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Improving simulations of extreme skew surges through waves' contributions

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Abstract—**The coastal flood risk assessment is an overriding priority for EDF to ensure the nuclear safety. For this reason, statistical methods linked to Extreme Value Theory (EVT) are carried out to evaluate extreme events associated to high return periods (up to 10^3 years). Usually, these evaluations are applied to time series from 30 to 50 years and extreme estimations are not very accurate. A potential way to improve statistical estimations of extreme events is the use of historical data ([6], [7], [4]). Before to properly use them in a statistical analysis, the validation of historical records is needed.**

Numerical models may be complementary to historical values and they may even validate historical values recovered and reconstructed from several sources. Firstly, it is necessary to achieve a deep examination of the numerical models during several well-known extreme events in order to be able to validate historical events. In this study, extreme sea levels and, in particular, extreme skew surges simulated by a TELEMAC-2D model are considered.

TELEMAC-2D allows to simulate free-surface flows in two dimensions and to compute sea levels taking into account meteorological conditions during a storm. Unfortunately, not considering waves' contributions in simulations ([15], [14]) leads to non-accurate results. Waves' contributions can represent a significant part of skew surge [21]. In the present work, waves' contributions are taken into account in the computation of the surface drag coefficient C_D, using the Charnock relation, and the consideration of wave stresses. A sensitivity analysis of the Charnock coefficient is studied to find an optimal value.
Extreme skew surges are computed from simulations and these values are compared to measurements. Better results are obtained considering waves' contributions.
The model is tested for three of the well-known storms that impacted French coasts in 1987, 1999 and 2010, respectively The Great Storm of 1987, Lothar-Martin storms and Xynthia storm.

I. INTRODUCTION

The safety of nuclear power plants located along the coasts is one of the main priorities for EDF. Indeed, due to their proximity to the sea, coastal nuclear stations are subjected to the aggressions of extreme meteo-oceanic conditions such as sea levels, surges and waves. It is crucial to provide an accurate coastal risk assessment in order to be able to design effective protections. As part of the prevention of risks, numerical models allow to simulate storm events to study the different physical variables and processes involved. In this context, a lot of effort has been spent to improve simulations of extreme sea levels. The model has to be suitable for extreme events and effective at representing skew surges and in particular the maximum skew surge, our variable of interest in this study. The skew surge is the difference between the maximum observed sea level and the maximum predicted astronomical tide level during a tidal cycle ([22], [23], [6]). The risk of coastal flooding is bigger at high water conditions and justifies working with the maximum skew surge. Skew surge time series at several locations along French and British coasts can be obtained with the model.

At the Saint-Venant Hydraulics Laboratory (LHSV), a surge numerical model based on TELEMAC-2D software was built a few years ago [15] and then globally validated with additional tests [14]. The model showed relatively bad performances for the estimation of maximum skew surges along some regions such as Pays de la Loire or Nouvelle-Aquitaine. Waves' contributions had not been taken into account yet in [14] and at least for this reason, skew surges may have been underestimated for most of the study sites along the French coastline. Storm surges are generated by the meteorological forcing, in particular wind and pressure [8], and also by the waves. Waves' contributions can be divided into three components [17]: sea surface drag coefficient modification with the nature of waves, bottom friction and wave set-up. The positive relevance to use wave set-up and atmospheric effects in simulations, for instance, through a better surface drag parameterization, has been shown as part of the Previmer-Surcotes project [13].

The aim of this study is to improve the performances of the TELEMAC-2D model in South of the North Sea, English sea, and Biscay Bay and to provide the best simulated skew surge during an extreme event. As a first step, satisfactory results for maximum skew surges for some recent and well-known storms are expected. For this reason, a comparison between observed skew surges recorded by tide gauges and simulated skew surges has to be done in order to verify the numerical model. Finally, the model may be used to validate historical skew surges. Since historical data can be associated with considerable uncertainties, simulations generated by a reliable model can help us to determine if these skew surges likely happened in the past and so if they should be taken into account in the statistical of extreme events or not.

This paper presents the implementation of the waves' contributions in the TELEMAC-2D surge model through Charnock formulation and wave stresses. In addition, a validation part with three well-known storms The Great storm of 1987, Lothar-Martin (1999) and Xynthia (2010) is carried out. All the physical processes involved and their modelling are fully described in Sect.2. Sect.3 presents the results for the estimation of the maximum skew surges for each storm in different sites along the French coasts.

II. NUMERICAL MODEL AND SIMULATIONS

In this study, TELEMAC-2D (T2D) solves the Shallow Water Equations and some user FORTRAN sub-routines (for instance, prosou.f) are adapted to simulate skew storm surges. The numerical model is based on the one of [14] but a sub-routine has been changed and some input data have been added in order to consider waves' contributions. The TELEMAC-2D model extends from 10°W to 14°E and from 42°N to 64°N and includes French and British coasts (Fig. 2). The mesh (called mesh 2 in Fig. 3) is unstructured: it is particularly refined near the coastline, with one node per kilometer. Off the French coasts, the greatest distance between two nodes is around 40 km. The bathymetry "North East Atlantic Europe" (NEA) provided by the LEGOS is used. The data base for the harmonic constants is provided by the LEGOS [11] atlas to be consistent with the bathymetry. Initial water level and tidal currents are computed from the Atlantic Ocean solution of TPXO [12] database by OSU. The bottom friction is parametrized by the Chézy formulation with a constant coefficient of 70 m$^{1/2}$/s.

The meteorological forcing is provided by The National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) [20]. In our study, mean level atmospheric pressure at the sea level and horizontal components of wind (at 10 m) are used. Selected hourly time-series variables are available from January 1979 to December 2010. Besides a great temporal resolution, the fine spatial resolution $(0.301° \times 0.301°)$ is necessary to represent precisely the atmospheric phenomena. Using a Python program, CFSR data are interpolated and a single SELAFIN file containing pressures and wind velocities data is obtained. To compute simulated skew surges, two simulations are achieved (Fig. 3): the first with meteorological forcing, the second one without (only tide propagation is used). Tidal simulations have been validated previously for several French harbours [14]. However, for some sites, an error up to 30 cm has been found during high tide. In our study, skew surges are considered and particularly the maximum skew surge as extreme values are sought. Substracting maximum predicted astronomical tide level to maximum observed water levels, potentially occurring with a time lag, leads to skew surge levels. The results are compared to those observed by the French Navy Hydrographic and Oceanographic (SHOM). For each storm event, a simulation, beginning seven days before the date of the storm and ending four days after, is run. The simulation time step is 30 s, according to [15].

III. IMPROVEMENT ON EXTREME EVENTS SIMULATIONS

The quality of a storm surge model depends on the accuracy of the input data, being the meteorological forcing, the spatial and temporal resolution and also the physical processes modelled. Storm surges were not properly modelled so far because at least waves' contributions were not taken into account: only the tide and the surge induced by the atmospheric forcing were integrated in the model. In order to improve skew surges estimations using waves' contributions in our model, the parametrization of the sea surface drag coefficient has to be firstly modified. This allows to describe more precisely the air-sea interaction. Secondly, wave stresses have to be considered during the simulations.

A. Sea surface drag coefficient

The wind influence is represented by a dimensionless sea surface drag coefficient C_D. This coefficient can be calculated with several formulations and most of them depend on the wind magnitude velocity at 10 m, U_N. C_D models complex phenomena. In fact, the wind influence depends on U_N but also on the roughness of the sea surface, which is itself dependent on the wind and the distance over which it is applied (fetch) [10].

In TELEMAC-2D, the wind influence is represented by the following formulation of Flather (Fig. 1): $C_D = 0.565 \times 10^{-3} if U_N \leqslant 5\,m/s$

$$C_D = (-0.12 + 0.137U_N) \times 10^{-3} if 5\,m/s \leqslant U_N \leqslant 19.22\,m/s$$

$$C_D = 2.513 \times 10^{-3} if U_N \geqslant 19.22\,m/s$$

With this formulation the coefficient only depends on U_N, whereas the wind influence may also depends on the roughness of the sea surface induced by the waves (characterized by the sea state). Charnock formulation suggests that the roughness length z_0 of the wind profile depends on the kinematic viscosity ν in the case of weak wind or on the Charnock relation (1) in the case of strong wind (above 20 m/s), for instance during a storm [9]:

$$z_0 = (\alpha_{CH} U_{STAR}^2)/g \qquad (1)$$

where α_{CH} is the dimensionless Charnock coefficient; U_{STAR}, defined by $U_N/25$ [9], is the friction velocity (m/s) and g is the gravitational acceleration (m/s²). z_0 is linked to the sea surface drag coefficient C_D according to the following relation (2):

$$C_D = \kappa^2 log(z/z_0)^{-2} \qquad (2)$$

κ=0.4 is the Von Karman constant and z is the altitude (m).

The Charnock coefficient models the surface roughness of the ocean and varies in time and space. α_{CH} (usually between 0.01 and 0.04, 0.018 is a typical value) depends on the sea state and on the wage age [24]. A wave model should be used to obtain a Charnock coefficient which takes into account the sea state. For example, WaveWatchIII gives α_{CH} from 1990 to 2018, based on CFSR or ECMWF reanalysis, and those data can be read in TELEMAC-2D. The consideration of waves' contributions through this database allows to improve the estimation of surges [18]. For the purpose of studying historical storms, a database for the Charnock coefficient that goes back further in the past is needed. The spectral wave model used at the LNHE, TOMAWAC, does not allow the computation of α_{CH} for the moment. It would require some developments that is why, as a first step, the formulation of Charnock has been implemented in TELEMAC-2D with a α_{CH} as a parameter fixed by the user and thus constant in time and space. The Charnock formulation gives more flexibility for the range of value of the drag coefficient. Higher values can be reached for the higher wind speed (increasing α_{CH}) in comparison with the formulation of Flather (Fig. 1). Thus, the Charnock coefficient can be used to strengthen, or not, the wind influence, depending on the value of α_{CH}. However, recent studies ([19], [5]) have shown that for winds greater than 33 m/s, the drag coefficient starts to decrease (Fig. 1). Hence, the Charnock formulation is not correct anymore and other formulations like Makin [16] should be used instead. In this paper, the maximum wind measured during the three considered storms is below 33 m/s so Charnock formulation has been kept.

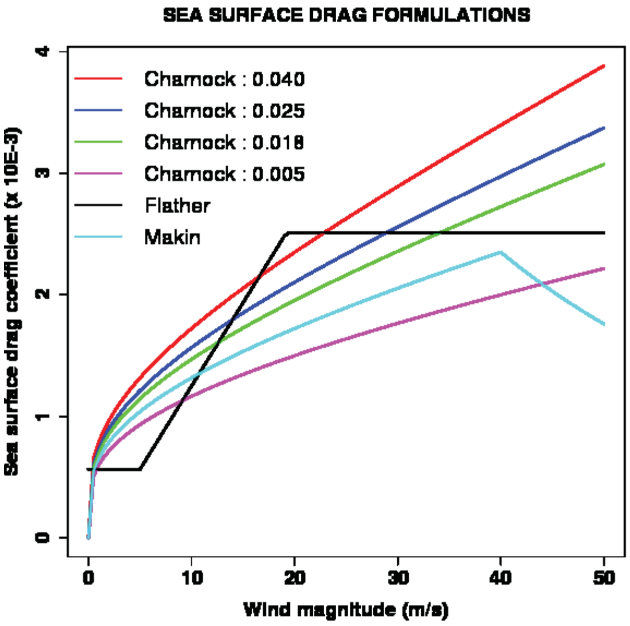

Figure 1. *Comparison between various formulations for the sea drag coefficient C_D and analysis of the influence of the Charnock parameter on this coefficient.*

Given that the performances of TELEMAC-2D were not homogeneous along the French coastline [14], a regional division (only determined by the latitude) based on French geographical areas is carried out. It is a first approach which has to be improved. Thus, four regions have been defined (Fig. 2): Hauts-de-France/Normandy, Brittany, Pays de la Loire and Nouvelle-Aquitaine. For each area, a different α_{CH} is applied, more appropriate locally, waiting to be able to calculate α_{CH} for each point of the mesh considering the sea state. The values for the Charnock coefficient have been chosen after several tests, depending on the results of our TELEMAC-2D model with the Flather formulation (if the maximum skew surge simulated by [14] was under the SHOM maximum skew surge, a high coefficient is fixed and conversely). In Sect. 3, details will be given about the α_{CH} used for each storm.

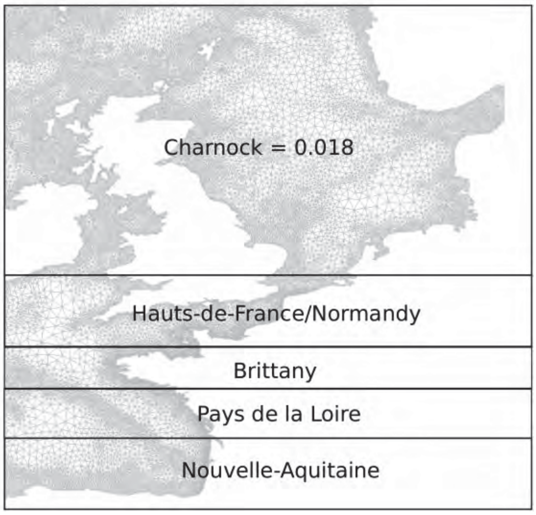

Figure 2. *Regional division for the adaptation of α_{CH}.*

B. *Wave stresses*

As TELEMAC-2D is used to simulate skew surges, waves are not taken into account. However, waves induce currents which may impact the surge and this effect can represent a significant part of the surge [21]. Those wave driven currents are calculated in TOMAWAC in the form of two forces F_u and F_v, called the wave stresses. The TOMAWAC software models wave propagation in coastal areas and estimates the mean characteristics of waves (water depth, direction, frequency). TELEMAC-2D is designed to be coupled with TOMAWAC but this requires to build a wave model on the same mesh as the one used for TELEMAC-2D (called mesh 2 in Fig. 3) with the determination of boundary conditions. Thus, for a first test of using wave stresses in the model, the data were taken from another project where a wave model is run with varying water level and currents due to tide (steps 1, 2 and 3 in Fig. 3). The same forcing conditions are used, but the computational domain is smaller and limited to close to the coast (called mesh 1 in Fig. 3). If the results are promising, a "real" 2-way-coupling will be implemented. With F_u and F_v as input data in

TELEMAC-2D, simulations with the contributions of wave induced currents are realized (step 4 in Fig. 3).

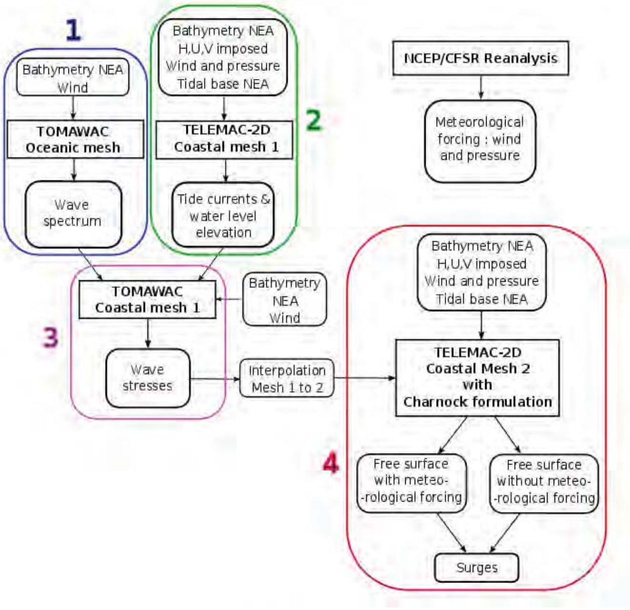

Figure 3. *Diagram of the chaining methodology to simulate surges.*

IV. RESULTS

A. Xynthia

Xynthia is a recent well-known storm for which the SHOM collected data in plenty of ports. This case study served to calibrate our TELEMAC-2D surge model and also to estimate the contributions linked to the Charnock formulation or the wave stresses.

Xynthia was a violent storm which crossed rapidly Western Europe between the 27th of February and the 1st of March 2010. The trajectory of the storm was quite unusual, from South-West to North-East and created a particular sea state in the Bay of Biscay [1]. The waves were really short and arched. This induced the effect of increasing the sea roughness and so the drag coefficient [2]. To model this phenomenon, a Charnock coefficient of 0.04 is applied in the region of Pays de la Loire and 0.018, the typical value, everywhere else. Nine harbours are concerned: Dunkerque, Dieppe, Le Havre, Saint-Malo, Roscoff, Saint-Nazaire, La Rochelle, Port-Bloc and Boucau. The results of the TELEMAC-2D model with or without waves' contributions are compared to the SHOM observations. For all the study sites, the maximum skew surge was underestimated by the model. Nevertheless, using the Charnock formulation rather than the Flather one (Fig. 1) permitted to reduce the error between the peak of the simulated skew surge and the peak of the observed skew surge (Table 1).

The wave stresses do not have positive influences on our results, except for Le Havre. The performances of the TELEMAC-2D model are still not homogenous between all harbours: for instance, at Port-Bloc, the correct numerical value for the peak of skew surge is simulated, whereas at Saint-Nazaire, it is clearly overestimated (Fig. 4). Further tests should be conducted with a lower value of α_{CH} in Pays de la Loire to approach the maximum skew surge recorded by the SHOM. At Boucau, regardless of the modifications of the model, the same result is obtained. We will see with the other storms that the region of Nouvelle-Aquitaine shows low sensitivity to the model parameters in general. The regional division should be modified: working with smaller regions could help to describe local effects.

TABLE 1: RESULTS OF ABSOLUTE RELATIVE ERROR FOR THE 9 SITES FOR THE MAXIMUM SKEW SURGES DURING XYNTHIA

Harbour	**Absolute relative error for the peak between the TELEMAC-2D model and the SHOM observations (%)**			
	Without waves' contributions	***With Charnock formulation only***	***With wave stresses only***	***With waves' contributions***
Dunkerque	16.05	1.23	17.28	1.23
Dieppe	12.63	2.11	14.74	1.05
Le Havre	35.64	25.74	7.92	1.98
Saint-Malo	16.47	4.71	17.65	4.71
Roscoff	31.67	28.33	33.33	30.0
Saint-Nazaire	19.81	26.42	33.96	24.52
La Rochelle	47.06	12.42	44.44	13.07
Port-Bloc	23.15	0.00	24.07	0.93
Boucau	43.90	39.04	46.34	41.46

In conclusion, taking into account the wind influence, through Charnock formulation, and the wave stresses helps to improve the estimation of the maximum skew surge for all sites for the Xynthia storm. To improve the results, the change of bathymetry database and the mesh refinement are prominent possibilities to take into account for future improvements. Of course, those promising results will lead to a complete coupling between TOMAWAC and TELEMAC-2D. The calibration of α_{CH} has to be refined eventually with a calculation directly in TOMAWAC.

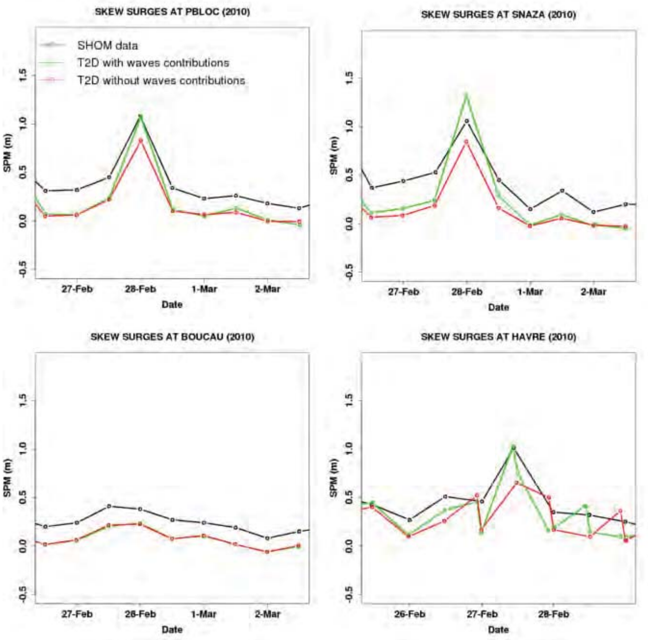

Figure 4. *Comparison between simulated skew surge (SPM) with (in green) or without (in red) the waves 'contributions with data recorded from tide gauge station (in black) during Xynthia storm.*

B. *Lothar-Martin*

Storm Lothar crossed Europe following a West-East track and peaked during the high tide of a moderate tidal range. It occurred on the December 26th, 1999. Less than 36 hours later, a second storm, called Martin, crossed France, a little further south, and affected almost of the same sites. This is quite unusual and during the tests of [15], the 1999 events were not correctly represented by the TELEMAC-2D model. Five tide gauges recorded the water level during both Lothar and Martin: Boucau, Cherbourg, Le Havre, Roscoff and Saint-Nazaire. La Rochelle tide gauge was not operating during those storms because of a general power failure. [3] simulated a skew surge value of 2.17 m for December 27th for storm Martin at La Rochelle so our results are compared with it (Fig. 5).

After some tests, the following values for the Charnock coefficient were chosen:

- 0.001 for Hauts-de-France/Normandy and Brittany,
- 0.04 for Pays de la Loire and Nouvelle-Aquitaine.

Indeed, the model used in [14] overestimated the peak of the skew surge in northern France, so a very small α_{CH} is used to reduce the wind influence and conversely for the South of France. For Cherbourg, Le Havre, Saint-Nazaire and Boucau, we manage to improve the results of the TELEMAC-2D model through waves' contributions (Fig. 5) but the numerical value of the maximum skew surge cannot be validated, except at Cherbourg. Finally, for La Rochelle, the waves' contributions lead to two skew surge peaks rather than three (Fig. 5). It could be more coherent as there is two really close storms but the simulated values are still far from measurements and the temporal occurrence is not quite exact.

To conclude, in this case, the implementation of the waves' contributions does not allow our model to describe correctly the 1999 events in all harbours. Results have been enhanced for some sites which encourages us to continue our work. As for storm Xynthia, a bathymetry and a mesh with a better resolution should have a benefit on our skew surge estimations as a precision of the geographical regions.

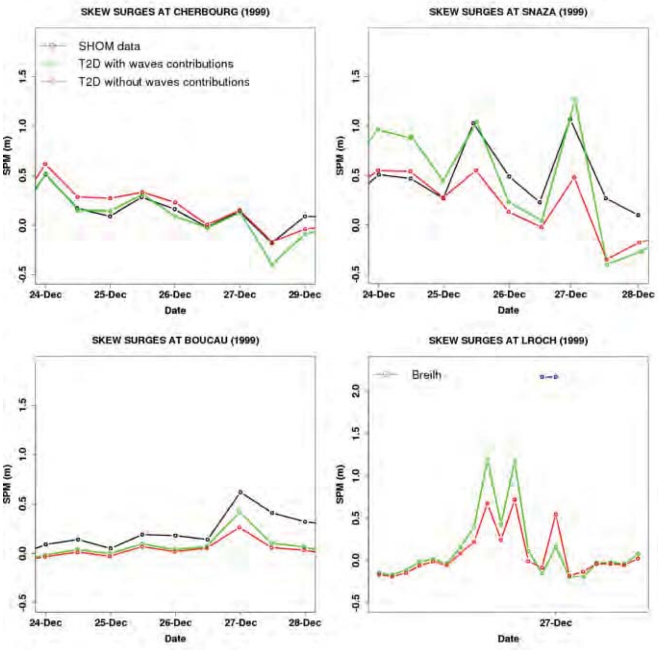

Figure 5. *Comparison between simulated skew surge (SPM) with (in green) or without (in red) the waves 'contributions with data recorded from tide gauge station (in black) during Lothar-Martin storms. Comparison with [3] (in blue) for La Rochelle.*

C. *The Great Storm of 1987*

This storm occurred in the middle of October 1987: a depression originated on the Bay of Biscay on the 15th and moved North-East. The Great Storm of 1987 impacted Brittany and then England. Eight French tide gauges recorded the sea level during this event: Dieppe, Le Havre, Cherbourg, Roscoff, Le Conquet, Port-Tudy, Verdon and Saint-Jean-de-Luz. For this study, we choose α_{CH} = 0.04 for Hauts-de-France/Normandy, α_{CH} = 0.35 for Brittany and α_{CH}= 0.018 for the other regions as the storm mainly affected the North of France.

Estimations of the maximum skew surge are improved only for six harbours. In fact, this storm does not strongly impact the sites of Le Verdon and Saint-Jean-de-Luz in which time series of skew surges are available. In addition, the Nouvelle Aquitaine region, to which these two sites belong, is poorly sensitive to the parameters of the TELEMAC-2D model. Results at Cherbourg and Roscoff (Fig. 6) allow us to get few ameliorations for the maximum skew surge. On the contrary, for Le Havre and for Port-Tudy (Fig. 6), the waves' contributions have a clear positive influence.

This case study needs a careful work especially for the regions of Hauts-de-France/Normandy and Brittany where the storm had the strongest impact. As the Great Storm of 1987 affected the English coasts too, skew surges simulations should be done for British harbours. As for the 2010 and 1999 storm events, the TELEMAC-2D model should be enhanced with more refined bathymetry and mesh. In addition, a coupling with TOMAWAC could be considered, rather than a chaining.

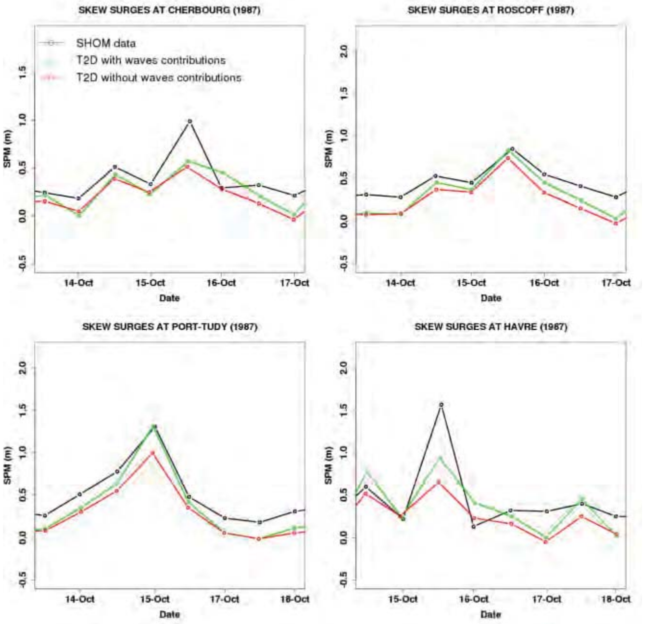

Figure 6. *Comparison between simulated skew surge (SPM) with (in green) or without (in red) the waves 'contributions with data recorded from tide gauge station (in black) during The Great Storm of 1987.*

CONCLUSIONS AND PERSPECTIVES

The storm surges model based on TELEMAC-2D built and validated a few years ago ([15], [14]) has been improved through the implementation of the waves' contributions. The formulation for the sea surface drag coefficient which translates the wind influence has been modified with the Charnock formulation. A regional division has been settled to affect a particular Charnock coefficient for each area. In addition, the wave stresses are now taken into account in our simulation thanks to a chaining with TOMAWAC. For the three storms studied, an improvement, nevertheless sometime small, of our estimations of the maximum skew surge is observed in most of the sites. The examination of the TELEMAC-2D model for several well-known storms is essential to be able to study extreme historical events later and thus validate historical values.

Work is still in progress at the LNHE. A new bathymetry from the SHOM with a resolution of 100 m should be tested and a new mesh will be soon developed. Indeed, all tide gauges are located in ports so there are influenced by local effects. A coupling between TOMAWAC and TELEMAC-2D could be considered as a promising way to still improve results. The Charnock formulation is valid for winds below 33 m/s, we may change for the Makin formulation [16] for other storms. Moreover, the geographic division has to be precise and the Charnock coefficient needs to be calculated for each node of the mesh, updated at each time step. This could be possible with the calculation of the coefficient directly in TOMAWAC. One advantage will be that our model would not be dependent anymore on a database such IOWAGA from WaveWatchIII and therefore it will ensure coherence between all the data used in our storm surges simulations. In addition, British ports should be studied to complete this work, especially for The Great Storm of 1987.

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