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***Abstract*—In this work, a depth-averaged coastal morphodynamic model (2DH) is developed on the basis of the Telemac-Mascaret modeling system. The model is implemented and validated in the Somme Bay zone (France), which suffers severe sediment deposition problems. Tides and waves are considered as the main driving forces for the sediment transport and offshore bathymetry. Therefore three different models are implemented to simulate tides, waves and morphodynamic conditions. Firstly a tidal and a waves model are developed and validated. Secondly, a coastal morphodynamic model is established by internally coupling the validated tidal and waves model to a sediment transport and bed evolution model. Finally, the validation of the sediment transport processes is performed in the Somme bay area for different scenarios.**

I. INTRODUTION

Beach and nearshore sediments are continually responding to interactions between waves, wave-induced littoral currents, currents induced by wind and tides, and the wind directly [1], [2]. However, the dominant factors that drive the sediment dynamics and beach shaping are usually the direct wave action and the wave-induced littoral currents, except near coastal inlets, where tide-induced flows can typically dominate.

The presence of a headland or a structure such a groyne or a jetty, oriented normal to the shoreline and attached to the shore will strongly interact with the active waves and currents and the resulting sediment transport in the vicinity of the structure [3]. In consequence, a shoreline harbor or a jettied inflow channel entrance will trap the sediment being transported down coast. To alleviate the resulting unwanted deposition in a harbor or a power station cooling water inlet, it become necessary to artificially deepen the water depth by dredging the sediment accumulated in the channel inlet or by mechanically bypass sediment deposited at the channel entrance.

Both sediment dredging and bypassing are, in general, costly operations that must be repeated several times over a project life. Therefore, it is of crucial importance to anticipate the forcing effects on the sediment and morphodynamic behavior in the vicinity of harbors or cooling water inlets to accurately predict the impact of coastal structures on the study area to efficiently optimize sediment dredging and bypassing operations. From the last few years, numerical coastal models are widely used to study this process.

The major goal of this work is to develop numerical models for the reliable prediction of the sediment dynamics and morphological evolution of coastal areas subject to the interaction of waves and tide-induced currents. These models, with appropriate waves, tides, bathymetric and sediment information, would allow the prediction of the behavior of the sediment dynamics and offshore bathymetry over a given period of time. Furthermore, future application of the models would be to evaluate the impact of coastal structures, such as jetties placed at the water intake channel, over any period of time. It is expected that the resulting validated models would also be used as a predictive tool for analyzing and evaluating dredging and sediment deposition management subject to different climate and forcing scenarios [4], [5].

II. MODEL APPROACH

Generally speaking, there are two types of coastal models: (i) *physical models*, which are normally smaller scale versions of the real (prototype) situation, and (ii) *equation-based models* involving the solution of the governing equations. The latter includes numerical models, used to predict both the spatial and temporal variation of the wave, current and sediment transport fields and analytical models which, although simpler, provide conceptual tools for analysis and understanding.

Traditionally, three types of numerical models have been developed [6], [7]: (i) *coastal profile models*, focuses on cross-shore processes and longshore variability neglected; (ii) *coastline models*, where the cross-shore profiles are assumed to retain their shape when the coast advances or retreats; (iii) *coastal area models*, where variations in both horizontal dimensions are resolved. The latter can be further subdivided into two-dimensional horizontal (2DH) models, which use depth-averaged equations, and three-dimensional (3D) models, which solve the vertical variations of flow and transport.

In this work, 2DH coastal area models are implemented. The general setup of the three-way processes model (wave, currents and sediment transport) is presented below and schematized in Fig.1:

i. Give initial bathymetry and initial conditions.

ii. Give boundary conditions for waves and flow, the coupled hydrodynamic process is computed.

iii. The sediment transport field is computed, based on the flow and wave fields, the bathymetry and the sediment properties.

iv. The bathymetry is updated based on the sediment transport gradients.

v. Back to [ii] and repeat process until final time.

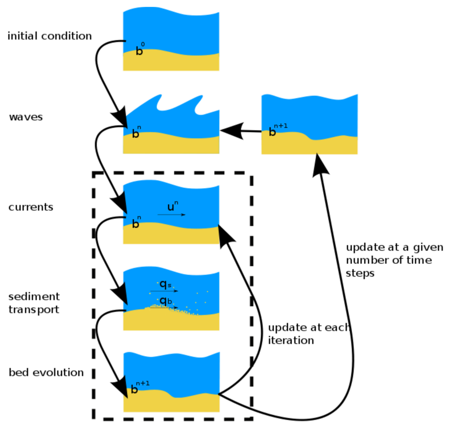


Figure 1. Schematic representation of the modelling coupling strategy used in this work

The Telemac-Mascaret modelling system (TMS) is selected as the modelling suite to simulate coastal processes. In particular, the version 7.0 of TELEMAC-2D (currents), TOMAWAC (waves) and SISYPHE (sediment transport and bed evolution) modules of the TMS will be used (released in December 2014).

III. Governing Equations

In this section, the mathematical models for the description of tidal currents, waves, and sediment dynamics are presented.

A. Currents

The hydrodynamic processes are described by the shallow water equations. These equations obtained by depth-averaging the Reynolds-Averaged Navier-Stokes, consisting of one continuity equation (1) and two momentum equations (2) and (3), are written in non-conservative form as follows [8]:

$$\frac{\partial h}{\partial t} + \mathbf{U} \cdot \nabla(h) + h \cdot div(\mathbf{U}) = S_h \qquad (1)$$

$$\frac{\partial U}{\partial t} + \mathbf{U} \cdot \nabla(U) = -g\frac{\partial h}{\partial x} + S_x + \frac{1}{h} div(h v_t \nabla U) \qquad (2)$$

$$\frac{\partial V}{\partial t} + \mathbf{U} \cdot \nabla(V) = -g\frac{\partial h}{\partial y} + S_y + \frac{1}{h} div(h v_t \nabla V) \qquad (3)$$

where h is the water depth, t is the time; $\mathbf{U}$ is the depth-averaged velocity vector, with components U and V in the x and y Cartesian coordinates respectively, v_t is the diffusion coefficient, g is the gravity acceleration, S_h is a source or sink term in the continuity equation. The source or sink term S_x and S_y in the dynamic equations represent the wind and the atmospheric pressure, the Coriolis force, the bottom friction and additional sources or sink of momentum within the domain in the two directions x and y.

For the astronomical tides, the water level ζ can be computed by means of a superposition of different tidal components [9]:

$$\zeta = \sum_{n=1}^{N} f_n A_n \cos\left[\omega_n t - G_n + (V_n + u_n)\right] \qquad (4)$$

where t is the time referred to 0 hour at Greenwich Me an Time (GMT), n is the index of the tidal constituent, A_n is the amplitude of the tidal constituent, f_n is the nodal fact or of the tidal constituent, ω_n is the frequency of the tidal c onstituent, G_n is the phase lag of the tidal constituent behin d the phase of the corresponding constituent at Greenwich, $V_n + u_n$ is the value of the equilibrium argument of the tidal constituent, V_n is the uniformly changing part of the phase of the constituent at the Greenwich meridian, and u_n is the n odal adjustment of the tidal constituent [10].

The values calculated according to Equation (4) can be used to define the water depth h in the shallow water equations at the open boundaries of the domain.

B. Waves

Statistical approach is used to describe the wave activity as a large amount of random parameters are contained in the wave field.

In the general case of wave propagation in an unsteady medium (sea currents and/or levels varying in time and space), a common way of describing the wave field is wave action, which is conserved during propagation [11]. The action balance equation governing the wave evolution in Cartesian coordinates in the following forms:

$$\frac{\partial \mathbf{N}}{\partial t}+\frac{\partial(\dot{x}\mathbf{N})}{\partial x}+\frac{\partial(\dot{y}\mathbf{N})}{\partial y}+\frac{\partial(\dot{k}_x\mathbf{N})}{\partial k_x}+\frac{\partial(\dot{k}_y\mathbf{N})}{\partial k_y}=S_{tot} \quad (5)$$

where $\mathbf{N}(k_x, k_y, x, y, t)$ is the wave action density, t is time, the position vector $\mathbf{x}=(x, y)$ for spatial location in a Cartesian coordinate system, the wave number vector $\mathbf{k}=(k_x, k_y)=(k\sin\theta, k\cos\theta)$ for directional spectrum discretization, θ denoting the wave propagation direction, S_{tot} is total source term.

For the propagation equations:

$$\dot{x}=\frac{\partial \Omega}{\partial k_x} \quad \dot{y}=\frac{\partial \Omega}{\partial k_y} \quad \dot{k}_x=-\frac{\partial \Omega}{\partial x} \quad \dot{k}_y=-\frac{\partial \Omega}{\partial y} \quad (6)$$

where Ω results from the Doppler relation applied to the wave dispersion.

The term S_{tot} includes wind input S_{in}, dissipation S_{ds} and non-linear wave-wave interactions S_{nl}. In deep water the main dissipation process is due to whitecapping S_{wc} [12]. Reducing water depth, a considerable amount of wave energy is also dissipated by wave-bottom interaction S_{bf} [13]. In extreme shallow water, depth-induced wave breaking S_{bk} dominates over all other dissipating processes [14].

C. Sediment transport

The transport rate due to the combined action of waves and current is provided by Soulsby-van Rijn formula [15]:

$$Q_{b,s}=A_{b,s}U\left[\left(U^2+2\frac{0.018}{C_D}U_0^2\right)^{0.5}-U_{cr}\right]^{2.4} \quad (7)$$

This formula can be used to estimate the components for total sediment transport rate (bed load Q_b and suspended load Q_s)

The bed load coefficient A_b and suspended load coefficient A_s are computed as:

$$A_b=\frac{0.005h(d_{50}/h)^{1.2}}{((s-1)gd_{50})^{1.2}} \quad (8)$$

$$A_s=\frac{0.012d_{50}D_*^{-0.6}}{((s-1)gd_{50})^{1.2}} \quad (9)$$

where U is the depth-averaged current velocity, U_0 is the RMS orbital velocity of waves, and C_D is the quadratic drag coefficient due to current alone. The critical entrainment velocity U_{cr} is given by the expression:

$$U_{cr}=\begin{cases} 0.19d_{50}^{0.1}\log_{10}\left(\frac{4h}{D_{90}}\right) & if\, 0.1mm \le d_{50} \le 0.5mm \\ 8.5d_{50}^{0.6}\log_{10}\left(\frac{4h}{D_{90}}\right) & if\, 0.5mm \le d_{50} \le 2.0mm \end{cases} \quad (10)$$

The validity range for the Soulsby-van Rijn formula is h = (1 – 20) m, U = (0.5 – 5) m/s, and d_{50} = (0.1 − 2.0) mm.

D. Bed level updating

The bed level updating module is described as:

$$(1-n)\frac{\partial Z_f}{\partial t}+\nabla\cdot Q_b=0 \quad (11)$$

where n is the non-cohensive bed porosity, Z_f is the bottom elevation, and Q_b (m^2/s) is the bedload transport per unit width, with components Q_{bx} and Q_{by} in the x and y Cartesian coordinates respectively.

IV. Study Site and Available Data

A. Study Area

The Somme Bay is located between Hourdel in the south and Saint-Quentin-en-Tourmont in the north (Fig. 2). It covers an area about 70 km^2 and comprises the Somme river, with a yearly average flow rate of about 30 m^3/s, controlled by a lock at Saint Valery sur Somme [16]. Within a distance of about 20km to the North, the Authie Canche bay is located, with a yearly average flow rate of about 10 m^3/s. The Somme bay is covered by a high percentage of tidal flats and salt marshes. From several years, this area endures severe sedimentation issues, with an increasing of the mean bed level of about 1.3 cm/year.

The domain is chosen to cover a large coastal area, about 60km offshore and along shore, to include Somme Bay and also some other areas of interest for EDF as the Penly and Paluel nuclear plants and the Fécamp offshore wind farm (Fig.2). The model can be profited to possess a large number of observation points in different zones of the domain, and it is expected that the validated model can be used as a predictive tool and applied directly in the other interesting areas of the same domain.

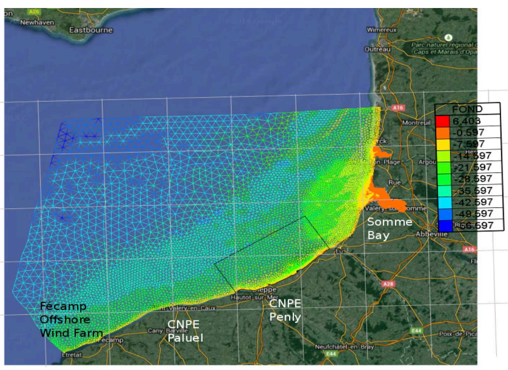


Figure 2. Location of the Somme Bay and extension of the numerical model

B. Bathymetry Data

The bathymetric data are taken from the following sources:

- In the intertidal part of the Bay of Somme, Light Detection and Ranging (LiDAR) data (1 sampling point/1m) have been acquired in June 2012 by the CLAREC operational team (M2C Lab, University of Caen).
- Field surveys Mosag07& Mosag08 on Thalia vessel [17], occurred about 30km South-West from the bay mouth in 2007 and 2008, and high resolution bathymetric data (1 sampling point/3m) were collected offshore during these surveys.
- Elsewhere bathymetric data collected by the "Service Hydrographique et Océanographique de la Marine" (SHOM) are used with a resolution of 2km offshore to 25m at some locations

C. Validation Data

During the Mosag07& Mosag08 [17] surveys, tide levels, flow velocities, wave height and period were measured for a neap spring cycle (~15days) [16]. Acoustic Doppler Current Profiler (ADCP) measurements occurred at locations C1 - C2 in 2007 and at C3 in 2008 (Fig.3).

The validation data for wave model comes from the Candhis database (National Center for Archiving Swell Measurements) in the location of Cayeux. Candhis refers to the coastal national network of in situ measurements provided by CETMEF (Centre d Etudes Techniques Maritimes et Fluviales).

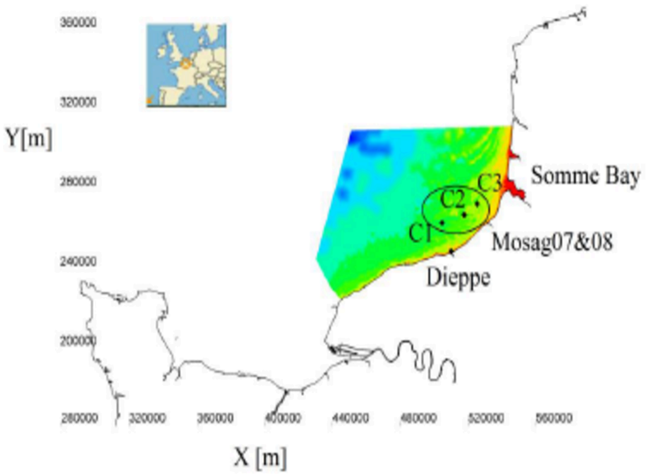


Figure 3. Mosag07&08 field survey

LiDAR data in Somme Bay acquired from CLAREC team is used here to validate the morphodynamic model. The evolution of the bottom in Somme bay is presented in Fig. 4.

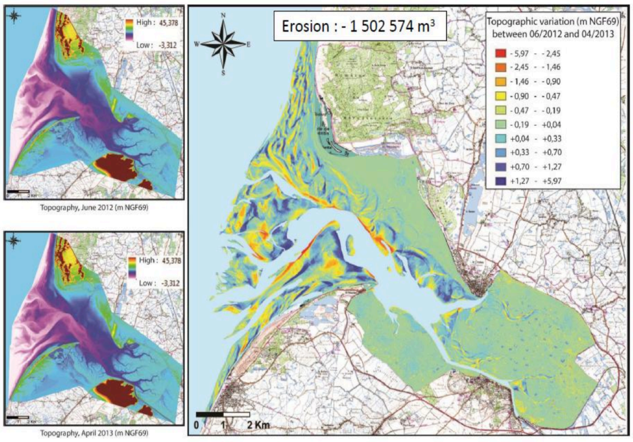


Figure 4. Measured LiDAR data for morphodynamic evolution (C. Michel M2C Rouen unpublished work)

D. Numerical Data

The wind data (wind velocity component at 10 m height and atmospheric pressure) used in the hydrodynamic model were obtained from the database of ERA Interim supplied by European Centre for Medium-Range Weather Forecasts (ECMWF). Each six hours a new set of U wind velocity and V wind velocity is given and the wind data is applied to the whole domain uniformly.

For the tidal level and velocities on offshore boundary the imposed values are calculated from harmonic constants provided by global or regional tidal model. 4 databases of harmonic constants are interfaced with TELEMAC-2D [18]. In this study domain, the global TPXO database and its regional and local variants are applied.

For the open boundary of wave module, the parameters of significant wave height, peak frequency, main direction and directional spread are given from the datasbase of Anemoc-2 (Atlas Numérique d'Etats de mer Océanique et Côtier) developed by EDF - LNHE (Électricité de France - Laboratoire National d'Hydraulique et Environnement) with support of CETMEF.

V. Numerical Results

A. Accuracy criteria

The comparison between the computation outputs and observation data is evaluated based on a quantitative criterion, the Relative Mean Absolute Error RMAE [19]. The RMAE is given by the expression:

$$RMAE = \frac{\langle |Y_c - X_c| \rangle}{\langle |X_c| \rangle} \qquad (11)$$

where $\mathbf{X}_c$ ($\mathbf{x}_1$, ..., $\mathbf{x}_N$) is a set of observations and $\mathbf{Y}_c$ is the model predictions. The mean value noted $\langle\ \rangle$ is defined by the expression:

$$\langle |X| \rangle = \frac{1}{N}\sum_{i=1}^{N}|x_i| \qquad (12)$$

The quality criteria associated with RMAE criteria is given in Table Ⅰ.

TABLE I. QUALITY CRITERION

	RMAE
Excellent	<0.2
Good	0.2-0.4
Reasonable	0.4-0.7
Poor	0.7-1.0
`Bad	>1.0

B. Tidal model

The module TELEMAC-2D is used as the numerical tool to develop and validate the hydrodynamic model with tides as driving force.

The tidal model is initialized with a constant water surface elevation and still water level equal to 5m over the whole domain. An alignment of the different temporal conditions of the boundary condition datasets was made to match the initial conditions as closely as possible to those observed.

The boundaries along the coast are treated as solid boundaries, in which no flux transfer is allowed. Constant flow rates imposed for the Somme and Authie rivers are ignored for validation of the model.

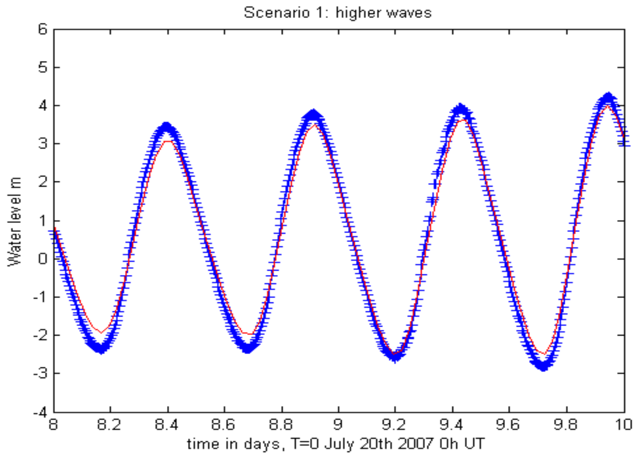
The Nikuradse formulation is chosen to impose the bed friction coefficient with a value of 0.5 m in the whole domain, in order to incorporate into the model the effects of skin friction and the presence of bed forms. For the tidal model, a constant eddy viscosity equal to 1 m^2/s is chosen for the numerical simulations. The inertia effect of the Coriolis force is also taken into account with a Coriolis coefficient equal to 0.000112 rad/s.

According to the field data, two time periods are chosen to test the tidal model under different wave (with higher or lower value) conditions. The basic information is summarized in Table Ⅱ. Δt_{T2D} is time step for TELEMAC-2D model.

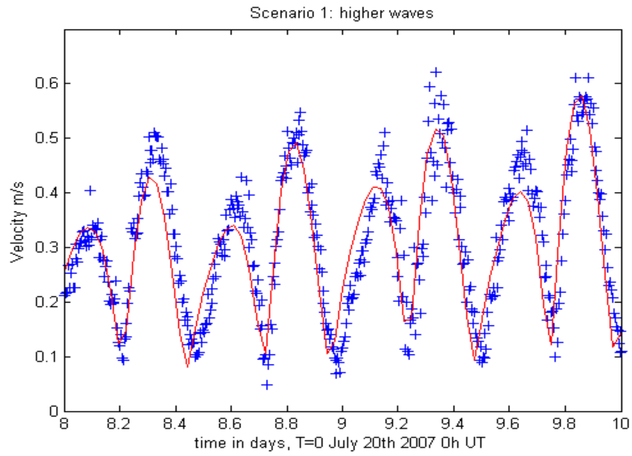
TABLE II. SCENARIOS FOR TIDAL SIMULATION

Scenarios	***From***	***Durations [Days]***	Δt_{T2D} ***[s]***	***Description***
1	2007/07/27	5	10	Higher waves
2	2007/08/01	5	10	Lower waves

The measurement velocity and water level in C2 are available for the model validation. In Fig.5, The cross marks represent the measured data, and the red lines represent the numerical results.



(a)



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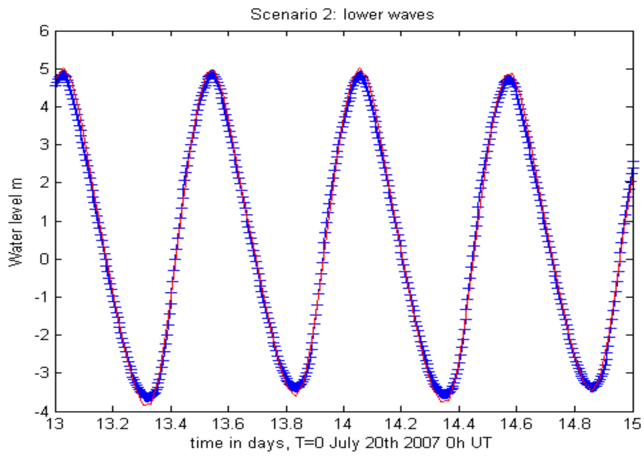
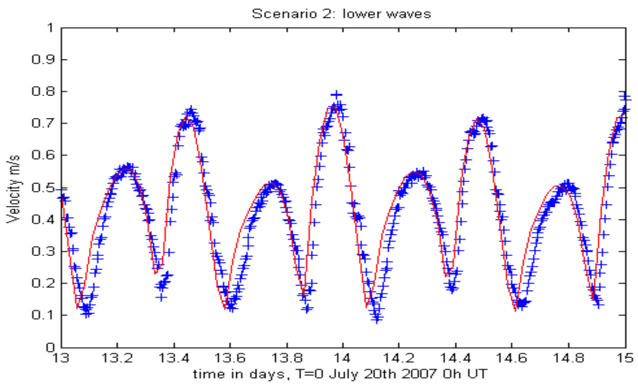


(c)



(d)

Figure 5. Validation of tidal model: (a) Tides with higher waves: water level; (b) Tides with higher waves: velocity; (c) Tides with lower waves: water level; (d) Tides with lower waves: velocity;

To quantitatively assess the tidal behavior under different wave conditions, RMAE scores are computed for each parameter in each scenario as well as the mean value, and a summary is presented in Table III as below.

TABLE III. RMAE SCORES FOR TIDAL MODEL RESULTS

Scenarios	***Velocity C1***	***Velocity C2***	***Water level C2***	***Average***
1	0.1586	0.1685	0.0996	0.1114
2	0.1484	0.1437	0.0617	0.1179

From the comparison of 2 scenarios, it can be found that the average RMAE values for the output parameters during the tidal period, characterized with lower waves, show in general a better accuracy level than the RMAE values evaluated during the tidal period corresponding higher waves. This is reasonable because without taking waves into account, the tidal model shows a poor performance during the period presenting a significant wave activity. However, both Fig.5 and RMAE results show a good agreement between simulated results and observation data are achieved for both scenarios.

C. *Wave model*

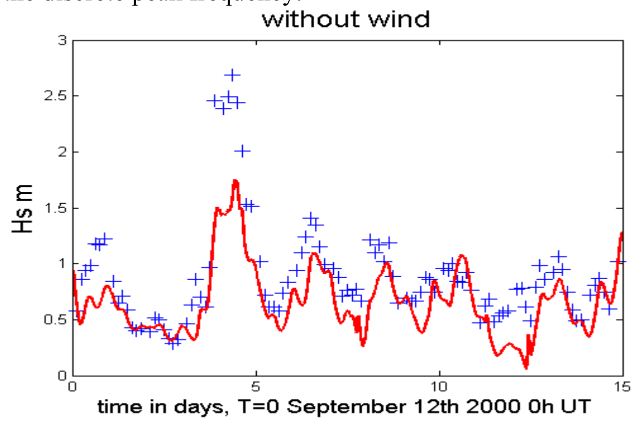
In this section, the module TOMAWAC is coupled to the module TELEMAC-2D to take into consideration of the driving force of waves.

To initialize the model, the significant wave height is set to be 0.99m, peak frequency 0.15 s^{-1}, main direction 140 °, and direction spread to be 0.6.

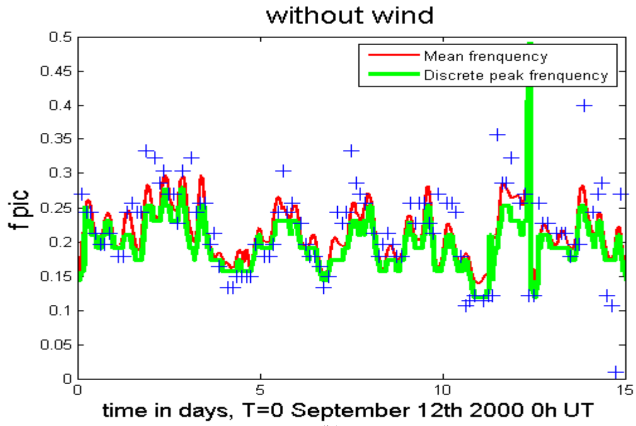
The Anemoc-2 data is used as input of boundary condition. The model includes energy loss due to white capping dissipation, non-linear quadruplet interactions, wave breaking dissipation and bottom friction. Bottom friction was applied uniformly across the domain with a coefficient value of $0.038m^2/s^3$.

Two simulations are launched from September 12^{th}, 2010 with a duration of 8 days. The time step in TELEMAC-2D is set to be 10s, and the model is coupled internally with TOMAWAC with a coupling period of 10, which means the time step in TOMAWAC is 100s. Wind is only considered in the second simulation to study the influence of wind on the numerical model.

The simulation results are compared and presented in Figure 6. The cross marks represent the measured data and the red lines represent the numerical results (significant wave height and mean frequency). The green line represents the discrete peak frequency.



(a)



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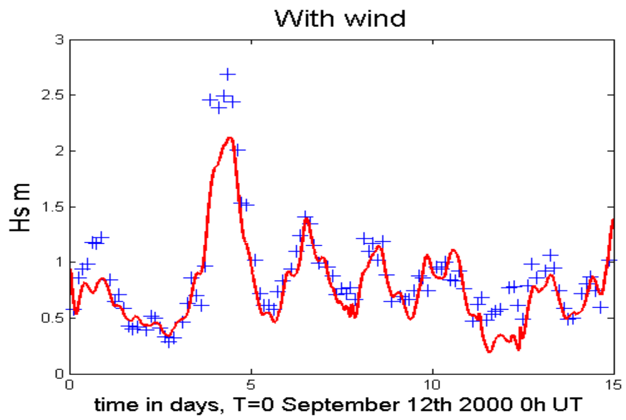

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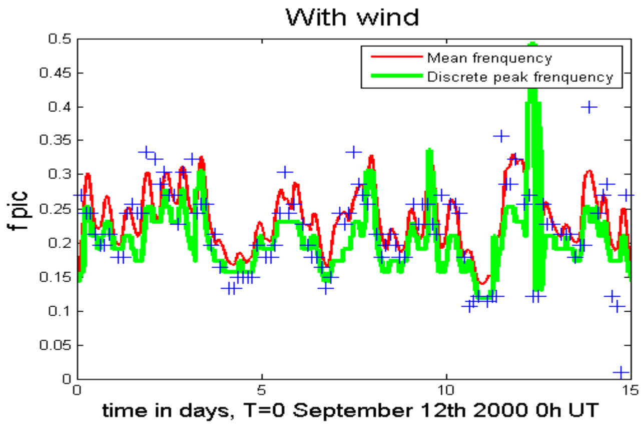

(d)

Figure 6. Validation of wave model: (a) Without wind: significant wave height; (b) Without wind: wave frequency; (c)With wind: significant wave height; (d) With wind: wave frequency.

From the simulation results and the comparison with the observation data, it is showed that for both simulations, the numerical results match well with the measured data. However, for the first simulation without the consideration of wind, the modeled results underestimate the values of the significant wave height for the highest peak the interval day 4 - day 5, with a difference of about 1 m.

By considering the influence of the wind, the model result is improved largely, especially for significant wave height, where the first peak is better captured with only a slightly underestimation of 0.5 m. It also appears a better agreement for the significant wave height for the interval day 5 - day 10.

RMAE scores of the two simulations are summarized in Table Ⅳ.

TABLE IV. RMAE SCORES FOR WAVE MODEL RESULTS

Scenarios	*Significant wave height*	*Mean frequency*	*Discrete peak frequency*	*Average*
1	0.3014	0.1289	0.1563	0.1955
2	0.1818	0.1346	0.1529	0.1564

From the results presented in Table Ⅳ, it can therefore be concluded that the wave model provides better predictions for significant wave height when the influence of the wind is considered in the numerical simulations. For both simulations, the average RMAE scores reach the excellent level according to the quality criterion.

D. Morphodynamic model

In this study, the sediment transport and bed evolution module SISYPHE is coupled with TELEMAC-2D and TOMAWAC. A uniform, non-cohesive sediment distribution is used for the numerical simulations, with a median diameter equal to 0.2mm. The bed porosity is set to be 0.4. Only bed load transport is considered in this study and Soulsby-van Rijn formula is used.

Long-term simulations are launched from June 2nd, 2012 to April 6th, 2013, when the LiDAR data is acquired (Fig.4). The topography evolution will be used as reference for the model validation.

In order to assess the separate impact of tidal and wave action, two different scenarios are carried out and compared by considering the driving force of tidal currents only (SISYPHE coupling with TELEMAC-2D), and tidal currents plus waves (SISYPHE coupling with TELEMAC-2D and TOMAWAC).

The time step is set to be 60s in TELEMAC-2D and SISYPHE, and 3600s in TOMAWAC.

The bathymetry evolutions from simulations under different force scenarios are shown in Fig. 7.

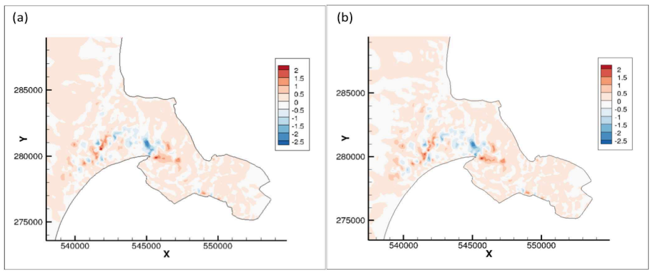

Figure 7. Bathymetry evolution from the morphodynamic simulation results by considering the effects of (a) tides (b) tides and waves.

From Fig.7, we can find that compared with the LiDAR survey, the simulation results show a good agreement with the observation according to the sediment erosion and deposition locations. Though a relatively lower estimation is obtained from the morphodynamic model, which is reasonable because suspension load is not taken into account, the magnitude of the bed evolution in Somme Bay from the model matches well with the observations.

An extra scenario is also developed based on a finer mesh to evaluate the influence of the mesh size on the morphodynamic model.

The comparison of the simulation results based on coarse and fine meshes are shown in Fig. 8.

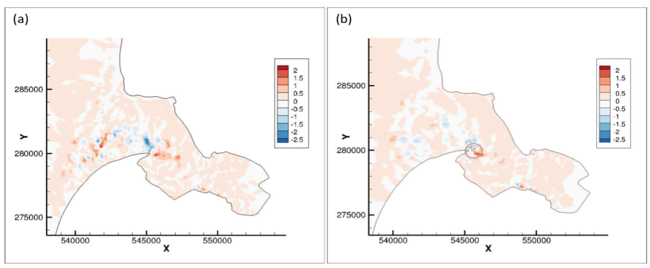

Figure 8. Bathymetry evolution from the morphodynamic simulation results by using (a) coarse mesh (b) fine mesh

With the refinement of the mesh, it can be seen that the sediment deposition and erosion are more concentrated in a corner in the left bank marked in the red circle in Fig. 8(b) with higher deposition and erosion values than the results in coarse mesh.

VI. CONCLUSIONS

In this contribution, the coastal morphodynamic model is developed by coupling well validated tidal and wave models to a sediment transport and bed evolution model. The assessment of the separate impact of tides and tides plus waves on the sediment dynamic of Somme Bay is implemented using this model. In a near future, Improvement of the morphodynamic model is necessary in order to get a better representation of the simulated phenomena with the following considerations:

- Use of a finer mesh to better capture the characteristics of the bed of the study domain.
- Consider graded sediment in the model based on the material sample collected during the field survey Mosag07&08 and SHOM database.
- To include the suspension load as an additional sediment transport process.
- To include the boundary conditions from the Somme and Authie Canche rivers.

ACKNOWLEDGEMENTS

The Research and Development division of Electricity of France (EDF R&D - LNHE National Hydraulics and Environment Laboratory) and Laboratory for Hydraulics Saint-Venant is gratefully appreciated for their financial support to this study. Antoine Joly and Amélie Laugel-Joly (EDF R&D) are thanked for providing Anemoc-2 numerical data used for the numerical simulations. Thanks to Robert Lafite, Sophia le Bot and Charotte Michel (M2C, Rouen) for the provision of field surveys Mosag 07 &08, ADCP, wave and bathymetric data. Thanks to Olivier Monfort (M2C Lab, University of Caen) for sharing the LiDAR data used in the study.

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