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Nicolas Guillou, Georges Chapalain. MULTIPHYSICS AND MULTISCALE COUPLINGS FOR WAVE HEIGHT MODELLING IN LE HAVRE HARBOUR. SimHydro 2012:New trends in simulation, Hydroinformatics & 3D modelling, Sep 2012, Nice, France. hal-01505299

HAL Id: hal-01505299

<https://hal.science/hal-01505299>

Submitted on 11 Apr 2017

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MULTIPHYSICS AND MULTISCALE COUPLINGS FOR WAVE HEIGHT MODELLING IN LE HAVRE HARBOUR

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KEY WORDS

tidal currents, Port 2000, Seine estuary, MISTRAL, COHERENS, TELEMAC, TOMAWAC, ARTEMIS.

ABSTRACT

A sensitivity study is performed to investigate the importance of multiphysics and multiscale couplings for modelling wave height in the outer Seine estuary (English Channel), the harbour of Le Havre and its new infrastructures Port 2000. Multiphysics coupling focuses on the effects of the tide in terms of time-varying water depths and currents on wind-generated surface-gravity waves. Simulations are based on the coupling of phase-averaged wave-propagation modules with circulation modules. This coupling is evaluated by comparing numerical results of the significant wave height with field data collected in November 2008 at two wave buoys moored in the access channel to Le Havre harbour. Predictions confirm a periodic local increase reaching 30 % of the wave height induced by current refraction. Multiscale coupling focuses on the importance of nested computational domains for predicting wave heights in the inner basin of Port 2000. A phase-resolving wave module is set up at this ultimate scale. Need of coupling this module with simulations at the scale of the outer Seine estuary is evaluated by comparing wave-agitation modellings driven by spatially-uniform and spatially-varying forcings with measurements in the inner basin. This comparison highlights the sensitivity of predictions to the directions of waves approaching the harbour entrance.

1. INTRODUCTION

Reliable predictions of wave conditions in coastal areas are of leading practical interest to coastal engineering applications associated with harbour/inlet maintenance and nearshore morphologic change. In the last decades, theoretical developments have refined our understanding of nearshore wave evolution focusing on the modifications of wind-generated surface-gravity waves by ambient currents [1, 2, 3]. Modelling systems have reached a high standard integrating this multiphysics coupling. Accuracy of numerical results increased also with standard use of multiscale embedded computational domains. Whereas high performance computations allow to enrich simulations very easily, the questions of incorporating multiphysics and multiscale couplings are raised to optimize simulations.

The purpose of the present study is to investigate the importance of both couplings for modelling the wave height in the outer Seine estuary (southern central English Channel), the harbour of Le Havre and its new infrastructures Port 2000 (Fig. 1). The area of interest is characterized by strong interactions between wave and tide with (i) spring tidal range of 7 m and current amplitude of 1.5 m s⁻¹ [4] and (ii) annual wave height over 5 m offshore [5]. Sensitivity to multiphysics coupling focuses on the effects of the tide-induced time-varying water depths and currents on wave height in the outer Seine estuary. Multiscale coupling investigates the importance of nested computational domains for predicting wave-height agitation within Port 2000 inner basin.

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Regional modelling is based on the coupling of phase-averaged wave-propagation modules with circulation modules at the scales of the English Channel and the North Sea, the bay of Seine and the outer Seine estuary (section 2.1.1). Local modelling consists in running a phase-resolving wave module at the scale of the harbour inner basin (section 2.2.2). Multiphysics and multiscale couplings are evaluated by comparing wave-height predictions with measurements characterized by noticeable semi-diurnal variations in the access channel to Le Havre harbour and its inner basin (sections 2.2 and 3.1). Tidal currents are found to have a significant influence on semi-diurnal wave-height variations in the access channel to Port 2000 exhibiting the importance of multiphysics coupling (section 3.2). Benefits of multiscale coupling are emphasized by the sensitivity of wave-agitation predictions to the direction of waves approaching the harbour entrance (section 3.2).

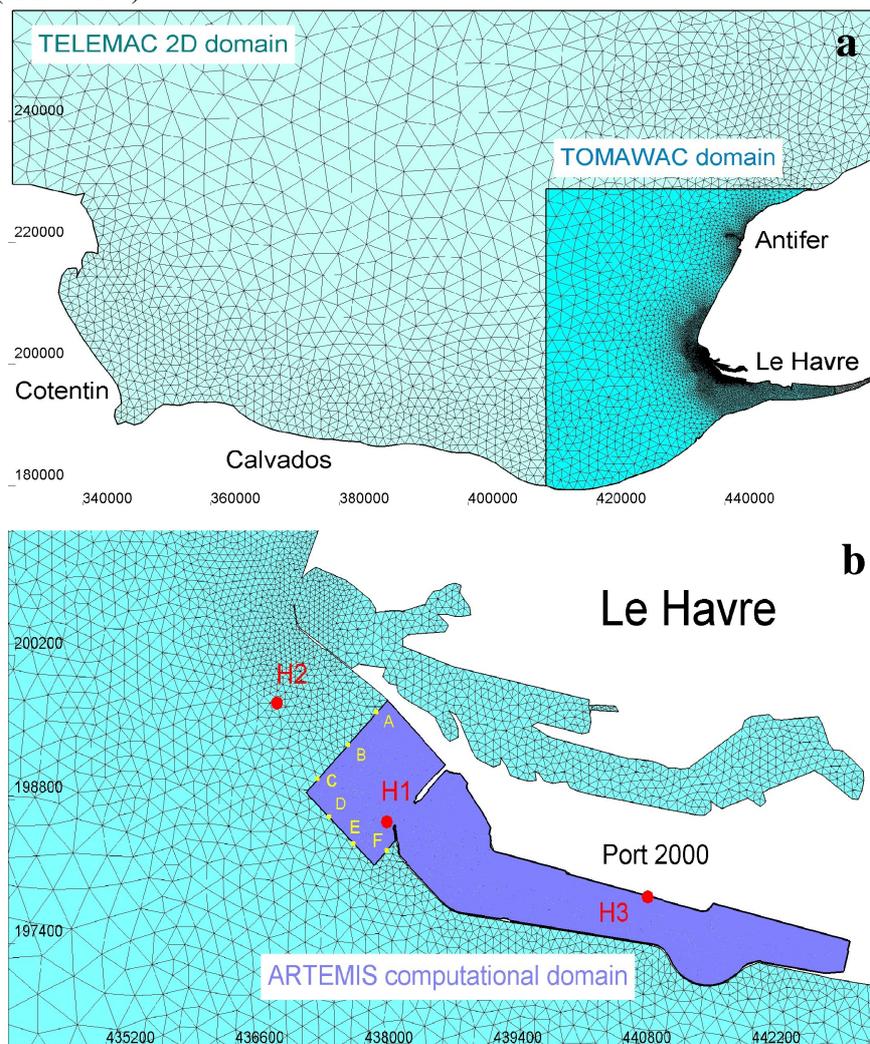


Figure 1: (a) TOMAWAC and TELEMAC 2D computational domains. (b) Close-up of the computational mesh near the harbour of Le Havre with ARTEMIS computational domain and the locations of (1) points A-F along its open boundary and (2) wave buoys H1, H2 and H3. Coordinates are indicated in meters according to the French system “Lambert I Nord”.

2. MATERIALS AND METHODS

2.1 Models Description and Setup

Modelling relies on regional and local computations dedicated to the analysis of multiphysics and multiscale couplings, respectively.

2.1.1 Regional Modelling

Regional simulations are performed with the two nested modelling systems: (1) MISTRAL (“Modélisation Intégrée pour la Simulation des TRANSPORTS Littoraux”) [6] in the English Channel and the North Sea and (2) TELEMAC [7, 8] in the Bay of Seine (Fig. 1-a). Each modelling system couples circulation and phase-averaged wave-propagation modules. MISTRAL is based on the coupling of the wave propagation module SWAN (Simulating WAVes Nearshore) [9] with the three-dimensional (3D) circulation module COHERENS (COupled Hydrodynamical Ecological model for RegioNal and Shelf seas) [10]. TELEMAC couples the wave propagation module TOMAWAC [7] with the bidimensional horizontal (2DH) circulation module TELEMAC 2D [8]. The coupling procedure is restricted to (1) the modifications of the wave fields by the time-varying water depths and currents and (2) the interaction between wave and current bottom boundary layers ignoring the generation of currents by waves. Preliminary tests showed the moderate impact of the second type of interaction on hydrodynamics computed by the circulation module. This makes it easier to investigate the effects of the first type of interaction. Further details about these two modelling systems, the numerical resolution, as well as the implementation at the regional scales are available in [11].

The analysis of multiphysics coupling relies on two numerical configurations: (1) case A in which waves modules are run without the effects of the tide on the wave field and (2) case B in which the effects of the tide on the wave field are implemented. Differences between both simulations are quantified with the average of the absolute differences in wave height predictions.

2.1.2 Local Modelling

Local modelling is based on the phase-resolving wave-agitation module ARTEMIS (Agitation and Refraction with Telemac on a MildSlope) [12] of the modelling system TELEMAC. ARTEMIS is implemented on a domain covering the inner basin of Le Havre harbour and its access channel (Fig. 1-b). Whereas numerical developments have been achieved in incorporating tidal-current in wave-agitation computations [13], the present modelling ignored these effects, focusing on the modulation induced by penetration of tide-influenced waves within the harbour basin. Time-varying water depths are however integrated from TELEMAC 2D numerical results. Open boundaries conditions (significant wave height, period and direction) are extracted from TOMAWAC regional predictions. Further details about ARTEMIS setup and parametrizations of coastal boundary conditions (reflection coefficients, direction of approaching waves and phase shift) within Port 2000 inner basin are available in [14].

Need of multiscale coupling between ARTEMIS and TOMAWAC is evaluated by comparing predicted wave agitations driven by spatially-varying and spatially-uniform forcings. The latter configuration is equivalent to drive ARTEMIS by external measurements at a single location in the entrance channel. A series of seven positions is retained to evaluate the possibility to drive the wave-agitation module by spatially-uniform forcings. This corresponds to six points titled A to F evenly spaced along ARTEMIS open boundary and the measurement point H1 (Fig. 1-b). Time series of significant wave height, period and direction are extracted from TOMAWAC simulation in case B (with tide) at each location. Differences between observations and predictions of each configuration are quantified through the standard statistical parameters of bias (positive bias represents in this investigation underestimates by the model), average of the absolute differences and root mean square error (RMSE).

2.2 Experiment Description

Measurements used here are provided by the “Grand Port Maritime du Havre” (G.P.M.H.). Measurements were made at three wave buoys H1, H2 and H3 in the access channel to Le Havre harbour and its inner basin (Fig. 1-b). The wave buoys H1 and H2 were implemented in the access channel as part of an observational system to regulate the ship routing. The wave buoy H3 was set up to complete measurements in the inner harbour. The period analyzed here is the month of November 2008. It is characterized by (1) a maximum significant wave height of 2.8 m in November 23, 2008 at point H1 and (2) a maximum tidal range of 7 m in November 14, 2008 at the tide gauge of the harbour. Further details about the instrumentation system are available in [11] and [14].

3. RESULTS AND DISCUSSION

3.1 Comparison of Model Predictions with Point Measurements

TOMAWAC predicted time series of wave height are compared with measurements at points H1 and H2 (Fig. 2). The comparison is not extended to point H3 as phase-averaged modules fail in simulating wave penetration within harbour basin. When the effects of the tide are integrated (case B), the numerical results reproduce the semi-diurnal variation of the wave height. An overall agreement is thus obtained between predictions and measurements. Numerical results tend to slightly overestimate the wave height at point H2 during the storms on November 21 and 24, 2008. This tendency is however reduced at location H1 with a difference less than 12 % on November 21, 2008.

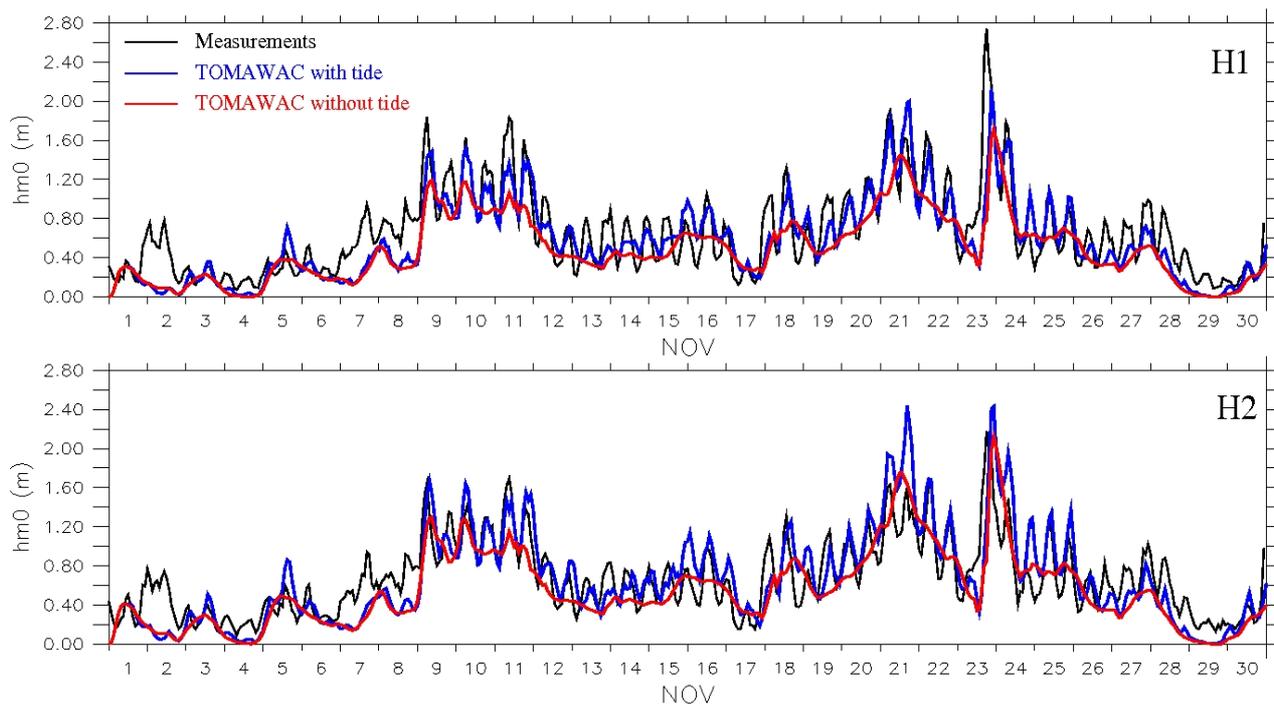


Figure 2: Measured and TOMAWAC computed for cases A and B time series of the significant wave height at locations H1 and H2 in November 2008 (from [11]).

Comparison of wave-agitation predictions with measurement is restricted to November 19-27, 2008 characterized by higher wave periods in order to satisfy the mesh-size constraints of the numerical resolution [14] (Fig. 3). Numerical results reproduce the semi-diurnal modulation of the wave height from the entrance channel till the inner harbour. Predictions approach the evolution of the significant wave height at point H3 while underestimating measurements at the beginning of the simulation from 19 to 20 November, 2008. Whereas predicted-storm wave-height of November 23 falls in the range of observed values, it presents a 30 min-time lag compared to measurements. Nevertheless, ARTEMIS computations constitute a satisfactory numerical approach of wave-height conditions at the measurement site within the harbour basin.

3.2 Sensitivity to Multiphysics Coupling

The comparison of predictions at points H1 and H2 between cases A and B exhibits the importance of the tide in the semi-diurnal wave-height modulation near the harbour of Le Havre (Fig. 2). The wave height (1) increases by approximately 30 % at high tide and (2) diminishes by about 10 % at low tide in the access channel to Port 2000. Further investigations integrating separately the effects of the time-varying water-depths and currents show that current-induced refraction is one of the main mechanism responsible for the tidal variation of the wave height in the access channel [11]. Outer modulations of the wave height are thus

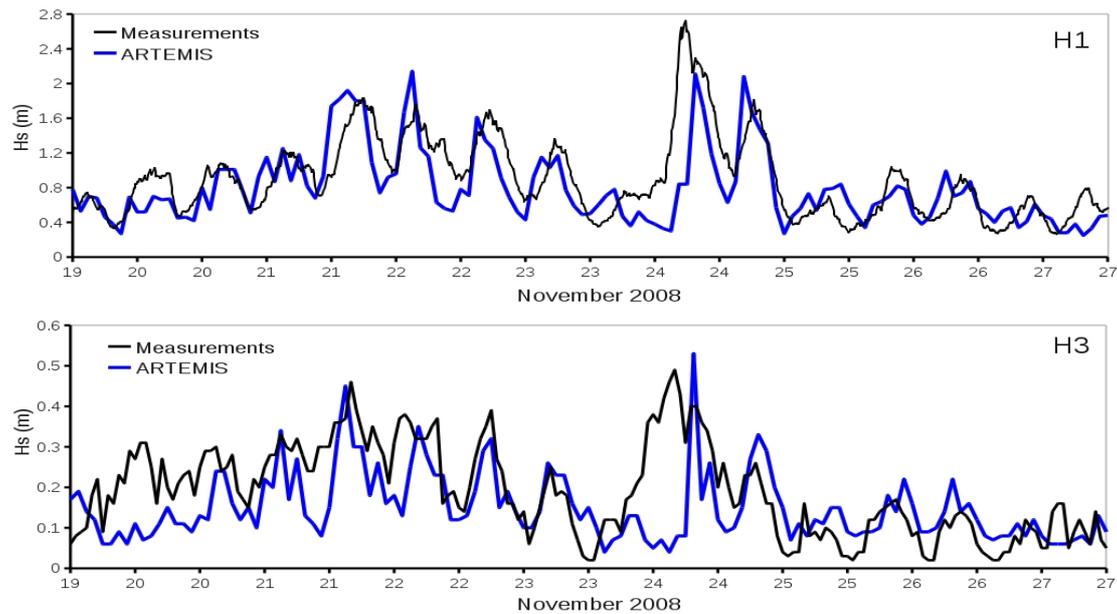


Figure 3: Measured and ARTEMIS computed time series of the significant wave height at locations H1 and H3 in November 19-27, 2008 (from [14]).

associated with changes in the approaching-wave direction exposing periodically the harbour entrance to high wave conditions.

This analysis is extended at the scale of the outer Seine estuary with a mapping of the areas where the wave heights are modified by the tide (Fig. 4). This mapping is based on the average of the absolute differences in wave heights between cases A and B. The spatial distribution of this criterion confirms the influence of the tide at the scale of the outer Seine estuary. Its average values is 0.12 m with maximum over 0.20 m in shallow waters and the access channels to the Seine River. Minimum values are obtained in areas of low agitation at the mouth of the Seine River.

3.3 Sensitivity to Multiscale Coupling

Weak differences are denoted in the evolution of predicted waves components at points C, D, E and F on November 19-27, 2008. It is restricted to slight variations in the time series of the approaching wave directions. Four locations are thus retained to perform the sensitivity analysis: A, B, C and H1. Table 1 compares the statistical results of the estimation of the observed wave height at location H3. Positive biases are obtained in all simulations, exhibiting the tendency of numerical predictions to slightly underestimate wave-height measurements. This tendency is associated with TOMAWAC predictions along the open boundary of ARTEMIS computational domain (Fig. 2). Best results are obtained with forcings at points C and H1. The associated average of the absolute differences and root mean square errors are similar to those obtained with spatially-varying forcings. Estimate of the bias is even better for the simulation driven by forcings at point C.

Further investigation is conducted by displaying the predicted maximum wave height in November 19-27, 2008 from simulations driven by spatially-varying forcings and spatially-uniform forcings at points C and H1 (Fig. 5). In the eastern part of the harbour basin, wave agitations obtained with spatially-uniform forcings are quite similar to initial numerical estimates with spatially-varying forcings. Significant differences are however exhibited at the western entrance. Prediction driven by forcings at point C is thus presenting a band with a width of 150 m directed towards the southern breakwater where the wave height exceeds 2.1 m. Simulation driven with forcings at point H1 results in lower maximum wave height at the western entrance with a weaker exposition of the southern breakwater than in the reference situation. Time series of waves components extracted from TOMAWAC simulations at points C and H1 vary mainly in the

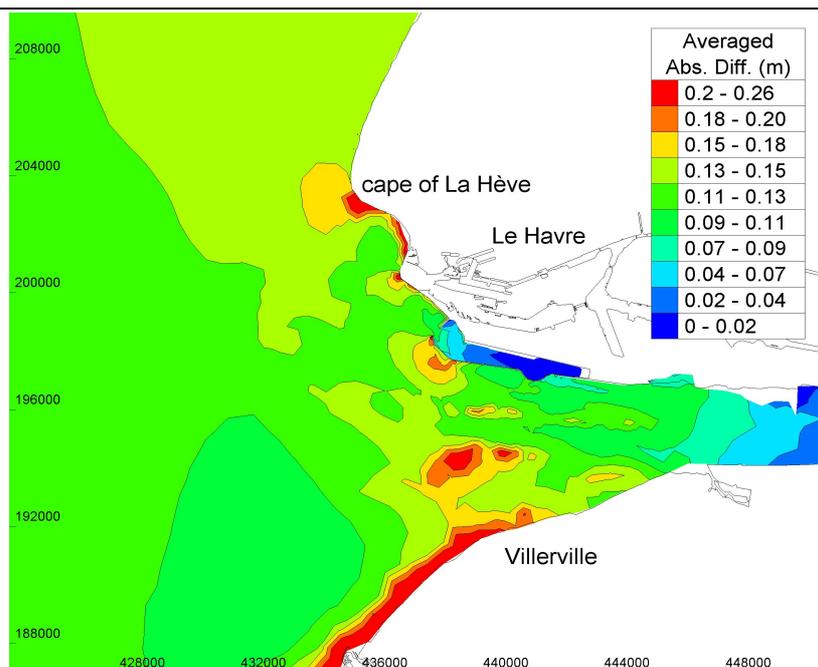


Figure 4: Average of the absolute differences between significant wave heights predicted from cases A and B in November 2008.

ARTEMIS boundary conditions		Bias (m)	Av. abs. diff. (m)	RMSE (m)
Spatially-varying forcings	Reference simulation	0.039	0.084	0.11
	Point A	0.101	0.110	0.14
Spatially-uniform forcings	Point B	0.045	0.094	0.12
	Point C	0.014	0.085	0.11
	Point H1	0.034	0.087	0.11

Table 1: Statistical results of ARTEMIS estimations of observed wave height at location H3 with various open boundary conditions.

prediction of the approaching wave direction. Differences between Figures 5-a, b and c may result from the sensitivity of model predictions to the direction imposed along ARTEMIS open boundary. Further measurements are however required to approach the variability of the approaching-wave direction in the access channel to Le Havre harbour and the wave height in the western area of the inner basin. The present investigation underlines the difficulty to drive the agitation module by external measurements at a single location.

4. CONCLUSIONS

Nested regional and local modelling systems based on the coupling of wave propagation and circulation modules have been used to investigate the importance of multiphysics and multiscale couplings in the outer Seine estuary and the harbour of Le Havre. The main outcomes of the present study are the following.

(1) Multiphysics coupling associated with the interaction between waves and tidal currents is fundamental for an accurate estimate of the wave height in complex coastal areas. Current-induced refraction is thus one of the main mechanisms responsible for the local tidal waves height variation in the access channel to Port 2000. Changes in the incident wave directions modulate the exposure of the measurement points increasing by approximately 30 % and decreasing by approximately 10 % the wave height.

(2) Multiscale coupling associated with the nesting of a phase-resolving wave module with a phase-averaged wave module remains the most appropriate method to approach wave agitation within the harbour basin. Driving the wave agitation module by external measurements at a single location suffers from the sensitivity of predictions to the approaching-wave directions in the western area close to the harbour entrance.

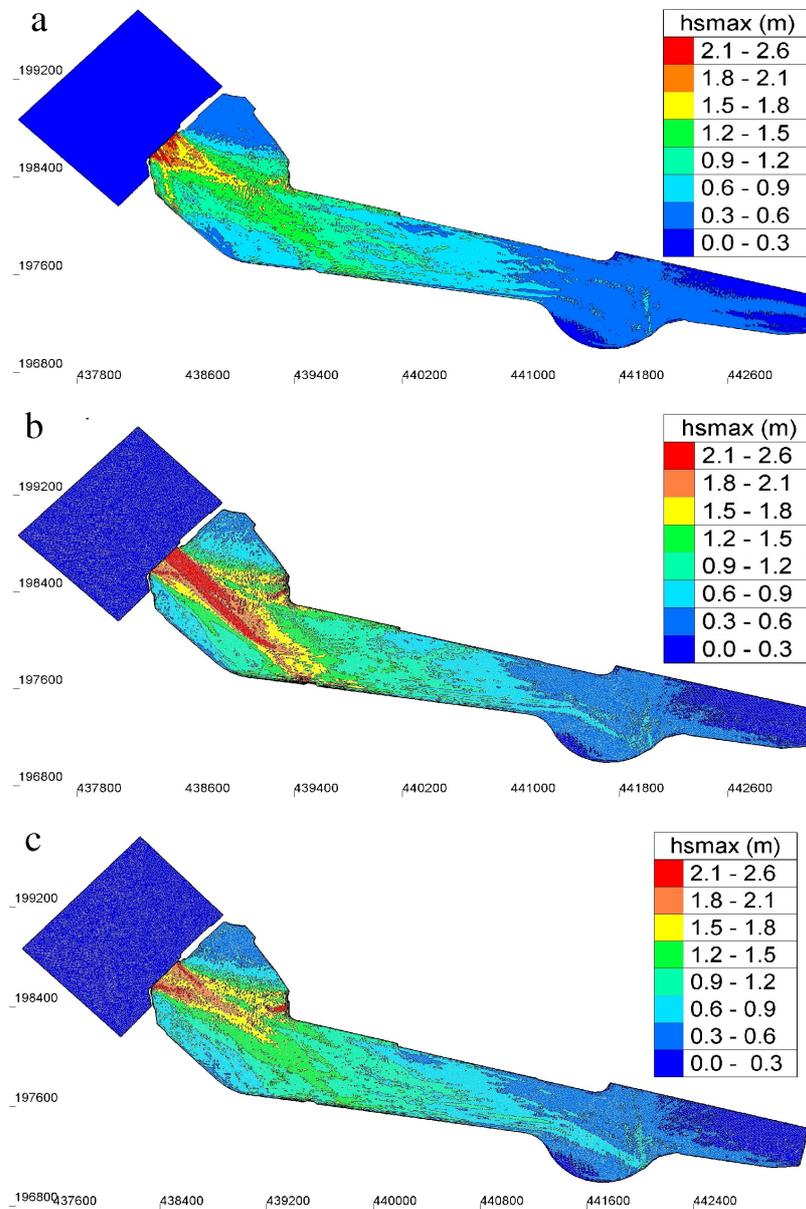


Figure 5: ARTEMIS predicted maximum wave height in November 19-27, 2008 in the inner basin of Le Havre harbour from simulations driven by (a) spatially-varying forcings and spatially-uniform forcings at points (b) C and (c) H1.

ACKNOWLEDGEMENTS

We are particularly grateful to Ronan Schubel (“Grand Port Maritime du Havre”, France) for providing us with bathymetry and wave buoys measurements in the harbour computational domain. The present study has been achieved in research projects HERMES/AZOLIM and HERMES/APORT of the Laboratory of Coastal Engineering and Environment (<http://memphys-lgce.fr.ht>).

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