Hydrodynamics and morphodynamic evolution of the nearshore zone using the coupling of SWAN, MARS and a sedimentary transport module

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Introduction

Nearshore areas are socio-economic and touristic areas of high concern. Presently, they exhibit a general erosion trend which should be reinforced by climatic changes. This is especially pronounced for the unconsolidated areas. This is thus worthwhile to quantify as well as possible the morphologic evolution of these areas.
These last years, research on hydro-sedimentary dynamics experienced significant progresses. More precisely, morphodynamics models have been developed and allow simulating the feedbacks between the seabed and the wave, and thus the morphodynamics of sandy seabed for more or less idealised cases [1] [1].
BGRM, UMR EPOC and IFREMER have initiated collaboration in order to go further and developed a modelling platform more adapted to natural environment (complex bathymetry, meteorological effects, tidal phenomena, high spatial resolution). This tool is based on the coupling of the SWAN and MARS models, as well as a sedimentary module (figure 1).

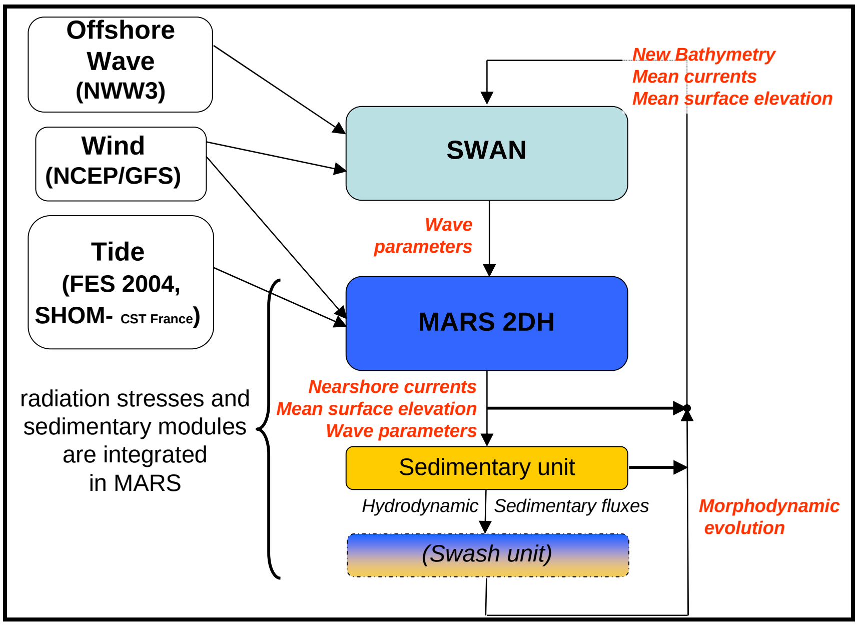

Figure 1 Modelling platform of the nearshore processes

The present paper describe the forcing data, the coupling between the various models, as well as first application exemples.

Forcing data

The used offshore wave data come from the global model set up with the code WaveWatch III (NWW3) operated by the NOAA [1]. A first validation with a limited measurement data set at 50 m of water depth exhibit a good behaviour of the NWW3 results (correlation coefficient $R^2 \sim 0.86$). The validation on a longer time series (figure 2) at the Gascogne buoy location confirm this good correlation (Scatter Index SI of 0.149 and $R^2 \sim 0.93$). One of the explanations of this performance is that the used NWW3 data (hindcast) include buoy measurement assimilation.

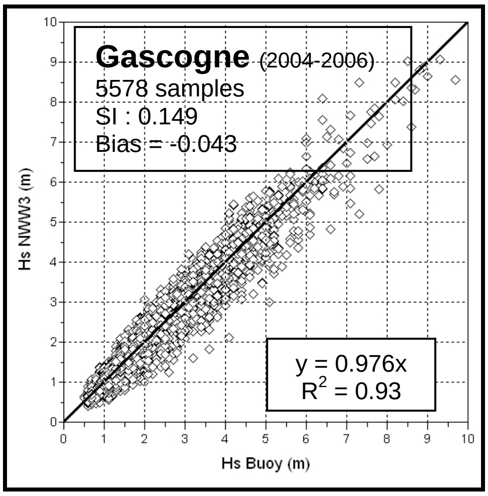

Figure 2 Comparison of the signigicant wave height Hs coming from NWW3 and measurements at the Gascogne biuoy location (45°N, 5.2°W). Data : November 2003 to September 2006.

Wind data come from the Global Forecasting System. It can be noticed that this is these data which are used to force (generate wave) the NWW3 wave model.
The tidal harmonic components come from the data base of FES 2004 (global cover) [1] and of the SHOM (Cst France) [1].

Description of the models and couplings

The wave model

The wave model use is SWAN (Simulating Waves Nearshore), a third generation model which resolved the spectral action balance equation. It is especially designed for coastal environnements. This model is used to compute the main wave caracteristics (significant wave height, mean wave direction, mean absolute wave period, fraction of breaking waves, …). These characteristics are then used to estimate the radiation radiation stresses, using the following formulation which comes from the linear wave theory [1]:

$$S_{ij} = \frac{E}{2}\left(\frac{k_i k_j}{k^2}\frac{2c_g}{c} + \delta_{ij}\left(\frac{2c_g}{c} - 1\right)\right) \qquad (1)$$

where E is the wave energy, c the wave velocity, cg the group velocity and k the wave number.

The depth averaged current model

The MARS model (Model for Applications at Regional Scale), developed by IFREMER, solves the Navier-Stokes equations in two (depth-integrated) or three dimensions. It is well-tested for tide and wind induced currents on the whole French coast. A considerable advantage is its low computational time due to the use of nested grids (Cartesian or spherical mesh). For the nearshore processes, we use the depth-averaged (2DH) model. In this case, the system consists of the horizontal momentum equations and continuity equation (shallow-water equations). By noting Ui the component in the direction i of the mean current velocity and ζ the free surface elevation, the governing equations are in shortened formulation (without the terms of wind surface stress and Coriolis forces):

$$\frac{\partial \zeta}{\partial t} + \frac{\partial h U_i}{\partial x_i} = 0$$

$$\frac{\partial U_i}{\partial t} + U_j \frac{\partial U_i}{\partial x_j} + g\frac{\partial \zeta}{\partial x_i} = \frac{\partial}{\partial x_j}\left(\nu_H \frac{\partial U_i}{\partial x_j}\right) - \frac{\tau_i^b}{\rho h} - \frac{1}{\rho h}\left(\frac{\partial S_{ij}}{\partial x_j}\right) \qquad (2)$$

with g the gravity, ν_H the horizontal eddy viscosity, ρ the mass density of salted water, τ_i^b the bed shear stress, h the mean water depth and S_{ij} the radiation stresses.
In order to model the undertow current, we correct the MARS output velocities in the following way according to [1]:

$$U_{i,Phillips} = U_i - \frac{Q_i^w}{h} \qquad (1)$$

with Q_i^w the volume flux associated with the organized wave motion.

To model the bottom shear stress induced by waves and currents, we implemented the weak flow approximation [1]:

$$\tau_i^b = \rho \, C_f \, U_w U_i \qquad (2)$$

where U_w is the orbital velocity and C_f the bottom friction coefficient.
We keep the horizontal eddy numerical viscosity implemented in MARS ν_{MARS} which remains constant during a simulation but we have added an eddy viscosity due to the turbulence generated by breaking waves in the surf zone applying the formulation of [1]. Thus, we obtain the total viscosity ν_H:

$$\nu_H = \nu_{MARS} + M \, h \left(\frac{D}{\rho} \right)^{1/3} \quad (3)$$

with D the energy dissipation of the waves, M a dimensionless coefficient and ν_{MARS} such as :

$$\nu_{MARS} = 0.01 \, f_{visc} \, dy^{1.15} \quad (4)$$

where f_{visc} is a constant parameter which we reduce to the maximum by keeping the stability of our solution ($f_{visc} = 2.5$) and dy the latitude step.

The sedimentary model

An internal module has been developed inside the MARS code to calculate the morphological evolution of the seabed, and sandy beaches especially. This module is decomposed in two main parts: the computation of the transported sediment fluxes and the resolution of the sediment mass conservation law.
Sediment fluxes are computed with the formulation of Bailard [1] which allows to take into account bed-load and suspension transport. Defining Q_b as the bed-load transport flux, $Q_{b\beta}$ the component of bed-load transport by slope effect, Q_s the suspension transport flux and its component by slope effect $Q_{s\beta}$, we obtain the transported total volumetric rate Q_t :

$$\vec{Q}_t = \vec{Q}_b - \vec{Q}_{b\beta} + \vec{Q}_s - \vec{Q}_{s\beta} \qquad (5)$$

with :

$$\begin{aligned} \vec{Q}_b &= \frac{\varepsilon_c f_{cw}}{g(s-1)\tan\varphi} \overline{\|U_b\|^2 \vec{U}_b} \\ \vec{Q}_{b\beta} &= \frac{\varepsilon_c f_{cw}}{g(s-1)\tan^2\varphi} \overline{\|U_b\|^3 \vec{\nabla} Z_b} \\ \vec{Q}_s &= \frac{\varepsilon_s f_{cw}}{g(s-1)\omega_s} \overline{\|U_b\|^3 \vec{U}_b} \\ \vec{Q}_{s\beta} &= \frac{\varepsilon_s f_{cw}}{g(s-1)\omega_s^2} \overline{\|U_b\|^5 \vec{\nabla} Z_b} \end{aligned} \qquad (6)$$

where $\overline{\langle . \rangle} = \frac{1}{T_m} \int_t^{t+T_m} \langle . \rangle \, dt$, T_m is the mean wave period, ε_c and ε_s are effectiveness factors, φ the internal friction angle of the sediment, f_{cw} the bottom friction coefficient, s relative density, ω_s the fall velocity of the suspended sediment, Z_b the bottom level and we take like approximation that the flow velocity close to the bottom U_b is given by:

$$\vec{U}_b(t) = \vec{U}_f + \vec{U}_w \cos(2\pi \, t / T_m) \quad (7)$$

with U_f the near-bottom current above the bottom using a logarithmic profile [1] and U_w the orbital wave velocity. In order to calculate the bottom friction factor, we use the formulation of [1] for the current only and the wave alone and we applied the model of [1] with the coefficients of [1] to obtain the bottom friction for both waves and current.
The new bottom level is computed solving the sediment mass conservation law with a centred second-order scheme which gives us the best results. This equation can be written in the following way:

$$\frac{\partial Z_b}{\partial t} + \frac{1}{1-p} \vec{\nabla} . \vec{Q}_t = 0 \quad (8)$$

with p the sediment porosity.

Application exemples

Here we present two application examples: one in the Marennes Oléron area and the other on an idealised beach of the Aquitaine coast.

Wave modelling – Marennes Oléron

Within the PNEC project, we study the influence of wave agitation on sedimentary dynamics in the Marennes-Olréan zone and the Arcachon lagoon. The modelling platform has been first developed on the Marennes-Oléron area. In what follows, only the wave modelling results are presented. It can be noticed that the MARS model is already implemented on this area (by IFREMER) and that it is actually in its validation phase for this area (IFREMER and BRGM).
The wave modelling requires three SWAN nested models: one large cover (1km x 1 km, figure 3b), one intermediate cover (300mx300m, figure 3c) and one local cover (100m x 100m, figure 3d).
Figure 4 shows the comparison of the wave heights obtained with this modelling (with or without wind) and the performed measurements at the Antioche location for a water depth of 23 m (figure 3a) and the 2002 November period (described in [1]). This figure show a better agreement between measurements and model when the wind (GFS) is taken into account (see period from 13 to 15 November). For instance the Hs scatter index is 0.23 when wind is not activated whereas it takes the value of 0.208 when wind is activated (table 1).

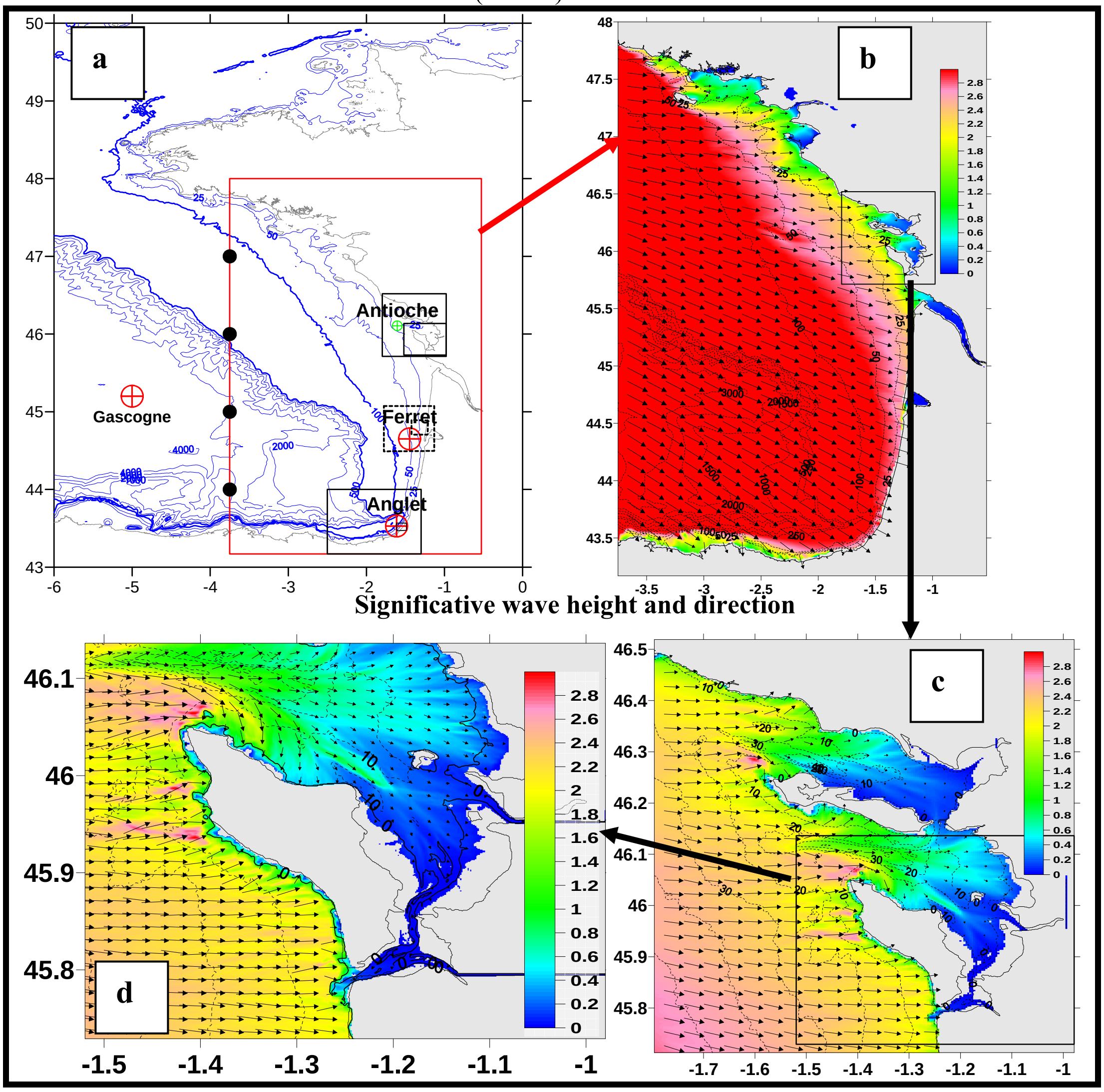

Figure 3 Wave modeling at Marennes Oléron, based on 3 nested models. Exemple: the 05/112002 00 :00 : a) black circles corresponds to the NWW3 nodes used to force the large cover wave model (using SWAN).

In order to improve the results synthesised in Table 1, tests are conducted using higher spatial resolution wind field (COAMPS-EUROPE, 0.2°x0.2°) and the Albes and Banner method to better take into account the swall-wind wave interactions (implemented in the last SWAN version).

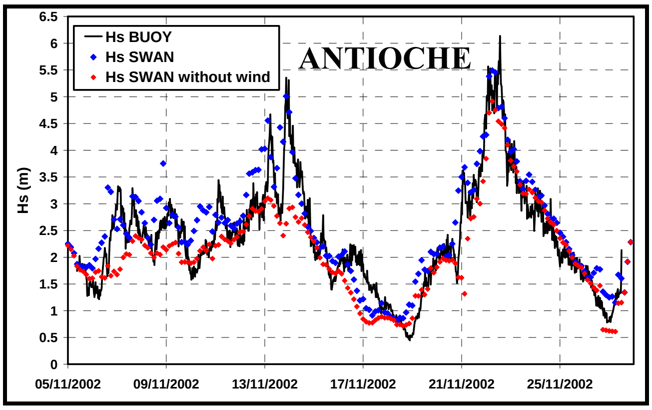

Figure 4 Comparison of the model results (SWAN, intermediate cover, with and without wind) and the measurements at the Antioche location.

	Hs			Tp			Dp		
	Mean	SI	Bias	Mean	SI	Bias	Mean	SI	Bias
Antioche Buoy	2.36			12.22			260.90		
SWAN	2.58	0.208	0.22	11.30	0.213	-0.92	271.37	0.086	10.47
SWAN without wind	2.11	0.230	-0.25	11.36	0.204	-0.86	276.80	0.087	15.90

Table 1 Statistics for Hs (significative wave heigt), Tp (pic period) and Dp (pic direction), based on model-measurements comparison (177 samples).

Morphodynamic Modelling – Idealised beach at the aquitanian coast

The modelling platform has also been applied for the case of an idealised beach characterised by a crescentic bar (figure 5a) [1]. The wave induced currents are plotted on figure 5b et 5c , respectively for a normal incidence and a 10° incidence. The currents pattern is in agreement with the studies of [1] and [1]. The figure 5c shows the beach evolution after 9 simulated days. New subtidal and intertidal bars can be distinguished. That is consistent with observation of [1].

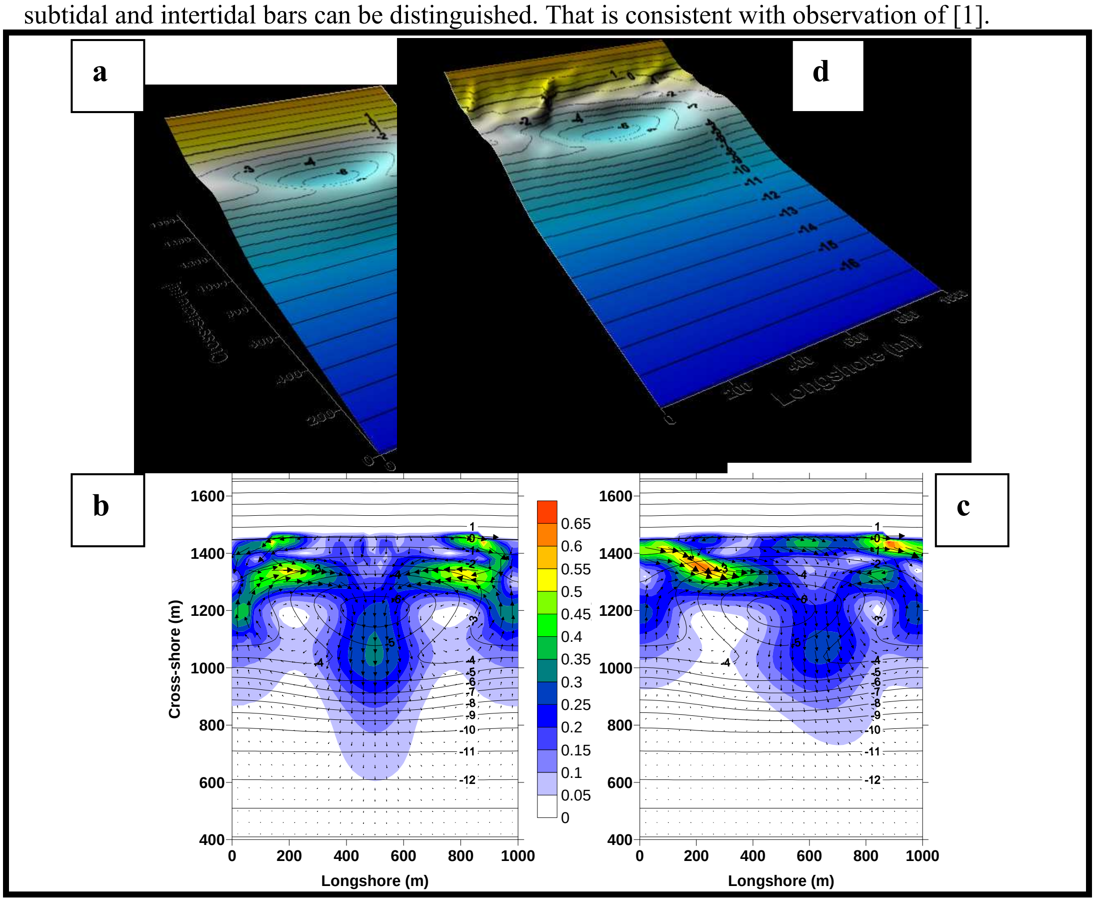

Figure 5 Hydrodynamic pattern and morphodynamic evolution of crescentic bar beach system. a) initial bathymetry ; b) wave induced current for Hs = 1.5m, Tmean = 12s and normal incidence ; c) as b) but with a 10° incidence ; d) bathymetry after 9 days evolution. Wave characteristics: same than c, tide is also included.

These first results should be improved including also the wave-current interactions, the wave asymmetry and the roller influence. A first application on a natural site will be performed for the Truc Vert site, during the first 2007 semester. The results of the 2001 PNEC field campaign [1] will be used for the first validations.

Conclusion

A modelling platform of coastal processes (hydrodynamics and morphodynamics) has been set up by the BRGM, the UMR EPOC and the IFREMER.

The first results are promising: the modelled wave fields have been validated at the continental shelf scale, the couplings of the hydrodynamics modules are satisfactory for the operational applications. However, progresses have to be done regarding the morphodynamic part, especially the integration of swash module, which is necessary for the sandy beach backshore modelling.

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