ROLE OF TIDES IN GENERATING DOWNDRIFT-ORIENTED CHANNELS ON EBB-TIDAL DELTAS

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Abstract: The influence of tides on the orientation of channels on ebb-tidal deltas is investigated using the state-of-the-art numerical model Delft3D-MOR in a highly schematized geometry. The water motion is described by the depth-averaged shallow water equations. It is forced with a limited number of tidal constituents at boundaries far away from the inlet. Due to the interaction of the water motion and the erodible bed, tidally averaged sediment fluxes occur which result in bedform changes. The sediment transport is modeled using a total load formula.

The resulting bathymetry resembles that of an ebb-tidal delta. If the sea surface is forced with a semi-diurnal (M_2) constituent only, the main channel on the ebb-tidal delta is always oriented downdrift with respect to the direction of propagation of the M_2 tidal wave. When forcing the sea surface with both an M_2 and mean component, both channel orientations are observed: if the difference in mean sea surface level is positive over the inlet, the resulting channel will be updrift oriented. A negative difference of mean sea surface level results in a downdrift-oriented channel. The apparent relation between channel orientation and difference in mean sea surface level over the inlet seems to be supported by an analysis of quai-realistic simulations of tidal motion in the Dutch Wadden Sea.

INTRODUCTION

In many coastal areas all over the world, sequences of barrier islands and tidal inlets are observed. On the seaward side of these inlets, shallow ebb-tidal deltas occur. In this contribution the focus will be on the Dutch Wadden Sea (see figure 1). The inlets are tide dominated and most of the main channels on the ebb-tidal delta have an updrift orientation with respect to the direction of propagation of the semi-diurnal (M2) tidal wave, see figure 2 (Sha & Van den Berg, 1993). However, downdrift orientation is observed as well (inlet nr. 2 and nr. 5 in figure 2).

A conceptual model was formulated by Sha (1989a,b) to explain the asymmetry of the ebb-tidal deltas of tide–dominated systems. Due to the interaction between shore–parallel currents and currents in the strait, the tidal currents on the downdrift side were argued to be weaker and more eccentric than on the updrift side. This would result in preferred deposition of sediment on the downdrift side, causing the channels to have an updrift orientation. In this conceptual model, preferred deposition of sediment on the updrift side could only result from wave action. In a recent study by Van Leeuwen et al. (2002), using a process-based numerical morphodynamic model, this conceptual model was tested. It was shown that, although the tidal currents were weaker and more eccentric on the downdrift side, this does not result in an asymmetric ebb-tidal delta.

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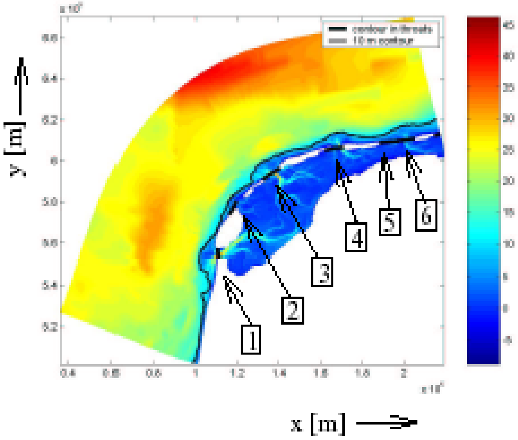

Figure 1: Bathymetry of the West-Frisian Waddensea (depth in m). The different inlets are number from 1 to 6. The drawn line indicates the 10 m depth contour.

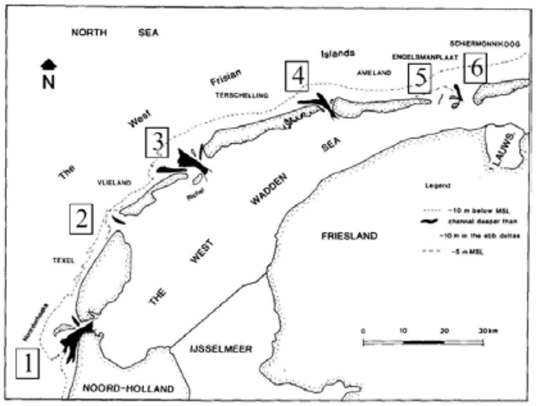

Figure 2: Orientation of the main channels on the ebb-tidal deltas of the West-Frisian Wadden Sea. Channels 1,3,4 and 6 are oriented updrift, channels 2 and 5 downdrift with respect to the direction of propagation of M2 tidal wave.

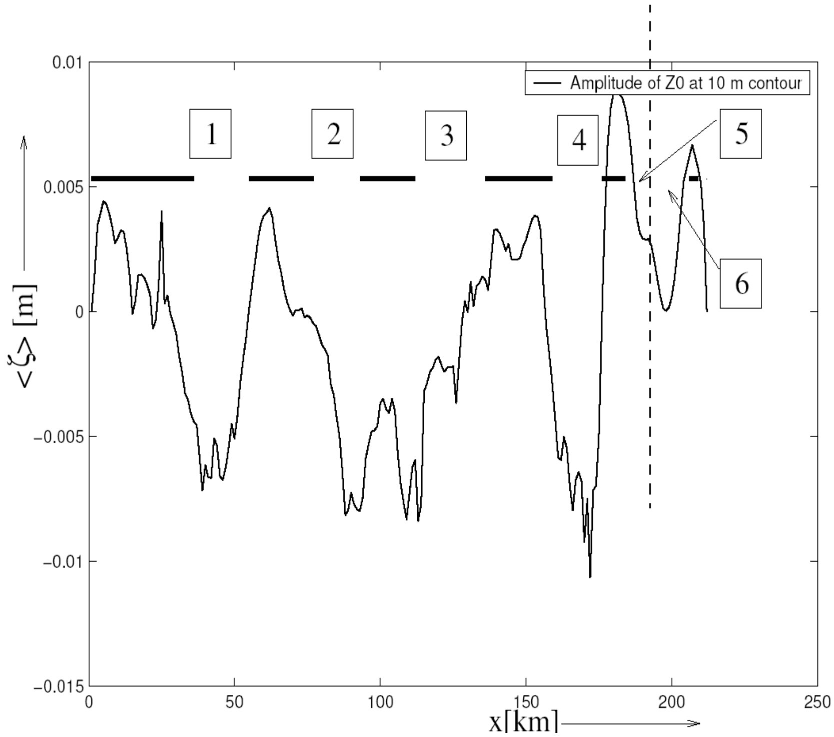

Figure 3: The time-independent part of the sea surface elevation (<ζ>) over the 10 meter contour line as shown in figure 1 is plotted. The difference in mean sea surface level is positive over all inlets except for the second and fifth.

In this contribution, it is shown that an asymmetry in the residual sea surface forcing results in an asymmetry in the orientation of the channels on the ebb-tidal delta. This result is obtained by numerical experiments in a simplified geometrical setting. Furthermore, realistic simulations of tidal motion in the Dutch Wadden Sea (Bonekamp et al, 2002) support this result: in figure 3 the simulated residual sea elevation is plotted over a 10 m depth contour. The thick lines indicate the position of the main land and barrier islands. Observations (see Sha (1989b) and figure 2) reveal that the main channel corresponding to the second and fifth inlet are downdrift oriented, while the other main channels are updrift oriented with respect to the direction of propagation of the M_2 tidal wave. Figure 3 shows that the difference in mean sea surface level is positive over all inlets except for the second and fifth. This suggests that the orientation of the main channels on the ebb-tidal delta is correlated with the difference in mean sea surface level over the strait.

MODEL DESCRIPTION

The numerical experiments are performed using the Delft3D-MOR model system (Roelvink & Van Banning, 1994) in a simple geometrical setting (see figure 4). The basin is always symmetric and the islands are aligned in order to study the proposed mechanism in isolation. The parameters that fix the geometry are the width and length of the straight and inlet. The distance between the eastern and western boundary is 60 km. The coastlines are assumed to be non-erodible whereas the bottom is erodible.

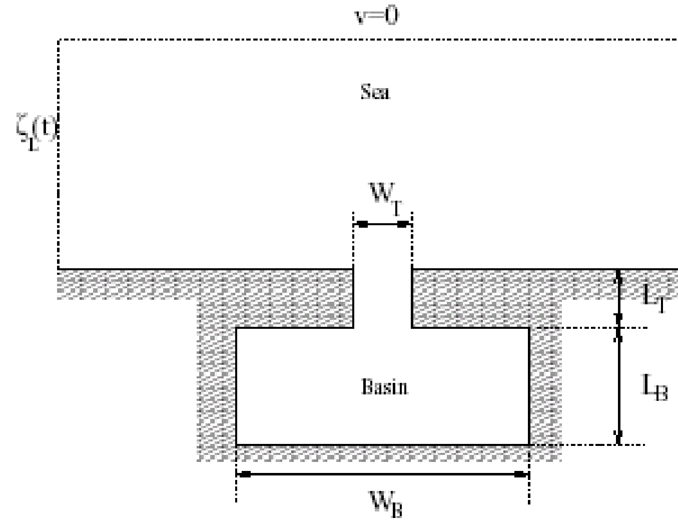

Figure 4: Geometry used in numerical experiments. W_T (W_B) and L_T (L_B) denote the width and length of the strait (basin), respectively. The sea surface elevation is prescribed at the eastern (ζ_L) and western (ζ_R) domain boundary.

The numerical model, used in this paper, consists of a hydrodynamic flow module, a sediment transport module and a bottom change module. In the hydrodynamic flow module, the water motion is modeled by the depth-averaged shallow water equations for a homogeneous fluid (Vreugdenhil, 1994) and a fixed bathymetry. The bottom roughness is modeled using a constant Chezy coefficient. As a forcing sea surface elevations are prescribed at both the eastern and western boundary. Both at the northern boundary and the coastlines the normal velocity has to vanish. In this contribution the focus is on the effects of a forcing with either only an M_2 or a combination of an M_2 and residual sea surface elevation. Using the velocity fields as obtained from the hydrodynamic module, the sediment transport is calculated using the total-load sediment transport formula proposed by Engelund and Hansen (1967). Due to divergences and convergences of these sediment fluxes, the bed evolves. With this new, updated bathymetry, the morphodynamic loop can be repeated, resulting in the morphologic evolution of the initial bathymetry.

NUMERICAL EXPERIMENTS

Table 1 displays the default parameter values as used in the numerical experiments. In the default experiment the sea surface is only forced with an M_2 tidal constituent. The amplitude at the western boundary is 0.9 m and at the eastern boundary 1.0 m. The phase difference is 40 deg. These parameter values have been obtained from field data. Note that the M_2 tidal wave travels from west to east. In the following, the updrift/downdrift orientation of the channels on the outer delta is understood with respect to the direction of propagation of the default M_2 tidal wave. In the default case, no mean pressure gradient is imposed. The water depth is constant. Furthermore, the default geometrical parameters are given in table 1.

In the next section, the numerical model results with the default parameter settings will be presented. The influence of embayment length on the resulting bathymetry will be shortly discussed as well. Following this section, a mean sea surface elevation is prescribed at the open sea boundaries. The initial bathymetric changes will be described and the influence of embayments length on the initial bathymetric changes will be presented.

Table 1: description of symbols and default parameter values

Description of symbol	Symbol	Default Value
amplitude of semi-diurnal tidal constituent at the western boundary	$\mathrm{amp}(\zeta_L)$	0.9 m
phase of semi-diurnal tidal constituent at the western boundary	$\mathrm{phase}(\zeta_L)$	0.0 deg
amplitude of semi-diurnal tidal constituent at the eastern boundary	$\mathrm{amp}(\zeta_R)$	1.0 m
phase of semi-diurnal tidal constituent at the eastern boundary	$\mathrm{phase}(\zeta_R)$	40.0 deg
amplitude of residual tidal constituent at the western boundary	$<\zeta_L>$	0.0 m
amplitude of residual tidal constituent at the eastern boundary	$<\zeta_R>$	0.0 m
initial, uniform water depth	H_{ini}	10.0 m
width of the strait and the basin	$W_T = W_B$	5 km
cumulative length of the strait and basin	$L = L_T + L_B$	20 km

Semi-diurnal Forcing of Sea Surface

In figure 5 the bed level change after one year is shown. In this experiment, default parameters as tabulated in table 1 are used. Continuation of this experiment for a longer time did not result in qualitatively different patterns, only the amplitude of the pattern as shown in figure 5 increased. In this experiment a clear region of deposition is observed on the updrift side of the inlet, whereas erosion occurs at the downdrift side, resulting in a bathymetry resembling a downdrift oriented channel on an ebb-tidal delta.

In figure 6, two results are shown of initial formation of an ebb-tidal delta for embayments with a cumulative length of both strait and basin of 40 km and 70 km, respectively. These embayment lengths have been chosen such that one is slightly shorter than the M_2 resonance length (approximately 50 km), whereas the other one is longer. For both embayment lengths, main areas of deposition are observed in the downdrift side and regions of erosion are mainly observed updrift. Hence, the orientation of the channel does not change with channel length, although the overall erosion-deposition patterns do change. One of the main differences with the experiment for an embayment of 20 km length is the presence of a much larger amount of sediment that is being deposited in front of the basin.

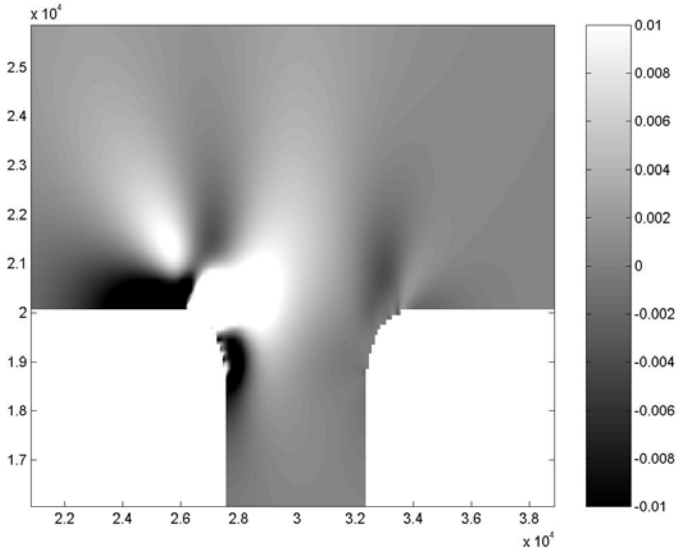

Figure 5: Initial formation of an ebb-tidal delta. Dark colors indicate erosion, light colors deposition. Default parameters are used. The resulting bathymetry is that of a downdrift oriented channel on an ebb-tidal delta.

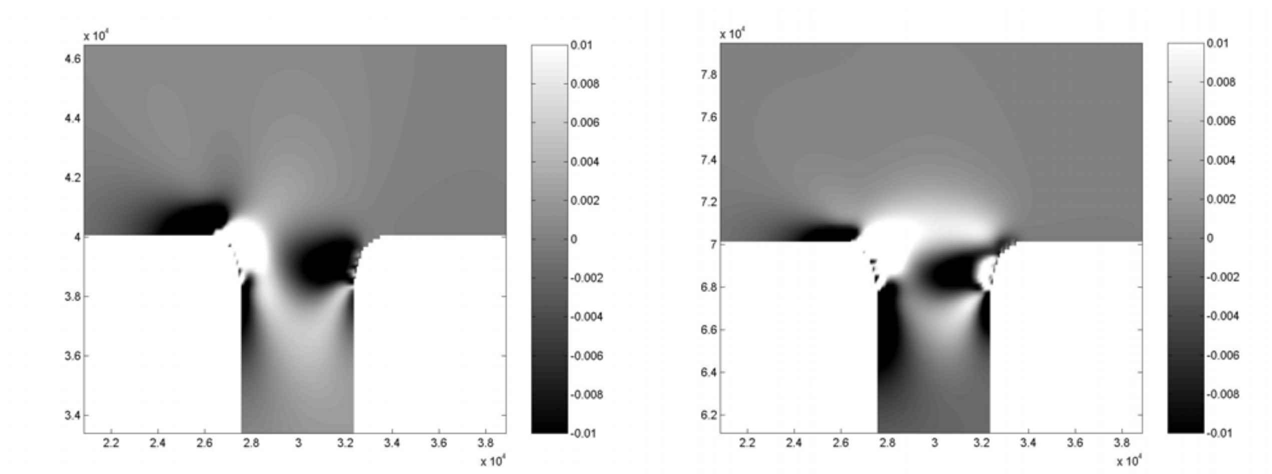

Figure 6: Initial formation of an ebb-tidal delta for different embayment lengths. Dark colors indicate erosion, light colors deposition. In both cases, the resulting bathymetry is that of a downdrift oriented channel on an ebb-tidal delta.

Semi-diurnal and Residual Forcing of Sea Surface

In this section, a mean sea surface elevation is prescribed on the eastern and western boundary. Other model parameters are set to default values. In figure 7 two results are shown of initial formation of an ebb-tidal delta for embayments with a cumulative length of both strait and basin of 20 km. In figure 7, left, the system is forced with a positive residual sea surface gradient, resulting in a updrift channel configuration, while a negative gradient results in an downdrift oriented main channel (figure 7, right).

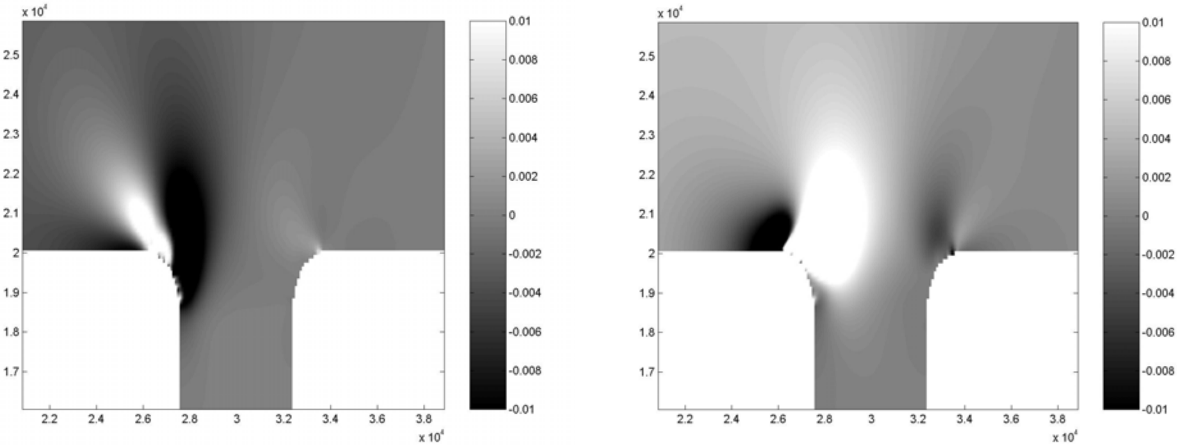

Figure 7: Initial formation of an ebb-tidal delta. Dark colors indicate erosion, light colors deposition. In the left (right) figure the system is forced with a positive (negative) M_0 sea surface gradient, resulting in an updrift (downdrift) oriented channel on the ebb-tidal delta. Other parameters have default values.

The initial formation of an ebb-tidal delta for an embayment with a cumulative length of 40 km and 70 km is shown in figures 8 and 9, respectively. In the figures on the left the sea surface is forced with a positive residual gradient, whereas the righthand side figures are forced with a negative residual sea surface gradient.

If the system is forced with a positive residual sea surface gradient, an updrift channel configuration is observed (figures 8 and 9, left panel), while a negative gradient results in an downdrift oriented main channel (figures 8 and 9, right panel). Again, the main difference with the experiment for an embayment of 20 km length is the presence of a much larger amount of sediment being deposited in front of the basin.

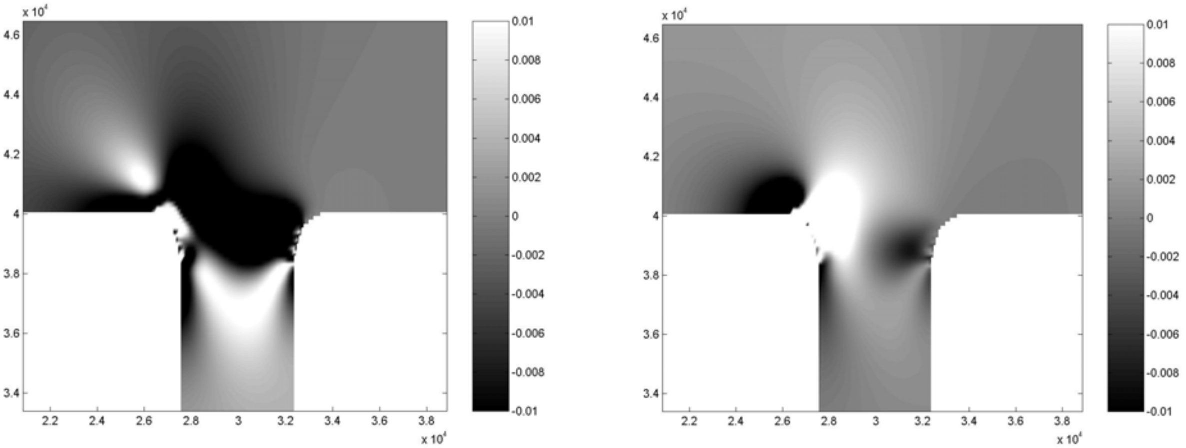

Figure 8: As figure 7, but the cumulative length of the strait and basin was 40 km.

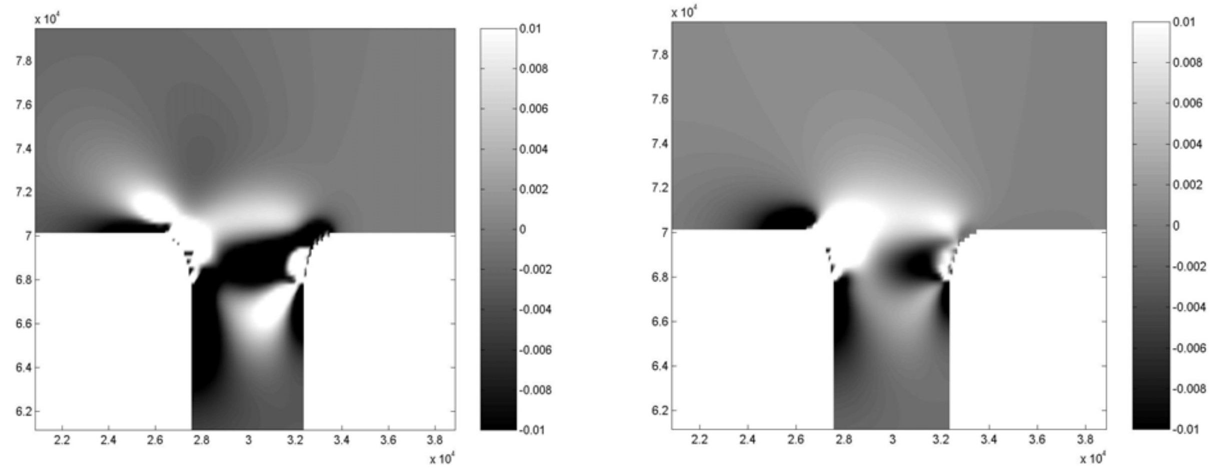

Figure 9: As figure 7, but the cumulative length of the strait and basin was 70 km.

DISCUSSION AND CONCLUSIONS

From the numerical experiments in which the sea surface is only forced with a prescribed semi-diurnal component, it can be concluded that the resulting channel orientation is always downdrift. This is in contrast with the observations in the Wadden Sea (figure 2): here most channels are oriented updrift. This implies that the orientation of the main channel cannot be directly related to the direction of propagation of the M_2 tidal wave and that an extra forcing or asymmetry is essential to explain the orientation of the main channels on the outer deltas. A possible mechanism that can result in the correct orientation of the channels on the outer deltas as compared to observations in the West-Frisian Wadden Sea is the inclusion of a prescribed residual sea surface elevation at the open boundaries: in figures 7-9 it is shown that if a positive (negative) M_0 sea surface gradient is imposed, an updrift (downdrift) oriented channel on the ebb-tidal delta is found. Increasing the embayment length results in outer deltas containing a larger volume of sediment, but the orientation of the main channel does not depend very sensitively on this parameter.

The mechanisms that can explain the above observations are currently under investigation. First results indicate that the orientation of the main channel is related to the spatial pattern of residual vorticity (the divergence-free part of the velocity field). This spatial pattern changes significantly when the external forcing is changed. This is most evident in the self-advection of the residual vorticity in the along-coast direction. In figure 10 this contribution is shown for an embayment length of 20 km. In the left panel, a positive, in the middle panel no and in the right panel a negative mean sea surface gradient is prescribed. The prescription of a positive mean sea surface gradient (left panel of figure 10) results in advection of negative vorticity towards the updrift side (compare with the situation with no mean sea surface foring). From the right panel it is clear that negative vorticity is advected towards the downdrift side when a negative mean sea surface gradient is added to the default forcing. This difference in vorticity distribution results in different bathymetries: the bathymetry corresponding to the pattern shown in the left panel has a main updrift oriented channel (see figure 7(a)), whereas a downdrift oriented channel is found in the other two cases (figure 5 and 7(b)). The vorticity patterns do not change significantly with varying embayment length.

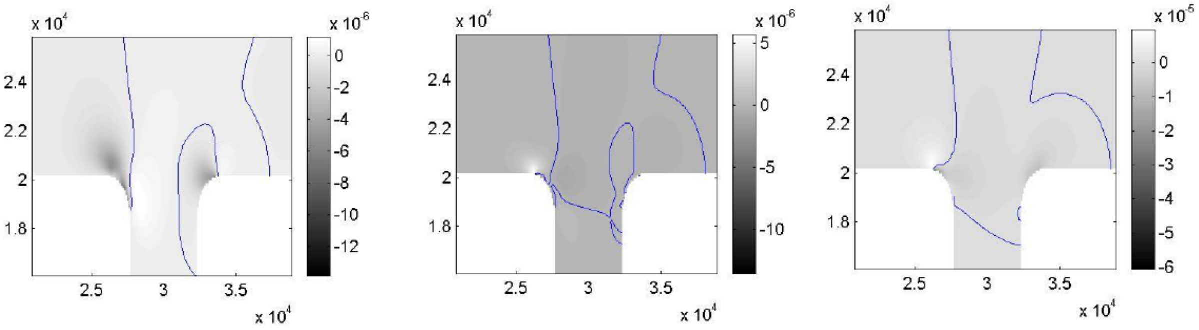

Figure 10: The self-advection of the residual vorticity in the along-coast direction. In the left panel, the mean sea surface is forced with a positive gradient, in the middle panel no and in the right panel a negative mean gradient is prescribed. Other parameters have default values.

The rotation-free part of the velocity field, however, does change significantly with increasing embayment length. In figure 11 the divergence of the residual velocity is shown for an embayment length of 20 (left panel), 40 (middle panel) and 70 (right panel) km. Due to the increase in embayment length the divergence of the residual velocity field increases, resulting in an increase of deposited sediment with increasing embayment length. For identical external forcing the vorticity patterns do not change significantly with increasing embayment length.

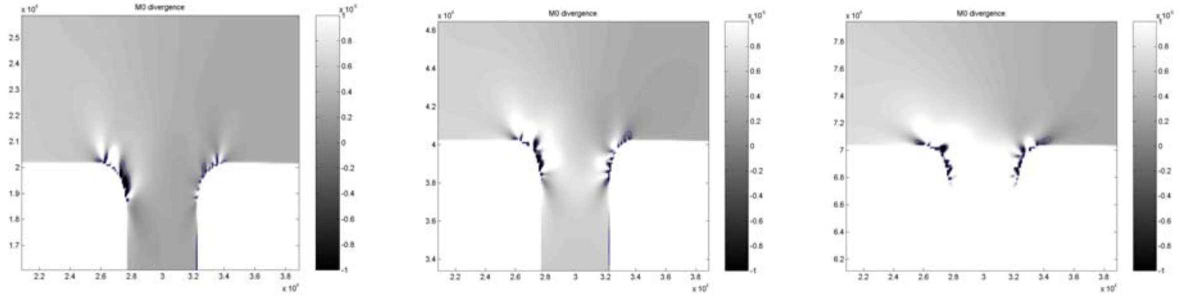

Figure 11: The divergence of the residual for different embayment lengths. Other parameters have default values.

Although the inclusion of the forcing of sea surface with a mean component results in the correct orientation of the channels on the outer deltas as compared to observations in the West-Frisian Wadden Sea, it cannot be concluded that the asymmetry in the residual sea surface elevation is the only or the most important mechanism for explaining the main channel orientation on outer deltas. It only indicates that asymmetry in tidal forcing conditions plays a role in the development of the asymmetrical shapes of outer deltas. Other possible mechanisms are the asymmetry induced by an externally prescibed overtide and the inclusion of wave action. A further dependency of the results for system parameters is currently being studied, as well as the sensitivity of the results for different initial bed profiles. Furthermore, the relative importance of this mechanism, compared to wave action and asymmetry induced by an externally prescibed overtide, is under investigation.

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