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Optimization of Empirical Storm Surge Forecast – Modelling of High Resolution Wind Fields

Jana Kristandt, Benedict Brecht, Helmut Frank and Heiko Knaack

Summary

Aim of this study is to improve the empirical storm surge forecast for the coast of Lower Saxony using modelled high resolution wind fields over the North Sea. The hindcast of historic storms is done by Deutscher Wetterdienst (German Weather Service, DWD) using their operational model chain (GME, COSMO-EU, COSMO-DE). COSMO was run in forecast and in nudging mode. The NLWKN-Coastal Research Station used the modelled wind fields to optimize the empirical storm surge forecast with a variety of empirical and neural network approaches.

Keywords

storm surges, storm surge forecast, artificial neural networks, empirical modelling, weather forecast models (GME, COSMO), wind simulation, North Sea

Zusammenfassung

Ziel der Untersuchung war eine Verbesserung der empirischen Sturmflutvorhersage für die Niedersächsische Küste auf Basis hochauflösender Windfelder über der Nordsee. Dazu wurden historische Stürme vom Deutschen Wetterdienst (DWD) mithilfe der operationellen Modellkette (GME, COSMO-EU, COSMO-DE) nachgerechnet. Die COSMO-Läufe wurden mit und ohne „Nudging“ modelliert. Die Forschungsstelle Küste des Niedersächsischen Landesbetriebs für Wasserwirtschaft, Küsten- und Naturschutz (NLWKN) nutzte diese Winddaten um ihre Sturmflutvorhersage durch verschiedene empirische Ansätze und künstliche Neuronale Netzwerke zu verbessern.

Schlagwörter

Sturmfluten, Sturmflutvorhersage, künstliche neuronale Netze, empirische Modellierung, Wettervorhersagemodelle (GME, COSMO), Windmodellierung, Nordsee

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1 Introduction

Storm surges are a severe risk for the low-lying coasts of the North Sea. Storm surges are induced by cyclones crossing Northern Europe from west to east. Strong westerly to northwesterly wind fields on the back side of the low pressure area can drive water masses into the German Bight and force the water level to increase by several meters along the coasts of the Netherlands, Germany and Denmark. If favorable meteorological conditions coincide with astronomical high tide, a storm surge is approaching the coast with the potential of heavy damages and risk of life (e.g. SCHMITZ 1978a; JENSEN and MÜLLER-NAVARRA 2008).

Over the last decades, different approaches were developed to forecast storm surges ranging from simple to elaborated empirical relations (e.g. ANNUTSCH 1978; MÜLLER-NAVARRA and GIESE 1997) or numerical hydrodynamic models (e.g. SCHMITZ 1978b; PHILIPPART and GEBRAAD 1997; DICK et al. 2001; MÜLLER-NAVARRA et al. 2003). A considerably large progress was enabled due to the enormous improvement of weather forecasting by numerical weather prediction from global scales to limited area models with high resolution. For many years the Deutscher Wetterdienst (DWD, German Weather Service) operates a chain of numerical weather forecasting models, which are continuously improved. The numerical weather prediction at the DWD started in 1968 with the BKL model (baroclinic model without moisture), followed in 1978 by the BKF model (baroclinic moisture model, 254 km mesh size; promet 2/3 1978). It was replaced in 1991 by the global model GM with 190 km mesh size and a limited-area model EM with 50 km mesh size. These were in turn replaced in 1999 by the GME (MAJEWSKI et al. 2002) with at that time 60 km mesh width and the regional model LM (now COSMO-EU) with 7 km mesh size. Now the model chain of the DWD ranges from the global model GME (20 km mesh size) via the limited area-model COSMO-EU with 7 km mesh size down to COSMO-DE (operationally since 2007) with 2.8 km mesh width. In 2014 the new global model ICON shall become operational with a mesh width of 13 km. The DWD provides the German coastal authorities with the necessary meteorological data.

In the 1990th the antecessor of the Lower Saxony Water Management, Coastal Defense and Nature Conservation Agency (NLWKN) established a regional storm surge

forecasting service for the coast of Lower Saxony. It uses an empirical approach based on predicted wind speed and direction in the southern part of the North Sea. Confronted with a lack of high resolution meteorological data over the North Sea during storm surge events, DWD and the Coastal Research Station of NLWKN started a project in 2011, to hindcast 39 historical storm surge events at the North Sea coast from 1962 till 2011 (see Tab. 1).

2 High resolution modelling of wind fields

2.1 Model chain

High resolution wind fields are necessary to predict the occurrence of storm flood events and their magnitude. Therefore DWD produced wind fields of 39 historical storm flood events (see Tab. 1) using its global model GME (MAJEWSKI 2002) and the limited-area non-hydrostatic model COSMO (COSMO model documentation 2014), which is run in the two versions COSMO-eu and COSMO-de. GME is a hydrostatic model operating on an icosahedral grid.

Table 1: Date and wind surge [cm] at Norderney of the modelled storm events.

no.	date	surge	no.	date	surge	no.	date	surge
1	16.02.1962	297	14	14.02.1989	159	27	05.02.1999	220
2	30.11.1966	206	15	25.01.1990	182	28	03.12.1999	201
3	23.02.1967	228	16	26.02.1990	250	29	30.01.2000	223
4	01.03.1967	206	17	20.08.1990	117	30	28.10.2002	146
5	19.11.1973	255	18	20.12.1991	197	31	01.11.2006	255
6	06.12.1973	241	19	22.01.1993	213	32	12.01.2007	199
7	14.12.1973	235	20	09.12.1993	147	33	18.01.2007	129
8	03.01.1976	275	21	20.12.1993	192	34	18.03.2007	216
9	21.01.1976	275	22	28.01.1994	247	35	09.11.2007	255
10	31.12.1977	248	23	13.03.1994	171	36	25.11.2007	147
11	24.11.1981	237	24	01.01.1995	201	37	13.03.2008	133
12	02.02.1983	223	25	10.01.1995	228	38	12.11.2010	155
13	05.12.1988	159	26	29.10.1996	165	39	04.02.2011	133

For these simulations GME has a mesh width of 30 km and 60 vertical layers. Operationally, GME runs on a 20 km grid. Here, GME is initialized four times a day (00, 06, 12, and 18 UTC) from reanalysis data of ECMWF. For storms before 1979 we use ERA-40 (UPPALA et al. 2005) which uses a 3-dimensional variational assimilation on a 125 km grid. In and after 1979 the ERAInterim analysis (DEE et al. 2011) is used. It employs a 12-hourly 4-dimensional variational assimilation scheme on a horizontal grid of about 80 km mesh width. GME provides initial and boundary data for COSMO-eu with a mesh width of 7 km and 40 vertical layers. COSMO-eu in turn drives COSMO-de which has a mesh width of 2.2 km and 65 vertical layers. At this resolution deep convection can be explicitly resolved (BALDAUF et al. 2011).

Therefore, only shallow convection is parameterized in COSMO-de. Compared to the operational COSMO-EU at the DWD the domain of COSMO-eu is smaller in the south and the east (see Fig. 1) as these regions are not important for storm surge predictions at

the North Sea coast. The domain of COSMO-de is increased in the north, west and south compared to the operational COSMO-DE (see Fig. 1). The vertical resolution is increased from operationally 50 to 65 layers. COSMO-de serves as test bed for a possible new operational setup of COSMO-DE.

At first all storms were simulated in pure forecast mode. I.e. one storm was simulated as a series of short range forecasts which started from new reanalysis data. During the first few hours of a forecast the models must adapt to the interpolated analysis. Therefore, these forecast hours are discarded.

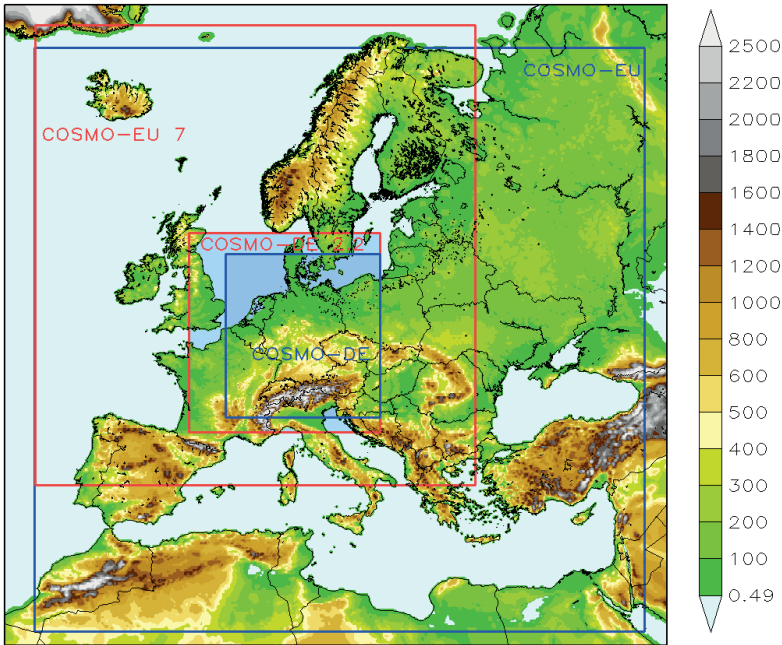


Figure 1: Domains of COSMO: The red lines show the domains of the 7 km COSMO-eu and 2.2 km COSMO-de. The blue lines show the domains of the operational versions COSMO-EU and COSMO-DE.

2.2 Nudging runs

To get the best possible analysis at high resolution the simulations with COSMO were additionally done with the Newtonian relaxation or nudging technique (STAUFFER et al. 1990) to obtain one continuous analysis without jumps. With this method the prognostic variables of the model are relaxed towards prescribed values within a timeframe (SCHRAFF 1997). In this case the prescribed values are direct observations, which is advantageous for synoptic observations (STAUFFER and SEAMAN 1994). The relaxation against the observations is done via additional terms in the prognostic equations. In practical applications, the nudging term should and usually do remain smaller than the largest term of the dynamics. This situation is related to the basic idea of the method that the model fields are to be relaxed towards the observed values without significantly disturbing the dynamic balance of the model (SCHRAFF and HESS 2002).

If available, the following observations are used: Radiosondes provide both the upper air and the surface horizontal wind, temperature and humidity as well as the pressure on the lowest model level. Aircraft measurements supply horizontal wind and temperature. Data from wind profilers yield the upper-air wind, and near surface observations give station pressure, 10 m wind, and 2 m humidity. 10 m winds are only used for stations below 100 m above sea level to select only stations in flat terrain. The 2 m temperature is not assimilated, due to the potential disadvantage to the stability of the planetary boundary layer (STAUFFER et al. 1991). A more detailed description of the nudging in COSMO is given by SCHRAFF and HESS (2002).

2.2.1 Availability of nudging data

The data availability increases from older to newer storms. The total available observations per 6 hours for the COSMO-eu area are 2000-3000 Synop land and ship (relation 10:1) observations for events from 1966-1976. It increased in 1977 to approximately 5000 per 6 h mainly due to an increased frequency of Synop measurements (to 3 hourly or hourly observations), and to the first use of drifting buoys and aircraft observations. Then, it slowly increased to 15000 observations in the year 2000. Wind profiler data is available since 2000, and radiosonde measurements since 1991. Since 2006 over 40000 observations in 6 hours are available. As an example Fig. 2 shows the coverage of available Synop land and ship data on 29th October 2006 during storm “Britta”.

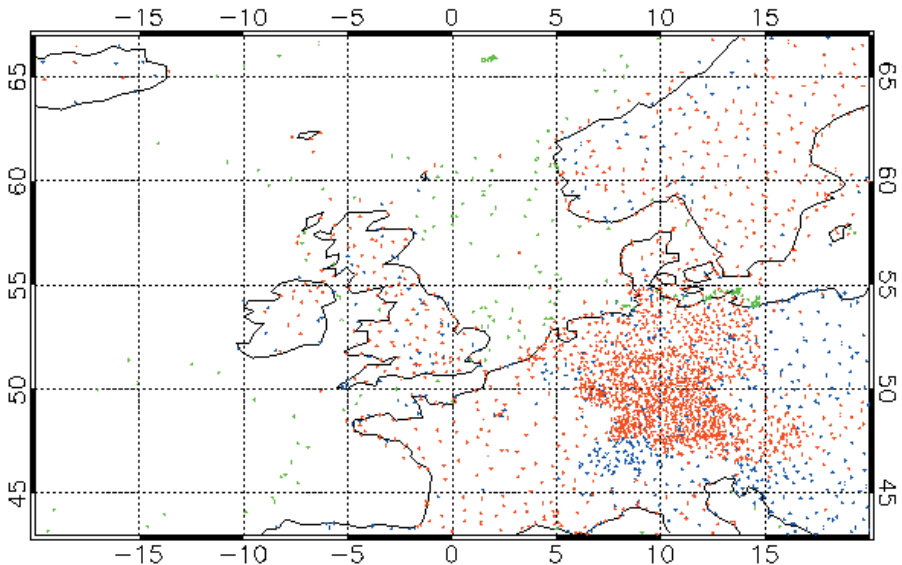


Figure 2: Data coverage of Synop land and ship data on 29th October 2006. The blue dots show the manned land stations, the red dots the automatic land stations and the green dots the ships.

The used data is less than the available data owing to the quality control, the availability of meta information like station height, or differences between real station height and model orography. Approximately 40 % to 90 % of the available data is used for the nudging.

For the storms from 1966-1976 only 40 %-50 % of the data are used by the model, mostly due to missing station altitudes of Synop land stations. From 1977-2000 80 %-90 % of the measurements are accepted. For later runs this ratio decreases again to 60 %-65 %.

2.3 Results

We present results for storm “Britta” in October 2006. This storm originated over Newfoundland. It travelled eastward crossing the Shetlands to the West coast of Norway. There “Britta” changed direction and moved southeastward over the Skagerrak. The water was pushed for many hours, first by northwesterly winds, and later by north northwesterly winds into the German Bight, see Fig. 3, which resulted in the high water level. As is typical for northern hemisphere mid-latitude storms the strongest winds of “Britta” occurred on the southwest side of the low pressure center behind the cold front.

2.3.1 Verification

The COSMO model data was verified with observations of up to 24 Synop stations at or near the North Sea coast of Denmark, Germany and the Netherlands, plus some stations in the North Sea (platforms, fire ships). However, not all stations were available for all storms. The verification was made for sea level pressure, pmsl, wind speed at 10 m, v_{10m} , and wind direction at 10 m, dd_{10m} . We calculated the bias of the model (model-obs), and the RMSE of the model values vs. the observation values. Here, we show the results of storm “Britta” in October 2006. The results of the other storms are qualitatively similar. For “Britta” observations from 18 stations were available for verification.

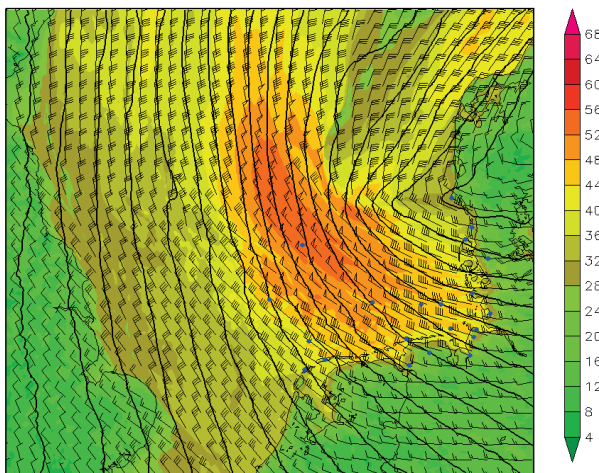


Figure 3: Wind field over the North Sea of storm “Britta” at the 29th October 2006, 1 UTC, 3 hours before the water reached the highest level at Norderney. Results from the COSMO-de nudging run are shown. The wind 10 m above ground is given in knots. Contour lines show pmsl in 2 hPa intervals. The blue dots indicate the locations of the stations which were used for verification.

For the verification we can compare both COSMO models, and nudging runs with forecast runs (see Fig. 3). For COSMO-eu the RMSE and biases for all 3 variables, v_{10m} , dd_{10m} , and $pmsl$, are less for the nudging analysis than for the forecast runs. The biases are 1.0 m/s compared to 1.2 m/s, 4° vs. 11° , and 0.1 hPa vs. 0.35 hPa (see Fig. 4 at the left). The RMSE values are 2.1 m/s vs. 2.3 m/s, 20° vs. 28° , and 0.6 hPa vs. 0.7 hPa (see Fig. 5 at the left). For this storm the results of the nudging runs were better than the forecast runs for all variables.

COSMO-de showed qualitatively similar behavior for the RMSE and the bias. The RMSE of the nudging runs versus the normal forecast runs were 1.9 m/s vs. 2 m/s, 19° vs. 25° , and 0.6 hPa vs. 0.7 hPa for $pmsl$ (see Fig. 5 at the right). Hence, the nudging runs were slightly better than the runs without nudging. The biases are 0.1 m/s compared to -0.3 m/s, 2.5° vs. 7° , and 0.01 hPa vs. 0.25 hPa (see Fig. 4 at the right). The sign of the 10 m wind speed bias of the normal forecast run changed compared to COSMO-eu. However, the nudging runs showed better results than the forecast runs.

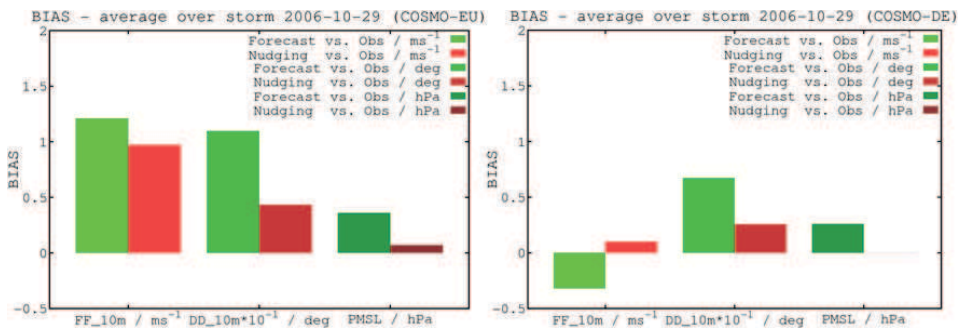


Figure 4: The biases of storm “Britta” for the three variables v_{10m} , dd_{10m} and $pmsl$ for COSMO-eu (left) and COSMO-de (right) and both for nudging runs (red) and runs without nudging (green).

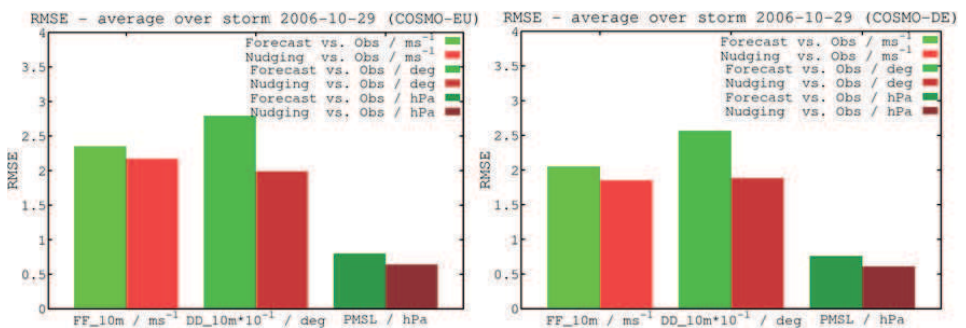


Figure 5: The RMSEs of storm “Britta” for the three variables v_{10m} , dd_{10m} and $pmsl$ for COSMO-eu (left) and COSMO-de (right) and both for nudging runs (red) and runs without nudging (green).

In general we saw that the largest improvement by the nudging results for the variable $pmsl$. For every time series of the nudging runs of any station the RMSE and biases of $pmsl$ were better than those of the normal forecast runs. For wind speed and direction

the forecast without nudging was better for a few stations compared to the nudging runs, but not averaged over all stations.

Comparing COSMO-eu and COSMO-de we obtained the following results. The RMSE values of COSMO-de are only minimally better than those of COSMO-eu. Also, the biases of COSMO-de are smaller. The 10 m wind speed bias of COSMO-de is much smaller than that of COSMO-eu. Where does this big difference of the wind speed bias come from? By calculating the mean wind speed difference of COSMO-eu and COSMO-de we saw the main difference over plain land outside the Alps which is the result of different roughness length, z_0 . The differences in z_0 come from the usage of different land use classifications. For COSMO-eu z_0 was derived from the GLC2000 data set (BARTHOLOMÉ and BELWARD 2005), whereas for COSMO-de the newer GlobCover data set (ARINO et al. 2008) has been employed. Outside the Alps z_0 is higher in the data derived from GlobCover which yields lower near surface winds which are in better agreement with the observations. In the Alps z_0 for COSMO-eu contains an additional contribution from the orographic variability. We ran COSMO-eu with z_0 derived from GlobCover for three storms (“Tilo” 2007, “Kyrill” 2007, and “Britta” 2006). The wind speed bias of COSMO-eu decreased by 0.2 m/s averaged over all stations, 0.1 m/s for sea stations and 0.35 m/s for land stations which is an improvement for the storm. Hence, GlobCover yields better roughness values for COSMO-eu than GLC2000.

2.3.2 Storm tracks

An interesting information for studies on storm surges is the path of the storms. Therefore we plotted storm tracks for the events, which led to an accumulation of water of more than 2 m at the gauge Norderney (23 events). A storm track is defined here as the path of the pressure minimum in time. The tracks of the storms with the eight highest water levels at Norderney are shown in Fig. 6. The highest water level for almost all stations at the German North Sea coast occurred during the severe storm “Capella” in 1976, but for gauge Norderney it was the storm flood in 1962.

According to PETERSEN and ROHDE (1991) we can distinguish three classes of storm paths.

The Scandinavia type crosses longitude 8° E between 60° N and 65° N. The low pressure systems of this type originate between Greenland and Iceland and travel slowly southeastwards. Despite lower wind speed than the other two types, the German Bight is filled with a lot of water, because of the long residence time. One example for this storm type is the flood on February 1962. Of the 23 highest water levels we found six of the Scandinavia type.

The Skagerrak type is characterized by very high water levels which affects mostly the whole North Sea. It is the most frequented type and crosses 8° E between the 57° N and 60° N. We found 12 out of 23 events of this type.

Storms of the Jutland type mostly develop at the North American coast (Newfoundland) and move rapidly eastwards over the British Isles to cross the 8° E between 55° N and 57° N. They are of short duration, but very strong storms with a wind direction first from southwest, later turning to northwest. They mostly affect the west coast of Schleswig-Holstein and the estuary of the Elbe. The storm “Capella” in 1976, for example, was of this type. Out of 23 storms we found 4 of this type.

One storm of the 23 highest events did not cross the longitude 8° E and remained nearly stationary in the North Atlantic east of Iceland (in February 1967, no. 4 in Tab. 1).

If we look at the genesis of the storms and their tracks until they hit the North Sea coast some storms are a combination of different types (GÖNNERT et al. 2001). For example, Fig. 6 shows the storm in December 1977, which developed between Iceland and Greenland like a Scandinavia type, but moved southward to cross 8° E as a Skagerrak type.

3 Empirical storm surge forecast

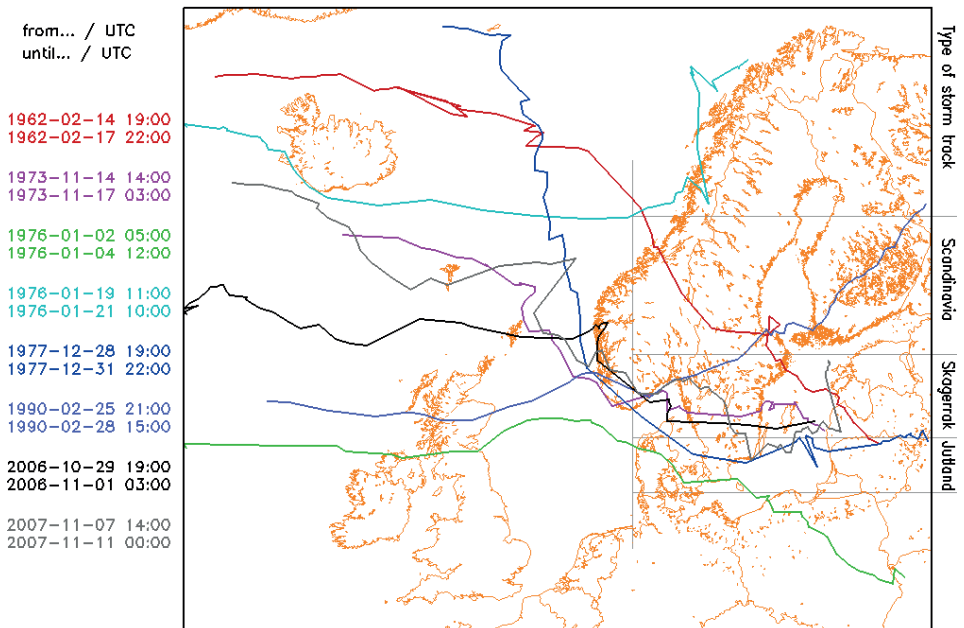


Figure 6: Tracks of the eight storms, which caused the highest accumulation of water at the gauge Norderney from 1962 till 2011. On the right side the storm flood types according to PETERSEN and ROHDE (1991) are shown.

The storm surge forecasting service of the NLWKN provides a 5day-forecast of the set-up at tidal high water -based on the weather forecasts of the DWD- for the gauges Norderney (representing the East-Frisian Islands), Emden (Ems-Estuary), Benseniel (East-Frisian Coast), Bremerhaven (Weser-Estuary) and Cuxhaven (Elbe-Estuary). The service was founded as an internal service for work scheduling of coastal protection and construction works. The information is also made available to the public via internet.

Based on the hindcasted wind fields an improvement of the storm surge forecast and an intense regionalization of the service were aimed for (the latter is not subject of this report).

3.1 Procedure and data base

3.1.1 Data availability

The DWD hindcasted 39 time series of 4 to 11 days, including 42 storm surges. The time series start 2 to 3 days before the actual storm surge and end roughly one day after. If two storm surges follow each other closely, the events are packed. Altogether the modelled wind data covers 335 high tides. Roughly one fifth of that are minor storm surges, 7 % are severe and less than 1 % are extreme storm surges. This data was used as input for the calculation of empiric formulas, neural networks and numerical modelling to conduct a variety of studies. A database with measured and astronomical water levels for numerous gauges along the Dutch and East-Frisian Coast was assembled as target and validation data. Due to limited time series in combination with large gaps in measured water level, especially during storm events, this project focused on the gauges of Norderney, Cuxhaven and Emden, where the most complete time series are available.

One limitation of this study is the unequal distribution of wind data (Fig. 1). Due to the focus on storm surges, all the modelled storms have main wind directions between west and northwest and -of course- high wind velocities. This means that the developed formulas are not meant to forecast low water situations with e.g. offshore winds. Even “normal” situations with low velocities must be regarded with caution.

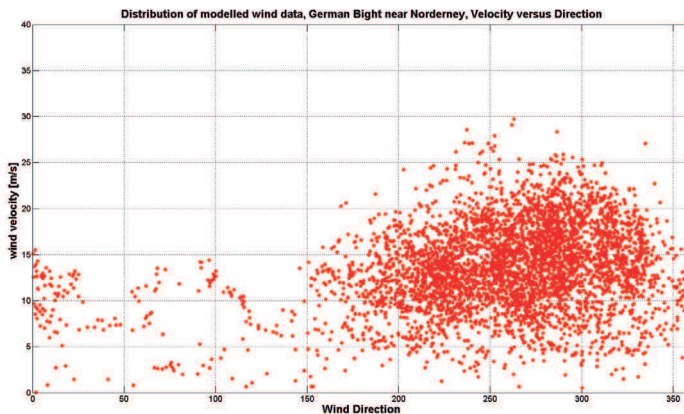


Figure 7: Distribution of wind direction versus velocity in the model output on sea near Norderney.

3.1.2 Data preprocessing

The previous used empiric relations between wind and surge were obtained from wind measurements. Data gaps and limited spatial distribution of measuring stations, especially over the open North Sea were a main limiting factor. Now in contrast, using spatial and temporal high-resolution modelled data, it was necessary to limit the number of wind data points to be used for analysis to keep the calculations practical and to not overfit the equations.

The modelled data was reduced to a grid with a cell distance of 1° (Fig. 8, left). Analysis with a stepwise-regression showed that the dominant influence of the wind on the water level along the Lower-Saxony Coast is localized in the German Bight, the entrance of the North Sea and the southwestern part in front of the coast of Norfolk. As not the exact position of the Wind input point is of importance, but the overall wind situation in the respective area, a spatial mean of up to 4 points (Fig. 8, left) was chosen to get rid of minor local and short-term effects. For the same reason, a temporal mean of three hours is used.

Within the German Bight eight positions were chosen to include the influence of the local wind directly in front of the coast (Fig. 8, right). The wind at these positions is already used in the presently used forecast formulas.

Analysis of the delay between wind occurrence and corresponding surge obtained a mean time lag of about 1h per 75 km. This fits well with the equation for velocity of shallow waves: $c = \sqrt{g \cdot d}$, ($g = 9.81 m/s^2$, $d =$ water depth). A depth of 100 m (mean depth of the North Sea) leads to a speed of roughly 100 km/h, a depth of 30 m as in the southern part of the North Sea to a speed of about 60 km/h.

For the derivation of new formulas, the data of the hind casted storm surges were split into two evenly distributed but independent. The validation data set consists of roughly 28 % of the data. The remaining was used for the setup of formulas and neural networks.

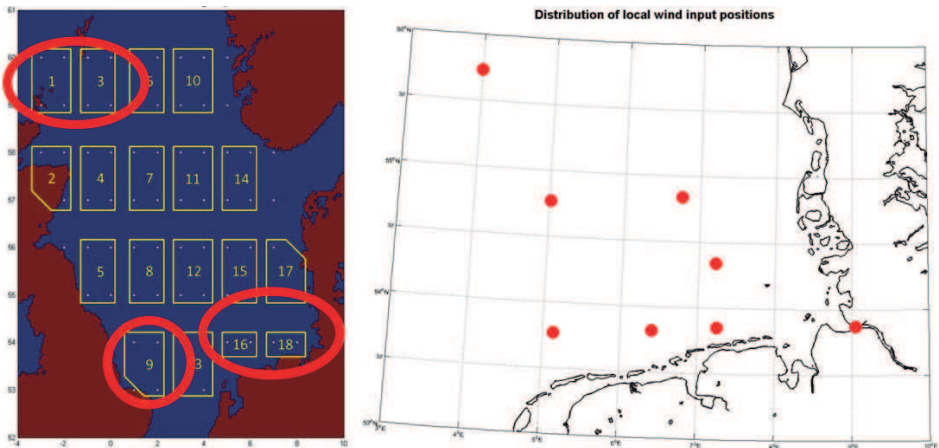


Figure 8: Reduction and choice of wind data points (left), position of local wind output (right).

3.2 Trigonometric approach

Based on the formula of ANNUTSCH (1978) a simple trigonometric approach was used to develop a new formula, taking into consideration not only the local but as well the wind on more distant parts of the North Sea:

$$\begin{aligned}
 Setup = a_0 + \sum_w a_{w1} * WS^2 * \sin(WD) + a_{w2} * WS^2 * \cos(WD) + a_{w3} * WS^3 * \\
 \sin(WD) + a_{w4} * WS^3 * \cos(WD) + \sum_{param} a_{param} * Value
 \end{aligned}
 \tag{1}$$

(with w number of the corresponding positions, WS windspeed, WD wind direction; $param$ are further parameters like air pressure (see below)). This approach works for exposed gauges directly at the open coast only. For estuary gauges it is necessary to implement a preceding gauge at the open coast near the estuary, from which the water level in consideration of the local wind is passed on to the destination gauge. This paper focuses on the forecast of the exposed gauge of Norderney.

In a first step of the study, the best wind input quantities concerning position, spatial and temporal interpolation and delay (see section 3.1.2) were identified. Secondly, the influence of further parameters like air pressure, changes in air pressure, astronomic set up and mean tidal water level on the setup was analyzed.

External waves were neglected due to existing studies (i.e. GÖNNERT 2003) and the impracticability for routine use due to the short timeframe.

3.2.1 Analysis of further parameter

Implementing the difference of air pressure to standard pressure of 1013hPa and the 3hourly-change in air pressure increases the quality of the forecast. SCHMITZ (1978b) has already pointed to the impact of air pressure and gradient. In the new approach it was realized by including the corresponding values from a point 70 km north of Norderney as representative for the German Bight.

The influence of astronomic offset was difficult to obtain due to a lack of data for the older storm surges. Own calculation of astronomical tides did not achieve the accuracy needed for the investigations. Some tests with limited data have shown that the implementation of astronomical residuals increase the quality of the model for set-ups in the “normal” range, when the astronomic residuals are in the same order than the wind set-up, whereas the general quality of the formula decreases within this tests due to the reduction of data amount. As the focus of this study is on the forecast of storm surges, the influence of astronomic residuals is neglected in the moment but is subject of the still running investigations.

As the tidal rise is in the order of a severe to extreme storm surge, the position of the mean tidal curve (i.e. high or low water) is of high importance for the calculation of storm surges (GÖNNERT 2003). Accordingly, the implementation of the mean tidal curve as time series on the approach shows a significant improvement for the forecast.

Altogether, the regression between measurements and the output of the described trigonometric approach shows a root mean squared error (“RMSE”) of about 31 cm (Fig. 9).

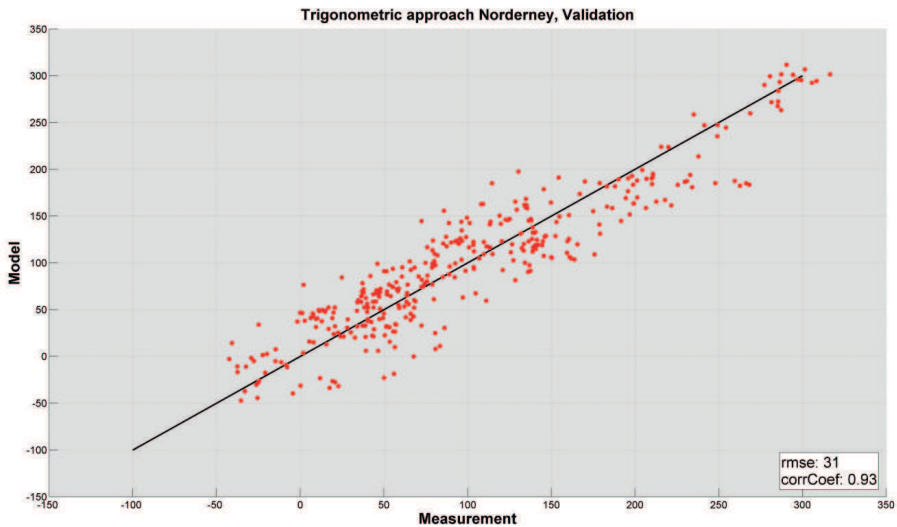


Figure 9: Validation of trigonometric approach for Norderney, measurement (x-axis) versus model (y-axis).

This sounds much, but taking into consideration the wide span of water set up between -50 and plus 300 cm, the neglecting of astronomical residuals – especially for low surge events- as well as the uncertainties in the modelled meteorological data together with the general difficulties in forecasting storm events the results seems good. The formulas are tested now in the operational forecast and have passed satisfyingly a first test during storm “Xaver” (section 3.4).

3.3 Neural network approach

Beside the trigonometric approach, the application of a neural network was tested. Due to the requirement of the NLWKN a network only using meteorological parameter and mean tidal cycles – as in the trigonometric approach – was favored to get a forecast of at least one day. Considering preceding (measured or modelled) water levels denote a much shorter forecasting interval.

As network structure a feed-forward net with 2 layers and 10 neurons in the hidden layer was chosen as the best fitting one (Fig. 10). The input is arbitrary expendable; the output is the setup of water level.

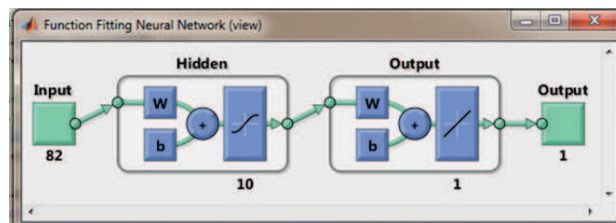


Figure 10: Schematic view of Neural Network.

As input the same data set as for the trigonometric approach was used for the neural network. The “RMSE” for Norderney is 25 cm (Fig. 11), meaning an even better result than for the trigonometric approach.

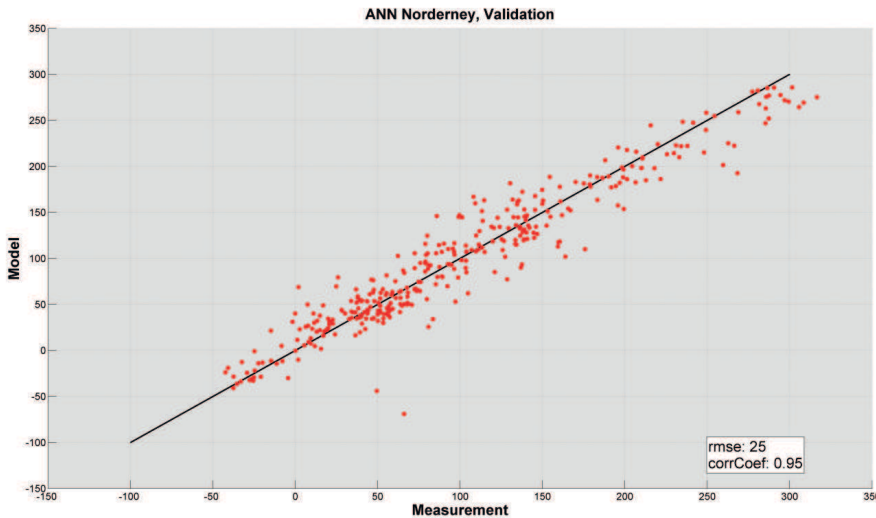


Figure 11: Validation of neural network for Norderney, measurement (x-axis) versus model (y-axis).

But it appears that the results must be regarded with caution, as the adding of only a few more wind datasets or other parameters leads to an evident overfitting of the model. Now working parallel to the daily forecast it must be checked if this tool is applicable for operational use. The test during storm Xaver at least was promising (see section 3.4).

3.4 First Test: Storm surge of 6th December 2013 (“Xaver”)

Both models, the trigonometric approach and the neural network, are used parallel to the operational forecast since November 2013. At the beginning of December, the cyclone “Xaver” led to a chain of storm surges of which the one of December 6th, early morning, was one of the highest storm surges at the Coast of Lower Saxony of the last hundred years. At the gauge of Norderney the storm surge with a height of 2.83 m above the mean high water level was only exceeded by the one of February 1962.

During this event, the new approaches proved to be valuable instruments for the storm surge forecast service of the NLWKN.

Exemplarily, the forecast results at the morning of 5th of December are shown in Fig. 12. The forecast based on the predicted wind and air pressure data provided by the DWD, using the COSMO-EU-Modell, run 12/5., 00:00UTC. The results of the present formula are plotted in dark blue, the trigonometric approach in green, the ANN-results in red and the measurements in black.

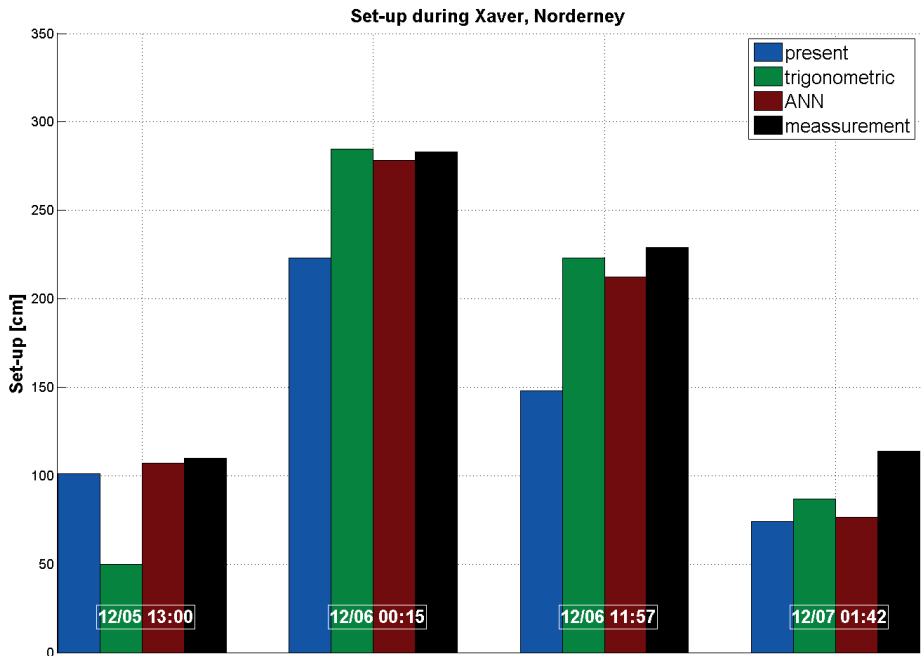


Figure 12: Modeled and measured surges during storm Xaver at Norderney, December 5-7, 2013, comparison of different forecast-models.

Both trigonometric and neural network approach forecasted the two main surges with very satisfying results with a deviation at Norderney less than 20 cm. The results of the new models are significantly better than the results of the present formula. The first surge as well was predicted quite well except the forecast of the trigonometric model for Norderney. The reason for the failing at this point is not clear to us. Deviations between prediction and measurement for the last surge on 12/7 are higher, but it has to bear in mind that there are more than 48 hours between the wind forecast and the resulting storm.

4 Conclusion and Outlook

Storm surges at the coast of Lower-Saxony are driven mainly by the local wind in the German Bight. Furthermore, the wind at the entrance of the North Sea and in the South-Eastern part next to the Norfolk Coast is of importance for empirical storm surge forecast.

To make available a data set with high resolution wind fields and other meteorological variables DWD simulated a set of 39 historical storm events from 1962 till 2011 in the project ‘‘OptempS-MohoWiF’’. The high resolution meteorological data for the North Sea is of great importance for the improvement of empirical storm surge forecasting and other questions about coastal development and protection.

The wind data was calculated with two versions of the limited area model COSMO of DWD. COSMO-eu provided data for the whole North Sea including the entrance of the North Sea bordering to the North Atlantic and the South-Eastern part with the English

Channel. For the German Bight additional data was provided by COSMO-de on a 2.2 km grid. Both models were run in nudging and normal forecast mode. I.e. we have a mini ensemble with 4 members for each storm event. Thereby DWD tested the 2.2 km horizontal grid resolution and 65 vertical layers for COSMO-de, which might become a new operationally setup of COSMO-DE. As expected we got better results for the nudging runs than for the normal forecasts. Comparing COSMO-de and COSMO-eu we see minimally lower values of RMSE of wind and sea level pressure for COSMO-de. The biases for pmsl differ marginally at very low values, but for the 10 m wind they differ significantly. It was shown, that using GlobeCover land use data instead of GLC2000 data could give better results for the wind speed biases for COSMO-eu. Further tests will be made testing a wind speed dependent Charnock constant to calculate the sea surface roughness length.

The newly determined empirical relation between wind, pressure and the surge at the coast of Lower Saxony seems to be a promising approach for the optimization of storm surge forecasting in that region. Its capability was shown at a first test in December 2013 during the severe storm surge "Xaver". On the other hand the test operation in winter 2013/2014 shows the limitation of the forecasting for less intense wind setup, induced by wind directions other than West to Northwest. This concerns especially the chosen approach with artificial neuronal networks. This limitation clearly relies on the focus of the training data set on storm surges with wind directions in the mentioned sector.

The new storm surge forecasting approach at the NLWKN has to be further tested and successive adjustments have to be made to new meteorological data which will be provided by the operational weather forecasting models of the DWD.

5 References

- ANNUTSCH, R.: Über das empirisch-statistische Sturmflutvorhersageverfahren des Deutschen Hydrographischen Instituts. *Promet*, 8 H. 4, 9-12, 1978.
- ARINO, O.; BICHERON, P.; ACHARD, F.; LATHAM, J.; WITT, R. and WEBER, J.-L.: GlobCover the most detailed portrait of Earth. *ESA Bulletin*, 136, 25-31, 2008.
- BALDAUF, M.; SEIFERT, A.; FÖRSTNER, J.; MAJESWKI, D.; RASCHENDORFER, M. and REINHARDT, T.: Operational Convective-Scale Numerical Weather Prediction with the COSMO model: Description and Sensitivities. *Mon. Wea. Rev.*, 139, 3887-3905, 2011.
- BARTHOLOMÉ, E. and BELWARD, A.S.: GLC2000: a new approach to global land cover mapping from Earth observation data. *Int. J. Remote Sens.*, Vol. 26, No. 9, 1959-1977, 2005.
- CONSORTIUM FOR SMALL-SCALE MODELLING: COSMO model documentation: <http://www.cosmo-model.org>, last visited: 07.01.2014.
- DEE, D.P.; UPPALA, S.M.; SIMMONS, A.J.; BERRISFORD, P.; POLI, P.; KOBAYASHI, S.; ANDRAE, U.; BALMASEDA, M.A.; BALSAMO, G.; BAUER, P.; BECHTOLD, P.; BELJAARS, A.C.M.; VAN DE BERG, L.; BIDLOT, J.; BORGMANN, N.; DELSOL, C.; DRAGANI, R.; FUENTES, M.; GEER, A.J.; HAIMBERGER, L.; HEALY, S.B.; HERSBACH, H.; HÓLM, E.V.; ISAKSEN, I.; KÁLLBERG, P.; KÖHLER, M.; MATRICARDI, M.; McNALLY, A.P.; MONGE-SANZ, B.M.; MORCRETTE, J.-J.; PARK, B.-K.; PEUBEY, C.; DE ROSNAY, P.; TAVOLATO, C.; THÉPAUT, J.-N. and VITART, F.:

- The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.*, Vol. 137: 553-597, 2011.
- DEUTSCHER WETTERDIENST: Das barokline Model BKF. *Promet* 2/3 1978, p. 48, 1978
- DICK, S.; KLEINE, E.; MÜLLER-NAVARRA, S.H.; KLEIN, H. and KOMO, H.: The operational Circulation Model of BSH (BSHcmod) – Model Description and Validation. *Ber. d. Bundesamtes für Seeschifffahrt und Hydrographie*, Nr. 29, 49p, 2001.
- FRANK, H. and MAJEWSKI, D.: Hindcasts of historic storms with the DWD models GME, LMQ and LMK using ERA-40 reanalyses. *ECMWF Newsletter*, Vol. 109, 16-21, 2006.
- GÖNNERT, G.: Sturmfluten und Windstau in der Deutschen Bucht. Charakter, Veränderungen und Maximalwerte im 20. Jahrhundert. *Die Küste* 67: 185-365, 2003.
- GÖNNERT, G.; DUBE, S.K.; MURTY, T. and SIEFERT, T.: Global Storm Surges: Theory, Observations and Applications - Preface and Contents. *Die Küste* 63, Global Storm Surges, 2001.
- JENSEN, J. and MÜLLER-NAVARRA, S.H.: Storm Surges on the German Coast. *Die Küste* 74, 92-124, 2008.
- MAJEWSKI, D.; LIERMANN, D.; PROHL, D.; RITTER, B.; BUCHHOLD, B.; HANISCH, T.; PAUL, G.; WERGEN, W. and BAUMGARDNER, J.: The Operational Global Icosahedral-Hexagonal Gridpoint Model GME: Description and High-Resolution Tests. *Mon. Wea. Rev.* 130, 319-338, 2002.
- MÜLLER-NAVARRA, S.H. and GIESE, H.: Empirische Windstauformeln für die Deutsche Bucht. *Deutsche IDNDR-Reihe* 7, 37-41, 1997.
- MÜLLER-NAVARRA, S.H.; LANGE, W.; DICK, S. and SOETJE, K.C.: Über die Verfahren der Wasserstands- und sturmflutvorhersage: Hydrodynamisch-numerische Modelle der Nord- und Ostsee und ein empirisch-statistisches Verfahren für die Deutsche Bucht. *Promet* 29, 117-124, 2003.
- PETERSEN, M. and ROHDE, H.: Sturmflut: Die großen Fluten an den Küsten Schleswig-Holsteins und in der Elbe. Neumünster, 1991.
- PHILIPPART, M.E and GEBRAAD, A.: A new storm surge forecasting system. In: STEL, J.H. et al. (Ed.). *Operational oceanography: the challenge for European co-operation: Proceedings of the First International Conference on EuroGOOS 7-11 October 1996, The Hague, The Netherlands*. Elsevier Oceanography Series, 62, 487-495, 1997.
- SCHRAFF, C.H.: Mesoscale Data Assimilation and Prediction of Low Stratus in the Alpine Region. *Meteorol. Atmos. Phys.* 64, 21 50, 1997.
- SCHRAFF, C. and HESS, R.: Datenassimilation für das LM. *Promet*, Jahrgang 27, Nr. 3/4, 156-164, 2002
- SCHMITZ, H.P.: Sturmfluterzeugende Vorgänge in der Nordsee. *Promet* 4, 2-5, 1978a
- SCHMITZ, H.P.: Vorhersageverfahren und ihre Probleme. *Promet* 4, 9-12, 1978b.
- STAUFFER, D.R. and SEAMAN, N.L.: Use of Four-Dimensional Data Assimilation in a Limited-Area Mesoscale Model Part I: Experiments with synoptic scale data. *Mon. Wea. Rev.* 118, 1250-1277, 1990.
- STAUFFER, D.R. and SEAMAN, N.L.: Multiscale four-dimensional data assimilation. *J. Appl. Meteorol.* 33, 416-434, 1994.

- STAUFFER, D.R.; SEAMAN, N.L. and BINKOWSKI, F.S.: Use of Four-Dimensional Data Assimilation in a Limited-Area Mesoscale Model Part II: Effects of Data Assimilation within the Planetary Boundary Layer. *Mon. Wea. Rev.* 119, 734-754, 1991.
- UPPALA, S.M.; KÁLLBERG, P.; SIMMONS, A.; ANDRAE, U.; DA COSTA BECHTOLD, V.; FIORINO, M.; GIBSON, J.; HASELER, J.; HERNANDEZ, A.; KELLY, G.; LI, X.; ONOGI, K.; SAARINEN, S.; SOKKA, N.; ALLAN, R.; ANDERSSON, E.; ARPE, K.; BALMASEDA, M.; BELJAARS, A.; VAN DE BERG, L.; BIDLOT, J.; BORMANN, N.; CAIRES, S.; CHEVALLIER, F.; DETHOF, A.; DRAGOSAVAC, M.; FISHER, M.; FUENTES, M.; HAGEMANN, S.; HÓLM, E.; HOSKINS, B.; ISARKSEN, L.; JANNSEN, P.; JENNE, R.; MCNALLY, A.; MAHFOUF, J.-F.; MORCRETE, J.-J.; RAYNER, N.; SAUNDERS, R.; SIMON, P.; STERL, A.; TRENTBETH, K.; UNTCH, A.; VASILJEVIC, D.; VITERBO, P. and WOOLLEN, J.: The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.*, Vol. 131, 2961-3012, 2005.