Keshtpoor, M, Carnacina, I and Yablonsky, RM

A New Statistical Approach to Select Surge-Producing Extratropical Cyclones from a 10,000-Year Stochastic Catalog

http://researchonline.ljmu.ac.uk/id/eprint/9344/

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Keshtpoor, M, Carnacina, I and Yablonsky, RM (2019) A New Statistical Approach to Select Surge-Producing Extratropical Cyclones from a 10,000-Year Stochastic Catalog. Journal of Waterway, Port, Coastal, and Ocean Engineering. 145 (3). ISSN 0733-950X

A New Statistical Approach to Select Surge-Producing Extratropical Cyclones from a 10,000-Year Stochastic Catalog

Mohammad Keshtpoor[1]; Iacopo Carnacina[2], Richard M Yablonsky[3]

[1]PhD, Scientist, AIR Worldwide, 131 Dartmouth Street, Boston, MA 02116, email: mkeshtpoor@air-worldwide.com; phone: 617-954-1750

[2]PhD, Senior Lecturer, Liverpool John Moores University, Byrom Street, Liverpool, UK, L3 3AF, email: i.carnacina@ljmu.ac.uk

[3]PhD, Senior Scientist, AIR Worldwide, 131 Dartmouth Street, Boston, MA 02116, email: ryablonsky@air-worldwide.com; phone: 617-954-1526

Abstract

Extratropical cyclones (ETCs) are the major storm surge-producing events along the Northwest European coastline. To evaluate the storm surge risk covering the return period up to 10,000 years in this region, a stochastic catalog is developed by perturbing European historical ETCs. Numerical simulation of the storm surge generated by the full 10,000-year stochastic catalog, however, is computationally expensive. Also, not all the stochastic ETC events are surge-producing storms. Here, we propose an efficient statistical approach to filter the stochastic catalog by estimating the storm surge elevation at tide gauges and then selecting only the non-negligible surge-producing events. The proposed approach reduces the number of stochastic storms that need to be numerically simulated by 78%, thereby saving

computational resources for high-resolution numerical simulations of surge-producing storms.

1. Introduction

A major water-born risk to coastal communities and infrastructure is storm surge, which can cause billions of dollars of financial loss in coastal regions (Wood et al., 2005; N'Jai et al., 1990; Steers et al., 1979; Wood and Bateman, 2005; Fritz et al., 2007; McRobie et al., 2005). There are two major types of surge-producing storms, tropical cyclones (TCs, including hurricanes) and mid-latitude extratropical cyclones (ETCs). In general, TCs produce larger maximum surge heights than ETCs (von Storch and Woth, 2008), owing to the higher surface wind speeds in major TCs relative to ETCs. However, TCs are smaller in size than ETCs, so the length of the coastline affected by TC storm surge is typically less than 200 km, but ETC storm surge can affect several hundreds of kilometers of coastline. Also, surge duration from TCs is usually less than half a day, while the surge from ETCs can last two to five days, covering multiple tidal cycles. Hence, some ETCs can cause storm surge losses that are comparable to that of TCs, particularly in Europe where ETCs are the dominant drivers of storm surge (Ulbrich et al., 2001; Della-Marta et al., 2009). One example is ETC Xaver (2013), for which United Kingdom (UK) Surge Watch reported $1.68 to $2.33 billion of insured losses across Northwest Europe (https://www.surgewatch.org), much of which was due to storm surge.

Scientists and engineers use numerical, analytical, and statistical models to simulate and study the storm surge from TCs and ETCs in an effort to assess the risk (e.g. Coles and Tawn, 1990; Bruun and Tawn, 1998; Lozano et al., 2004; von Storch and Woth, 2008; van der Grinten et al., 2013; Keshtpoor et al., 2014a; Keshtpoor et al., 2014b; Carnacina et al., 2015). Numerical models need sufficient resolution to capture the physics of the surge in coastal zones. Complex coastal geometry and bathymetry may require a more refined mesh, which can be computationally expensive, especially for simulating a large number of synthetic events in risk assessment studies. Even though the computational speed is significantly enhanced in statistical and analytical approaches, the physics of the problem may not be fully incorporated, leading to less accuracy. These models, however, can be calibrated to produce acceptable results efficiently.

To understand the potential risk of storm surge at continental scale, catastrophe modelers need to simulate numerous combinations of tidal conditions and meteorological events. The variability of ETCs is such that the available historical record is insufficient to account for the range of possible occurrences. This variability is handled by perturbing historical storms to develop a stochastic catalog, with various techniques not discussed in this paper. A set of historical storms can be selected based on their strength to form a set of seeds. By perturbing these historical seeds, AIR Worldwide's meteorology team developed a 10,000-

year stochastic catalog for ETCs in Europe. This catalog contains numerous events that may cause wind-damaging losses, surge-damaging losses, or both. For storm surge modeling, only the non-negligible surge-producing ETC events are of interest. Here, a fast-processing multivariable regression model is developed to reconstruct the ETC-generated storm surge elevations at tide gauges in Northwest Europe using local atmospheric parameters, thereby reducing the heavy computational burden of numerical modeling. The regression model is used to identify the surge-producing storms from a 10,000–year stochastic ETC catalog. The resulting surge-producing storms are then used to force a numerical model to accurately simulate the coastal flooding. This study is focused to refine the European stochastic catalog for UK storm surge. Even though all the Northwest European tide gauges are used to develop the regression model, the calibration of the model is based on the storms reported by UK surge watch (details are in Section 3.2.4).

2. Study Area

2.1. Location, Coastal Geometry, and Bathymetry

Figure 1 shows the bathymetry within the study area, which includes the coast of Northwest Europe. The coastal regions within the study area (specified by green box in Figure 2) are prone to high water levels during extreme ETC events traversing the Atlantic Ocean and North Sea. In addition to atmospheric factors, the coastal geometry and the nearshore bathymetry play important roles in the resulting storm surge. The water piles up against the coast once it is forced by an ETC's wind field or, to a lesser extent, impacted by the ETC's low pressure center (inverted barometer effect). The surge height is enhanced over the shallow bathymetry within the North Sea and exposes more inland assets to storm surge risk. During two major ETC events in Northwest Europe, The Great Storm of 1953 and Storm Xaver in 2013, the east coast of UK experienced extreme water elevations that affected major coastal zones (Wadey et al., 2015; Spencer et al., 2015; Sibley et al., 2015). In addition to bathymetric effect, the increase in water elevation is enhanced when the storm surge enters the channels, bays, and narrow waterways. The Irish Channel, English Channel, Bristol Channel, and southwestern portion of the North Sea are examples of coastal geometries that enhance the surge elevation (Figure 1).

The North Sea is a shallow basin where the water depth does not typically exceed 200 m (except near the Norwegian coastline) and is below 50 m within a few hundred kilometers of southeastern coastline of UK. In such shallow water, strong ETC forcing in the shoreward direction can displace a significant fraction of water column shoreward with a minimal recirculation toward offshore. For example, under the Great Storm of 1953, water accumulated along the east coast of UK and southern shorelines of the North Sea due to strong northerly winds, and the surge was further enhanced within the bays and water channels. These types of events put coastal communities near bays and channels (e.g. Thames River) at risk.

2.2. ETC Events

AIR Worldwide's Extratropical Cyclone (ETC) Model for Europe leverages version 3 of the Weather Research and Forecasting (WRF; Powers et al., 2017) model with a single domain that has a horizontal grid spacing of 16 km and is initialized and internally nudged from the ECMWF's ERA-Interim reanalysis dataset. The reanalysis dataset provides global atmospheric variables such as wind, temperature, and humidity at regular time intervals (6 hrs) and on a T255 spectral grid (~80 km). The extent of the WRF model domain covers all of mainland Europe and extends west to 25°W longitude. The WRF-modeled wind footprints are downscaled to approximately 1 km using high-resolution gust and friction factors, which over land account for land use and land cover characteristics. Over the water, the model leverages a wind-speed dependent downscaling factor following Charnock (1955).

Figure 2 shows the tracks of 1750 historical ETC events derived from the aforementioned WRF model output that are subsequently used as historical seeds to generate a 10,000-year stochastic ETC event catalog. The general longitudinal trend of the historical ETC event tracks indicates that ETCs generally travel from west to east, embedded in the mid-latitude westerlies. Although some storm tracks are outside of the study area (green box), part of the vorticity field associated with these storms can occur inside the study area and produce storm surge.

The 10,000-year stochastic catalog of ETCs is developed by perturbing a set of 1750 historical ETC storm seeds spanning January 1953 – April 2015. The resulting 484,075 perturbed storms in the stochastic catalog account for a statistically robust sample of realistic storm scenarios that could occur in the study area, assuming present-day climate. However, only a fraction of the stochastic catalog contains significant surge-producing storms that require a numerical hydrodynamic model to accurately simulate the storms surge. To avoid the intense computational burden of numerical simulation of all stochastic ETC events, a regression model is developed based on numerical results of the 1750 historical seeds and utilized to select only the non-negligible surge-producing storms from the stochastic catalog.

3. Approach

To develop the regression model (see Section 3.2 below) and select the surge producing ETCs, both atmospheric and surge parameters are required. The atmospheric parameters are provided by the WRF model output (see Section 2.2

above) and the surge parameters are provided by a numerical hydrodynamic model that is explained in Section 3.1 below.

3.1. Numerical Hydrodynamic Model

The Dutch Continental Shelf Model (DCSM) is used here to numerically simulate the storm surge for the 1750 historical storm seeds. This model was originally developed by Deltares using Delft3D-Flexible Mesh and is widely used to predict storm surge in Northwest Europe (Zijl et al., 2013; Zijl et al., 2015; Carnacina et al., 2015). The computational domain (green box in Figure 2) covers the whole coastal waters of Northwest Europe. The offshore boundary of the computational domain is situated seaward of the continental shelf. The grid resolution is 8 km in deep water and is refined to roughly 2 km near the shoreline. The DSCM was previously calibrated using 2007 tidal levels and validated using the water levels recorded during three Northwest Europe ETC events in 2006, 2007, and 2013 (Carnacina et al. 2015). Here, the DCSM is validated for 1750 historical events.

All tide gauge stations used in this study are shown in Figure 3. The numerical points are selected to be as close as possible to the actual tide gauge locations. The model is validated by comparing the maximum computed and observed total water levels (TWLs) at the location of 196 tide gauge stations in Northwest Europe during the 1750 historical ETCs. Figure 4a shows the model-data comparison for the maximum TWL of each storm. The root mean square error (*RMSE*) is 0.3 m. Figure 4b shows the bias (modeled - observed) for the maximum TWL. The absolute maximum bias is less than 1.5 m, and the residuals are normally distributed about zero with a minimal bias. The frequency of observed and modeled maximum TWL is shown in Figure 4c. The model frequency is generally higher than observations for maximum water elevations less than 2 m. This trend reverses for maximum TWLs between 2 and 3 m. For larger maximum TWLs, the frequency difference is minimal.

The resulting TWLs from the numerical model are sampled at 15-minute intervals and used as an input parameter for the regression model (see Section 3.2).

3.2. Regression Model

3.2.1. Formulation of the Model

High water levels during a storm are generated by the combination of tidal forcing and the surge residual (difference between the TWL and the astronomic tide); the surge residual is produced by wind speed and atmospheric pressure deficit (ETC parameters). The spatial and temporal distributions of the ETC parameters play a key role in generation of the surge in coastal areas. The storm surge can be related to the local ETC parameters at the location of interest (e.g. at tide gauges).

Figure 5 shows an example of the correlation between the storm parameters and the surge residual from the numerical hydrodynamic model (surge residual noted as SR in Figure 5) at the location of two UK west coast tide gauges [Heysham (#12) and Milford Haven (#26)] and two UK east coast tide gauges [Cromer (#6) and North Shields (#33)] during four major historical storms. At gauge #12 and #26 (west coast), all storm parameters are important in the generation of surge residual. At gauge #12, the first surge residual peak approximately coincides with the maximum U and V (x- and y- components of wind speed), and the second peak coincides with the local maximum magnitudes of all storm parameters. Similarly, at gauge #26, the maximum surge residual is correlated with maximum U, V, and ΔP ($\Delta P = P_{atm}-P_{surge}$ is the sea level pressure deficit between the standard atmospheric pressure (1013 hPa) and the atmospheric pressure during the surge event). However, along the UK east coast, the surge residual is highly correlated to the northerly ($-V$) component of the wind speed at the location of the tide gauges. The correlation at gauge #6 during storm #1 (Figure 5.k and 5.l) and at gauge #33 during storm #1651 (Figure 5.o and 5.p) indicates that surge residual retains the maximum values when the northerly wind pushes the water south and against UK east coast within the North Sea. Generally, major storms that enter the North Sea and travel south or south east introduce a large magnitude of V along the east coast of UK. The correlation between the ETC parameters and the surge residual is expressed in a two-equation model to statistically develop a surge-wind model at the location of tide gauges. This model is then used to reconstruct the surge at the given tide gauge stations in Northwest Europe.

Here, we propose equations 1 and 2, which represent the regression model developed at Northwest Europe tide gauge stations (shown in Figure 3 by red dots):

$$res_{max_{j,k}} = \boldsymbol{a} + \boldsymbol{b} * \Delta P_{max_{j,k}} * sign\left(\Delta P_{max_{j,k}}\right) + \boldsymbol{c} * U_{max_{j,k}} * sign\left(U_{max_{j,k}}\right) + \boldsymbol{d} * V_{max_{j,k}} * sign(V_{max_{j,k}}) \qquad (1)$$

$$res_{(t)_{j,k}} = \boldsymbol{e} + \boldsymbol{f} * V_{(t)_{j,k}} \qquad (2)$$

In these equations, *res* is the surge residual, ***a***, ***b***, ***c***, ***d***, ***e*** and ***f*** are regression coefficients, *j* and *k* are the tide gauge number and the historic storm number, respectively, and *t* represents the time dependency of a variable. The sign function on variable *Var* is defined as below:

$$sign(Var) = \begin{cases} +1 & if\ Var \geq 0 \\ -1 & if\ Var < 0 \end{cases} \qquad (3)$$

Equation 1 is used for the stations where the maximum surge elevation (*res*) is correlated to the local maximum *U*, *V* and *ΔP* fields (all stations except those located along the east coast of UK), and Equation 2 is used at the tide gauges where time series of *res* is better correlated to the local time series of *V* component of the wind field (stations along the east coast of UK).

The regression model 1 (RM1) is developed based on the maximum historical surge values, whereas the regression model 2 (RM2) is based on the surge elevation throughout the whole duration of the intense events that significantly impacted the east coast of UK.

It should be noted that the presence of *sign* function in RM1 prevents resolving the negative surge values. This function, however, plays a key role in resolving the correct surge values induced by the wind speeds blowing from different directions onshore.

The regression model is developed based on 1750 historic storms at the location of 196 tide gauges and validated using the reported storms by UK Surge Watch (http://www.surgewatch.org/events/). The UK Surge Watch reported 56 major storms that affected the UK coasts within the time period of 1979 – 2015. The skill of the regression model is assessed primarily based on the number of Surge Watch reported storms that are selected by running the regression model on the historical storm catalog. A larger number of selected Surge Watch storms by the regression model indicates higher skill of the model. The regression model, with further refinement to exclude small events (see Section 3.2.4), is then used to select the surge-producing events from the 10,000-year stochastic catalog (484,075 storms). As a second benchmark, the skill of the model is assessed based on the resolved return periods at the location of the tide gauges. The storms selected by running the regression model on the stochastic catalog retain a range of return periods that need to be comparable to the return periods of the recorded water levels at the tide gauge stations. Details on the development of the regression model are provided in Section 3.2.2.

3.2.2. Model Development

The regression equations in Section 3.2.1 reconstruct the surge residual. The regression coefficients are different at different gauge stations. In addition to regressed surge residuals, tidal elevations are incorporated to construct the TWL. Regardless of the magnitude of the surge residual, if the surge residual happens during low tide, then the increase in TWL might be even less than local high tide with no major impact in coastal areas. Even if the surge residual is considerable, the impact of TWL can be minimal. On the other hand, the coincidence of surge residual with the maximum tide may lead catastrophic water levels. Thus, in addition to reconstructed surge residual, timing of the surge residual is required to add appropriate tide elevations for calculating the TWL. Here are the steps to develop TWL:

1) Develop the regression model based on modeled surge residuals and maximum storm parameters of 1750 historical storms. The matrices of variables (*res*, *U*, *V*, and $\varDelta P$) in the regression model are constructed at each gauge station and for all historical storms. The Regression Model 1 (RM1, Equation 1) is developed at all 196 tide gauge stations except stations 33, 43, 16, 6, 25, 11, 9, 37, 8, and 31 where the Regression Model 2 (RM2, Equation 2) is developed.
2) The timing of the reconstructed surge residual is determined based on the correlation between the maximum surge residual and the maximum magnitude of the storm parameters. Along the east coast of UK, the maximum surge residual is correlated to the maximum magnitude of *V* (where RM2 is used); elsewhere (where RM1 is used), the maximum *U*, *V*, and $\varDelta P$ do not necessarily coincide, and the correlation coefficient is assessed based on three scenarios in which maximum surge residual coincides with: a) maximum *U*, b) maximum *V*, or c) maximum $\varDelta P$. For each tide gauge where RM1 is used, the regression model is developed for all three scenarios to reconstruct the TWLs. At a given tide gauge station, the largest correlation between reconstructed and numerically-modeled water elevations during all historical storm events determines the storm parameter to be used in associating the timing of the

maximum surge residual. For example, at all tide gauges located in Southwest UK, the correlation retains the highest values when the maximum surge residual coincides with the maximum magnitude of the *V*-component of wind speed. That is, in Southwest UK, the timing of the maximum surge residual is same as the timing of *V*. An example in Southwest UK is shown in the second column of Figure 5. At gauge #26, for all storm events, the correlation coefficient between the reconstructed surge residuals and the numerically-modeled surge residuals is higher if the reconstructed surge coincides with the maximum *V* (even though all storm parameters are used to develop the regression coefficient at this location). So, the maximum surge occurs approximately at the same time as the maximum value of *V*. Therefore, in the second step of model development, the timing of the surge residual is determined as follows: For Southwest UK, West UK, Northwest UK, East UK, and along the coastline of the countries south of North Sea, the time-determining storm parameters are *V*, ΔP, *V*, *V*, and *U*, respectively.

3) In this step, the time series of tide elevation is constructed throughout the storm based on the timing determined in step 2. The t_tide package (Pawlowicz et al., 2002) is used to reconstruct the tidal elevations. The constructed tide elevation at each station is then added to the regressed surge (*res*) in order to reconstruct the TWL.

3.2.3. Regression Model Validation

Figure 6 compares the regressed and the modeled surge residual (using Delft3D-FM; DCSM) at gauge stations # 6 (Cromer – Figure 6a, b, c), # 26 (Milford Haven – Figure 6d, e, f), and # 12 (Heysham – Figure 6g, h, i) during ETC historical events # 1, 2, 3, 12, 200, 320, 827, and 1541. The black line represents the surge values modeled using DCSM (numerical model), and the red line represents the regressed surge values. Readers should note that the time series of the surge residual can be produced for RM1 by substituting *max* with *t* in equation 1. The results of RM1 are shown at stations # 26 and # 12. The model successfully reconstructs the surge pattern for positive surge values at the UK west coast. This study is focused on the selection of surge-producing events that cause positive surge values; evaluating negative surge values is not relevant to the context here. The high frequency oscillations, due to nonlinear coastal processes typically observed within bays and waterways, are not resolved in the regressed surge. However, the pattern of regressed surge agrees well with the modeled surge, especially for high positive values. RM2 (for station # 6) successfully resolves the pattern of surge values along the UK east coast. The comparisons shown in Figure 6a,b,c illustrate the high dependency of the surge to *V* along the UK east coast.

Figure 7 shows the skill of RM1 at 12 UK tide gauge stations during all 1750 historical storms. The correlation coefficient (r^2) of RM1 ranges from 0.32 to 0.65. The lowest correlation values are observed at the tide gauges that are situated within bays or channels where storm surge is impacted by complex coastal processes. The skill of RM2 is also shown in Figure 8, where the maximum reconstructed and modeled surge values are compared at stations 33, 16, 6, and 37. The value of r^2 ranges from 0.31 to 0.51 for RM2. Generally, the maximum *RMSE* does not exceed 0.43 m for RM1 and 0.57 m for RM2 at all associated tide gauges. We also performed cross-validation on the regression models by developing the models using 40% of the data points and predicting the remaining 60%. The r^2 of the predicted surge values (not shown here) were different by 1% to 3% across the tide gauges.

3.2.4. Storm Selection

Historical and stochastic surge-producing storm events are selected through a two-step process. First, a thresholding condition is applied on the regression results to prevent the selection of non-surge-producing events. If the standard deviation of the whole regressed surge does not exceed 0.06-0.15 m (depending on the tide gauge station), the reconstructed surge is multiplied by a small number to diminish the regressed residuals and filter out small surge events, which often produce surge values with small deviation.

Then, in the second step, a peak-over-threshold selection is applied to filter out events with TWL smaller than the threshold. In other words, a selection of a storm requires the satisfaction of Equation 3.

$$TWL_{max} > \left[tide_{2-year\ max} + \varepsilon\right] \tag{3}$$

where, TWL_{max} is maximum reconstructed TWL during a storm event, $tide_{2\text{-}year\ max}$ is the maximum value of tide over 2 years, and ε is a calibration factor. At a given tide gauge, for a given storm, the storm is selected if the maximum reconstructed TWL exceeds the maximum tide experienced over the period of 2 years plus a calibration factor.

The calibration factor (ε) represents the model uncertainties and reduces the gap between regressed and numerical surge values. This factor is tuned at each tide gauge based on the number of storms selected from 1750 historical seeds by the regression model that match the major events reported in the UK Surge Watch database (http://www.surgewatch.org/events/).

A small value of ε would result in the selection of non-surge-producing storms, while a large ε may be too restrictive and remove some major surge events from selection. At non-UK gauges, ε was determined such that at least 20 historic events were selected at each tide gauge. The minimum value of 20 major storms at these gauge stations appeared to be the optimum value to select unique storms at non-UK stations, and this value is in line with the maximum number of the selected Surge Watch events used for UK tide gauges.

Figure 9 shows an example of storm selection where the condition in Equation 3 is satisfied. The TWL is the regressed surge (red line in Figure 9) added to the tide (green line in Figure 9) at gauge station # 6 (Cromer) during storm # 1 (Great Storm of North Sea in 1953). The $tide_{2\text{-}year\ max}$ is 2.45 m and ε is 0.23 m. This storm generates *TWL* that exceeds the threshold (the horizontal blue line in Figure 9) and is identified as surge-producing event. Note that ε can be greater than or equal to 0, depending on the tide gauge station.

4. Results

The storm selection algorithm was applied to both historical and stochastic catalogs. 379 storms out of 1750 historical events (~22%) and 104,910 storms out of 484,075 stochastic events (~22%) were selected. Out of the 379 selected historical storms, 51 storms are among 56 historical surge-producing storms reported by UK Surge Watch (91% matches). Therefore, 328 historical storms were selected that are not in Surge Watch; however, further refinement of the catalog based on return period analysis removes extraneous storms (see Section 5.1).

The selected stochastic storms were used as the forcing condition in DCSM, and the resulting maximum water levels were analyzed to validate the skill of the selection algorithm at each tide gauge station. A Generalized Extreme Value analysis was used to fit the return period curves for historical and recorded maximum TWLs. Also, an empirical ranking technique was used to associate the return period values to the maximum stochastic water elevations. This technique is based on ranking of the maximum yearly TWL. For a 10,000-year catalog, at a given gauge station, the annual maximum TWL is ranked from highest to lowest, and then the ranked water elevations are assigned to the corresponding return periods. For example, the first, second, and third highest water elevations at the location of interest are assigned to 10,000, 10,000/2 = 5,000 and 10,000/3 ~= 333 years, respectively.

Figure 10 shows examples of the return period analysis of the TWL for modeled historical, modeled stochastic, and measured data at eight tide gauge stations along the UK coastline. Each dot represents the annual maximum water elevation at a given return period (up to 10,000 years). The pattern and trend of measured and modeled historical water elevations are well-preserved by the selected stochastic storms. For high return periods, in particular, there is a good correspondence between the modeled stochastic water elevation and the observed water elevation, with errors on the order of 10-15 cm. At the same time, the selection algorithm shows good performance in retaining smaller storms with values that range well below the 10-year return period.

The skill of the regression model in preserving the TWLs of different return periods at all tide gauges is shown in Figure 11. The TWLs associated with different return periods and at all tide gauges are extracted for observed, modeled-historical, and modeled-stochastic and plotted against each other. The stochastic TWLs are extracted for the return periods where historical (Figure 11a) and observed (Figure 11b) TWLs exist. Similarly, the historical TWLs are extracted for the return periods where the observed TWLs are recorded and exist (Figure 11c). The RMSE is 0.02 m in Figure 11a and 0.05 m in Figure 11b,c.

5. Discussion

5.1. Storm Selection

The regression model was used in the selection of the surge-producing stochastic storms and led to selection of 104,910 out of 484,075 storms. This selection can be further refined using the return period analysis by selecting storms with a higher return period value as a cut-off threshold. Here, the analysis is performed on three cut-off thresholds: 2-year, 3-year and 5-year; results are shown in Table 1. The number of the selected storms reduced from 104,910 to 44,932, 31,812, and 21,060 for 2-year, 3-year and 5-year return periods cut-off thresholds, respectively. This result implies that a large percentage of storms are not major surge-producing events. Typically, the 2-year threshold is an acceptable criterion to select the storms generating surge above the local high tide. However, this threshold can change in accordance with the purpose of a given storm surge modeling study.

An important result of this analysis is that the recurrence of storms for 5-year threshold is ~2.1 storms per year (21,060 in 10,000 years), which is slightly higher than the recurrence reported by UK Surge Watch (1.8 storms per year). Readers should note that UK Surge watch analysis is based on the storms that produce TWLs higher than the 5-year threshold. Consequently, the proposed storm selection method can be considered a conservative approach that keeps all significant surge-producing storms in the final catalog.

5.2. Role of the tide in the event selection

Tide amplitudes cover a broad range in the study area, from 1 m in Northeast UK to 7 m in Southwest UK. The tide amplitude exceeds 7 m within Bristol Channel, and it ranges from 2 to 4 m along the UK east coast and from 2 to 5 m along the

UK west coast north of Bristol Channel. Figure 12 shows the tide amplitude only along the UK coastline. The tide range along the Belgium, Netherlands, and Germany coastlines is similar to that along the Southeast UK coastline. The large range of tidal variation increases the importance of the storm occurrence time. The coincidence of maximum storm surge and the high tide can significantly increase the risk in coastal communities. However, the occurrence of maximum storm surge at low tide does not categorize the storm as a non-surge event. The duration of the storm also plays an important role in the surge produced by an ETC event. Figure 13 shows an example of the modeled TWL (red line), tide (blue line), and surge residual (black line) at tide gauge # 6 (Cromer) during historical storm # 1 (Great Storm of North Sea in 1953). The surge residual stays above 1 m for more than 24 hours, covering two high tide cycles. The surge residual retains values above 2 m, however, for only ~4 hours, and this period does not coincide with a local high tide. Regardless, the fact that the TWL exceeds the local high tide by ~1.5 m indicates that this event is likely to cause coastal flooding and potential property losses.

6. Conclusion

In this paper, a new methodology to select surge-producing events from a 10,000-year ETC stochastic catalog at all tide gauge stations along the Northwest Europe coastlines has been proposed. The results of the investigation indicate that:

1- A regression model that correlates the surge residuals to the pressure deficit and the *U*- and the *V*-components of the wind field at the location of the tide gauge stations successfully preserved the surge-producing storms. Using a threshold based on the 2-year return period, 104,910 ETCs were selected out 484,075 events, representing a 78% reduction in the storm population in the final catalog.

2- The skill of the regression model was assessed by r^2 (between the modeled and regressed surge values), with values of r^2 ranging from 0.31 to 0.65. Typically, the model results in high r^2 values at the location of the tide gauges that face open water. The regression model does not resolve the high frequency oscillations within the bays and waterways. However, the model successfully reconstructs the pattern of high surge values.

3- A given ETC event is selected as a surge-producing event if the reconstructed TWL generated using the regression model exceeds the sum of maximum local 2-year tide and a calibration factor. This factor is tuned to select the maximum major surge-producing ETC events reported by UK surge watch and allows the users to counter the over/under-estimation of the model.

References

von Storch H, Woth K (2008) Storm surges: perspectives and options, Sustainability Science, Volume 3, Issue 1, pp 33–43. doi:10.1007/s11625-008-0044-2.

Wood RM, Drayton M, Berger A, Burgess P, Wright T (2005) Catastrophe loss modelling of storm-surge flood risk in eastern England, Philosophical Transactions of the Royal Society A, DOI: 10.1098/rsta.2005.1575.

N'Jai A, Tapsell SM, Taylor D, Thompson PM, Witts RC (1990) FLAIR: flood loss assessment information (FLAIR) report. London:Flood Hazard Research Centre, Middlesex Polytechnic.

Steers JA, Bayliss-Smith TP, Stoddart DR, Spencer T, Durbridge PM (1979) The storm surge of 11 January 1978 on the east coast of England. The Geographical Journal, Vol. 145, No. 2, pp. 192-205, DOI: 10.2307/634386.

Wood RM, Bateman W (2005) Uncertainties and constraints on breaching and their implications for flood loss estimation, Philosophical Transactions of the Royal Society A, 363, 1423–1430, DOI: 10.1098/rsta.2005.1576.

Fritz HM, Blount C, Sokoloski R, Singleton J, Fuggle A, McAdoo BG, Moore A, Grass C, Tate B (2007) Hurricane Katrina storm surge distribution and field observations on the Mississippi Barrier Islands, Estuarine, Coastal and Shelf Science, Volume 74, Issues 1–2, pp 12–20.

McRobie A, Spencer T, Gerritsen H (2005) The Big Flood: North Sea storm surge, Philosophical Transactions of the Royal Society A, 363, 1263–1270, doi:10.1098/rsta.2005.1567.

Ulbrich U, Fink AH, Klawa M, Pinto JG (2001) Three extreme storms over Europe in December 1999. Weather, 56: 70–80. doi:10.1002/j.1477-8696.2001.tb06540.x

Della-Marta PM, Mathis H, Frei C, Liniger MA, Kleinn J, and Appenzeller C (2009) The return period of wind storms over Europe. International Journal of Climatology., 29: 437–459. oi:10.1002/joc.1794.

Lozano I, Devoy RJN, May W, Andersen U (2004) Storminess and vulnerability along the Atlantic coastlines of Europe: analysis of storm records and of a greenhouse gases induced climate scenario, Marine Geology, Volume 210, Issues 1–4, Pages 205–225.

Carnacina I, Van der Kaaij T, Zijl F, Verlaan M, Lima Rego J (2015) The 2013 Xaver storm surge and the resilient response of the North Sea defense system, 36th IAHR World Congress.

Keshtpoor M, Puleo JA, Shi F, DiCosmo NR (2014a) Numerical simulation of nearshore hydrodynamics and sediment transport downdrift of a tidal inlet, Journal of Waterway, Port, Coastal, and Ocean Engineering, DOI: 10.1061/(ASCE)WW.1943-5460.0000273.

Keshtpoor M, Puleo JA, Shi F (2014b) Downdrift Beach Erosion Adjacent to the Indian River Inlet, Delaware, USA., Shore & Beach, Vol. 82, No. 1.

Coles SG, Tawn JA (1990) Statistics of Coastal Flood Prevention, Philosophical Transactions of the Royal Society A, Volume 332, issue 1627, DOI: 10.1098/rsta.1990.0126.

Bruun JT, Tawn JA (1998) Comparison of approaches for estimating the probability of coastal flooding, Volume 47, Issue 3, pp 405–423, DOI: 10.1111/1467-9876.00118.

Zijl F, Verlaan M, Gerritsen H (2013) Improved water-level forecasting for the Northwest European Shelf and North Sea through direct modelling of tide, surge and non-linear interaction, Ocean Dynamics, 63 (7).

Zijl F, Sumihar J, and Verlaan M (2015) Application of data assimilation for improved operational water-level forecasting on the Northwest European Shelf and North Sea. Ocean Dynamics, 1-18.

Pawlowicz R, Beardsley B, Lentz S (2002) Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE, Computers & Geosciences 28 (2002) 929–937.

Powers JG, Klemp JB, Skamarock WC, Davis CA, Dudhia J, Gill DO, Coen JL, Gochis DJ, Ahmadov R, Peckham SE, Grell GA, Michalakes J, Trahan S, Benjamin SG, Alexander CR, Dimego GJ, Wang W, Schwartz CS, Romine GS, Liu Z, Snyder C, Chen F, Barlage MJ, Yu W, Duda MG (2017) THE WEATHER RESEARCH AND FORECASTING MODEL, AMERICAN METEOROLOGICAL SOCIETY, DOI:10.1175/BAMS-D-15-00308.1.

Wadey MP, Brown JM, Haigh ID, Dolphin T, Wisse P (2015) Assessment and comparison of extreme sea levels and waves during the 2013/14 storm season in two UK coastal regions, Nat. Hazards Earth Syst. Sci., 15, 2209–2225, doi:10.5194/nhess-15-2209-2015.

Spencer T, Brooks SM, Evans BR, Tempest JA, Moller I (2015) Southern North Sea storm surge event of 5 December 2013: Water levels, waves and coastal impacts, V. 146, pp. 120-145. https://doi.org/10.1016/j.earscirev.2015.04.002.

Sibley A, Cox D, Titley H (2015) Coastal flooding in England and Wales from Atlantic and North Sea storms during the 2013/2014 winter, Weather, doi:10.1002/wea.2471

Charnock H (1955) Wind stress on a water surface, Quarterly Journal of the Royal Meteorological Society, DOI: 10.1002/qj.49708135027.

van der Grinten RM, de Vries JW, de Swart HE (2013) Impact of wind gusts on sea surface height in storm surge modelling, application to the North Sea, Nat Hazards, 66:1313–1326, DOI 10.1007/s11069-012-0112-x.