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INTERACTION OF WIND-WAVES AND CURRENTS IN ESTUARIES WITH FOCUS ON CLIMATE CHANGE

Hein H.[1], Mai, S.[2], Barjenbruch, U.[3]

Abstract: *In coastal regions and estuaries, physical processes influence many economic and ecological processes as well as security issues. In a context with climate change, these physical processes are subject to inherent changes. In order to get an impression of future changes and the probability of their occurrence, physically consistent simulations are needed, which describe how wind-waves and currents interact and moreover, how they control estuarine processes.*

In this paper, we present a coupled simulation of HAMSOM (HAMburg Shelf Ocean Model) and SWAN (Simulating Waves Nearshore). The state-of-the-art models HAMSOM and SWAN are computationally fast, so that they offer an opportunity to simulate hydrological conditions and physical processes over a longer time period, e.g. years or decades.

The scope of the coupled models is shown by means of an example of a North Sea estuary (Germany). Statistics of the simulations are validated and analysed with wave- and sea-level-data from wave and tide gauges. For one single event joint probabilities of interactions are estimated. The influence of currents on waves in a coupled model seldom exceeds 10 %. It can be assumed, than these influence can be neglected in many cases.

Improvements of parameter estimations due to model coupling are shown and discussed. Long-term simulations need to be simplified, thus a method, which bypasses the direct coupling of models, is discussed. This method yields an optimisation concerning computationally economic and physical consistent simulations.

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

INTRODUCTION

In coastal regions and estuaries, in the long-term, currents as well as wind-waves control the changes of economic and ecological processes as well as coastal protection. Thereby, a single storm surge can destroy dykes or erode a broad coastal area. However, mean (tidal-)currents and wind-waves work continuously in the estuary: The whole frequency scale of hydrologic processes

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causes slightly changes, which can be analysed with a probabilistic approach. In order to get an impression of the future changes and the probability of their occurrence, physically consistent and certainly simplified long-term simulations are needed.

In this study the Ems-Dollart-Estuary (Germany) is considered as an example of a North Sea estuary (Fig. 1). Several external forces control the distribution of currents and waves. The most important are wind and tides, which both are subject to the conditions of the North Atlantic. 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 the change of processes in an estuary related to global warming, the long-term natural variability must be determined. Even in recent times, this implication asks for local impact models which are relatively simple, but which are valid to reproduce the governing processes, forced by wind and tides.

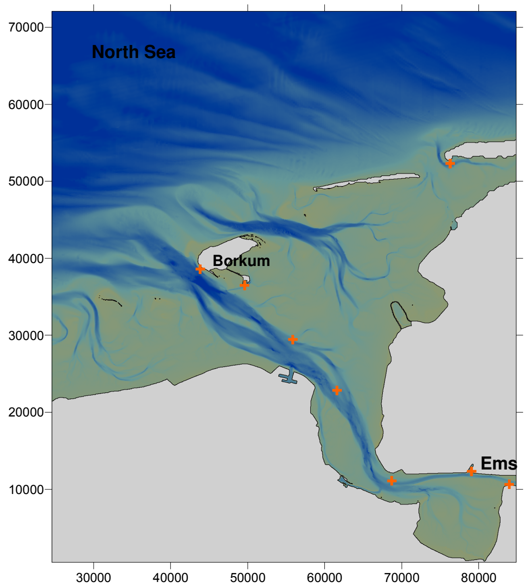

Fig. 1: Topography of the Ems-Dollart-Estuary. Orange crosses mark the positions of tide gauges.

This study takes a main physical process into account - the interaction of wind, waves and currents. Recent studies (e.g. Mai et al., 2004, Nicolle et al., 2009; Pleskachevsky et al., 2009) show in general two issues: 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 calculating wave-current interactions. Hence, parameter improvement with a coupled simulation of waves and currents is tested to reduce the uncertainty of simplified climate impact models.

METHODS

To simulate currents and sea-level, the hydro-numerical model HAMburg Shelf Ocean Model (HAMSOM) is used. HAMSOM - a veteran of hydro-numerical models - was first set up in the mid-eighties by Backhaus (Backhaus, 1983; Backhaus, 1985). HAMSOM has be used 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 combined with the hydrostatic assumptions are implemented. The basic equations can be found in Schrum (1994) and Pohlmann (1996a). The simulation of the estuarine circulation yield several numeric requirements to the model (Hein, 2007). Therefore, high order formulations are used for the momentum equation and the transport equation. The importance of diffusion processes on (de-) stratification in estuaries are 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 had been 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 (Dick, 2001).

For the calculation of waves the third-generation wave model SWAN ("Simulating Waves Nearshore"; Ris, 1997; Ris et al., 1999; Booij et al., 2004) is used. The 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 as a base for improved long-term simulations. Moreover, because an overall goal of climate process studies, yield the use of standard model-parameter. At first, tides and currents are computed without recognizing the influence of waves on the momentum transfer. Secondly, wind-waves are simulated with and without the influence of currents. The simulation results of wave parameter are discussed for the use of parameter-optimization of the hydrodynamic model.

VALIDATION

To follow the ideas of Dee (1995), a model can only be valid for the explicit use. 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 acting community on 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-Dollart-Estuary. At first, it is depicted, that the hydrodynamic model has the ability to reproduce tidal dynamics. The results of a short time run (October – December 2006) are analysed. In fig. 2a the grey area represents the probability density function (PDF) of the differences between measurements of tide gauges and simulation results. Thereby, the measurements of six gauges (fig. 1, orange crosses) are compared with the local results of the hydrodynamic model. The differences are combined in the PDF. The orange line is a theoretical Gaussian distribution curve with a standard error of 8 cm. The similarity of the PDF and the orange curve demonstrate that the uncertainty of the hydrodynamic model is in general from stochastic nature, with only a small systematic error.

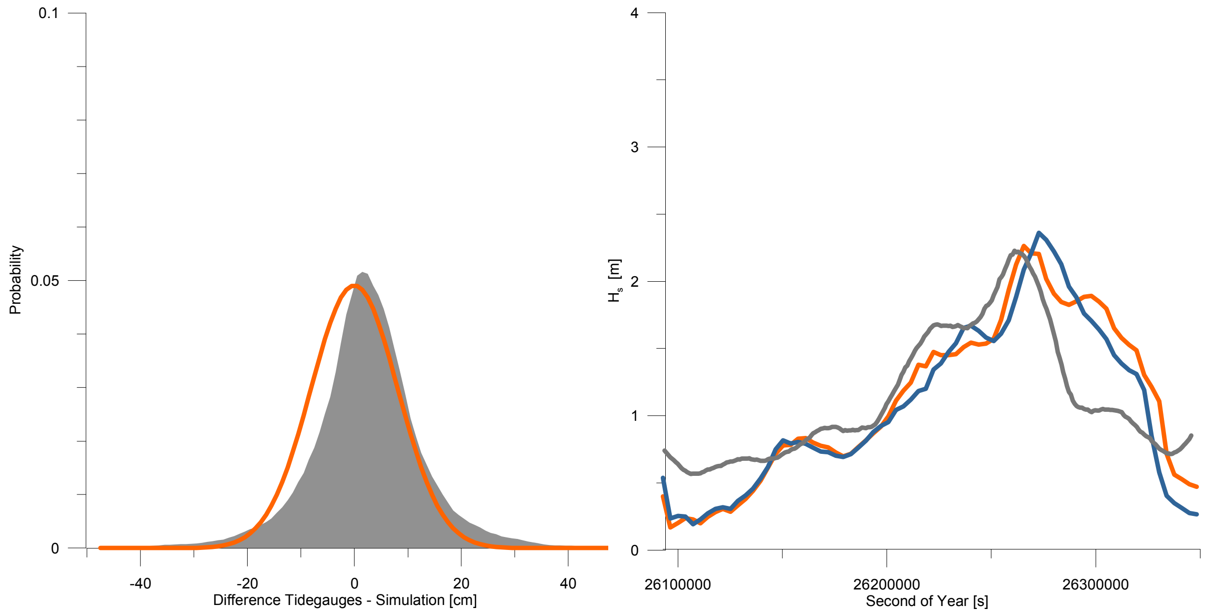

Fig. 2: a) PDF of the difference between simulation and tide gauges (grey), theoretical Gaussian distribution curve (orange); b) Significant wave height from observations (grey) and simulations (others).

For the wave model a comparison between observations and simulations in the Ems-Dollart-Estuary is done by Mai (2008). However, to simplify these climate impact model, the resolution had been lowered. Fig. 2b shows simulated significant wave-heights (H_S) and observed significant 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 depicted. More information about the used dataset of observed waves can be found in Barjenbruch and Wilhelmi (2008). In the figure the grey line represents the observations, while the blue line represents wave simulations without the effect of currents and the orange line shows the results which include this effect. Both curves fit well to the observations. The increase of the waves heights as well as the maximum H_S during 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 spatial 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 illustrated accuracies both model allow simulations on required time scales for climate projections.

RESULTS

Fig. 3a shows the simulated sea-level (grey) and the Mean Sea Level (MSL, blue) over the simulation time. The presented sea-level is a spatial average of the region near Borkum, indicated with the orange 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 typical estuarine standing wave.

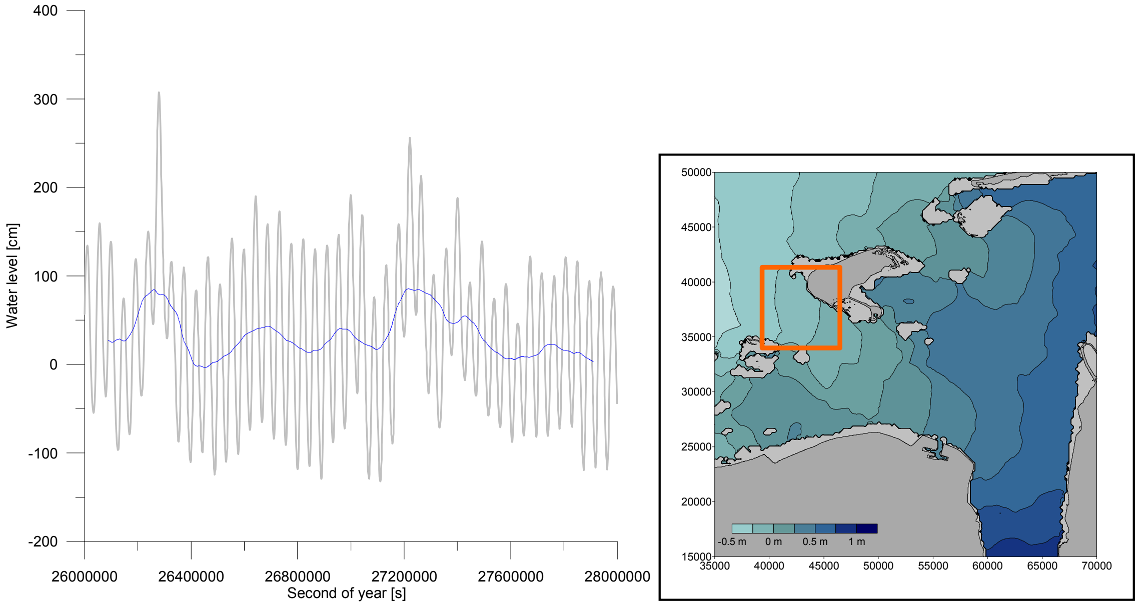

Fig. 3: a) MSL of the short time run in a region near Borkum, b) Sea Level snap shot of the outer estuary.

Although the simulation-time of our test study is too short for climate purposes, on scales of days and weeks an unsteady variability of the MSL is obvious. The variability represents rather typical weather time scales, than spring-neap tides and it has a stochastic random nature. However, our test study on the interaction of currents and waves is restricted to first of the extreme events, which are visible in fig. 3a. During this time, the range of the MSL is one meter. This is in a comparable magnitude 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 a H_s, which is in general in between 0.5 m and 2 m. Main differences are displayed 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. It can be seen, that the error induced by the neglect of current-wave interaction seldom exceeds 10 % of the significant wave heights. Especially in the shallow mud-flats the interaction of waves and currents can be neglected. In the tidal channels the waves are decreased by the strong currents flowing into the region. In the region of the basement of the mud-flats (northwest of Borkum) waves are increased (25 %) by currents during the storm event.

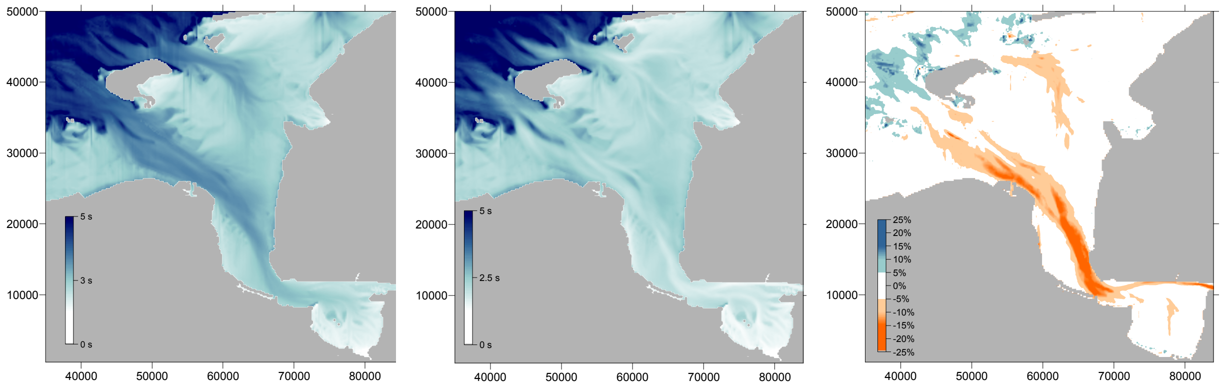

Fig. 4: Significant wave heights, a) with current-interaction, b) without current-interaction, c) difference in percent.

Fig. 5 shows the same as fig. 4, but for the wave-period (T_{m01}). As well as H_s the wave period shows only significant differences in the tidal channels, where the period is simulated too high, if currents are neglected. In the shallow regions, in the mud flat and the foreland the influence of the currents on the wave is not important.

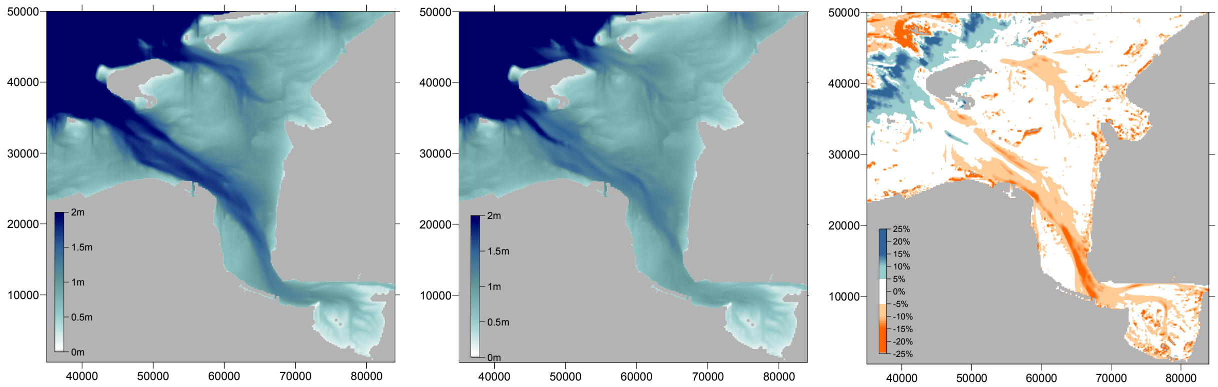

Fig. 5: Wave period T_{m01}, a) with current-interaction, b) without current-interaction, c) difference in percent.

DISCUSSION

The results show that in the outer-estuary significant wave heights in the order of 1 m - 2 m can occur and a non-coupled model induces errors of about 10 %. At the tide gauge Borkum-Süd a difference is not noticeable (fig. 2b). A study (Tolman, 1991) on a basin-wide scale estimated errors in the same order than we do in our study. In difference to that study, our resolution allows to represent tidal channels, in which errors are more pronounced due to less frictional dissipation.

As our results show that an influence of currents on the wind-waves is only found in these tidal channels. Thus, the use of coupled models depend on the specific aim of a study. If the aim of the study is to find near realistic $H_{S,}$ a one way coupling seems to be useful. However, if the purpose is to study sedimentation processes, a coupling of the models can be assumed to be unimportant as the error is relatively small. A study on a more coarse scale for the North Sea of van der Molen (2004) discusses, that the influence of wind and waves on the net-transport of sand is only important in regions where tidal currents are small.

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

A second process is the modification of the bottom friction coefficient if waves are present (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, a part of the wave energy is directly transferred into momentum.

In this study we take only the first process into account, hence 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:

$$\tau_s = \rho_a C_D |U_{10}| U_{10} \tag{1}$$

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 varies with the sea state. Assuming a linear relation between wind and waves, it is common to use a linear approach of the coefficient, which depends on the wind velocity:

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

where a and b are empirical coefficient. 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 that studies the averaged coefficient are of about $a = 0.7 \pm 0.04$, $b = 0.08 \pm 0.03$ can be calculated. The studies show a wide range of values for the coefficients dependent on the region of the observations or the method of estimation. Thus, no consistent values exists for the drag coefficient. However, the results of the wave simulations provide to estimate the coefficients for the Ems-Dollart region.

With the definition of C_D as the quadratic 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 studied estuary, which depends on the local sea state. Therefore, we use the 3/2-power law, which was proposed by Toba(1972):

$$H_S = \beta (g u_*)^{1/2} T_S^{\ 3/2} \tag{4}$$

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 on, based on equation (3) and (4) we then can find a regional parameter for the linear drag coefficient (3), which is related to the sea-state of the estuary. However, the simple relationship of the 3/2 power law breaks down under significant swell, but it can be used also with stationary wave data, which are available for German coastal and estuarine regions (www.fi.uni-hannover.de/seegangsatlas/). Because this method bypasses coupled simulations, it is a appropriate solution, especially if it is necessary to decease the computing time of climate impact models.

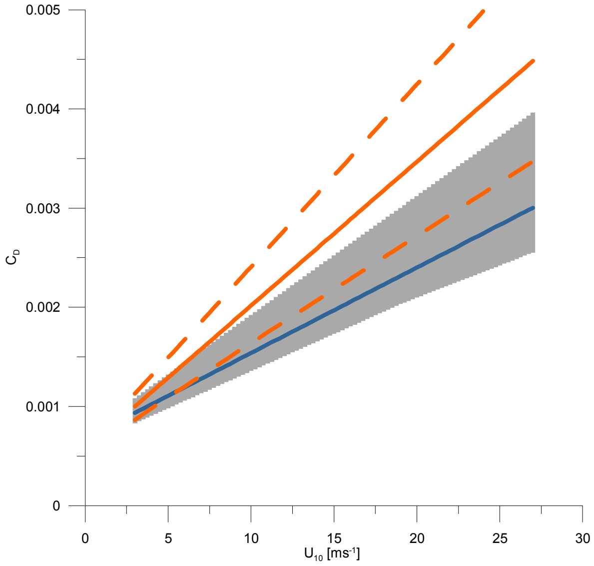

Fig. 6: Relation between drag coefficient and 10m wind stress, our study (orange), former studies (grey, blue).

In fig. 6 the local estimation of the drag coefficient in relation to the wind velocity is depicted. The orange line shows the regional optimized linear drag coefficient calculated from our model results. The dashed lines define a upper and lower limit of the spatial variability of the parameter estimation. The grey region defines the upper and lower limit of the drag coefficient taken from former studies and the blue line is the average from former estimations.
To calculate the graphs the linear regression of the simulated relation between U_{10} and C_D was used. This yield values of $a = 0.6 \pm 0.05$ and $b = 0.15 \pm 0.04$, which are higher than the values mentioned in most former estimations mentioned before. This can be explained by the fact that in difference to other studies, our region is dominated by a shallow near-shore region.

The importance of the sea-state in the region of the Ems-Dollart on the transfer of momentum from the atmosphere to the sea is obvious. However, instead of taking these process into account it is a common way in hydrodynamic models to modify the bottom stress to reduce uncertainties. In contrast we show a simple method to estimate a local drag coefficient. This yields physical consistent and computably effective simulations.

CONCLUDING REMARKS

Despite the short period of simulation, it reveals a strong fluctuation of the MSL. This variation is, 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 necessary. Simulations have to be performed by models which represent the physical processes and which are particularly fast. The study shows that with regard to the uncertainties and computing time, the tested models fulfill the requirement and can be used for long-term simulations.

The need to use coupled models for wind-wave simulations depends on the aim of the study. Generally, in shallow regions the reduction of the uncertainty of the coupled model is less than 10 %. Hence, the influence of currents on waves can be neglected for many processes, e.g. sedimentation processes, morphologic changes and coastal protection on climatic scales.

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

REFERENCES

Backhaus J. O., 1985. A three-dimensional model for the simulation of shelf sea dynamics. *Dt. Hydrogr. Z. 38, 165-187.*

Backhaus, J. O., 1983. A semi-implicit scheme for the shallow water equations for applications to shelf sea modeling. *Continental Shelf Research 2 , 243–254.*

Barjenbruch U., Wilhelmi, J. 2008. Application of radar gauges to measure the water level and the sea state, Proc. of 31st ICCE, 687-695, Hamburg.

Booij, N., Haagsma, I.J., Holthuijsen, L. H., Kieftenburg A., Ris R., van der Westhuysen A. and Zijlema M., 2004. *SWAN User Manual, Version 40.41. Delft Uni. of Tech., Netherlands.*

Davies, A. M., and J. Lawrence, 1995. Modeling the effect of wave-current interaction on the three-dimensional wind-driven circulation of the Eastern Irish Sea, J. Phys. Oce., 25, 29–45.

Dee, D. P. 1995. A pragmatic approach to model validation*, Quantitative Skill Assessment for Coastal Ocean Models, Kap. 1, pp. 1–13, American Geophysical Union, 1995.*

Dick, S., E. Kleine, S. H. Müller-Navarra, H. Klein, H. Komo, 2001. The Operational Circulation Model of BSH (BSHcmod) – Model description and validation. *Berichte des Bundesamtes für Seeschifffahrt und Hydrographie 29, 49 pp.*

Ebuchi, N., Y. Toba, and H. Kawamura, 1992. Statistical study on the local equilibrium between wind and wind-waves by using data from ocean data buoy stations. *J. Oceanogr., 48(1), 77-¬92.*

Garratt, J.R., 1977. Review of drag coefficients over oceans and continents. *Mon. Wea. Rev., 105, 915-929.*

Hein, H., Karfeld, B., Pohlmann, T., 2007. Mekong water dispersion. Measurements and consequences for the hydrodynamic modelling, *J. of Water Res. and Env. Eng., Special Issue, August 2007, 21 – 28.*

Hein, H., 2008. Vietnam Upwelling - Analysis of the upwelling and related processes in the coastal area off South Vietnam, *http://www.sub.uni-hamburg.de/opus/volltexte/2008/3931/*

Hurrell, J.W., 1995. Decadal Trends in the North Atlantic Oscillation: Regional Temperatures and Precipitation. *Science: 269, 676-679.*

Leterme S.C, Pingree, R., Skogen, M.D., Seuront, L., Reid P.C., Attrill, M.J., 2008. Decadal fluctuations in North Atlantic water inflow in the North Sea between 1958-2003. impacts on temperature and phytoplankton populations, *OCEANOLOGIA, 50 (1), 59-72.*

Mai, S., Stoschek, O., Geils, J., Matheja, A., 2004. Numerical Simulations in Coastal Hydraulics & Sediment Transport. *Proc. of the NATO Advanced Research Workshop (ARW), 149 - 169.*

Mai, S., 2008. Statistics of Waves in the Estuaries of the Rivers Ems and Weser - Measurement vs. Numerical Wave Model. *Proc. of the 7th Int. Conf. on Coastal and Port Engineering in Developing Countries COPEDEC, CD-ROM, Dubai, United Arab Emirates, 2008.*

Nicolle, Karpytchev, M., Benot, M., 2009. Amplification of the storm surges in shallow waters of the Pertuis Charentais (Bay of Biscay, France), *Ocean Dynamics, 59 (6).*

Pleskachevsky, A., Eppel, D., Kapitza H., 2009. Interaction of waves, currents and tides, and wave-energy impact on the beach area of sylt island", *Ocean Dynamics, 59 (3), 451-461.*

Pohlmann, T., 1996a. Predicting the Thermocline in a Circulation Model of the North Sea --Part I. Model Description, Calibration and Verification. *Continental Shelf Res., 16 (2), 131-146.*

Pohlmann, T., 1996b. Calculating the annual cycle of the vertical eddy viscosity in the North Sea with a three-dimensional circulation model. *Continental Shelf Res., 16 (2), 147-161.*

Pohlmann, T., 2006. A meso-scale model of the central and southern North Sea: Consequences of an improved resolution. *Continental Shelf Res. 26, 2367 – 2385.*

Ris, R.C., 1997. Spectral Modelling of Wind-waves in Coastal Areas, *Communications on Hydraulic and Geotechnical Engineering, Report No. 97-4, Delft University, 1-160.*

Ris, R.C., Holthuijsen, L.H., Booij, N., 1999. A third-generation wave model for coastal regions, Verification*, Journal of Geophysical Research, 104, 7667-7681.*

Schrum C., 1994. Numerische Simulation thermodynamischer Prozesse in der Deutschen Bucht. *Berichte aus dem Zentrum für Meeres- und Klimaforschung, Reihe (B), Nr.15. 175 S.*

Smith, S.D. and Banke, E.G., 1975. Variation of the sea surface drag coefficient with wind speed. *Quarterly Journal of the Royal Meteorological Society 101, pp. 665–673.*

Tsimplis M. N., Shaw A. G. P. , Flather R. A. and D. K. Woolf. 2006. The influence of the North Atlantic Oscillation on the sea-level around the northern European coasts reconsidered. the thermosteric effects. *Philosophical Transactions of the Royal Society A 364. 845-856.*

Tolman, H.L., 1991. Effects of Tides and Storm Surges on North Sea Wind-waves*, J. Phys.Oceanogr., 21, 766-781.*

van der Molen, J., 2002. The influence of tides, wind and waves on the net sand transport in the North Sea, *Continental Shelf Research, Volume 22, Issues 18-19, Pages 2739-2762.*

Wu, J.. 1980, ‘Wind-Stress Coefficients over Sea Surface near Neutral Conditions - A Revisit’, *J. Phys Oceanogr. 10,727-740.*

Zubkovskii S. L., and T. K. Kravchenko, 1967. Direct measurements of some turbulence in the near-water layer. *Izv. Atmos. Oceanic Phys, 3, 127–135.*