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High-resolution multi-scale modelling of coastal flooding due to tides, storm surges and rivers inflows. A Cork City example

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ABSTRACT

This paper demonstrates the capability of a new state-of-the-art flood modelling system consisting of multiple nested models to simulate urban coastal flood inundation. A flood event in Cork City, Ireland which occurred in November 2009 is analysed in detail. The new flood modelling system comprises of two dynamically linked models: an ocean model (POM) of the northeast Atlantic (ca. 5 km grid) and a coastal flood model, MSN_Flood, which resolves the hydrodynamics of Cork Harbour and its sub region at four spatial scales 90 m, 30 m, 6 m and 2 m through a cascade of four nested grids. Flood water propagation through Cork City floodplains is simulated by the 2 m grid model.

The POM-MSN_Flood modelling system, presented for the first time in this paper, was used to investigate the dynamics of coastal flooding resulting from a complex set of tides, storm surges, rivers inflows and the interactions between them. Unlike many flood models, the modelling system used in this research provides a full description of water levels and flow regimes, both in coastal waters and urban floodplains. Validation results clearly demonstrate that the model is capable of resolving hydrodynamics at scales commensurate with flow features including the large scale processes of the NE Atlantic Ocean and the fine resolution circulation of coastal waters. With regards to urban flooding, the model was found to accurately determine flood wave propagation patterns, flood wave heights, speeds and inundation extents. Ultimately, the model was used to investigate mechanisms of flooding resulting from multiple process drivers and to assess flood risk to human safety. Such an analysis facilitates better understating of the mechanics and dynamics of complex coastal urban flooding and would therefore be of interest in the field of coastal management.

1. Introduction

Due to fertile soils, abundant food sources and access to the sea coastal zones are generally densely populated. As of 1990, population densities in coastal zones are three times the global mean and over 1.2 billion people are living within 100 km of the coast in areas where the land height is less than 100 m above sea level [62]. A significant portion of that population is concentrated around the world's largest coastal cities that constitute a considerable percentage of global GDP and wealth [3]; these regions therefore represent a significant value in property and infrastructure. The downside of coastal zone development is their exposure to natural hazards such as storm surges, waves, tsunamis and/or high river flows. These hazards may have catastrophic consequences on human settlements and result in loss of life, damage to properties and disruption to services. Coastal flooding is one such natural disaster.

Coastal flooding occurs in low-lying coastal areas when high water levels due to tides and storm surges, together with waves, overtop or breach coastal defences and inundate low lying areas. While astronomic tides are a deterministic component of sea surface elevations, storm surges and waves are stochastic in nature generated by storm events. Storm surge is a water setup resulting from synoptic variations of atmospheric pressure and wind blowing towards the coast [16]. Surge propagation and characteristics on the European Continental Shelf as well as the relation between wind and pressure-driven components of surge are explained in Olbert and Hartnett [51]. Wind waves result from strong winds blowing over adjacent seas; the mechanism of their generation is understood in principle [21]. Nevertheless, the combined effect of surges, tides and waves on total water levels still needs further research due to complex interactions between the three signals in shallow waters. In some areas such as deltas and estuaries, the complexity of the tide-surge-wave flood mechanism can be further exacerbated by a fluvial component, which due to heavy precipitation during storm events results in high river flows and may, therefore, contribute to coastal flooding. These processes are of particular importance and interest in the field of coastal

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flood risk assessments.

Historic events show that coastal flooding can have devastating social and economic effects. In the southern North Sea, the 1953 storm surge, apart from severe damage, caused ca. 1800 deaths in the Netherlands and over 300 deaths in the United Kingdom [20]. The 1991 Bangladesh storm surge caused the deaths of about 140,000 people [40]. More than 440,000 people have been killed in two storm tide events occurring in 1970 and 1991 in Bay of Bengal. More recently, in the United States of America, the devastating Hurricane Katrina in 2005 caused over 1800 deaths, while the storm surge from Cyclone Nargis in 2008 killed over 130,000 people in low-lying delta of the Irrawaddy, Burma. Typhoon Haiyan which hit the Philippines in November 2013 affected 14 million people and caused ca. 6200 deaths.

Mid latitude storms, as often developed in the north east (NE) Atlantic, are usually less devastating and easier to predict than the tropical cyclones [67]. Storms generated in the Atlantic ocean frequently pass through, or are in close proximity to, the European Continental Shelf; the majority of most severe storms occur during winter months [66]. During such events, storm surges both propagated from the deep ocean to the shelf and generated locally together with wind waves tend to cause a significant rise of water level above the expected tidal level [51].

The island of Ireland, located most westward on the north west (NW) European Continental Shelf, and therefore directly exposed to atmospheric and oceanic conditions present in the NE Atlantic, is at particular risk of coastal flooding. Here, storminess generating water setups and intense precipitation is responsible for both coastal and fluvial flooding and is considered as the major threat to flood-defence structures. Since developments and infrastructure along the Irish coastline are concentrated around urbanized embayments, sheltered to some extent from ocean swell and large wind waves occurring at open coast, the impact of swell and waves on coastal flooding is of secondary importance; this is similar to many regions of the world (e.g. [18,38]). However, wind waves may have an effect on storm surge development ([5] and [7]) and therefore indirectly contribute to coastal flooding; this effect will be discussed in the paper. Nonetheless, in Ireland flooding of the coastal hinterlands is generally caused by three phenomena: high astronomical tides, storm surges and high river flows or a combination of all three [54]. Over the last 30 years, storms caused serious flooding around the Irish coastline with overall damage cost running to hundreds of millions of euro. Although, the majority of flood events occur primarily from fluvial mechanism (August 1986, November 2002, November 2009, June 2012), the most devastating are those driven by extreme sea levels in coastal areas (where extreme storm surge coincides with high spring tide) or high sea levels (where extreme sea level is a product of a combination of moderate-to-high-surge occurring at spring tide or an extreme surge occurring with moderate-to-high tide) exacerbated by large river inflows from heavy precipitation. The severe tidal flooding on the east coast of Ireland in February 2002 due to combined high spring tides and extreme surge, generated by a 930 hPa depression passed to the NW of Ireland, impacted most acutely Dublin port areas and coastal residences of Dublin city; this event resulted in 1200 houses flooded and an estimated damage of €60 M. The tidal flood of October 2004 hit the south of Ireland strongest with severe floods in Cork City and communities along Cork Harbour. Similar scale event was also observed in June 2012. However, the most severe tidal flood on record was reported in January of 2014 where extreme surge coincided with a high tide and exceptionally heavy rainfall in many parts of Ireland resulting in loss of 2 lives and €69 M in damage.

The dynamics of coastal flooding resulting from a particular combination of multiple process drivers is very complex. Understanding flooding mechanisms, predicting extents of inundation and potential damage become important issues in coastal management. One of the key measures to prevent and reduce losses due to floods is to identify future flood-prone areas and provide reliable information to the public about the flood risk. This can be achieved through flood inundation maps which also may also serve in rescue and relief operations post flooding [11]. Towards this direction, the 2007 Flood Directive adopted by European Union obliges all member states to produce flood inundation and risk maps for their territory by 2015. Technologies exist for producing and delivering flood assessments, such as LIDAR data and GIS for mapping topography, high resolution bathymetry data, dense networks of tidal and river gauges and a range of modelling frameworks, yet these tools are still rarely integrated by authorities into best practice guidelines on how to assess flood risks.

Approaches of varying complexity based on computer models have been used to assess coastal flood extents; they can be either static or dynamic in their implementation. The most simplistic approach is the static inundation method which utilizes total sea water level to inundate locations hydraulically connected with the sea. While this method is relatively accurate for small distance between the coastline and the landward boundary [9] or steep terrains [56], it significantly over-predicts flood extents for mildly sloping landscapes or larger distances [19,56,68]. In the semi-dynamic method, the water volume discharge to floodplains in calculated based on timeseries of modelled water levels, hence the flooding is considered as non-instantaneous. Although this is an improvement in comparison to the static method, it still exhibits over-predictive tendencies [68]. The advantage of both methods, however, is their quick deployment and therefore ease of flood maps production [26]. The flood intensity index method [13] is another semi-dynamic approach based on a mathematical index considering local topography and flood scenario information. Although, it is found to provide satisfactory predictive skill of flood extent [68], the detail and accuracy of the method cannot be compared with that of hydraulic models [13]. Considering that high population densities, valuable assets and critical infrastructure are often located in coastal floodplains, accurate modelling of inundation in coastal areas is critical. In this context, hydraulic modelling is a tool, not only to allow one estimate water levels for particular flood events and flood extents but also to facilitate adequate flood risk management and assist the design of coastal defence structures including the effects of future climate change. The implementation of hydraulic models to simulate inundation progress and ultimate inundation extent can be considered as a dynamic method of coastal flood hazard mapping.

In recent years, along with the availability of high resolution altimetry data (such as LiDAR) and improved computational capabilities, a considerable effort in the development of hydraulic models has been made. The complexity of these models varies greatly from simple 1D hydraulic models (e.g. [41]) through, reduced complexity 2D models [4,61], 1D-2D linked models (e.g. [14,33]), shallow-water mass and momentum conserving 2D (e.g. [10,31,43]) and 3D models (e.g. [70]) to short wave energy, flow and infragravity wave propagation models (McCall, [42]) or coupled wave-circulation models [7,57]. Advantages and disadvantages of some of these models in regards to model accuracy and computational cost are briefly discussed in Comer et al. [11] and will be further elaborated in this paper. Usually, satisfactory model accuracy incurs the computational expense of high resolution or, vice versa, low model accuracy is compensated by the lower computational effort of coarse resolution. In this research, a new modelling framework involving multiscale nesting is applied; this approach was developed recently by Nash and Hartnett [47] and their multiscale nested model (MSN) was found to achieve a good balance between accuracy and computational effort. An additional advantage of MSN is its unique method of treatment of flooding and drying on a complex nested boundary. This aspect is particularly beneficial in flood modelling where sections of the numerical domain are subject to flooding and subsequent drying. For these two reasons, the MSN model seems perfectly suited for coastal flood modelling and thus was used to develop MSN_Flood.

The main aims of this paper are to