Analysis of the physical processes controlling the storm surge during Xynthia (February 2010)

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ABSTRACT. – The Xynthia storm severely hit the coastlines of Charente Maritime and Vendée (central part of the Bay of Biscay) in the night between the 27th and the 28th February 2010. The associated storm surge exceeded 1.5 m in La Rochelle while being in phase with a high spring tide, which caused the overall sea-level to reach the exceptional value of 8.0 m above marine chart datum. Numerous dykes and dunes were flooded or breached and large coastal areas were inundated. This study aims to analyse the main physical processes that controlled the storm surge during Xynthia. A modelling system fully-coupling the codes SELFE (Zhang *et al.*, 2008) and WWMII (Roland *et al.*, 2012) was implemented over the North-East Atlantic Ocean and resulted in tides and wave predictions with errors of the order of 1 to 2% and 15%, respectively. The storm surge was well predicted in the Bay of Biscay, with a 0.1 to 0.2 m underestimation of the peak. The analysis of model results revealed that the storm surge was due mainly to the SW wind that induced an Ekman transport, amplified by the presence of young and steep waves in the Bay of Biscay. This particular sea state was related to the uncommon track of Xynthia, which crossed the Bay of Biscay from SW to NE, limiting the fetch to a few hundreds of km.

Key-words: Storm surge, Xynthia, Ekman transport, young waves, Bay of Biscay.

Analyse des processus physiques contrôlant la surcote pendant Xynthia (février 2010)

RÉSUMÉ. – La tempête Xynthia a sévèrement touché les littoraux de Charente Maritime et de Vendée dans la nuit du 27 au 28 février 2010. La surcote associée a dépassé 1.5 m à la Rochelle et était en phase avec une marée haute de vives-eaux, si bien que le niveau de la mer a atteint la cote exceptionnelle de 8.0 m par rapport au zéro hydrographique. De nombreuses digues et cordons dunaires ont été submergés et se sont rompus et de larges territoires ont été submergés. Cette étude vise à analyser les processus physiques qui contrôlent la surcote associée à Xynthia. Un système de modélisation réalisant le couplage complet entre les codes SELFE (Zhang *et al.*, 2008) et WWMII (Roland *et al.*, 2012) a été implémenté sur l'Atlantique NE et permet de reproduire les marées et les vagues avec des erreurs de l'ordre de 1 à 2 % et 15 %, respectivement. Le pic de la surcote pendant Xynthia est également reproduit de façon satisfaisante dans l'ensemble du Golfe de Gascogne, avec une sous-estimation de l'ordre de 0.1 à 0.2 m. L'analyse des résultats du modèle montre que la majeure partie de la surcote est due au vent de SW qui a généré un transport d'Ekman, amplifié par la présence de vagues jeunes et cambrées dans le Golfe de Gascogne. Cet état de mer particulier est expliqué par la trajectoire atypique de Xynthia, qui a traversé le Golfe de Gascogne du sud-ouest vers le nord-est en limitant le fetch à quelques centaines de km.

Mots-clés : Surcote, Xynthia, transport d'Ekman, vagues jeunes, Golfe de Gascogne.

I. INTRODUCTION

Due to a large continental shelf combined to their location on the track of mid-latitude winter storms, European coastlines are subjected to storm surges that regularly exceed one meter. Low lying zones, such as the Wadden Sea, the Havres Normands or the Pertuis Charentais are thus vulnerable to marine flooding. The Xynthia Storm, which severely hit the central part of the Bay of Biscay in the night from the 27th to the 28th of February 2010, has reminded this vulnerability. A 970 hPa storm, associated with a SW wind ranging from 100 to 130 km/h over the Bay of Biscay (maximum gusts of 160 km/h in Ré Island, Fig. 1) induced a storm surge exceeding 1.0 m between the Loire and the Gironde estuaries (Bertin *et al.*, 2012) with a maximum value estimated to more than 1.5 m in La Rochelle. This storm surge matched a high spring tide, which caused the overall water level to reach 8.0 m in La Rochelle with respect to marine charts datum, a value totally unpublished since the deployment of a digital tide gauge (28th of April 1997). Many dykes and natural barrier were flooded or breached, which led to the inundation of large area of low-lying zones that cost 47 lives and caused huge material damages estimated to more than 1.5 billion Euros. Beside the human and material catastrophes, the case of Xynthia is interesting scientifically since the associated storm surge is exceptionally high compared to the intensity of the storm. This study presents a modeling based analysis of the main physical processes controlling the storm surge associated with Xynthia, that were preliminarily identified in Bertin *et al.* (2012).

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II. THE STORM SURGE MODELLING SYSTEM FOR THE NORTH-EAST ATLANTIC OCEAN

A circulation model was implemented over the North East Atlantic Ocean (NEAO) based on the code SELFE (Zhang and Batista, 2008). SELFE solves the Reynolds Averaged Navier-Stokes Equation (RANS) equation using a combination of finite volume and finite element methods and a Lagrangian treatment of advective terms. In this study, SELFE was used in 2DH barotropic mode and the equations were discretized using an unstructured grid where the mesh size ranges from 30000 m in the deep Ocean and 500 m around La Rochelle. The model was forced along its open boundaries by tidal elevations computed from the 18 main tidal harmonic constituents retrieved from the regional tidal model of Pairaud *et al.* (2008). The tidal model yields very good tidal predictions in the NEAO and the North Sea with normalized root mean square errors of the order of 1 to 2%. A detailed validation can be found in Bertin *et al.* (2012). The model is forced by fields of sea-level pressure and 10 meters wind originating from the 0.25° Arpege model of Météo France.

Bathymetric map of the Bay of Biscay

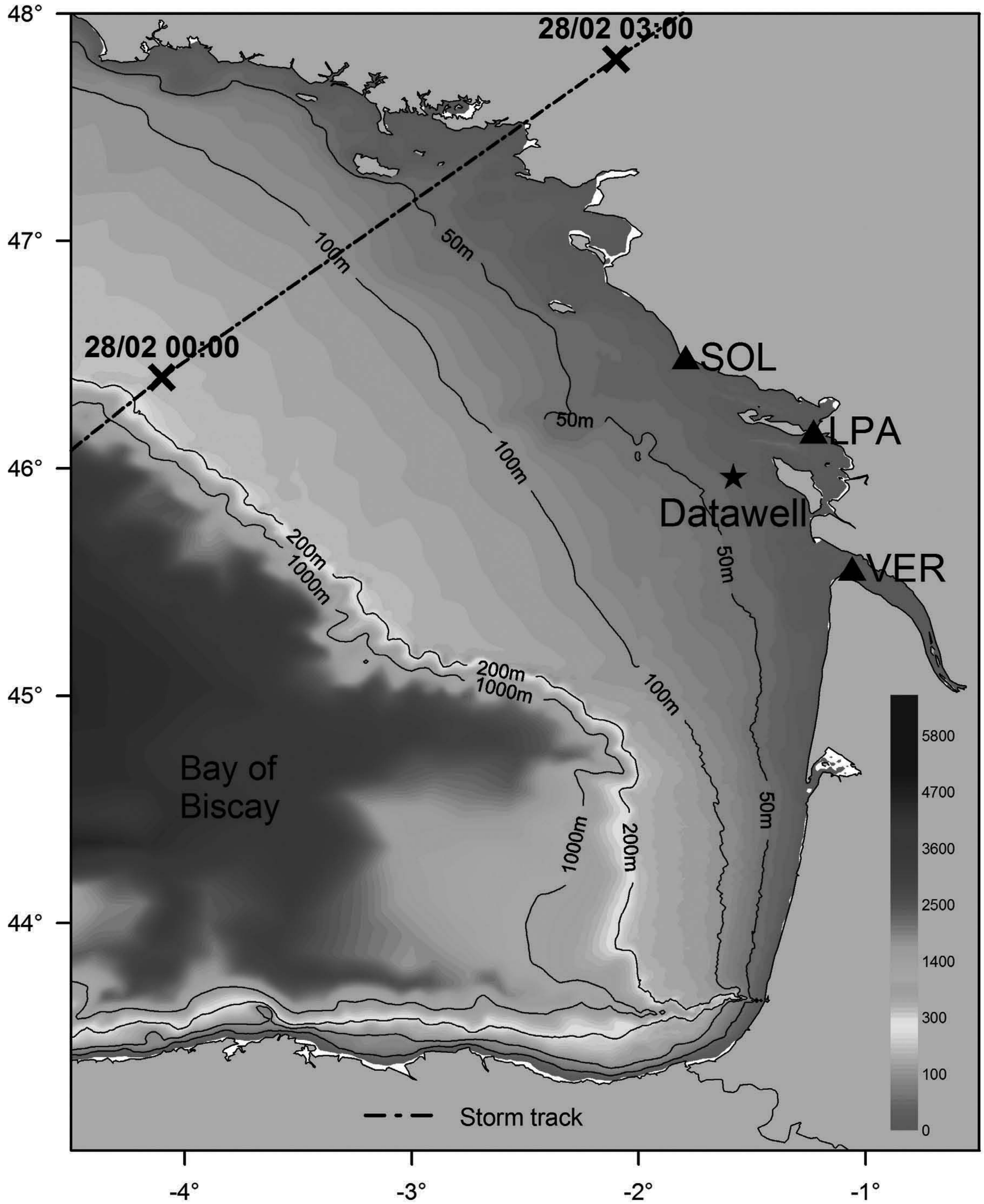

Figure 1: *Bathymetric map of the Bay of Biscay showing the location of the tide gages of Sables d'Olonne (SOL), La Pallice (LPA) and Verdon (VER), the location of the Datawell buoy and the track of Xynthia.*

This circulation model was fully coupled with the spectral wave model WWMII (Roland *et al.*, 2012), which uses the same unstructured grid and domain decomposition as SELFE. WWMII solves the wave action equation using hybrid splitting methods based on residual distribution schemes (Abgrall, 2006) for the advection in geographical space and Ultimate-Quickest schemes in spectral space. WWMII is fed by currents, water levels and wind fields originating from SELFE and provides SELFE with wave radiation stress and surface friction velocity. Nevertheless, due to the coarse grid resolution along the coastline, the wave-induced setup can only be partly represented by our model. Surface friction velocity can optionally be used in SELFE to compute a wave-dependant surface stress (Janssen, 1989; Mastenbroek *et al.*, 1993), which is a decreasing function of the wave age (hereafter W_a).

Wave predictions were compared against measurements carried out the west of Oleron Island by means of a Datawell wave buoy deployed by 50 m water depth (Fig. 1). This comparison shows firstly that significant wave height (Hs) is reasonably reproduced during Xynthia, with a root mean square of the difference (RMSD) of 0.68 m (20% once normalized by the data, NRMSD). Peak wave direction (P_{dir}) and peak wave periods (T_p) are also well reproduced with RMSD of 20° and 1.8 s (18% NRMSD), respectively. In more details, the drops of Pdir and Tp at the beginning of the storm are reasonably well captured. The ratio between Hs (3-7.5 m) and Tp (6-10.5 s) during Xynthia is rather uncommon for the NEAO and traduces a sea state characterized by young and steep waves.

Storm surge predictions were compared against estimations from tide gauge data at Sables d'Olonne, La Pallice and Verdon (Fig. 1). For these three stations, the storm surge was computed as the difference between the observed and the predicted tide. The tidal prediction was made using astronomic constituents only, obtained by a harmonic analysis performed over 3 years' time series. The modeled storm surge was computed as the differences between our baseline simulation and a simulation where tide only is considered. This comparison shows that the storm surge is well reproduced, with a RMSD of 0.13 m, 0.14 and 0.12 m for Sables d'Olonne, La Pallice and Verdon, respectively. In details, the peak surge is underestimated by 0.20 m in Sables d'Olonne and 0.05 m in La Pallice.

III. MODELLING-BASED ANALYSIS OF THE PROCESSES CONTROLING THE STORM SURGE

The comparison with the available tide gages in the central part of the Bay of Biscay revealed that our modeling system was able to reproduce well water levels and storm surges during Xynthia. In details, the surge peak is slightly underestimated but this problem is being solved by using a much higher resolution grid, which allows for a proper representation of nearshore processes such as wave-induced setup. Nevertheless, the modeling results presented in this paper are reasonable-enough to argue that the main physical processes controlling the storm surge are well captured by our modeling system. This section investigates those processes by means of numerical experiments.

III.1. Ekman transport

In the deep Ocean and under steady state, the Coriolis Effect causes water masses to be transported at 90° to the

Validation wave prediction

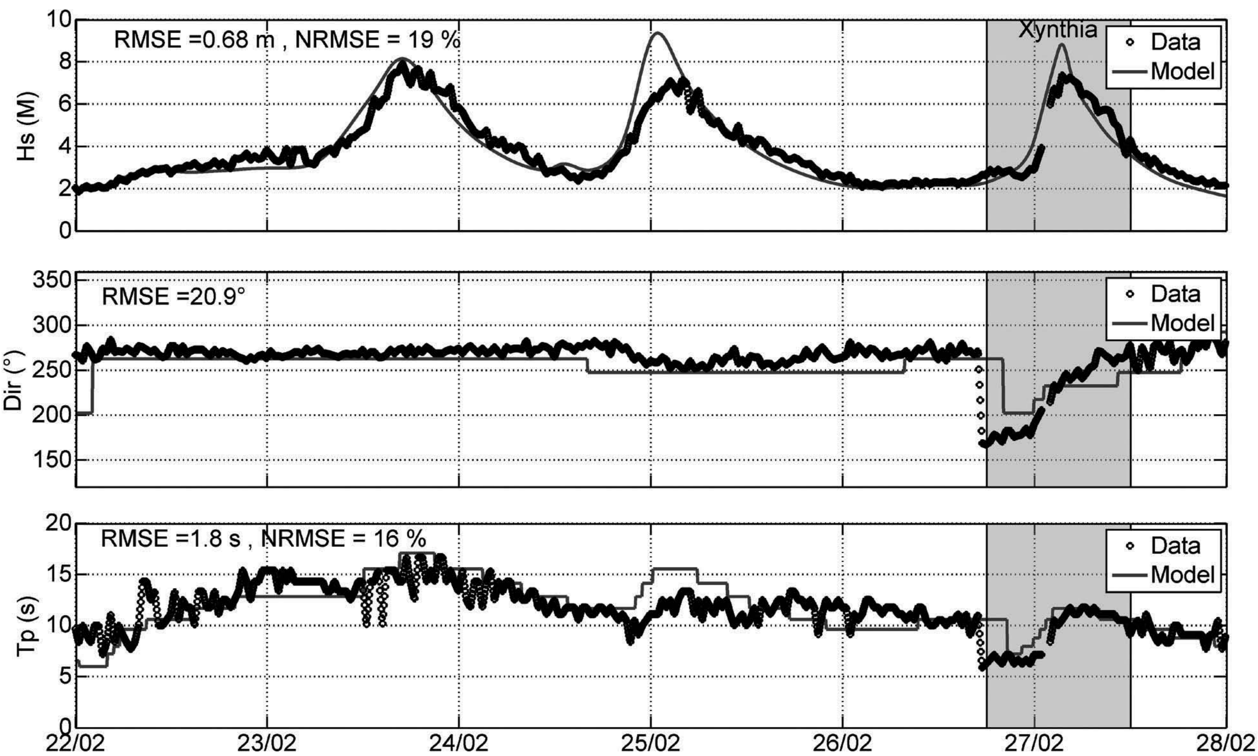

Figure 2: *Comparison between modeled and measured wave parameters at Oléron station the week before Xynthia: (A) Significant wave height; (B) peak wave direction and (C) peak wave period.*

Validation of storm surge prediction

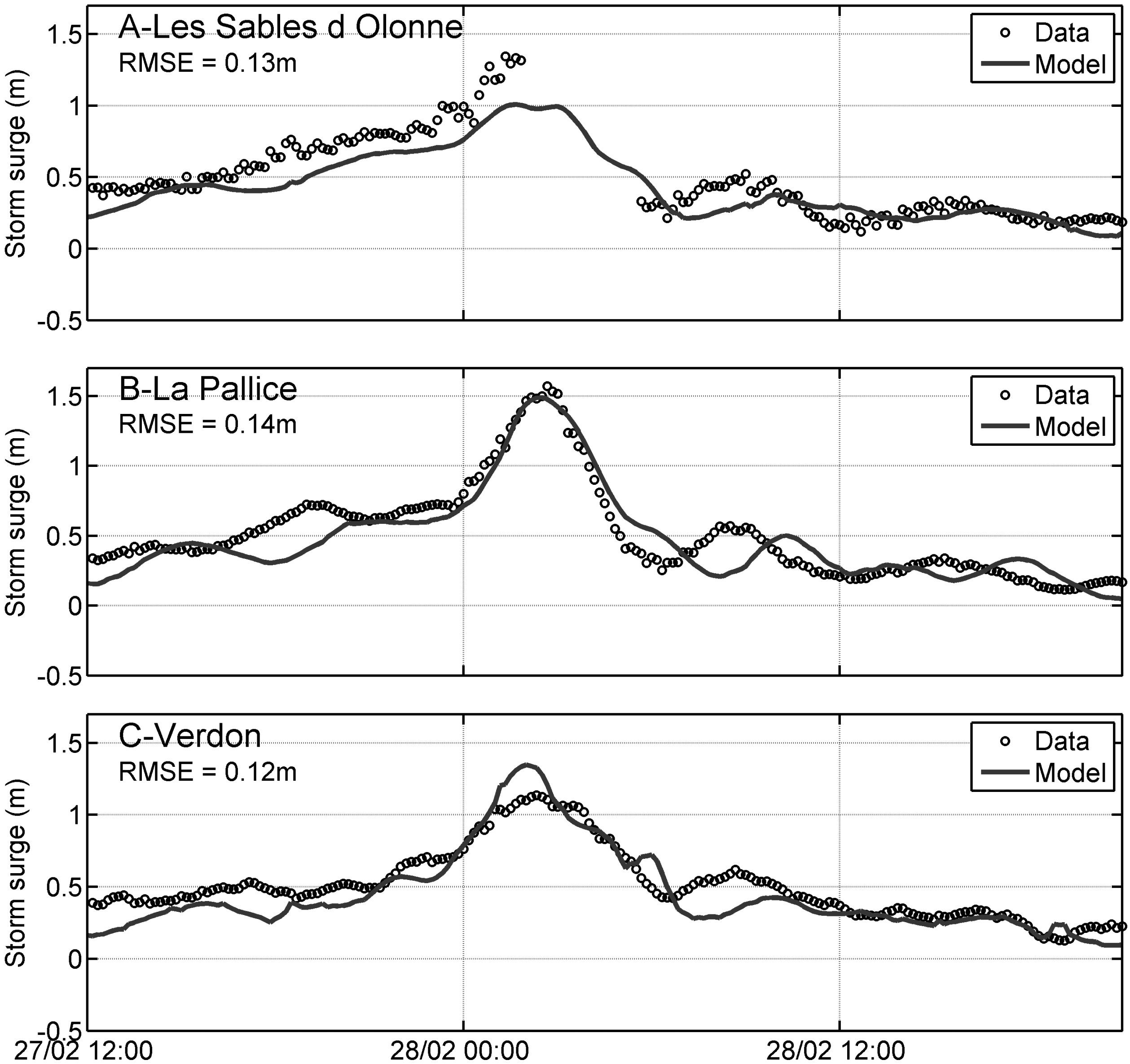

Figure 3: *Comparison between modeled and estimated storm surge at: (A) Sables d'Olonne; (B) La Pallice and (C) Le Verdon.*

right (left) of the wind direction in the Northern (Southern) hemisphere. When approaching the coast, mass transport is closer to the wind direction as and when the water depth decrease. The SW wind direction during Xynthia is thus expected to have induced an Ekman transport towards the coast that may have contributed to the storm surge significantly. In order to quantify this phenomenon, a comparison between a simulation with and a simulation without the Coriolis Effect was performed. Since the Coriolis Effect has a strong impact on tides, tides were switched off for this numerical experiment.

This comparison shows that the storm surge is 0.2 to 0.3 m larger when the Coriolis Effect is taken into account (Fig.4). This result demonstrates the importance of the SW-oriented wind during Xynthia and suggests that the storm surge would have been lower with a different wind orientation (e.g. NW).

III.2. Enhanced surface stress due to young waves

At an earlier stage of this study, we employed the wind-only-dependant formula of Pond and Pickard (1998) to compute the wind-induced surface stress and this approach yielded an underestimation of the storm surge by 0.2 to 0.5 m (Fig. 5). As shown by Mastenbroek *et al.*, (1993), the sea-state can impact the total surface stress and thereby the magnitude of the storm surge significantly. As a consequence, we implemented a wave-dependant method to compute the total surface stress, based on the friction velocity and through the simple following relation:

$$\tau_s = \rho_a \cdot U_*^2 \qquad (1)$$

Where ρ_a is the air density and U_* corresponds to the friction velocity computed by WWMII. This friction velocity is

Importance of Ekman transport

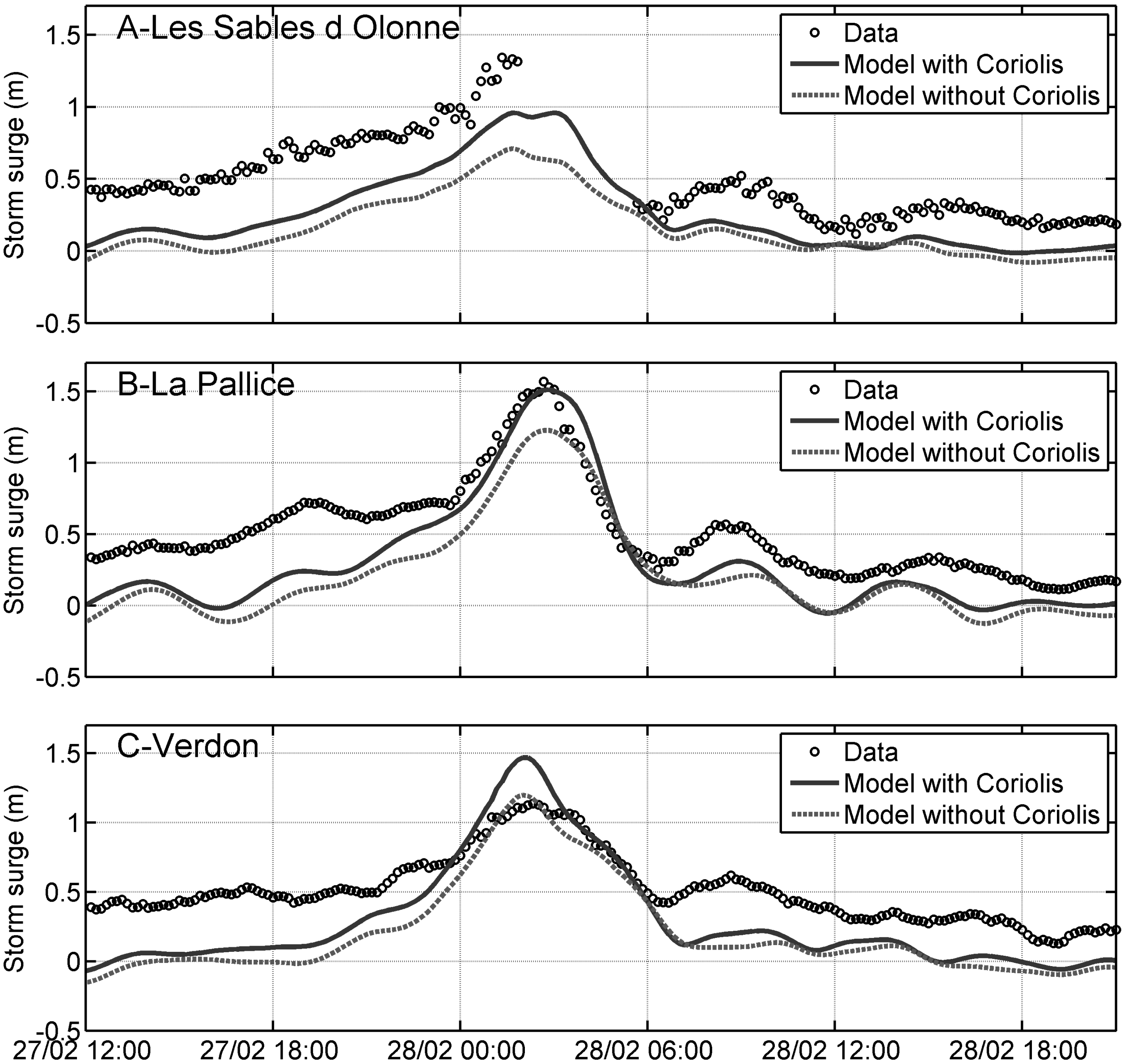

Figure 4: *Comparison of storm surge prediction for simulations with and without Coriolis Effect, showing the importance of Ekman transport at: (A) Sables d'Olonne; (B) La Pallice and (C) Le Verdon.*

obtained following the procedure proposed by Bidlot *et al.* (2002) at the European Center for Medium range Weather Forecast (ECMWF), which relies on the quasi-linear theory for wave-atmosphere interactions introduced by Janssen (1989, 1991). The comparison between both approaches shows that the storm surge is much better predicted with the wave-dependant parameterization, with differences reaching 40% in La Pallice (Fig. 5). The larger difference between both approaches in La Pallice is explained by the surrounding shallower waters, which cause the surface stress to contribute more to the overall storm surge compared to Les Sables d'Olonne and Le Verdon, located along open coasts.

Nevertheless, such differences are larger than usually observed in the literature (e.g. Mastenbroek, 1993), suggesting that a particular sea-state has occurred during Xynthia. We propose that this surface stress enhancement was caused by abnormally young and steep waves ($H_s > 7.0$ m with T_p of the order of 7-11 s; Bertin *et al.*, 2012). This particular sea state is related to the unusual track of Xynthia, which reduced the fetch to a few hundreds of km while storms having a West-East track rather have fetches larger of a few thousands of km.

IV. CONCLUSIONS AND FUTURE WORKS

A new storm surge modeling system was developed for the NE Atlantic Ocean and resulted in good wave and storm surge predictions during Xynthia, although the surge peak was slightly underestimated. Numerical experiments were performed to investigate the physical processes explaining the abnormally large storm surge

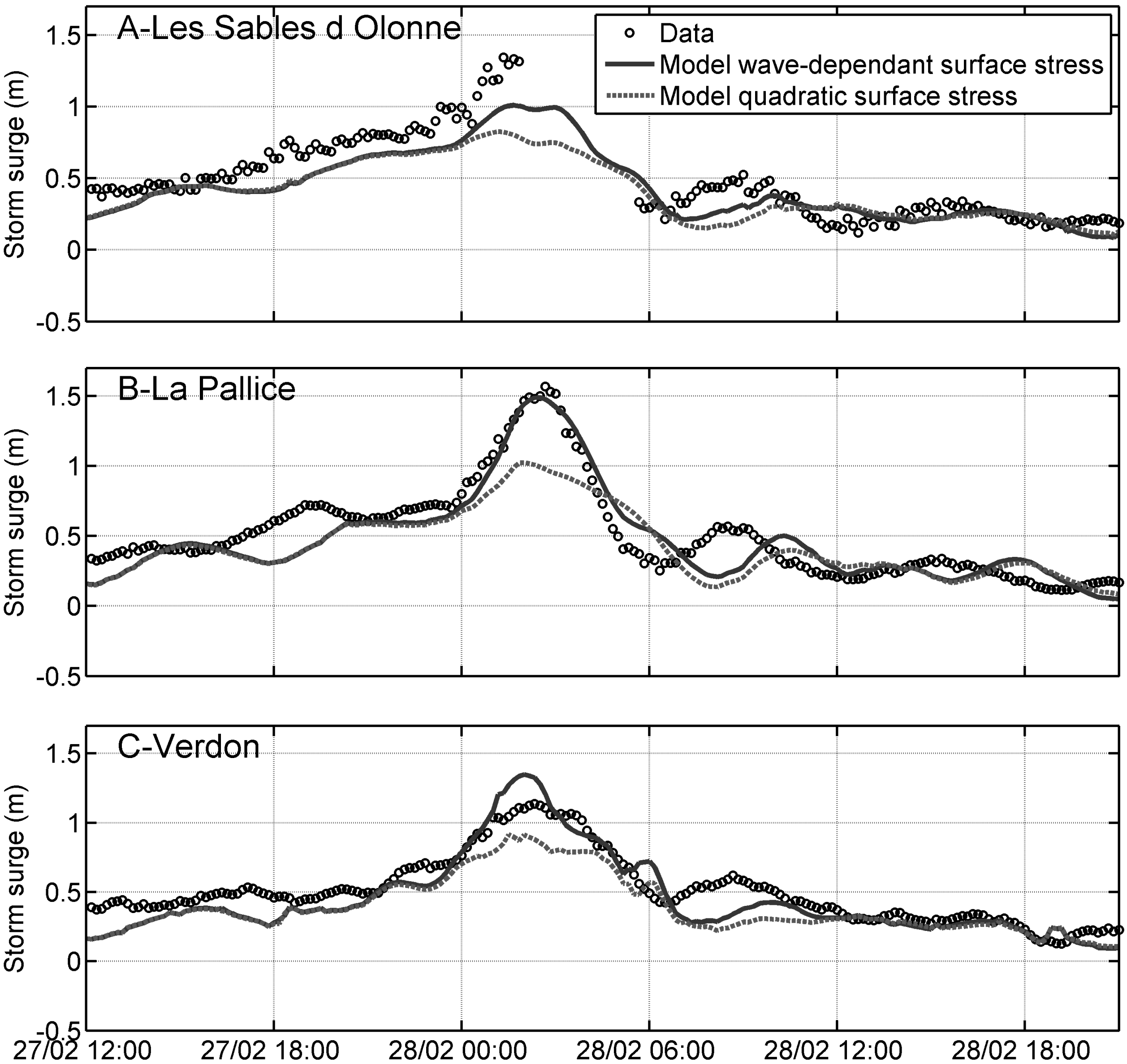

Figure 5: *Comparison of storm surge prediction for simulations with a wind-only and a wave-dependant surface stress showing the importance of the sea state during Xynthia at: (A) Sables d'Olonne; (B) La Pallice and (C) Le Verdon.*

compared to the intensity of the storm. These experiments revealed that the SW-oriented wind induced an Ekman transport directed towards the coast and strongly enhanced by the presence of young and steep waves. This particular sea state was explained by the unusual track of Xynthia, which reduced the fetch to a few hundreds of km. Our computational grid is currently being refined along the coast (up to less than 10 m mesh size) and extended towards the flooded areas. This finer resolution will allow for a proper representation of nearshore wave-induced processes such as enhanced bottom stress and radiation stress gradients. The preliminary results obtained from this refined grid suggest that the storm surge is no longer underestimated in the central part of the Bay of Biscay. Preliminary simulations of the flooding associated with Xynthia are also very promising.

V. ACKNOWLEGMENTS

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