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A modeling-based analysis of the flooding associated with Xynthia, central Bay of Biscay

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ABSTRACT

Storm-induced coastal flooding is among the most destructive natural disasters, as seen recently in the Bay of Bengal, the Gulf of Mexico and the Philippines. This study presents a high resolution hindcast of the flooding associated with Xynthia, a mid-latitude storm that severely hit the central part of the Bay of Biscay in February 2010. A 2DH fully coupled modeling system is applied to the North-East Atlantic Ocean, with a resolution locally reaching a few meters along the coastline of the study area. Such a fine resolution was required to adequately represent the dikes and the barriers that usually prevent the area from flooding, but results in a >1,700,000 element unstructured grid. The comparison with the available data reveals that waves and water levels are reproduced with normalized errors of the order of 10% and 5%, respectively. The extension of the flooding is also well reproduced, although with some underestimations along the coastline and overestimation in the inner part of large marshes. These limitations are explained by a lack of spatial resolution locally and the absence of several processes in the model such as infragravity waves and wave runup. The comparison between our baseline simulation and a simulation where the flooding is disabled by increasing the dike height reveals differences in maximum water levels locally reaching 1.0 m. This result is of key importance for coastal management strategies and also questions classical engineering approaches relying on one-way nesting.

1. Introduction

Tropical hurricanes and extra-tropical storms reaching coastal zones are among the most costly natural disasters. At low-lying coasts, the property damages and loss of human lives associated with coastal flooding are usually larger compared to those directly related to wind. Coastal flooding generally occurs concomitantly with 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. Storm surges are primarily driven by wind, but are also influenced by atmospheric pressure, short-waves, rainfall and river-flow. In shallow waters, the wind contribution is usually dominant compared to the other forcing mechanisms because the wind effect is inversely proportional to the water depth. As a consequence, coastal zones located on the track of tropical hurricanes and extra-tropical storms and bordered by extensive shelves and shallow waters are particularly vulnerable to flooding. 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 State (2012) and Haiyan in the Philippines (2013) dramatically call for a better understanding of the physical processes responsible for these phenomenons.

Storm surges are being investigated using numerical models since the mid-1960s (e.g. Jelesnianski, 1965), which resulted in abundant literature on the mechanisms controlling these phenomena. For instance, the better understanding of the interactions between the atmosphere and the ocean in the nineties demonstrated that accounting for the sea-state to compute the surface stress could improve storm surge predictions significantly (Bertin et al., 2012, 2014; Brown and Wolf, 2009; Donelan et al., 1993; Mastenbroek et al., 1993; Moon, 2005; Olabarrieta et al., 2012). More recently, the increase in computational power and the advent of parallel computing allowed representing properly short-wave breaking zones and wave-induced setup at regional scale (e.g. Dietrich et al., 2010). Once oceanic water levels are correctly reproduced, the simulation of associated flooding would theoretically be easily achievable. However, the proper simulation of storm-induced flooding constitutes a multi-scale and very challenging problem for several reasons. First, large geographical extensions are required to adequately reproduce wave development and atmospheric pressure effect while very high resolution (i.e. <10 m) should be employed locally to represent correctly built dikes and natural barriers. Second, efficient and stable numerical methods should be employed to deal with large variability of Courant numbers, strong spatial gradients

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along the dikes and barriers and wetting and drying. These challenges probably explain why successful simulations of storm-induced flooding remain scarce in the literature.

This study presents a high-resolution hindcast of the flooding associated with Xynthia, a mid-latitude extra-tropical storm that severely hit the central part of the Bay of Biscay in the night between the 27th and the 28th of February 2010. The studied area and storm are described in the section following this introduction. The fully-coupled modeling system and its implementation are presented in Section 3 and the modeling results are compared against the available observations of wave, water levels and extension of the flooding in Section 4. The results are analyzed and discussed in Section 5, with some emphasis on the implications of sea level limitation due to flooding. Finally, the main findings of this study are summarized in the conclusion and future improvements and recommendations to mitigate storm-induced flooding are proposed.

2. The studied area and storm

2.1. Geomorphic setting

The study area is located along the French Atlantic coast in the central part of the Bay of Biscay. The morphology of this stretch of coastline is dominated by two big islands and several embayments and estuaries, the largest of which is the Gironde Estuary to the South (Fig. 1). These embayments correspond to drowned incised valley segments (Chaumillon et al., 2008) and their inner part consists of extensive intertidal mudflats, locally reaching 5 km width. Landward, these shallow mudflats are bordered by extensive dikes (240 km) and natural barriers, which isolate large marshes and coastal plains from the sea. The analysis of LiDAR data by Breilh et al. (2013) showed that, considering a coastal band of 10 km, about 50% of this territory is located below the highest astronomical tides. This setting causes the study area to be the most vulnerable area in France to marine flooding.

2.2. Hydrodynamic setting

Tides in the study area are semi-diurnal and range from less than 2 m during neaps to more than 6 m during springs. Tides are dominated by M2, which amplitude grows from 1.3 m along the shelf break (Le Cann, 1990) to more than 1.8 m in the inner part of the estuaries. Tides display small diurnal asymmetries and the associated diurnal waves K1 and O1 have amplitudes of the order of 0.07 m and display little spatial variations. In contrast, quarter diurnal waves M4, MS4 and MN4 are amplified more than 10 times throughout their propagation over the continental shelf, which causes the incident tide to be already distorted at the entrance of the estuaries and embayments. This phenomenon was explained analytically by Le Cann (1990) and then confirmed numerically by Bertin et al. (2012) as a resonant amplification over the shelf in the central part of the Bay of Biscay.

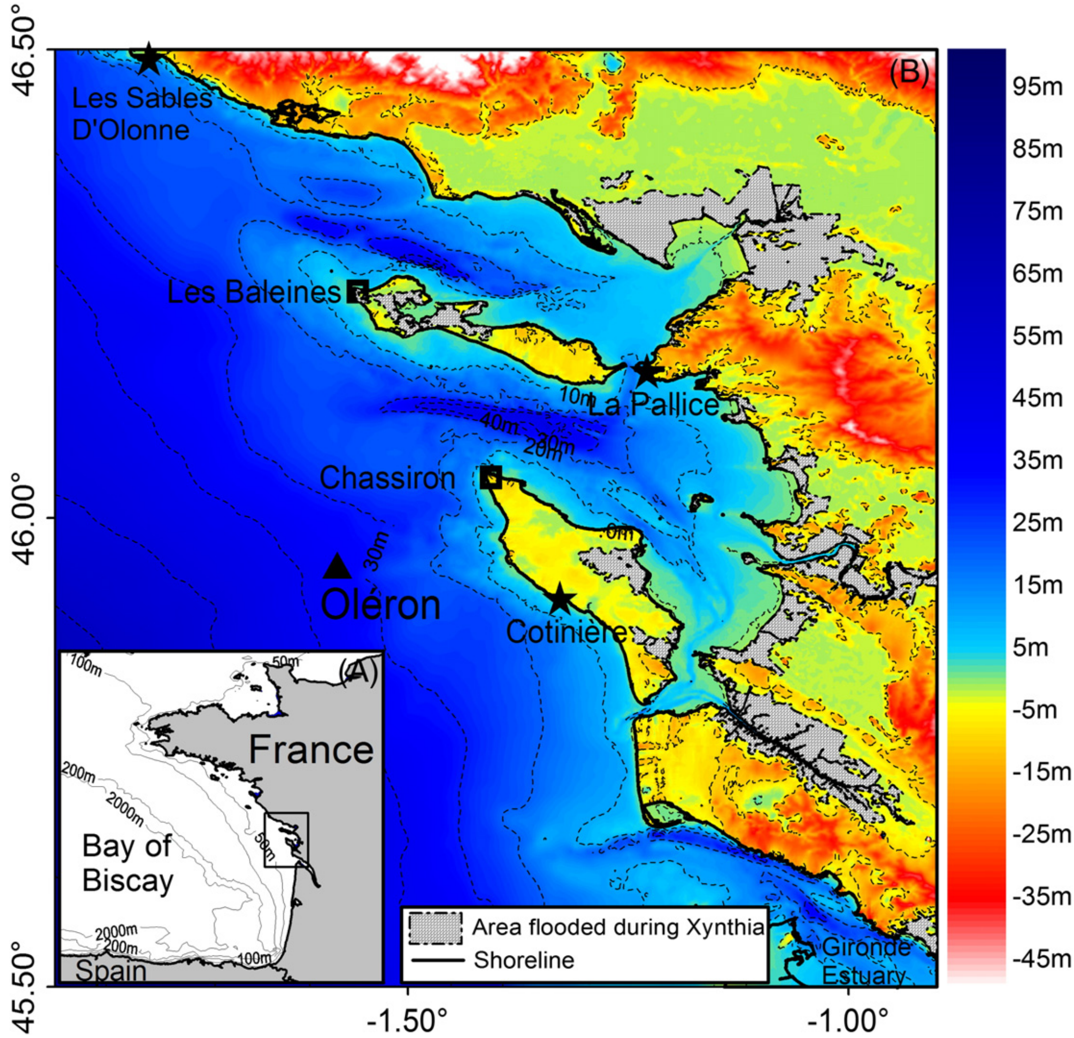

Fig. 1. (A) Location of the study area in the Bay of Biscay and (B) detailed bathymetric and topographic map of the study area with respect to mean sea-level with the location of tide gauges (stars), wave buoys (triangles) and meteorological stations (squares) used in this study.