UNCERTAINTIES OF DRYING PERIODS

OF COARSE COASTAL CLIMATE IMPACT MODELS

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Abstract

In coastal regions the estimation of most accurate drying periods of tidal flats is important for heat flux processes. In relation with climate change impact on coastal regions, the rising sea level and increased tidal amplitudes result in shorter drying periods of tidal flats. Due to the different albedo of seawater and tidal flats the heat balance changes. Moreover, heat budget in coastal wetlands is important for the health of the ecosystems.

Our study investigates into the uncertainty of drying periods, due to an uncertain representation of the topography in coarse coastal climate impact models. Therefore we use an example region: the east Frisian Wadden sea between the island Borkum and the German coastline. To simulate likely future states of drying periods we use a so called “model-chain”, which is the synonym for the regionalization or downscaling of global climate scenarios toward the regional coast.

Our results show the importance of the numerical algorithm (e.g. first-order or high-order). Dependence of the grid-size of simulations is crucial to the drying period. With higher resolution of the topography, individual tidal creeks are better represented. In general, we conclude that the coarser the grid-size, the shorter the drying periods. With the indicated rising sea non-linear aspects play a significant role. One must conclude that inhomogeneous grid-sizes result in inaccurate estimations of changes in coastal heat budgets and may cause false interpretation of future health changes of the coastal ecosystem.

Introduction

Coastal regions are often dominated by small-scale low-lying morphologic features, which are partly overlaid with shallow water. Consequently, tidal motion results in sub-areas, which can be both - dry and covered with water during one tidal cycle. One pronounced example region is the southern German Bright, where wide areas of tidal flats exist. Figure 1 shows the tidal flat at the outer Ems-Dollard Estuary; here the test area of this study is located.

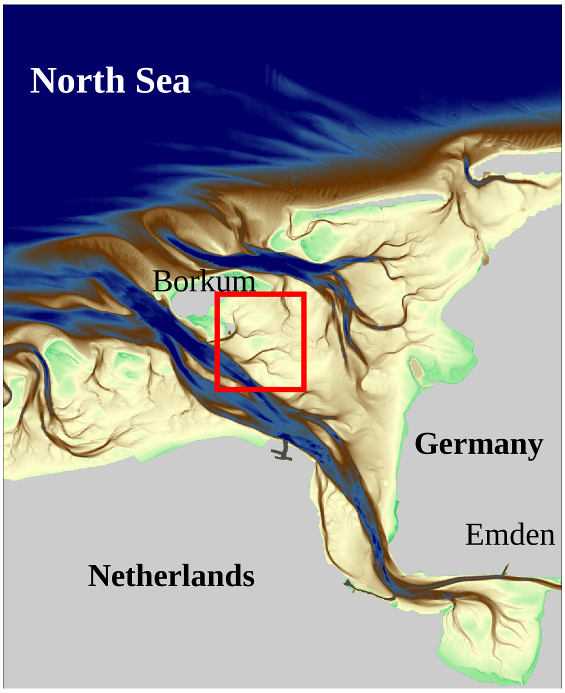

Figure. 1: Model area, black crosses indicate tide gauges, the red box is the test area.

For the numerical hydrodynamic modeling of such regions the accurate topographic representation is of importance, at least for three reasons: Of course to ensure local self-oscillations of the tides. Moreover, if the modeling task includes baroclinic processes, the heat balance may play an important role. If we take into account that the albedo of mud-areas and sea water is different, we have to compute periods in which the flats are dry in an accuracy that the errors do not lead to misinterpretation of the results. Finally, if the hydrodynamics should establish the basis for ecological studies, the drying periods are one crucial factor.

These three reasons are especially from importance if we investigate into *long-term* changes of the hydrological, morphological or ecological system. In this case it is additionally necessary to use hydrodynamic models, which are efficient in the sense of computer resources. Therefore these models allow only relatively coarse spatial resolutions.

Generally, drying-wetting numerical solutions can be classified by two major methods: The first one is based on the modification of the grid sizes at the coastal boundary (e.g. Sielecki and Wurtele, 1970). However, this method may not be a practical solution for the modeling of long-terms, because it's computably inefficiency and its data storage requirements. The second kind of methods are the eulerian or flux-limited methods, which are proved since years and well reviewed by Balzano (1998).

With ongoing implementation of increasingly more hydrodynamic models several numeric solutions for wetting and drying processes can be found in literature (e.g. Burchard et al., 2004; Jiang et al. 2005; Begnudelli and Sanders, 2007). There seems to be no perfect solution, in any bullet we always have to bite. So, it can be stated that some of the solutions allow negative water depths to support conservation of mass. This has the advantage of stability, but may result in unphysical flow in dry areas. For example, this then leads to inaccuracies in studies of dispersal of substances. In other implementations, which base on the idea that if the water is very shallow a simple balance between external pressure gradient and friction prevails (Burchard et al., 2004). One recent publication (Gourgue et al. 2009) presents a flux limiting method for the wetting and drying process, which is generally mass conservative and there is no transport though dry areas.

As stated at the beginning, in this study the mayor challenge is addressed, that the coarse grid solution, which is needed for the long-term computation, may do not solve the topography in an adequate manner. For example, small tidal creeks or thin anthropogenic structures (e.g. groynes) disappear in the gridding process. To overcome this, literature refers to a few possible solutions, which allow grid elements to be partly wet and also partly dry (Hervouet and Janin 1994; Tchamen and Kawahita 1998; Casulli, 2009).

Methods

To simulate currents and sea-level, the hydro-numerical model HAMburg Shelf Ocean Model (HAMSOM) is used. HAMSOM was first set up in the mid-eighties by Backhaus (Backhaus, 1983; Backhaus, 1985). 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, 2006). The simulation of the estuarine circulation yield 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 on (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 had been chosen as it allows the representation of tides, storm-surges and long-term baroclinic processes as well as long-term simulations. The time step is set to 40 s, which allows to resolve almost all of the representative overtides in these coastal region. The applicability for this model in the region was presented by Hein et al. (2011a).

For comprehension the drying-wetting process is presented in detail. However, the first-order solution it is about the same as that of Burchard et al.(2004) and we therefore skipped here the detailed derivation. A general aplicability of this method was shown by Hein et al. (2011a).

For the high-order solution we define the topographic details on the sub-grid level, this can be either analytical or numerical. Figure 2 shows the effect of the high-order solution with the numerical represention of a high-order topography. On the left pannels, which show the coarse resoltution, topography has a "block-like" style. On the right panals, the resotution allows to seprate spatially single tidal creeks, or also single harbour basins.

For the high-order numerical solution, we define the actual total water depht (H) for each sub element:

$$H_{i,j,ii,jj,t} = \eta_{i,j,ii,jj,t} + h_{i,j,ii,jj} \qquad (1)$$

where t is the time, i and j the grid indicees, directed in sothern and western direction, respectivelly. The sub-grid indicees are represented by ii and jj. η is the free surface, which is interpolated towards the sub-grid with a bi-linear aproache. For the conservation of mass negative water depth are detected. We use a flux correcting method, approximataly in the same manner like it is presented by Gourgue et al. (2009).

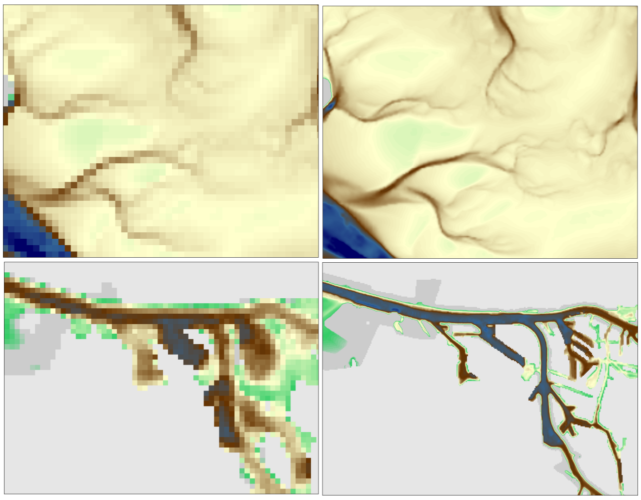

Figure. 2: Representation of the topography. Left: The topographic level used by the hydro-numeric solver, right: The topographic level used for drying-wetting, friction, horizontal turbulence, structure detection. Upper: Tidal creeks in the investigation area. Lower: Example for Harbor Basins in the Elbe River.

After flux corretion the continue equation is calculated again. To solve the nonlinear system the free surface is calculated again with the SOR-iteration (Schrum, 1994). In the second step the formulation of (1) follows to define a so a called sub-grid existensfunction:

$$EXs_{i,j,ii,jj,t} = \begin{cases} 1 \Leftarrow H_{i,j,ii,jj} > 0 \\ 0 \Leftarrow H_{i,j,ii,jj} \leq 0 \end{cases} \qquad (2)$$

The drying process is calculated on the cell edge regions with an additional wall detection algorithm, this allows the defination of a at the u-points and v-points flux-existencefunction in the Arakawa C grid:

$$\begin{aligned} &EXu_{i,j,t} = \\ &\min(1., \mathrm{maxval}(\mathrm{f}(\mathrm{EXs}_{\mathrm{i,j,ii,jj,t}})_{j+0.5,i,t})) \\ &EXv_{i,j,t} = \\ &\min(1., \mathrm{maxval}(\mathrm{f}(\mathrm{EXs}_{\mathrm{i,j,ii,jj,t}})_{j,i+0.5,t})) \end{aligned} \qquad (4)$$

Here f is a function of the possible paths (with elements of EXs = 1) in the sub-grid exitence function. The function is conditioned in such way, that only one single interconnected and possibly meandering row is sufficient to allow a flux at the cell edge. The meaning of this is that the algorithm in this first step allows to block fluxes between two grid cells, for example between two naigbouring harbour basins or in the presense of groynes. Grid cells are set to dry if all fluxes of the flux limititing existencefunctions are zero:

$$\begin{aligned} &EXz_{i,j,t} = \min(1., \mathrm{maxval} \\ &(\mathrm{EXu}_{\mathrm{i,j_{+0.5}}} + \mathrm{EXv}_{\mathrm{i_{+0.5},j}} + \mathrm{EXu}_{\mathrm{i,j_{-0.5}}} + \mathrm{EXv}_{\mathrm{i_{-0.5},j}})) \end{aligned} \qquad (5)$$

In the following we test this formualtion against the simple first-order solution. The influence of the resultion of the grid on the drying-wetting process is tested. Moreover, aplicability with an climate test case is shown.

Results

At first the differences between the first and the high-order solution is presented. Figure 3 shows the dry area is the example region about at tidal low water on the left in the sub-grid resolution of 40 m and on the right the according wet cell on the dynamically resolved grid (200 m). The difference is obvious. With the high-order mechanism morphologic structures are resolved. This is important because this information is additionally used for the calculation of the frictional forces as well as for the estimation of a high-order Smagorinsky-scale-factor. But, it can also be shown that the major tidal creeks are to be found also in the coarse resolution. From that we can assume that tidal oscillations with wavelengths of about 1 km to 2 km are spatial resolved. We can evaluate, that a higher spatial resolution reduces associated time-steps, which reduce the efficiencies for long-term modeling. In the middle an area is indicated, where the flux is blocked by the sub-grid model. Hence, at this position without the high-order solution modeled tracers could pass unrealistically.

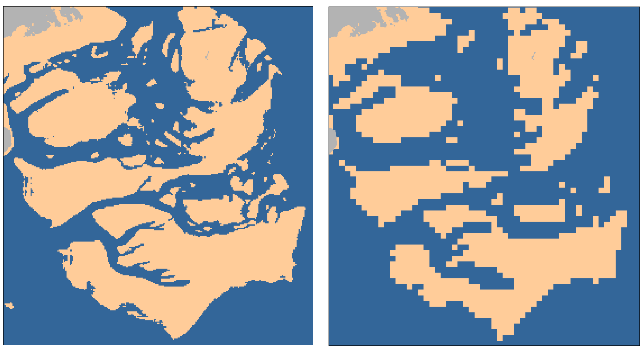

Figure. 3: Comparison of dry-region during a low tidal water level; Left: high-order solution, right: First-order solution.

Next, we show the differences of the spatial extend of the dry areas of the two solutions. With a realistic topography this becomes to a distribution and it is ad hoc not one single number. Figure 4 shows the distribution of the two drying-wetting solutions of the test area. For tidal flats this distribution has typically a bi-modal characteristic. This reflects the two different behaviors of on the one hand tidal flats and on the other hand the water supplying tidal creeks. We can see the clear non-linear shift between the two distributions. Hence, in general with the coarser resolution the dry-falling area is smaller. Additionally, the change in the left peak let us know that also it is more likely that tidal creeks remain to be covered with water.

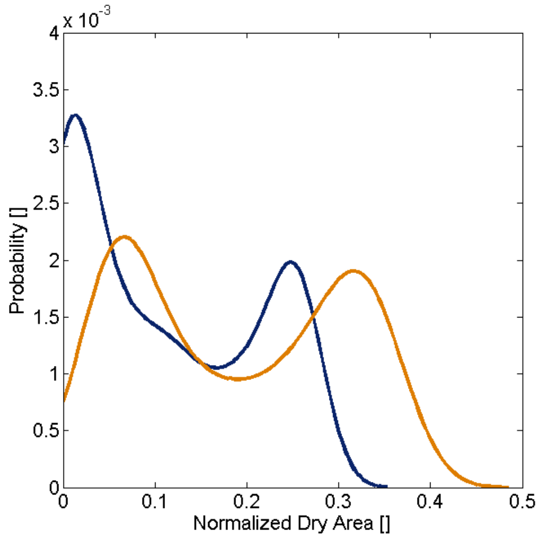

Figure. 4: Normalized dry area during a tidal cycle of the test region (dry area relative to the dry and wet area in the test region. Blue line: First-order solution; orange line: high-order solution.

This differences have considerable effects on the drying period itself (Figure 5). Against, it is supported that drying periods of an area - objective by definition - can only be a distribution. With the high-order resolution the probable drying period is more or less linear increasing form being always wet to being only two hours covered with water. The coarser solution fails in reproduction of this drying process, in general the drying period is shorter. This strong differences are surprising results, if we remember that the resolved dynamic processes are calculated on the same grid-size. Hence, we can show that high-order or sub-grid solutions are an effective and modern way to simulate estuarine or coastal processes.

The potential is not high enough to be underestimated, because it allows also coastal engineering to use such methods, which are in other disciplines state of the art, for example: Modeling of ensembles. The method is also interesting, since scale-compliant modeling is possible, ie the dispersion characteristics of the momentum is represented numerically well. Here, we want to give a small example for long-term modeling.

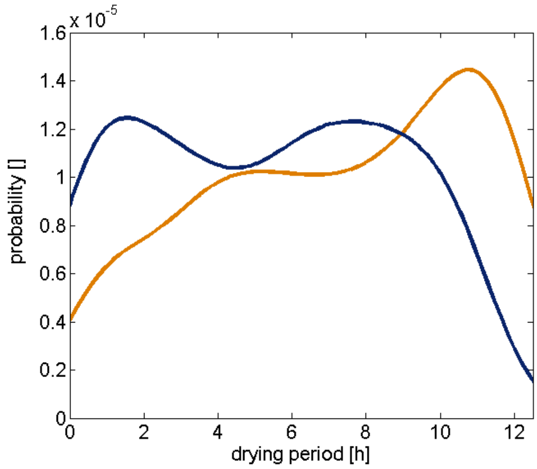

Figure. 5: Normalized dry period during a tidal cycle of the test region (dry area relative to the dry and wet area in the test region. Blue line: First-order solution; orange line: high-order solution.

Application to climate change

“Climate in a narrow sense is usually defined … as the statistical description in terms of the *mean and variability* of relevant quantities over a period ranging from months to thousands or millions of years. Climate in a wider sense is the state, including a statistical description, of the climate system (IPPC, 2007).” The local coastal-hydrological climate is the characteristic frequency distribution of the hydrodynamic conditions and processes during a sufficiently long period. Therefore, if we want to make reliable statements about the impact of climate change on hydro-dynamics, we cannot avoid operating long-term models. In the last section we presented an efficient and scale conform high-order solution of the drying-wetting process which may allow to simulate long-terms.

The most important change at coastal regions is the climatic sea level rise. A detailed description of the future regional sea level in the study region is not to be found. To simulate likely future states of drying periods we use a so called “model-chain”, which is the synonym for the regionalization or downscaling of global climate scenarios toward the regional coast. Our result show a range from -20 cm to 80 cm in the fluctuation of sea level from 1950 to 2100. For the applicability-test our future assumptions base on the results of the historic rise in the study region and what we have to learn about future states (Hein et al., 2011b). The central estimate of the *extreme* scenario for the Netherlands (Katsman et al., 2011) is 85 cm for the year 2100, so our result are in an acceptable range. Additionally, an increase in the range of shallow water tides due to sea level rise is recognized (Müller et., 2011).

Figure 6 shows the estimated distributions of the dry areas, for 20 cm increasing steps (e.g. -20 cm, 0 cm, 20 cm, 40 cm 60 cm, 80 cm). Due to the future rise the distributions change their forms in a non-linear meaning. Hence, the balanced bi-modal characteristics of the distribution in our days changes with the rising sea to a more unbalanced distribution.

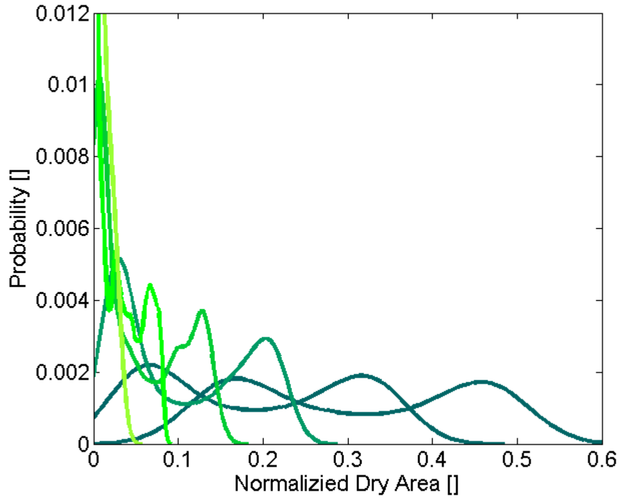

Figure. 5: Normalized dry area during a tidal cycle of the test region. Mean sea level slices of sea level fluctuations: -20 cm (dark green) to 80 cm (light green).

The change of the drying period is non-linear as well (Figure 7). The most likely period decreases a long time not significantly and stay at about 11 hours like in our days. But then with a rise of more than 60 cm the drying period lower significantly with a step to a double peak of 0 hours and 6 hours, respectively.

The results of the drying period itself in this study should not used for impact studies; here they only used to show a general applicability. If one compare figure 5 and figure 7, it is obvious that the use of the course resolution allows yields uncertainties, which may leads to misinterpretations.

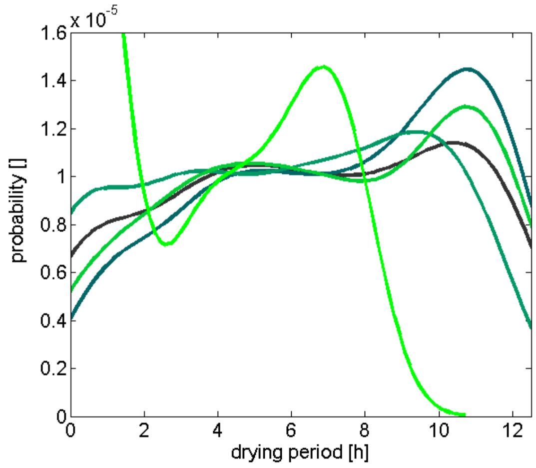

Figure. 6: Normalized drying period during a tidal cycle of the test region. Mean sea level slices of sea level fluctuations: -20 cm (dark green) to 80 cm (light green).

Conclusions

If we want to model future states of estuaries and coastal regions we need long-term models. Because of available computer power these models must be effective. That means on the on hand they must have coarse resolution on the other hand there is the need that the processes resolved well. Dependence of the grid-size of simulations is crucial. With higher resolution of the topography, individual tidal creeks are better represented. In general, we conclude that the coarser the grid-size, the shorter the drying periods.

This study presented a modern approach to reduce the uncertainties of wetting-drying processes. The method is also interesting, since scale-compliant modeling is possible, ie the dispersion characteristics of the momentum is represented numerically well. One benefit of the method is not presented here: The high-order solution improve also the phase-speeds of the tidal signal. This additional effect is in a explainable with both, the optimized representation of frictional processes and the revised Smagorinsky-Scheme. Detailed descriptions of this story will written elsewhere.

Our results emphasize the importance of numerical algorithms (e.g. first-order or high-order), which can overcome ineffective banally increase in the grid resolution. With the rising sea non-linear aspects play a significant role. Moreover, one can conclude that inhomogeneous grid-sizes in models results in inaccurate estimations of changes in coastal heat budgets and may yield false interpretation of future health changes of the coastal ecosystem.

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