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# Operational wave forecast in the German Bight as part of a sensor- and risk based early warning system

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**ABSTRACT**

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Today's available flood- respectively storm surge warning systems for the German North Sea coast consist exclusively of water level forecasts. Other hydrodynamic loads caused by wind waves and local currents as well as the resistance of the flood protection structure itself (e.g. coastal dikes, flood protection walls etc.) are not taken into account. Therefore, an operational now- and forecast system for waves and wave induced hydrodynamic loads is set up that consists of available field measurements and data from numerical wave simulations in the German Bight. A hybrid model approach is used for the forecast of hydrodynamic loads on sea dikes. The approach combines numerical results from the phase integrated spectral wave forecast model (SWAN) and an empirical wave run-up approach (EurOtop) for the now- and forecast of average wave run-up heights at a sea dike on the North Frisian Island of Pellworm. The operational system is demonstrated exemplarily for the forecast of a severe storm event on the 5-6$^{th}$ December 2013 (German name "XAVER"). The qualitiy of the forecast is assessed seperately for the local nearshore wave conditions as well as the average wave run-up heights on the basis of available field measurements.

**ADDITIONAL INDEX WORDS:** *German Bight, SWAN, North Sea, wave forecast, early-warning system, Cosmo-EU model, ICON model, hydrodynamic loads, wave run-up, EurOtop.*

## INTRODUCTION

Federal and regional sea dikes are a main element of coastal protection methods along the German North Sea coast. In example, federal sea dikes at the west coast of the Federal State of Schleswig-Holstein (cp. Figure 1, red line) are protecting a total length of 360km of the coastline with a low lying hinterland area of 1,633 km² and a population of ca. 142,000 inhabitants and ca. 22 billion € assets (MELUR-SH, 2013).

Operational ocean respectively wave forecasting in the German coastal waters are issued at the Federal Maritime and Hydrographic Agency (BSH), see e.g. Brüning *et al.* (2014), respectively the marine weather service of Germany's National Meteorological Service, the Deutscher Wetterdienst (DWD).

Today, most of the weather- and climate information are accessible free of charge from the DWD's geoserver (www.dwd.de/opendata) to support official warnings against hazardous weather events and to support authorities responsible for civil protection and disaster management.

Nevertheless these forecast systems are in general not used for information on a local scale (with a horizontal resolution of a few meters) and warning systems do normally have a comparatively coarse spatial resolution (up to few hundred meters), which is much too coarse for a direct assessment of hydrodynamic loads on coastal- and flood protection structures.

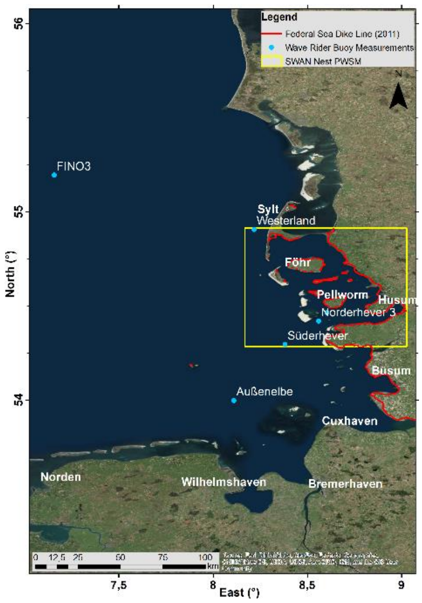


Figure 1. Focus area (yellow box), federal sea dike line of Schleswig-Holstein (in Red) provided by LKN-SH and selected wave measurements (in Blue) in the German Bight

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Hence, the knowledge of the wave-induced hydrodynamic loads including their high temporal and spatial resolution on the dike in combination with actual water levels is still a challenge and of crucial importance of any risk-based early warning system.

In 2015 the German joint research project "EarlyDike" (2015-2018), founded by the Federal Ministry of Education and Research (BMBF), was launched to develop a sensor- and risk based early warning system, taking into account the wave-induced hydrodynamic loads on the coastal protection structure and the resistance of the structure.

The new and innovative early warning system integrates different spatial sensor data (e.g. deformation, soil temperature and humidity inside the dike) and numerical model data (e.g. forecasts of local water levels and waves) into a sensor and spatial data infrastructure (SSDI) which enables open access to all relevant data (Becker *et al.*, 2016). The system will be used to generate in time warnings and provide reliable and robust real-time data for decision makers that are available within a GeoPortal to support disaster prevention and management.

As one part of the system, the wave monitor provides hydrodynamic information from numerical wave simulations in the whole German Bight. Moreover, information from high-resolution numerical wave simulations and local field measurements are available within a focus area, as shown in Figure 1.

In the following sections of this paper, the operational forecast of waves and wave run-up as one part of the early warning system is exemplarily shown and discussed. For more details about the sensor- and risk based early warning system and the integration of all relevant data, the reader is referred to Becker *et al.* (2016) and Krebs *et al.* (2017).

## METHODS

In the following section, the different methods that are used to forecast hydrodynamic loads on the dike are explained. The loads are derived within a hybrid approach that consists of numerical forecasts of water levels and waves in combination with empirical approaches (e.g. for the calculation of average wave run-up heights on the dike). Two operational modes exist that depend on different time scales: i) operational now- and forecast mode, ii) analysis of single events.

In the results section of this paper, results from the operational forecast mode are shown and discussed.

### Operational Wave Forecast

The operational forecast of the phase averaged wave conditions in the German Bight and in the focus area is based on nonstationary numerical simulations with the wave model SWAN (Booij, Ris, and Holthuijsen, 1999). The wave model has been used and validated in different coastal engineering studies (see e.g. Dreier and Fröhle, 2016; Fröhle *et al.*, 2009). In this study, the SWAN version 41.10 is applied and the different forecast models are run on two multiprocessor systems with 24 cores each using OpenMP parallelization.

Two forecast horizons are realized for the numerical forecast of the wave conditions: i) long-term forecast T+72h at 12-hourly forecast intervals 00/12 UTC and ii) short-term forecast T+24h at 6-hourly forecast intervals 00/06/12/18 UTC, each with a hourly time interval and running on a single multiprocessor system.

The wave conditions are calculated from the North Sea over the Wadden Sea areas up to the assessment site using a nesting approach and a spherical coordinate system.

The coarse model covers the entire North Sea (acronym "NSSM") with a horizontal resolution of $\Delta x = \Delta y = \sim 6$km. The NSSM-model runs under sea ice-free conditions and at a mean water level. Since the spectral wave conditions are derived in deep water as boundary conditions for the nested fine model, the time dependent changes of the local water level are neglected in the coarse simulations. The effects of local storm water levels on the significant wave heights ($H_s$) in the deep water areas of the coarse wave model have been assessed to be non-significant (change of $H_s \leq +5\%$) according to a sensitivity analysis.

The following boundary conditions are used as input for the NSSM-model: i) freely available 10m forecast wind fields from the operational weather forecast model of the DWD, namely the ICON-EU nest and ii) freely available bathymetric data for the deep water areas in the North Sea (GEBCO, 2014). The effects of wave boundary conditions at the open boundaries to the Atlantic Ocean on the wave conditions in the German Bight during storm surges have been assessed to be non-significant according to a sensitivity analysis that was carried out on the basis of a hindcast of wave conditions that is freely available from the historical archive of NCEP (NOAA).

The fine model (acronym "PWSM") covers the focus area near the Island of Pellworm (cp. yellow box in Figure 1) with a high horizontal resolution of $\Delta x = \Delta y = \sim 50$m.

The spectral boundary conditions of the NSSM-model are applied at the open boundaries of the PWSM-model. The PSWM-model assumes sea-ice free conditions but, in contrast to the NSSM-model, information about the local water levels from the forecast of water levels in the German Bight are integrated.

Moreover freely available nearshore bathymetric data for the year 2012 is used from the Federal Ministry of Education and Research (BMBF) project "AufMod". The data is available within the Marine Data Infrastructure Germany (MDI-DE; see Lehfeldt and Melles, 2014).

Both wave models are run at an hourly time interval and with a directional resolution of $\Delta\Theta = 2.5°$ and 42 frequencies ($f_{low} = 0.05$ Hz, $f_{high} = 1$ Hz). The number of iterations for the non-stationary simulations was limited with 3 respectively 6 iterations for the NSSM- respectively PWSM-model as a result from a sensitivity analysis.

### Operational Wave Nowcast

The operational nowcast (with a forecast time of T+15min) of the wave conditions directly at the dike is based on the analysis of waves directly at the dike foot and 50m in front of the dike based on pressure and current measurements. The measurements are part of a local measurement chain that is operated in cooperation with the local authority responsible for coastal protection in the Federal State of Schleswig-Holstein (LKN-SH).

The measurement chain starts in the outer Wadden Sea area (cp. Figure 1, near the wave buoy location "Süderhever") and continues over the tidal inlet (wave buoy locations "Norderhever2" and "Norderhever3" as shown in Figure 2) towards the beach near Untjehörn on the Island of Pellworm.

Local waves on the beach are derived from measurements of currents with conventional bottom mounted ADCPs (TRDI

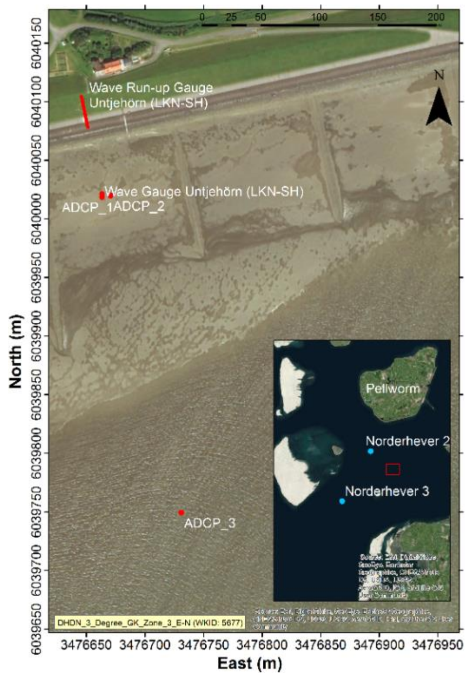


Figure 2. Measurement chain for nearshore waves, currents and hydrodynamic loads on the sea dike near Untjehörn, Island of Pellworm.

Sentinel workhorse 1200kHz) and from measurements with pressure gauges (cp. Figure 2).

Wave run-up events are measured at the landward end of the measurement chain on the seaward slope of the dike during storm surges since 2007 with an in-house solution for a wave run-up gauge developed by the LKN-SH (Jensen and Scheider, 2006). The measurement principle is based on conductivity measurements with 64 graphite electrodes that are distributed along the seaward slope of the dike every 30cm. Results from the wave run-up measurements are shown in the next section.

## RESULTS

In the first part of this section, results from a forecast of wave conditions during a winter storm on the 5-6$^{th}$ December 2013 (German name "Xaver") are presented. The remarkable storm event caused maximum gust wind speeds up to 44 m/s (Deutschländer *et al.*, 2013) and two consecutive storm surges occurred in the focus area with local water levels up to +2.81m above the mean tidal high water level (+1.51m above mean sea level / in German "MThw").

In the second part, results from the long-term forecast of wave run-up on the dike near Untjehörn are presented and compared with field measurements during the storm.

### Long-term Forecast of Waves at the Assessment Site

Near surface wind fields at 10m above the surface from the long-term forecasts of the former operational weather model COSMO-EU model (DWD) are used as meteorological boundary conditions for the long-term forecast (T+72h) of waves within the German Bight and the focus area near the Island of Pellworm.

Moreover, spectral boundary conditions are applied from the nesting of the fine PWSM-model into the coarse NSSM-model.

Local water level fields have been derived from the time series of the measured water level nearby the Island of Pellworm instead of the forecast of water levels, for the latter were temporarily not available to be included in the forecast of the waves.

The measurements at the water level gauge station "Pellworm Anleger" have been provided by the German Federal Waterways and Shipping Agency (WSV). The time series of the water level is applied at every grid point in the PWSM-model.

A comparison between the forecast of significant wave heights in the PWSM- model at approx. 50m in front of the dike near Untjehörn and measurements is shown in Figure 3.

From Figure 3, a good agreement between the forecast of significant wave heights in the PWSM-model and available wave measurements is found. The comparison of other waves parameters is summarized in Table 2 at the time of the occurrence of the maximum local water level on 6$^{th}$ December 2013 04 UTC.

Table 2. *Forecast of wave parameters and local measurements in front of the dike near Untjehörn on the 6$^{th}$ December 2013 04 UTC*

| | SWAN Forecast | Observation | Difference | Difference (%) |
|---|---|---|---|---|
| Depth (m) | 4.31 | 4.31 | 0.00 | 0 |
| $H_s$ (m) | 1.01 | 1.16 | -0.15 | -13 |
| $T_{m02}$ (s) | 2.62 | 3.90 | -1.28 | -33 |
| $T_{m-1.0}$ (s) | 4.71 | 6.10 | -1.39 | -23 |
| $T_p$ (s) | 4.18 | 4.50 | -0.32 | -7 |
| $\theta_m$ (°) | 244 | 247 | -3 | |

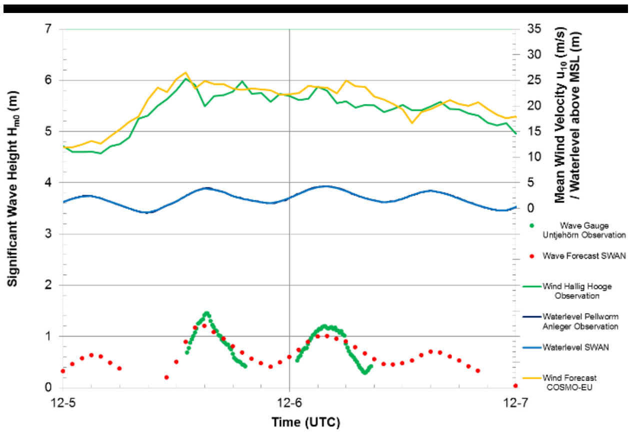


Figure 3. Forecast of significant wave height (bottom, in Red) and 10m wind velocity (top, in Yellow) compared with measurements (in Green) in front of the dike near Untjehörn during storm "Xaver", December 2013

### Long-term Forecast of Wave Run-up at the Assessment Site

A hybrid approach is used for the long-term forecast (T+72h) of wave run-up at the sea dike near Untjehörn. For the forecast of average wave run-up heights the empirical EurOtop (2016) approach is applied. The calculation is based on the time series of simulated wave parameters ca. 50m in front of the dike and the measured water levels during the storm as hydrodynamic input.

The average wave run-up height ($R_{u2\%}$) is calculated according to the mean value approach, as introduced in EurOtop (2016).

The wave run-up height $R_{u2\%}$ is defined as the run-up height that is reached or exceeded by 2% of the incoming waves within a wave record. From a sensitivity analysis with different wave records lengths of 500, 1000 and 1500 waves, minor impacts on the calculated average wave run-up height $R_{u2\%}$ were noted.

Moreover, the complex geometry of the dike, effects of oblique wave attack and the surface roughness have been taken into account according to the EurOtop (2016) approach.

The comparison between the long-term forecast of the wave run-up height $R_{u2\%}$ and measurements during the storm "Xaver" on the 5th December 2013 is exemplarily shown in Figure 4.

In general, a good agreement between the long-term forecast and measurements is found (cp. Figure 4, red and black lines).

In Figure 4, the maximum wave run-up heights ($R_{u,max}$) of single wave run-up events are plotted with black points above the height of the local water level (cp. blue line in Figure 4). The heights of the first four electrodes of the wave run-up gauge are indicated by dashed grey lines.

From Figure 4 it can be seen, that the first two electrodes have been partly covered by water during the peak of the water level. Please note that the second electrode was out of function, hence no data points are plotted on the second grey line.

The average wave run-up heights during the storm are summarized in Table 3. The uncertainty of the long-term forecast in comparison with measurements lies within a range of -5% to +32% (cp. Table 3, last column).

## DISCUSSION

The results of the long-term forecast of the local significant wave height and mean wave direction ca. 50m in front of the dike are in good agreement with measurements. In contrast the mean ($T_{m02}$), spectral ($T_{m-1.0}$) and peak wave period ($T_p$) are underestimated by up to -50%.

Table 3. *Average wave run-up heights ($R_{u2\%}$) from the long-term forecast and measurements at the dike near Untjehörn during the storm "Xaver"*

| | $R_{u2\%}$ Forecast (m) | $R_{u2\%}$ Observation (m) | Difference (m) | Difference (%) |
|---|---|---|---|---|
| 2013-12-05 15:00:00 | 1.94 | 2.03 | -0.09 | -4.5 |
| 2013-12-05 16:00:00 | 1.89 | 1.93 | -0.04 | -2.1 |
| 2013-12-05 17:00:00 | 1.82 | 1.51 | 0.31 | 20.7 |
| 2013-12-06 03:00:00 | 1.64 | 1.48 | 0.15 | 10.4 |
| 2013-12-06 04:00:00 | 1.58 | 1.47 | 0.11 | 7.4 |
| 2013-12-06 05:00:00 | 1.61 | 1.55 | 0.06 | 3.5 |
| 2013-12-06 06:00:00 | 1.66 | 1.26 | 0.40 | 31.7 |

The underestimation of wave periods by SWAN is known from other coastal engineering studies (e.g. Dreier and Fröhle, 2016; Schlamkow and Fröhle, 2008; van der Westhuysen *et al.*, 2012) due to discrepancies between the simulated and measured wave energy density spectra.

The spectral wave period ($T_{m-1.0}$) at the dike foot is one of the most relevant input parameter for the calculation of the average wave run-up height in the EurOtop (2016) approach.

Since the wave periods are underestimated by SWAN in the long-term forecast, the uncertainty of the forecasted average wave run-heights may be larger than 1/3rd compared to the measured values.

In contrast, this problem does not occur in the nowcast (T+15min) of average wave run-up heights based on local wave and water level measurements directly at the dike foot.

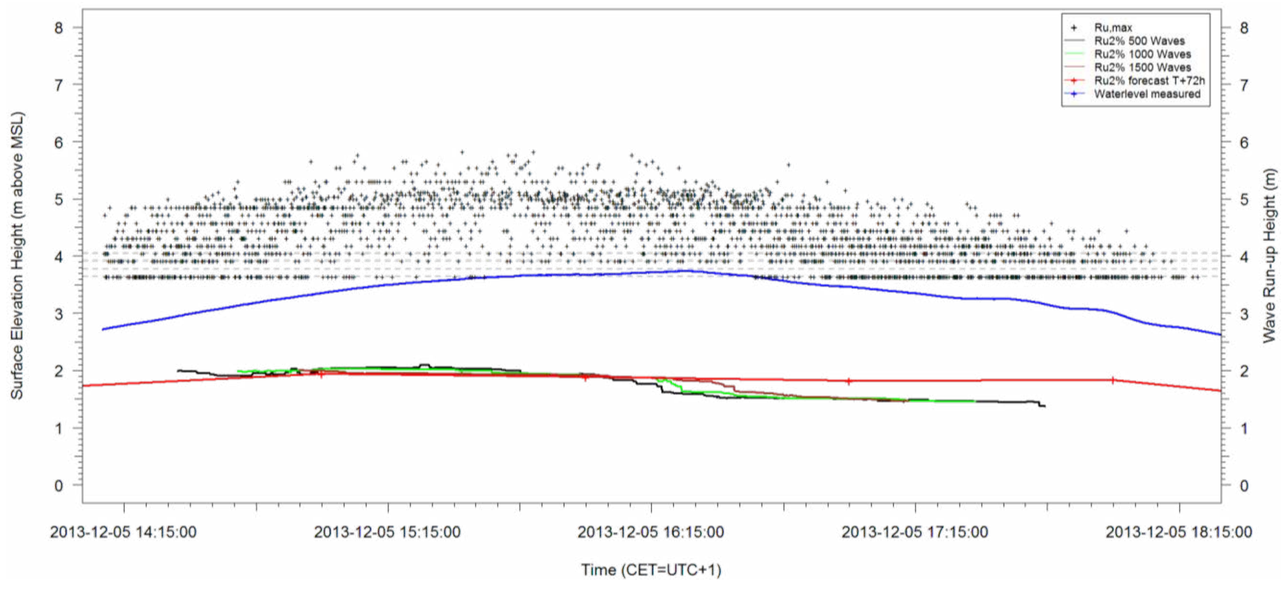


Figure 4. Maximum ($R_{u,max}$) and average wave run-up heights ($R_{u2\%}$) from the long-term forecast (in Red) and measurements (in Black, Green and Brown) at the dike near Untjehörn during "Xaver", 5th December 2013

Moreover, the uncertainty of the results depends significantly on the quality of the forecast of the local water levels. The long-term forecast of local water levels could not be taken into account within this study, but will be included in the future long-term forecast of the average wave run up-heights.

## CONCLUSIONS

This study examines the forecast of local wave conditions in the German Bight and the forecast of wave run-up at a sea dike near Untjehörn on the Island of Pellworm as part of an new and innovative risk and sensor based early warning system for the German North sea coast developed within the German joint research project "EarlyDike".

As a basis for the system, an operational wave now- and forecast model is set up that consists of available field measurements of waves, water levels and currents and data from the forecast of waterlevels and waves in the German Bight. The wave induced hydrodynamic loads on a sea dike are calculated with the help of a hybrid approach that combines the numerical wave forecast results (SWAN) with an empirical wave run-up approach (EurOtop, 2016).

The operational forecast of waves and wave run-up is demonstrated exemplarily for the long-term forecast (T+72h) of a severe storm event on the 5-6th December 2013 (German name "XAVER"). The forecast of the average wave run-up heights $R_{u2\%}$ at the dike overestimates the measurements up to +30%. Nevertheless, the forecast results for other past storms have to be analyzed and assessed to provide a more robust estimate of the uncertainty of the forecast system.

Finally the forecast of the waves and wave run-up will be integrated with other relevant information, like e.g. the forecast of the local water levels, into the early warning system and can be accessed through a GeoPortal in real-time.

## ACKNOWLEDGEMENTS

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