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Numerical modelling of the turbidity maximum dynamics in a macrotidal estuary: sensitivity to hydrodynamic and hydrological forcing

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SUMMARY
The estuarine sediment dynamics, resulting from hydrological and hydrodynamic forcing, controls sediment exchanges between the river basins and the coastal sea. Here, we used a 3D numerical model to investigate the impact of tides, waves and river discharge on sediment dynamics at the mouth of the Seine macrotidal estuary, directly related to the turbidity maximum dynamics. As expected the turbidity maximum was dominantly driven by tides and in some extent by the river discharge. However, this study revealed that wave occurrence increased the suspended sediment mass by factors of 2 to 3 in the turbidity maximum zone and 2 to 8 in the global estuary mouth, highlighting the necessity to take into account this forcing when investigating estuarine sediment dynamics.

1. INTRODUCTION

The turbidity maximum (TM) is a key pattern in estuarine sediment dynamics. This highly-concentrated zone of suspended particle matters (SPM) buffers sediment exchanges between continental and coastal waters, controls channel siltation and drives bio-geo-chemical processes. The magnitude and the location of the TM is known to be strongly modulated by the river discharge and the tidal amplitude. Nevertheless, waves may also significantly affect the TM dynamics, resuspending flushed out TM sediments and hence accelerating TM reformation. Besides the quantification of the TM sediment mass and its spatial extension, the challenge is to understand its role on sediment exchanges between the river basins and the coastal sea. Based on a process-based numerical model, this study investigates the TM dynamics of the macrotidal Seine estuary (France) open to the English Channel. Since engineering works through the 20th century, the TM has been shifted downstream close to the mouth, which is exposed to strong westerly wind-waves [1, 2, 3]. The main objective of this study is to investigate the TM sensitivity to different hydrodynamic and hydrological forcing, focusing on wave effects.

2. METHODS

We used the MARS3D hydrodynamic model forced by main tidal components at the sea boundary, a realistic river discharge and wind stresses provided by ARPEGE, a meteorological model. Waves were simulated using the WAVEWATCH III® model on a series of embedded computational grids, from a large-scale model of the Atlantic Ocean down to a local model at the same resolution as the circulation model. The hydrodynamic model is coupled with a sediment model for sand and mud mixtures [4] taking into account different particle classes and suspension-deposition processes. Here, the model used one class of gravels, three classes of sand and two classes of mud, initialized according to the Seine estuary sediment distribution. A curvilinear mesh was chosen to better respect the estuarine shape, to optimize the computation costs by lengthening meshes in the direction of dominant tidal flows and to improve sediment flux estimates. Long-term (several months) *in situ* measurements of water level, velocity, hydrology, sediment resuspensions and turbidity were carried out at several locations in the estuarine mouth, the TM zone, and upstream, in order to calibrate and validate the hydrodynamic and sediment models.

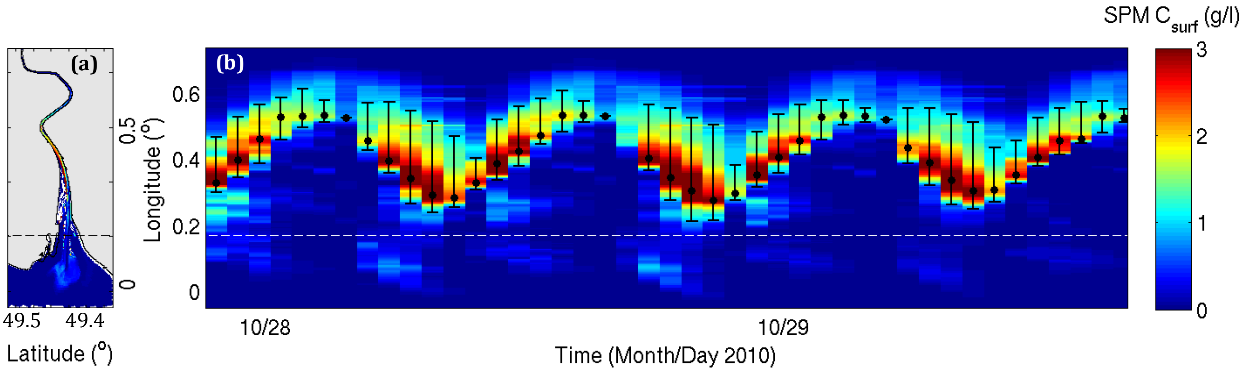

Figure 1. Reference test simulations: (a) top view of the surface SPM concentration C_{surf} in the estuary mouth domain on October 28th, 2010; (b) spring tide hourly time stacks of C_{surf} averaged across the main estuary channel stretching from offshore of the ETD zone (longitude = -0.05°W) to upstream of the TM zone (longitude = 0.74°E). The black circles represent C_{surf} maximum, and the black vertical brackets define the TM extension for C_{surf} > 1 g/l. In (a) and (b) the horizontal dashed lines represent the arbitrary boundary between the TM zone and the ETD zone.

One-year simulations (Aug. 2010 ï Aug. 2011) were run with three different hydrological and hydrodynamic forcing: (1) a reference test with realistic forcing (wind, waves, and river discharge), (2) a test without waves, and (3) a test with twice the realistic river discharge. On the one hand, simulation analysis was based on the TM longitudinal excursion and extension. The TM location was estimated from the maximum SPM concentration at the surface in the main channel of the estuary mouth (see Fig. 1). Even if the ETD sediment banks were constituted of a significant amount of sand, almost all of the SPM was constituted of mud. On the other hand, knowing that in the Seine estuary a large amount of sediments are resuspensed by waves in the ebb tidal delta (ETD) zone, the SPM mass was computed in two different domains of the estuary mouth: (i) the TM zone (longitude = [0.17°E:0.74°E]), and (ii) the ETD zone (longitude = [-0.05°W:0.17°E]), as illustrated in Fig. 1.

3. RESULTS

3.1. TM dynamics under realistic wind, tides, river discharge and waves

The reference test, combining realistic wind, tides, river discharge and waves from August 2010 to August 2011, simulated a consistent TM dynamics along the estuary: the TM was shifted outside the mouth in winter and moved upstream afterwards, with simulated SPM concentrations of the same order as the field observations. At time scale of days, the TM dynamics was essentially dominated by tides (Fig. 1). During a tidal cycle, it moved upstream (downstream) during flood (ebb) flows, characterised by a larger extension during ebb flows. TM SPM mass increased with tidal flows, especially during flood, and decreased around slack water. It is also readable that the TM extended more upstream than downstream. At a fortnightly scale, the TM moved downstream during spring tides, with a larger extension, associated with a SPM mass increase (few g/l), and inversely during neap tides (Fig. 2). Moreover, the TM shifted downstream close to the ETD in winter as the result of the increased river discharge (not shown here). We observed that the SMP mass ratio between the TM and the ETD zones was significantly related to the offshore significant wave height H_s (at longitude = -0.05°W) averaged on the previous 12 hours (Fig. 3a). Globally, the TM SMP mass was twice larger than the ETD SPM mass for H_s ~ 0, but was twice smaller for H_s ~ 2 m.

3.2. Influence of hydrological and hydrodynamic forcing

The effects of different hydrological and hydrodynamic forcing, as waves and river discharge, on TM dynamics were investigated (Fig. 2). Firstly, we observed that changing the river discharge modified to some extent the TM location/extension, but did not affect significantly the SPM mass. However, comparing the ñreferenceò and ñno waveò tests revealed that waves had considerable impacts on TM dynamics. Waves increased the TM SPM mass around twice to three times (Fig. 3b), even for small

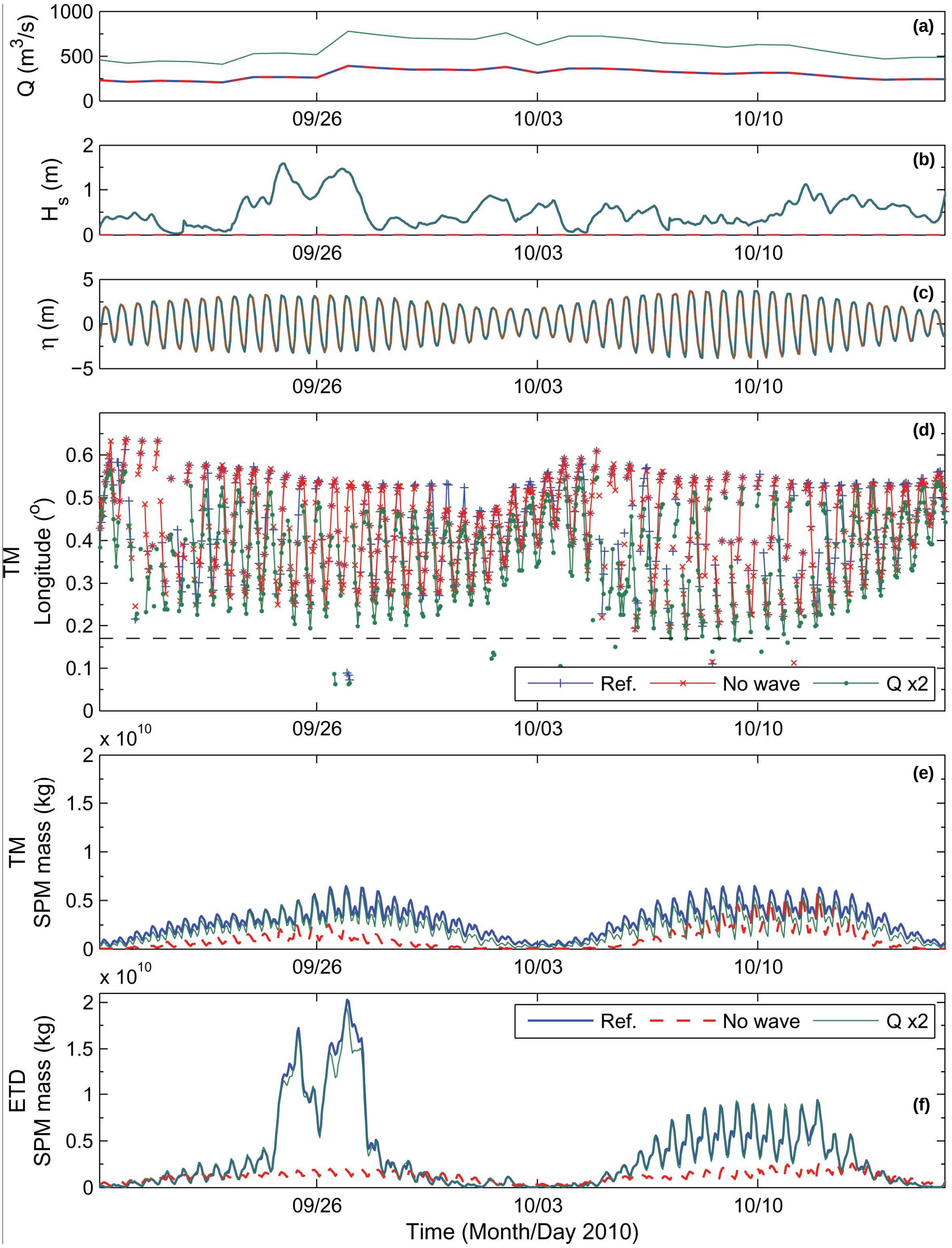

Figure 2. Time evolution of (a) measured Seine rive discharge Q, and simulated (b) offshore significant wave height H_s (at longitude = -0.05°W), (c) sea surface elevation η (at longitude = 0.17°E), (d) TM location along the main estuary channel, and SPM mass in the (e) TM zone (longitude = [0.17°E-0.74°E]), and (g) the ETD zone (longitude = [-0.05°W:0.17°E]). Simulations for three different forcing: (thick blue-solid line) reference test, (thick red-dashed line) no wave test, and (thin green-solid line) double discharge test. In panel (d), the horizontal dashed line represents the arbitrary boundary between the TM and the ETD zones (longitude = 0.17°E).

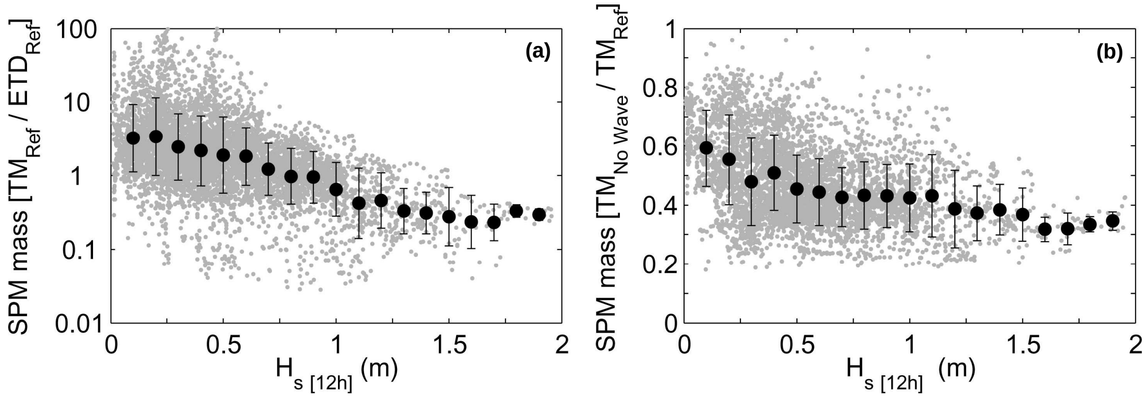

Figure 3. (a) SPM mass ratio between the TM and ETD zones for the ñreferenceò test versus the offshore significant wave height H_s (at longitude = -0.05°W) averaged on the previous 12 hours and (b)TM SPM mass ratio between ñno waveò and ñreferenceò tests versus offshore significant wave height H_s (at longitude = -0.05°W) averaged on the previous 12 hours. Simulations from September 2010 to April 2011. Circles represent class-mean values according to Hs every 0.1±0.05 m; the vertical brackets are ±1 standard deviation.

significant wave heights. In addition, waves increased the SPM mass at the estuary mouth by factors of 2 to 8 (not shown here), as waves resuspended a large amount of sediment in the ETD zone. However, it is difficult to conclude why the TM SMP mass ratio between the ñno waveò and ñreferenceò tests did not reach one when Hs Ÿ 0. It may be due to constant significant wave-induced resuspension or may result from SPM resuspended by stronger past events. This highlights that considering wave effect on estuarine sediment dynamics is here necessary, as it can represent more than 50% of the SPM mass in the estuary mouth. Nevertheless, it is interesting to point out that the TM SPM mass at the beginning of spring in April was similar for both the ñreferenceò and ñno waveò tests. It would suggest that wave-induced suspended sediment during storm events does not determine the TM SPM during following calm periods.

4. CONCLUSIONS

The TM dynamics in a macrotidal estuary was numerically investigated under different hydrological and hydrodynamic forcing (waves, river discharge). Changes in river discharge mainly affected the TM location/extension, potentially leading to TM expulsion out of the estuarine mouth during humid periods (e.g. winter). This study revealed that waves during storm events had an important impact on estuarine sediment dynamics. Waves resuspended a large amount of sediment in the ebb tidal delta zone and increased the TM SPM mass twice to three times. Consequently, waves must be taken into account for properly simulating the estuarine sediment dynamics. These advances on the numerical modelling of suspended sediment dynamics will enable to improve the simulation of estuarine morphodynamics at various time scales from events to years.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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