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A Hydrodynamic Numerical Model for the Simulation of Storm Surges in the North Sea: Set-up and Sensitivity Analysis

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Abstract

A numerical model has been set-up to simulate the tidally and meteorologically driven hydrodynamics in the North East Altantic and North Sea region. The hydrodynamics are driven by astronomical tidal water level at the open lateral boundaries. At the surface boundary wind and pressure fields are prescribed. Meteorological fields of different sources (NCEP/NCAR, PRISMA, QSCAT) are directly inter-compared, and with regard to their effect on the resulting hydrodynamics. An algebraic method for the temporal interpolation between global wind- and pressure fields for open surface boundaries is proposed which overcomes shortcomings connected to direct linear or blockwise interpolation. The model is able to hindcast tidally driven water levels and surges induced by pronounced North Sea storm.

1 Introduction

Storm surges are caused by the superposition of astronomical and barometrical tides and wind driven water level set-up. Depending on the tidal stage, the pathway, strength, direction and duration of storms, and local morphological conditions, the effect of this kind of extreme events can be of significant hazard to the densely populated coastal areas. Although the general mechanisms leading to extreme water levels are well understood, the diversity of forcing, local conditions, and climate variability calls for dedicated studies on storm surges.

Hydrodynamic numerical models for the simulation of marine processes nowadays are standard tools for various applications in research, administration, and engineering. Numerous studies have proved the applicability of different modelling systems to river, estuarine, coastal, shelf and ocean dynamics by model verification and validation. The North Sea's shelf and coasts has been subject to several modelling studies on the dynamics of storm-surges. For an extensive literature review see e.g. Gönnert et al. (2001), and the references therein. Amongst others Dolata et al. (1983), Gerritsen and Bijlsma (1988), Flather et al. (1998), Langenberg et al. (1999) and Kauker and Langenberg (2000) have shown that storm surges and their statistics can be satisfactorily simulated with hydrodynamic models, especially if the focus is set on long-term statistics rather than on single events (Woth et al., 2006).

As numerical storm surge model simulations are driven by wind- and pressure fields at the surface boundary, it is obvious that the quality of the hydrodynamic simulation is highly dependant on the quality and characteristics of the given meteorological boundary conditions. Direct measurements of the required wind and pressure in sufficient temporal and spatial resolution are not feasible for such large areas like the North Sea, thus data has to be obtained by other means. Possible sources are local or global climate model simulations, data re-analysis products, or remote sensing analysis. These synoptic meteorological data typically are obtained as gridded (10m) wind velocities and atmospheric surface pressure values given at different time intervals.

The North Sea hydrodynamics are not only influenced by local storms (internal surges), but also by meteorological events over the North Atlantic (external surges). Petersen and Rohde (1991) and Gönnert et al. (2001) characterise three different storm types, according to their place of origin and pathways: The strong "Jutland type" storms usually cross the North Sea from middle-England towards the Danish West coast between N55 and N57 latitude. The "Scandinavia type" storms originate in the area of Greenland and Island, head in South-Easterly direction and cross Scandinavia between N60 and N65 latitude. In between these, the "Skagerak type" storm pathways travel from WNW to ESE (Figure 1).

In this study, we use a numerical model of the North Sea and North-East Atlantic region, to study the effect of different wind- and pressure fields applied as surface forcing of hydrodynamic simulations. A major storm surge, of Jutland type, which occurred December 3-4, 1999 has been chosen to evaluate model performance, and stress out different aspects in simulating extreme events.

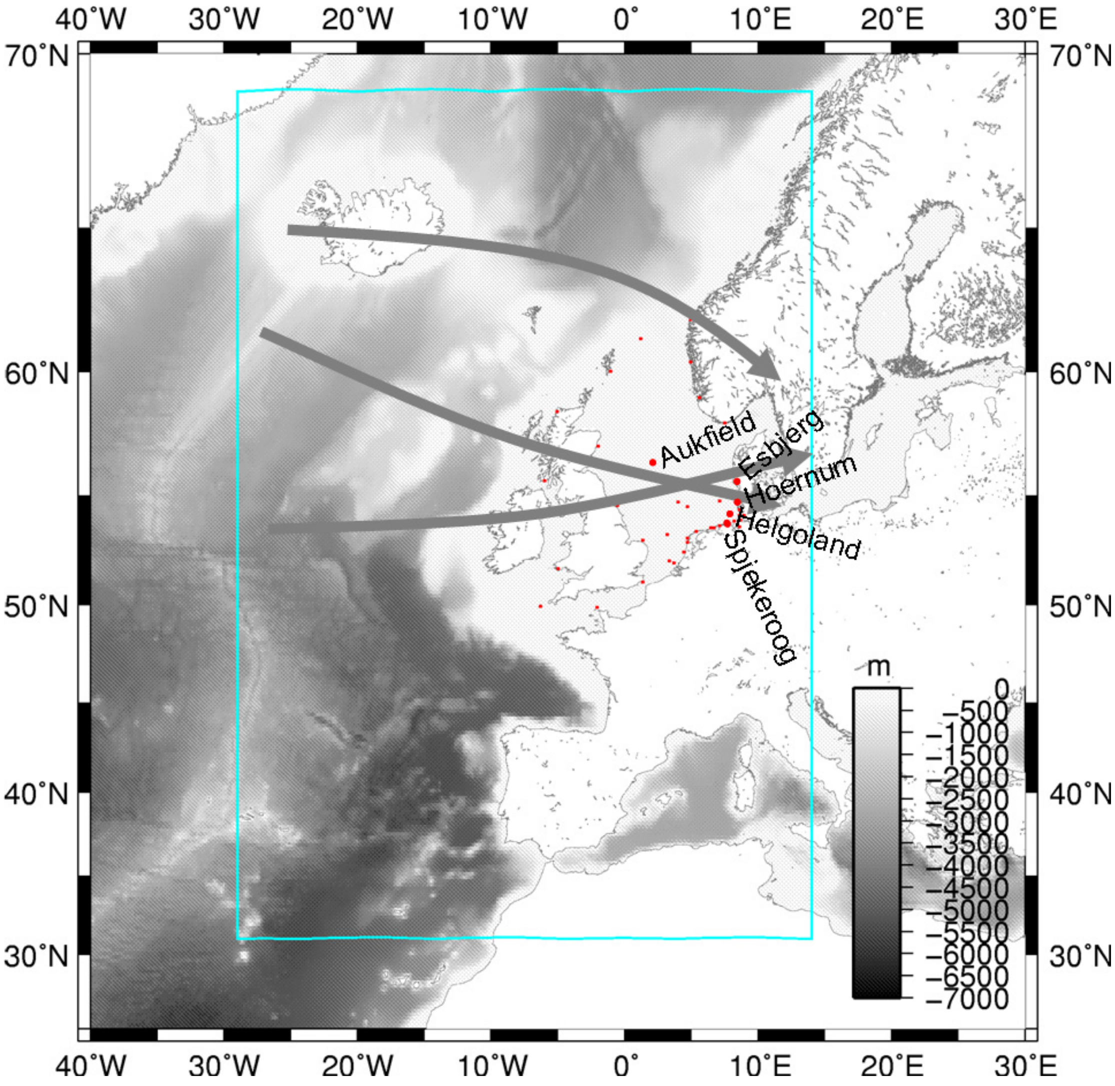

Figure 1 Model extension, main stom pathways in Northern Europe (Petersen and Rohde ,1991). Also indicated are gauge stations mentioned in the text

2 Methods and Data

The model domain covers the North Sea and adjacent North East Atlantic region between W29° and E15° longitude and N31° and N69° latitude (Figure 1). Thus it can be assumed that the typical pathways of cyclones leading to storm floods in the North Sea fall into the model domain. Model code of the Princeton Ocean Model (POM) has been adopted, a numerical modelling system, which solves the shallow water equations on a spherical computational grid using a finite difference solving scheme (Mellor, 2004). The grid elements have a resolution of 10 minutes in latitude and longitude. The model bathymetry has been compiled from a global dataset (Smith and Sandwell, 1997) and in the southern North Sea from the operational German ocean general circulation model BSH-cmod (Kleine, 1994). The extension of the North East Atlantic model (NEAM) domain is plotted in Figure 1 .

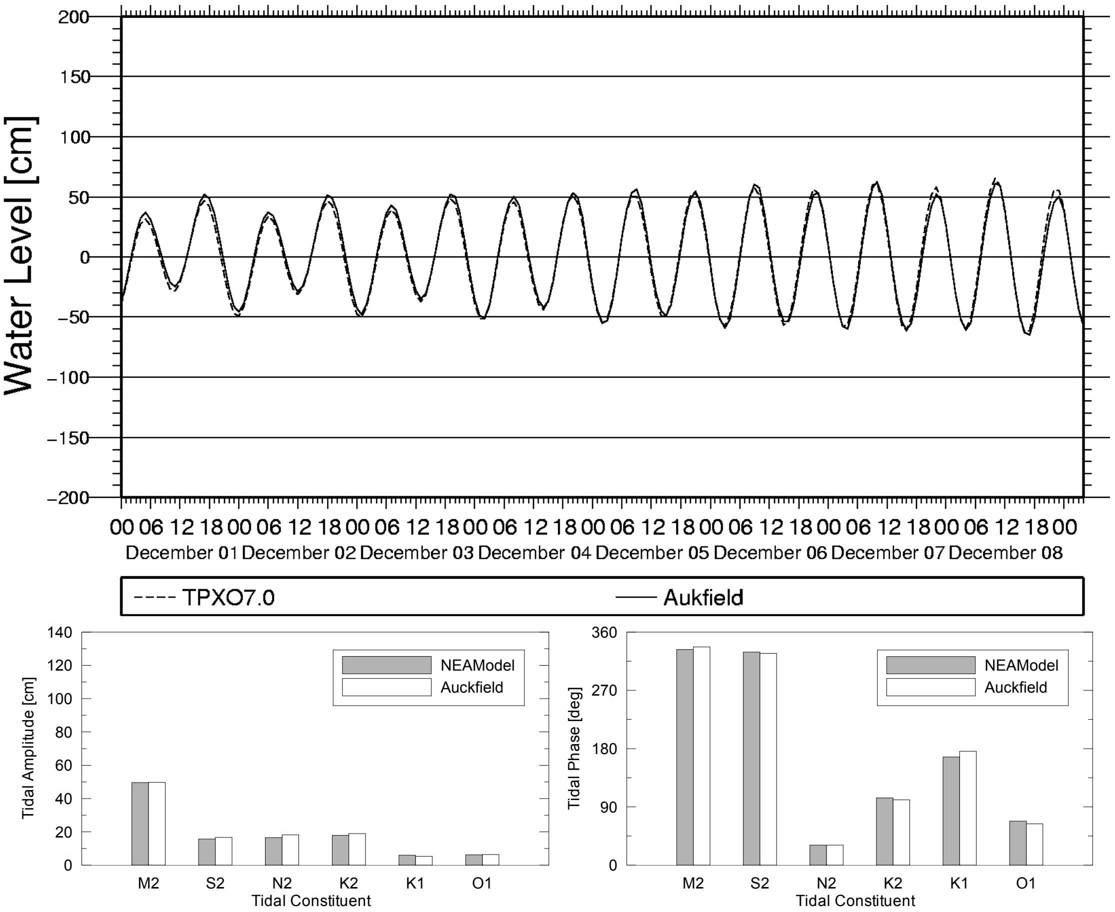

Figure 2 Observed astronomical tide and TPXO7.0 tide at station Auckfield (see Figure 1)

2-1 Lateral Open Boundary Conditions

At the lateral open boundaries the model is forced by vertical astronomic tides. The surface water elevations are derived from the OSU TPOEX/Poseidon global inverse model TPXO 7.0 (Ebgert et al., 1994; Egbert et al., 2002). Here TPXO7.0 is treated as a subroutine of the NEA Model to calculate the water level along the open boundaries at each time step. The 8 major harmonic constituents M2, S2, N2, K2, K1, O1, P1 and Q1 are used. The TOPEX Poseidon data has been exemplarily verified for an offshore tidal gauge of Auckfield platform (see Figure 1). As the discrepancy between the global tidal data and the observed tidal signal is below gauge data accuracy sufficient data quality of the tidal boundary conditions are assumed.

2-2 Surface Boundary Conditions

In addition to the astronomical tides, storm surge generation involves wind stress terms and the horizontal gradient of atmospheric pressure at the sea surface. In deep water, surge elevations are approximately hydrostatic; 1 HPa decrease in atmospheric pressure results in about 0.01 m increase in surge elevation from $P = \rho g h$. The wind stress can be evaluated by:

$$\tau_u = \rho_a C_D u|u| \tag{1}$$

In which ρ_a is the density of air and C_D is the wind drag coefficient, which can be derived e.g. by the standard Smith and Banke (1975) formulation:

$$C_D = 0.001 * (\alpha + \beta|V|) \tag{2}$$

In which V is the wind velocity magnitude, and the calibration constants read $\alpha = 0.63$ and $\beta = 0.066$.

The correct specification of meteorological data is crucial for a good representation of the natural dynamics. Meteorological data can be obtained from large- or regional scale climate models, remote sensing analysis or data re-analysis. Typically these products are recorded and provided in gridded formats, i.e. spatially interpolated to discrete grid nodes and given for different time intervals.

2-2-1 Meteorological Data Sources

In this study, the hydrodynamic model has been driven by 10m wind and sea surface atmospheric pressure fields derived by global atmospheric re-analysis, satellite data, and synoptic interpolation of observation data. The three different datasets are exemplarily inter-compared for the situation of December 03 1999, 12:00 UTC (Figure 3). The cyclone of storm “Anatol” at this time was centered over the North Sea at N7 latitude and E4 longitude (Bissolli et al., 2001).

Global atmospheric re-analysis data has been obtained from the National Centers for Environmental Prediction (NCEP) and Atmospheric Research (NCAR), available in an earth-spanning 2.5 degree grid (145*73 elements) since 1/1/1948, with 6 hours resolution (Kalnay et al., 1996; Figure 3a).

Ocean surface wind data are also derived from QUICKSCAT data, i.e. spatial blending of high-resolution satellite data (QSCAT) and global weather center analyses (NCEP), resulting in 6-hourly, 0.5 x 0.5 degree datasets, available since July 1999 (Figure 3b).

Wind velocity and atmospheric pressure obtained from land and sea based observations have been interpolated on a 42*42km grid by using a multi-variate analysis interpolation model of the Max Planck Institute for Meteorology, Hamburg, Germany (Luthard 1987). The data is available in timesteps of three hours, for the North Sea area (Figure 3c).

These different datasets are inter-compared exemplarily for the location of Helgoland in the German Bight, southern North Sea for a 12 day period (Figure 4). Although general characteristics are similar, as the different wind fields’ data follow the locally observed wind speeds, absolute magnitudes are somewhat higher for the main storm event. It is obvious that small oscillations of the wind velocity signal cannot be resolved by the wind fields which provide data in timesteps of three resp. six hours.

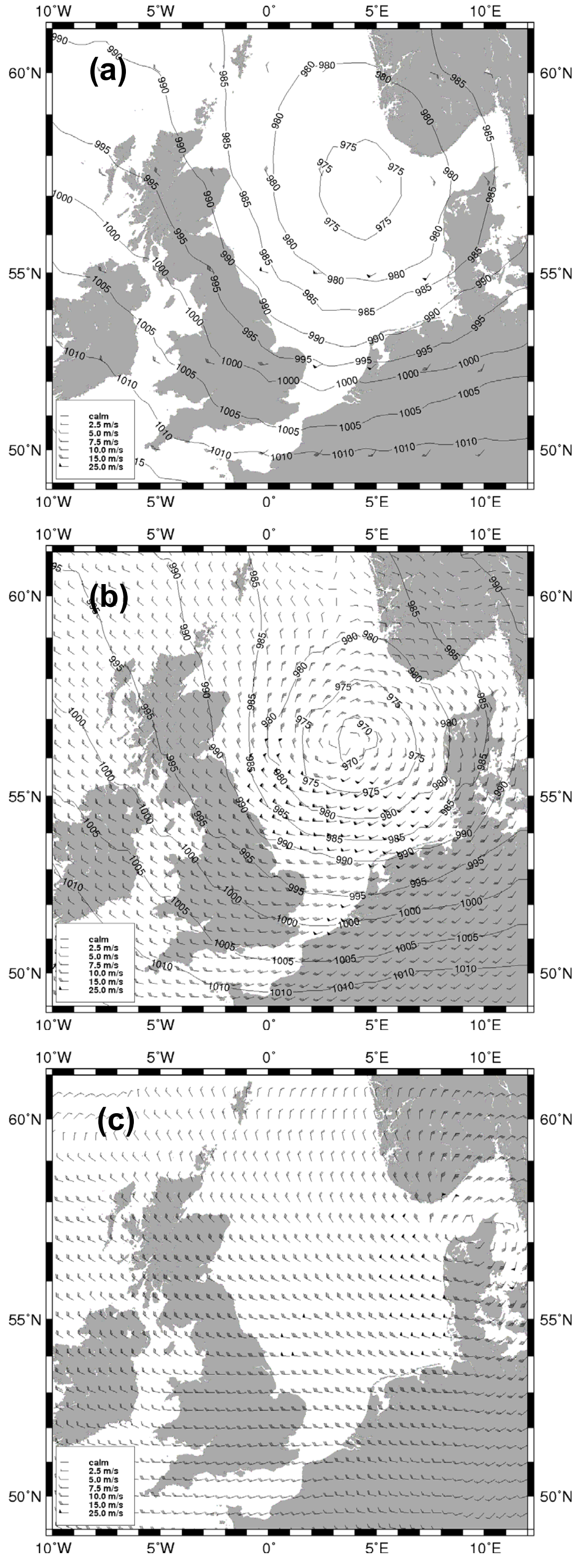

Figure 3 Wind and pressure fields on Dec 03 1999, 12:00 as given by (a) NCEP, (b) PRISMA, and (c) QSCAT (only wind fields)

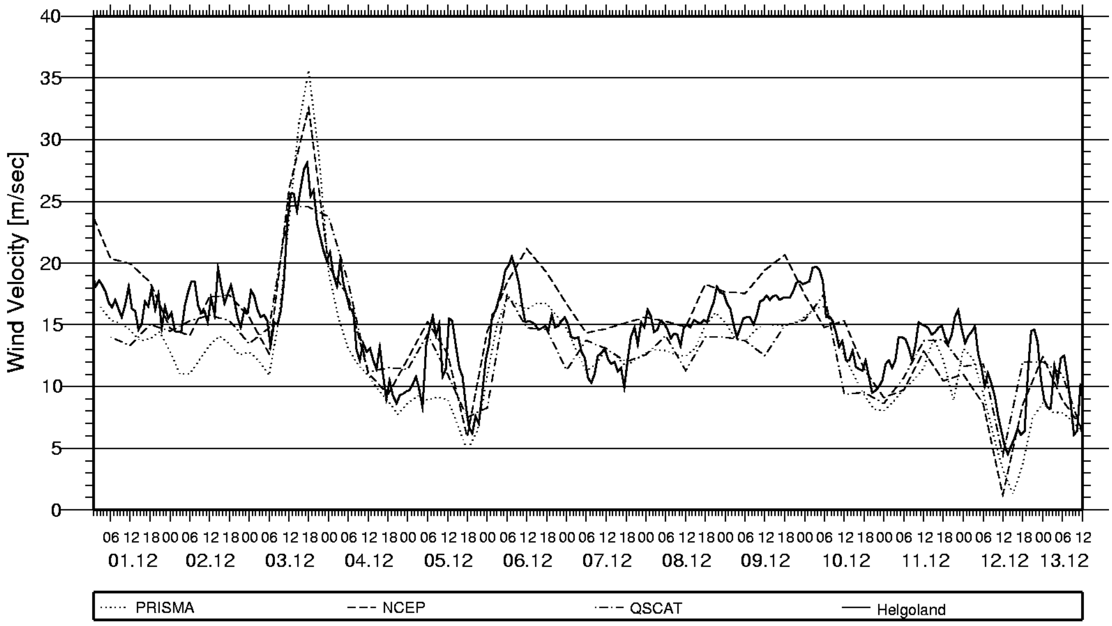

Figure 4 Observed wind velocity at station Helgoland and interpolated from NCEP, PRISMA, QSCAT data.

2-2-2 Meteorological Downscaling

The numerical hydrodynamic simulation requires wind and pressure information at every grid node and for every computational time step. This required resolution cannot be provided directly by the climate data sets, which feature much coarser temporal and spatial scales. Thus a downscaling of meteorological data is to be applied. Methods for downscaling of meteorological data cover the broad range of simple (linear, blockwise or higher order) interpolation schemes in space and time to statistical methods (e.g. IPCC, 2001) to regional high resolution climate models nested into global models (e.g. Feser et al, 2001; Weisse et al., 2005).

Under the assumption that relevant meterological features as e.g. the cyclone structure are sufficiently resolved by the grid, a direct spatial interpolation between grid nodes seems feasible as exemplarily shown for Helgoland station in Figure 4. However, although commonly applied in hydrodynamic modelling applications, a direct interpolation between different fields in time cannot account for realistic dynamic migration of storms. Instead, a fast moving cyclone, which is captured by the meteorological data only at some positions along its pathway, would appear as a chain of appearing and vanishing events, if interpolated linearily in time. A blockwise stepping interpolation between meteorological states instead would induce abrupt changes in wind strength and direction. Thus local dynamic climate models of higher resolution are often used to provide boundary conditions at higher resolution. However, despite the fact that local models – although driven at the open model boundaries by reliable re-analysis data – not necessarily simulate the real dynamics of the meteorological system, an adaption of local climate models, the set-up, validation and operational application may not be feasible for every domain of investigation.

Here a simple method for the temporal interpolation of extreme events is proposed, that takes into account the pathway and evolution of cyclones, and thus keeps track of the wind and pressure dynamics in time and space. It is assumed that the cyclone center migrates on a straight line between two points in time. Also a linear change of the wind velocities and atmospheric pressure relative to the center of the cyclone is assumed during that period. As the location of the center and the magnitude of the adjacent wind and pressure field can be calculated, the evolution of the cyclone can be described at any point in time.

This pathway method is demonstrated and compared to results of simple linear interpolation on the above mentioned storm of December 3rd, 1999. Figure 5 shows the wind and pressure distribution as obtained from NCEP/NCAR re-analysis data for 6:00 and 18:00 UTC. At the former situation the cyclone is centered over Northern Scotland, the latter shows the cyclone after its passage across the North Sea, over Northern Denmark. Also shown is the approximated storm track.

The state of 12:00 UTC as given by NCEP/NCAR is compared to the results of linear interpolation, and of the pathway method on Figure 6. It becomes clear that main characteristics of the storm are not captured when using the linear interpolation: Neither wind fields (cf. e.g. the strong North-Westerly winds along the British East coast) nor the pressure distribution can be reproduced. A block interpolation would result in an abrupt change from Figure 5a to 5b at this time. In contrast the pathway method does produce a similar result, although the center of the cyclone is approximately one degree latitude off track. This error is due to the estimated straight aligned stormtrack. The results are quantified along the cross-section in Figure 7 to Figure 10. It is assumed that the error of assuming a linear pathway reduces when taking into account smaller periods in between meteorological fields.

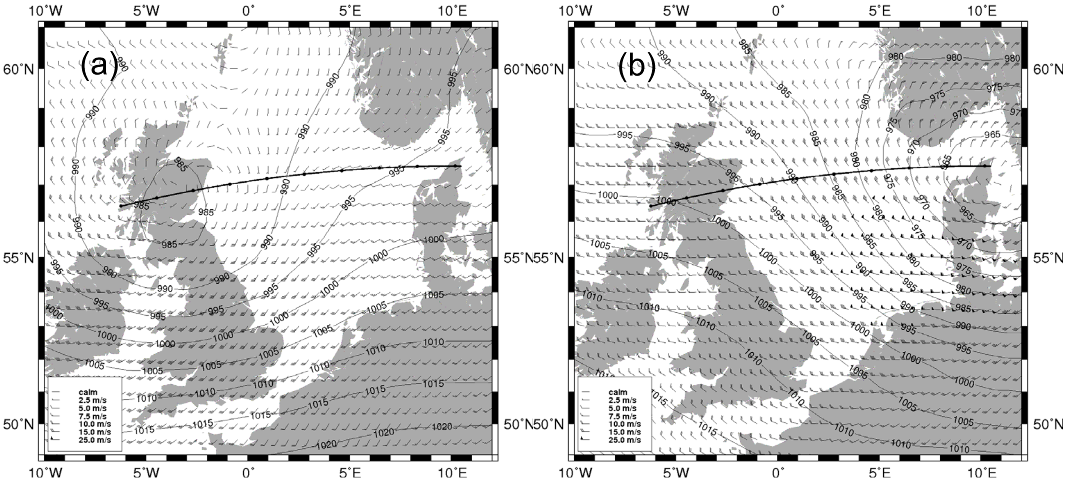

Figure 5 NCEP wind field at 1999 12 03, shown is a cross-section along the estimated pathway for further analysis. a) 06hr ; b) 18 hr

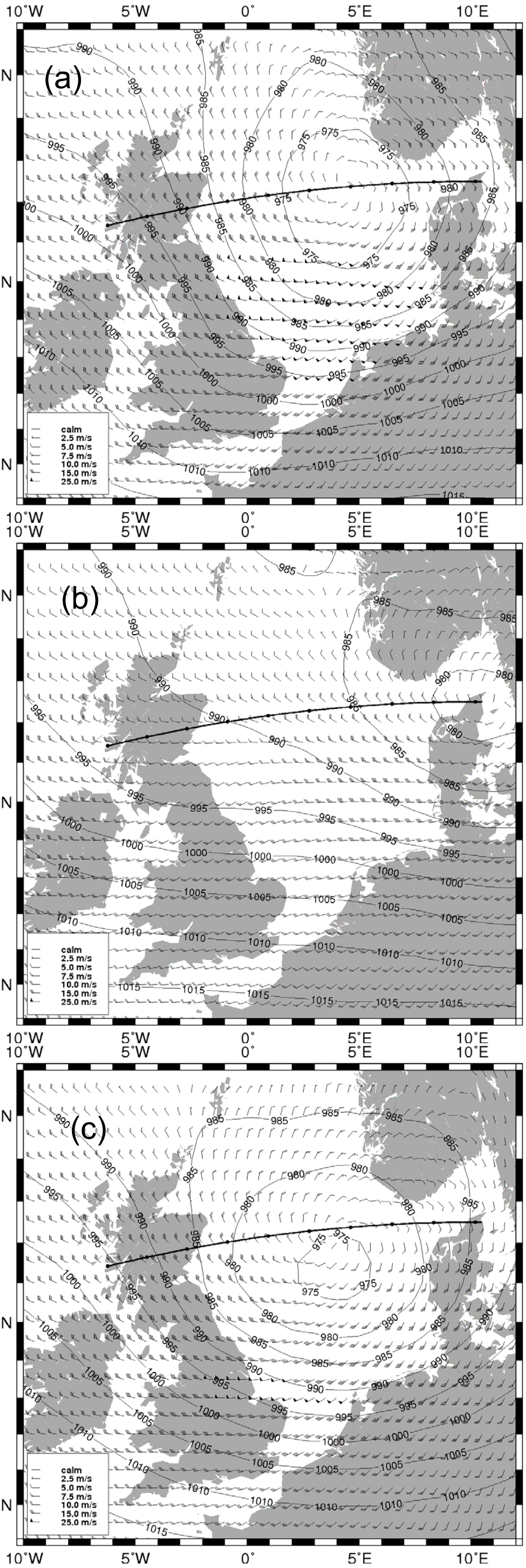

Figure 6 a) NCEP data at 12:00, b) Linear interpolation for 12:00, c) Pathway interpolation for 12:00

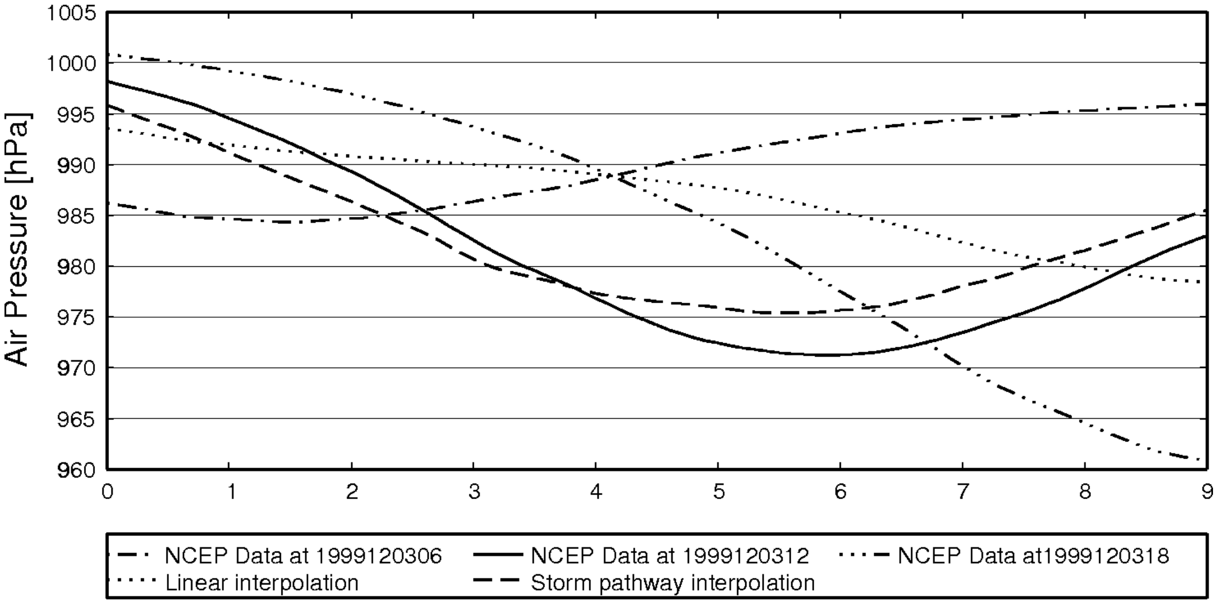

Figure 7 Atmospheric pressure as obtained from NCEP/NCAR for 6:00, 12:00, 18:00 and calculated by linear interpolation and pathway interpolation

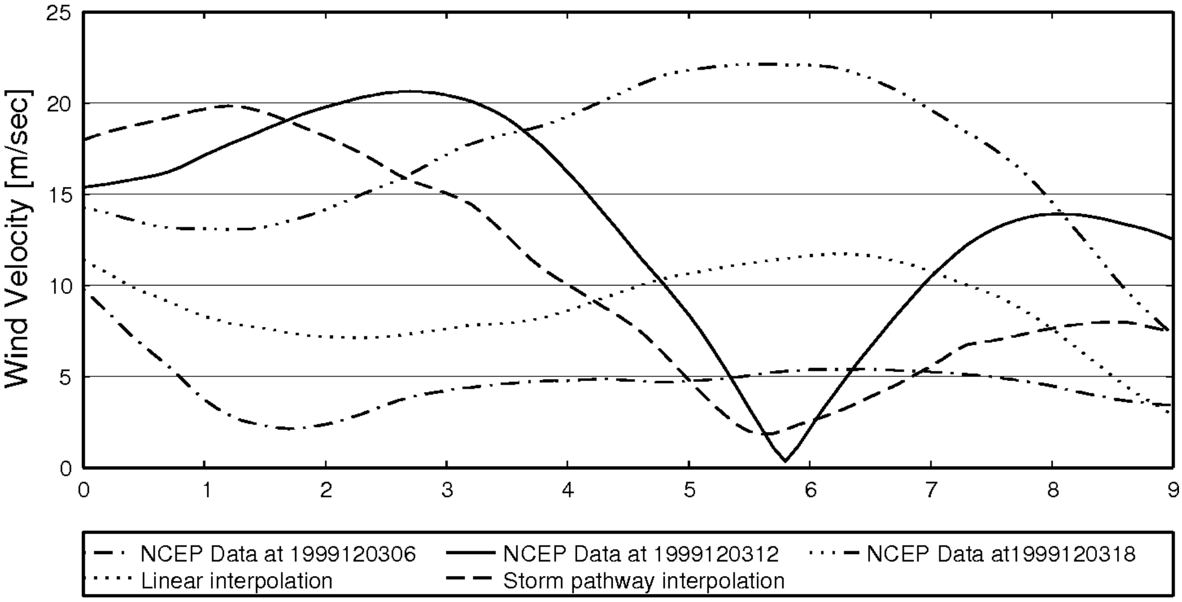

Figure 8 Velocity magnitude along cross-section as obtained from NCEP/NCAR for 6:00, 12:00, 18:00 and calculated by linear interpolation and pathway interpolation

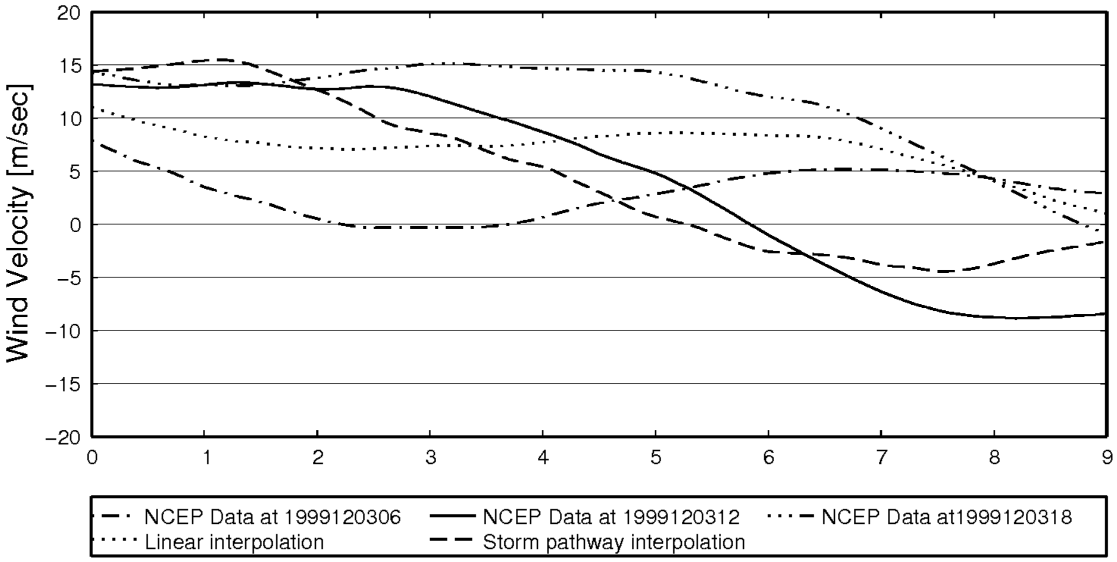

Figure 9 Velocity Longitudinal Wind Velocity as obtained from NCEP/NCAR for 6:00, 12:00, 18:00 and calculated by linear interpolation and pathway interpolation

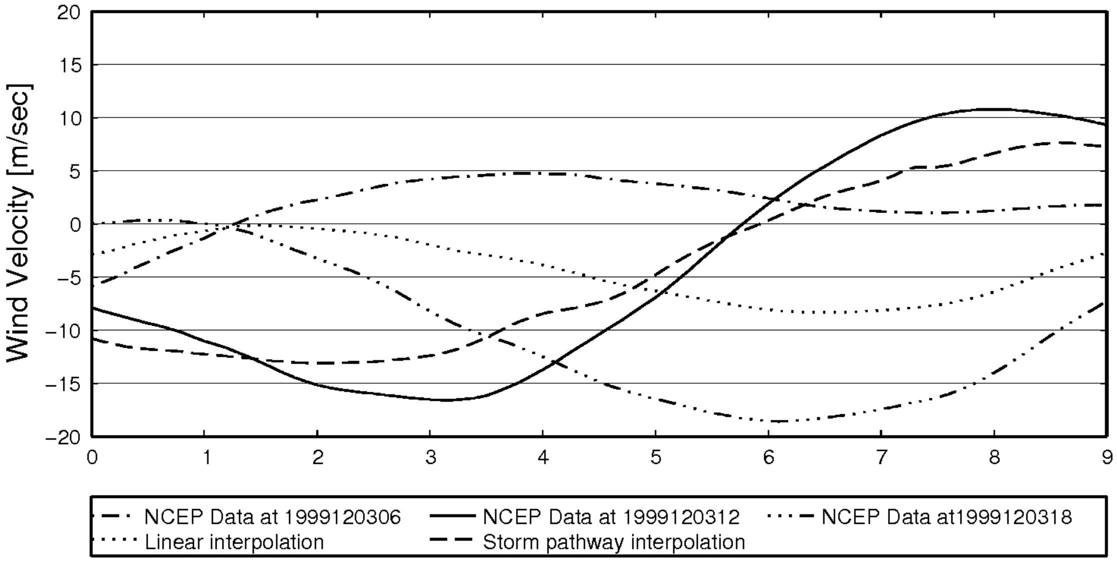

Figure 10 Latitudinal Wind Velocity as obtained from NCEP/NCAR for 6:00, 12:00, 18:00 and calculated by linear interpolation and pathway interpolation

3 Results and Discussion

The NEA model introduced in this study is not expected to reproduce tidal water levels or current velocities at coastal stations with high accuracy, as the coastal bathymetry, which is of great influence on the hydrodynamic characteristics, cannot be discretised by a coarse computational grid. Thus a detailed model calibration has been omitted at this stage. However, to allow for a quantitative evaluation of model quality, three exemplary gauge stations have been chosen. In the next section the model quality is evaluated in terms of astronomical tides only. The following sections describe the impact of different meteorological fields and interpolation schemes on the resulting changes in simulation.

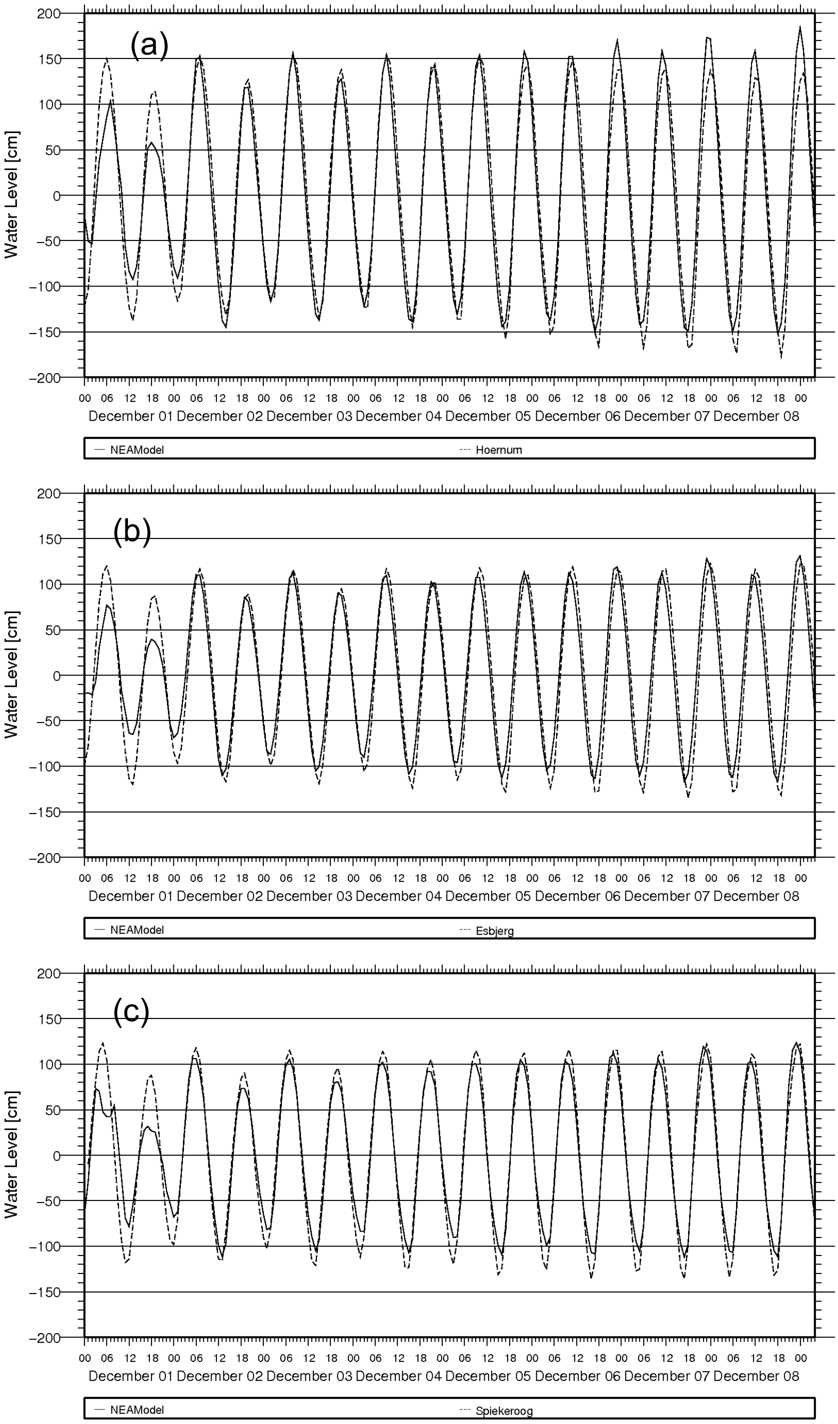

Figure 11 Tidal simulation NEA Model at the gauges

(a) Hoernum, (b) Esbjerg, and (c) Spiekeroog

3-1 Model Quality Tidal Forcing

Figure 11 shows one week of NEAM simulation, driven only by astronomical tides at the lateral open boundaries compared to the re-composed data based on a tidal analysis of three coastal gauges. Apart from the model spin up time on the first day, the tidal maxima are captured within centimeter accuracy. The larger differences between measured and calculated minimum water levels are due to the low resolution of tidal channels and could be adjusted by a local reduction of bottom roughness. Tidal amplitudes and phases are compared in detail in Figure 12.

3-2 Effect of Different Wind and Pressure Fields

The differences between the NCEP/NCAR, PRISMA and NSCAT meteorological data fields have been described above. In the following, their effect on the hydrodynamic simulation is inter-compared at some exemplary coastal stations. As commonly applied, we first use a direct linear interpolation between wind fields, with uniform wind drag coefficients, $\alpha = 0.63$ and $\beta = 0.066$ (Peeck et al, 1983). The effect of different wind fields are shown in terms of surge water levels only (after subtraction of tidal signal) at three exemplary stations (Figure 13): PRISMA data leads to best agreement between measured and computed water levels in times of low wind celerities. However, the maximumm water levels are highly over-estimated. The application of

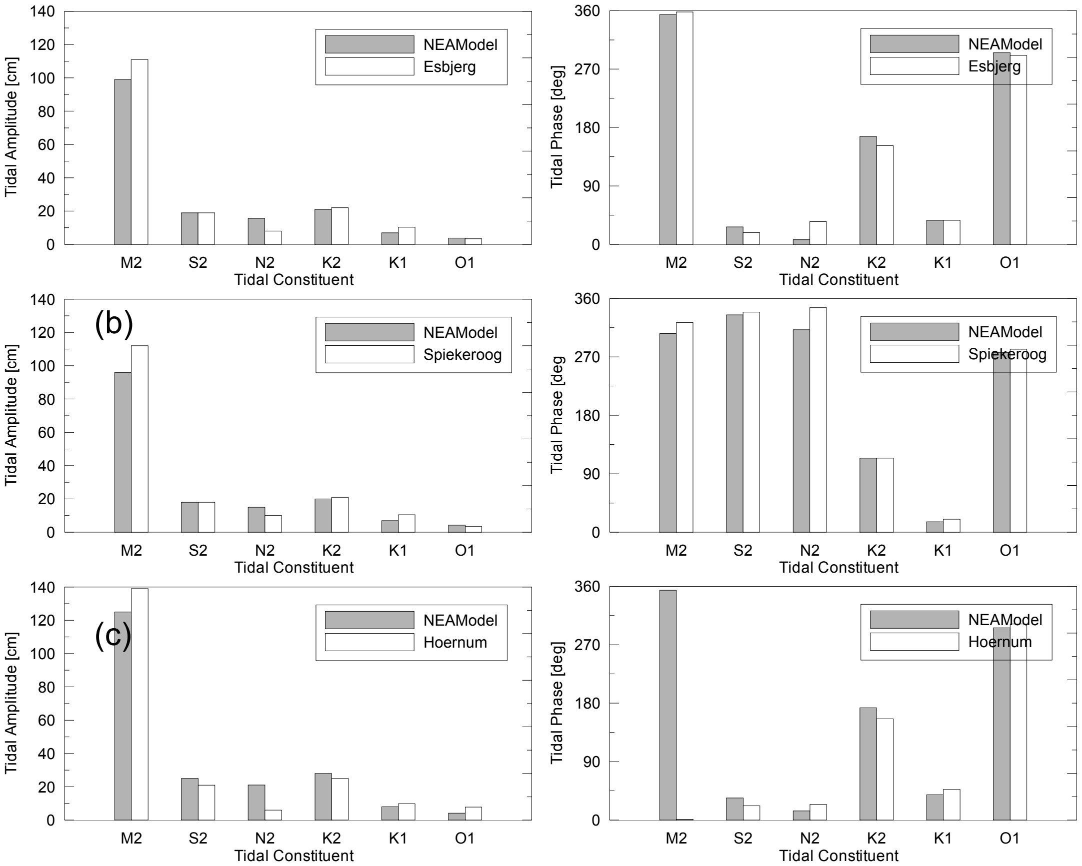

Figure 12 Model validation: Tidal amplitudes and phases of astronomical constituents of tidal gauges (a) Esbjerg, (b) Spiekeroog, and (c) Hoernum

NCEP/NCAR generally results in water levels too high compared to the measured.

QSCAT data seems to capture the maximum water levels, but lacks characteristic oscillations during the calmer period. Note that all model simulations ignore the second pronounced peak around December 4, 6:00, of the measured storm water levels.

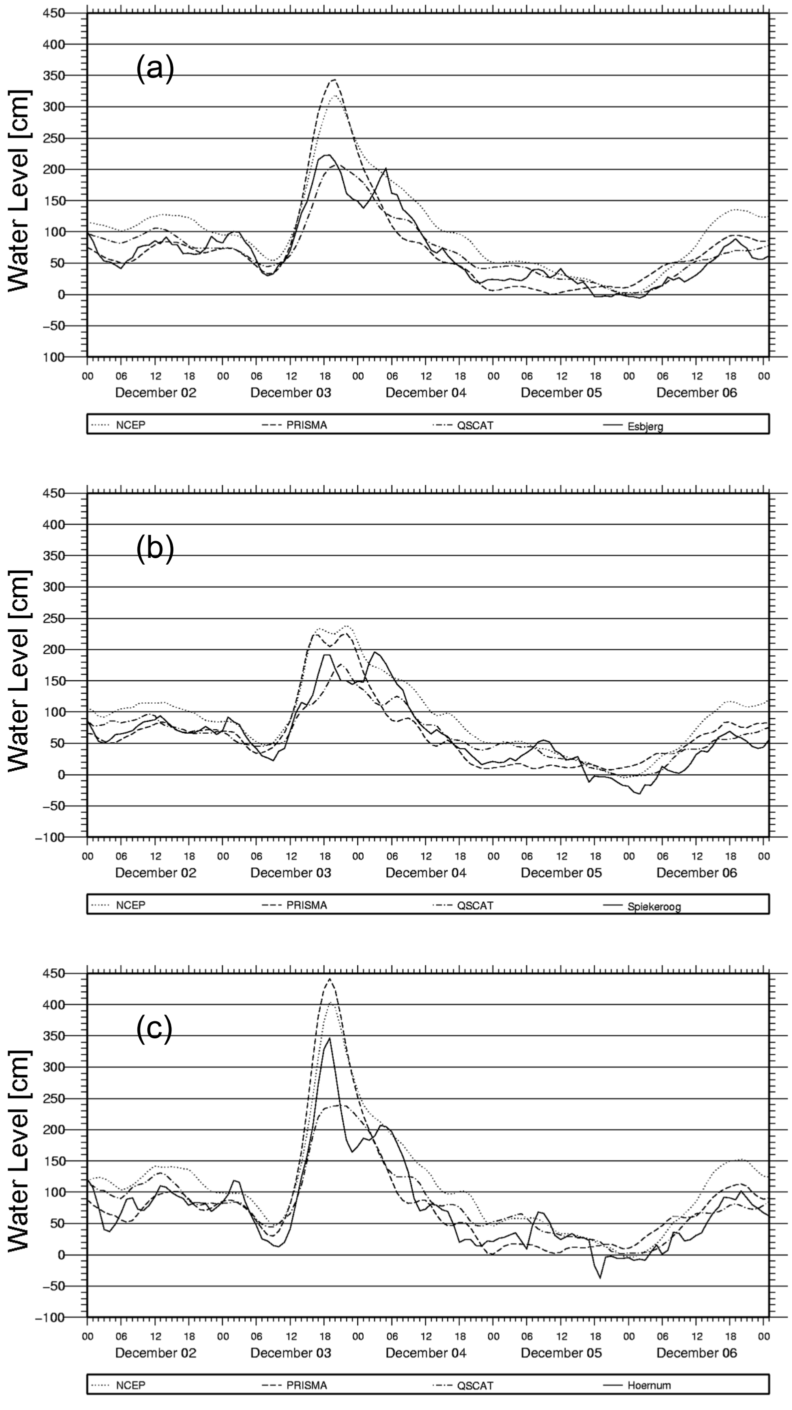

Figure 13 Comparison of measured and computed water level timeseries at different coastal stations (linear interpolation) of tidal gauges (a) Esbjerg, (b) Spiekeroog, and (c) Hoernum

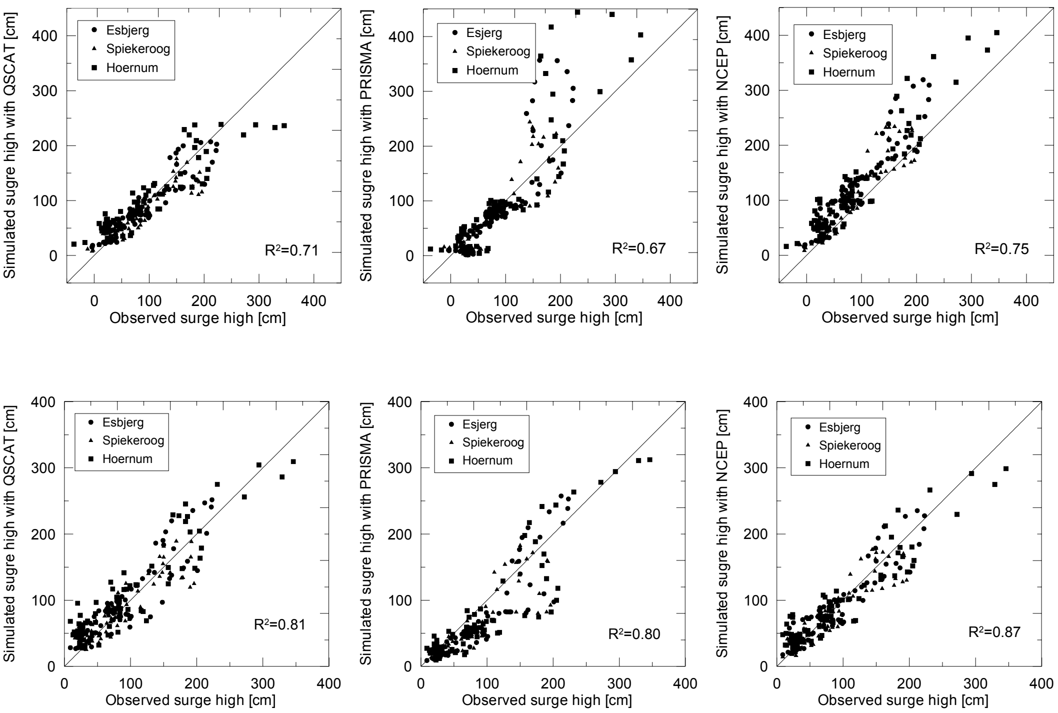

Figure 14 Regression of observed and simulated water levels at three stations before (upper) and after (lower) adjustment of wind drag coefficient for three different wind fields

Table 1 Adjusted coefficients applied in Equation 3 to calculate Drag coefficient

Wind fields	α	β
NCEP	0.44	0.046
PRISMA	0.42	0.043
QSCAT	0.70	0.073

As seen in Figure 13 different wind and pressure fields do not only lead to quantitative differences, but also differences in qualitative characteristics. For a direct comparison between wind fields an adjustment of the wind drag coefficient based on the squared regression coefficent between measured and calculated timeseries was performed. Figure 14 shows the concerning regressions before and after adjustment according to Table 1. Results using wind fields and the adjusted wind drag coefficients are given in Figure 15.

Although the model can be calibrated to reproduce maximum water levels by an adjustment of the wind drag coefficients, it becomes clear that the simulations do not capture the dynamic characteristics of the measured signals.

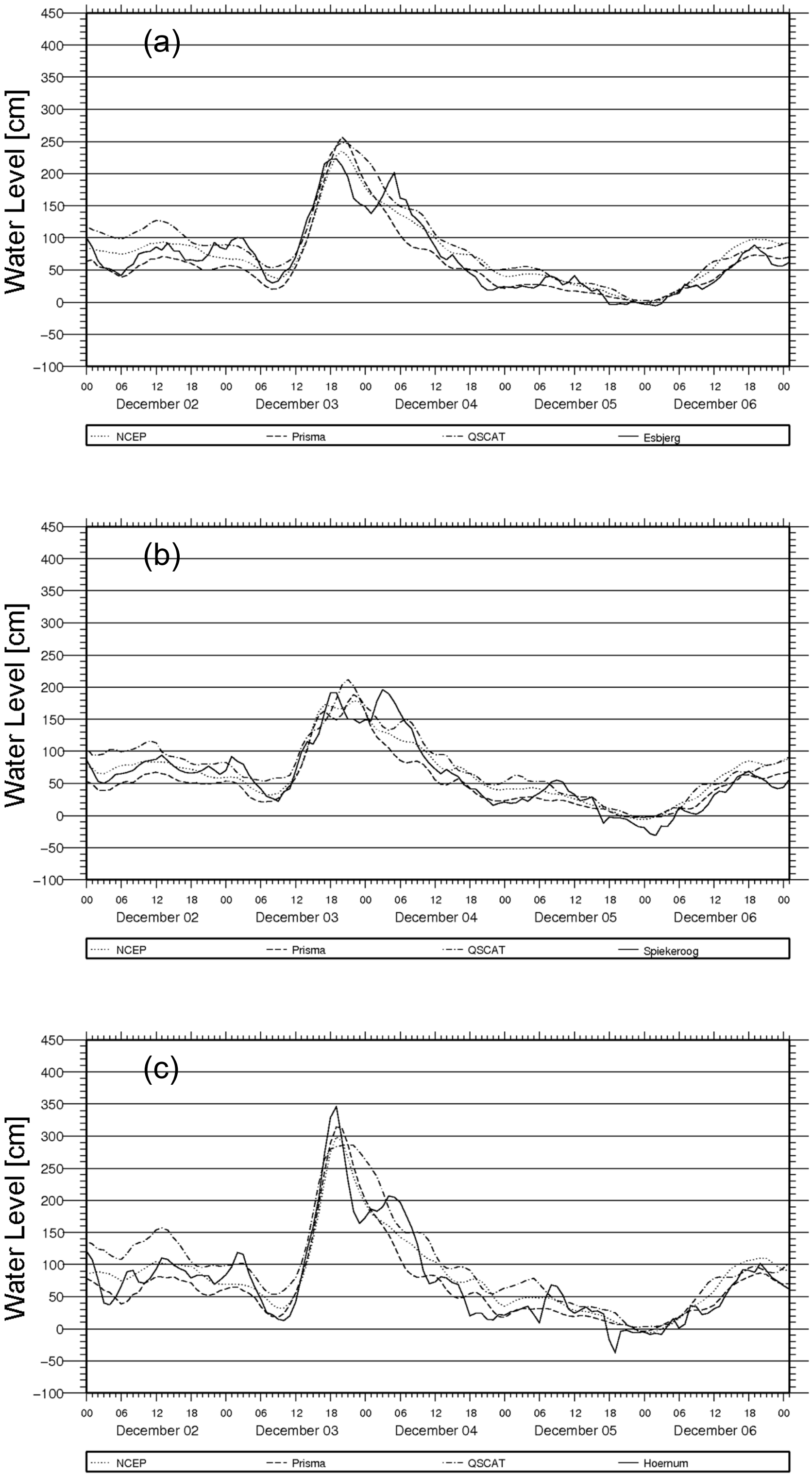

Figure 15 Comparison of measured and computed water level timeseries at different coastal stations after adjustment of wind drag coefficient of tidal gauges at (a) Esbjerg, (b) Spiekeroog, and (c) Hoernum

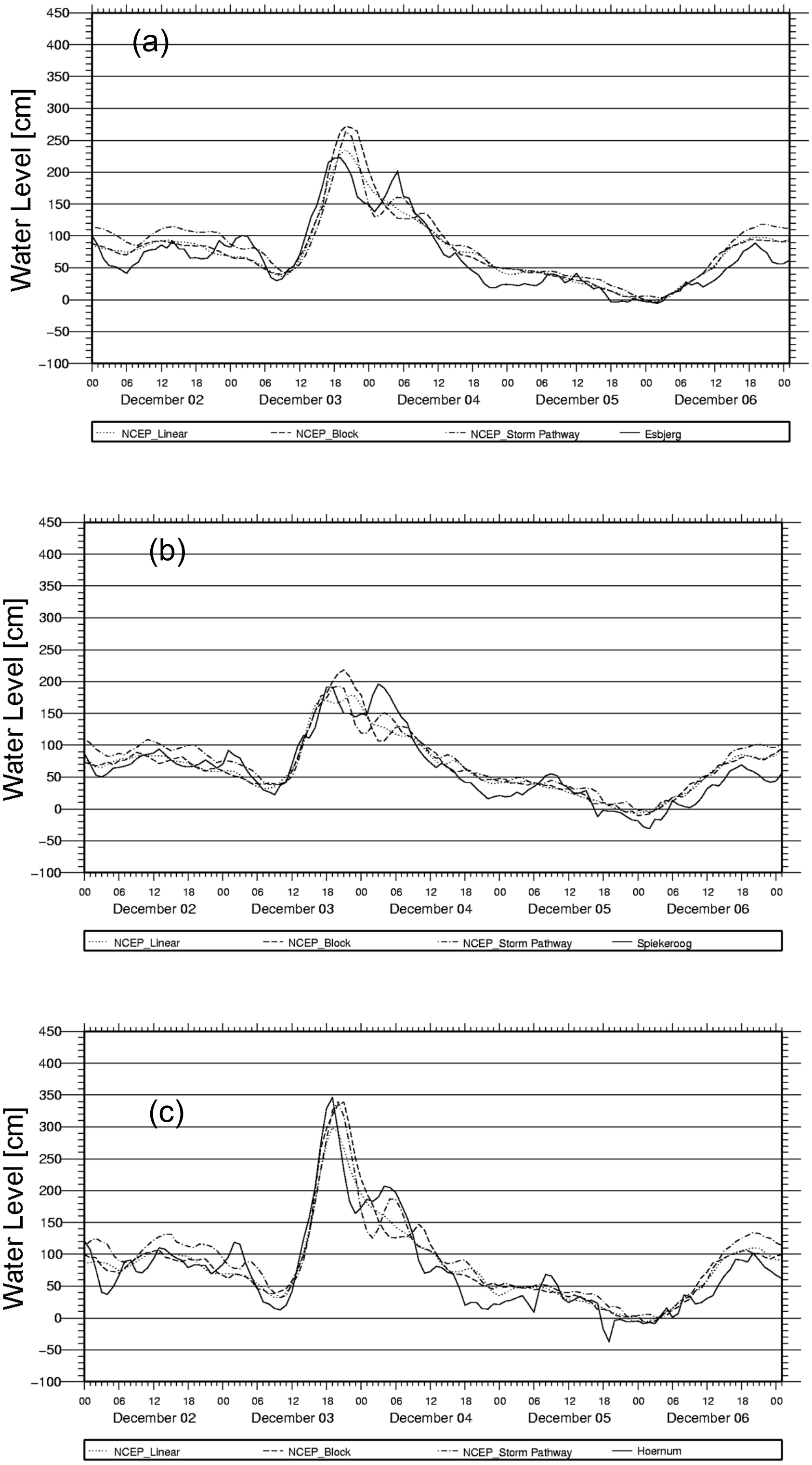

Figure 16 Comparison of measured and computed water levels at coastal stations considering different interpolation methods: NCEP data at (a) Esbjerg, (b) Spiekeroog, and (c) Hoernum

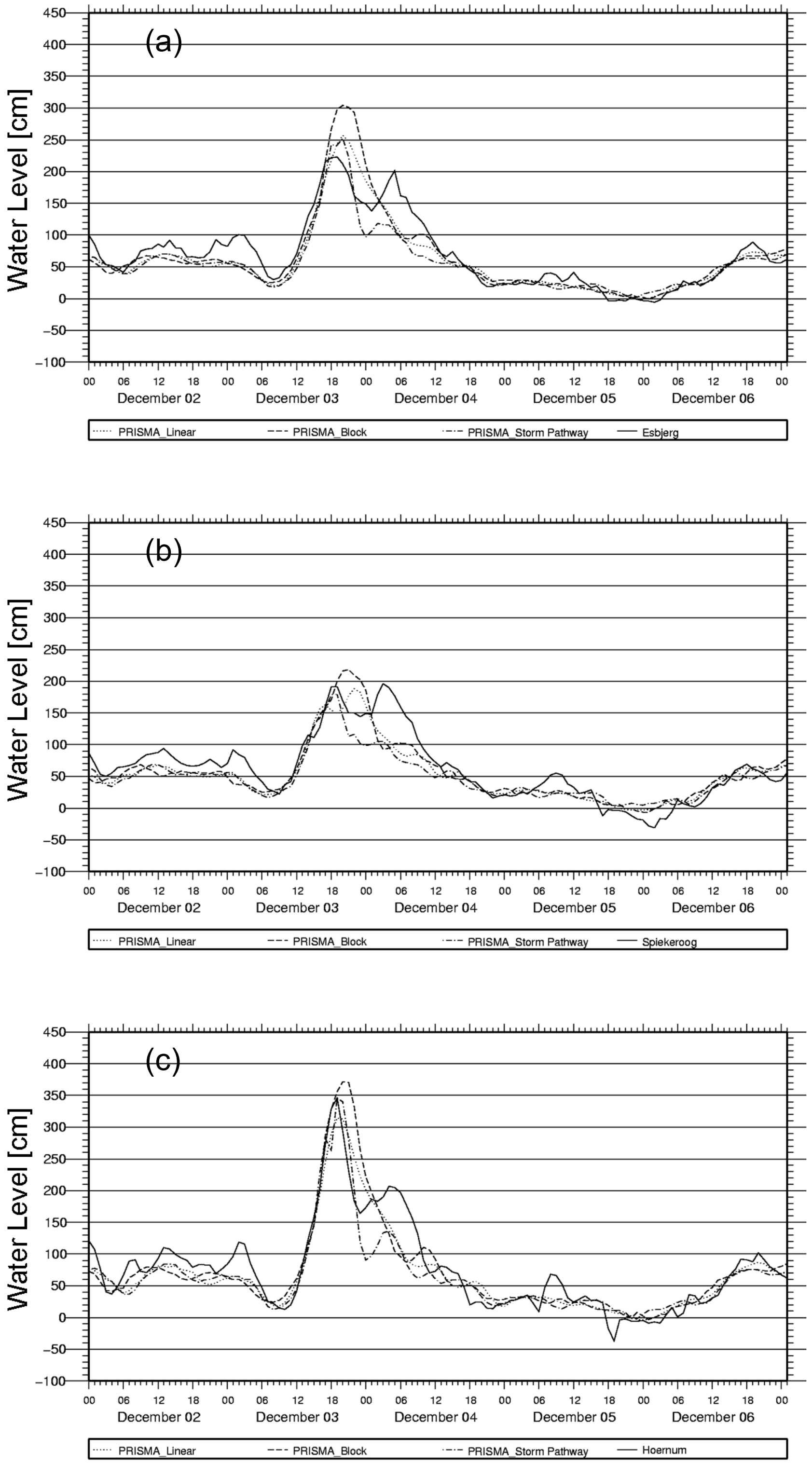

Figure 17 Comparison of measured and computed water levels at coastal stations considering different interpolation methods PRISMA at (a) Esbjerg, (b) Spiekeroog, and (c) Hoernum

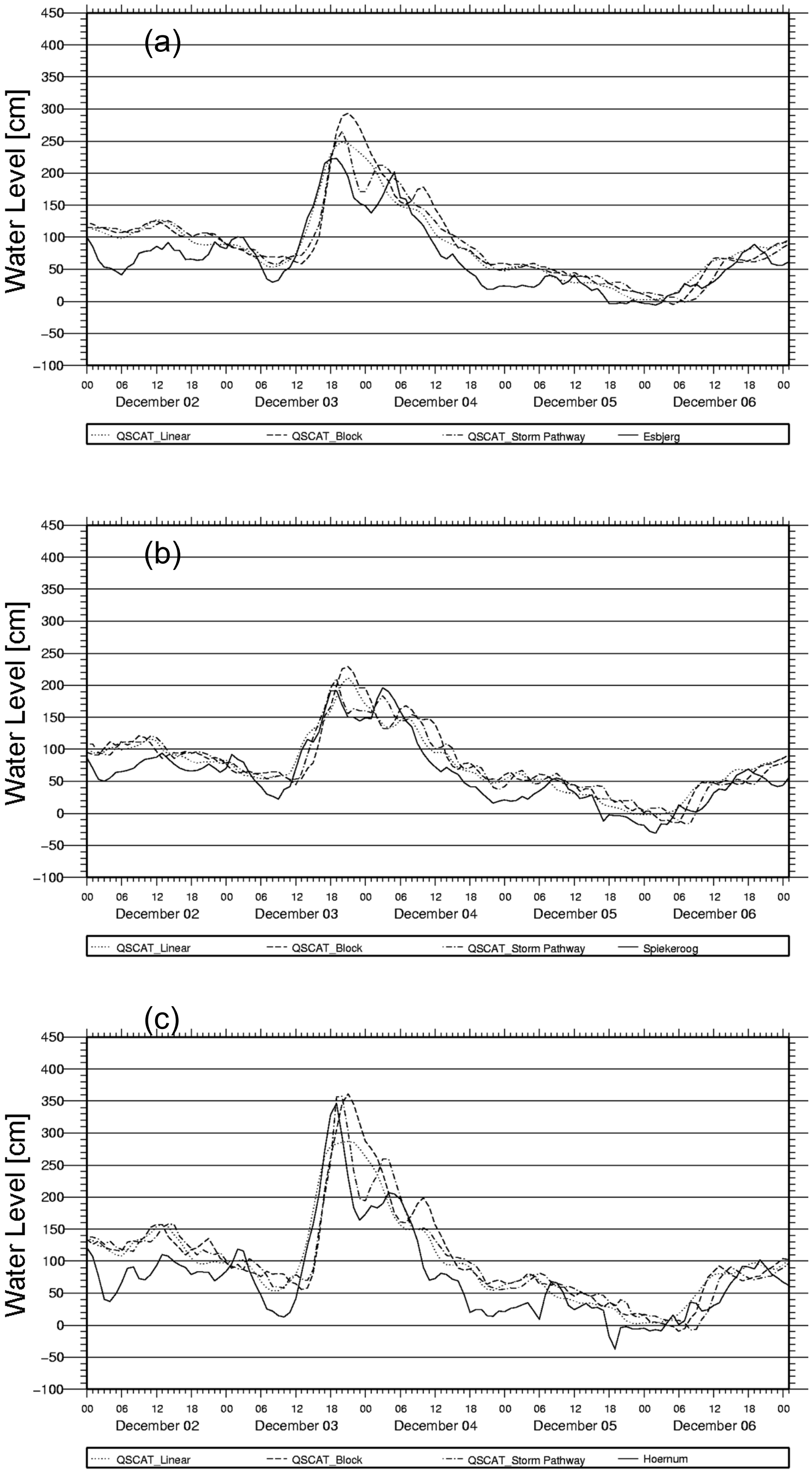

Figure 18 Comparison of measured and computed water levels at coastal stations considering different interpolation methods QSCAT at (a) Esbjerg, (b) Spiekeroog, and (c) Hoernum

3-3 Effect of Interpolation Methods

As shown above, a direct linear interpolation between wind fields in time might lead to unrealistic dynamics of wind and pressure patterns. In the following the effect of this and other interpolation methods is shown in terms of hydrodynamic model quality. The model has been forced by wind and pressure data derived by NCEP (Figure 16), PRISMA (Figure 17), and QSCAT (Figure 18). For every data set the measured water level at exemplary coastal gauge stations has been compared to three different model simulations applying linear interpolation, block interpolation, and storm pathway interpolation in time respectively. Data sets have been reduced to surge water levels only by subtracting the astronomical tide from the measured and computed signal to allow for a focused comparison and analysis.

Generally all model simulations show surge characteristics similar to the observed data. Results are in the same order of magnitude, but eventually significant deviations from the measurements and between simulations occur. Distinct observed oscillations at low energetic times before and after the main surge are hardly reproduced by the model. The maximum surge levels are well captured at two of the shown stations, but over-predicted at the other. The second peak of the surge, as described before, is only captured by simulations using a storm pathway interpolation.

3-4 Model Quality Surge Simulation

The model results for different wind- and pressure fields when using the storm pathway method are again inter-compared in Figure 19.

Finally results are compared on the basis of the Mean Absolute Error (MAE) of simulations, which is a robust measure of accuracy, less influenced by outliers than mean square errors or root mean square errors:

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|y_i - x_i\right| \tag{3}$$

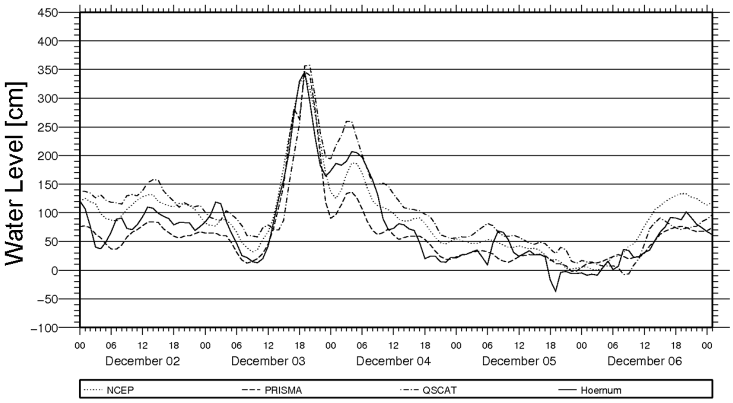

Figure 19 Comparing the effect of different wind- and pressure fields using storm pathway interpolation for the station of Hoernum.

Table 2 Mean Absolute Error and Relative Mean Absolute Error

Station name	NCEP		Prisma		QSCAT	
	MAE [cm]	RMAE	MAE [cm]	RMAE	MAE [cm]	RMAE
Esbjerg 37	17.8	0.22	21.1	0.27	17.6	0.22
Spiekeroog 48	18.5	0.26	18.4	0.26	18.2	0.25
Cuxhaven 51	22.7	0.54	16.8	0.41	15.3	0.36
Hoernum 52	27.5	0.32	31.6	0.37	25.8	0.29
Europlattform 54	14.3	0.42	11.3	0.34	9.9	0.29
Noordwijk 57	25.4	0.54	19.3	0.42	16.7	0.35

In which $X=x_i$ are series of measured and $Y=y_i$ computed values, where $i=1,N$ with N as the total number of data pairs.

If MAE is made dimensionless by dividing it by the mean of the observations it forms the Relative Mean Absolute Error (RMAE). It deviates from zero according to the scale of incongruity between observed and simulated values:

$$RMAE = \frac{\frac{1}{N}\sum_{i=1}^{N}\left|y_i - x_i\right|}{\frac{1}{N}\sum_{i=1}^{N}\left|x_i\right|} \tag{4}$$

Table 2 lists the statistical measures MAE and RMAE for some coastal gauge stations of the North Sea.

4 Concluding Remarks

A hydrodynamic numerical model has been set-up to simulate the tide- and wind driven dynamics in the North East Atlantic and North Sea region. We have stressed out the importance of the surface boundary conditions for the quality of model simulations. The limited validity of simple linear or block interpolation in time between meteorological fields is shown. Alternatively a method is proposed which overcomes these shortcomings at very low computational cost. It is stressed out that an ocean model of comparatively coarse resolution cannot be expected to reproduce the shallow water effects that influence the special characteristics of coastal gauges. Thus the model should be used for providing boundary conditions for highly resolved local coastal models.

5 Acknowledgements

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