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Understanding the variability of an extreme storm tide along a coastline

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ABSTRACT

Correctly determining the peak storm tide height along the coastline, and expressing the associated natural variability, is essential for a robust prediction of coastal flood risk. A new approach is proposed that calculates a storm tide relationship (relative to a tide gauge) by using a storm surge model to describe the natural spatial variability based on the features of a large number of very high storm tides. Two historic flood events (1953 and 2007) were used to validate this characteristics approach along the East Anglia coastline (U.K.), and predicted water-levels were found to be in good agreement with tide gauge observations (Root Mean Squared Error of 36 cm), especially when compared to the method of assuming a storm tide of constant return period (Root Mean Squared Error of 59 cm). Detailed observations of storm tide height between tide gauge locations are rare; therefore, Synthetic Aperture Radar (SAR) was employed to calculate the LiDAR geo-referenced storm tide height along the North Somerset coastline of the Bristol Channel (U.K.). Two SAR observed "extreme" storm tide events were used to validate the characteristics approach between tide gauges (Root Mean Squared Error of 1.2 m and 0.7 m), and indicated the presence of localised wave effects to the observed storm tide height that could have a significant effect to flood risk estimates.

1. Introduction

To determine current and future flood risk, an inundation model (typically based on the depth-averaged shallow water equations), is used to simulate flooding inland of sea defences. In the U.K. long, high quality tide gauge records can be used (with extreme value theory) to estimate an extreme water-level that has an associated probability of exceedance, called the return period; for example, the "1 in 200 year water-level" (see Coles, 2001). The forcing water-level time-series of a coastal inundation model is typically derived using an extreme water-level scenario (e.g. Dawson et al., 2005a; Purvis et al., 2008), which is capable of characterising the long-term statistics of the extreme sea level climate at all coastal locations (subject to a dense network of sea level observations and an effective means of interpolation). However, during an extreme event it is highly unlikely that the storm tide will exhibit a constant return period along a coastline due to local scale bathymetric and topographic effects.

A better way to derive the extreme water level boundary condition for a coastal inundation model (within a U.K. region) might be to use the so-called characteristics approach of Lewis et al. (2011). This characteristics approach spatially interpolates a robust extreme water-level estimate at a single location (e.g. a tide gauge) along a coastline and can describe the natural spatial variability of an extreme storm tide, which is essential for a robust flood risk prediction (see Lewis et al., 2011). Utilising the 12 km CS3X storm surge model early warning forecast system (see Flather, 2000; Horsburgh et al., 2008), and its relatively long archive (http://www.environmentagency.gov.uk/research/policy/116129.aspx), the characteristics approach calculates the difference between the water-level observed at a local tide gauge, compared to that predicted by the CS3X model along a region's coastline for extreme storm tides. This interpolated "characteristics" offset can be applied to any estimated (or observed) extreme water-level at a local tide gauge to give the estimated storm-tide height along the coast based on the spatial characteristics of real events (hence called the characteristics approach).

Before being adopted by flood risk managers, the characteristics approach should be evaluated for other regions and validated. Therefore, this spatial storm tide interpolation approach was applied to the historically flood prone East Anglia region of the U.K., and for a much greater length of coastline than studied in Lewis et al. (2011) (~400 km instead of ~60 km). The East Anglia characteristics offset was then validated using tide gauge observations from two historic storm tide events: (1) The devastating 1953 North

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Sea flood (see Wolf and Flather, 2005); and (2) The 2007 "near-miss" event, which had the potential to result in severe inundation (see Horsburgh et al., 2008). Tide gauges tend to be located in sheltered harbours or estuaries; however, the storm tide height, and the contribution from waves, is likely to vary along an exposed coastline due to local scale effects (e.g. bathymetry). Correctly resolving the still water-level in a coastal inundation model is more important than some intra-modelling uncertainties (i.e. roughness value choice; see Lewis et al., 2011), and considering wave set-up and run-up may add metres to the total water-level (Wolf, 2008; Poulos et al., 2012); accurately estimating the peak storm tide height along a coastline's length (including wave effects and natural variability) may be vital for accurate coastal flood risk prediction (e.g. Chini and Stansby, 2012).

Due to a lack of *in situ* storm tide height observations between tide gauges, no ground validation of the characteristics approach can be made along an exposed coastline. However, Synthetic Aperture Radar (SAR) has been shown to be an effective method of inundation area observation (e.g. Delmeire, 1997; Smith, 1997), due to the specular reflection of microwaves from open smooth water bodies in all-weather capabilities. Indeed, SAR imagery has been used to determine the shoreline position using the waterline method (e.g. Mason and Davenport, 1996; Mason et al., 1998); therefore, it is hypothesised that the storm tide height along a coastline could be estimated by geo-referencing the SAR derived shoreline position with LiDAR (Light Detection And Ranging) topography data. The characteristics approach has been previously applied to the North Somerset coast (Lewis et al., 2011); however, for the first time, we measure extreme storm tide height using SAR imagery and use the resultant water-level observations to validate the characteristics approach between tide gauge observations.

2. Methodology

2.1. The characteristics approach

Lowestoft was chosen as the tide gauge with which to calculate the characteristics offset because of the record length, which includes the two historic extreme water-level events that will be used to validate the characteristics approach: 1953 (see Wolf and Flather, 2005), and 2007 (see Horsburgh et al., 2008). Following the characteristics methodology of Lewis et al. (2011), the difference between the peak storm tide observed at Lowestoft tide gauge and that predicted by the CS3X storm surge model along the coastline (between Cromer and Sheerness), was calculated for all storm tide events observed at Lowestoft to be greater than 2.0 m Ordnance Datum Newlyn (ODN), which is approximately the 1-year return water-level (Dixon and Tawn, 1997). By following this definition, 26 storm tides (tide + surge) were identified between 1981 and 2007, and the peak storm tide predicted at each of 37 CS3X storm surge model cells (closest to the East Anglia coastline) were extracted from the U.K. Coastal Monitoring and Forecast System's archive (http://www.environmentagency.gov.uk/research/policy/116129.aspx).

The peak storm tide offset (at each of the 37 CS3X model cells along the East Anglia coast) was found to significantly correlate with the peak storm tide observed at Lowestoft tide gauge for the 26 events (although the strength of this Spearman rank correlation spatially varied). Furthermore, the variance within each CS3X model cell's offset (of the 26 events) was found to be normally distributed (using the Lilliefor's test). This was also found within the North Somerset characteristics offset, which was based on 17 events and 5 CS3X model cells (method C; see Lewis et al., 2011). Therefore, the mean offset can be used to interpolate the peak storm tide along the coast from an observed (or estimated) extreme water-level at the Lowestoft tide gauge, and the spatial storm tide uncertainty can be quantified using the observed natural variability within the offset (i.e. 95% of observed variability can be accounted for by the mean $\pm$ 2 standard deviations).

A mean offset of -0.23 m was calculated at the CS3X model cell that includes the Lowestoft tide gauge; however a calibration was also required for the offset of the North Somerset region, which was attributed to the 12 km resolution of the CS3X storm surge model (see Lewis et al., 2011). Therefore, a spatially uniform (equal) calibration was applied to all mean offset values of the CS3X model cells so that the mean offset at the offset tide gauge was zero. The spatially interpolated calibrated mean offset for East Anglia is shown in Fig. 1, alongside the North Somerset mean offset which was calculated using the same characteristics methodology but with Avonmouth as the offset tide gauge (see Lewis et al., 2011). The mean offsets of both regions (North Somerset and East Anglia, see Fig. 1) shall be used to validate the characteristics approach.

2.2. Characteristics approach validation for East Anglia

No SAR images from the European Space Agency (ESA) database (http://earth.esa.int/resources/) were available for East Anglia at times of an extreme storm tide (at Lowestoft). However, to validate the characteristics approach for the East Anglia coastline, tide

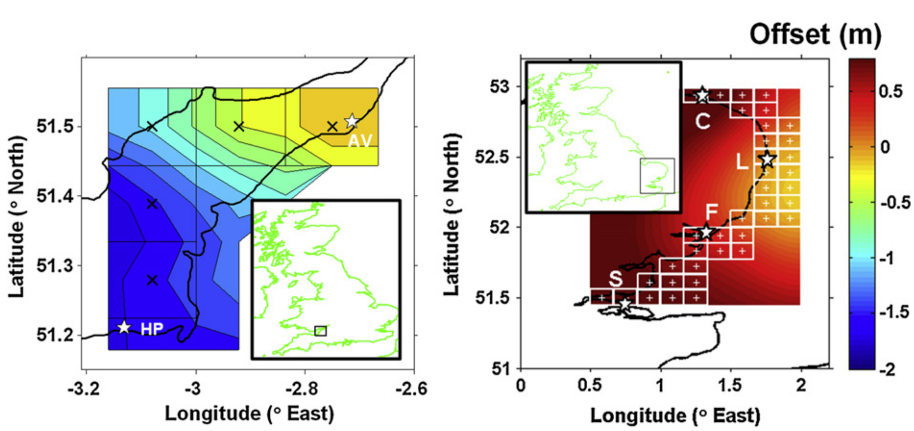

Fig. 1. The interpolated characteristics offset (m), relative to the Avonmouth tide gauge (AV) for the Bristol Channel (Left panel), and relative to the Lowestoft (L) tide gauge for East Anglia (Right panel). Tide gauges (used to validate the Characteristics method) are shown as HP (Hinkley Point) for the Bristol Channel (LHS), and C (Cromer), F (Felixstow), as well as S (Sheerness) for the East Anglia (Right panel).