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The contribution of short-waves in storm surges: Two case studies in the Bay of Biscay

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ABSTRACT

This study investigates the contributions of short waves in storm surges through the hindcast of two storms that hit the central part of the Bay of Biscay recently. Despite displaying comparable wind speed and directions in the study area, these two storms induced different storm surges and sea states. Xynthia (27–28th of February 2010) was characterized by large (up to 7 m significant wave height H_s) and short-period waves and induced an exceptional storm surge, locally larger than 1.6 m. The second storm, Joachim (15–16th of December 2011), was characterized by very large (up to $H_s > 10$ m) and long-period waves but only induced a storm surge almost two times lower. To investigate these differences, a new unstructured grid and fully coupled modeling system is applied, with a spatial resolution fine-enough to adequately represent the surf zones over most of the study area (25 m). The analysis of the modeling results and the available field observations reveals firstly that the exceptional surge during Xynthia originated from young and steep waves, enhancing surface stress. This particular sea-state is explained by the abnormal track of Xynthia, which restricted the fetch to a few hundred km. The wave radiation stress gradient locally induced setup larger than 0.4 m along the coastlines fully exposed to ocean waves, while wave setup in the range 0.1–0.2 m was also shown to develop regionally and to propagate in sheltered harbors. Comparatively, wave-enhanced bottom stress appears to be a second-order process and has a more limited impact on storm surges.

1. Introduction

Tropical cyclones and extra-tropical storms making landfall in coastal zones are among the most costly natural disasters (Smith, 1996; Nicholls et al., 2007). Historically, the main part of the material and human losses in coastal zones is associated with coastal flooding rather than direct wind effects (Zhang et al., 2008). Coastal flooding predominantly occurs in low-lying zones under the concomitance of a large storm surge and a high spring tide, although the importance of this concomitance also depends on the ratio between the storm surge and the local tidal range. For instance, the more than 8 m storm surge induced by hurricane Katrina in 2005 (Blake, 2007) would have induced a major flooding in the microtidal coastlines of Louisiana, whatever the tidal phase might have been. The major catastrophes that occurred over the last decade, such as Katrina in the Gulf of Mexico (2005), Nargis in the Bay of Bengal (2008), Sandy in the New York area (2012) and Haiyan in the Philippines (2013) remind us of the necessity of being able to predict storm surges accurately, although the physical processes controlling these phenomena remain only partly understood.

The effects of atmospheric pressure gradients and winds on sea-level were recognized early (e.g. Doodson, 1924) and were integrated in pioneer modeling approaches (e.g. Jelesnianski, 1965). Following these early quantitative approaches, many studies have shown that the wind-induced surface stress was the dominant process at coastal zones bordered by large and shallow shelves (Flather, 2001; Rego and Li, 2010; Kennedy et al., 2012). Tide–surge interactions were also shown early to be significant at some locations (e.g. Proudman, 1957; Rego and Li, 2010; Idier et al., 2012). By contrast, the contribution of short-waves in storm surges has only been investigated more recently. Thus, for a long time, it has been common practice to compute the wind surface stress based on bulk formula (Eq. (1)):

$$\tau_s = \rho_a C_d U_{10}^2 \tag{1}$$

where ρ_a is the air density, U_{10} is the 10 m wind speed and C_d is a drag coefficient corresponding to the sea roughness that increases

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linearly with the wind speed for low to moderate winds (e.g. Smith and Banke, 1975; Pond and Pickard, 1998). However, based on the pioneer work of Charnock (1955), Stewart (1974) proposed that the sea roughness should also depend on the wave age for a given wind speed. The dependence of the surface stress on the sea state was then corroborated in many studies (Donelan et al., 1993; Mastenbroek et al., 1993; Brown and Wolf, 2009; Sheng et al., 2010; Olabarrieta et al., 2012). More recently, field measurements under extreme winds showed that the sea roughness could reach a maximum or even decrease due to wave-induced streaks of foam and sprays for winds larger than 35–40 m/s (Powell et al., 2003; Takagaki et al., 2012; Holthuijsen et al., 2012). In shallow water, orbital motions associated with short-wave propagation can also enhance bottom stress, thereby usually reducing storm surges (e.g. Nicolle et al., 2009). Nevertheless, the impact of this phenomenon on the surge peak is often found to be limited (Xie et al., 2003) while storm surge predictions are not always clearly improved when accounting for this process (e.g., Jones and Davies, 1998). In the nearshore, wave dissipation induces gradients of radiation stress (Longuet-Higgins and Stewart, 1964) that drive a setup easily reaching several tens of centimeter during storms. However, the proper representation of this phenomenon requires employing a very fine spatial resolution (e.g. of the order of 10 m), which poses a serious computational challenge when simulating storm surges at regional scale. This difficulty probably explains why only a limited number of studies have successfully accounted for wave setup at regional scale (e.g. Dietrich et al., 2010).

This study investigates the contribution of short waves in storm surges based on the hindcast of two extra-tropical storms that recently hit the central part of the Bay of Biscay (France): Xynthia on the 27–28th of February 2010 and Joachim on the 15–16th of December 2011. This study builds on a preliminary hindcast of the storm surge associated with Xynthia, which used an offline coupling between a circulation model and a spectral wave model and a coarse spatial resolution that prevented the representation of nearshore wave-induced processes (Bertin et al., 2012). Although both storms displayed comparable wind speed and directions over the study area, they induced different storm surges and sea states. The main purpose of this paper is to take advantage of these contrasting case studies to investigate the contribution of short waves in storm surges. The section following this introduction describes the data and the fully coupled modeling system used in this study. Section 3 describes the studied area and both storms. The next section presents the modeling results in terms of atmospheric forcing, sea states and storm surges. Section 5 discusses the contribution of the three main wave-induced processes in storm surges: wave-enhanced surface and bottom stress and the gradients of radiation stress. Finally, the main findings of this study are summarized and some perspectives are given in the conclusion.

2. Methods and data

2.1. The storm surge modeling system

2.1.1. General overview

In this study, we applied the numerical modeling system Semi-implicit Eulerian–Lagrangian Finite Element (SELFE; Zhang and Baptista, 2008; Zhang et al., 2011), which now includes modules to simulate water quality (Rodrigues et al., 2011), oil spills (Azevedo et al., 2014) and sediment transport (Pinto et al., 2012). Recently, a full coupling was undertaken with the spectral wave model Wind Wave Model II (hereafter WWMII, Roland et al., 2012). The two codes share the same unstructured grid and the same domain decomposition, which makes this modeling system very computationally efficient and allows for massive parallel techniques. More details regarding coupling can be found in Roland et al. (2012). The unstructured grid used in this study employs 201,701 nodes (385,980 elements) and its resolution ranges from 30,000 m in the deep Ocean and far from the study area to 25 m along the shoreline of the study area (Fig. 1). Such a fine resolution together with the coupling strategy allow for a proper representation of nearshore wave-induced processes, which constitutes a major improvement compared to the preliminary hindcast of Xynthia described in Bertin et al. (2012). The computational grid is bounded by the shoreline, which means that the coastal areas flooded during Xynthia are not represented. Bertin et al. (2014) conducted

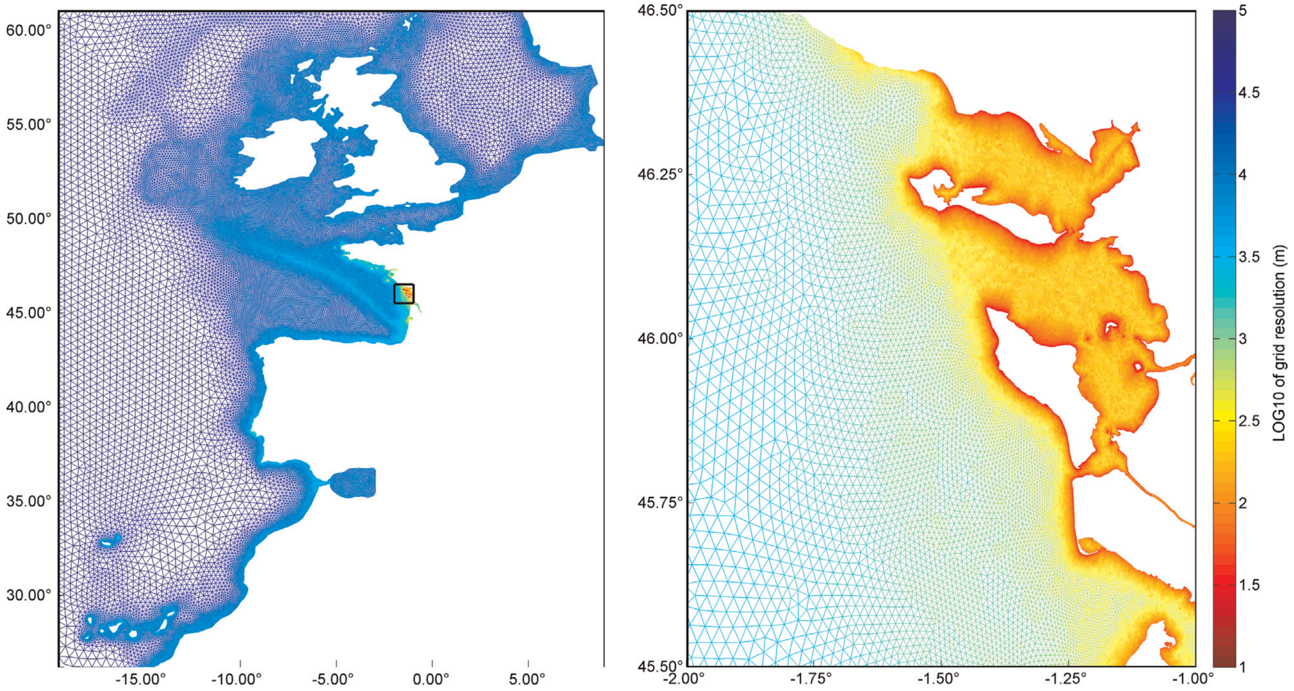

Fig. 1. Unstructured grid used in this study, showing a resolution ranging from 30,000 to 25 m.