Die Küste, 81 (2014), 319-342

Extreme Storm Surge Prediction Using Hydrodynamic Modelling and Artificial Neural Networks

Mohamed Tayel and Hocine Oumeraci

Summary

On coastlines with shallow shelf areas (e.g. North Sea), a combination of high tides, storm surges, wind waves and mutual interactions generally represent the major sources of coastal flood risks: The contribution of the mutual interactions between the various components still remains the most unknown, despite the now routine linking of tidal and surge components in the current operational hydrodynamic storm-tide models. In fact, a proper physically-based coupling of all constituents will probably take decades to be implemented in the current operational models due to the highly complex and stochastic nature of the entire storm-tide system. Meanwhile, rather a more pragmatic data-driven approach is required to assess the contributions of these non-linear interactions to the resulting extreme storm-tide. Such a pragmatic approach is proposed, which is based on two types of artificial neural networks (ANNs) models called NARX (Nonlinear AutoRegressive eXogenous inputs): (i) NARX neural network model to predict the extreme storm-tide (Type-A), (ii) NARX neural network model to nonlinearly correct the numerical storm-tide results from TELEMAC2D and TOMAWAC (Type-B). Ensembles methods are then used to reduce variance and minimize error especially in extreme storm-tide events. The approach was applied for two pilot sites in the North Sea (Cuxhaven and Sylt). The results show that the ensemble models are able to extract the contribution of the nonlinear interaction between the different extreme storm-tide components at both sites by subtracting the results of the hydrodynamic models (linear superposition of storm-tide constituents) from the ensemble results. In most extreme storm-tide events considered in this study, the contribution of the nonlinear interaction resulted in the reduction of the extreme water levels when compared with the linear superposition of extreme storm-tide components. However, under certain conditions, the nonlinear interactions might result in higher storm-tides than the linear superposition (e.g. storm of January 2000 at Cuxhaven and Sylt).

Keywords

extreme storm-tide, North Sea, storm surge constituents, non-linear interactions, artificial neural network (ANN), hydrodynamic modelling, hybrid modelling

Zusammenfassung

Bei Küsten mit flachen Schelfgebieten wie die Nordsee, stellen extreme Sturmflut-Wasserstände aus Windstau und Gezeiten, Windwellen und deren Wechselwirkungen in der Regel die Hauptquelle von Hochwasserrisiken im Küstenbereich. Der relative Beitrag dieser Wechselwirkungen zwischen den Sturm-

flut-Komponenten zum resultierenden Extremwasserstand ist immer noch weitestgehend unbekannt – trotz der mittlerweile routinemäßigen Kopplung der Komponenten aus Windstau und Gezeiten in den derzeitigen operationellen hydrodynamischen numerischen Modellen (HNM). Aufgrund der hochkomplexen und stochastischen Natur der gesamten Sturmflut, wird die Implementierung einer weitgehend physikalisch-basierten Kopplung aller Sturmflut-Komponenten wahrscheinlich in die operationellen HNM noch Jahrzehnte Forschung benötigen. Mittlerweile wird eher ein pragmatischer datenbasierter hybrider Ansatz benötigt, um die nicht-linearen Wechselwirkungen zwischen allen Komponenten der resultierenden extremen Sturmflut-Wasserstände zu ermitteln. Solch ein pragmatischer Ansatz wird hier vorgeschlagen, der auf zwei Arten von KNN-Modellen (Künstliche Neuronale Netze) bezeichnet als NARX (Nichtlineare AutoRegressive exogene Eingänge) basiert: (i) NARX neuronale Netzwerkmodell für extreme Sturmflutvorhersagen (Type-A), (ii) NARX neuronale Netzwerkmodell für die Korrektur der in HNM wie TELEMAC2D und TOMAWAC ermittelten nichtlinearen Effekte (Type-B). Besonders bei extremen Sturmflutereignissen, werden Methoden der Ensemble-Modellierung verwendet, um die Varianz zu reduzieren und Fehler zu minimieren. Der vorgeschlagene hybride Ansatz wurde beispielhaft für zwei Pilot-Standorte an der deutschen Nordseeküste (Cuxhaven und Sylt) implementiert. Die Ergebnisse an beiden Standorten zeigen, dass der hybride Ansatz in der Lage ist, die Beiträge der nichtlinearen Wechselwirkungen zwischen allen Sturmflut-Komponenten durch Subtraktion der Ergebnisse der hydrodynamischen Modelle (lineare Überlagerung aller Sturmflut-Komponenten) von den Ergebnissen der Ensemble -Modelle zu extrahieren. Für die extremsten Sturmflutereignisse im Zeitraum 1991-2007, die in dieser Studie berücksichtigt wurden, führte der Beitrag der nichtlineare Wechselwirkung im Vergleich mit der linearen Überlagerung von extremen Sturmflut-Komponenten in der Regel zur Reduzierung der resultierenden Wasserstände. Jedoch zeigten die Ergebnisse, dass unter bestimmten Bedingungen die nichtlinearen Wechselwirkungen auch zu höheren Sturmflut-Wasserständen als die lineare Überlagerung führen können (z. B. Sturm vom Januar 2000 bei Cuxhaven und Sylt).

Schlagwörter

Extreme Sturmfluten, Nordsee, Sturmflutkomponenten, nicht-lineare Effekte, künstliche neuronale Netze (KNN), hydrodynamische numerische Modelle (HNM), hybride Modellierung

Contents

1 Introduction

It is uncertain whether nature has yet had enough time to "implement" all the physically possible worst combinations of all constituents for the generation of the most extreme storm-tide ("perfect storm-tide"). In fact, extreme storm-tide events depends on many factors that can be classified into three categories as depicted in Fig. 1 (a) Meteorological factors with non-stationary and stochastic characteristics such as wind speed and direction, storm characteristics and its track, sea level pressure, and rivers discharge. (b) Deterministic factors like astronomical tides and tidal resonance, which may greatly affect the tidal ranges in a shelf sea like the North Sea and depends on geometry, friction and rotation. (c) Local factors in a shallow water region, such as local bathymetry changes, roughness of the continental shelf and shoreline geometry. In the North Sea, the external surges that are generated outside and then propagate to the interested area contribute also nonlinearly to the resulting extreme storm-tide level.

The greatest difficulties towards the determination of the physically possible "perfect storm-tide" essentially arise from the fact that the nonlinear interactions between the various constituents are still unknown. Despite the now routine approaches of linking the tide and surge components in present operational storm-tide models and the substantial progress in recent research of air-sea interactions, a proper process-based coupling of all constituents will certainly take decades to be implemented in the current numerical models.

So the main objective of this study is the development of a new hybrid modelling approach which has been performed in collaboration with the joint XTREM-Risk project (OUMERACI et al. 2009) in which considerable data for Sylt and Cuxhaven have been collected, generated and analyzed (GOENNERT and GERKENSMEIER 2012) and (WAHL et al. 2012). The new approach combines NARX models with the hydrodynamic numerical model TELEMAC2D (HERVOUET and VAN HAREN 1994; HERVOUET 2007) and wave field model TOMAWAC (BENOIT 2003; BENOIT et al. 2001)), that can be applied to coastal areas and estuaries as an "operational", low cost modelling tool in order (i) to account for the high nonlinearity of the processes at the two sites exemplarily considered in this study (Sylt island and Cuxhaven) in the North Sea, Germany and (ii) to fill the gaps in long-term data series by using sequential time series predictions at the given sites.

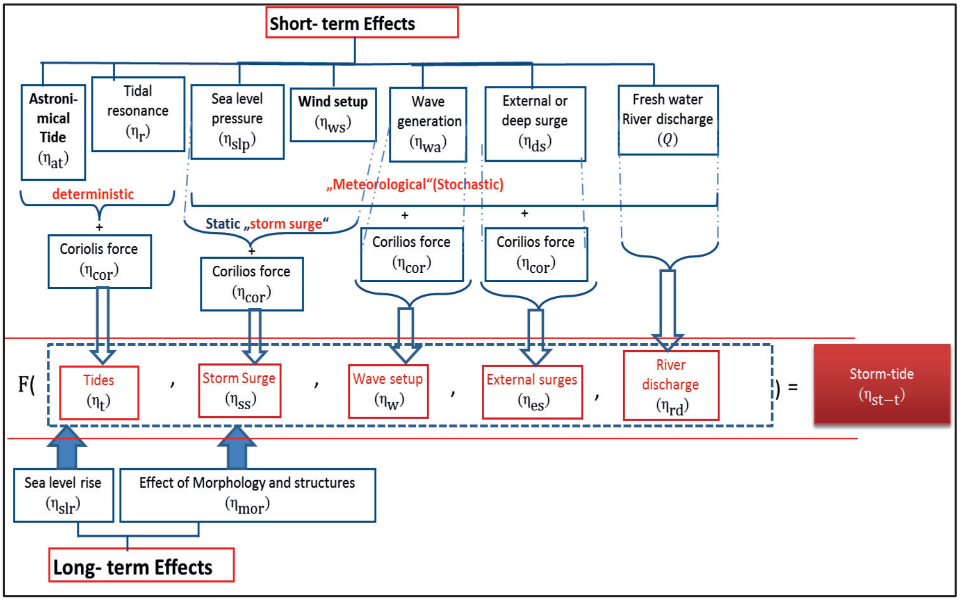

Figure 1: Main components contributing nonlinearly to the generation of extreme water levels and used terminology (modified from OUMERACI (2009)).

2 Development of the NARX models for extreme storm surge prediction at Cuxhaven and Sylt

Using the hourly meteorological forcing between 1970 and 2007 generated by the Regional Climate Model (RCM) SN-REMO (VON STORCH et al. 2000), along with the observed water level data from 1997 to 2007 for Cuxhaven and from 1999 to 2007 for Sylt, two types of ANNs models called NARX (Nonlinear AutoRegressive eXogenous inputs) were developed: (i) NARX neural network model to predict the extreme storm-tide (Type-A), (ii) NARX neural network model to nonlinearly correct the numerical storm-tide results from TELEMAC2D (Type-B).

The construction of each NARX model type is performed in two phases (see Tab. 1), due to the large number of neural architectural parameters (e.g. the number of hidden layers and number of hidden neurons in each layer) that can be modified. The first phase deals with the determination of the optimum number of input variables time series lags that should be included as input, also the optimum architectural parameters and best training algorithm using STATISTICA Automated Neural Networks (SANN). In the second phase, the final NARX model type is developed using Matlab neural networks toolbox for further structural parameters configuration and modifications that are based on the optimum structure obtained by SANN.

The use of ensembles methods can significantly reduce variance and minimize error especially in extreme storm-tide events. The ensemble forecasting method averages results from the best NARX models. Several different ensemble fitting neural network (EFN) models are developed and tested, varying the architectural parameters used for each ensemble.

Finally, the two types of NARX models and their ensemble prediction results are validated in terms of correlation coefficient (r), root mean square of error (RMSE) and standard deviation (σ) using observed water level data, in order to determine the models with the best prediction performance for water levels at the two locations between 1991 and 2007 (TAYEL and OUMERACI 2014; TAYEL 2015).

2.1 Input variables selection and preparation for the developed NARX models

Extreme water levels at an open coast may consist of the following six components: wind setup due to wind shear at the water surface; wave setup caused by wind-induced waves transferring momentum to the water column; pressure setup due to the atmospheric pressure decrease over the spatial extent of the storm system; Coriolis forced setup or setdown due to the effects of the rotation of the earth acting on the wind driven alongshore current at the coast; seiche due to resonance effects initiated by moving wind system, and an astronomical tide component.

The ANN models in the learning phase capture the nonlinear nature between extreme water level components using a moderate time span (approximately 5 years) of the observed water levels at Cuxhaven and Sylt. A subset of the observed water level data at Cuxhaven and Sylt for learning and validating the models should be selected such that it does not contain gaps and/or a substantial amount of improbable observed values. This criterion is fulfilled for Cuxhaven data between 1998 and 2007, while for Sylt between 2000 and 2007. The observed water level data for each year of the above selected periods are recorded with time interval between 10 minutes and 1 hour, which are temporally interpolated in order to be synchronized with the available meteorological data every hour (TAYEL and OUMERACI 2012).

Tab. 2 shows the input and output data for the two developed NARX models at Cuxhaven and Sylt. The input deck of the two NARX models types consists of the astronomical tidal forecasts, significant wave height produced by TOMAWAC numerical wave model, the two wind speeds components in east-west direction (wind U component or zonal component) and in south-north direction (wind V component or meridional component), external surge from Wick station, and sea level pressure for Cuxhaven and Sylt in addition to the Elbe river discharge (in case of Cuxhaven only).

2.2 NARX models for Cuxhaven and Sylt using ensemble methods

The input deck of the ensemble fitting neural network (EFN) models (Fig. 2) consists essentially of four different storm-tide prediction results from the best three NARX Type-A models and the best NARX Type-B model. In addition, the input deck contains the time lagged meteorological forces (sea level pressure, zonal and meridional wind speed components) for Cuxhaven or Sylt. The output of the EFN models is the difference between the observed storm-tide (η_{OB}) and the predicted storm-tide by NARX Type-B (η_B) either at Cuxhaven or Sylt. So, the developed EFN networks are trained in a way that makes the developed EFN models learn more nonlinear interaction terms "if possible" without changing the long term time series prediction performance gained from the results of both NARX Types A and B.

Table 1: Development phases 1 and 2 for NARX models Type A and Type B at Cuxhaven and Sylt.

Phase I: using SANN for the determination of

- optimum input variables time series lags.
- optimum architectural parameters for the developed time series ANN networks.

Determination of the extreme storm-tide components according to their physical generation process that are effective for the North Sea e.g. wind, pressure and external surges.

- Determination of the teaching set for Cuxhaven (1998-2007) and Sylt (2000-2007) such that it doesn't contain gaps or imporable values.
- Determination of the ANNs input variables(e.g. pressure, wind and tide) and output variable (observed water level).
- Selecting of three independent series of data: a training series, a validation series and a testing series from the teaching set by ratio 70%,15% and 15% respectively.

Development of the two ANN networks models types using different architecture parameters that:
1. use of lagged input variables up to previous 24 hours, which leads to better predictions in a dynamic system (dependence on effective meteorological forces duration).
2. use of SANN time series regression ANNs type, which changes the number of previous input variables time series lags from 1 to 24.
3. change the number of neurons in the hidden layer from 1 to 10 neurons.
4. change the type of activation function in the hidden and output layers.

- SANN automatically use several training or teaching algorithms for ANNs models trainning like back propagation, conjugate gradient descent, quasi-Newton, and Levenberg-Marquardt.
- After training of the two models type for Cuxhaven and Sylt by 25 trials each, from each trial the best five neural networks in performance were retained according to the highest correlation coefficient (R) and the lowest sum square of error (SSE).

lead to

Determination of the optimum ANNs architectural parameters that can be further improved using Matlab neural toolbox:
- three layers feedforward MLP neural networks with one hidden layer are suitable for extreme strome surges modeling in Cuxhaven and Sylt in order to decrease the overfitting chance.
- the output layer has only one neuron with linear activation function.
- the types of activation function of neurons in the hidden layer were either tangent sigmoid (tansig) or logarithm sigmoid (logsig).
- The results for the two models types for Cuxhaven indicate an increase in the correlation coefficient and stable decrease in the SSE until time lag=18 hours,while for Sylt indicate the same behavior but until time lag=16 hours.
- The optimum number of neurons in the hidden layer of the best selected MLP neural networks changes from 3 to 10 neurons for both stations, which would give rise to a very large network that increase the overfitting chance.

Phase II: using Matlab neural networks toolbox for

- determination of the number of nodes in the hidden layer
- improve the developed SANN time series ANN models by using instead the Nonlinear AutoRegressive eXogenous inputs (NARX) neural network in Matlab neural toolbox.

The numbers of hidden neurons of both NARX models types were determined using the exhaustive search in the range [3~10]. These had been carried out in 8 trials for each NARX models type, through the following two stages of NARX networks developments:
1. in each trial, the the optimum identified architectural parameters of time lags=18 hours for Cuxhaven and time lags=16 hours for Sylt are used. Moreover, the activation functions for the hidden and output layers are tangent sigmoid and linear respectively.
2. develop and train the NARX network of each trial using the Levenberg-Marquardt algorithm since it will have the fastest convergence.

Result: the optimum number of neurons in the hidden layer of both NARX models types for Cuxhaven and Sylt is eight neurons according to the mean square of error (MSE).

Improve the developed SANN time series models by using instead the Nonlinear AutoRegressive eXogenous inputs (NARX) neural network in Matlab neural toolbox that capture the dynamics of the nonlinear extreme storm surges behavior since in it:
- the output is feedback to the input layer (global feedback) and so it has information about the state of the system at previous temporal steps.
- include the input variables data at the prediction time step t+1, so it gains higher prediction performance.

Development of the two NARX networks models types using the identified optimum architecture parameters with 8 hidden neurons in 4 trials that:
1. each trial is repeated 6 times with the same NARX architecture because of the random initialization of weights.
2. change the type of activation function in the hidden layer either Tansig or logsig.
3. change the type of activation function in the output layer either linear or tansig.

Result: The best performance was for NARX type-B in both locations but unexpectedly because it contain the TELEMAC2D results in the input, in some storm events it underestimate or overestimate the peaks of the extreme water level.

Development of an ensemble ANN fitting model that consists of three layers and uses one neuron in the hidden layer.
- ensemble input: the best three NARX type-A (change only in activation function) and the best NARX type-B.
- ensemble output: the difference between observed water level and the results of the best NARX type-B.
- the types of activation function of neurons in the hidden and output layers were either logsig and tansig respectively.

Table 2: Input and output for the developed NARX models Type A and Type B at Cuxhaven and Sylt.

Description	**Cuxhaven (Type-A and Type-B)**	**Sylt (Type-A and Type-B)**
Input	• Time series of wind U component. • Time series of wind V component. • Time series of sea level pressure. • Time series of observed water level. • Time series of Elbe River discharge. • Time series of external surge at Wick. • Astronomical tidal prediction time series. • TOMAWAC Significant wave height (Hs) results time series. • TELEMAC2D surge-tide results time series (for Type-B only).	• Time series of wind U component. • Time series of wind V component. • Time series of sea level pressure. • Time series of observed water level. • Time series of external surge at Wick. • Astronomical tidal prediction time series. • TOMAWAC Significant wave height (Hs) results time series. • TELEMAC2D surge-tide results time series (for Type-B only).
output	Time series prediction of extreme water level every hour	Time series prediction of extreme water level every hour
Training period	1998 to 2005	2000 to 2005
Prediction period	1991 to 2007	1991 to 2007

The optimum architectural parameters (Fig. 2) are: one neuron in the hidden and output layers with the time lags of meteorological input variables d_u=18 hours for Cuxhaven and d_u=16 hours for Sylt. Only the activation function type is changed for the hidden and output layers. The transfer functions tansig or logsig are possible in the hidden layer, while for the output layer tansig, logsig and linear functions are more appropriate candidates. The development of EFN models has been implemented in six trials using the built-in matlab Levenberg-Marquardt algorithm. In each trial, the activation function type is changed either for the hidden or output layers.

Using the observed water level during storms from 1998 to 2007 for Cuxhaven and from 2000 to 2007 for Sylt, the EFN model prediction results (η_{EFN}) were "validated" in terms of correlation coefficient (r), RMSE and σ. The results show that the logsig and tansig activation functions in the hidden and output layers respectively give the best performance (lowest RMSE and highest correlation) for Cuxhaven and Sylt. For the EFN models in Cuxhaven, the lowest RMSE is 0.148 m with a correlation of 0.99. The best EFN model for Sylt has an RMSE of 0.124 m and a correlation of 0.98.

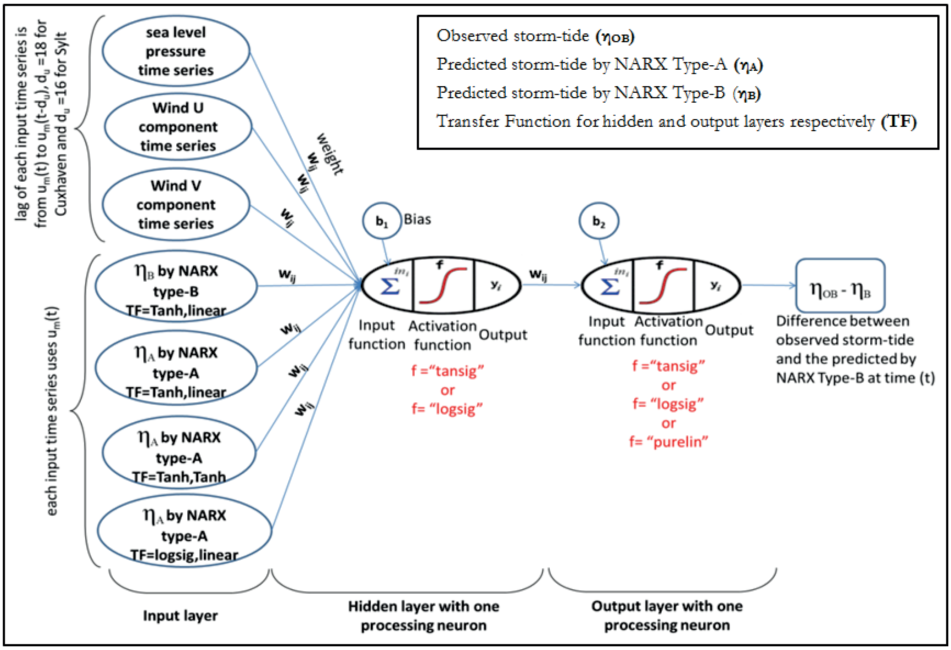

Figure 2: Input and output variables of the Ensemble Fitting Network (EFN) for Cuxhaven and Sylt with one neuron in the hidden and output layers.

The validation results of best η_{EFN} are close in value to its counterparts from the best NARX Type-B results at both sites Cuxhaven and Sylt. So, the long term prediction performance gained with the results of NARX model Type-B is inherited inside the η_{EFN} as shown in Fig. 3. During the storm of January 2000 at Sylt and in December 1999 at Cuxhaven (Fig. 3), the height and occurrence time of η_{EFN} highest peak are approximately the same as those of the actually observed water level η_{OB}.

The inter-comparison of the actually observed water level (η_{OB}), the numerically predicted water level $(\eta_{su-t\,TEL})$ and the ensemble results (η_{EFN}) is graphically summarized by meaningfully making use of the Taylor diagram approach (TAYLOR 2001) as shown in Fig. 4. The η_{OB} data from 1998 to 2007 for Cuxhaven and from 2000 to 2007 for Sylt are used for this comparison. The position of each label on the Taylor diagram is determined by the values of the correlation coefficient (r), root mean square of error (RMSE) and standard deviation (σ). In the Taylor diagrams, these statistical parameters are normalized by dividing both the RMSE and the σ of the compared results by the standard deviation of the observations $(\sigma_{\text{observed}})$. The key issue in the Taylor diagram approach (TAYLOR 2001) is to recognize the relationship between the four statistical parameters of interest (here RMSE, σ_{result}, σ_{observed} and r):

$$(\mathrm{RMSE})^2 = (\sigma_{\text{result}})^2 + (\sigma_{\text{observed}})^2 + 2^*\ \sigma_{\text{result}}{}^*\sigma_{\text{observed}}{}^*\mathrm{r} \qquad (1)$$

The η_{EFN} results have a correlation of 0.99, 0.98 and a normalized RMSE of 0.13 m, 0.17m at Cuxhaven and Sylt, respectively. Moreover, the EFN models perform better during the individual extreme storm events than NARX model Type B as depicted in

Fig. 3 during the storms of December 1999 at Cuxhaven and January 2000 at Sylt .The ensemble models (η_{EFN}) predict correctly the occurrence time of the η_{OB} highest peak during the storm of December 1999 at Cuxhaven, while the occurrence time of η_B highest peak predicted by NARX model type B is delayed by one hour. Moreover, the η_{EFN} highest peak resulting from the ensemble model reaches 3.84 m, which is better predicted than by NARX model type B with η_B peak of only 1.9 m. However, there is still a difference of 0.66 m between η_{EFN} and η_{OB} during the storm of December 1999 (called Anatol) at Cuxhaven, which is mainly due to the overestimation of the predicted sea level pressure by the climate model SN-REMO as compared to the observed pressure. The observed core pressure of Anatol on 3rd of December is 953 hPa (Nilsson et al. 2005), while the predicted by SN-REMO reaches 986 hPa. It decreases the water level by one centimeter for each hPa increase in pressure, which reaches 33 cm. Moreover, this increase in sea level pressure results in a reduction of predicted wind speed than the observed during the storm, which reaches up to 5 m/s (Nilsson et al. 2005) and decrease further the predicted water level. Hence, this leads to the shift down of η_{EFN} curve even at the trough, which occurs before the highest peak (see Fig. 3 (a)). During the storm of January 2000 at Sylt, the η_{EFN} highest peak is exactly the same as the η_{OB} highest peak with 3.02 m, while the η_B maximum highest peak predicted by NARX model type B is overestimated.

3 Evaluation of the effect of nonlinear interactions between extreme storm-tide constituents

The used hydrodynamic model "TELEMAC2D" (version 6.2 in parallel processing mode) solves the non-conservative form of the shallow water equations, written with h (depth) and u, v (flow velocity components) as the unknowns (HERVOUET 2007). It considers the propagation of long waves such as surge and tide, including the non-linear interaction between them. The numerical solution of these equations is based upon the fractional step method with two steps: (i) Advection and (ii) Propagation, diffusion and source terms (representing the wind, Coriolis force, bottom friction, a source or sink of momentum within the domain). The method of characteristics has been applied to solve the advection of velocities u and v. The propagation, diffusion and source terms are solved by the finite element method, where an implicit time discretization allows the elimination of the non-linearity in the equations. In that case, the nonlinear terms are approximated linearly in time. Variation in the formulations and space discretization transform the continuous equations into a linear discrete system, which is solved using an iterative procedure based on the conjugate gradient method (HERVOUET and VAN HAREN 1994). This treatment of the nonlinear terms can lead to either underestimated or overestimated water level peaks during extreme storms and to incorrect prediction of their occurrence times.

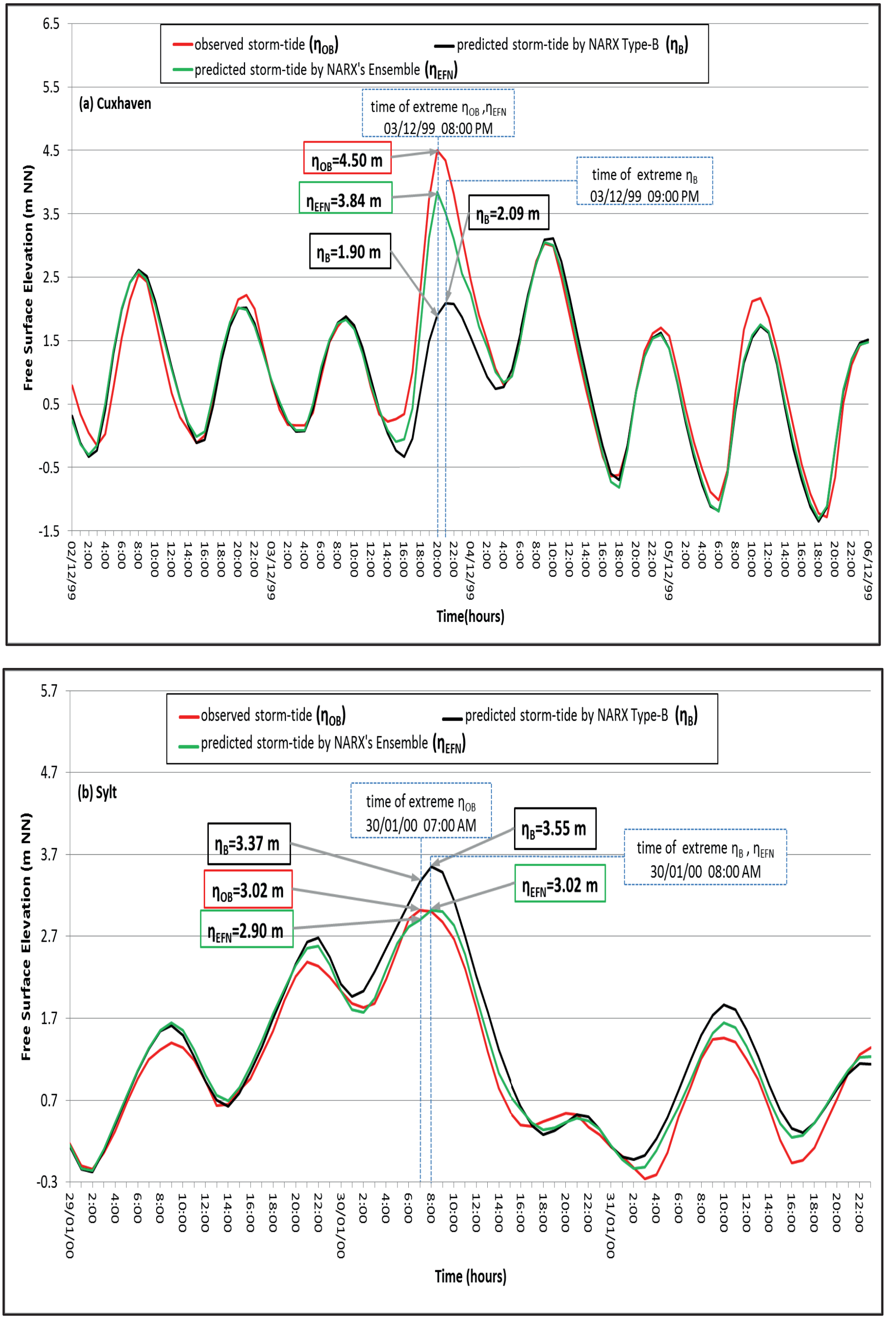

Figure 3: Results of NARX ensemble models and NARX Type-B models at Cuxhaven during the storm of December 1999 (a) and at Sylt during the storms of January 2000 (b).

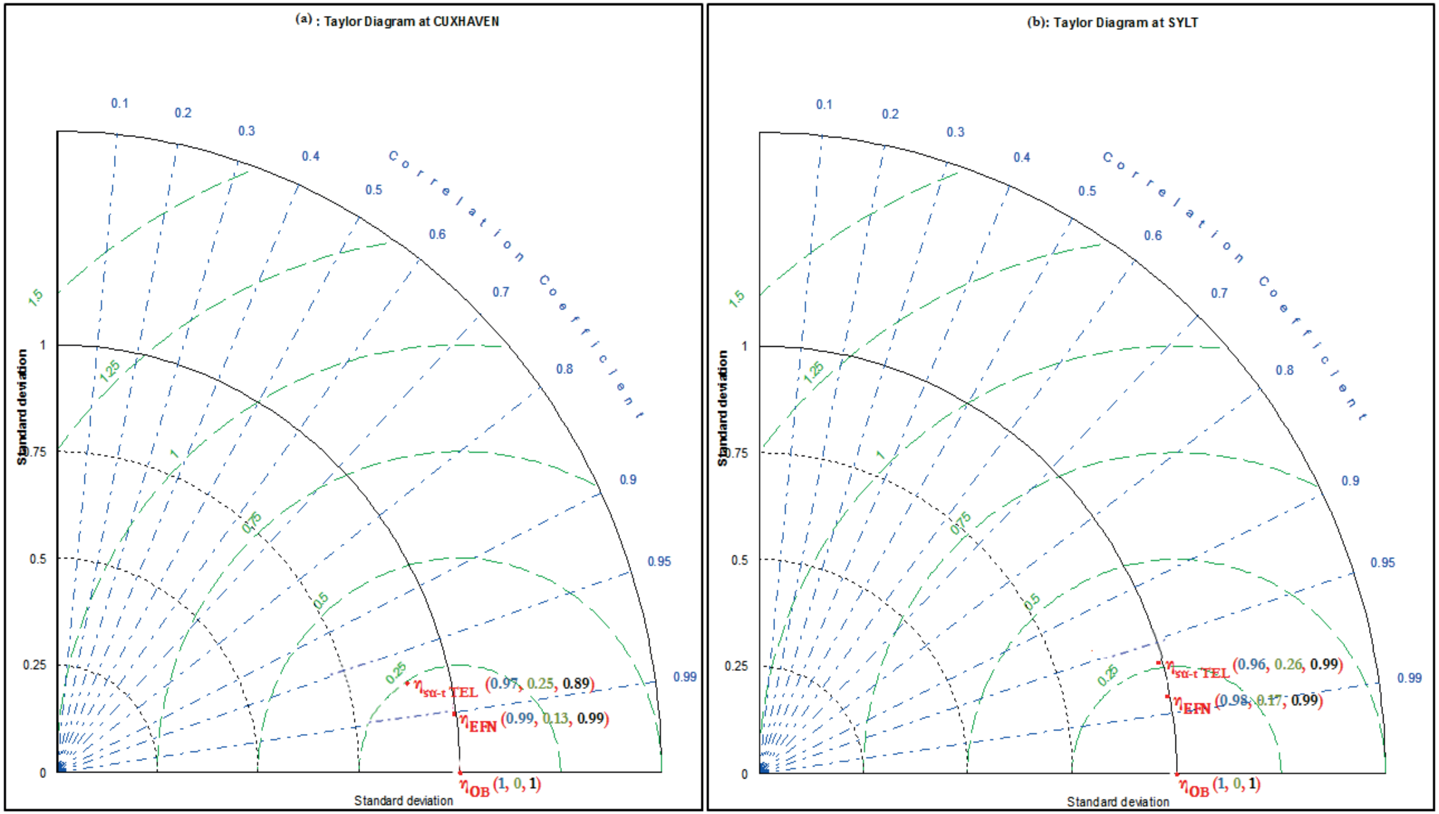

Figure 4: TAYLOR diagrams of the observed storm-tide (η_{OB}), the predicted surge-tide $(\eta_{su-t\,TEL})$ by TELEMAC2D and the predicted storm-tide (η_{EFN}) by NARX Ensemble models at Cuxhaven (a) and Sylt (b) based on the correlation coefficient (r), normalized root mean square error (RMSE) and normalized standard deviation (σ).

3.1 Overall approach

A proper prediction based on the complete understanding of the processes underlying the nonlinear interactions may require several decades to be implemented in the current operational hydrodynamic models. Therefore, the data-driven modeling using ANN methodology is used for complementing the nonlinear interaction terms by learning from the observed water levels. Through a combined use of the developed NARX ensemble and a state of the art hydrodynamic model such as "TELEMAC2D", it is possible to extract the nonlinear interaction between the different extreme surge components as summarized in the following nine steps (Fig. 5):

1. Prescribe the forcing responsible for the generation of all extreme storm-tide components to the North Sea mesh in TELEMAC2D (Fig. 6) as "inputs" along with their boundary conditions (e.g. sea level pressure, meridional and zonal wind speed components represent the forcing factors for storm surge component).
2. Evaluate each component of the extreme storm-tide η_{st-t} (as defined in Fig. 1) independently using the North Sea mesh in TELEMAC2D (Fig. 6). So, the boundary conditions of each component are prescribed separately for the North Sea model area.
3. The components obtained from step 2 are linearly superposed in order to predict the linear surge-tide for Cuxhaven or Sylt (η_L); i.e. the nonlinear interaction between the components is not considered. The linear surge-tide does not include the wave setup effect (η_w), since it has almost no contribution to the observed storm-tide at Cuxhaven and Sylt.
4. Drive the North Sea mesh in TELEMAC2D using the boundary conditions of all components, which are prescribed simultaneously in order to predict the surge-tide $(\eta_{su-t\,TEL})$.
5. Calculate the difference between $\eta_{su-t\,TEL}$ predicted in step 4 and η_L predicted in step 3 in order to extract the nonlinear interaction between the components as approximated in TELEMAC2D (η_{NLT}).
6. Calculate the difference between the observed storm-tide (η_{OB}) and the approximated surge-tide by TELEMAC2D $(\eta_{su-t\,TEL})$, which are assumed to represent the complementary nonlinear interaction (η_{NLE}): so $\eta_{NLE} = \eta_{OB} - \eta_{su-t\,TEL}$
7. Train and develop the NARX ensemble models using the η_{NLE} calculated in step 6, which is not considered by TELEMAC2D.
8. Predict the complementary nonlinear interaction η_{NLE} using the developed NARX ensemble models for Cuxhaven and Sylt from 1991 to 2007.
9. Linearly add the approximated nonlinear interaction η_{NLT} by TELEMAC2D of step 5 and its complementary η_{NLE} by NARX ensemble models of step 8 in order to get the total nonlinear interaction (η_{NL}): $\eta_{NL} = \eta_{NLT} + \eta_{NLE}$.

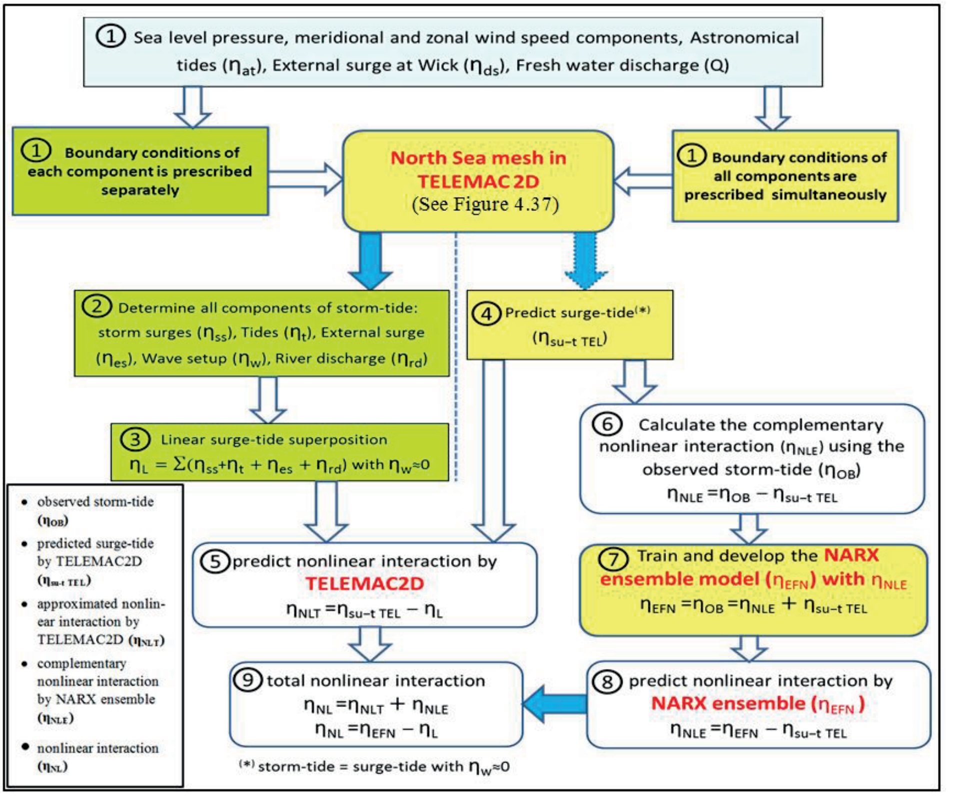

Figure 5: Extraction of the component η_{NL} resulting from the nonlinear interactions between the different extreme surge components for Cuxhaven and Sylt.

3.2 Extraction of the nonlinear interaction approximated by the numerical model in the $\eta_{\text{su-t TEL}}$ results (steps 1 to 5 in Fig. 5)

Procedure

For the extraction of the approximated nonlinear interaction effect (η_{NLT}) considered in the predicted surge-tide by TELEMAC2D $(\eta_{su-t\,TEL})$, the linear superposition of the extreme surge-tide components (η_L) should be subtracted from the $\eta_{su-t\,TEL}$: $\eta_{NLT} = \eta_{su-t\,TEL} - \eta_L$. The η_L consists of the linear addition of tide (η_t), storm surge (η_{ss}), external surge (η_{es}) and rivers discharge (η_{rd}) effects, which are simulated independently from each other by TELEMAC2D over the North Sea area (Fig. 6). The effect of wave setup (η_w) on the extreme storm-tide depends on the location of the selected site (inside or outside the surf zone). Both sites are outside of the surf zone and the effect of wave setup on the η_L and $\eta_{su-t\,TEL}$ can thus be neglected.

For the surge-tide $\eta_{su-t\,TEL}$ simulations by TELEMAC2D, the boundary conditions of the North Sea hydrodynamic model are prescribed using all of the extreme storm surges components between 1991 and 2007 (TAYEL and OUMERACI 2012). These boundary conditions are shown in Fig. 6, on the northern open sea boundary (Northern border: Scotland-Norway), the tidal water level on each node and the external surge either from Wick or Lerwick stations are linearly added. On the western boundary (West border: France-England) only the tidal water level is prescribed at each node. So, the influence of the shallow water can be taken into account when the tidal wave plus external surge propagate from the open boundary up to the German coast. On the southern onshore edge of the estuaries the fresh water discharge of the adjacent rivers / estuaries are prescribed at each river section.

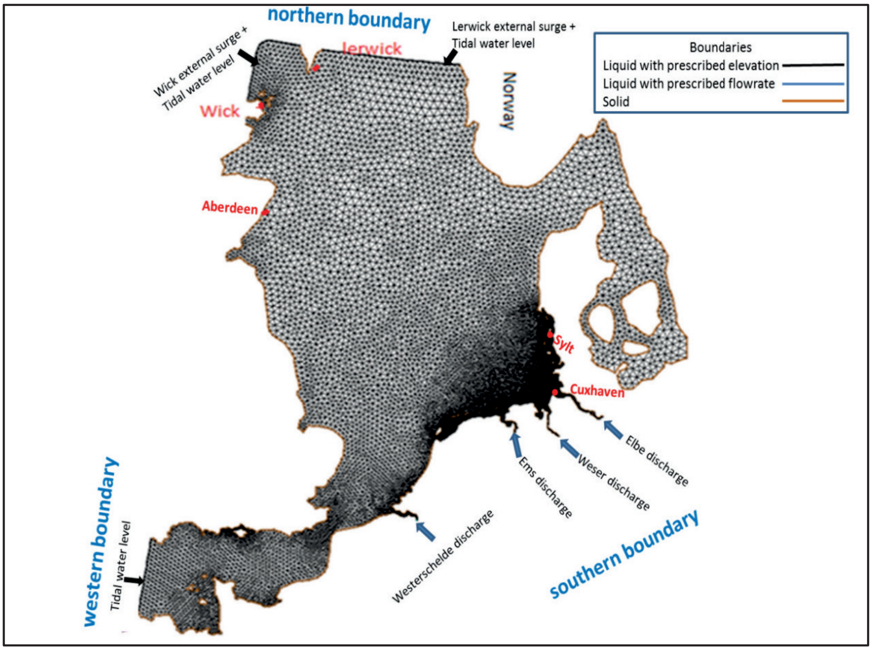

Figure 6: Boundary conditions of the North Sea mesh inside TELEMAC2D with the prescribed water elevation at open-sea and flow rate of southern fresh water discharge.

In the linear superposition surge-tide η_L simulations, the boundary conditions for each component are prescribed separately in order to evaluate its effect during storms. For example, only the tidal water level on each node of the Northern and West borders are prescribed for evaluating the tidal effect, while the meteorological forces only drive the model for evaluating the storm surge effect without prescribing any of the open-sea or river discharge boundary conditions.

Results

During the storms of January 2000, November 2006 and November 2007, the temporal variations of the predicted linear superposition η_L with the contribution of each component at Cuxhaven and Sylt are predicted. At the times of the observed extreme water level η_{OB} $\left((\eta_{\mathrm{OB}})_{\max}\right)$ during these three storms, the highest η_L peaks at Cuxhaven reach 3.22 m, 3.17 m and 3.31 m for the storms in January 2000, November 2006 and November 2007, respectively, which are higher than their counterparts at Sylt of 2.52 m, 1.96 m and 2.44 m, respectively. Since the contribution of storm surge (η_{ss}) and tide (η_t) at Sylt are lower than those at Cuxhaven due to the difference in geographical locations of the two sites. The storm surge, tide and external surge components have the largest contribution to the η_L at both sites, while the effect of rivers discharge and wave setup are almost negligible. Fig. 7 shows the contribution of each extreme storm-tide component during the storm of January 2000 at Cuxhaven and Sylt. The highest contribution is from storm surge effect with maximum of 3.00 m and 2.28 m at Cuxhaven and Sylt, respectively. The tide effect is less than the storm surge at the time of $(\eta_{OB})_{\max}$ in both sites; it reaches 1.00 m and 0.56 m at Cuxhaven and Sylt, respectively. Only during the storm of January 2000, the external surge has positive effect on η_L in Cuxhaven and Sylt at the times of $(\eta_{OB})_{\max}$ by 0.34 m and 0.26 m, respectively. In contrast during the storms of November 2006 and 2007 in both sites, the external surge has negative effect on η_L ranging from -0.05 m to -0.13 m at the times of $(\eta_{OB})_{\max}$.

For Cuxhaven and Sylt during the storms of January 2000, November 2006 and November 2007, the heights of η_L peaks overestimate always the $\eta_{su-t\,TEL}$ peaks that include the nonlinear interaction η_{NLT} approximated by the numerical model TELEMAC2D. At the times of $(\eta_{OB})_{\max}$ during these three storms, the predicted $\eta_{su-t\,TEL}$ reach 3.04 m, 2.97 m and 3.19 m respectively at Cuxhaven, which are lower than the predicted η_L of 3.22 m, 3.17 m and 3.31 m, respectively for the storms in January 2000, November 2006 and November 2007.

Fig. 8 shows the temporal variations of the predicted linear superposition η_L and surge-tide $\eta_{su-t\,TEL}$ by TELEMAC2D in addition to the approximated nonlinear interaction (η_{NLT}) at Cuxhaven and Sylt during the storm of January 2000. The extreme linearly predicted water level η_L $((\eta_L)_{\max})$ and the extreme predicted surge-tide $\eta_{su-t\,TEL}((\eta_{su-t\,TEL})_{\max})$ at Cuxhaven reach 3.37 m and 3.24 m respectively, while they were 3.28 m and 3.04 m at Sylt respectively. At both sites, the occurrence times of $(\eta_L)_{\max}$ and $(\eta_{su-t\,TEL})_{\max}$ during this storm are exactly the same. Moreover, the $(\eta_{su-t\,TEL})_{\max}$ at Sylt during the storms of January 2000 and November 2006 occur before the $(\eta_{OB})_{\max}$ by 9 hours. Since the highest storm surge peak at Sylt during these storms are synchronized approximately with high tide (see Fig. 7(b)). Moreover, the maximum positive external surge of 0.5m (Fig. 7(b)) at Sylt occurred at the time of storm surge peak during the storm of January 2000.

3.3 Extraction of the complementary terms for the nonlinear interaction using the predicted η_{EFN} results (steps 6 to 8 in Fig. 5)

Procedure

The predicted storm-tide by NARX ensemble (η_{EFN}) includes the complementary terms (η_{NLE}) for the approximated nonlinear interaction by TELEMAC2D (η_{NLT}). The complementary terms (η_{NLE}) are basically the linear addition of

(i). Difference between the predicted storm-tide by NARX Type-B model (η_B) and the predicted surge-tide by TELEMAC2D $(\eta_{su-t\,TEL})$.

(ii). Difference between the predicted storm-tide by NARX ensemble (η_{EFN}) and the predicted storm-tide by NARX Type-B model (η_B).

So, the predicted η_{NLE} is obtained by direct subtraction of the predicted $\eta_{su-t\,TEL}$ from η_{EFN} (i.e. $\eta_{NLE} = \eta_{EFN} - \eta_{su-t\,TEL}$). Since the developed NARX ensemble is trained based on the observed water level (η_{OB}), so the predicted storm-tide by η_{EFN} and η_{OB} are considered as equivalent (see step 7 in Fig. 5).

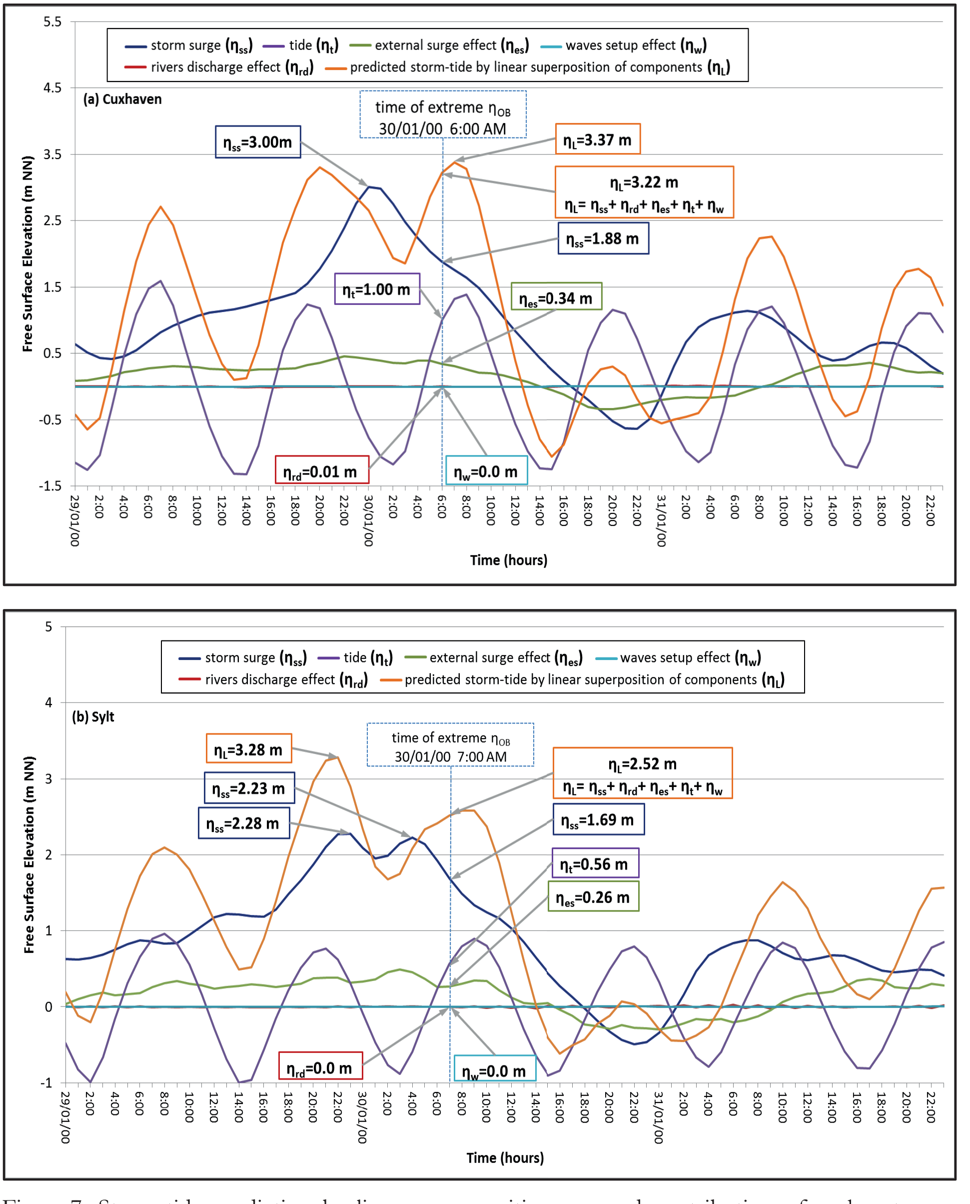

Figure 7: Storm-tide prediction by linear superposition η_L and contribution of each extreme storm-tide component during the storm of January 2000 at Cuxhaven (a) and Sylt (b).

Results

The temporal variations of η_{EFN} with the complementary terms (η_{NLE}) at Cuxhaven and Sylt are predicted for the storms of January 2000, November 2006 and November 2007. The η_{EFN} peaks, which occur directly before the times of $(\eta_{OB})_{\max}$ at both sites, are always overestimated by the predicted $\eta_{su-t\,TEL}$ peaks and η_L peaks. This is due to the strong reduction of η_{EFN} peaks by η_{NLE} and η_{NLT}. At Cuxhaven during these three storms, the effect of η_{NLE} causes a reduction of the η_L peaks, which occurs directly before the times of $(\eta_{OB})_{\max}$, by -0.12 m, -0.36 m and -0.14 m in addition to the reduction of η_{NLT} by -0.34 m, -0.18 m and -0.34 m respectively for the storms of January 2000, November 2006 and November 2007. In contrast, at the times of $(\eta_{OB})_{\max}$ in Cuxhaven and Sylt, The η_{NLE} results in the overestimation or underestimation of the η_{EFN} peaks when compared with the $\eta_{su-t\,TEL}$ and η_L peaks according to the following two conditions:

(i). If the η_L and $\eta_{su-t\,TEL}$ peaks, which occur directly before the time of extreme η_{EFN} $\left((\eta_{EFN})_{\max}\right)$, are < 3.00 m and < 2.50 m respectively, then their following peaks would overestimate the peak of η_{EFN} at the time of $(\eta_{EFN})_{\max}$. Since the peaks of η_{EFN}, η_L and $\eta_{su-t\,TEL}$, which occur before the times of peak $(\eta_{EFN})_{\max}$, do not increase the mean water level (MWL) during the storm significantly. Therefore, the following peaks of η_{EFN}, η_L and $\eta_{su-t\,TEL}$ will propagate under a pronounced shoaling effect that increase their heights simultaneously. For example, the η_{NLE} decreases $(\eta_{su-t\,TEL})_{\max}$ by -0.08 m and -0.11 m respectively during the storms of November 2006 (see Fig. 8(d)) and November 2007 at Sylt. Moreover, the η_{NLT} causes a decrease of $(\eta_L)_{\max}$ by -0.04 m and -0.14 m respectively, which is added to the η_{NLE} decrease and support it.

(ii). If the η_L and $\eta_{su-t\,TEL}$ peaks, which occur directly before the time of $(\eta_{EFN})_{\max}$, are ≥ 3.00 m and ≥ 2.50 m respectively, then their following peaks would underestimate the peak of η_{EFN} at the time of $(\eta_{EFN})_{\max}$. Since only the peaks of η_L and $\eta_{su-t\,TEL}$, which occur before the times of $(\eta_{EFN})_{\max}$, increase the MWL during the storm to a limit by which their following peaks will propagate under no shoaling effect. Therefore, the following peaks of η_L and $\eta_{su-t\,TEL}$ will propagate in deeper water with less pronounced shoaling, which decrease their heights simultaneously. In contrast, the peak of η_{EFN} propagates under strong shoaling effect that increases its height, as their counterparts in condition (i). For example, during the storms of January 2000 (Fig. 8(a)), November 2006 (Fig. 8(c)) and November 2007 at Cuxhaven, the η_{NLE} increases $(\eta_{su-t\,TEL})_{\max}$ by 0.53 m, 0.21 m and 0.29 m respectively. However, the η_{NLT} decreases $(\eta_L)_{\max}$ by -0.14 m, -0.20 m and -0.12 m respectively for the storms of January 2000, November 2006 and November 2007.

During these three storms, the times of $(\eta_L)_{\max}$ and $(\eta_{su-t\,TEL})_{\max}$ are shifted with the same amount of time from the time of $(\eta_{OB})_{\max}$ at both site. Therefore, only the complementary nonlinear terms η_{NLE} can be considered as the main factor to shift the times of $(\eta_{EFN})_{\max}$. During the storm of November 2006 at Sylt (see Fig. 8(d)), the times of η_L and $\eta_{su-t\,TEL}$ peaks occurred two hours before the time of $(\eta_{OB})_{\max}$ and $(\eta_{EFN})_{\max}$.

3.4 Nonlinear interaction between all storm-tide components (step 9 in Figure 5)

Procedure

Since the predicted storm-tide by η_{EFN} and η_{OB} are considered as equivalent (see step 7 in Fig. 5), the nonlinear interaction between all storm-tide components at Cuxhaven and Sylt (η_{NL}) is the difference between the predicted storm-tide by NARX ensemble (η_{EFN}) and the linear storm-tide (η_L): $(\eta_{NL} = \eta_{EFN} - \eta_L)$. So, the η_{NL} obtained in step 9 in Fig. 5 can be considered as equivalent to the linear superposition of the nonlinear interaction η_{NLT} approximated in step 5 by TELEMAC2D and the complementary nonlinear terms η_{NLE} predicted by NARX ensemble (EFN) trained in step 7 by the results of step 6: $\eta_{NL} = \eta_{NLT} + \eta_{NLE}$.

Results

At Cuxhaven during the storms of January 2000, November 2006 and November 2007, the inclusion of the total nonlinear interaction η_{NL} in the predicted η_{EFN} leads to overestimate the result $(\eta_L)_{\max}$ obtained from linear superposition in Step 3 by 0.39 m, 0.01 m and 0.17 m respectively. Moreover, the time of arrival for $(\eta_{EFN})_{\max}$ during the storm of November 2006 at Cuxhaven is delayed by one hour (Fig. 8(c)). Since the increase effect by η_{NLE}, which is mainly from the storm-tide wave shoaling, results in the slowing down and increasing height of $(\eta_{EFN})_{\max}$. In contrast, at Sylt during the storms of November 2006 (Fig. 8(d)) and November 2007, the inclusion of the η_{NL} in the predicted η_{EFN} leads to underestimate the $(\eta_L)_{\max}$ by -0.12 m and -0.25 m respectively, since the reduction induced by η_{NLE} is supported by the reduction of η_{NLT}.

The proposed hybrid approach is applied in Fig. 9 to analyze comparatively the extreme effect of nonlinear interaction by all extreme storm-tide components during the period between 1991 and 2007. The results in Fig. 9 a and b for Cuxhaven and Sylt, respectively, are summarized in the following three stages:

Stage 1- Predict the highest possible storm-tide from 1991 to 2007 $\left((\eta_{EFN})_{\max}\right)$ (steps 1 to 9 in Fig. 5), which occurs at time t_{max}, using the developed NARX ensemble model. This also includes the nonlinear interaction component η_{NL} at time t_{max} (step 9 Fig. 5).

Stage 2- Evaluate the effect of each extreme storm-tide component depicted in Fig. 1 and their nonlinear interaction on $(\eta_{EFN})_{\max}$ at time t_{max} as follows:

2.1. Using TELEMAC2D (steps 1 and 2 in Fig. 5), predict each storm-tide component independently at time t_{max} (occurrence time of the peak $(\eta_{EFN})_{\max}$ predicted in Stage 1).

2.2. Apply the proposed hybrid approach in Fig. 5 to evaluate the effect of nonlinear interaction (η_{NL}) between the components predicted in sub-stage 2.1 at time t_{max} (steps 3 to 9 in Fig. 5).

Stage 3- Evaluate the highest physical limit of storm-tide from 1991 to 2007 as follows:

3.1. Evaluate each storm-tide component independently, which occurred over the entire period from 1991 to 2007 using TELEMAC2D (steps 1 and 2 in Fig. 5).The coupling between TELEMAC2D and TOMAWAC is used to predict the wave setup component for years 2000, 2006 and 2007 only.

3.2. Apply the proposed hybrid approach in Fig. 5 to predict the nonlinear interaction (η_{NL}) between the components obtained from sub-stage 3.1, which occurred over the entire period from 1991 to 2007.

3.3. Extract the highest peak of each storm-tide component evaluated in sub-stage 3.1 and the highest peak of their nonlinear interaction $((\eta_{NL})_{\max})$ predicted in sub-stage 3.2, independently of their occurrence in time over the entire period 1991-2007; i.e. the extracted peaks do no not necessarily occur at the same time.

3.4. Superpose linearly the extracted highest peaks from sub-stage 3.3 $((\eta_{all})_{\max})$ which might be considered to represent the highest physical limit of extreme storm-tide over the entire considered time period, though it is very improbable that the peaks of superposed storm-tide constituents will occur at the same times.

The linear superposition $((\eta_{all})_{\max})$ is always higher than the highest possible storm-tide $(\eta_{EFN})_{\max}$ (see Fig. 9) at both sites over the entire time period1991-2007. Since the maximum of each component and nonlinear interaction occur independently at different times. The $((\eta_{all})_{\max})$ and $(\eta_{EFN})_{\max}$ at Cuxhaven, which are respectively 7.21 m and 4.00 m, are higher than their respective counterparts at Sylt of 5.66 m and 3.2 m. However, the percentages of $(\eta_{NL})_{\max}$ and external surges maximum $((\eta_{es})_{\max})$ at Cuxhaven, which are respectively 21 % and 9.5 %, are lower than their respective counterparts at Sylt of 25.80 % and 10.97 %. Since the storm surges and tide at Cuxhaven are higher than their counterparts at Sylt, which leads to deeper water depth at Cuxhaven with less pronounced shoaling effect. Furthermore, the effect of nonlinear interaction η_{NL} on $(\eta_{EFN})_{\max}$ at Cuxhaven results in a reduction of water level by 4 %. In contrast, the η_{NL} at Sylt results in increase of water level by 18.6 %.

Fig. 9 shows that the relative contribution of wave setup $((\eta_{w})_{\max})$ is negligibly small with maximum values up to 1.2 % at both pilot sites. Moreover, the contribution of river discharge maximum $((\eta_{rd})_{\max})$ at Sylt and Cuxhaven is not more than 1 % and also without any noticeable effect.

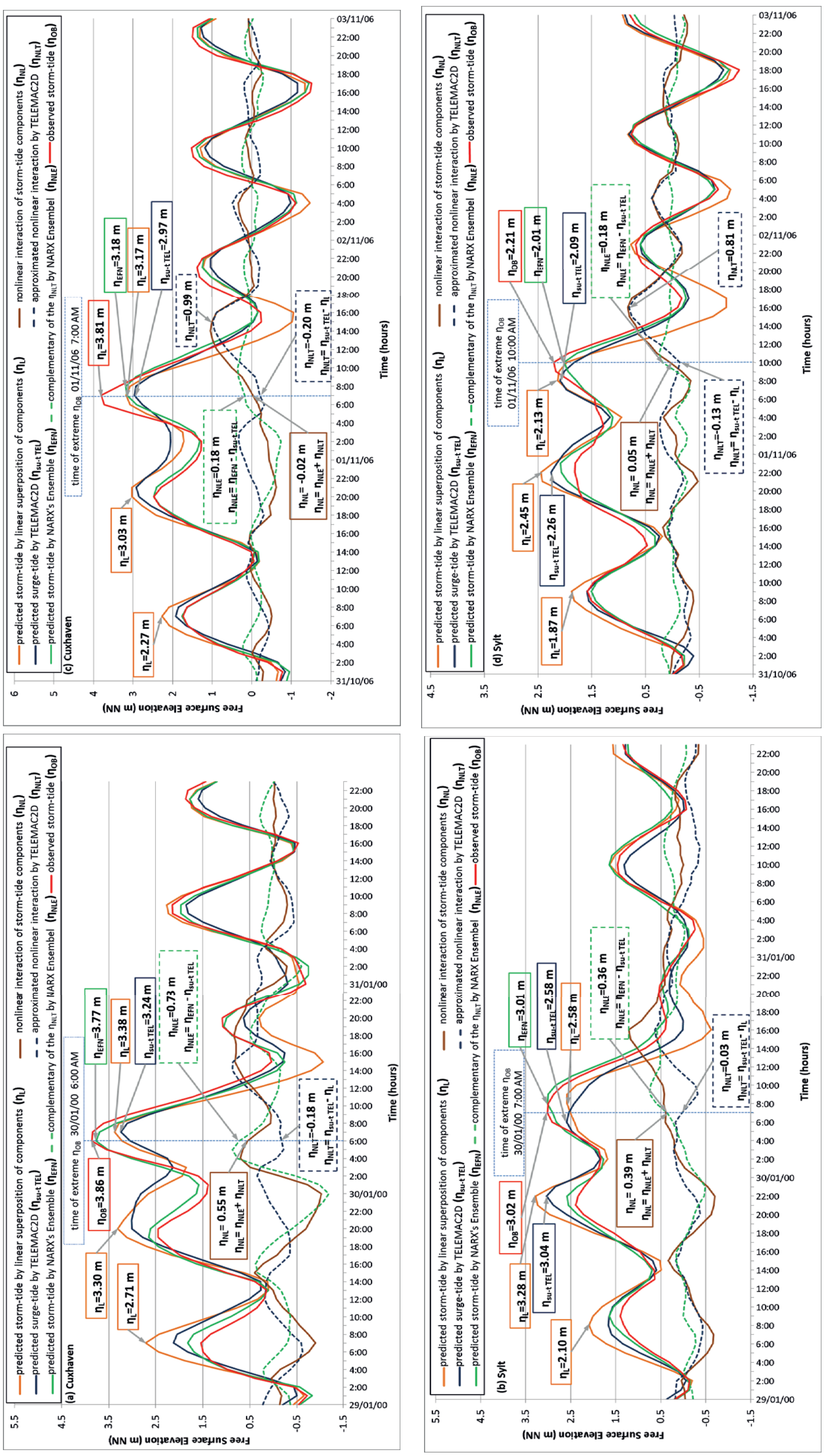

Figure 8: Storm-tide prediction by linear superposition η_L, TELEMAC2D $\eta_{su-tTEL}$ and NARX ensemble η_{EFN} with the effect of nonlinear interaction η_{NL} between extreme storm-tide components during the storm of January 2000 and November 2006 at Cuxhaven (a and c respectively) and Sylt (b and d respectively).

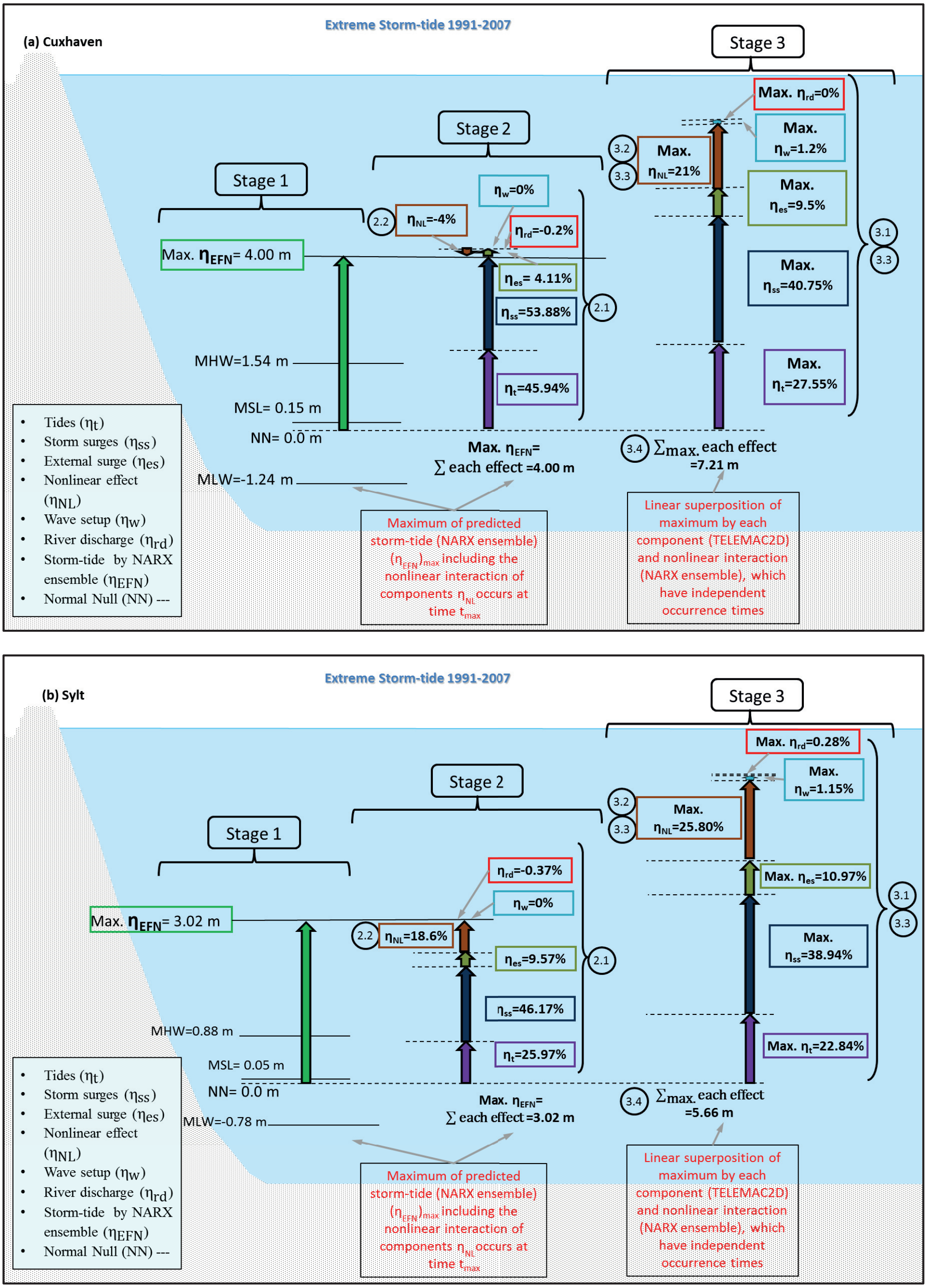

Figure 9: Maximum combination of the constituents in Fig. 1 along with the nonlinear interaction between them $\left(\eta_{NL}\right)$ and the predicted storm-tide by NARX ensemble $\left(\eta_{EFN}\right)$ at Cuxhaven (a) and Sylt (b) during the period from 1991 to 2007.

4 Concluding remarks

Combining the strengths of ANN methodology with those of numerical modelling (TELEMAC2D and TOMAWAC) provides a powerful and computationally efficient operational model system for storm-tide prediction as exemplarily shown in Cuxhaven and Sylt. It can also be applied for reconstructing the missing data using sequential time series predictions by NARX ensemble, which reduces the amount of training data (usually five years show very good performance). Another advantage of the hybrid model system is its capability to account for nonlinear interaction between the extreme storm-tide constituents, so the substantial errors in both magnitude and timing of the results predicted by numerical modelling can be corrected. Two types of NARX models and their ensemble were developed and validated using the observed water level between 1999 and 2007 at Cuxhaven and Sylt. For Cuxhaven's NARX ensemble model, the lowest RMSE is 0.148 m with a correlation of 0.99. The NARX ensemble model in Sylt has an RMSE of 0.123 m and a correlation of 0.98.

The account for nonlinear interaction by NARX ensemble models may result either in the reduction or increase of the highest water level during storms when compared with the linear superposition of extreme storm-tide components according to the following two situations at both locations (Cuxhaven and Sylt):

(i). If the η_L peak resulting from linear superposition, which occurs directly before the time of $(\eta_{EFN})_{\max}$ resulting from the NARX ensemble model, is less than 3 m, then its following peak would overestimate the peak of η_{EFN} at the time of $(\eta_{EFN})_{\max}$. Since the peaks of η_{EFN} and η_L, which occur before the time of $(\eta_{EFN})_{\max}$, do not increase significantly the mean water level (MWL) during the storm. Therefore, the following peaks of η_{EFN} and η_L will propagate under more pronounced shoaling effect that increases their heights simultaneously.

(ii). If the η_L peak, which occurs directly before the time of $(\eta_{EFN})_{\max}$, is larger than 3.00 m, then its following peak would underestimate the peak of $\boldsymbol{\eta_{EFN}}$ at the time of $(\eta_{EFN})_{\max}$. Since only the peak of η_L, which occurs before the time of $(\eta_{EFN})_{\max}$, increases the MWL during the storm to a limit by which its following peak will propagate under less pronounced shoaling effect.

The highest peak of each constituents predicted series by TELEMAC2D and the nonlinear interaction (η_{NL}) predicted by the NARX ensemble over the entire time period 1991-2007 at Cuxhaven and Sylt are added together linearly $((\eta_{all})_{\max})$. The result is assumed to represent the highest physical limit of extreme storm-tide over the entire considered time period, though it is very improbable that the peaks of superposed storm-tide constituents will occur at the same times. The peak obtained through linear superposition $((\eta_{all})_{\max})$ at Cuxhaven, which reaches 7.21 m, is higher than its counterpart at Sylt of 5.66 m. The maximum effect of the nonlinear interaction $(\eta_{NL})_{\max}$ at Cuxhaven, which reaches 21 %, is lower than its counterpart of 25.80 % at Sylt. Since the storm surges and tide at Cuxhaven are higher than their counterparts at Sylt, thus resulting in higher water level with less pronounced shoaling effect.

The still ongoing PhD work is now focusing on the determination of the worst extreme water levels, which are physically possible in the 21st century under the projected climatic change for the North Sea area. Moreover, since long-term water level observations at Sylt may be not available in the past, it is valuable and cost effective for a coastal engineering study to establish the nonlinear relationship in order to predict the water levels at Sylt using the available water levels at Cuxhaven.

5 Acknowledgement

Financial support provided for the first author by German Academic Exchange Service (DAAD) for pursuing the doctoral studies in the frame of the GERLS 2009/2010 programme (German Egyptian Research Long-term Scholarship) is gratefully acknowledged. Furthermore, the Federal Ministry for Education and Research (BMBF) is acknowledged for funding the project XtremRisK (grant number 03F0483A) led by the co-author. Thanks to Prof. Jensen from Research Institute for Water and Environment-University of Siegen, Dr. Gönnert from Agency of Roads, Bridges and Waters, Dr. Plüß from the Federal Waterways Engineering and Research Institute (BAW) and Dr. Weisse/Dr. Meyer from Helmholtz-Zentrum Geesthacht (HZG) in Hamburg for sharing their data and all their support, especially at the beginning of the PhD study.

6 References

BENOIT, M.: Logiciel TOMAWAC de modélisation des états de mer en éléments finis. Notice de la version 5.2, Rapport HP-75/02/065/A, EDF-LNHE., 2003.

BENOIT, M.; MARCOS, F. and BECQ, F.: development of a third generation shallow-water wave model with unstructured spatial meshing, Coast. Eng. Proc., 1(25), doi:10.9753/icce.v25., 2001.

GOENNERT, G. and GERKENSMEIER, B.: a new method of approaching extreme storm events for design level or risk analysis, Coast. Eng. Proc., 1(33), management. 2, 2012.

HERVOUET, J.-M.: Hydrodynamics of Free Surface Flows: Modelling with the Finite Element Method, John Wiley & Sons., 2007.

HERVOUET, J.-M. and VAN HAREN, E.: TELEMAC-2D Principle Note. Electrité de France, Technical Report., 1994.

NILSSON, C.; BÄRRING, L. and GOYETTE, S.: Relating Forest Damage Data to the Wind Field from High Resolution RCM Simulations: Case study of Anatol Passing Sweden in December 1999, in Geophysical Research Abstracts, vol. 7, p. 09883., 2005.

OUMERACI, H.: Storm Surge and design water levels (lecture notes in German), 2009.

OUMERACI, H.; JENSEN, J.; GÖNNERT, G.; PASCHE, E.; KORTENHAUS, A.; NAULIN, M.; WAHL, T.; THUMM, S.; UJEYL, G. and GERSHOVICH, I.: Flood risk analysis for a megacity: The German XtremRisK project, in Proc. Conference on Road Map towards a Flood Resilient Urban Environment, p. 8., 2009.

VON STORCH, H.; LANGENBERG, H. and FESER, F.: A spectral nudging technique for dynamical downscaling purposes. Mon. Weather Rev., 128(10), 2000.

TAYEL, M.: Combined Neural Network and Numerical Model for Extreme Storm Surges, PhD thesis TU-Braunschweig, Germany, 2015 (in preparation).

TAYEL, M. and OUMERACI, H.: Meteorological data preparation from 1970 to 2007 and configuration of the North Sea TELEMAC2D model. Leichtweiß Inst. Hydraul. Eng. Water Resources Braunschweig. Germany, Internal report (Nr. 3), 90, 2012.

TAYEL, M. and OUMERACI, H.: A hybrid approach using hydrodynamic modelling and artificial neural networks for extreme storm surge prediction, Submitt. J. Coast. Eng. Jpn., (XtremRisK Special Issue), 32, 2014.

TAYLOR, K.E.: Summarizing multiple aspects of model performance in a single diagram, J. Geophys. Res., 106(D7), 7183–7192, doi:10.1029/2000JD900719, 2001.

WAHL, T.; MUDERSBACH, C. and JENSEN, J.: Statistical assessment of storm surge scenarios within integrated risk analyses4results of the XtremRisK project, Compr. Flood Risk Manag. Res. Policy Pract., 22, 2012.