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INVESTIGATIONS ON THE INFLUENCE OF THE WIND DRAG COEFFICIENT IN STORM SURGE MODELS

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Abstract:
This paper summarises results of investigations aiming at the improvement of the understanding on the variation of the wind drag coefficients with emphasis to stronger wind conditions. A three-dimensional flow model coupled with a spectral wave model covering the entire Baltic Sea was used. The wind shear stresses were determined iteratively by the wave model and applied at the free surface of the flow model. Simulations covering about 30 extreme storm scenarios lead to approximately 200 million wind drag coefficients that were used in the analysis. The results revealed a high variability of wind drag coefficients for wind speed classes up to around 30m/s. For wind speeds above 30m/s a distinction between decreasing and increasing wind drag coefficients most probably associated to wave breaking in deep water is observed. Comparisons of modelled and computed water levels for a storm in February 2002 using different formulations of wind drag coefficients proved the adequacy of the iterative procedure.

Keywords: wind, drag, coefficient, storm, surge

INTRODUCTION

Accurate predictions of storm surge water levels along the coast remain a major difficulty. This is mainly associated with inaccuracies of the applied wind fields and the uncertainties regarding the wind drag coefficients. Although significant improvements have been made in the development of meteorological models there are still fundamental doubts regarding the variation of wind drag coefficients in particular for high wind velocities. The wind drag coefficient represents the effects of the sea surface roughness and is closely related to the wave field which is not always fully determined by the wind.

In most numerical storm surge models the wind shear stresses on the free surface enter the momentum equations as boundary condition at the water surface. The magnitude of the wind shear stress (τ) is usually determined by $\tau = \rho_a \cdot C_D \left|U_{10}\right| U_{10}$ in which ρ_a is the air density, C_D is the wind drag coefficient and U_{10} is the wind speed at 10m above the free surface.

Several usually adopted empirical equations for the estimation of C_D as a function of the wind speed are shown in Figure 1 together with measurements by Powell et al. (2003) and Donelan et al. (2004). Most empirical formulations are only valid for wind speeds below approximately

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25m/s. In the application of storm surge models usually extrapolations of the formulations leading to a further increase of the wind drag with increasing wind speed as indicated by the dashed lines in Figure 1 are applied.

Other formulations, like the one from Onvlee (1993), as well as the evidence from the cyclone measurements, suggest constant or even decreasing C_D values for higher wind speeds. These major discrepancies in the wind drag coefficients above 30m/s lead to significant uncertainties in the prediction of storm surge water levels. Moreover do the empirical relations between U_{10} and C_D not account for swell or wave growth limitations due to fetch-length and water depth.

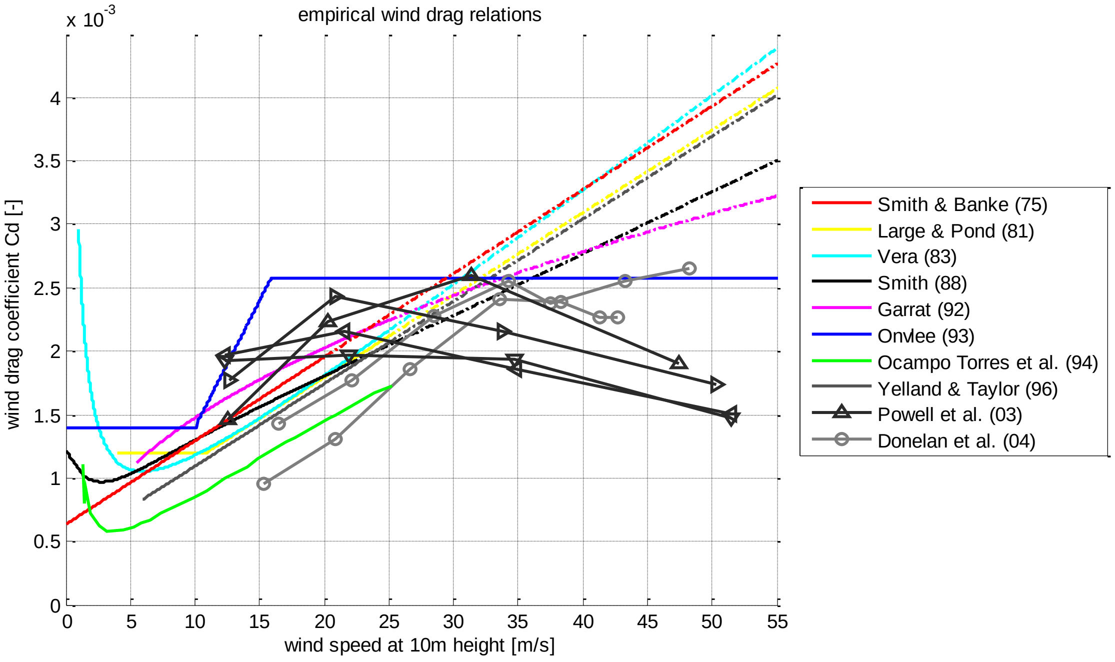

Fig. 1: Empirical formulations and measurements of wind drag coefficients

In this paper, results of investigations on the variability of the wind drag coefficients with emphasis to high wind velocities are summarized. The resulting wind drag coefficients obtained from simulations covering several storm events are used to improve the understating of the variation of the wind drag coefficients. Comparisons between measured and computed water levels at several locations using different formulations for the wind drag coefficients including the iterative procedure adopted in this study are presented. The investigations have been carried out in the framework of the research project MUSTOK, funded by the German Ministry of Education and Research from 2006 till 2009. The study area is the German Baltic Sea.

EXPERIMENTAL SET UP

In the course of the research project MUSTOK sea states and water levels were determined at the German Baltic Sea coast for a number of extreme storms (Bruss et al. 2008). The applied meteorological storm scenarios comprise of physically consistent weather situations that were computed using the Ensemble Prediction System (EPS) of the European Centre for Medium-

Range Weather Forecasts in Reading (Schmitz 2007). The maximum wind speeds attained in the scenarios are up to 56m/s, i.e. well within the range of uncertainty of the empirical formulations of the wind drag coefficients.

The hydrodynamic model system used in this study is based on the MIKE model family developed by the Danish Hydraulic Institute in Denmark (DHI). Covering the entire Baltic Sea up to the Kattegat, a three-dimensional flow model was coupled with a spectral wave model. Figure 2 shows the model domain, the grid resolutions of the two models, and the coupling strategy. The storm surge model implements baroclinic three-dimensional flow approximations in finite difference on a regular grid. The horizontal resolution varies between 3nm in the eastern parts and 600m in the German part of the Baltic Sea whereas in the vertical a layer thickness of 2m is used. The phase-averaged spectral wave model (SWM) solves the equations for wave action conservation using finite volumes on a flexible triangular mesh. The grid spacing varies from 20km to 900m close to the coast. Wind effects, nonlinear wave-wave interaction, energy dissipation due to white-capping, bottom friction and wave-breaking are taken into consideration.

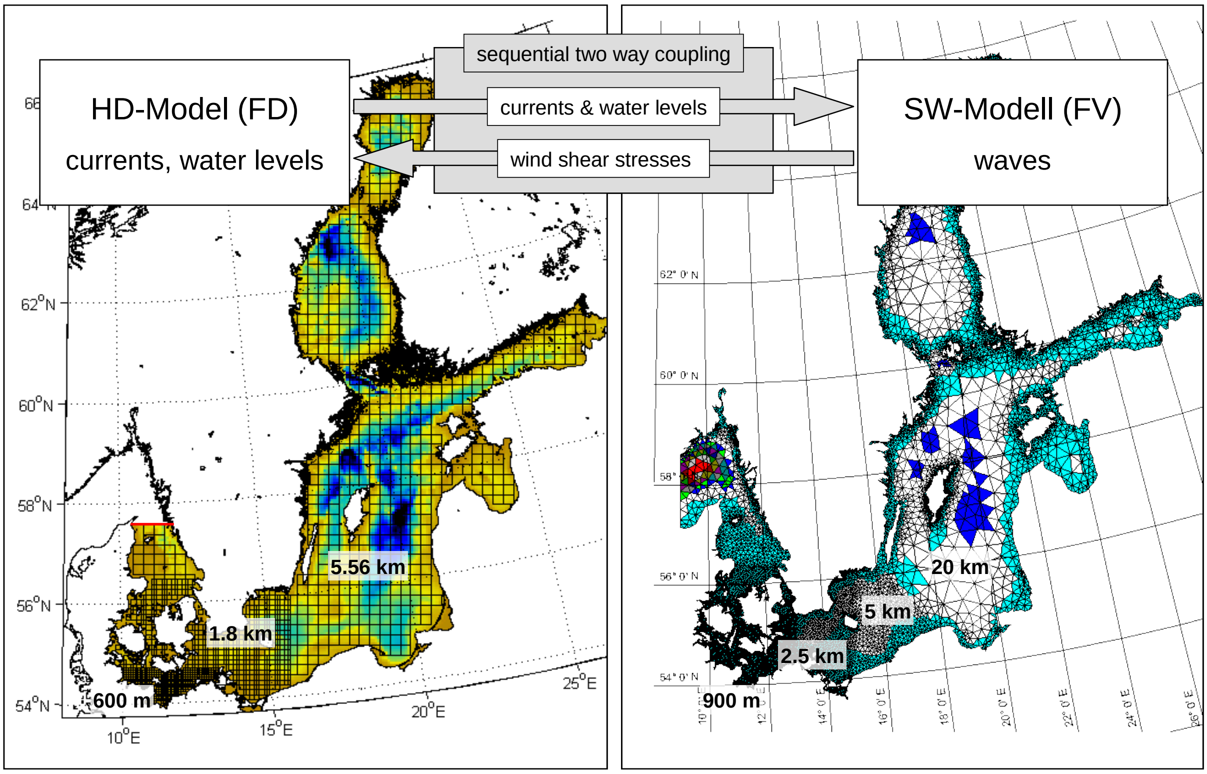

Fig. 2: Model domain and coupling strategy

In this study the output of the SWM was used to improve the description of the wind drag coefficients in the flow model. The wind shear stresses acting on the free surface are determined iteratively by the SWM. This is done similarly to the air-sea coupling implemented in the WAM Cycle 4 model which is based on the wind-over-waves coupling theory proposed by Janssen (1989, 1991). However, to account for some deficiencies identified in the WAM Cycle 4 model, several improvements have been implemented in the MIKE SWM. The resulting shear stresses were applied directly as boundary conditions at the free surface of the storm surge model.

VALIDATION OF THE PROCEDURE FOR ESTIMATION OF C_D VALUES

The effectiveness of the procedure used for the estimation of the wind shear stresses is confirmed by comparing measured and computed water levels for a storm event in February 2002. During this storm the wind magnitude attains values of around 28m/s over the central Baltic Sea. Simulations were carried out with the wind-drag formulations proposed by Onvlee (1993) and Smith and Banke (1975) as well as using the surface stresses obtained on the basis of the SWM. Figure 3 shows comparisons between measured and computed water levels at four locations along the German Baltic Sea coast.

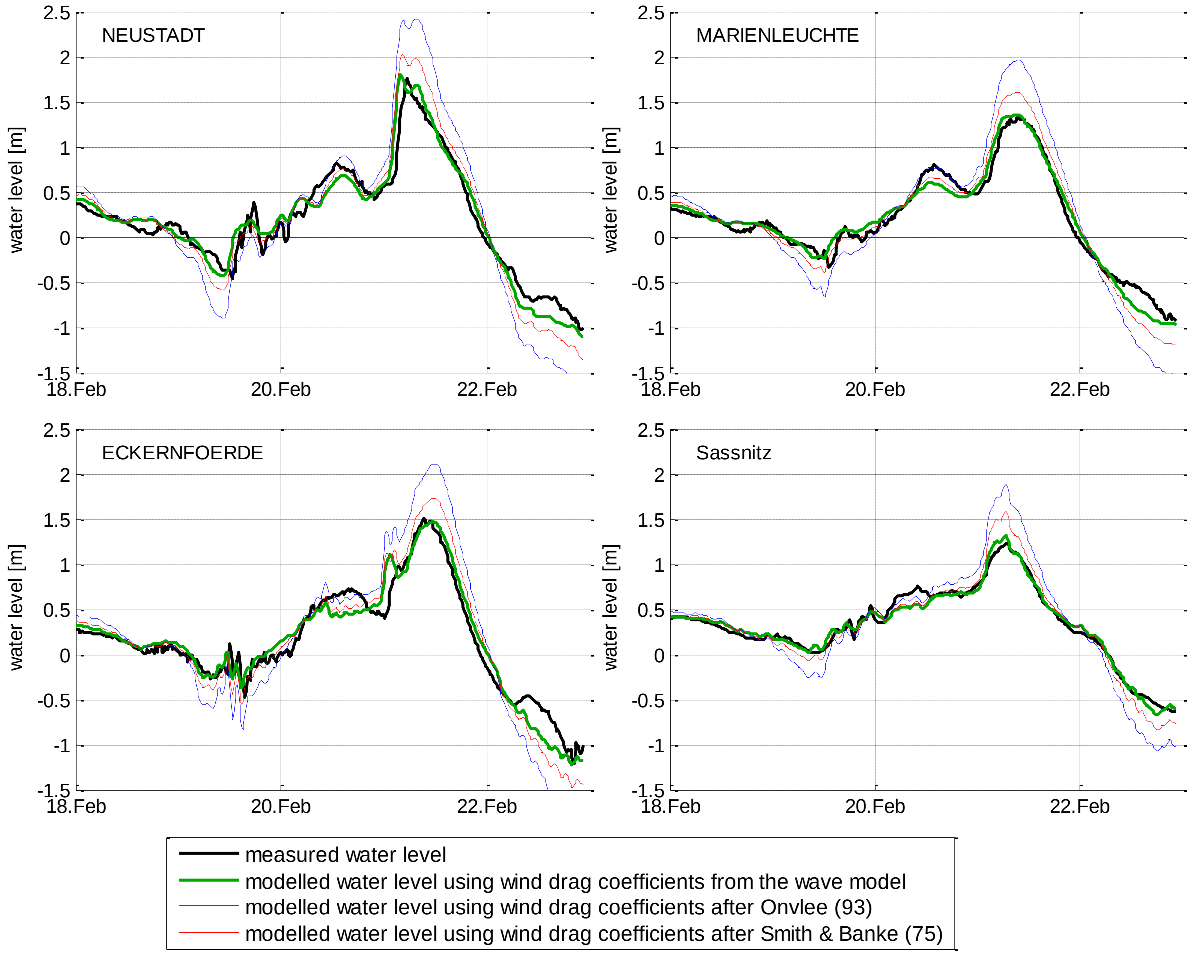

Figure 3: Comparisons of measured and computed water levels

The modeled water levels obtained from the application of the equations by Onvlee (1993) and Smith and Banke (1975) overestimate the measurements at the peak of the storm by up to 35cm and 60cm respectively. In the wind speed range between 15m/s and 30m/s which is responsible for the surge during this storm the higher wind drag coefficients of Onvlee (93) have a strong influence on the computed water levels. The application of the iterative procedure for the estimation of the wind shear stresses yielded to water levels in close agreement with the measurements and therewith to a clear improvement in the model during periods of high wind speeds.

VARIATION OF THE C_D VALUES

To improve the understanding on the variation of the C_D with wind speed, hydrodynamic model simulations have been carried out for 30 extreme storm scenarios generated using the meteorological EPS. The resulting around 200 million C_D values covering the entire simulated periods and model domain are plotted in Figure 4. In order to visualize the density distribution of the C_D values the scatter cloud is plotted as sample density in percentage of the total number in logarithmic gray scale. The frequency of occurrence of the wind speed of the abscissa is displayed in normal gray scale in the horizontal bar.

The scatter of the C_D values is related to the spatial and temporal variation of the relevant factors such as fetch length, wind duration and wave age. In comparison to the empirical formulations these values represent a more realistic spectrum.

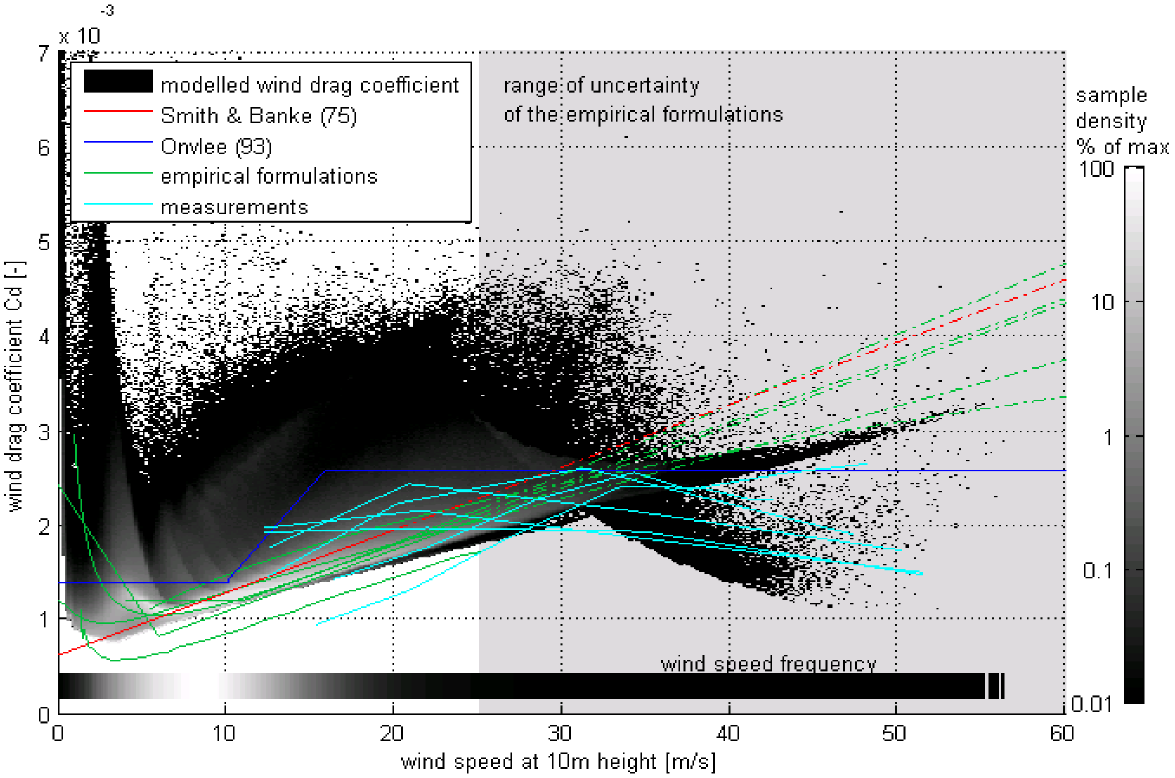

Figure 4: Wind drag coefficients for storm scenarios

The extremely high C_D values at low wind speeds and their decrease until wind speeds of about 5.5m/s is related to aerodynamically smooth flow regime as described in Garratt (1992). In the wind range between 5m/s and 30m/s the scatter of the C_D values indicated by the empirical formulations and the measurements is comparatively small and roughly coincides with the region of highest density of the values obtained by the SWM.

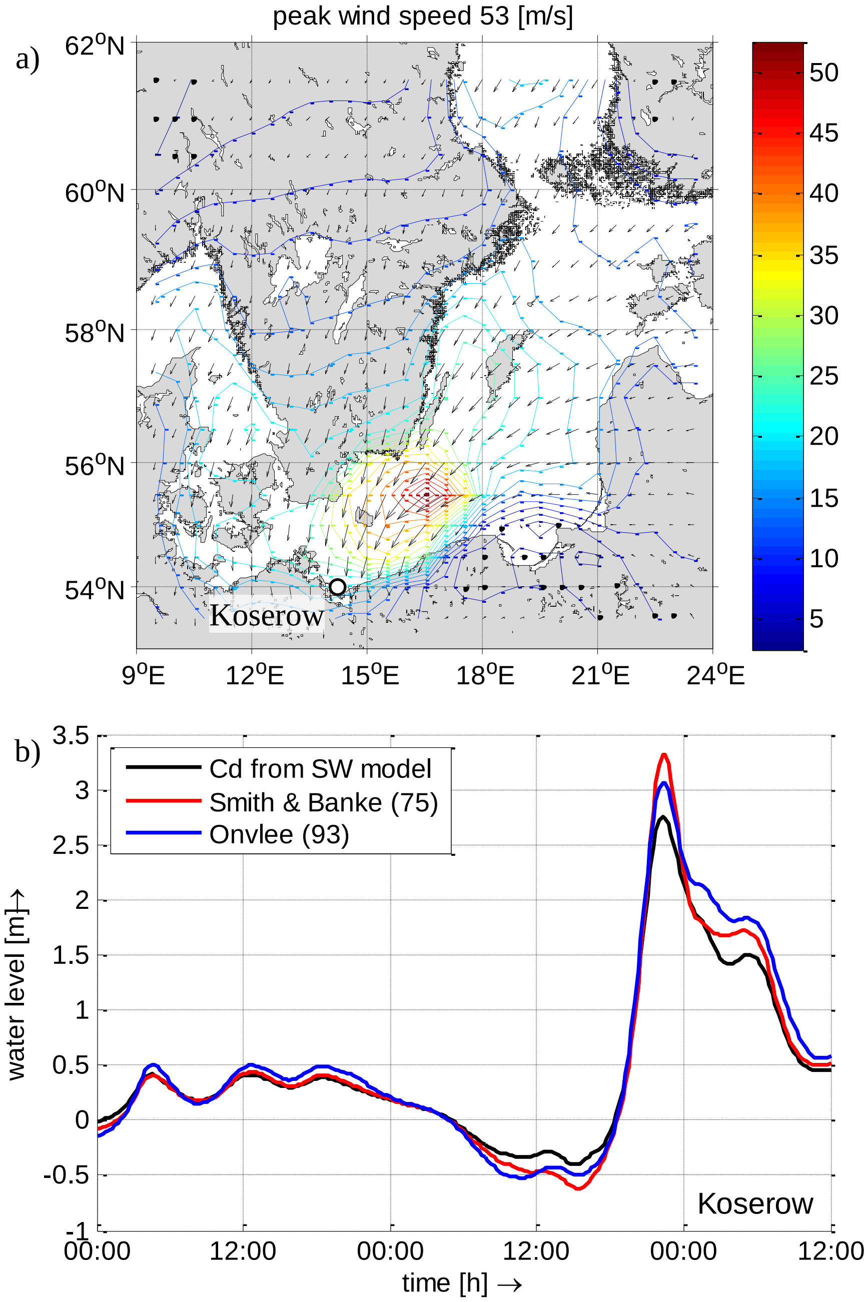

Figure 5: Peak wind field of an exemplary storm scenario (a), and resulting water levels in Koserow computed with different wind drag coefficients (b).

It can be seen that the density of the computed values is comparatively low for wind speeds higher than 30m/s. Still two different trends in the variation of the computed C_D values might be observed clearly: a continuous increase up to values of about $3.2 \cdot 10^{-3}$ and a certain decrease down to about $1 \cdot 10^{-3}$. Preliminary analysis revealed that this behavior is associated with wave breaking in deep water for high wind speeds. This is in agreement with the observations by Powell et al. (2003) who suggested the development of a sea foam layer at the air-sea interface caused by wave breaking and being sheared off by strong wind as possible explanation for the decrease of the wind drag. The measurements by Donelan (2004) and the formulation proposed by Onvlee (1993) suggest a rather constant wind drag coefficient for higher wind speeds.

In order to verify the influence of different drag formulations on the computed water levels under extreme wind conditions, four set-ups were tested for one of the storm scenarios. Figure 5 (a) gives an impression of the wind field at the peak of the storm with local wind speeds up to 53m/s. Figure 5 (b) shows the resulting water level time series at a station in the southwestern Baltic Sea.

The peak water levels range between 2.7m using the wind stresses from the SWM and 3.4m using the extrapolated wind drag formulation of Smith and Banke (1974). The effect of the applied wind drag formulation on the water levels becomes quite relevant. Comparing both empirical formulations, the Smith and Banke (1974) approach lead to a better agreement with the observations during the storm of the validation with wind speeds up to 28m/s whereas in this case of wind speeds around 50m/s the constant wind drag coefficient of Onvlee (1993) appears to be more adequate. Still the wind stresses from the SWM again lead to the lowest peak water levels.

CONCLUSIONS

A coupled flow and wave model system of the entire Baltic Sea was run for 30 extreme storm cases. The physical consistency of the storm scenarios that were generated using the Ensemble Prediction System of the European Centre for Medium-Range Weather Forecasts in Reading enabled the iterative determination of realistic wind drag coefficients with the spectral wave model for wind speed ranges up to 56m/s. The wind stresses determined in the wave model are directly applied as boundary condition at the free surface of the storm surge model.

The verification of the procedure for a storm event in 2002 by comparing the resulting water levels to measurements revealed the adequacy of the approach. As result from the simulations of the 30 extreme storms the variation of around 200 million computed wind drag coefficients was compared to empirical approaches. The regions of high scatter density of the computed values coincide with the scatter of conventional empirical formulations and cyclone measurements. Most extrapolations of empirical formulations to high wind speeds however exceed the computed values. For wind speeds above 30m/s a distinction between increasing and decreasing wind drag coefficients is observed in the model results. This separation is most probably associated to wave breaking in deep water. The main advantages of the application of the proposed method in storm surge models are therefore the independence of wind speed related empirical formulations with limited validity ranges and the consideration of local and temporal effects such as fetch length and wave age

The results obtained represent conditions in the Baltic Sea during deep pressure cyclones moving about the southern part of the Baltic Sea leading to strong winds from the northeast. Other cyclone paths or other areas with different topographic settings like e.g. the less structured North Sea might lead to different wind drag relations and are currently being investigated.

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