1029/2012GL053381
- Warren I.R. & Bach H.K. (1992) MIKE 21: a modelling system for estuaries, coastal waters and seas. *Environmental Software*, Vol. 7, pp.229–240
- Yates M.L. (2009) Seaonsal Sand Level Changes on Southern California Beaches: Observations and Modeling, PhD thesis, University of California, San Diego, https://escholarship.org/uc/item/09717515
- Yates M.L., Guza R.T., O'Reilly W.C. (2009) Equilibrium shoreline response: Observations and modeling. *Journal of Geophysical Research: Oceans*, Vol. 114, C09014
- Yates M.L., Le Dantec N., Chataigner T. (2022) Reduced-Complexity Modeling of Cross-shore and Longshore Beach Evolution, International Conference on Coastal Engineering, Sydney, Australia