<table>
<thead>
<tr>
<th>Title</th>
<th>Storms and surges in Irish coastal waters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Author(s)</td>
<td>Olbert, Agnieszka Indiana; Hartnett, Michael</td>
</tr>
<tr>
<td>Publication Date</td>
<td>2010-04-29</td>
</tr>
<tr>
<td>Publisher</td>
<td>Elsevier ScienceDirect</td>
</tr>
<tr>
<td>Link to publisher's version</td>
<td><a href="http://dx.doi.org/10.1016/j.ocemod.2010.04.004">http://dx.doi.org/10.1016/j.ocemod.2010.04.004</a></td>
</tr>
<tr>
<td>Item record</td>
<td><a href="http://hdl.handle.net/10379/5843">http://hdl.handle.net/10379/5843</a></td>
</tr>
<tr>
<td>DOI</td>
<td><a href="http://dx.doi.org/10.1016/j.ocemod.2010.04.004">http://dx.doi.org/10.1016/j.ocemod.2010.04.004</a></td>
</tr>
</tbody>
</table>

Downloaded 2018-12-29T14:05Z

Some rights reserved. For more information, please see the item record link above.
Storms and surges in Irish coastal waters

Agnieszka I. Olberta*, Michael Hartnett a

a Environmental Change Institute, National University of Ireland, Galway, Ireland

* Corresponding author:
A.I. Olbert
tel.: +353 91 493208
fax: +353 91 494507
e-mail address: indiana.olbert@nuigalway.ie
postal address: Environmental Change Institute, NUIG, Galway, Ireland

Abstract

Mechanisms of storm surge formation and severity on the north European continental shelf and, in particular, in the Irish coastal waters are examined in this paper. A numerical surge model was developed and used in combination with meteorological forcing and hydrographic records to analysis aspects of surge mechanics. An attempt is made to estimate sea level response to meteorology and to quantify pressure and wind contributions as a driving force. Results show that the inverted barometer term contributes to more than 80% of surge residual in the Celtic Sea and to approximately 55% along the British coast in the Irish Sea. Local winds on the Irish Sea have less of an impact on storm surge heights than previously reported; the Irish Sea surges are predominantly caused by the propagation of external surges into the basin from the north and south channels.

An analysis of sea level variability due to wind or pressure was undertaken to select regions of positive and negative interactions. Negative correlation between wind and pressure driven surges found in the Celtic Sea explains generally low magnitudes of surges in this region, while medium level correlation coefficients could be responsible for generally high surges in the eastern Irish Sea and coast of Scotland. Following a regression analysis it was determined that in these regions a drop of atmospheric pressure by 1 mbar implies a rise of sea level by 1.2 cm.

Non-linear tide-surge interactions are also investigated. Relationships between surge and tidal phase are determined at numerous locations in the Irish coastal waters. Analysis shows that interaction characteristics vary from site to site due to shallow water dynamics and variations in topography. The regional pattern of tide-surge interactions is quite remarkable.

Finally, a characterisation of the statistical properties of extreme surges is given. An efficient approach is adopted considering statistics of extremes. A hybrid GEV-EV1 statistical solution was used to estimate the 10, 50 and 200-years extreme surge in the Irish coastal waters.

Keywords:
North East Atlantic, Irish Sea, sea surge, mid-latitude depression, POM, extreme surge

1. Introduction

Flooding and damage to coastal areas of the European Continental Shelf are frequently reported. The disastrous storm of 1953 caused flooding in southeastern England and, particularly, in the Netherlands (Bode and Hardy, 1997). During the last century, serious flooding around the Irish coastline has been also observed. Over the last 50 years 7 events induced significant water level rise in Cork City due to surge, tide and river inflow (Halcrow, 2008). Historical data reveals many occasions of flooding throughout towns and villages along the Irish coastline.
Storm surges are the sea level response to meteorological conditions. Detailed studies of meteorological forcing in oceanic regions and adjacent continental shelf edges have been widely reported in literature, and the surge physics of these regions is well understood (Ponte 1994). The propagation of surges in shallow coastal water differs from their propagation in deeper offshore regions and still requires further understanding. In particular, the non-linear nature of tide-surge interaction (Horsburgh and Wilson, 2007) and wind effects on surge development and propagation (Jones and Davies, 1998) require further analysis. The propagation of surges around the Irish coastal waters is complex due to open ocean waters of the west coast, the semi-enclosed nature of the Irish Sea and complex topography and bathymetry. Oceanic flows and topography are identified as the key factors driving the flow and influencing its on-shelf excursion (Jones and Davies, 2006). Although, it is known that external surges are generated in the North East Atlantic and propagate into the Irish Sea through north and south channels, the contribution of external and locally-generated surges within the basin has not been fully established. Prandle and Wolf (1978) found that the dynamics of wave propagation prevent maxima surge levels occurring coincidently with high tide. Tide-surge interactions are local and vary considerably from one region to another, from virtually no clear relationship to high dependency between the two processes. Also, relationships between phase of tide and surge diverge regionally. Attempts to quantify spatial variability in the dependency between tide and surge have been made by Defra (2005), however, this analysis was restricted only to co-occurrence of surge on rising, close-to-high tides. The severity of storm surges depends primarily on wind speed, wind direction and duration (Woth et al., 2006). Reduced atmospheric pressure also plays an important role in the temporary rise of water level above expected tidal level (e.g Wells, 1997). The contribution of each signal to total water setup varies spatially. For example, in the North Atlantic the response to pressure is essentially static or close to inverted barometer solution and dominates sea level variability (Ponte, 1994). Whereas, on the continental shelf deviations from this relation are expected due of wind-forcing and resonant responses (Trupin and Wahr, 1990). Restrictions on flow through narrow channels into isolated basins may also have local effects (Ducet et al., 1999). Over the past three decades there have been many publications dealing with dynamic modelling of tides and surges in the shelf region west of Ireland. Particularly, significant progress has been made since the work of Heaps (1983) and Heaps and Jones (1979). The 2D model of western Irish Sea developed by Heaps and Jones (1979) was subsequently replaced by a three-dimensional version to compute surge currents (Davies and Jones, 1992). However, more recent models of Flather et al. (1998), Lowe et al. (2001) or Jones and Davies (2006) showed that storm surge as a first-order process can be very well described by two-dimensional vertically integrated shallow water equations when proper parameterization of wind input at the surface and bottom friction is made to the momentum equation.

This paper presents the results of research undertaken by the Authors on a number of aspects of surge mechanics around the Irish coast that had not previously been addressed in such detail. The influence of North Atlantic storm tracks and depression characteristics on propagation of surge waves around the Irish coast is investigated. Surge propagation is complicated by the semi-enclosed nature of the Irish Sea, with surge waves propagating both northward and southward into the sea. Further research was undertaken to assess relative contributions of local and distant wind fields on surge mechanics. Tidal dynamics varying considerably around Ireland, spatial variations in tide-surge interactions around the coast were investigated. Coastal defence structures must be designed to protect against surges with low frequency return periods. An analysis of historical surge extremes was undertaken and used to estimate surges with extreme return periods.

2. Methodology

To undertake surge analyses, major surge events incident around the Irish coastline were isolated. Historical records of water elevation gauges in Dublin Bay and Fishguard were reviewed; the records were de-tided to develop surge residuals. For the purposes of this research, only when surge residuals exceeded 0.5m is an event considered as a candidate surge
event. From the de-tided records, the largest 48 surge events between 1959 and 2005 were selected for the surge analysis.

2.1 Atmospheric forcing

For each low pressure system event, a four-day period was added prior to the event and a two-day period was added subsequent to the event to allow for model spin-up and complete development of surge conditions throughout the domain. For the above 48 events, data sets consisting of mean sea level pressures and 10 m wind fields were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). Regional reanalysis ERA-40 data (Uppala et al., 2005) and operational model level first-guess data set (Simmons et al., 1989) were used for the storm duration and the additional days before and after. The duration of storms differed and in some instances one low pressure system was quickly followed by another. In these cases, the ECMWF dataset was extended to cover both periods. These data provided the necessary meteorological parameters required in the numerical model to simulate a series of low pressure systems tracking across the NE Atlantic. As a result the shortest event simulated was 12 days and the longest was 21 days. One of the advantages of having relatively short duration events is that there is no need to remove the isostatic and eustatic trends in mean sea level (Butler et al., 2006). Fig. 1 shows the trajectories of three low pressure systems that tracked consecutively across the NE Atlantic over a 14 day period.

ECMWF hindcast parameters were provided as 3-hr instantaneous values on a spatial grid of 1.125 degree prior to 1991, and at a resolution 0.5 degree from 1991 onwards. The dataset was linearly interpolated in time at every surge model timestep to ensure a smooth transition from one set of meteorological forcing to the next. Similarly, spatial interpolation was performed to match the high spatial resolution of the hydrodynamic model of 5 minutes by 2.5 minutes in zonal and meridional direction, respectively.

2.2 Tide-surge model

The hydrodynamic modelling of tide and surge conditions in NE Atlantic was performed using the Princeton Ocean Model (POM), (Blumberg and Mellor, 1987; Mellor, 2001). A detailed description of the model can be found in Elliott et al. (2007). Although POM has been developed as a full 3D primitive equation model, the depth-averaged version of the code was used. The choice of 2D calculations was dictated by computational economy. Sensitivity analysis was carried out, results showed that surges calculated by the 2D model were almost identical to 3D model calculations. The model equations were solved using a finite difference method. The hydrodynamic model is forced by a variable surface elevation and meteorological conditions. At open boundaries a radiation condition relates the normal component of the depth mean current to the sea surface elevation accounting for tidal input. A temporally- and spatially-variable wind stress is applied to the model in form of pressure and wind speed climatology.

Wind stresses were parameterized as a quadratic function of the 10 m wind speed. Changes in the roughness of ocean surface were included through a varying drag coefficient. The bottom stress term was determined matching velocities with the logarithmic law of the wall. A constant value of 0.0025 for the frictional parameter was used.

Two separate model runs were carried out for each surge analysis. In the first run, both tide and meteorological forcing were applied and total water surface elevations calculated. In the second run, tidal forcing was applied along open boundaries in the absence of meteorological forcing. Water surface elevations, relative to mean sea level, were output from both tide and surge models as instantaneous values at 5 minutes interval. Surge residuals and currents computed by the model were determined by subtracting a tide-only solution from the tide and surge calculations.
2.3 Numerical Model setup for North-East Atlantic

Surge developments in Irish coastal waters are complex and prevail over a large surface area. Depression systems are frequently generated far west of the continental shelf and subsequently propagate into Irish coastal waters. Thus, in order to simulate surges around Ireland, it is necessary that the numerical model domain is large enough to include surge formations in the NE Atlantic. The computational domain of the tide and surge models is bounded by coordinates: 30° W to 0° W and 40° N to 60° N as shown in Fig. 2. In the south the domain reaches the northern part of Spain and the Bay of Biscay and in the north it extends to south of the Faroe Banks. In the east-west direction the domain stretches from the Greenwich meridian in England to the central Atlantic including the Porcupine Bank and the Rockall Trough.

A high-resolution horizontal grid was developed (1/12° longitude by 1/24° latitude); the domain has 173641 grid points. The model bathymetry was constructed from the General Bathymetric Charts of the Oceans (GEBCO) 2004 dataset and high resolution data from the Irish National Seabed Survey (INNS) data. The simulation of astronomical tides in the model domain was driven by vertical oscillations of water levels at the open boundaries; water elevations were defined at 5 open sea boundaries (open boundaries 1-5 shown in Fig. 2(a)). The timeseries of tidal elevations along these boundaries was extracted from the global hydrodynamic model FES99 and interpolated onto the model grid.

2.4 Model validation

The surge model was validated using records of detided water surface elevations for a number of storms and at different locations. Details are presented here of model validation against field records at four locations for a period 15/10/2002-28/10/2002 that covers the duration of the three storms shown in Fig. 1. Records of water elevations were obtained from two tidal gauges along the east coast of Great Britain (Fishguard and Newlyn) and at two locations in Ireland (Bangor and Cork). These stations are quite representative of the storms within the Irish Sea and its approaches (see Fig. 2). These validation stations allow an assessment of model behaviour in both the semi-enclosed basin of Irish Sea and the open Celtic Sea. UK data were provided by the BODC, while Cork records were available through the Irish Office for Public Works (OPW). Water elevations at all stations were recorded at 15 minutes intervals. Surge residuals were extracted from datasets using harmonic analysis to remove the dominant tidal signal from observed water levels. The surge residuals detided from the BODC data (Fig. 3) contain a portion of tidal signal, which is associated with tide-surge interaction in shallow water as explained by Horsburgh and Wilson (2007). A positive surge increases the phase speed of both tide and surge as they travel along the coast. A simple arithmetic of subtracting two phase-shifted sinusoids (observed water level and tide prediction) generates a semidiurnal oscillation. This feature is not reproduced in the model.

Fig. 3(a)-(d) shows comparisons between numerical model output and field data during the October 2002 storms. Each station detects three surge peaks that mirror three consecutive depression systems that developed successively in the proximity of the Irish coast. The numerical model reproduces magnitudes and times of surge peaks very well with correlation coefficients of 0.85, 0.83, 0.84 and 0.84 for Fishguard, Bangor, Newlyn and Cork, respectively. The level of model performance is comparable at all stations, despite different topographic and dynamic characteristics of each location.

Root-mean-square errors (RMSE) at Fishguard, Bangor, Newlyn and Cork are 0.11, 0.11, 0.08, and 0.10 m, respectively. The small errors are followed by low standard deviations (STD) of 0.11, 0.11, 0.09, and 0.10 m for the above stations. The decimal difference between RMSE and STD
indicates close agreement of mean value between observation and simulation. Further validation results have been published in Elliott et al. (2007).

2.5 Statistical methods

Large surge events that occurred during the years 1959 – 2005 were simulated by applying hindcast reanalysis meteorological data of 48 events to the numerical model, and subsequently statistically analysing surge distributions. Statistics of extremes was used to estimate extreme return periods of surges in the model domain. An important advantage of the statistical method is the ability to draw inferences about the extremes of a stochastic process using only data from relatively extreme values of that process (Butler et al., 2006). Well fitted statistical models can be utilized in projecting the magnitude of future extremes. However, the method is sensitive to the choice of the distribution and the fitting procedure (Woth et al., 2006), therefore, if done carelessly, leads to erroneous solution.

In the present analysis probability distributions were investigated for fitting the surge maxima in a similar manner as in Walton (2000). The following extreme value distribution models were tested:

- Log-normal (2 parameter),
- Exponential (2 parameter),
- Logistic (2 parameter),
- Type I Pareto (2 parameter),
- Generalized Pareto-GPD (3 parameter),
- Log-Pearson Type 3 (2 parameter),
- Weibull (2 parameter),
- Gumbel-EV1 (2 parameter) and
- Generalised Extreme Value-GEV (3 parameter).

All above distributions were assessed graphically (not shown here) to determine how well they fitted model simulations. In addition to full dataset fitting, three distributions, Weibull, EV1 and GEV, were tested for goodness of fit to ‘peak over threshold' dataset. A median value of the extreme surge dataset was chosen for a lower cut-off point.

The quality of statistical model was determined from assessment of the model fit to the upper tail of extreme surge probability distribution. Two models, EV1 (Gumbel, 1958) and GEV (Coles, 2001), were found to approximate the distribution of extreme surges particularly well and were subsequently used in the extreme surge analysis. The EV1 distribution has been frequently employed in extreme value studies over many decades (e.g. Gumbel, 1958; Smith, 1986; Lowe et al., 2001). In recent years however, the GEV model has become more popular with many successful applications to hydraulic studies (e.g. Butler et al., 2006; Stephenson and Tawn, 2004; Katz et al., 2002)

3. Results

3.1 Propagation of surge wave

For a given coastline configuration and bathymetry, the mechanisms of storm surge development and evolution are related to the characteristics of depression systems. In mid-latitude regions, the severity and distribution of surges depend then on the extra-tropical cyclone location and magnitude, forward speed and movement direction of the eye of the cyclone, cyclone radius and wind speed. In this study, all 48 storm events were examined and the impact of storm on surge was assessed. Storm tracks were drawn and compared with corresponding surge distributions. Surprisingly, in spite of very diverse storm paths, only a few patterns of surge distributions were
distinguished. Each storm was classified into one of five groups; characteristics of each group are summarized in Table 1.

Surge propagation mechanics was also investigated. Each storm group gives rise to characteristic patterns of surge propagation and associated timings of surge maxima. Surge propagation in coastal waters is very complex and difficult to determine due to the fact that surge wave dynamics is altered by the depression dynamics. Although surge pathways vary from one storm to another, typical features of propagation can be clearly distinguished for each storm group. Pathways of representative low pressure systems paired with associated surge distributions are visually presented in Fig. 4.

A northern storm (NS) generated off the continental shelf induces water setup firstly on the west coast of Ireland, from where it travels northward and southward along the coast to the Irish Sea. As the depression progresses onto the continental shelf, surge propagation into the Irish Sea through the North Channel becomes more significant. Surges entering initially through the south entrance are subsequently followed by higher peaks from the north, which propagate southward. The highest surges within the Irish Sea and Celtic Sea are attributed to surge waves travelling from the north.

North-western storms (NWS), western storms (WS) and central storms (CS) invoke surges of very similar pathways. As the west and south of Ireland are directly exposed to ocean processes these regions are affected by surge waves first. Later, the wave gradually moves along the coast into the Irish Sea. Surges travelling through the south entrance fill the basin faster than surges approaching from the north but they are generally weaker. The time delay between surge peaks on the Atlantic coast and within the Irish Sea could not be explicitly established. The travel time from south-west coast of Ireland to Dublin-Holyhead line varies greatly and is generally within the range of 15-24 hours. However, this depends on the depression structure and, in particular, the speed of movement.

In the case of southern storms (SS), propagation patterns are more predictable. Along with the depression moving northward, the surges developed initially on the south-west coast of Ireland propagate northward through the Irish Sea and along the west coast.

The common feature of most of the storm groups analyzed here (except SS) is a time lag between the surge peak on the west or south-west of Ireland and within the Irish Sea. Timings of maximum surge in coastal waters are presented as 3-hour contour plots in the right column of Fig. 4. The presence of the island of Ireland protects the British coast from direct impact; on one hand it delays the arrival of surge but on other hand it is responsible for surge amplification within the semi-enclosed, narrow Irish Sea.

3.2 Winds and pressure effect on sea level

In this section the Authors consider sea level response to aspects of meteorological forcing. In general, sea level changes due to synoptic situations are attributed in various degrees to variations in atmospheric pressure and associated sustained winds. The response to pressure forcing is due to dynamic pressure signal and the inverted barometer (IB) term estimated from approximations given by Ponte (1994). The wind-driven signal contains local wind-driven forcing and non-local effects propagating into the area of interest. The importance of wind and pressure signal to the variability in sea level of Irish coastal waters is assessed separately for each component by running a numerical model forced with only pressure or wind data. The total surge height $S$ is separated into pressure-driven component $S_P$ and wind-driven component $S_W$, defined as:

$$S_P = \frac{\sum_{i=1}^{N} S_{P_{\text{max}}}(i)}{N} \quad (1)$$
\[
S_W = \frac{1}{N} \sum_{i=1}^{N} S_{W,max}(i) \tag{2}
\]

\[
S = \frac{1}{N} \sum_{i=1}^{N} S_{max}(i) \tag{3}
\]

where \( S_{max} \) is a maximum surge residual generated by both pressure and wind forcing during the event \((i)\), \( S_{P,max} \) and \( S_{W,max} \) are maximum surge residuals during the event \((i)\) derived from pressure-forced model and wind-forced model, respectively; \( N \) is a total number of events equal to 48. The contributions of both terms to the total response are presented in Fig. 5.

The pressure term contributes substantially to surge generation in the model domain; pressure terms contribute over 60% in the Irish Sea and up to 100% on the offshore continental shelf (Fig. 5a). Wind stress does not affect water levels offshore and in general its importance increases with proximity to the coastline. The strongest response to wind is observed in the eastern Irish Sea, where over half the value of the total surge is generated by wind forcing (Fig. 5b). This is because the effect of sea levels increases inversely with the water depth and is most important when the wind blows over extensive regions of shallow water (Pugh, 1987). Thus, higher surges on the west coast of Britain appear to be generated by the prevailing westerly and south-westerly winds.

The strong effect of local inverted barometer term in the Celtic Sea corroborates findings of Lowe et al. (2001) who estimated that the IB term at Newlyn (see Fig. 2 for location) constitutes 84% of total surge generated by the action of pressure and wind together. However, for the eastern Irish Sea the results diverge; Lowe suggests that wind forcing dominates surge height contributing up to 72%, whereas the current research suggests wind contributes approximately 55%.

From Fig. 5(a) and Fig. 5(b) it can be seen that both ratios are, in general, complementary throughout most of the domain and their sum for each grid point gives approximately 1. The exception is the eastern Irish Sea and Celtic Sea where a simple summation is greater than unity. In the Irish Sea, shallow water physics generate non-linear effects as wind-induced currents modify frictional levels in a non-linear manner and therefore influence surge. In the Celtic Sea case, a sum of 1.2 may be attributed to the anticorrelation behaviour of pressure- and wind-driven signals.

A map of correlation between surge generated by pressure term and surge generated by wind term is presented in Fig. 6. The correlation coefficient is a mean value of 48 correlation coefficients obtained from 48 runs and is based on timeseries of surge residuals produced every timestep. It is shown that continental shelf and parts of the Celtic Sea are regions of weak negative correlation. The negative correlation in the Celtic Sea may explain generally low magnitudes of surges in this region. A weak positive relationship around Ireland rises to medium level of 0.4 along the coast of Great Britain.

Sea level response to meteorological forcing is also quantified through regression analysis. The regression coefficient relates the IB term (independent variable) and surge residual (dependent variable). The expected relation is that a pressure fall of 1 mbar is accompanied by a sea level rise of about 1 cm (Gregory et al., 2001). Deviation from this relation is due to wind forcing and resonant response (Trupin and Wahr, 1990).

Fig. 7(a) and Fig. 7(b) respectively present analysis of results from a model forced with pressure fields only, and from a model forced with pressure and wind. The regression coefficient is a composite of the results of all 48 events. For each run, the coefficient is obtained by calculating the IB term at every timestep and then regressing it against the corresponding surge residual from a model run. Analysis of the surface heights and barometric pressure over the continental shelf yields regression coefficients (RC) of approximately 1 cm/mbar (Fig. 7a). A RC of one means that IB term is the main driver of sea level setup (Ponte, 1994). The likely reason for RC
less than 1 in the Irish Sea is due to resonant response (Ponte and Gaspar, 1999) and due to restrictions on flow through narrow channels into isolated basins (Ducet et al., 1999). When wind forcing is included, the regression analysis of sea level with IB term generally yields RC values higher than expected for the IB response (Fig. 7b). In the eastern Irish Sea and along the west coast of Scotland a drop of atmospheric pressure by 1 mbar is associated with a rise of sea level by 1.2 cm. This could be associated with positive correlation between pressure- and wind-driven signals, as Ponte (1994) suggests.

The significance of wind stress on water elevations is most evident in the eastern Irish Sea, where wind is responsible for over 50% of total surge height. In this region water setup generated by winds is approximately twice as large as that observed in other regions of the Irish Sea.

The current analysis addresses whether water setup is due to local wind effect or wind-generated external surges. A simple test was performed with a numerical model forced by wind fields blowing over (1) the entire domain of NE Atlantic and (2) the entire domain excluding the Irish Sea. Defining relative surge as surge values with wind excluded divided by surge values with a wind stress over whole domain Fig. 8 presents the distribution of relative surges. Surge values in both cases (1) and (2) are calculated from 48 surge maxima, each maximum value corresponding to a different event. The results show that the impact of local wind on sea level is smaller than previously reported. From the current research the local wind is a secondary contributor to surge magnitude. The local effect is strongest in the eastern Irish Sea and comprises only 36% of total wind effect. Jones and Davies (1998) suggested equal importance of local wind blowing over the eastern Irish Sea and external surge entering the region, but their model was applied to one storm only and the numerical domain restricted to the eastern Irish Sea. However, the effect of local wind as determined from the model may be mis-estimated due to the resolution of ECMWF data that is too coarse to adequately describe fine scale processes.

The area most affected by local wind is in the vicinity of the Solway Firth, this is also an area of maximum surge height in the Irish Sea. The wind-driven surge within the Irish Sea is generated mainly outside the Irish Sea and is introduced through the south and north entrances. Both surge waves meet southwest of the Isle of Man if the prevailing westerly and south-westerly winds do not force water towards the eastern Irish Sea.

3.3 Coastal tide-surge interaction

Surge is dependent on the tide in shallow water areas, where the major source of interaction is the quadratic friction. This interaction is characteristic of externally generated surges that propagate with the tide through the shallow water area. A solution for the propagation of an externally forced tide and surge into an estuary was given by Proudman (1955, 1957) who studied impact of shallow water and bottom friction on the timing and magnitude of high water. Rossiter (1961) found that interactions between the tide and surge are associated with mutual phase alteration. Flather and Williams (2000) postulate possible alteration in the tidal wave length and modifications in propagation and dissipation of tidal energy due to tide-surge interactions. Prandle and Wolf (1978) and Heaps (1983) present further insights into these interactions; no full physical explanation to all mechanisms has been presented yet. Recent work of Horsburgh and Wilson (2007) shows that the main effect of surge on tide is an alteration of the propagation speed of the tidal wave. The main effect of tide on surge is elusive, but is probably connected with surface currents.

In this section, surge dependency on tidal phase is considered and spatial variations in tide-surge interactions are investigated. This analysis is based on the assumption that the tide and surge are independent processes if surge peaks are uniformly distributed throughout the tidal cycle. Conversely, if interaction exists, the number of surges per tidal band would be expected to differ over the tidal cycle.

In this experiment, the tidal cycle was split into eight equal bands. Forty eight surge peaks, from the events simulated above, were reviewed in the context of timings of their peak, and classified and assigned into groups depending on the tide-phase band they fall in. The tide bands, against
which peak residuals were counted, were defined from tide only run of the model. Fig. 9 quantifies the level of tide-surge interactions; the regional character of interaction patterns is quite obvious. Distributions of surges throughout the tidal range are shown for four locations: North Channel, Holyhead, Workington and Galway. The highest interactions are observed within the Irish Sea. In the eastern Irish Sea (Fig. 9c) over half of all surge peaks coincide with the rising tide. The dependency gets stronger in the western Irish Sea (75 %) and in the North Channel, where approximately every second surge coincides with high water levels, Fig. 9(a). On the west coast of Ireland (Fig. 9d) around 40% of peaks fall into high water bracket, while remaining maxima distribute uniformly over other tidal bands.

Fig. 9(a)-(d) demonstrates also the spatial variations in tide-surge interactions. Weaker dependencies are observed on the open coastline and stronger in the Irish Sea as surge and tide propagate into the basin. Semi-strong interactions at the southern entrance rise to strong dependency in the Bristol Channel and eastern Irish Sea, and to very strong interactions in the western Irish Sea and at the north entrance. Consistency in a temporal sequence of peak events is also observed. Surges entering the Irish Sea from the south tend to peak just around low water, while surges further to the north develop their peaks at subsequent phases of rising tide. In the western Irish Sea and North Channel surge maxima coincide very strongly with high water. Tests with modified surge-to-tide phase showed that within the Irish Sea surges tend to peak at one particular tidal phase and the non-linear interactions modify magnitude and phase of surge. For example, in the eastern Irish Sea, the phase of surge was advanced when tide raised and retarded for low water levels. Also surge amplification due to interactions was sensitive to the shape and time profile of surge; amplification increases with decreasing surge duration.

3.4 Distribution of surge residuals

Due to the nature of Atlantic storms and the propagation of surges around Ireland the distributions of surge residuals around the Irish coast are highly variable. Thus, an analysis was conducted on 48 large storm surge events to consider some surge statistics and spatial variations in surges around the coastline. For each of the above 48 historical depression systems that tracked over the North East Atlantic the maximum surge heights were extracted at each model grid point. A characterization of peak distributions and underlying properties was then determined. Fig. 10(a) presents the distribution of the 98th percentile residual surge heights in Irish coastal waters. The distributions and magnitudes of large surge heights are comparable to those of Flather (1987) derived from a combination of model results and extreme surge field observations. Comparing results to other numerical models, very good agreement was also found with surge model results of Wang et al. (2008). Spatially, the results also correspond well to outputs of Flather et al. (1998) and Lowe et al. (2001) but their models are found to underestimate the magnitudes of extremes at the coast (Lowe et al., 2001; Flather et al., 1998). Results from the Author’s research also show that a time slice approach, where only a number of large storm events are hindcast instead of a long-period simulation, is sufficient to estimate surge extremes. A similar approach recently used by McInnes et al. (2009) was also found to be adequate while greatly reducing the computational effort.

Maximum surge heights in the model domain occur in the Bristol Channel, north-west England and Scotland (Fig. 10a), where values exceed 2 metres. Surges around the Irish coastline are generally lower with peaks of 0.8 m along the south coast and 1.5 m along the Northern Ireland coastline. Results also show that for the same latitude, surges on the west coast of Ireland are up to 20 % higher than surges on the east coast of Ireland. This phenomenon is largely due to wind direction but can also be attributed to the semi-enclosed nature of the Irish Sea. The relative 70th percentile (70th percentile divided by 98th percentile), shown in Fig. 10(b), determines the level of vulnerability to extremes. Highest values of relative 70th percentile correspond to the smallest expected increase in return level with increasing return period. Although the percentile approach provides robust results, it is usually unsuitable for extreme value analysis or where a long dataset is needed. Extreme value statistics are generally preferred.
as they provide solutions for large return periods (RP), while the analysis requires data containing only moderately extreme values for a relatively short timescale. The method, however, does not avoid difficulties associated with procedure of fitting statistical distributions.

The 48 surge residual dataset extracted above from the 48 events covering a 46 year period was used in the extreme surge analysis at each computational grid point. Two distributions EV1 and GEV were fitted to each dataset and extreme surges for RP of 10, 50, 100 and 200 years were computed. Comparisons of surge levels between the two distributions and model outputs were conducted initially at RP’s of 1 to 46 years and results are shown in Fig. 11(a)–(c). The GEV statistical model is seen to fit the dataset quite well (Fig. 11a), whereas the use of the alternative EV1 function (Fig. 11b) yields significantly poorer results. The surge levels computed by the GEV and EV1 models and compared for 200-year RP (Fig. 11c) show differences in the Irish Sea of over 0.5 m.

Fig. 12 shows a quality of model fit plotted as return levels of surge residuals against 46 return periods. The uncertainty associated with using statistical models was measured individually at every grid point (Fig. 12a-c) and estimated spatially using a polling method (Fig. 12d). In the spatial analysis, there is very good agreement between the GEV model and dataset, the EV1 significantly overestimates for higher return periods. Fig. 11(d) presents a map of locations where a particular statistical model provides better approximation to the model dataset than the other statistical model. The selection between the GEV and EV1 at a location was based on the smallest standard error for that point. The statistical model suitability map was used ultimately to determine locations where outputs of a particular statistical model are utilized to estimate surge residuals for higher return periods. The surge residual maps for 10, 50 and 200 years presented in Fig. 13 constitute therefore a hybrid of GEV and EV1 model outputs.

The analysis of extreme surge residuals without considering total water levels is of little use for coastal defence purposes. With regards to flood defences, planners are primarily interested in knowing levels which are attainable for either (1) moderate surge occurring at spring high tide or (2) extreme surges occurring with a moderate tide (Dixon and Tawn, 1994). The simplest indirect method of estimating extreme sea level is the joint probability method (JPM) by Pugh and Vassie (1979, 1980). The JPM was subsequently extended to cases where surge depends on the state of tide (Tawn, 1992) and revised further by Dixon and Tawn (1994, 1995, 1997). The method, however, requires good estimation of local tide-surge interactions. Understanding this behaviour in the Irish coastal waters requires a more thorough examination of the nature of the interactions than is warranted here. Such analysis is suggested as part of future research.

4. Discussion and Conclusions

Aspects of the mechanics of storm surge formation on the European continental shelf and, in particular, in Irish coastal waters were investigated in this research. A numerical model was developed and used in combination with historical synoptic meteorological conditions and hydrographic records. A dataset of atmospheric conditions obtained from the ECMWF was employed to recreate a series of 48 storm events over the NE Atlantic. The numerical model forced with these data was found to be capable of accurately hindcasting storm surges.

The main findings from this research are summarised here:

- Storms were classified into groups based on storm tracks, giving rise to characteristic surge distributions. Most storm surges initially peak along western and southern coasts of Ireland. The surges then tend to travel into the Irish Sea from the more open southern entrance of the St. George’s Channel, causing an initial lower peak, followed by a large peak due to surge propagating into the Irish Sea from the North Channel. Although individual storm surge dynamics vary, surge peaks in the centre of the Irish Sea are typically between 15-24 hours after west coast surges. Southern storms differ from most others as they induce surge waves that propagate predominantly northwards through the Irish Sea and along the west coast of Ireland.
• The semi-enclosed Irish Sea causes a significant delay of the arrival of most surges along the west coast of Great Britain; however, it also appears to cause amplification in peak surge heights. Irish east coast peak surges are attenuated relative to Irish west coast peaks. Coastal monitoring along Irish west and south coasts could be used to develop accurate early warning systems for impending coastal flooding.
• Wind and pressure fields both play significant roles in surge dynamics and their respective roles are strongly influenced by external factors. The effect of wind stress on surge height becomes more significant closer to coasts. Current research agrees with Lowe et al. (2001) that the inverted barometer pressure term contributes to more than 80% of total surge in the Celtic Sea. However, current research suggests that wind stress contributes to about 55% of surge peaks along the British coast in the Irish Sea; this disagrees with an estimate by Lowe et al. (2001) of a wind stress contribution of 74%.
• Local winds on the Irish Sea have less of an impact on storm surge heights than previously reported; the maximum effect observed was 36% of total surge in a small region of the eastern Irish Sea, see Fig. 8. Previously Jones and Davies suggested that local wind stress contributed about 50% to total surge heights, but this analysis was based on the analysis of one storm surge event. Thus, Irish Sea surges are predominantly due to the propagation of surges into the basin from the north and south channels.
• Negative correlation between wind- and pressure-driven surges in the Celtic Sea explains generally low magnitudes of surges in this region, while medium level correlation coefficients could be responsible for generally high surges in the eastern Irish Sea and coast of Scotland. Following the regression analysis, in these regions a drop of atmospheric pressure by 1 mbar implies a rise of sea level by 1.2 cm.
• Spatial distributions of tide-surge interaction characteristics vary remarkably; tide-surge dependencies of 40% are observed at southern and northern entrance of the Irish Sea, and up to 75% dependency is observed in the western Irish Sea. Also, the phase of tide with which surge interacts varies regionally too and is significant.
• Different extreme value distributions were assessed for goodness of fit in predicting extreme surge return periods. The most appropriate distribution for this region is a spatial hybrid of GEV and EV1; the distributions used provide very similar results to models output for the 48 events simulated. The approach adopted of analysing extreme historical events provides almost identical results to results achieved by Wang et al. (2008) who simulated surges over a period of 30 years. The approach adopted herein is highly efficient computationally and analytically.

Acknowledgments

This work has been carried out while under funding of the Environment Protection Agency. The authors would like to thank Professor Conleth Cunnane from the National University of Ireland, Galway for his many helpful suggestions in a field of statistics. Also useful suggestions from the two reviewers are appreciated. Tidal gauge data for the United Kingdom were provided by the British Oceanographic Data Centre and for Ireland from the Office of Public Work, Ireland.
References


Hydrology Report, April. OPW, Ireland.


Fig. 1 Storm tracks over period 15/10/2002-28/10/2002

Fig. 2 (a) The bathymetry of North-East Atlantic model and (b) selected locations in coastal waters. IS stands for Irish Sea, CS – Celtic Sea, NC – North Channel, BC – Bristol Channel, GC – St. George’s Channel, SF – Solway Firth
Fig. 3 The simulated and observed surge at (a) Bangor (54.66N, 5.67W), (b) Fishguard (52.01N, 4.98W), (c) Newlyn (50.10N, 5.54W) and (d) Cork (51.85N, 8.28W)
Fig. 4 (a) Depression system tracks, (b) maximum surges generated by these storms and (c) timing of occurrence of maximum surge. Pressure values in hPa, surges in meters, timing expressed in hours. Note that scale for maximum surges varies. NS represented by meteorological conditions for period 23/10/1995 00:00 – 26/10/1995 00:00 UTC, NWS for 25/12/1998 12:00 – 27/12/1998 12:00 UTC, WS for 16/11/1963 00:00 – 19/11/1963 00:00 UTC, CS for 01/12/1966 00:00 – 03/12/1966 00:00 UTC, SS for 06/03/1962 12:00 – 08/03/1962 12:00 UTC

Fig. 5 Ratio of (a) S_P/ S and (b) S_W/ S. See text for definition of variables

Fig. 6 Correlation coefficient between timeseries of S_P and S_W. A composite result of 48 storm events
Fig. 7 Regression coefficient between timeseries of IB term and surge residuals forced by (a) pressure, (b) pressure and wind. A composite result of 48 storm events

Fig. 8 The contribution of local winds over the Irish Sea on surge residual height expressed as a ratio of surge residual driven by wind excluding the Irish Sea to surge residual driven by the wind blowing over whole domain
Fig. 9 Number of occurrences of surge peak for particular phase of tide at (a) North Channel, (b) Holyhead, (c) Workington and (d) Galway. See Figure 2 for map of locations. LW stands for low water, HW - high water, MF - mid flood, ME - mid ebb
Fig. 10 Surge residuals from numerical model runs (a) 98th percentile, (b) relative 70th percentile

Fig. 11 Difference (m) in surge residual level between (a) GEV for 46-year RP and 98 percentile
from numerical model, (b) EV1 for 46-year RP and 98 percentile from numerical model, (c) GEV and EV1 for 200 RP, (d) spatial map of statistical model suitability (grey-GEV, white-EV1)

Fig. 12 Return periods of surge residuals derived from GEV and EV1 at (a) Fishguard, (b) North Channel, (c) Galway and (d) spatially-averaged (over whole domain) using pooling method

Fig. 13 Surge residual values from hybrid GEV-EV1 model for RP of (a) 10 years, (b) 50 years and (c) 200 years. The GEV and EV1 were applied according to map in Fig. 11 (d)