Interaction of Wind-Waves and Currents in the Ems-Dollard Estuary

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Abstract
Physical processes in coastal waters and estuaries extend their influences on many economic and ecological processes in the coastal regions and affect the safety of the coastal defences. In a context with the global climate change, these physical processes underlie also inherent modifications. In order to win an impression of such future changes and of the probability of their occurrence, physically consistent simulations of these processes are used to describe how wind-waves and currents interact.

This paper presents an offline-coupled simulation using the models HAMSOM (HAMburg Shelf Ocean Model) and SWAN (Simulating Waves Nearshore). These state-of-the-art models excel by high computing speed, so that they offer an opportunity to simulate hydrological conditions and physical processes over longer time periods, e.g. decades. For the influence of currents on the waves, we estimate less influence on tidal flats, but stronger influence in the tidal channels.

Improvements in parameter estimation that were achieved by the interaction of currents and waves are described and discussed; we estimate new drag-coefficients for the hydrodynamic simulation. Because long-term simulations need to be simplified, a method is examined and presented that by-passes the direct online-coupling of models. For the aim of long term simulation improvements of the surface drag coefficient are useful, because online-coupled wind-wave models overcome the available machine time for climate runs. Our method yields an optimization regarding computing economy and physical consistency of simulations.

Keywords: coupled simulations; wind-waves; hydrodynamics; estuary

1. INTRODUCTION

In a long-term perspective, currents and wind-waves have significant influences on changes in the economic and ecological processes and the safety of the coastal defences in coastal regions and estuaries. A single storm surge can destroy dykes or erode a broad coastal area. However, mean (tidal-) currents and wind-waves are exerting their forces rather continuously in the estuary: Over the whole frequency range of hydrologic processes one might find slight changes, which can be analysed with a probabilistic approach. In order to gain an impression of potential future changes and the probability of their occurrence, physically consistent and simplified long-term simulations are needed.

This study considers the Ems-Dollard-Estuary (Germany) as an example of a North Sea estuary (Fig. 1). Several external forces control the distribution of currents and waves. The most important ones are wind and tides, both of which depend on the conditions prevailing in the North Atlantic region. Inter-annual to decadal oscillations of the North Atlantic region (NAO, Hurrel 1995) influence the North Sea and hence the adjacent estuaries (Leterme et al., 2008; Tsimplis et al., 2006). Thus, to estimate to which extent the changes of processes in an estuary are related to global warming, knowledge of their long-term natural variability must be obtained. This can be achieved by local impact models, which are relatively simple, but are valid to reproduce the governing processes, forced by wind and tides.

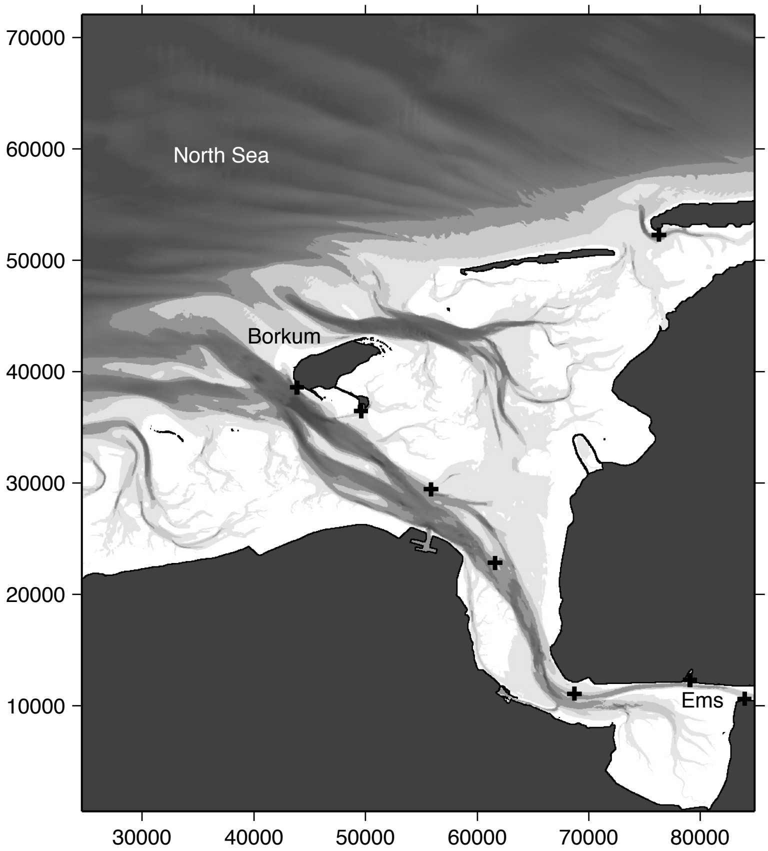

Figure 1. Topography of the Ems-Dollard-Estuary. Black crosses mark the positions of tide gauges

This study focuses on one main physical process – the interactions between wind, waves, and currents. Recent studies (e.g. Mai et al., 2004, Nicolle et al., 2009; Pleskachevsky et al., 2009) identified in general two challenges: (1) Reduction of uncertainties in storm-surge prediction using wave information in the wind-stress calculations and (2) reduction of uncertainties in wind-wave simulations based on calculating wave-current interactions. Hence, parameter improvement with a coupled simulation of waves and currents was tested to reduce the uncertainty of simplified climate-impact models.

2. METHODS

To simulate currents and sea-levels, the hydro-numerical model HAMburg Shelf Ocean Model (HAMSOM) was used. HAMSOM – a veteran among the hydro-numerical models – was first set up in the mid-1980s by Backhaus (Backhaus, 1983; Backhaus, 1985). HAMSOM has been used since then by a wide range of scientist to simulate oceanic, shelf, coastal, and estuarine dynamics. In general, it is a three-dimensional, prognostic-baroclinic, frontal- and eddy-resolving model with a free surface. The numerical scheme of HAMSOM is defined in z-coordinates on an Arakawa C-grid. The governing equations for shallow water are combined with the hydrostatic assumptions. The basic equations can be found in Schrum (1994) and Pohlmann (1996a). The simulation of the estuarine circulation poses several numeric requirements to the model (Hein et al., 2007). Therefore, high-order formulations are used for the momentum equation and the transport equation. The importance of diffusion processes for (de-) stratification in estuaries is considered by sub-grid stochastic simulations: The vertical turbulent viscosity is calculated by a Kochergin-Pohlmann scheme (Pohlmann, 1996b). The horizontal sub-grid processes are estimated by a Smagorinsky scheme (Hein, 2008). The model has a resolution of 200 m in the horizontal and 3 m in the vertical. This resolution was chosen as it allows the representation of tides, storm-surges, and long-term baroclinic processes as well as long-term simulations. The model is nested into the operational model of the *Bundesamt für Seeschifffahrt und Hydrographie* (German Federal Maritime and Hydrographic Agency, Dick et al., 2001).

Waves are computed by means of the third-generation wave model SWAN ("Simulating Waves Nearshore"; Ris, 1997; Ris et al., 1999; Booij et al., 2004). This parametric model is based on the wave-action balance equation with sources and sinks. A finite difference scheme is implemented to compute random, short-crested, wind-generated waves. It allows spectral wave input at specified boundaries. Several physical processes, such as wave propagation, wave generation by wind, whitecapping, shoaling, wave breaking, bottom friction, sub-sea obstacles, wave set-up, and wave-wave interactions are implemented in the model. The model was used in several studies to simulate the wind-waves in German estuaries (Mai, 2008).

In this study, we use both models in a one-way coupling to test the interaction to improve long-term simulations. Because of the need to use standard model-parameters in studying climatic processes there is also a need to optimize them. At first, tides and currents are computed without considering the influence of waves on the momentum transfer. Secondly, wind-waves are simulated with and without the influence of currents. The simulation outputs of wave parameters are discussed for parameter-optimization of the hydrodynamic model.

3. VALIDATION

According to Dee (1995), a model can be valid only for the explicit use for which it was made. It is never a general carte blanche. At first, the source code itself must be valid. So we note, both models are open-source models and they are used by a worldwide community in countless projects. Secondly, both models fulfil the requirements to calculate the governing processes in coastal regions, e.g. baroclinic processes are calculated in the hydro-numeric part and near-shore processes like whitecapping, shoaling, wave breaking are implemented in the wave model.

Furthermore, Fig. 2 shows that both models are valid for simulations of the Ems-Dollard-Estuary. At first, we proved that the hydrodynamic model has the ability to reproduce tidal dynamics. In general we use global standard parameter to run both models. For the hydrodynamic model, both, the horizontal coefficient of the Smagorinsky sub-grid model (Hein, 2008) as well as the global friction parameter were tuned. This has been performed with "virtual pool" experiments, as well as a slight optimization of both

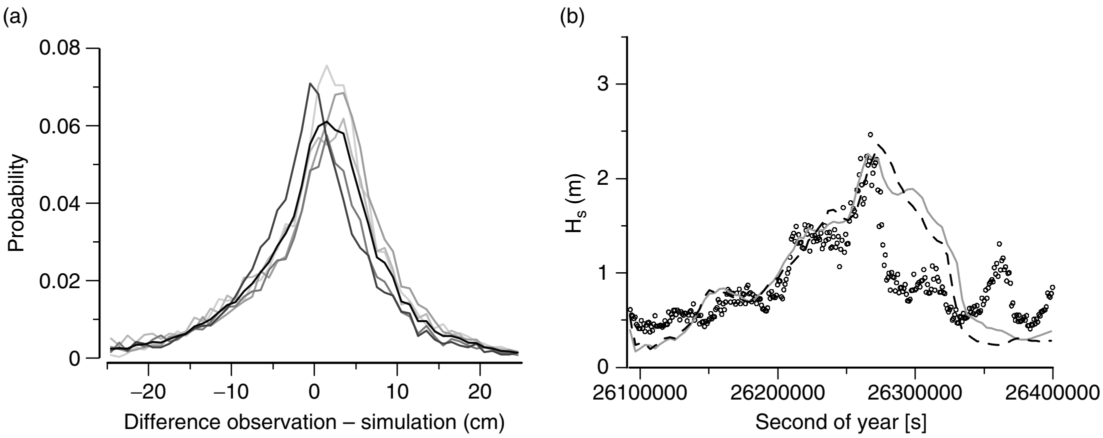

Figure 2. (a) PDF's of the difference between tide-gauge observations and hydrodynamic simulation; (b) Significant wave height from observations (dots) and simulations (grey line: with currents; black dashed line: with out currents)

parameters in the "Ems-Dollard" model realisation for the period January 2006 to April 2006. The results of a validation-time (October – December 2006) are analysed in the following: The grey area in Fig. 2a represents the differences between measurements of tide gauges and simulation results during the storm event. Thereby, the measurements of six gauges (Fig. 1, black crosses) are compared with the local results of the hydrodynamic model. The differences between the water level of the simulation and the gauges are shows with six probability density functions (PDF). The similarity of the single PDF's to a Gaussian distribution and the mode near null indicates that uncertainty of the hydrodynamic model is in general of stochastic nature, with only a small systematic error.

A comparison between observations and simulations with the wave model in the Ems-Dollard-Estuary was made by Mai (2008). However, here the resolution had been reduced to simplify the climate-impact model. Fig. 2b shows simulated significant wave-heights (H_S) and observed H_S during a single storm event at the beginning of November 2006. Results from high-resolution observations at the tide gauge "Borkum-Südstrand" are presented. This is a special tide gauge (wave-gauge), one-of-a-kind in this region, here a sea state solving radar-senor is mounted and water level are saved with a rate of 20 Hz. More information about the dataset of observed waves from the radar gauge can be found in Barjenbruch and Wilhelmi (2008). The black dots in the figure represents the gauge observations, while the grey line represents wave simulations without the effect of currents, and the black dashed line shows the results which include this effect. Both curves fit well to the observations. The increase in wave heights as well as the maximum H_S during the storm is well reproduced by the model. However, the difference of the slope of the decreasing waves after the storm-event may indicate an overestimation of the groundswell or a spatially too coarse wind field.

Summarizing, Fig. 2 shows the validity of both models. The approximate computation time of the hydrodynamic model is one week per simulation-year on a single CPU. HAMSOM allows parallel calculation on a state-of-the-art multiprocessor computer (Pohlmann, 2006). First tests show rates up to three simulation-years per day. Thus, together with the given accuracies both models allow simulations on required time scales for climate projections.

4. RESULTS

Fig. 3a shows the simulated sea-level (grey) and the Mean Sea Level (MSL, black) over the simulation time of one year. The presented sea-level is a spatial average of the region near Borkum, highlighted in the black dashed box in Fig. 3b. A snap-shot of the sea-level (Fig. 3b) shows the importance of this region for the transformation of the coastal Kelvin-wave into the estuarine standing wave.

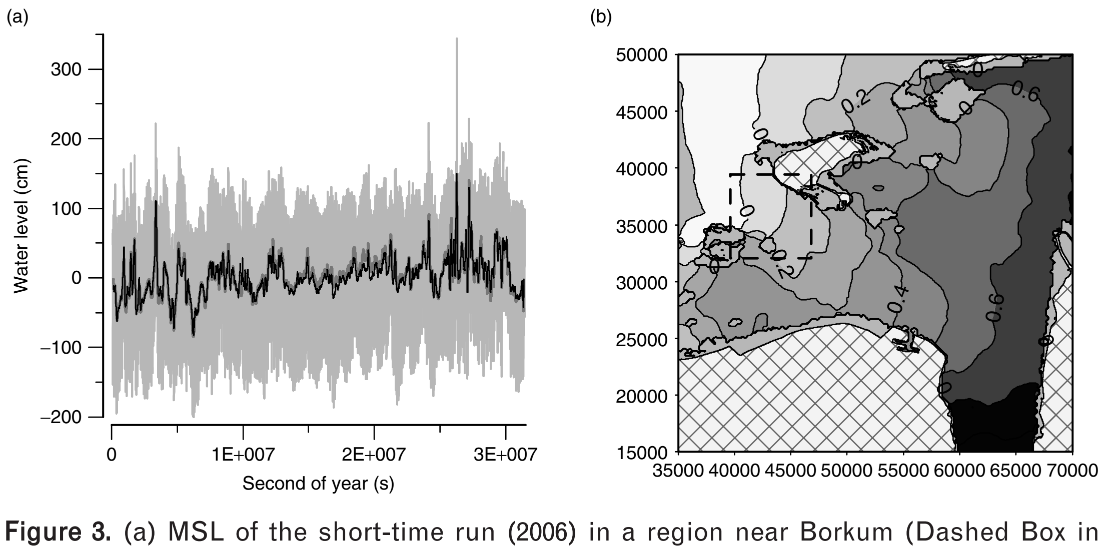

Figure 3. (a) MSL of the short-time run (2006) in a region near Borkum (Dashed Box in b) and (b) Sea-level snap-shot of the outer estuary

Although the simulation-time of our test study is, in fact, too short for climate purposes, an unsteady variability of the MSL is obvious on scales of days and weeks. This variability represents rather typical weather time-scales, and it has a stochastic random nature. However, our test study on the interactions of currents and waves is restricted to the first of the extreme events that are visible in Fig. 3a. During this time, the range of the MSL was one meter. This is a comparable magnitude like that of the decanal aleatoric uncertainty of the local MSL.

Fig. 4 shows the significant wave height H_s during the extreme event – Fig. 4a with and Fig. 4b without current interactions, respectively. Tidal and surge-related changes of the water level are considered in both simulations. Both simulations show that H_s is generally between 0.5 m and 2 m. Main differences are found in the tidal channels. In this region, currents are high and if wave-current-interaction is neglected, waves are overestimated. Fig. 4c shows the event-averaged difference between both simulations, calculated as percentage of H_s. From the two simulations, it can be seen that the error caused by the neglect of the current-wave interaction seldom exceeds 10% of the significant wave heights. Especially in shallow mud-flats, the interaction of waves and currents can be neglected. In the tidal channels, the waves are reduced by the strong currents flowing into the region. On the other hand, in the region of the basement of the mud-flats (northwest of Borkum) wave heights are increased (25%) by currents during the storm event.

Fig. 5 shows the same situation like Fig. 4, but for the wave-period (T_{m01}). Just like H_s, the wave period shows significant differences only in the tidal channels, where the period is simulated too high if currents are neglected. In the shallow regions, in the mud flat, and in the foreland the influence of the currents on the waves is insignificant.

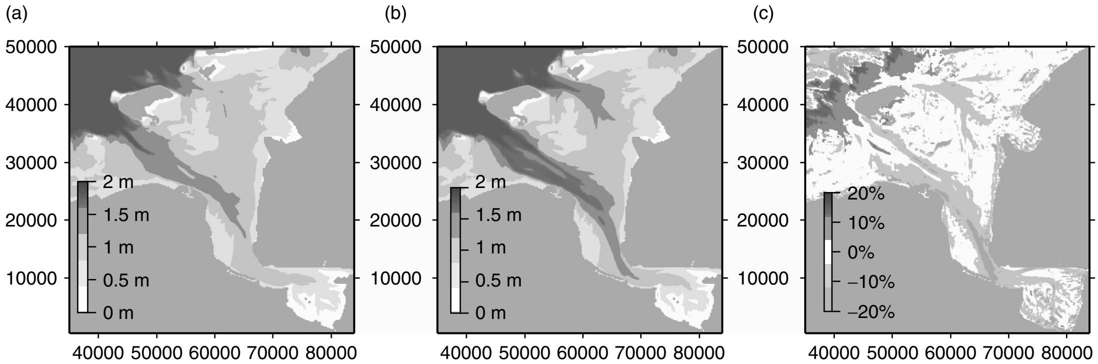

Figure 4. Significant wave heights, (a) with current-interaction, (b) without current-interaction, (c) difference in percent

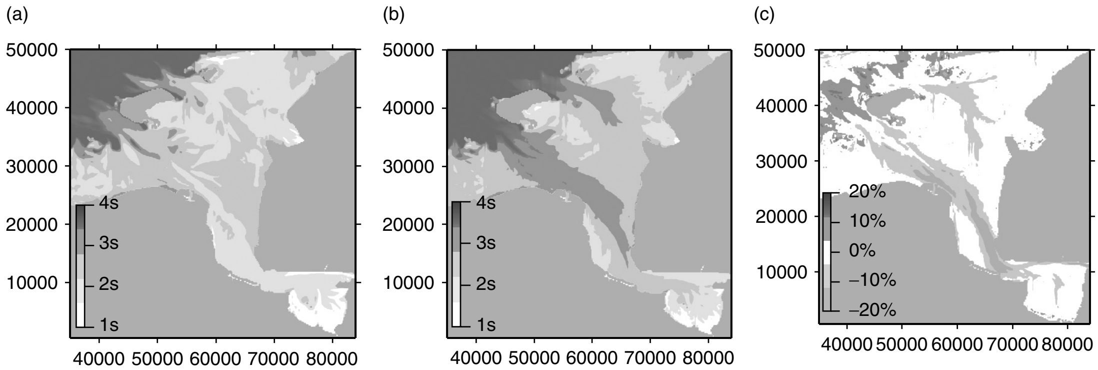

Figure 5. Wave period T_{m01}, (a) with current-interaction, (b) without current-interaction, (c) difference in percent

5. DISCUSSION

The findings show that significant wave heights in the order of 1–2 m may occur in the outer estuary and that a non-coupled model induces errors of about 10% in this region. At the wave-gauge Borkum-Süd, no significant difference is noticeable (Fig. 2b). At the other tide-gauges (figure 1), the sensor techniques do not allow the observation of waves until now, which let the estimation of uncertainties be difficult. With the renewal of the tide-gauges, hopefully a stepwise installation of wave-resolving radar sensors will be mounted.

A study (Tolman, 1991) on a basin-wide scale estimated errors in the same order like in our study. In contrast to that study, our resolution allows to represent tidal channels, in which errors are more pronounced due to less frictional dissipation. Our results show that an influence of currents on the wind-waves is found only in these tidal channels. Thus, the use of coupled models depends on the specific aim of each study. If the aim of the study is to find near-realistic H_s, one-way coupling seems to be appropriate. However, if the purpose is to study sedimentation processes, coupling of the models can be assumed to be irrelevant since the error is relatively small. A study by van der Molen (2002) on a more coarse scale for the North Sea argues that the influences of wind and waves on the net-transport of sand are important only in regions where tidal currents are weak.

Waves in the near-shore region are related to the tidal cycle. The changes in the water-level influence the statistic of the significant wave heights (Mai et al., 2004). In the Ems-Dollard estuary the tide is dominated by the M2 (semidiurnal) constituent of the tide, spring-neap-cycle is less pronounced. Figure 6a shows the frequency spectrum of H_s of the wave gauge observations, the frequency peak of the M2 is indicated (0.04 in the normalised spectrum). The figure shows also 2 to 3 over-tides of the M2 which are also detectable in the wave observations however, they are less important. Therefore, we divide the observation of H_s from the wave gauge into H_s during high-tide, H_s during low-tide. The exceedance probability of H_s shows the influence of the water level on the waves at the wave gauge (figure 6b). During high-tide the risk of higher waves is increased in comparison to the period of low-tide. However, during the storm event (gray-line) the risk is significantly more increased, than the differences, due to the tidal cycle.

Moreover, errors in the momentum transfer from the atmosphere to the sea lead to errors in the wind-driven currents, which results in artificial increases or deceases of wind surge (water-level). In our study region, the water-level influences the extent of the flooding area in the mud-flats. Because of the water-storage effect of these regions, also tidal amplitudes are affected. In the scope of climatology, this effect is important, because it produces rather a systematic error than a stochastic uncertainty.

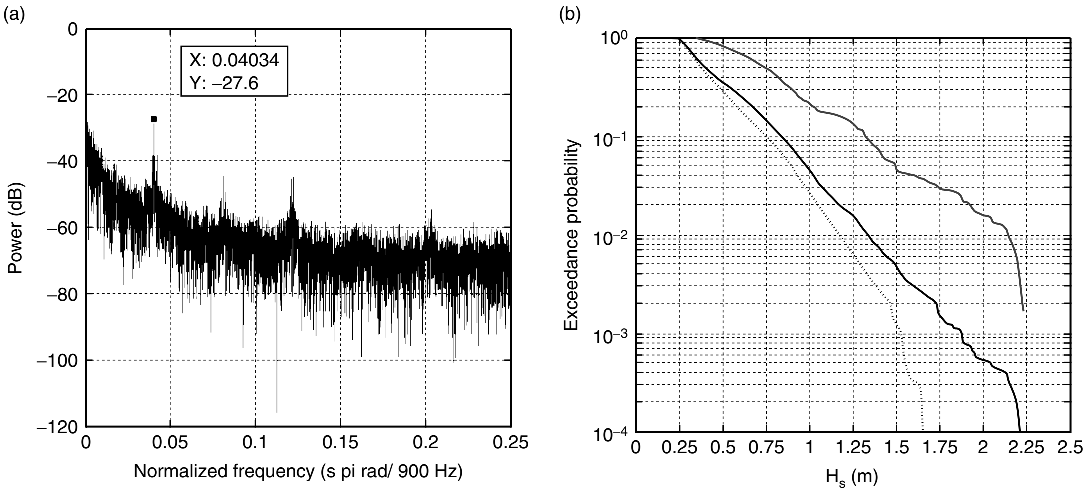

Figure 6. (a) Observed frequency spectrum of H_s (b) Exceedance probability functions of H_s at the tide gauge "Borkum Südstrand" in relation to the Tides. Black line: H_s during high-tide, black dashed line: H_s during low-tide, grey line: H_s during the storm event

A second process is the modification of the bottom friction coefficient in the presence of waves (Davies and Lawrence, 1995). Both the mechanisms of energy dissipation by friction and the processes of (de-) stratification are modified in the estuarine frontal zones. A third process – the radiation stress – leads to an alongshore momentum transfer in the near-shore region. Hereby, part of the wave energy is directly transferred into momentum.

In this study we take only the first process into account, namely the influence of waves on surface momentum transfer by wind-stress forcing. For a given wind velocity, the surface wind stress can be calculated by:

$$C_D = (u_* / U_{10})^2 \tag{1}$$

where ρ_a is the density of air, U_{10} represents a wind velocity vector at a height of 10 m above the sea surface, and C_D is a drag coefficient. C_D is not a constant but varies with the roughness length of the sea surface, which – in turn -varies with the sea state. Assuming a linear relation between wind and waves, it is common to use a linear approach of the coefficient that depends on the wind velocity:

$$C_D = \left(a + b\left|U_{10}\right|\right)10^{-3} \tag{2}$$

where a and b are empirical coefficients. Generally, values of a and b are estimated by observations of wind and currents or waves, e.g. Smith and Bank (1975), Garratt, (1977) Wu (1980), and Zubkovskii and Kravchenko (1967). From these studies, the averaged coefficients $a = 0.7 \pm 0.04$, $b = 0.08 \pm 0.03$ can be calculated. The studies found a wide range of values for the coefficients depending on the region of the observations or the method of estimation. Thus, no consistent values exist for the drag coefficient. However, the results of the wave simulations allow to estimate the coefficients for the Ems-Dollard region.

With the definition of C_D as the square relation between friction velocity u_* and U_{10}:

$$C_D = (u_* / U_{10})^2 \tag{3}$$

We are able to determine a characteristic drag coefficient for the estuary under review, which depends on the local sea state. Therefore, we used the 3/2-power law, which was proposed by Toba (1972) to calculate the velocity u_*:

$$u_*^2 = H_s(\beta^1 g^{1/2} T_s^{3/2})^{-1} \qquad [4]$$

where g is the standard value of Earth's gravitational acceleration at sea level (9.81 m/s^2) and β is a universal empiric constant (0.062 ± 0.01; e.g. Ebuchi et al.(1992)). Hence, knowing the significant wave height and the wave period (here T_{m01}) we can calculate the friction velocity u_*. Further, based on Equations [3] and [4] we can find a regional parameter for the linear drag coefficient [3], which is related to the sea-state in the estuary. However, the simple relationship of the 3/2 power law cannot be applied under conditions of strong swell. A more complex solution than here, recognising the influence of swell on the drag coefficient was presented by Garcia-Nava et al. (2009). However, for long term climate simulation our estimation can be used with stationary wave data, which are available from German coastal and estuarine regions (www.fi.uni-hannover.de/seegangsatlas/). Because this method by-passes coupled simulations, it is an appropriate solution, especially if it is necessary to decease the computing time of climate-impact models.

Fig. 7 presents the local estimation of the drag coefficient in relation to the wind velocity. The black line shows the regional optimized linear drag coefficient calculated from our model outputs. The

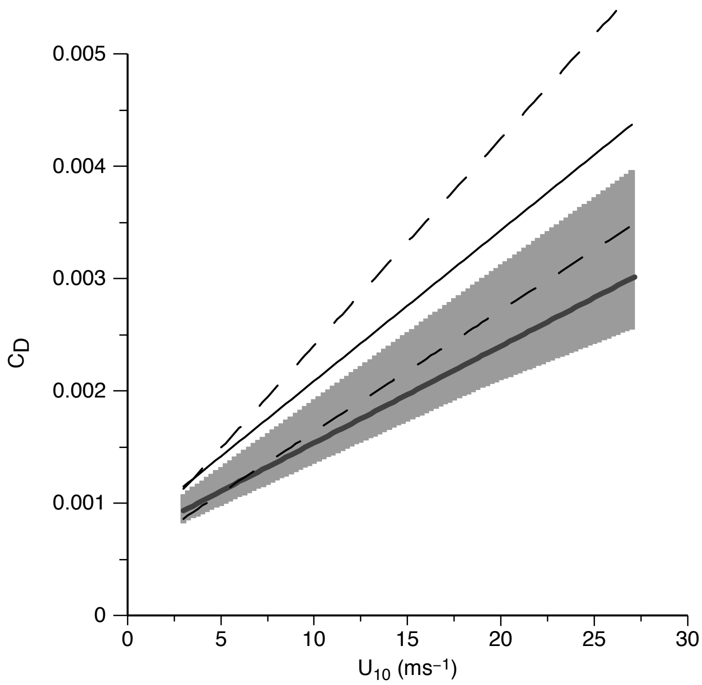

Figure 7. Relation between drag coefficient and 10 m wind stress, our study (orange), earlier studies (grey, blue)

dashed lines define an upper and a lower limit of the spatial variability of the parameter estimation. The grey region defines the upper and lower limits of the drag coefficient taken from earlier studies, and the dark grey line is the average of earlier estimations.

The graphs were calculated with the linear regression of the simulated relation between U_{10} and C_D. This yields values of $a = 0.6 \pm 0.05$ and $b = 0.15 \pm 0.04$, which are higher than the values mentioned in most of the earlier estimations mentioned above. This can be explained by the fact that in contrast to other studies, our study area is prevailingly a shallow near-shore region.

The importance of the sea-state in the Ems-Dollard region on the transfer of momentum from the atmosphere to the sea is obvious. However, instead of taking these processes into account, it is a common procedure in hydrodynamic models to modify the bottom stress in order to reduce uncertainties. In contrast, we show a simple method to estimate a local drag coefficient and thus achieve physically consistent and efficiently computable simulations.

6. CONCLUSION

Despite the shortness of the simulation period, it reveals strong fluctuations of the MSL. These variations are, however, not statistically distributed, but must be regarded as random. Hence, it can be concluded that for the interpretation of climate-related changes long-term series of observations and simulations are needed. Simulations have to be performed by models which represent the physical processes and are particularly fast in computing. This study shows that with regard to uncertainties and computing time, the tested models fulfil the requirements and can thus be used for long-term simulations as well.

The need to use coupled models for wind-wave simulations arises from the aim of each study. Generally, in shallow regions the difference between the simulation of waves, with and without currents is less than 10%. Hence, the influence of currents on waves can be neglected in many processes – e.g. sedimentation, morphologic changes, and coastal protection – on climatic time-scales. On the other hand, inside tidal channels the difference can exceed 25% – here, studies with an additionally sediment model must show, how sensitive the sedimentation processes react on this difference.

Moreover, we show a simple method to calculate a regional drag coefficient to reduce uncertainties of wind-surges, which influence the statistics of the MSL. Hence, to return to the purpose of studying changes on climate scales, a (small) step forward to physical consistent impact models has been done in this study.

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