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Presence and possible cause of periodicities in 20th-century extreme coastal surge: Belfast Harbour, Northern Ireland

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ABSTRACT

Identifying 20th-century periodic coastal surge variation is strategic for the 21st-century coastal surge estimates, as surge periodicities may amplify/reduce future MSL enhanced surge forecasts. Extreme coastal surge data from Belfast Harbour (UK) tide gauges are available for 1901–2010 and provide the potential for decadal-plus periodic coastal surge analysis. Annual extreme surge-elevation distributions (sampled every 10-min) are analysed using PCA and cluster analysis to decompose variation within- and between-years to assess similarity of years in terms of Surge Climate Types, and to establish significance of any transitions in Type occurrence over time using non-parametric Markov analysis. Annual extreme surge variation is shown to be periodically organised across the 20th century. Extreme surge magnitude and distribution show a number of significant cyclonic induced multi-annual (2, 3, 5 & 6 years) cycles, as well as dominant multi-decadal (15–25 years) cycles of variation superimposed on an 80 year fluctuation in atmospheric–oceanic variation across the North Atlantic (relative to NAO/AMO interaction). The top 30 extreme surge events show some relationship with NAO per se, given that 80% are associated with westerly dominant atmospheric flows (+NAO), but there are 20% of the events associated with blocking air massess (−NAO). Although 20% of the top 30 ranked positive surges occurred within the last twenty years, there is no unequivocal evidence of recent acceleration in extreme surge magnitude related to other than the scale of natural periodic variation.

1. Introduction

Coastal surge is defined as the observed displacement of water in a positive sense ('+' surge) above that tidally predicted, and is usually taken to be synonymous with storm-based atmospheric-generated processes that enhance very short term sea-level elevation (<hours). Surge by this definition, assumes that mean sea level is consistent throughout the time series, such that tidal predictions are superimposed on a consistent mean sea level (MSL) datum. However, "atmospheric-generated processes that enhance sea-level elevation" may operate in conjunction with oceanographic forcing at a range of time scales and over a range of elevations, thus contributing to the apparent surge increment. This paper is initially directed at extreme surges that are generated by short-term atmospheric forcing (day-scale), but recognises that though such short term changes can be supplemented by seasonal to inter-annual rises in MSL that are also atmospheric-oceanic driven, there is likely to be an order of magnitude difference in their relative contribution to the total extreme surge.

Estimating extreme storm surge distribution has become a strategic element of managing future coastal vulnerability (Wadey et al., 2013), and key to such an approach is knowledge of point and/or regional surge distributions, which are often based on model interpretations of limited empirical observations (Wang et al., 2008; UKIP09, 2009; Olbert and Hartnett, 2010; Arns et al., 2013; Lewis et al., 2013; Weisse et al., 2014). Again, central to managing coastal vulnerability is identifying accelerating storm surge in the 21st century related to climate change (e.g. Wang et al., 2008; Olbert and Hartnett, 2010; Weisse et al., 2012). However, Wong et al. (2014) identify the difficulties in establishing the likelihood of 21st-century coastal surge change per se, given the small number of controlled regional storm surge studies available together with the different atmospheric forcing factors and modelling approaches used. A further difficulty in forecasting future coastal surge is whether contemporary surge has underlying periodicities that may account for future magnitude increases that are part of natural background, rather than newly accelerated variation. Likewise, low values of existing periodic surge may counterbalance future predicted extremes based solely on rising mean sea level.

Modelling to establish surge distribution from limited observations may influence any temporal surge assessment (Gonnert, 1999), such that establishing any rhythmicity in surge component is limited, without recourse to observed data series equal to the rhythm's wavelength. The use of any surge proxy requires as Coles (2001) indicates, 'long-

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term' tide gauge records to help substantiate extreme event models, where 'long-term' needs to be measured in multiple decades up to century scale. Likewise the issue of establishing rhythmic extreme surge at multi-annual to multi-decadal scales needs similar long-term data sets.

A sequence of five tide gauges working in Belfast Harbour, Northern Ireland (Lat: 54° 37′ 06″N; Long 5° 53′ 54″W) during the 20th-century, provides a record of near-instantaneous sea-level variation that commenced (in terms of extant record) in 1901 and is still operational at the present time. This makes the Belfast gauge one of the longest daily tidal records in northwest Europe, and underlines the importance of the site for analysis of extreme surge variation at a range of scales from multi-decade to sub-annual. The ability to produce such a Belfast surge record for the 20th-century fills in the major void left in the calibration of instrumental records for integrated water-level variation around the British Isles (Haigh et al., 2009).

Given this context, the paper's objectives are therefore: i) to specify the 20th-century extreme surge variation recorded at Belfast Harbour; and ii) to deconstruct extreme surge variation into potential significant periodicities. If significant surge periodicities are found, then the third objective is to compare them with potential North Atlantic atmospheric–oceanic forcing variation for time association.

2. Methods

2.1. Data availability and continuity

There have been five different tide-gauge positions/machine types (TG1-5) within Belfast Harbour over the period 1901–to date. Details of gauge changes and data recording/abstraction are supplied by Murdy et al. (2015). Gauges were mainly analogue recording of float variation with the latest (TG5) being digital. These tide-gauges were unfortunately never permanent in spatial terms during the 20th-century (see Fig. 3 in Murdy et al., 2015), with gauges changing position on three occasions. However, at every change, the tide-gauge reference level, or Tide Gauge Zero (TGZ) remained constant to Belfast Harbour Datum (also UK Admiralty Chart Datum). The observed elevations recorded at Belfast Harbour for the period 1901–2010 (c 3.83×10^6 observations) were all within the range of $+3$ to -3 m OD Belfast (relative to Mean High Water Springs [MHWS] at $+1.5$ m OD and Mean Low Water of Springs [MLWS] at -1.6 m OD). All elevations were determined to within an accuracy of 1 cm, however a switch in tide gauge recording format of the current gauge (TG5) to the nearest 10 cm elevation interval after 2001 has repercussions for analyses of 21st century data. This point will be reconsidered in Section 4.1.

The paper marigram record supported by Belfast Harbour Commissioners (deposited with BODC, National Oceanographic Centre, Liverpool, UK) was replaced in 1987 by a digital printout until 2001 when it was replaced by a full digital tide-gauge measuring and recording system. The complete Belfast tide gauge record was digitally retrieved from the original analogue (daily) records and merged with the post-2001 digital series to allow the full Belfast water level series to be retrieved (Murdy et al., 2015). Extreme water level data sampled at both 10 and 60 min (Pugh, 1987) have been rectified for any marigram distortions, timing issues and datum control and validated using annual sample variances. Murdy et al. (2015) present the full data acquisition methodology and the varying stages of data (marigram and digital) transposition and merger required to develop a consistent dataset sufficient for determination of extreme surge.

The 20th-century data record is not continuous due to: missing years, breaks in annual records due to tide-gauge malfunction and planned maintenance periods. The latter two absences are less restrictive for determining annual characterisation of surge, but missing years add to the uncertainty of any decade-plus scale analysis. There are no extant Belfast Harbour records available for 1903, 1907–1909, 1919, 1928–1930 and 1933–1935. Despite disruptions in further annual records (25 years) they contain substantial surge data and as such these reduced year datasets are included in the full century-plus analysis.

The basic sampling interval used in the analysis is 10 min throughout the original analogue record. This interval substantially reduces the associated problem of missing highest surge values and the need for 'skewed surge' evaluation (Weiss et al., 2012). Reporting digital outputs (between 1987 and 2001) were set to a 15 min interval by Belfast Harbour, from which only the 60 min values were used in the new digital record. In the validation of the 10 min record, there were years where successful reconciliation or reduction of elevation variances could not be obtained given the absence of contemporary engineers' commentaries by which adjustments of datum could be established. This meant that records for 1974, 1986, 1997 and 1998 were excluded where issues of timing or elevation uncertainties dominated the record. Given all these caveats, Murdy et al. (2015) obtained a 66% time coverage using 10 min sampling between 1901 and 2010. This study used the 10 min set augmented with a 60 min sampling for 1987–2001 to extend the analysis range to 78%. The missing data inevitably added a major control on the analytic method (essentially non-parametric) used to establish any potential periodicity in extreme surge.

Fig. 1A shows the monthly averages of observed sea level. IOC (2006) has identified standards concerning entry of annual data to valid MSL change analyses. These standards indicate the minimum observations available per month and minimum number of months per year, by which "useful" data, i.e. includable annual characterisation, can be used for MSL change determination. Only 59% of the 1901–2010 data range could be included in determining MSL, working with the "useful year" criteria. The use of monthly, rather than annual, averaged data extended the data coverage to 78% of the 1901–2010 period. All the observed surge values were detrended for any long-term (secular) change in MSL, using the linear trend in the monthly MSL over the 20th-century [MSL (cm) $= -45.666 + 0.0232$ (year)].

Tidal state predictions were calculated using T-tide™ based on MATLAB (Pawlowicz et al., 2002), working with 67 tidal constituents generated from the 1951 observed water level data set (Murdy et al., 2015). The mean predicted tide was then set to each year's detrended mean observed water level.

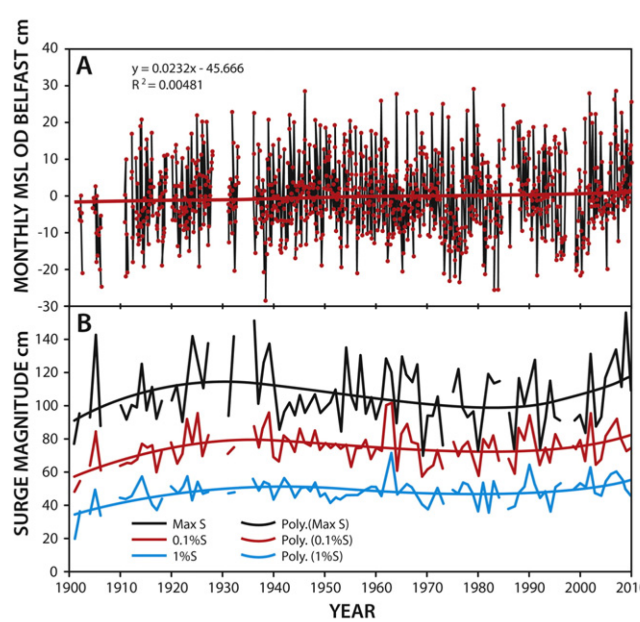

Fig. 1. A–B: (A) Mean sea level trend (0.4%RSS): based on monthly averages of MSL over the 20th-century at Belfast Harbour. (B) The annual Belfast Harbour maximum surge (S_{max}), the top 0.1% and top 1% values of annual surge plus their characteristic long-term trends (10.1%, 18.1%, & 25.5%RSS, respectively) during the 20th-century.