Effects of the coupling between TELEMAC2D and TOMAWAC on SISYPHE modelling in the outer Seine estuary.

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Abstract—The present study investigates the need to consider the modifications of the waves fields by the ambient water-depths and currents for sediment transport computations with the TELEMAC modelling system. The application is dedicated to the outer Seine estuary (France, English Channel). The wave propagation module TOMAWAC is coupled with the bidimensional horizontal circulation module TELEMAC 2D. Times histories of depth-averaged mean currents and waves heights are compared with field data collected in the access channel to the harbour of Le Havre. Predictions exhibit a local increase by 30 % of the wave height induced by the current. The sensitivity study compares numerical results issued from SISYPHE integrating hydrodynamics of uncoupled and coupled TOMAWAC – TELEMAC 2D simulations. Computations are performed considering successively suspended transport of cohesive mud and bedload transport of sand. The effect of the hydrodynamic coupling is analysed through the variability of the total maximum wave and current bottom shear stress, the maximum suspended sediment concentration and bedload transport rates and the resulting seabed evolutions.

I. Introduction

The importance of combined surface gravity waves and currents on nearshore sediment transport has long been recognized ([1], [2]). The acquisition of the ability to model accurately the interactions between waves and currents is fundamental in many aspects of coastal, estuarine and offshore engineering. Ways in which waves interact with the currents include at the scale of the continental shelf [3] (1) the interactions between the wave and current bottom boundary layers and (2) the modifications of the wave field by the ambient current. The first type of interaction has been the subject of numerous modelling dedicated to sediment transport ([4], [5]) as it determines the increase of the total wave and current bottom shear stress [2]. Nevertheless, investigations dedicated to the second type of interaction were restricted to the quantification of the wave height modulation and the associated storm surge ([6], [7]).

The purpose of the present study is to analyse the significance of this interaction for sediment transport. The application is dedicated to the outer Seine estuary (France, English Channel) (Fig. 1) characterized by strong interactions between wave and tide with (1) spring tidal range of 7 m and current amplitude of 1.5 m/s [8] and (2) annually wave height over 5 m offshore [9].

At the scale of the outer Seine estuary, the modelling is based on the hydro-informatic finite elements system TELEMAC (section II). The hydrodynamic modelling (section II-A) is based on the coupling of the wave propagation module TOMAWAC [10] with the bidimensional horizontal (2DH) circulation module TELEMAC 2D [11]. The coupling is restricted to (1) the modifications of the wave fields by the time-varying water depths and currents and (2) the interactions between the wave and current bottom boundary layers ignoring the generation of currents by the waves. Sediment transport and morphodynamic evolution of the seabed are computed with the module SISYPHE [12] (section II-B) considering successively two grain-size classes of bottom sediments: mud and sand.

Hydrodynamic numerical results are compared with field data collected with two current meters and two wave buoys in the access channel to Port 2000 (harbour of Le Havre) (section III-A). This comparison exhibits for the month of November 2008 the importance of the modifications of the wave field by the currents for predictions of the significant wave height near the harbour of Le Havre (section III-B). The significance of the modification of the wave field by the ambient water depths and currents is further investigated by identifying the variability of "key" parameters for sediment transport in November 2008 (sections III-B and III-C): (1) the total maximum wave and current bottom shear stress, (2) the maximum suspended sediment concentration (SSC) and bedload transport rates and (3) the resulting seabed evolutions.

II. Model description

The modelling procedure is conducted in three steps successively dedicated to (1) the hydrodynamics of the circulation and wave, (2) the sediment transport and (3) the seabed morphological evolution.

A. Hydrodynamic Modules

Simulations of the circulation and wave propagation are performed with the two nesting modelling systems (i) MISTRAL (Modélisation Intégrée pour la Simulation des TRAnsports Littoraux) [13] at the regional scale of the English Channel and the North Sea and (ii) TELEMAC ([10], [11]) at the local scale of the Bay of Seine and the infrastructures of the

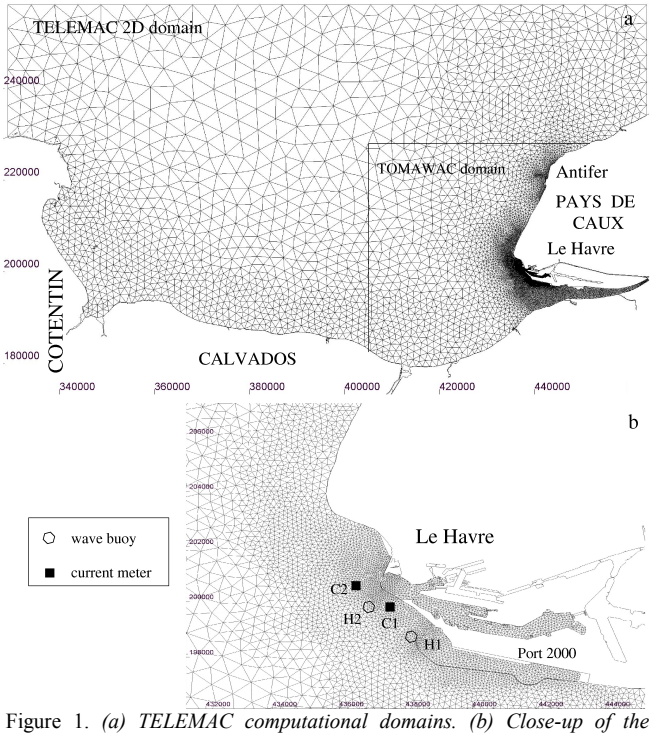

Figure 1. *(a) TELEMAC computational domains. (b) Close-up of the computational mesh near the harbour of Le Havre with the locations of the current meters and wave buoys. The coordinates are indicated in meters according to the French system Lambert I Nord (from [19]).*

harbour of Le Havre (Fig. 1). Each modelling system integrates wave propagation and circulation modules. MISTRAL is based on the wave propagation module SWAN (Simulating Waves Nearshore) [14] and the three-dimensional (3D) circulation module COHERENS (Coupled Hydrodynamical Ecological model for RegioNals and Shelf seas) [15]. TELEMAC considered the wave propagation module TOMAWAC [10] and the 2DH circulation module TELEMAC 2D [11]. The coupling procedure between the circulation and wave propagation modules integrates (i) the interaction between the wave and current bottom boundary layers and (ii) the modifications of the wave fields by the time-varying water depths and currents.

The effects of the interaction between the wave and current bottom boundary layers are implemented in the circulation modules through the increase of the apparent bottom roughness parameter z_{0c} felt by the current above the wave boundary layer. The computational method is based on the formulation proposed by [16]. The module of the total maximum wave and current bottom shear stress is given by

$$\tau_{b,c\omega}^{max} = \rho\, u_{*,c\omega} \tag{1}$$

where $\rho = 1025$ kg/m^3 is the density of clear water and

$$u_{*,c\omega} = u_{*\omega}\left[1 + 2\left(\frac{u_{*c}}{u_{*\omega}}\right)^2 |\cos\phi_{c\omega}| + \left(\frac{u_{*c}}{u_{*\omega}}\right)^4\right]^{(1/4)} \tag{2}$$

is the total maximum wave and current bottom shear velocity. u_{*c} is the shear velocity arising from the current alone and computed from the depth-averaged current U following a Chezy's law. u_{*w} is the shear velocity associated with the wave and given by

$$u_{*,\omega} = \sqrt{\frac{1}{2} f_\omega U_\omega} \tag{3}$$

where U_w is the wave bottom orbital velocity issued from the wave propagation module. f_w is the wave friction factor evaluated with the empirical relations

$$\begin{aligned} f_\omega &= 0.13\,(k_b/a_b)^{0.4} \quad \text{if} \quad k_b/a_b < 0.08 \\ f_\omega &= 0.23\,(k_b/a_b)^{0.62} \quad \text{if} \quad 0.08 \leqslant k_b/a_b < 1 \\ f_\omega &= 0.23 \quad \text{if} \quad k_b/a_b \geqslant 1 \ . \end{aligned} \tag{4}$$

where a_b is the near-bottom excursion amplitude and $k_b = 30 z_0$ is the Nikuradse parameter with z_0 the bottom roughness parameter.

Finally, ϕ_{cw} is the angle between the wave and current directions and the expression of z_{0c} is given by

$$z_{0c} = \delta_\omega^{1-\left|\frac{u_{*c}}{u_{*c\omega}}\right|} z_0^{\left|\frac{u_{*c}}{u_{*c\omega}}\right|} \tag{5}$$

where δ_w is the thickness of the wave bottom boundary layer parametrized according to [2]. Equations (1) to (5) must in principle be solved with an iterative procedure as the current shear velocity depends on z_{0c} which in turns depends on u_{*c}. Following [17], a simpler numerical approach is considered whereby the value of z_{0c} calculated at each time step is used in the computational method at the next time step.

The wave propagation modules integrates the effects of the time-varying water depths and currents computed by the circulation modules. The major associated modifications have recently been reviewed by [18]. The variation of the water depths modulates the dissipation of the wave energy by bottom friction and the wave breaking. Opposing tidal flow induces steepening of the incident wave field thus increasing the wave height. Finally, the combination of the time-varying water depths and currents leads to wave refraction and a semi-diurnal variability of the incident wave energy at specific coastal locations. A noticeable resulting effect of these processes is the tidal modulation of the wave height in the coastal region.

Further details about the coupling between the different circulation and wave propagation modules are available in [19].

B. Sediment Transport Modules

SISYPHE [12] computes the bedload and suspended load of bottom sediments as a function of the hydrodynamic parameters issued from modules TELEMAC 2D and TOMAWAC.

Suspension is computed using a concentration-based approach where the instantaneous SSC C_s of mud satisfies the depth-averaged advection-diffusion transport equation

$$\begin{aligned} &\frac{\partial}{\partial t}(hC_s) + U_{conv}\frac{\partial C_s}{\partial x} + V_{conv}\frac{\partial C_s}{\partial y} = \\ &\frac{1}{h}\left[\frac{\partial}{\partial x}\left(h\epsilon_s\frac{\partial C_s}{\partial x}\right) + \frac{\partial}{\partial y}\left(h\epsilon_s\frac{\partial C_s}{\partial y}\right)\right] + \frac{(E-D)_{z=z_{ref}}}{h} \end{aligned} \tag{6}$$

where U_{conv} and V_{conv} are the depth-averaged convective flow velocities in the x and y directions, respectively. t denotes times, h is the instantaneous total water depth and ϵ_s is the horizontal eddy diffusivity parametrized as a function of the friction velocity [12].

The entrainment rate E and the deposition rate D are specified at the reference level z_{ref} following the classical Krone and Partheniades formulations. The entrainment rate is given by

$$E = M\left[\left(\frac{u_{*c\omega}}{u_{*e}}\right)^2 - 1\right] \quad \text{for} \quad u_{*c\omega} > u_{*e} \tag{7}$$

where the empirical coefficient M is set to M=0.0005 kg/m^2/s and u_{*e} is the critical shear stress velocity for erosion. The mathematical expression of the deposition rate is

$$D = w_s C_s\left[1 - \left(\frac{u_{*c\omega}}{u_{*d}}\right)^2\right] \quad \text{for} \quad u_{*c\omega} < u_{*d} \tag{8}$$

where w_s is the settling velocity of suspended sediment and u_{*d} is the critical shear stress velocity for deposition.

Bedload is computed with the formulation extended by Bijker [20] in combined waves and currents conditions. The instantaneous bedload transport rate expressed as

$$q_b = \phi_b\left[g(s-1)\,d_b^3\right]^{1/2} \tag{9}$$

where

$$\phi_b = b\theta_c^{0.5}\exp\left(\frac{-0.27}{\theta_{c\omega}}\right) \tag{10}$$

is the dimensionless bedload transport rate and θ_c and θ_{cw} are the non-dimensional shear stresses associated with the current alone and the combined wave and current, respectively. The Bijker formula is recommended by [21] in conditions of combined wave and current for its reliability, simplicity and flexibility. Finally, b is set to b=2 according to [22].

The resulting evolution of the seabed is computed by solving the Exner equation extended to total load (including the suspended load).

C. Model Setup

Further details about the setup of the regional circulation and wave propagation modules COHERENS and SWAN are available in [19]. The present section focuses on the implementation of the TELEMAC modelling system in the outer Seine estuary.

TELEMAC 2D is set-up on a outer domain #1 covering the Bay of Seine between the longitudes 1°380 W and 0°433 E and the latitudes 49°253 N and 50°005 N (Fig. 1). The computational domain comprises 8,708 nodes and 16,414 finite elements with a size of 4 km offshore to a few tens of meters close to Le Havre. The time step is set to 10 s. The bottom friction coefficient is computed following a Chezy's law and the heterogeneous roughness parameter derived from the observed grain size distribution dataset [23]. The circulation module incorporates the wind fields from the database of the National Centers for Environmental Predictions (NCEP) [24]. TELEMAC 2D is driven by the free surface elevations and the depth-averaged currents extracted at one hour intervals from COHERENS regional simulations. The wave fields are provided every 90 min from SWAN regional simulations. Finally, an average flow of 450 m^3/s is prescribed at the entrance of the Seine river [25].

TOMAWAC is implemented on a inner domain #2 close to the Seine estuary extending from 0°245 W to 0°354 E and 49°253 N to 49°743 N (Fig. 1). The computational mesh comprises 2,462 nodes and 4,507 finite elements with a size of 2 km offshore to a few tens of meters close to the harbour of Le Havre. The module runs with 30 exponentially spaced frequencies ranging from 0.05 Hz to 1 Hz, 15 evenly spaced directions (resolution of 24°) and a time step of 20 s. The sink term of dissipation by bottom friction is parametrized with an uniform bottom friction coefficient C_b=0.038 m^2/s^3 according to [26]. TOMAWAC is driven by the wave components extracted every 90 min from SWAN regional simulations. The time-varying water depths and currents are given every 30 min by TELEMAC 2D.

SISYPHE is set-up on the inner domain #2 with the same computational mesh as for the wave propagation module. Total water depths and depth-averaged currents are interpolated from TELEMAC 2D simulations in the inner domain. The bottom friction coefficient is parametrized as in the circulation module. The bed is considered of an uniform single grain size with a rigid bed set 100 m below the superficial sediment layer. In order to investigate the effects of the coupling between the circulation and wave propagation module on sediment transport, simulations are performed considering successively (1) suspended transport of cohesive mud and (2) bedload transport of sand. Consolidation is not taken into account. Sensitivity analyses performed by [27] reveal that consolidation slightly affects the suspended sediment patterns. Furthermore, the localisation of computed deposition patterns appears globally in agreement with field data as most of the mud deposited on neap tide is resuspended during spring tides. The mud shear strength is set to the mean value of 0.5 N/m^2 which corresponds to a critical shear stress velocity of u_{*c}=0.022 m/s [27]. This value is a little high for a fresh deposit (fluid mud) but low for a consolidated mud. The critical stress for deposition is taken equal to 10 N/m^2 (u_{*d}=0.098 m/s) following [27]. Flocculation processes are not integrated but implicitly accounted for through a high settling velocity of 1 mm/s according to [28]. Bedload considers sand of a diameter of 200 µm. The critical shear stress is computed according to [29] with a value of 0,17 N/m^2. Finally, the sediment transport module runs with a time step of 10 min during the month of November 2008.

In order to investigate the effects of the modification of the wave field by the time-varying water depths and currents, three numerical experiments are conducted (Tab. 1). Experiments E1 considered the effects of the currents alone without taking into account the superimposed effects of the waves for sediment transport. Experiments E2 and E3 integrate the effects of the waves for sediment transport without and with the modification of the wave field by the ambient water depths and currents. In each experiments, the circulation module integrates the increase of the apparent bottom roughness parameter felt by the current above the wave boundary layer. The fields of the water depths and currents used in each experiments remain consequently the

same. This makes it easier to compare the numerical results between each experiment.

III. Model Application and Results

A. Comparison With Point Measurements

TELEMAC 2D predictions of the depth-averaged currents are compared with measurements realized in the access channel to Port 2000 (harbour of Le Havre) in mean water depths of 19 m at points C1 (λ=0°091 E, ϕ=49°476 N) and C2 (λ=0°077 E, ϕ=49°484 N) (Figs. 1, 2 and 3). The current measurements were realized over the two spring tide periods of 15-16 November 2005 at point C2 and 2-3 January 2006 at point C1. The instrumentation is an upward looking Acoustic Doppler Current Profiler (ADCP) placed on the bottom. The numerical results reproduce the flood/ebb asymmetry at the two measurements points characterized by (1) a magnitude of the flood three times greater than during ebb and (2) a duration of the flood limited to four hours whereas extended to seven hours for ebb. The magnitude of the flood peak is approached with a difference lower than 15 %. A slight phase lag with an average value less than 15 min is however noticed in the comparison of the measured and predicted depth-averaged current directions. Nevertheless, theses numerical predictions are considered reliable for an integration in the wave propagation module.

TOMAWAC predictions of the significant wave height are compared with measurements realized at points H1 (λ=0°104 E, ϕ=49°465 N) and H2 (λ=0°087 E, ϕ=49°475 N) as part of an observational system to regulate the ship routing close to the harbour of Le Havre (Fig. 1). The period of comparison corresponds to the month of November 2008 characterized by continuous records with a tidal range of 7 m in November 2008 and a significant wave height of 2.8 m in 23 November 2008 at point H1. When the effects of the time-varying water depths and currents are integrated (case E3), the numerical results reproduce the semi-diurnal variation of the wave height (Fig. 4). An overall good agreement is thus obtained between predictions and measurements. A slight overestimation of the wave height is however noticed at point H2 during the storms of 21 and 24 November 2008. This tendency is reduced at location H1 with a difference lower than 12 % in 21 November 2008. Considering the difficulties to compute the tide-induced modulation of the wave height [30], the present wave modelling seems acceptable to proceed further analysis.

TABLE I. List of experiments for the hydrodynamic forcing integrated in SISYPHE

Experiments	*TELEMAC 2D with time-varying waves*	*TOMAWAC without time-varying water depths and currents*	*TOMAWAC with time-varying water depths and currents*
E1	X		
E2	X	X	
E3	X		X

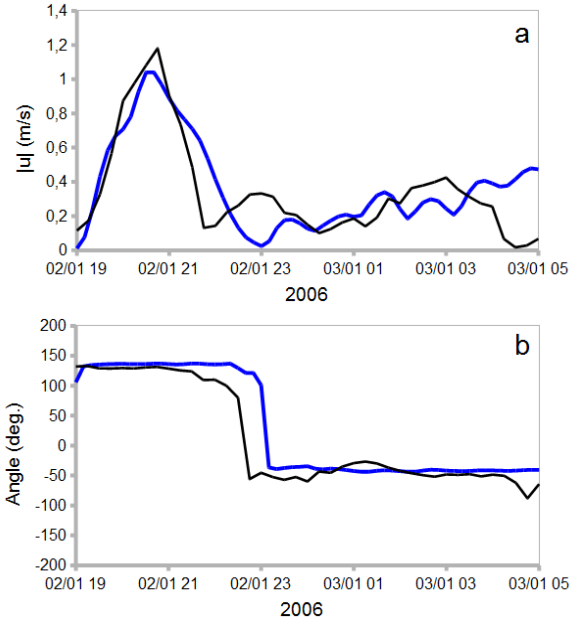

Figure 2. *Measured (black) and computed (blue) time series of (a) the module and (b) direction (clockwise from the north) of the depth-averaged currents at location C1 in January 2006 (from [19]).*

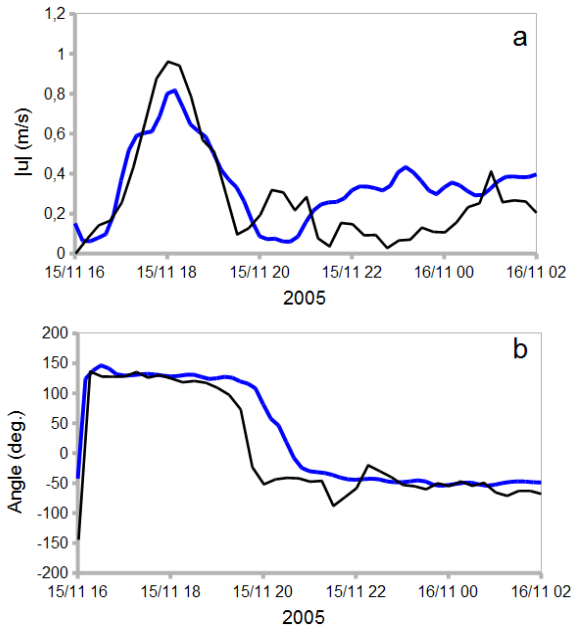

Figure 3. *Measured (black) and computed (blue) time series of (a) the module and (b) direction (clockwise from the north) of the depth-averaged currents at location C2 in November 2005 (from [19]).*

B. Effects of the Coupling on the Hydrodynamics

The comparison of the predictions at points H1 and H2 between cases E2 and E3 exhibits the importance of the tide in the semi-diurnal wave height modulation near the harbour of Le

Havre (Fig. 4). The wave height (1) increases by about 30 % at high tide and (ii) diminishes by about 10 % at low tide in the access channel to Port 2000. Further analyses [19] reveal that current-induced refraction appears to be one of the main mechanism responsible for the tidal waves height variation in the access channel to Port 2000. At the regional scale of the outer Seine estuary, the effects of the tidal currents overcome globally the effects of the water depths for the variation of the wave height with local exceptions in shallow waters off the cape of La Hève, the shoals of the Seine estuary entrance and along the southern coastline.

The effect of this coupling on the hydrodynamics is further investigated focusing on the total maximum wave and current bottom shear stress (Eq. 1) as it is a key parameter for sediment transport. Figure 5-a and 5-b displays the maximum values of the bottom current shear stress and the total maximum wave and current bottom shear stress for case E3 in November 2008. When waves are neglected (Fig. 5-a), the maximum shear stress appear in the three access channels to the Seine river with an average value of 5-6 N/m^2. Highest values over 9-10 N/m^2 are obtained at the entrance of the river and along the southern breakwater of the harbour of Le Havre. This patterns appear also with the superimposed effect of the waves (Fig. 5-b) as the inner Seine estuary is dominated by the action of the tidal current. Nevertheless, waves exhibit the total bottom shear stress over the shoals of the outer Seine estuary and the nearshore areas with average values of 11-12 N/m^2. Figure 5-c shows the relative difference of the maximum value of the total wave and current bottom shear stress predicted in November 2008 between cases E3 and E2:

$$Reldiff = 100\left(\frac{\tau^{max}_{b,c\omega}(E3) - \tau^{max}_{b,c\omega}(E2)}{\tau^{max}_{b,c\omega}(E2)}\right) \quad (11)$$

The modification of the waves components by the time-varying water depths and currents has a major impact in the shallow waters of the outer Seine estuary. The maximum value of the total wave and current bottom shear stress is thus increasing by 50 % over the shoals of the Seine river entrance and decreasing by 8 % in the three access channels. These differences may be attributed to the effects of the time-varying water depths. Over these regions, the reduction of the water depths favours the action of the wave on the seabed in spite of an increase dissipation of the wave energy with bottom friction and wave breaking.

C. Effects of the Coupling on the Sediment Transport

The effect of the modification of the wave fields by the ambient water depths and currents is further analysed by mapping the maximum SSC of mud (Fig. 6) and bedload transport rates of sand (Fig. 7) in November 2008 at the scale of the outer Seine estuary. Waves exhibit the suspension of bottom mud sediments over the shoals of the Seine river entrance with depth-averaged SSC reaching 4 g/l (Fig. 6-a). The hydrodynamic coupling (case E3) globally increases the maximum SSC with a relative difference over 30 % in the shallow waters of the southern Seine estuary (Fig. 6-b). Nevertheless, the depth-averaged SSC appears to decrease by 30 % close to the shoals of the Seine river entrance in relation to the reduction of the total wave and current bottom shear stress (Fig. 5-c). Advection processes are seemingly playing a role in the variability of the SSC restricting the correlation between the suspension and the bottom shear stress (Figs. 5-c and 6-b). The effect of the hydrodynamic coupling is less significant for the maximum bedload transport rates of sand (Fig. 7-a). The tidal currents have a major influence on bedload with highest transport rates along the three access channels to the Seine river.

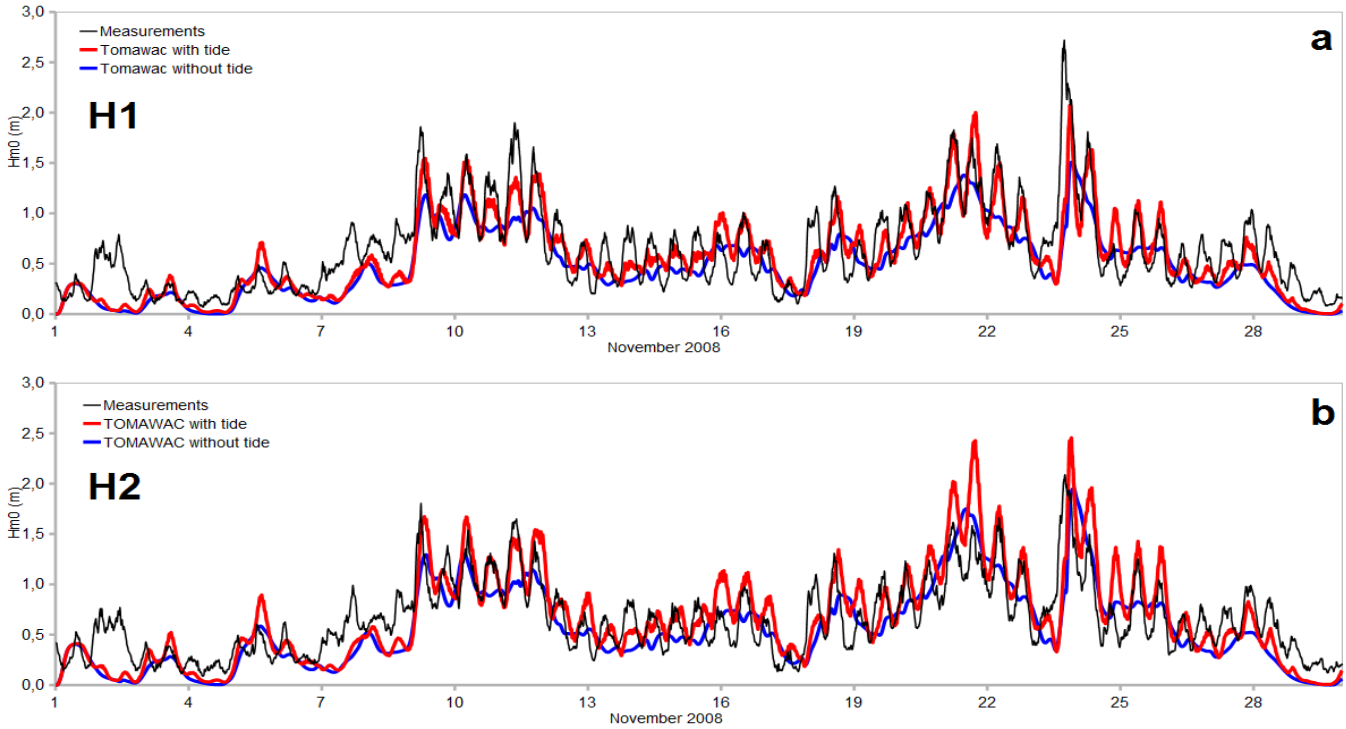

Figure 4. *Measured and computed (from experiments E2 and E3) times series of the significant wave height at locations (a) H1 and (b) H2 in November 2008 (from [19]).*

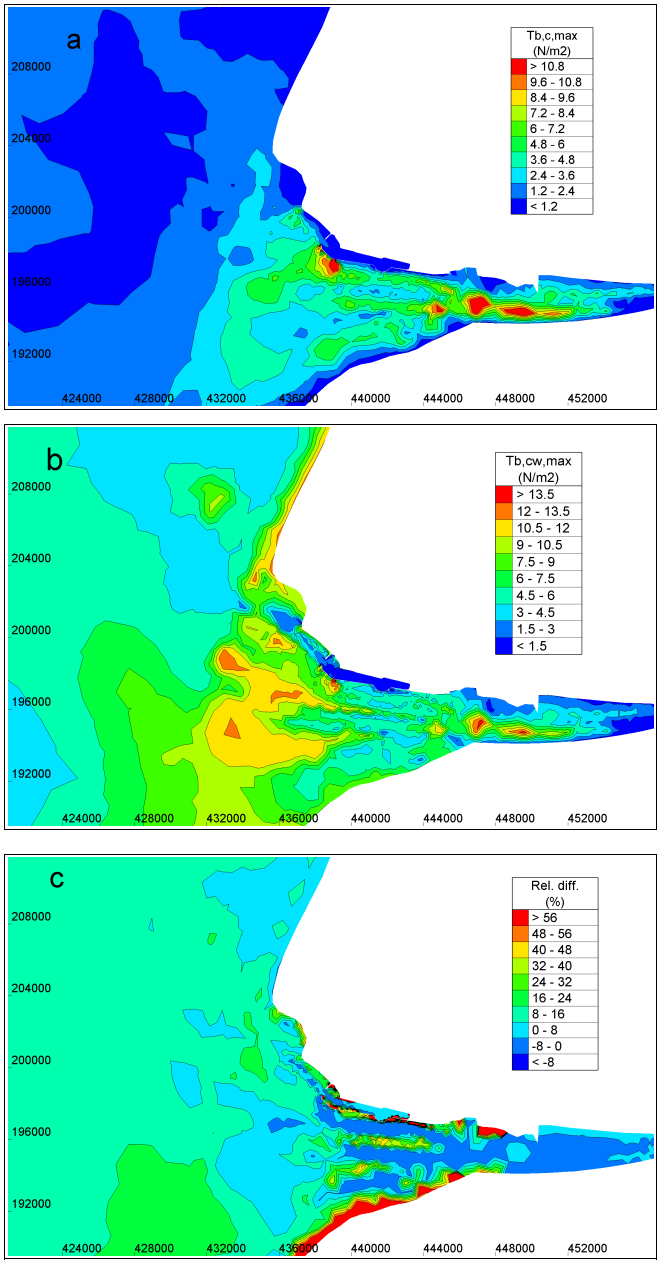

Figure 5. *Maximum values of (a) the bottom current shear stress and (b) the total maximum wave and current bottom shear stress for case E3 in November 2008. (c) Relative difference of the maximum value of the total maximum wave and current bottom shear stress in November 2008 between cases E3 and E2.*

A close relationship is thus obtained between the maximum current bottom shear stress (Fig. 5-a) and the maximum bedload transport rates when waves are integrated (Fig. 7-a). The increase of the total wave and current bottom shear stress with the hydrodynamic coupling (Fig. 5-b) results in a slight increase by 0-10 % of the total bedload transport rate (Fig. 7-b).

The resulting seabed evolutions at the end of November 2008 (Figs. 8 and 9) exhibit also the influence of the hydrodynamic coupling on sediment transport. Concerning the suspension of mud, waves increase the erosion of the shoals at the entrance of the Seine estuary and the deposition in the central channel located close upstream (Fig. 8-a). The hydrodynamic coupling tends to favour this evolution increasing noticeably the deposition patterns (Fig. 8-b). Numerical results present a slight final evolution by bedload of sand (Fig. 9-a) with tendencies to fulfil the channel entrance to the Seine river as well as the access channel to Port 2000 (harbour of Le Havre). Weak erosion appears over the northern shoal. The hydrodynamic coupling tends to increase the erosion at the entrance of the Seine estuary (Fig. 9-b).

IV. Conclusions

A numerical modelling based on circulation, wave propagation and sediment transport modules has been implemented in the outer Seine estuary to investigate the effect of the modification of the wave field by the time-varying water depths and currents on sediment transport. The main outcomes of the present study are the following:

(1) The time-varying currents have a major influence in the modulation of the significant wave height near the harbour of Le Havre.

(2) The integration of the time-varying water depths in the wave propagation module is fundamental to estimate the increase of the wave bottom shear stress and the total wave and current bottom shear stress in shallow waters.

(3) The integration of the time-varying water depths and currents in the wave module is leading to differences in sediment transport modelling, particularly noticeable for the SSC and the associated seabed evolution.

The present study is restricted to the combined effect of water depths and currents on sediment transport predictions. A prospective will consist in drawing the line between the impact of the water depths and currents. A second prospective is the implementation in the modelling application of sand-mud mixtures formulation for erosion/deposition near the bottom and consolidation effects.

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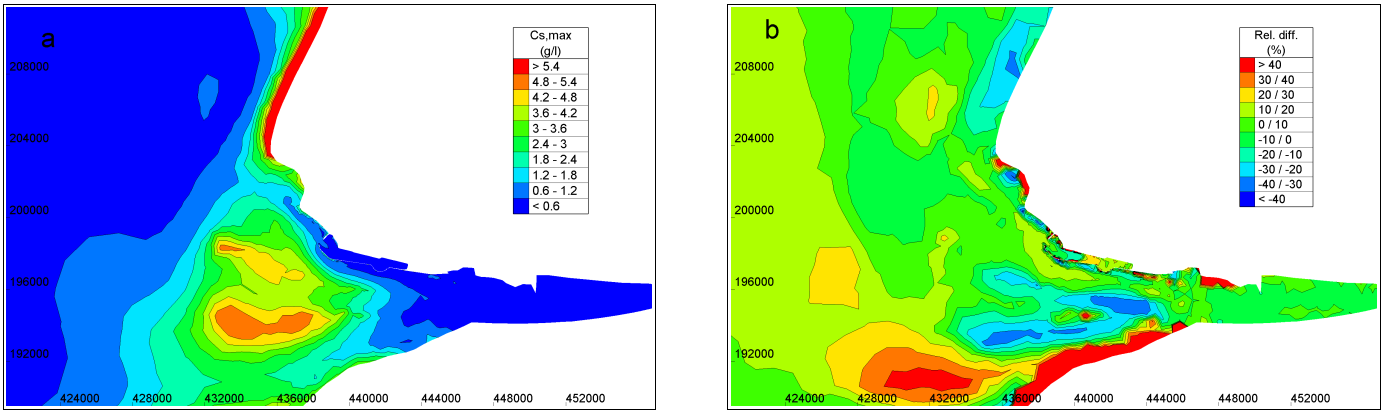

Figure 6. *(a) Maximum depth-averaged SSC of mud for case E3 and (b) relative difference of the maximum depth-averaged SSC between cases E3 and E2 in November 2008.*

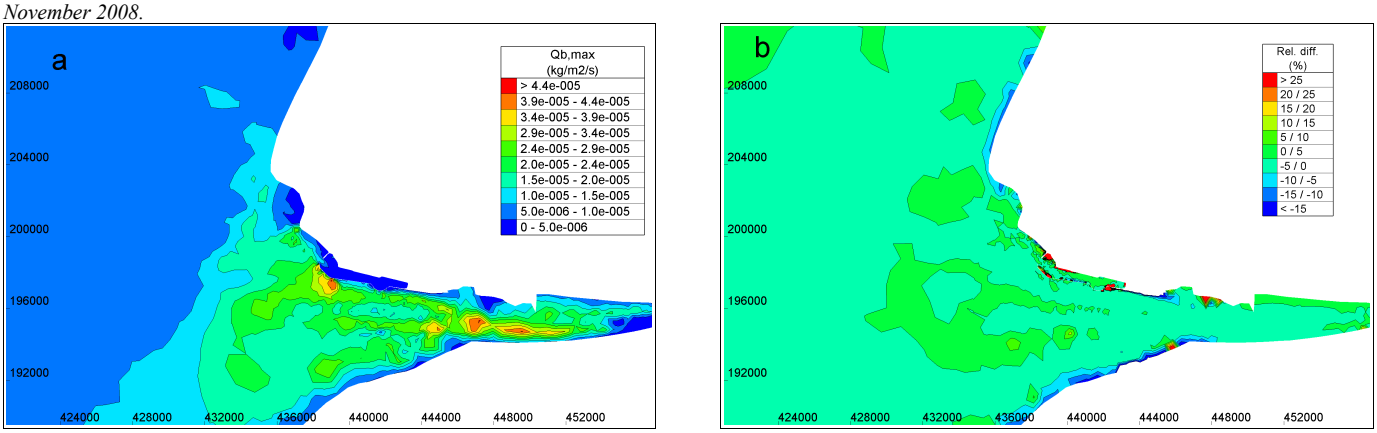

Figure 7. *(a) Maximum bedload transport rates of sand for case E3 and (b) relative difference of the maximum bedload transport rates between cases E3 and E2 in November 2008.*

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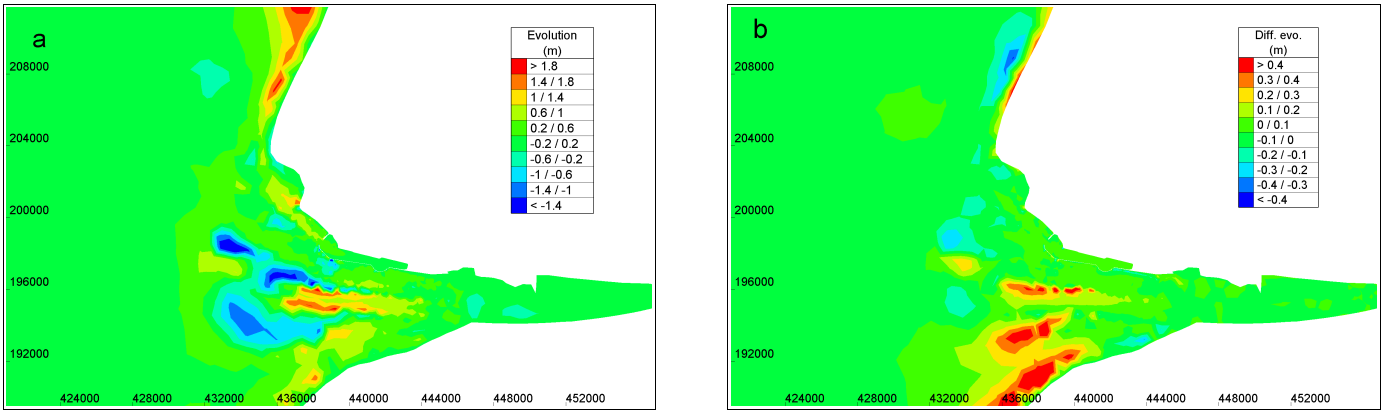

Figure 8. *(a) Seabed evolution by suspension of mud at the end of the month of November 2008 for case E3. (b) Differences between the final evolution computed for cases E3 and E2.*

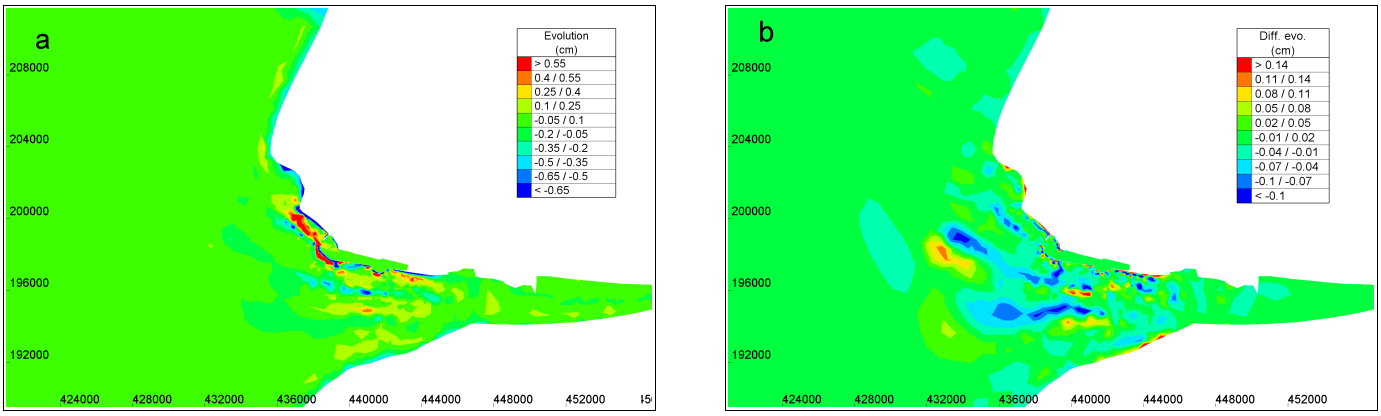

Figure 9. *(a) Seabed evolution by bedload of sand at the end of the month of November 2008 for case E3. (b) Differences between the final evolution computed for cases E3 and E2.*

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