Three simple indicators of vulnerability to climate change on a Mediterranean beach: A modeling approach

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A R T I C L E   I N F O

Article history:
Received 8 November 2012
Accepted 30 October 2013
Available online 12 December 2013

Keywords:
Coastal morphology evolution
Numerical simulation
Climate change
Indicator of vulnerability

A B S T R A C T

This study assesses three different approaches for evaluating coastal vulnerability using indicators. We began by establishing a procedure for binding three codes to simulate realistic or idealized climates. The procedure was validated in terms of hydrodynamics and beach morpho-dynamics. We then defined and studied the vulnerability of the coast on the basis of in situ observations and model results taken from a set of simulations based on different scenarios. We present three simple indicator methods developed to analyze the vulnerability of a sandy beach based on the results of simulations for different wave climate scenarios. The first method is based on the wave energy, and specifically how it differs as a function of climate change scenario. The second method consists of estimating the maximum grain size mobilized. Note that the calculation of stress at the sea bottom is routinely estimated solely on the basis of simulated velocity post-wave. Here, we calculate the maximum grain size potentially mobilized with a simpler approach, based on analysis in different points along the cross-shore profile. The third method presented is the analysis of the time-course evolution of cross-shore sea bed profiles in response to different climate change scenarios.

1. Introduction

Hydrodynamic and morphodynamic processes in coastal environments are recognized as important not only from a scientific point of view, but also for many aspects of human activities, including design of coastal protection structures or environmental risk assessments (Dally et al., 1984; Larson and Kraus, 1989; Nairn and Southgate, 1993; Bradford, 2000; Damgaard et al., 2002). Numerical modeling can run repeatable simulations that are extremely useful for testing the influence of morphogenic parameters, making it possible to predict the future evolution of coastal systems, notably in response to global climate change. To study these environmental problems numerically, the various approaches developed are based on beach models, including beach state models, profile evolution models, and beach evolution models.

There are two kinds of beach state models: (1) equilibrium models, which predict the shape of near-shore features (e.g. bars and troughs), under constant incident wave conditions...
Most profile evolution models consist of three parts: hydrodynamic modeling, sediment transport modeling and profile response modeling. In hydrodynamic modeling, the primary concern is wave properties, particularly in the surf zone. In general, it is safe to state that the wave transformation model together with the associated mean water level change governs the behavior of the beach evolution model, since wave transformation and around the surf zone is sensitive to sea bottom topography. Profile response modeling virtually always uses the mass conservation equation for bed material. Beach evolution models are classified into three models, the coastline model (long-term), the coastal area model (medium-term) and the beach profile model (short-term) (De Vriend et al., 1993).

Deeper insight into coastal processes hinges on developing an “in-situ” database and on developed and improved mathematical models and numerical codes. Recent advances in the numerical modeling of physical processes and field survey technologies now make it possible to develop numerical models with extensive data sets.

The work of De Vriend (1987) and De Vriend and Stive (1987) shows the important extensions of the so-called medium-term scale models (as used in this paper) compared to profile models. These extensions are specifically required due to the alongshore non-uniformity gradients in the alongshore flow field, which create sediment transport divergences and convergences. This approach for charting beach morphodynamics was recently used by Reniers et al., 2004; Roelvink, 2006; Smit et al., 2008. Two important limitations to this kind of numerical approach are the off shore boundary conditions and the choice of sediment transport formula. Thus, improving this simulation model hinges on a better understanding of the representation of weather in the input conditions, of the error in the velocity field simulated, and of beach profile evolution.

The impact of climate change on ecosystems and on coastline evolutions is becoming increasingly obvious (Watson et al., 1997). Rising sea level and increasing storm frequency and intensity are all parameters that modify the evolution of today’s coastline. These changes associated with the decrease in available sediment stock are not indicators of the stability of the coasts that are already largely in erosion. Thus, in order to anticipate these changes, it is essential to model them so as to provide answers to coastline managers.

Here, we report a modeling approach employed to analyze the sensitivity of a microtidal barred beach (Sète, southern French Mediterranean) to forcing condition changes and the abilities of numerical models to predict near-shore evolution and build indicators of vulnerability (e.g. maximum grain size mobilized) of sandy beaches according to predicted climate change scenarios for 2030. However, it should be noted there is even more uncertainty over future wave conditions than over predicted rise in sea level rise due to climate change (IPCC, 2007; Rahmstorf, 2007). Storm surges also play a significant role in the dynamics of coastal areas.

The objective of testing the feasibility of a single indicator may be common to several types of sandy beaches. This work is part of a program analyzing and studying climate change at four sites along the French coast. This paper focuses on a particular site to provide a basis for comparison against measured data and analyze the pertinence of these three approaches for assessing indicator power simply and with a minimum of input parameters. Our method applies the same rule to calculate the indicators used for all sites in our Mediterranean sample. We can thus conclude on the feasibility of studying vulnerability to climate change at one site based on knowledge from this triple approach already used over all 4 sites (Larroudé and Brivois, 2012).

The objective of this work is therefore to model and simulate sediment transport processes on sandy beaches under varied weather conditions in the medium-term time-scale (days to months). Coastal morphology evolution cannot be represented with average climatic conditions but needs to simulate extreme events such as storms, and so in a long term approach, morphological evolution is the result of the combination of storm events and calm periods. Most such studies analyze field-measured data and compare it to outputs from numerical models.

The aims of this paper are: [1] to set up a procedure linking three codes (wave, flow field and bed evolution models, Telemac) to able to simulate realistic climates (e.g. the full duration of a storm event). This procedure has been validated in terms of the hydrodynamics and beach morpho-dynamics (Larroudé, 2008); [2] to use this procedure to compare and study the contribution of the various sediment transport formulae (Camenen and Larroudé, 2003) during the Rising-Apex-Waning of a two specific high wave events (Robin et al., 2010); [3] to propose a simple indicator method built on these results for analyzing the vulnerability of a sandy beach.

Section 2 gives short presentation of the ANR Vulsaco project. Section 3 introduced the field site and in-situ data. Section 4 explains the applied model set-up and equations. Section 5 reports the comparison between the in-situ data and the numerical results, and goes on to discuss the possibilities and limitations of three simple methods to extract an indicator of vulnerability from 2DH numerical simulations: one based on wave energy, one based on maximum grain size potentially mobilized and one based on the temporal evolution of cross-shore sea bed profiles.

2. Description of the Vulsaco program on sandy coast vulnerability

A third of the French coastline is composed of sandy beaches. Under this national research program, we are investigating the influence of climate change on four different beaches in France. These study areas are representative of the linear sandy beaches of the coastal region, and are also representative of forcing and various other important factors.

The 4 sites studied (see Fig. 1) were chosen to give complementary hydrodynamic settings (covering a number of hydrodynamic and wave conditions found on French mainland coast). The VULSACO project (VULnerability of SAndy COast to climate change and anthropic pressure), studies present and potential future erosion. The main objective is to assess indicators of vulnerability to climate change between 2010 and 2030 for sandy beaches with or without anthropic pressure. The project is based on the study of four coastal units located in different places representative of various environments: Mediterranean Sea, Atlantic coast and North Sea coast. The methodology for studying the all the sites is the same. The physical presentation of the sites is described in Vinchon et al. (2008).

This paper focuses on Sète beach (on the Mediterranean coast), specifically on hydrodynamic and morphodynamic modeling and how the simulations can help analyze the influence of climate change.

We focus on a set of scenarios chosen to represent current climate but also to investigate the sensitivity of beach evolution to climate variability. The present-day scenarios are based on off-shore wave analysis and completed by expert knowledge on each site and other observations (Le Cozannet et al., 2009). These scenarios use two idealized initial bathymetries to represent the

(Greenwood and Davidson-Arnott, 1979; Short, 1975; Bowen, 1980; Holman and Bowen, 1982); (2) sequential morphologic state models, which predict the sequence of bar-trough shapes and scales under varying incident wave conditions (Wright and Short, 1984; Wright et al., 1985; Lippmann and Holman, 1990).
calf and stormy weather (see Fig. 2j). The variability scenarios are based on small variations in wave and storm surge characteristics (Table 1) through 230 scenarios. A global set of about 500 cases has been simulated with the different models, including tests with and without a geotextile on the offshore bar (tests with geotextile are not presented in this paper). The results were analyzed to extract the present-day limits of the models and gauge the sensitivity of morphological change to climate change, sea-level (tide and storm surge), wave direction and initial bathymetry (Idier et al., 2010b). Each model yields vast amount of spatio-temporal data. A tool code has been developed to extract variables for analyzing all simulations across every study area (Castelle et al., 2006; Idier et al., 2007, 2011, 2013; Maspataud et al., 2010; Cartier et al., 2012).

3. Field sites and measurement methodology

The studied area is located in the vicinity of Sète, on the Mediterranean coast (Gulf of Lion, France; Fig. 1). A majority of waves in the region have a mean significant height (Hs) of under 2 m, with 30% of values < 1 m, predominantly in summer. The directions are 140°–220° N (Fig. 1) associated with sea breeze. Only 2% of waves have Hs more than 4 m high, associated with SE-to-E wave directions, with periods from 5 to 10 s. These storms typically last only 24 h. Tidal range does not exceed 0.30 m (Akouango, 1997; S.H.O.M., 2003). Nevertheless, higher water level variations are observed in response to set-up and set-down under the influence of wind and atmospheric pressure fluctuations. In extreme cases, set-ups can reach 0.50 m at 450 m from the shore during storms (Akouango, 1997) and 1 m near the shore (Certain, 2002) under the added action of breaking waves. The studied area is 500 m wide and extends 1000 m seawards (Fig. 2a) to 10 m depth. Several lines of field evidence and a simple calculation show this depth to be around the depth of closure (Durand, 1999), i.e. the limit of topographic changes due to wave-induced sediment transport.

The backshore consists of an erosive dune. The beach is narrow (20–50 m) and subject to erosion. The rate of shore retreat is 1 m y⁻¹. The sand volume lost in the last ten years is approximately 3400 m³ (Certain, 2002). The nearshore has a 1% slope and is composed of a system of double bars and troughs (Fig. 2a). The inner system (inner trough and inner bar), between the shore and outer trough is 50–150 m wide but at times disappears as the inner bar merge into the beach. The inner bar crest is about 1.5–2 m deep, whereas the inner trough is 0.5 m deeper. The outer system (outer trough and outer bar) is positioned between the inner bar and the lower shoreface, and is generally 250–300 m in width. The outer trough is about 5 m deep, while the top of the outer bar is 4 m deep. Beyond the outer bar, the lower shoreface has a gentle 0.85% slope. Bars are linear, and the wave-dominated beach is classified as intermediate-barred to dissipative-barred (Ω value around 6) according to the conceptual beach model of Masselink and Short (1993); also see Short and Aagaard (1993), Gourlay (1968). Sediment grain size decreases from 320 μm onshore to 130 μm offshore with coarser sand in the troughs and finer sand over the crests (Certain, 2002; Certain and Barusseau, 2006). Akouango (1997) described a variable grain size distribution depending on wave climate. The beach is characterized by fine sand during the fair-weather conditions of summer, but following a short autumnal period of transition the beach becomes coarser grained under the more dynamic winter conditions. The finer sediment is transported offshore where conditions are less agitated (Barusseau et al., 1994). As a result, sandstone can be seen in the outer trough and on the lower shoreface. The sandstone is old and is the basis of sediment available on site.

Hydrodynamic measurements were made with a cross-shore transect. Different instruments were deployed from 15 December 2008 to 25 February 2009, cumulating at 73 observation days. The material used is 3 Nortek ADV (Acoustic Doppler Velocimeter with pressure sensor), 2 RDI 600 kHz bottom-mounted ADCP (Acoustic Doppler Current Profiler with pressure sensor) and an electromagnetic current meter and pressure sensor (S4DW Interocean). For a good estimate of velocity profile in the whole water depth, two non-magnetic structures fitted with an ADV (near the bed) and an ADCP were installed. The cross-shore instruments transect covers 4 locations at, approximately 65 m, 95 m, 185 m and 600 m from the beach corresponding to water depths of 3.15 m, 3.45 m, 2.75 m and 4 m (2 positions during the field work) and 6.65 m, respectively. The different instrument locations were chosen relative to the sand bar system (Fig. 2a). Starting from the beach, the first two stations G1 (ADV) and G3 (ADV+ADCP) are located in the inner trough, the 3rd station (G2 (ADV+ADCP) is on the bar lower shoreface and the 4th (S4DW) is off-shore over the external bar. ADV data were collected at a 2-Hz frequency with a burst duration of 20 min every 2 h for current and 20 min every 3 h for wave parameter. ADCP data were collected at a 2 Hz frequency with a burst duration of 1 min every 3 min for current parameter.
and 20 min every 3 h for wave parameter. The wave characteristics were processed by standard spectral analysis using fast Fourier transforms. The Fourier coefficients of the free surface elevation fluctuations were obtained from the corresponding ones computed from the pressure time-series, using the frequency-dependent transfer function inferred from linear wave theory.

Fig. 2. (a) Cross shore profile of Sète beach with the location of the four pieces of equipment for the in-situ data collection: G1 (Nortek ADV), G2 (Nortek ADV and RDI ADCP), G3 (Nortek ADV and RDI ADCP) and S4 (Interocean S4 current meter), (b–e) show the vertical velocity profile or value at a given depth measured in February 2009 at the apex of the storm. The solid line represents the numerical value (integrated in the vertical: 2DH model) and also shows the position of points used for calculations of maximum grain sizes (see Table 3). (f) Time series of significant wave height, $H_s$ (m), during the survey month. (g–i) Represent the vertical velocity profile at three dates in February 2009 at position G2. Finally (j) shows idealized bathymetry used for scenario of climate change on the site of Sète (©ANR Vulcaco programme).
Velocity measurements from ADV and ADCP tended to become noisy in highly-turbulent flows. Signal correlation values recorded by this instrument were used to identify such potentially spurious data. When signal correlation for a given acoustic beam was less than 80%, the data were discarded. Long-shore and cross-shore currents were defined with reference to the coastline and crest bars.

4. Model and simulation methodology

Sediment evolution was modeled under the action of the oblique incident waves and coupled with different numerical tools dedicated to the other processes involved in the near-shore zone. A chain of three codes was built. The initial data needed is the bathymetry, and with the wave conditions as an input, the first code gives wave propagation and radiation stress. These forces are the input with sea level in the second code which simulates the current. Finally, the third code uses the currents with some sediment data (such as sand grain diameter) to calculate the morpho-evolution of the sea bed (see Fig. 3b).

The wave description was done by means of a hyperbolic rewrite of the elliptic extended mild-slope equation (see e.g. Lee et al., 1998). The wave module takes into account surge energy dissipation (EDF-LNHE, 2009). The Artemis code (Agitation and Refraction with Telemac2d on a Mild Slope) solves the Berkhoff equation taken from vertically averaged Navier–Stokes equations (EDF-LNHE, 2010a).

\[ \nabla . v = q \]

where \( C = \omega / k \) is phase velocity and \( C_g = 1/2[1+2kh/sh(2kh)]\) is group velocity.

Table 1

Retained wave classes for the modelisation of the actual climate and the variation for the future climate use to build all the scenario for all the simulation.

<table>
<thead>
<tr>
<th>Wave class</th>
<th>Hs (m)</th>
<th>Hrms (m)</th>
<th>Tp (s)</th>
<th>Incidence (deg)</th>
<th>Duration (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8</td>
<td>0.57</td>
<td>8</td>
<td>-12</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>1.2</td>
<td>0.85</td>
<td>6</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>1.8</td>
<td>1.27</td>
<td>6</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Future climate</td>
<td>± 10%</td>
<td>± 10%</td>
<td>± 10%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To take into account energy dissipation due to breaking and the stress at the sea bottom we use a supplementary term

\[ \text{div}(Cg \text{grad} \phi) + \omega^2 \frac{C_g}{C} k \text{grad} \phi = 0 \]

with \( \mu = W/(C_g)1/2 \) as dissipation coefficient where \( W \) is the dissipation function.

The main results are, for every node of the mesh, the height, phase and incidence of the waves. Artemis can take into account the reflection and refraction of waves on an obstacle, bottom friction, and the breakers. One of the issues with Artemis is that a fine mesh has to be used to get good results whereas Telemac2d does not need such a fine mesh.

The hydrodynamic module calculates wave-induced currents, based on the concept of radiation constraints obtained via the wave module. Telemac2d is designed to simulate the free surface flow of water in coastal areas or in rivers. This code solves Barré Saint–Venant equations taken from vertically averaged Navier–Stokes equations (EDF-LNHE, 2010a).

\[ \frac{\partial h}{\partial t} + \vec{U} \cdot \nabla h \frac{\partial h}{\partial t} = q \]

\[ \frac{\partial \vec{u}}{\partial t} + \vec{U} \cdot \nabla \vec{u} = -\frac{\partial \vec{Z}_b}{\partial t} \nabla h + \frac{1}{h} \text{div}(h \vec{u} \cdot \nabla \vec{u}) + S_x \]

\[ \frac{\partial \vec{v}}{\partial t} + \vec{U} \cdot \nabla \vec{v} = -\frac{\partial \vec{Z}_b}{\partial t} \nabla h + \frac{1}{h} \text{div}(h \vec{v} \cdot \nabla \vec{v}) + S_y \]

where \( h \) (m) is sea level, \( U \) is the velocity vector, \( u, v \) (m/s) are velocity component, \( g \) (m/s²) is gravity, \( \nu \) (m/s²) is momentum diffusion coefficient; \( Z_b \) (m) is sea bed level, \( q \) (m/s) is source (only use in the case of an intake or outflow on the bottom, or if we consider sub-soil seepage, so not use in this study); \( S_x, S_y \) (m/s²) are source term.

We will now cover in detail the terms called \( S_x, S_y \) so far, i.e., volume forces other than pressure and weight. Some of these forces, such as the influence of wind, are negligible in dimension three but appear in the Saint–Venant equations as source terms applied to the entire water mass. This is because the equations represent a vertical average. We also cover bottom friction, Coriolis force, influence of wind, atmospheric pressure, and sources of momentum.

\( S_x, S_y \) are source terms representing wind, Coriolis force, bottom friction, a source or a sink of momentum within the domain. The different terms of these equations are processed in one or more steps (in the case of advection by the method of characteristics): the advection of \( h, u, v \) and \( T \), the propagation, diffusion and source terms of the dynamic equations, the diffusion and

![Fig. 3](image-url). Technical drawing (a) classic dimension for cross-shore and long-shore distance. (b) Loop on a weather time-step used in our simulations with the chain of the three codes (Artemis–Telemac–Sisyph: ATS), with input and output data for each code.
source terms of the tracer transport equation. Any of these steps can be skipped, in which case different equations are solved. In addition, each of the variables $h$, $u$, $v$ and $T$ can be advected separately. This makes it possible for example to solve a tracer advection and diffusion equation using a fixed advecting velocity field. Turbulent viscosity may be user-defined or determined by a model simulating the transport of turbulent quantities $k$ (turbulent kinetic energy) and $\varepsilon$ (turbulent dissipation).

The $S_h$ and $S_v$ terms include a lot of parameters from different terms. In our simulation, we do not take into account Coriolis force and wind. The main source terms in our simulations are radiation stress from the wave module, shear stress at the bottom and turbulence diffusion.

Thus the main results are, for every node of the mesh, the water depth and the velocity averaged over the depth. Telemac2d is able to represent the following physical phenomena: propagation of long periodic waves, including non-linear effects, wetting and drying of the intertidal zone, bed friction, turbulence, and more (Hervouet, 2007).

The sediment module integrating the combined actions of waves and currents (2D or 3D) on sediment transport, Sisyphe code (EDF-LNHE, 2010b), solves the bottom evolution equation which expresses the conservation of matter by directly using a current field result file given by Telemac2d.

\[
\frac{\partial z_b}{\partial t} + \text{div} \vec{Q}_s = 0
\]  

$\vec{Q}_s$ is sediment discharge per unit width (m³/s) (porosity is taken into account). Several of the most currently empirical or semi-empirical formulae are already integrated in Sisyphe. The main results are, for every node of the mesh, bottom evolution and solid transport. The equations of the three modules are detailed in Hervouet (2007).

We set up a procedure to use the Artemis–Telemac2d–Sisyph coupled codes (Larroudé and Camenen, 2004; Larroudé, 2008) (Fig. 3b), and more particularly we improved the treatment of the boundary conditions in order to be able to work on fields of calculation close to the coastal zone and equivalents in dimension for the three codes (Fig. 3a). The wave module grid is equal to the lateral and seaward boundaries of the grid. The higher boundaries of the flow model are defined as real water levels. For the simulation of sea bed evolution with a selected sediment transport formula, the code loop is updated at every time-step of the survey (Robin et al., 2010).

This sandy beach morphodynamics modeling methodology is already validated in terms of mesh, time-step and convergence in Falques et al. (2008) and Larroudé (2008). In the present study, the numerical domain is 800 m in the cross-shore direction and 1500 m in the long-shore. Spatial step, the time-step and boundary conditions are reported in Table 2. We used the Bijkers sand morphodynamics formulae for this study. In terms of CPU time, a step of 3 h of real weather (simulated with the chaining of the 3-code Artemis–Telemac2d–Sisyph: ATS) procedure is equal to 460 s CPU time on a 2.66 GHz PC with 2 Go RAM.

## 5. Results and discussions

The simulation results are analyzed against the measured in-situ data. The objective is to look at the difference at each step of the code chain of the simulation methodology. The pertinence of the wave simulation is examined by comparing the significant wave height at different points of the main cross-shore profile of the survey area. We will attempt to give the first simple indicator of vulnerability extracted from the wave simulation by using wave energy.

In the second step, the current field simulation is also compared with the measured in-situ data and a second simple indicator is extracted using the velocity field to obtain the maximum size of sediment grain that can be set in motion. Finally, we look at whether sea bed evolution based on these vulnerability simulations is a potential indicator, especially after using different sediment transport formulae.

### 5.1. The wave simulation

In the code, the boundary conditions are given by the weather forcing (February 2009 period). Fig. 3f shows the significant wave height ($H_s$) during this period of the survey. This $H_s$ with the period ($T_p$) and the wave incidence are the input offshore data at each weather step of our simulation. Fig. 4 shows the comparison between the in-situ data and the simulations. Note that at the entrance of the bar system (S4 measurement) the results are very realistic throughout the month of simulation (Fig. 4b). This is not surprising, as the offshore inputs of our model are the S4 data. This means the model well propagates the wave from the offshore boundary limit to the measurement point. For the comparison at the outer trough (G2, Fig. 2a) (Fig. 4a), the propagation over the outer and inner bar is good except during a few hours at the apex of the storm. At this place, the wave model overestimated the wave height value. The wave simulation results fit with the data over the whole month except for 2 days at the apex of the storm, and so they can be used later in the discussion of wave height as a parameter to calculate the simple indicator of vulnerability based on wave energy.

### 5.2. The current simulation

Fig. 2(b–e) compares the measured against numerically-predicted velocity. Since we use a vertical integrated model, only one value is obtained for the entire vertical profile of the water column. Values from two measurement stations (G3 Fig. 2c and G2 Fig. 2d) provide a basis for comparing the numerical value against a complete vertical ADCP profile measurement (Robin et al., 2010). The aim is to obtain a good prediction of the deep velocity value (close to the sea bed) to use as input in the third code (Sisyphe: sea bed evolution). This validation is doubly important since the velocity value will also be used in the calculation of maximum grain size mobilized. This last parameter will be the second indicator tested in this study.

Fig. 2 shows that numerical values were visibly on the same all-round scale as the data in three places along the cross-shore profile. Comparisons were done at the apex of the storm and, as explained below, it is difficult to get a good numerical approximation of velocity at this moment of the storm. However, we only have this vertical velocity profile at the apex. We can estimate that

## Table 2

<table>
<thead>
<tr>
<th>Code</th>
<th>BC type (see Fig. 4a)</th>
<th>Space step (m)</th>
<th>Time step (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artemis (waves)</td>
<td>1 and 2 or 2 and 3 incident waves</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td>Telemac2d (current)</td>
<td>1, 2 and 3 Sea level</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Sisyph (morpho)</td>
<td>1 and 3 Sand flux if necessary</td>
<td>10</td>
<td>60</td>
</tr>
</tbody>
</table>
our integrated velocity is close to the measured value near the sea bed, except in G2 (Fig. 2a). Moreover, the estimation of the indicator will remain unaffected since the mean velocity values used were taken in three other positions in the cross-shore profile (Fig. 2a).

To complete this code comparison and calibration phase, we ran numerous simulations while varying individual parameters or data such as domain size, the space size step of the mesh, and convergence criterion, among others. From all these tests, we extracted the best simulation in terms of comparison against wave and velocity data for the whole month of February 2009. Fig. 5 compares the vertical velocity profile and our integrated velocity at several time-points at position G2 (Fig. 2). We observe that correlations with the in-situ data were better at the beginning of the simulation with calm weather and even at the two measurements before the apex of the storm. Fig. 5 charts the numerical results and in-situ data over the entire simulation month and at all four measurement points. Most of the simulations struggled to capture the exact value during the apex of the storm, except at point G2 on the offshore face of the inner bar. On the other hand, most of these simulations were good during the rising and waning of the storm. Note, however that for the simple indicator parameter analysis, the climate change simulation on idealized bathymetry will use a constant wave condition for the duration of the scenario (see Table 1). We thus conclude that the methodology proposed here for obtaining the velocity is good for use in the simple indicator parameter based on current field results.

5.3. The morphology simulation

Beach morphodynamics were compared against the data only in the cross-shore bathymetry profile at the beginning and the end of the storm survey. The sediment transport formulae used are not described here but are cited in reference in the title of each figure. Fig. 6 shows that there is no significant evolution in cross-shore bathymetry profile and that all the sediment transport formulae used converge to virtually identical results except the Bijker and Soulsby–Van Rijn formulae which overestimated morphological sea bed evolution. To achieve an accurate comparison and choose the most appropriate formulae to use on this site would require measured sediment fluxes as in Cartier et al. (2012). Finally, the third criterion has to be improved on the beach studied as sea bed evolution was more significant in the data and in the climate change simulation on the idealized bathymetry. Sea bed evolution also appears to be a significant indicator on some other Vulsaco program sites (Larroudé and Brivois, 2012).

5.4. Vulnerability indicator taken from the numerical solution

This section looks at three approaches to gauging the potential vulnerability of beaches by analyzing the results of simulations of different scenarios.

Table 3 charts the four scenarios: the base scenario for each site is the scenario constructed from current data, the second scenario involves a 120% increase in storm surge, the third scenario changes the height of significant waves with a 10% increase from scenario case 2 (Hs+10% and Ss +120%), and the fourth scenario (case 4) changes the direction of incident waves.

In the ANR Vulsaco program, the general vulnerability indicator based on Coelho et al. (2006) gives the following value for Sète beach: W1 = 3.3, W2 = 4.0 and W3 = 3.7, normalized on a 1–5 scale where 1 signals low vulnerability and 5 flags high vulnerability. These indicator values suggest that Sète beach is vulnerable to climate change. The next step is to check whether the approach proposed here shows the same tendency.

The first approach is to look at wave energy along the cross-shore profile. To calculate this energy we use the result of Eq. (2) from the wave module (Artemis) and the equation $E = 1/8 \rho g H^3$.
where $H$ is wave height, $g$ the gravity and $\rho$ the density of the water. Fig. 7 shows the cross-shore profile of this energy for the four climate change scenario cases presented here. The highest energies are obtained for case 1 (the actual climate) and case 3. The lowest wave energy came from the case 2, which seems normal since in this case-scenario we just increase sea level by the increasing storm surge. However, the most problematic case in terms of beach vulnerability prediction is probably case 4, where we obtained high energy very close to the beach. This shows the influence of the incidence of offshore waves in the propagation of the highest energy closer to the beach.

The second approach is based on the method described in Idier et al. (2006, 2010a). We start out by looking at the maximum grain size mobilized using a simpler approach. Indeed, the calculation of bottom stress will be estimated solely from the simulated velocity driven by waves on the study site. Table 3 shows the results for maximum grain size mobilized according to the inverse method. We calculate maximum grain size mobilized within a few points along the cross-shore profile (see Fig. 2).

This criterion needs to be confirmed by analysis of all the simulations, but it does not appear wholly relevant to beach vulnerability. What beach vulnerability criteria can we extract from these results? If the maximum diameter mobilized decreases, it means a greater amount of sand along the profile will get removed, in which case we can imagine that the risk of beach erosion increases, especially if the point used is close to the beach. This configuration was not found on Sète beach (only Dunkirk beach presents this configuration; see Larroudé and Brivois (2012)).

The third approach investigated is to analyze the temporal evolution of sea-bed cross-shore profiles over the site under the same scenarios as presented above. Fig. 8 shows that the sea bed evolution on the cross-shore profile can provide complementary information to a vulnerability study using conventional indicators. The figure illustrates the entire cross-shore profile (Fig. 8a) with no difference between the four simulation cases but if we zoom in (Fig. 8b) close to the beach, the results show that cases 1 and 4 lead to the greatest erosion of the beach profile. Indeed, the increase in storm surge and, the change in direction of incident waves or the increase in significant height of waves have visibly little influence on morphodynamic evolution. It also appeared that sea bed evolution was relatively non-dependent on sediment transport formulae used on this study site.

### 6. Conclusions

This paper presents three simple indicators of beach vulnerability to climate change. We show how the method of simulation with Telemac codes is adapted to reproduce waves, mean velocity and sea bed evolution during a storm. We link this study to the ANR Vulsaco program by comparing the classical indicator of vulnerability to the indicator derived from our numerical simulations. Our approach shows some limits, especially with the some indicator criterion. This study will be complemented by a systematic analysis of all simulations performed within the Vulsaco program framework on all types of beach and all types of climate change scenario. We also show that as the waves are well-simulated, the simple indicator of vulnerability derived here could be a good parameter for beach erosion or not. However, we still have to improve numerically-predicted velocity close to the
Table 3

Results of the maximum diameter mobilized (mm) with the inverse method of Sète site.

<table>
<thead>
<tr>
<th>Site 1: Sète</th>
<th>Base scenario</th>
<th>Storm surge (Ss + 120%)</th>
<th>Hs + 10%</th>
<th>Incidence (10^-12)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point 1.1</td>
<td>5.83</td>
<td>5.84</td>
<td>5.90</td>
<td>5.80</td>
</tr>
<tr>
<td>Point 1.2</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
<td>5.80</td>
</tr>
<tr>
<td>Point 1.3</td>
<td>5.81</td>
<td>5.81</td>
<td>5.80</td>
<td>5.80</td>
</tr>
</tbody>
</table>

Case 1  Case 2  Case 3  Case 4
sea bed and the estimation of sediment flux before drawing solid conclusions on the last two simple indicators. In terms of further perspectives, more data is required in order to refine the calibration of the morpho-evolution of sandy beaches.

Acknowledgments

This work was supported by the French Research National Agency (ANR) through the Vulnerability Milieu and Climate program (VULSACO project, No. ANR-06-VMC-009) and RELIEF-MICROLIT. The authors benefited from highly constructive discussions with D. Idier, (BRGM, Orléans, France). We thank a lot ATT technical and scientific translation company for the English corrections.

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