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AN IDEALIZED METEOROLOGICAL-HYDRODYNAMIC MODEL FOR EXPLORING EXTREME STORM SURGE STATISTICS IN THE NORTH SEA

M. van Ledden[1,2], N.J.F van den Berg[1], M.S. de Jong[3], P.H.A.J.M. van Gelder[4], C. den Heijer[5],
J.K. Vrijling[2], S.N. Jonkman[2], P.C. Roos[6], S.J.M.H. Hulscher[6], A.J. Lansen[7]

This paper explores an alternative method to determine extreme surge levels at the Dutch Coast. For this exploration, specific focus is on the extreme water level at Hoek van Holland, The Netherlands. The alternative method has been based on a joint probability model of the storm characteristics at the North Sea. The intent of this method is to provide a better physical and statistical insight into the effects of meteorological characteristics on surge levels and surge duration, especially for surges of more extreme storms currently not captured in existing water level measurement records. The meteorological part is an analytical parametrical model based on the Holland model for hurricanes, which results in time- and space-varying wind and pressure fields of North Sea storms. The wind and pressure forcing is then applied in the hydrodynamic model which numerically solves the nonlinear depth-averaged shallow water equations in a one-dimensional domain from the edge of the continental shelf between Scotland and Norway to Hoek van Holland. Validation against wind observations from historical storms at one location in the entire domain shows good results. Results of the calibrated surge level model are reasonable if peak surge levels are considered. The surge duration, however, is underestimated by the model. Next, the model has been applied to define extreme surge levels using Monte Carlo Analysis. Probability density distributions for the storm parameters based on historical data have been used as input. The computed surge level (including tide) with a statistical return period of 10,000 years appears to be close to the value from statistical extrapolation of surge levels. The output also indicates that the average duration of computed surges with a return period of 10,000 year is roughly two hours longer than the storm duration currently adopted.

Keywords: Storm surge levels; North Sea; Joint probability analysis, Extreme value statistics

INTRODUCTION

Following the 1953 flood in the Netherlands, the Delta Committee advised the Dutch government in taking measures to prevent a next flood disaster. Based on cost-benefit analysis, the Delta Committee recommended improving the sea defense system of the western part of the Netherlands to withstand a storm surge with a probability of occurrence of 10^{-4} – 5 x 10^{-4} per year (Deltacommissie, 1961). Since then, extreme value analysis has been combined with numerical storm surge modeling .to define extreme surge levels in this design frequency range at the Dutch North Sea Coast. In this approach, Hoek van Holland near Rotterdam is used as a basis.

The extreme water level at Hoek van Holland is determined by extrapolation of historical water levels, by using non-parametric (or distribution-free) statistical methods (Dillingh et al., 1993). Two-dimensional depth-averaged modeling is applied to define the relationships between Hoek van Holland and other coastal stations (Gerritsen et al., 2005). A weighted average of the extreme value analysis and the numerical modeling determine the water levels for design of the new flood protection structures. For Hoek van Holland, the 10^{-4} / year water level is about 5.10 m above Dutch Ordnance Datum for today's situation (Ministerie van Verkeer en Waterstaat, 2007).

The current approach for defining design water levels in the Netherlands entails a large uncertainty. This is due to the relatively short time series of water level measurements (150 years) for the statistical analysis compared to the return period of interest (2,000 – 10,000 yr). The standard deviation of the error in the 10,000yr design water level for Hoek van Holland is 0.90 m (Dillingh et al., 1993). Another important aspect of this method is that the characteristics of the governing design storm are not known.

However, the aspect of duration is very important for dune and dike design. The time that the water level remains close to the maximum surge level is the primary determining factor for the amount of dune erosion during the storm surge (Steetzel et al., 2007). Also, a quick decline of the water level can

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[1] Royal HaskoningDHV, George Hintzenweg 85, Rotterdam, The Netherlands, mathijs.van.ledden@rhdhv.com

[2] Delft University of Technology, Stevinweg 1, PO Box 5048, 2600 GA Delft, The Netherlands

[3] Heerema, Vondellaan 55, 2332 AA Leiden, The Netherlands

[4] Delft University of Technology, TBM Delft, The Netherlands

[5] Deltares, Rotterdamseweg 185, Delft, The Netherlands

[6] University of Twente, Drienerlolaan 5, Enschede, The Netherlands

[7] Royal HaskoningDHV, Ho Chi Minh City, 236/ 26C Dien Bien Phu Street, Ward 17, Binh Thanh District, Vietnam

result in dike failure, for example by piping, failure of revetments on the top layer due to overpressure and sliding of the outer slope.

The purpose of this study is to explore an alternative method to determine extreme surge levels at the Dutch Coast. For this exploration, specific focus is on the extreme water level at Hoek van Holland, The Netherlands. The alternative method has been based on a joint probability model of the storm characteristics at the North Sea (Figure 1). In this study, we focus on the contributions of wind, pressure and tide to the total water level. The effect of waves on the water level due to wave set-up has been neglected at this moment.

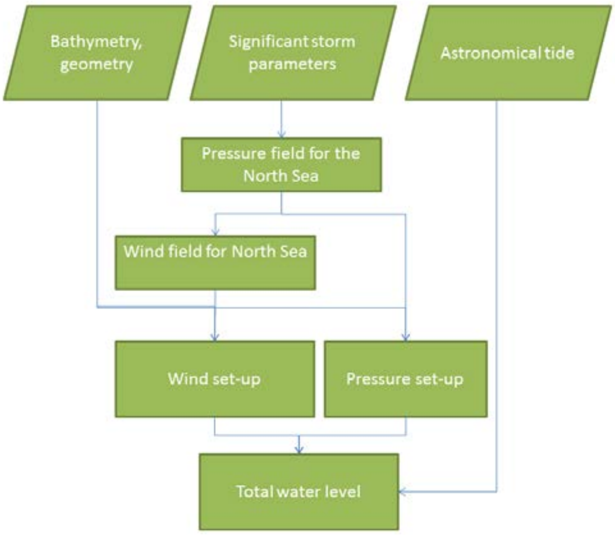

Figure 1. Outline of the approach followed in this study.

The outline of this paper is as follows. First, a meteorological-hydrodynamic model is set up to describe the physical behavior at the North Sea. Next, validation against historical storms is carried out for both the wind and the surge levels to investigate the model performance. Thereafter, the model has been applied to define extreme surge levels using Monte Carlo Analysis. Probability density distributions for the storm parameters based on historical data have been used as input. This paper closes with conclusions and recommendations for further research.

MODEL SET-UP

North Sea storms

The area of interest in this study is the North Sea, a marginal sea between Great Britain, Belgium, The Netherlands, Germany, Denmark and Norway (Figure 2). The size is about 1000 kilometers from north to south and 600 kilometers in east-west direction, the Southern Bight being only 200 kilometers wide. The depth varies between more than 100 meters in the northern part but is only 25 – 35 meters deep in the southern part. The tide in the North Sea is semi-diurnal with a typical tidal range of 2 – 6 meters depending on the location along the North Sea coast. Waves are present due to local winds but also swell from the Atlantic Ocean. Average offshore wave heights are about 1 - 2 meters, but these can increase up to 10 – 15 meters during severe storms.

Severe storms at the North Sea generally occur during the winter period (October – March). These extra-tropical storms develop because cold air from the pole meets warm air from tropical regions at the polar front. Because of difference in speed, waves and ridges develop at this front where these air masses interact. When occlusion takes place, the storm depression will become fully grown and a low pressure system is created. Due to the direction of the jet stream, these low pressure systems travel from the North Atlantic Ocean towards Europe. The associated wind field of these storms is anti-clockwise due to Coriolis effects.

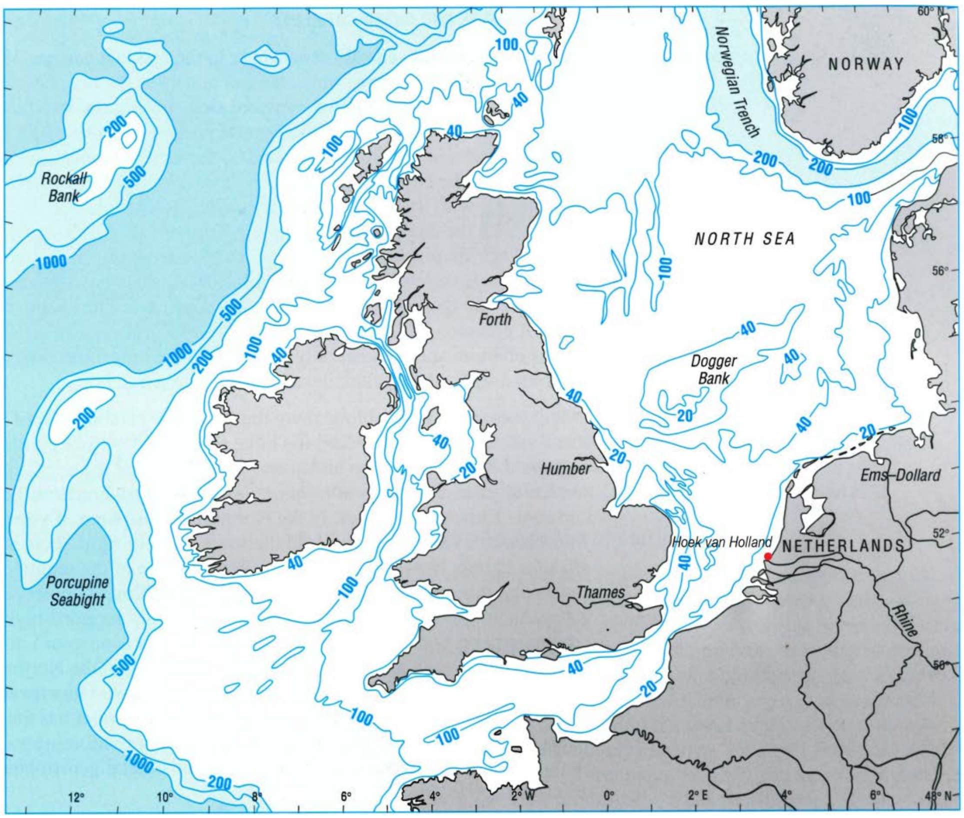

Figure 2. North Sea basin with contour lines of depths below MSL.

The origination of storms relevant for the Dutch coast can differ significantly. However, storms generating significant storm surge at the Dutch coast generally travel north of Scotland towards Denmark or North Germany. With this storm track, the NW winds of the storm depression push water into the North Sea basin. This can result in a storm surge of 1.5 – 3 meters in the Dutch coastal region. Depending on the phasing with the tide, the water level can exceed 4 – 5 meters above MSL.

Meteorological model

The starting point of our modelling approach is a parametric description of the meteorological behavior of North Sea storms (pressure, wind field). For tropical storms, several parametric models exist such as the Rankine vortex model, the Fujita model, the Holland-B model and the model of DeMaria, all discussed by Leslie & Holland (1995). The model of Bijl (1997) proposes a description of the pressure field for extra-tropical storms. It builds on the Holland-B model but includes two extra geometry parameters to account for non-circular pressure fields of storm depressions. Herein, the model of Holland (1980) is chosen as the one that will be used in this study. It is recognized that this model, originally derived for tropical storms, lacks certain phenomena of extra-tropical storms (e.g. fronts). However, it is chosen herein because of its simplicity since it only needs 4 parameters. Through (limited) validation, it will be shown that the modeling approach captures the large-scale wind variation (both wind speed and direction) of North Sea storms.

The parametric Holland-B model uses four parameters to describe the pressure p of the storm at a distance r from the center (Figure 3):

$$p = p_c + \Delta p \; e^{\left[-\left(\frac{R_{max}}{r}\right)^{B}\right]} \qquad (1)$$

in which p_c is the central pressure, Δp the pressure difference between the central pressure and the ambient pressure, R_{max} the radius to maximum winds and B the Holland-B parameter.. During analysis, it turned out that the pressure field can be well approximated using a constant ambient pressure (1050 mbar) for all historical storms.

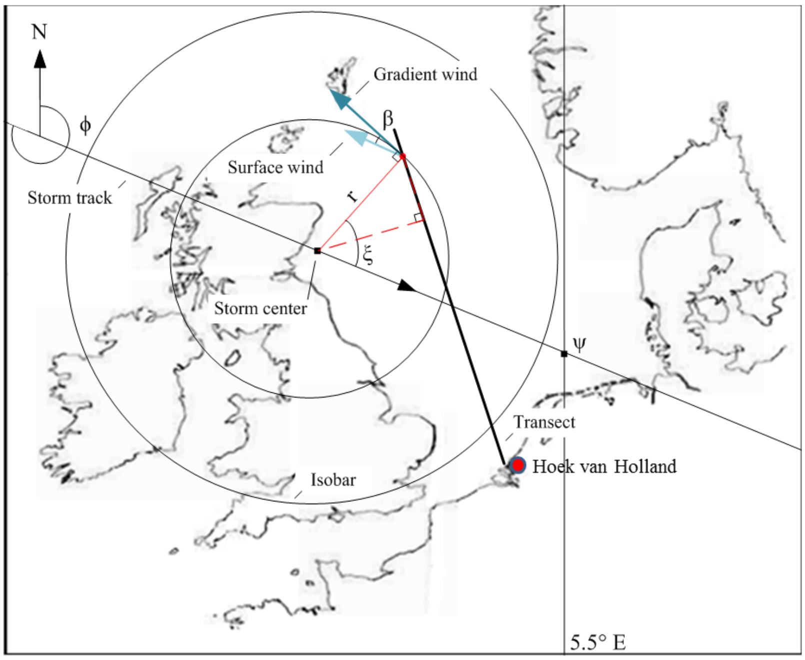

Figure 3. Application of the Holland-B model for North Sea Storms, also showing the 1D model transect (thick black line).

Although in reality storms may exhibit complex movements, historical data suggests that most of the storms follow more or less a straight path between the north of Scotland and Denmark. Therefore, the storm movement is modeled as forward movement of the pressure field along a straight line at the North Sea. In our model, the storm path is thus defined by its origin, viz. the latitude (Ψ) at which the storm path crosses at longitude 5.5°E, and the direction towards its origin (Φ), see Figure 3. The forward speed of the storm (C_f) along this storm path is assumed constant.

The associated wind field of the storm has been based on the gradient wind speed (see Holland, 1980). This gradient wind speed is corrected for the forward movement of the storm and also for friction at the earth's surface. Herein, the approach of Brunt (1934) is adopted resulting in a ratio 2/3 between the surface wind speed and the gradient wind speed. For a given set of storm parameters (central pressure, radius to max winds, etc.), the surface wind speed V_s can be calculated as follows (see e.g. Van den Berg, 2013):

$$V_s = \frac{2}{3}\left(W + \sqrt{W^2 + \frac{\Delta p B}{\rho_a}\left(\frac{R_{max}}{r}\right)^B e^{\left[-\left(\frac{R_{max}}{r}\right)^B\right]}} \right) \qquad (2)$$

With

$$W = \frac{C_f \sin\xi - rf}{2} \qquad (3)$$

where f is the Coriolis parameter, ξ the angle between storm track direction and direction of the radius from the storm center to the location of interest, and ρ_a the air density (= 1.27 kg/m^3). For a single storm, eq. (1) - (3) prescribe the two-dimensional pressure field and wind field at a certain moment in time, respectively. In our model, this storm moves in time following the storm path definition. In this model setup, each storm is characterized by 6 parameters, viz. three storm path parameters (forward speed C_f, direction Φ, latitude Ψ at longitude 5.5°E) and three storm intensity characteristics (central pressure p_c, radius to maximum winds R_{max}, and Holland-B parameter).

Hydrodynamic model

In reality, the water level response at Hoek van Holland results from (two-dimensional) interaction between the meteorological forcing, the bathymetry/geometry and tidal behavior of the basin. In our modeling approach, however, we focus on the key interactions between the storm and the surge level response. Therefore, we neglect the interaction with the tide since this effect is probably an order of magnitude smaller than the wind setup itself. To allow many computations within reasonable computation time in the Monte Carlo Analysis, we also follow a one-dimensional approach for the hydrodynamic behavior. The model domain heads from a location at the Northern boundary of the North Sea towards Hoek van Holland at the Dutch coast (see Figure 3). The bathymetry along this transect, shown in Figure 4, varies from a water depth of around 120 meters below Dutch Ordnance Datum at the edge of the continental shelf to less than 10 meters close to Hoek van Holland.

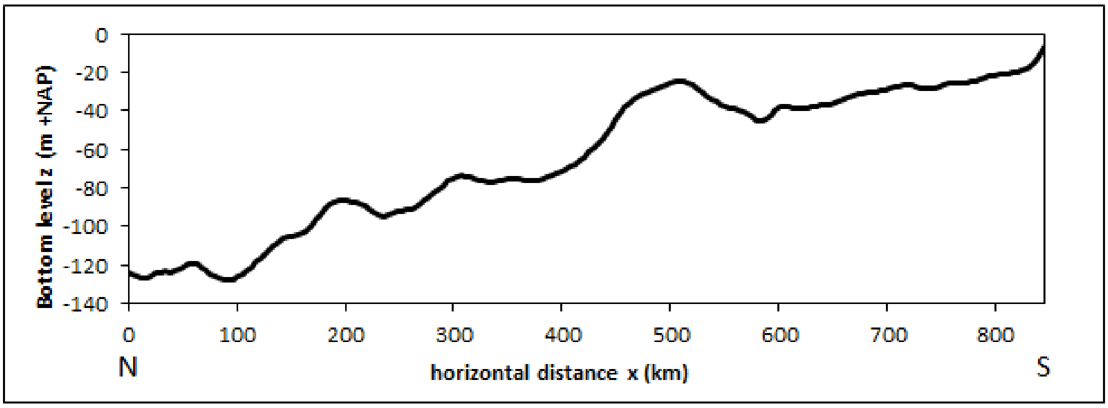

Figure 4. The bathymetry of the transect of the hydrodynamic model. The boundary located between Scotland and Norway is located at the left, the boundary at the Dutch coast (Hoek van Holland) is located on the right. Data is obtained from the British Oceanographic Data Centre of the North Sea.

The hydrodynamic model solves the nonlinear depth-averaged shallow water equations. The momentum equations include a wind friction term and also an atmospheric pressure gradient term. The atmospheric forcing (wind, pressure) are imposed as forcing terms to this model equation. Following Wu (1980), the wind friction term follows a quadratic friction law. The dimensionless friction coefficient in this friction law is prescribed proposed by Amorocho & De Vries (1980). This friction coefficient is linear for low wind speeds and has an upper limit of $2.54x10^{-3}$ for wind speeds higher than 26.8 m/s. Bottom friction is implemented using a quadratic friction term in which the Chezy coefficient is calculated using a Manning coefficient of 0.025 $s/m^{1/3}$. This is a reasonable value for a sandy North Sea bed at which large ripples/dunes are often present.

MODEL PERFORMANCE

Historical storm data

To define the storm parameters in the hydro-meteorological model, historical storm data have been gathered. A data set of 21 storms has been established starting in 1895 till 2008. Sources used for this dataset are the Delta report (Deltacommisie, 1961), storm surge reports and weather charts from the KNMI archive, the online database of the Wetterzentrale (Wetterzentrale, 2011), the storm catalogue (Groen & Caires, 2011) and the KNMI weather chart archive Europe (KNMI, 2013). The following criteria were applied in selecting these storms:

1. Storm data are available to define the storm parameters,
2. Storm surge data at Hoek van Holland are available to check the model performance,
3. The observed setup is higher than 1.5 meters,
4. The direction of the storm path is in the NW quadrant.

From the various data sources, the six storm parameters defined in the previous section (i.e. central pressure cp, radius to max winds Rmax, Holland-B, forward speed Cf, latitude Ψ, direction Φ) have been established. Estimating the storm intensity parameters (central pressure cp, radius to max winds Rmax) from these historical records turned out to be difficult in some instances. To obtain uniformity, it has been decided to extract the three storm intensity parameters (central pressure cp, radius to max winds Rmax) from one information source (Wetterzentrale, 2011). Table 1 provides an overview of the storm parameters from the historical analysis derived in this study.

Table 1. Historical storm parameter information for North Sea Storms based on various information sources (Wetterzentrale, 2011; Deltacommissie, 1961; KNMI, 2013; Groen&Caires, 2013).

Storm	Central pressure (mbar)	Rmax (km)	Holland B (-)	Forward speed Cf (m/s)	Latitude Ψ (degrees)	Direction Φ (degrees)
1	960	1310	1.4	12.1	62.4	327.8
2	975	921	0.9	13	55.7	276.2
3	975	965	1.5	18.2	57.3	311.2
4	985	716	1.1	24.7	56.6	290.1
5	980	755	1.0	15.4	57.9	306.6
6	960	921	1.3	6.8	59.5	275.9
7	975	955	1.4	8.5	60.1	296.1
8	985	664	0.9	10.9	57.9	309.6
9	985	741	1.3	12.2	57.8	291.8
10	975	858	1.0	8.9	56.4	289.6
11	990	599	1.1	16.2	56.3	295.8
12	985	653	1.5	10.1	55.8	312.3
13	970	828	1.2	14.1	57.9	297.8
14	980	728	1.2	22.5	61.7	286.5
15	960	958	1.5	16.6	66.4	311.4
16	970	547	1.2	10.9	56.4	292.5
17	985	555	1.3	17.5	57.7	272.6
18	975	545	1.1	19	61.3	337.1
19	980	779	0.9	13.3	55.5	273.8
20	980	674	1.5	11	60.1	293.1
21	965	1039	0.9	26.1	60.1	291.2

Wind validation

The meteorological model provides wind speed and wind directions along the entire model transect. Actual wind is observed at weather stations located at the mainland and at oil rigs at sea. Herein, the weather station of Hoek van Holland has been selected to compare the model results with the measurements. Wind speed is measured at 16.6 m height and corrected to the wind speed at 10 m high (surface wind). Data are given per hour from 1962 until present and is provided by the KNMI (2011). Therefore, only 8 out of 21 storms have been used in this wind validation.

The validation has been carried out for a time span of 24 hours around the maximum wind speed during the storm. As an example, the 2008 storm is presented in Figure 5. The computed wind speed matches the course of the observed wind speed. The storm peak is somewhat underestimated, wind speed before and after the peak are underestimated. This can be explained by the . multiple depressions succeeding one another during this storm, which is not captured by the Holland model. Nevertheless, observed wind direction is described fairly well by the model.

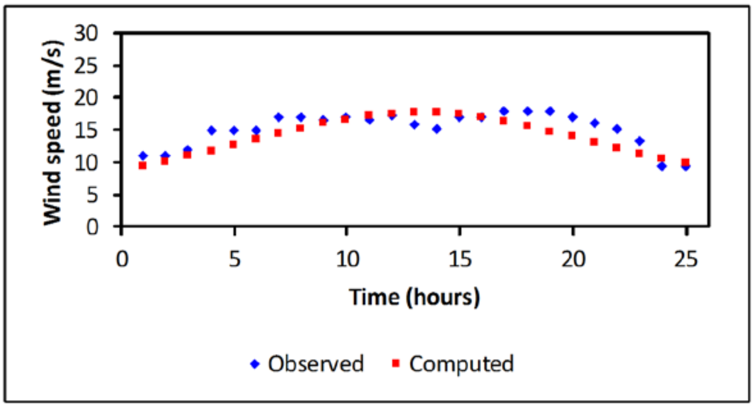

Figure 5. Observed and computed wind speed for the storm at March 1, 2008.

To quantify the performance of the model, the hourly wind speed and wind direction have been compared (Figure 6). This has been carried out at an hourly basis for 8 storms resulting in 8 x 25 = 200 data points. The resulting scatter shows that the agreement is far from perfect. Further inspection shows that especially the two storms of 1962 contribute to this deviation. For many storms, the results are rather good for such a relatively simple model of the complex meteorological processes at hand. It should be noted that the current validation is only valid for one single point at Hoek van Holland. It is therefore not known how the model performs for other places along the transect.

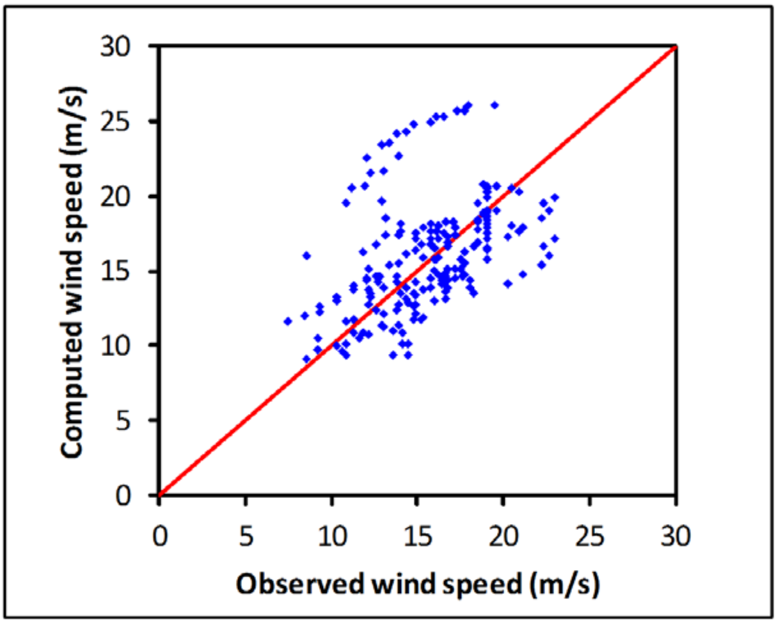

Figure 6. Observed and computed wind speed for 21 storms.

Surge level calibration

A first comparison with surge levels of the historical storms showed that calibration of the surge level results was needed to minimize errors between observed and computed wind setup. The calibration has been carried out using a dimensionless calibration coefficient C which has been defined as the ratio between observed and calculated wind setup. This calibration coefficient C is a linear sum of the various (normalized) storm parameters. The various calibration constants have been tuned in such a way that the overall error is at its minimum. For more details, the reader is referred to Van den Berg (2013).

Table 2. Observed and computed surge levels of 21 historical storms at the North Sea after calibration

Storm	Observed surge (m)	Computed surge (m)	Error (%)	Storm	Observed surge (m)	Computed surge (m)	Error (%)
1	1.83	2.39	31%	11	2.35	2.23	-5%
2	1.73	2.07	20%	12	3.27	2.69	-18%
3	3.42	2.96	-14%	13	2.41	2.22	-8%
4	2.19	1.80	-18%	14	1.83	1.54	-16%
5	2.03	2.16	7%	15	2.26	1.86	-18%
6	1.98	1.52	-23%	16	2.11	2.49	18%
7	1.91	1.97	3%	17	2.01	2.23	11%
8	2.58	2.09	-19%	18	1.86	2.43	31%
9	2.04	2.83	38%	19	1.80	2.08	16%
10	1.90	1.66	-13%	20	2.12	2.86	35%
				21	1.86	2.37	28%

The observed and computed peak surges of the historical storms are listed in Table 2, including the error. From this table, it can be concluded that the error in the peak surge level for most storms is limited (say 10-20%) with a few outliers. For example, the computed surge of storm 9 (38%) and storm 20 (35%) show stronger deviation from the observations. Nevertheless, the overall (absolute) error of all historical storms in the peak surge level for the calibrated model is 19%. This result is considered reasonable given the simplifications in this modeling approach.

Apart from the peak surge, also the computed variation of the surge in time is compared with measurements. As an example, the peak surge level is shown for the 2008 storm (see Figure 7). The rise and fall of the surge level is in reasonable agreement with the measurements. However, the surge duration is somewhat underestimated by the model. Analysis of other storms shows that the model systematically underestimates the surge duration with a few hours on average.

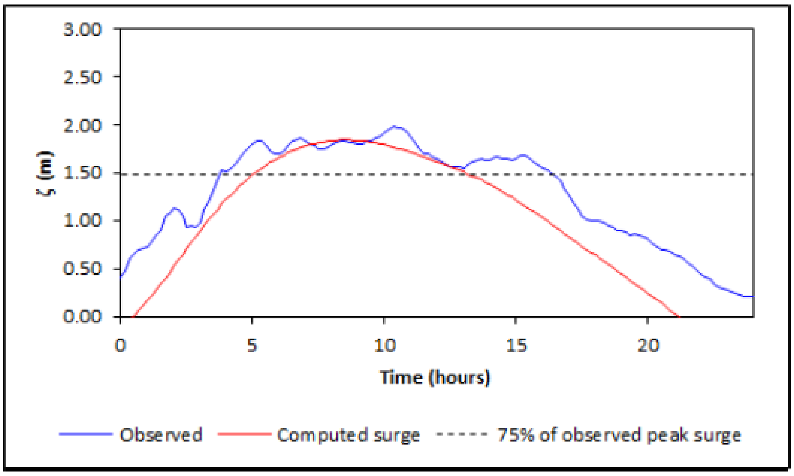

Figure 7. Observed and computed surge for the storm at March 1, 2008.

DETERMINATION OF EXTREME WATER LEVELS

Probability density distributions

This section presents the determination of extreme water levels using Monte Carlo Analysis (MCA). For this purpose, a large number of computations (10^6) have been carried out with the hydro-meteorological model of the North Sea presented in the previous section. This model computes the surge due to the storm. This result needs to be corrected for the tide and the average water level to define the extreme water level for each storm. The tide is added to calculate the total water level. In our analysis, the average tidal amplitude at Hoek van Holland is applied (0.87 meter) independent of each storm. This assumption follows the method used in the hydraulic boundary conditions (Ministerie van Verkeer en Waterstaat, 2007). In addition to this, the average water level is set at 0.07 m above Dutch Ordnance Datum.

Table 3. Probability distributions of the storm characteristics.

Parameter	Probability distribution	Mean	Standard deviation
Latitude (degrees)	Lognormal	58.61	2.6
Direction (degrees)	Rayleigh	22.46	-
Forward speed Cf (m/s)	Lognormal	14.67	5.25
Pc (mbar)	Normal	975	9.03
Rmax, given by ε (km)	Normal	0	191.13
B (-)	Lognormal	1.21	0.05

Inputs for this MCA are the probability density distributions of the storm characteristics. Table 3 lists the probability density distributions which have been derived using the information of the 21 storms (see Table 1). From the storm data, it turns out that a dependency exists between the central pressure (pc) and the radius to maximum winds (R_{max}). Herein, we assume a linear dependency between these parameters: R_{max} (in km) = -14.77 p_c (in mbar) + 15207 + ε where ε represents the uncertainty of R_{max}. The distribution parameters of ε are also listed in Table 3.

The model has been evaluated 10^6 times to compute a surge for a specific combination of storm characteristics. For each run, the storm characteristics have been set using the probability density distributions presented in Table 3. The storm surge has been corrected afterwards for tide and the average sea level at Hoek van Holland resulting in a set of 10^6 extreme water levels. For each water level, the return period has been determined using the method of Gringorten (1963). In this method, the water levels are ranked and probability is associated to each water level. The return period has been adjusted using a factor 108/18 since the input database includes 18 storms occurring in a period of 108 years.

Extreme storm surges

Figure 8 presents the results of this extreme value analysis from the Monte Carlo analysis (in blue). This figure also includes the historically observed storm surge levels (in green) and a Gumbel distribution fit through the measurements (in red). Despite all simplifications in the modeling, it is remarkable that the computed storm surge level (including tide) with a statistical return period of 10,000 years (5.2 m) is relatively close to the value found based on statistical extrapolation of measurements (5.4 m). Another interesting feature is that the model results do not follow a Gumbel distribution. The origin of this behavior needs further investigation.

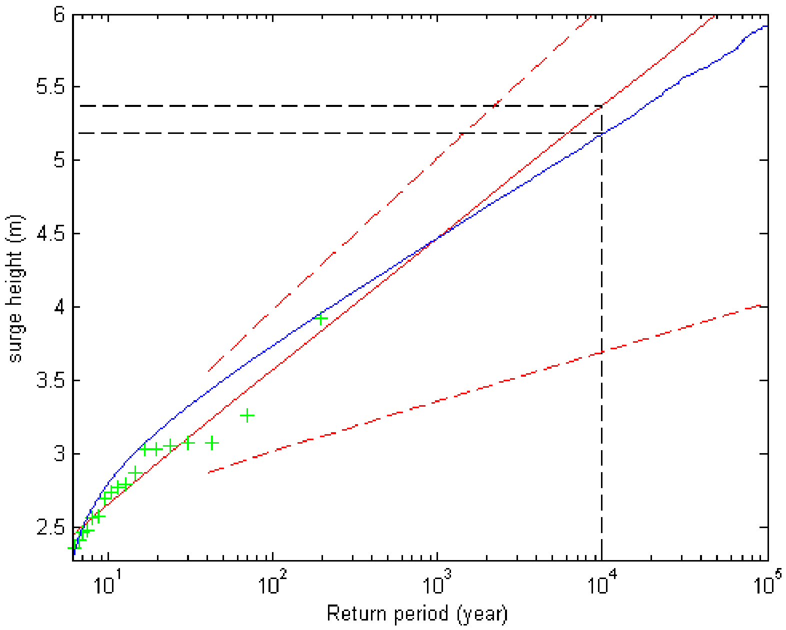

Figure 8. Surge levels based on model output are denoted in blue. Statistical extrapolation based on extrapolation of measurements (green plusses) is shown by the solid red line. The corresponding 95% probability interval is shown by red dashed lines.

The storms resulting in a 10,000 yr surge peak have been analyzed further to assess the storm characteristics. Figure 9 presents the distribution of the storm characteristics for the entire set of computations and also the distribution for storms resulting in a 10,000 yr storm surge at Hoek van Holland. This figure indicates track location, track direction and radius to maximum winds of 10,000 yr events is not very different from the entire population. However, the propagation speed is slightly higher and the central pressure is significantly lower. The Holland-B parameter is clearly higher for these severe storms compared to the entire data set. A relatively low central pressure and a relatively high Holland-B parameter both result in a stronger pressure gradient and thus higher wind speeds. This in turn causes high surges at the Dutch coast.

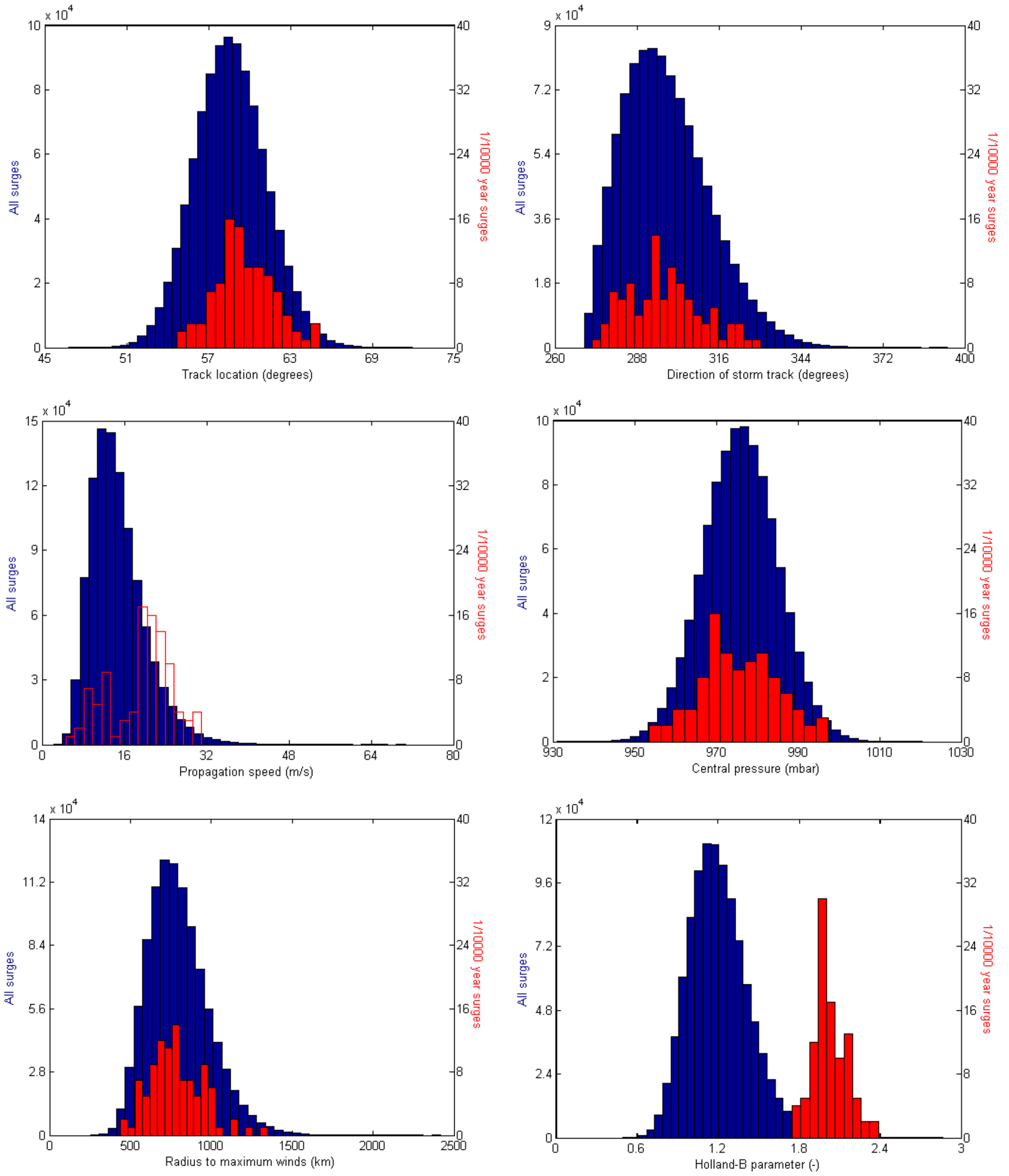

Figure 9. Distribution of storm parameter values of all surges (in blue) and surges with return period of +/- 10,000 yr (in red).

Storm duration

The model also provides insight into the temporal variation of the storm surge. To analyze this, a set of 100 storms have been extracted from the output of the Monte Carlo analysis. All these storms have a peak surge equivalent to the 10,000 year storm surge. The temporal variations of the storm surges of these storms have been normalized with the peak surge and are shown in Figure 10 (blue lines). The current storm surge course for design of the Dutch sea defenses is a symmetrical curve of 35 hours storm with a 4 hour time window around the peak at which the surge is more or less constant. This storm surge course is indicated in red in Figure 10.

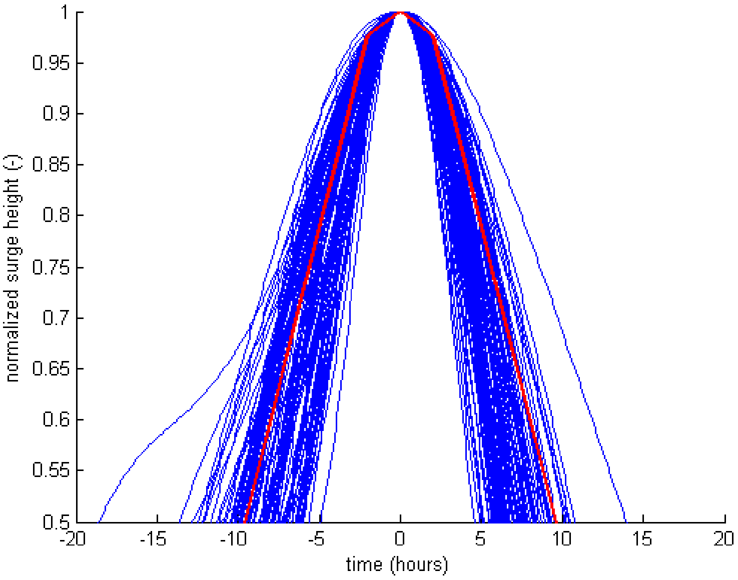

Figure 10. The course of 100 normalized modeled surge levels (in blue) and the currently adopted surge course for design of the Dutch sea defences (in red).

Figure 10 indicates that the currently adopted surge course during a storm matches the 10,000 yr storm results. Further inspection reveals that the average duration of the modelled peak water levels is slightly longer than the currently adopted time window. It must be kept in mind that the validation of the hydrodynamic model suggested that the model underestimates the surge duration in reality. Thus, the discrepancy between the currently adopted storm duration and storm duration for these extreme events could be larger (probably 1 – 2 hours). It is recommended to further study this aspect since it is important for dune erosion and dike revetments during storms.

Discussion

Despite the simplifications of the model, the results in the previous sections show that the newly developed model is able to capture the surge response at the North Sea. Also, the probabilistic analysis provides realistic results of the extreme surge levels and also storm duration. The added value of this approach compared with traditional statistical extrapolation of surge levels is twofold in our view.

First, the approach provides more insight into the extreme storm events and the governing physical parameters. For example, this study suggests that the exact location and angle of the storm is not very different for extreme storms compared to the entire data set. On the other hand, the central pressure and Holland-B turn out to be important parameters for the extreme storms. These findings need to be further verified with more analysis and sophisticated modeling (e.g. 2DH modeling).

Second, the approach presented in this paper provides information of both extreme surge and the storm duration. In principle, this model could also be extended to account for waves. For design and assessment applications of sea defenses (e.g. dunes, dikes), the combined temporal behavior of surge and waves during storms is important. In contrast to traditional statistical extrapolation methods, this physics based model provides an opportunity to study the joint behavior of surge and waves in more detail.

CONCLUSIONS AND RECOMMENDATIONS

This paper has presented an alternative method to determine extreme surge levels at the Dutch Coast. For this exploration, specific focus is on the extreme water level at Hoek van Holland, The Netherlands. The alternative method has been based on a joint probability model of the storm characteristics at the North Sea. The following conclusions are drawn:

1. An idealized meteorological-hydrological model has been set up to calculate storm surge at Hoek van Holland in the Netherlands due to storms crossing the North Sea. Despite the simplifications, validation shows that the model is able to capture the key aspects of the storms

and the storm surge response in the North Sea. After calibration, the computed surge levels showed an average error of 15% compared to the measurements.

2. Probability density distributions have been established for the different storm characteristics. These distributions are input for a Monte Carlo Analysis to define extreme water levels. The results show that the computed 10,000yr surge level (including tide) matches well with the number based on statistical extrapolation. The results also suggest the average duration of computed surges with a return period of 10,000 year is roughly 1-2 hours shorter than the storm duration currently adopted.
3. The advantage of the presented alternative approach is twofold: (1) it gives more insight in the role of storm characteristics associated with these extreme events, and (2) that it provides information on other relevant storm parameters (e.g. storm duration).

Two directions are recommended for further research. First, it is advised to further explore different types of models to better capture the North Sea storms. For example, the storms from 1962 suggest that not all storm parameters are correct. The model of Bijl (1997) could be applied as an alternative to investigate whether this improves the results. Second, the presented hydrodynamic model can be extended to two dimensions (2DH). This may improve the surge level results but a drawback is increasing computation time.

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REFERENCES

Amorocho, J. & DeVries, J. J. (1980). A new evaluation of the wind stress coefficient over water surfaces. Journal of geophysical research, 85 (C1).

Berg, N.J.F. van den (2013). On the influence of storm parameters on extreme surge events at the Dutch coast. Msc. thesis, University of Twente, Enschede, The Netherlands.

Bijl, W. (1997). Impact of a wind climate change on the surge in the southern part of the North Sea. Climate Research, 8.

Brunt, D. (1934). Physical and dynamical meteorology. Cambridge University Press.

De Jong, M. (2012). Developing a parametric model for storms to determine the extreme surge level at the Dutch coast. Msc. thesis, Delft University of Technology, Delft, The Netherlands.

Deltacommisie (1961). Rapport deltacommissie, deel 4. Bijdragen 3: Beschouwingen over stormvloeden en getijbewegingen. Technical report, Rijkswaterstaat.

Dillingh, D., de Haan, L., Helmers, R., Können, G., & van Malde, J. (1993). De basispeilen langs de Nederlandse kust. statistisch onderzoek. Technical report, Rijksinstituut voor Kust en Zee.

Gerritsen, H., de Vries, J., & Philippart, M. (2005). The Dutch continental shelf model. Quantitative skill assessment for coastal ocean. American Geophysical Union.

Groen, G. & Caires, S. (2011). Storm catalogue the Netherlands. http://www.knmi.nl/samenw/hydra/stormcatalogus/.

Holland, G. (1980). An analytical model of the wind and pressure profiles in hurricanes. Monthly weather review, 108.

Leslie, L. & Holland, G. (1995). On the bogussing of tropical cyclones in numerical models: A comparison of vortex profiles. Meteorology and Atmospheric Physics, 56 (1-2).

Ministerie van Verkeer en Waterstaat (2007). Hydraulische randvoorwaarden primaire waterkeringen voor de derde toetsronde 2006-2011.

Steetzel, H., Diermanse, F., van Gent, M., Coeveld, E., & van de Graaff, J. (2007). Dune erosion. Product 3: Probabilistic dune erosion prediction method. Technical report, WL Delft Hydraulics.

Wetterzentrale (2011). Ncep reanalysis: Informationen. www.wetterzentrale.de.

Wu, J. (1980). Wind stress coefficients over sea surface near neutral conditions - a revisit. Journal of Physical Oceanography, 10.