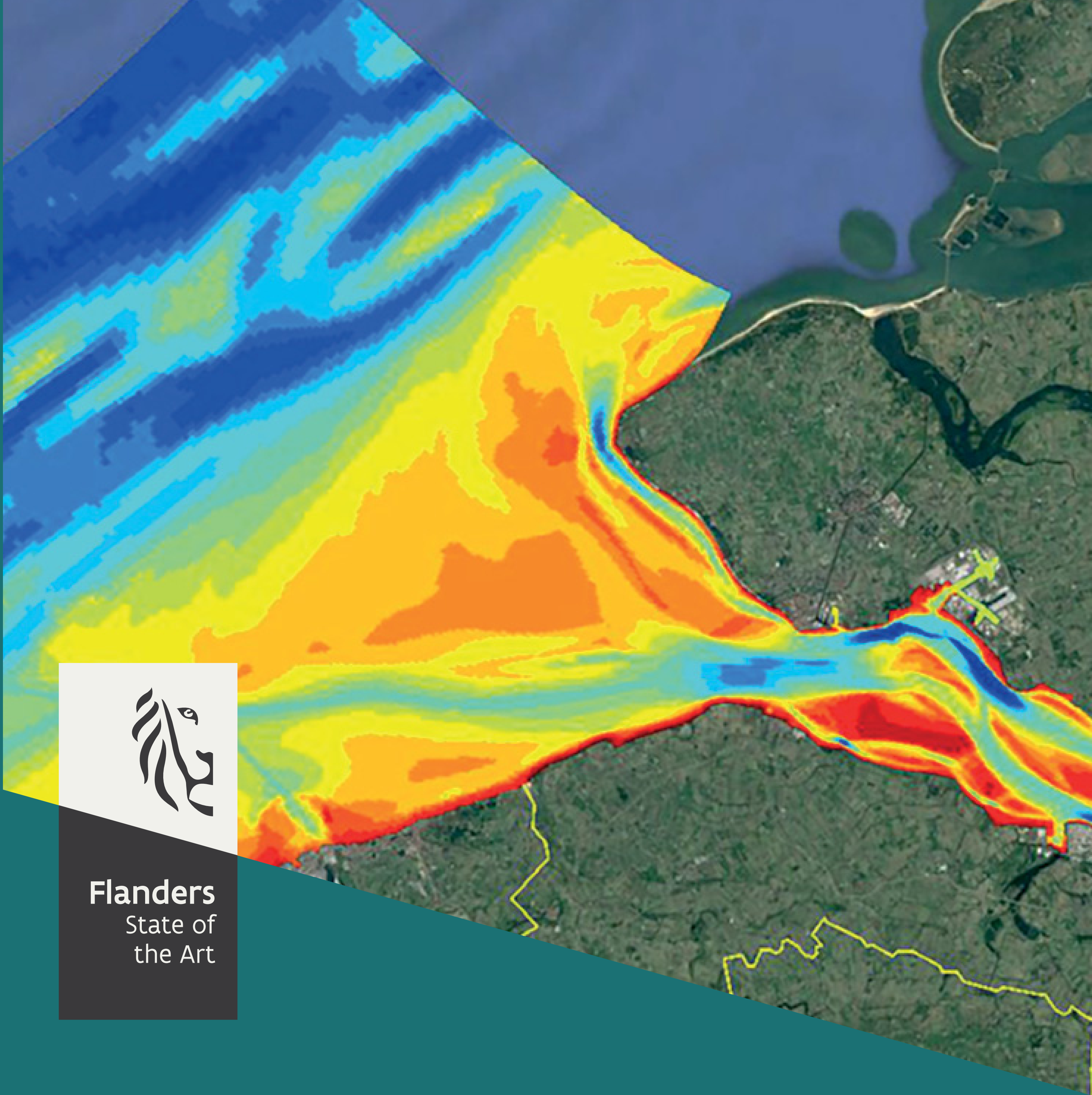

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Morphodynamic modeling of the Scheldt estuary and its mouth

Effects of sea level rise

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Effects of sea level rise

Nnafie, A.; De Maerschalck, B.; Vanlede, J.; Schramkowski, G.; Mostaert, F.

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Abstract

The morphology of the Scheldt estuary and its mouth varies as a result of natural evolution and human impacts. Particularly sea level rise has become an important driver for policy makers dealing with the long-term management of this area. The overall aim of this report is to increase fundamental knowledge of effects of sea level rise on the morphodynamic evolution of the Scheldt estuarine system, using the coupled Delft3D-SWAN morphodynamic model of Nnafie *et al.*, 2017b. The impacts of different rates of sea level rise, as well as the impact of a time-varying tidal forcing on this evolution are also addressed.

Model results indicate that a rising sea level at a rate of 2 mm/yr results in an slight landward retreat of the ebb-tidal delta of the mouth area, whereby channels and shoals undergo increased sedimentation over time (0.25 mm/yr on average). This sedimentation is the result of increased sand import from the offshore areas. The latter changes become stronger with increasing rate of sea level rise. In the Western Scheldt estuary, a rising sea level rather causes the redistribution of sand in this area, such that sand is deposited on the shoals and tidal flats. The overall sedimentation rate in the latter area is 0.15 mm/yr. Higher rates of SLR increase sedimentation on the shoals, which is mostly provided through deepening of channels and the reduction of the sand loss to the mouth area.

In the case that the amplitude of tidal currents remains fixed in time, sedimentation rates in the mouth and the Western Scheldt are too small for these areas to keep up with the rising sea level, which eventually might lead to the drowing of the estuarine system. However, the inclusion of stronger tidal currents increases sedimentation rates on the shoals, and it increases the volume of the deep channels, thereby counteracting the drowning of the estuarine system caused by SLR. These results suggest that the observed increasing tidal amplitudes in this area, most likely resulting from the rising sea level, is crucial for the estuarine system to keep pace with the rising sea level.

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Nederlandse samenvatting

Het doel van dit rapport is om fundamenteel inzicht te verschaffen in de invloed van zeespiegelstijging op de morfodynamische evolutie van de Scheldemonding en de Westerschelde. Hierbij wordt gebruik gemaakt van een gekoppelde Delft3D-SWAN model (zie Nnafie *et al.*, 2017b voor een beschrijving van dit model). Er wordt onder meer onderzocht hoe de morfodynamische evolutie van dit gebied verandert als gevolg van 1) het vergroten van de snelheid van zeespiegelstijging, en van 2) het laten toenemen van de getijamplitude in de tijd.

Model resultaten laten zien dat een zeespiegelstijging van 2 mm per jaar leidt tot een toename van het zandvolume van de monding (ongeveer 0.25 mm per jaar), waarbij de geulen verzanden, de banken en platen hoger worden, en de eb-getijde delta zich enigzins terugtrekt in landwaartse richting. Deze veranderingen worden sterker naarmate de zeespiegel sneller stijgt. In de Westerschelde lijkt de zeespiegelstijging er eerder voor te zorgen dat sediment opnieuw herverdeeld wordt, waarbij de platen hoger worden met zand dat voornamelijk vrijkomt als gevolg van de uitdieping van de geulen. De zanduitwisseling tussen de Westerschelde en de monding neemt af met zeespigelstijging. De gemiddelde sedimentatie in dit estuarium is ongeveer 0.15 mm per jaar. Dit betekent dat in zowel de monding als het estuarium de sedimentatie rates niet voldoende groot zijn om een zeespiegelstijging van 2 mm per jaar bij te benen, hetgeen impliceert dat dit gebied op lange termijn zal verdrinken. Echter, wanneer de getijamplitude toeneemt, hetgeen leidt tot een sterkere getijstroming in dit gebied, de verzanding van de geulen neemt sterk af, en meer zand wordt aangevoerd naar de monding (0.5 mm per jaar), waarbij sedimentatie op de banken en platen sneller toeneemt. In de Westerschelde worden de geulen dieper en de platen hoger (1 mm per jaar). Deze resultaten laten zien dat een toename van de getijamplitude, wat hoogstwaarschijnlijk door de zeespiegelstijging wordt veroorzaakt, ervoor zorgt dat de verdrinking van dit gebied wordt tegengegaan.

1 Introduction

The morphology of the Scheldt estuary and its mouth varies as a result of natural evolution and human impacts. Particularly sea level rise has become an important driver for policy makers dealing with the long-term management of this area. This is because sea level rise might affect the hydrodynamics, which in turn can lead to morphological adaptation of the system, which potential implications for navigation, fishery and other estuarine values. For instance, channels might undergo increased sedimentation resulting from SLR (Pethick, 2001), which will require more dredging maintenance.

The overall aim of this report is to increase fundamental knowledge of effects of sea level rise on the morphodynamic evolution of the Scheldt estuarine system, following an idealized modeling approach by schematizing forcing conditions, initial bathymetry and excluding as many processes as possible.

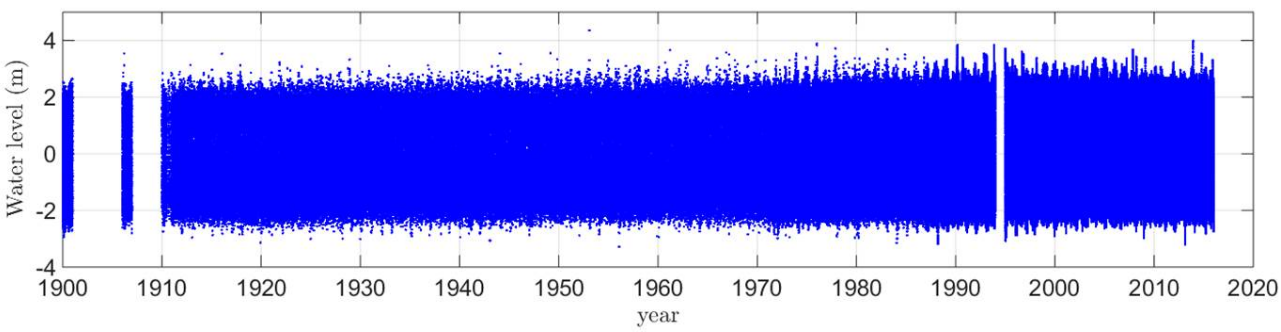
The specific aims of the present report are threefold. The first is to investigate effects of sea level rise on the morphodynamic evolution of shoals and tidal channels. Particular attention will be paid to the impact of sea level rise on the development of evolution of volume of channels and shoals. The second objective is to examine sensitivity of model results to different rates of sea level rise. The third is to examine the joint impact of sea level rise and the observed increase in the tidal currents. To this end, the coupled Delft3D-SWAN morphodynamic models described in the previous report by Nnafie *et al.*, 2017b, are used in this study. Further details can be found in the latter report.

2 Historical sea level rise in the Scheldt estuary

Time series of water levels in the Western Scheldt have been measured since the 19th century. In the beginning, the water levels were obtained by manually reading of tide gauges of high and/or low water levels, while nowadays full automatic water level data acquisitions exist every 10 minutes (Kuijper and Lescinski, 2012). These data are free accessible and can be downloaded from live.waterbase.nl, or they can be obtained from the Helpdesk of Water of Rijkswaterstaat (RWS). To quantify the historical development of the mean sea level and the amplitudes and phases of the tidal constituents M_2, M_4 and M_6 in the estuary, time series of water levels at Vlissingen are used, which have been acquired since 1900. These time series are depicted in Figure 1. Prior to 1900, water level data have been recorded once a day, and therefore, they are not sufficiently accurate to be used in the analysis. Occasionally, there are some gaps in the data, particularly between 1900 and 1910 (Figure 1).

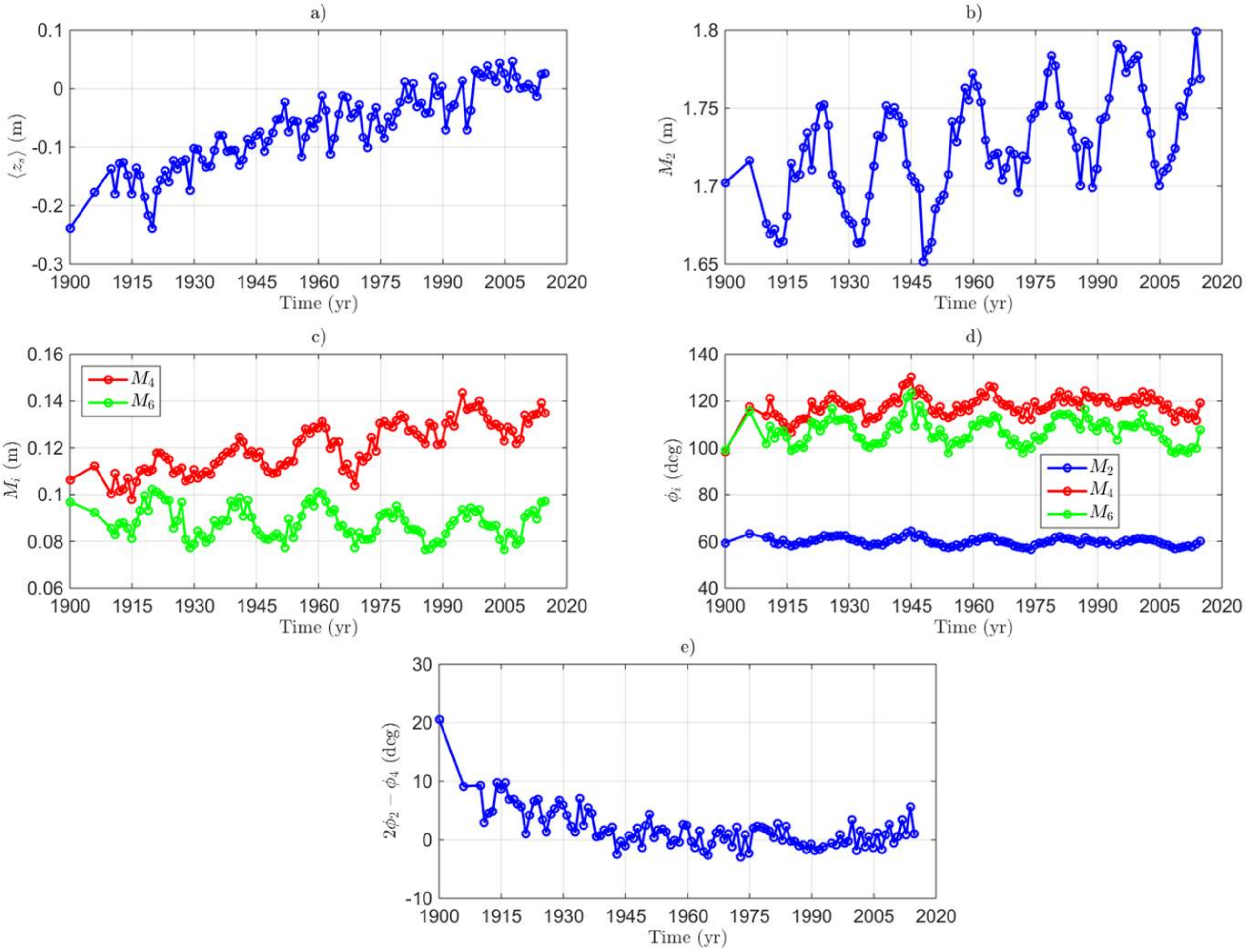
The historical development of the amplitudes and phases of the tidal constituents M_0, M_2, M_4 and M_6 is retrieved from the water level time series using the harmonic analysis toolbox t_tide (Pawlowicz *et al.*, 2002). Note that the M_0 tidal component expresses variations in the mean sea level $\langle z_s \rangle$. Results from this analysis are presented in Figure 2. A linear fit through the $\langle z_s \rangle$-data of panel a reveals that the mean sea level has been rising at a rate of approximately 2 mm/yr between 1900 and present, which is consistent with the rate found in the studies by e.g. Baart *et al.*, 2012 and Wahl *et al.*, 2013. Similarly, the amplitudes of M_2 and M_4 tidal components have risen at rates of ~ 0.6 mm/yr and ~ 0.3 mm/yr, respectively, while hardly any changes appeared in the amplitude of M_6. The phase difference between the M_2 and M_4 tidal components ($2\phi_2 - \phi_4$) was decreasing in the first half of the 20th century (panel e), which is attributed to variations in the phase of M_4 during this period (panel d). Note the large influence of the 18.6 year nodal cycle on the amplitudes and phases of the tidal constituents, which is caused by decadal variations in the lunar nodal cycle (Baart *et al.*, 2012).

Figure 1 – Historical water level time series at Vlissingen between between 1900 and present.



Data source: RWS.

Figure 2 – Time evolution of the amplitude of the residual tidal component M_0 (i.e., mean sea level $\langle z_s \rangle$, panel a), and of the amplitudes of M_2 (b), M_4 and $M6$ components (c), and their corresponding phases (d) at Vlissingen between 1900 and present. Panel c shows the phase difference between M_2 and M_4 ($2\phi_2 - \phi_4$).



The harmonic analysis toolbox t_tide (Pawlowicz *et al.*, 2002) has been used to retrieve amplitudes and phases of these components.

3 Experimental setup

3.1 Model configuration

In this study, the version of the model described in the report by Nnafie *et al.*, 2017a is used to examine effects of SLR on the morphodynamic evolution of the mouth and the Western Scheldt estuary (hereafter referred to as WS). Here, this version is extended such that it accounts for SLR, as well as for time-varying amplitudes of the tidal constituents M_2 and M_4. Specifically, the extension of the model is established by imposing a water level ζ at the seaward boundaries, given by the following equation

$$\zeta(x,y,t) = \langle z_s \rangle + \hat{\zeta}_2 \cos(\omega t - \phi_2) + \hat{\zeta}_4 \cos(2\omega t - \phi_4) + \hat{\zeta}_6 \cos(3\omega t - \phi_6), \quad (1)$$

where $\langle z_s \rangle$ is the mean sea level, which increases in time according to

$$\frac{\partial \langle z_s \rangle}{\partial t} = R, \quad (2)$$

with R the rate of SLR. Furthermore, to mimic effects of SLR on the amplitudes $\hat{\zeta}_2$ and $\hat{\zeta}_4$ of the M_2 and M_4 tidal constituents, respectively, these amplitude increase in time according to

$$\frac{\partial \hat{\zeta}_2}{\partial t} = R_2, \qquad \frac{\partial \hat{\zeta}_4}{\partial t} = R_4. \quad (3)$$

Here, R_2 and R_4 were determined from the observations at Vlissingen, i.e., $R_2 = 1.9 \times 10^{-11}$ m/s ($= 0.6$ mm/yr) and $R_4 = 9.5 \times 10^{-12}$ m/s ($= 0.3$ mm/yr) (Figure 2). Based on the latter figure, amplitude $\hat{\zeta}_6$ of the M_6 tidal constituent does not change with time. For simplicity reasons, the phases of all tidal components (ϕ_2, ϕ_4 and ϕ_6) are assumed constant. Other model settings described in the report by Nnafie *et al.*, 2017a are kept the same in the present model. See Table 1 for an overview of all model parameters.

3.2 Overview experiments

to assess the effects of SLR on the morphodynamic evolution of the mouth and WS, the bedlevel from the spinup experiment that is conducted in the study by Nnafie *et al.*, 2017a is used as an initial bathymetry to run the model. All the experiments that are carried out are presented below. See also Table 2 for an overview of these experiments.

As a first experiment, the model is run without adding SLR. This experiment ('Reference' in Table 2) serves as a reference run in this study, allowing to quantify the relative impact of SLR compared with the situation without SLR. In the second experiment ('SLR-Default'), the mean sea level rises at a rate $R = 2$ mm/yr, whereby amplitudes of the M_2, M_4 and M_6 tidal constituents remain constant in time ($\hat{\zeta}_2 = 1.6$ m, $\hat{\zeta}_4 = 0.1$ m and $\hat{\zeta}_6 = 0.05$ m). See also Figure 4 (blue lines) for a graphic representation of how the components of the water level ζ imposed at the seaward boundaries change with time. Next, a series of experiments are carried out ('SensToR' in Table 2) to examine sensitivity of model results to 1) different rates R of SLR, ranging between 1 mm/yr and 10 mm/yr; and to

2) a rate R that linearly increases in time from 0 to 10 mm/yr over a time period of 200 years, i.e., $R = 0.05t$ ('Variable-R'). Consequently, in the latter run, the mean sea level increases according to $\langle z_s \rangle = 0.05t^2$. This run aims at quantifying the impact of an accelerated SLR, although observations at Vlissingen do not provide any evidence of the occurrence of such an acceleration in the last century. Furthermore, to investigate the joint impact of a rising sea level and an increasing amplitude of the water level, first, a run ('Higher-M2M4') is conducted where amplitudes of M_2 and M_4 are suddenly increased from $\hat{\zeta}_2 = 1.6$ m and $\hat{\zeta}_4 = 0.1$ m to 1.8 m and 0.16 m, respectively, at the start of the simulation ($t = 0$), which is a crude representation of the observed gradual increase of these amplitudes (Figure 2). In the subsequent runs, more realistic scenarios are explored by 1) gradually increasing only the amplitude $\hat{\zeta}_2$ of M_2 tidal constituent according to Equation 3 ('Variable-M2'); and 2) by increasing both amplitudes $\hat{\zeta}_2$ and $\hat{\zeta}_4$ according to the latter equation ('Variable-M2M4'). See also Figure 4 for a graphic representation of how the mean sea level and the tidal constituents vary with time in the case of runs 'Variable-M2' and 'Variable-M2M4'.

All experiments are conducted for a simulation period of 200 years. The analysis of these experiments focuses on differences dz between bedlevels z_b obtained from runs with and without SLR, i.e., $dz = (z_b)_R - (z_b)_{R=0}$. This analysis further quantifies the changes in the total volume of channels and shoals of the mouth (marked by the thick white lines in Figure 3) and WS (area between Vlissingen and the Dutch-Belgium border) with respect to their volumes at $t = 0$ ($\Delta V_{\text{channels}}$ and ΔV_{shoals}, respectively, see Figure 5). Finally, this analysis addresses the relative contributions of the different channels and shoals to the volume changes by computing the hypsometry (i.e., amount of channel and shoal surface area below a specific bedlevel z_b) of the mouth and WS. It is stressed that

Table 1 – Overview model parameters.

	Parameter	Value	Description
Flow	f	1.43×10^{-4} s^{-1}	Coriolis parameter.
	C	65 m$^{1/2}$s^{-1}	Chézy coefficient.
	ν	1 m^{2}s^{-1}	Eddy viscosity.
	$\left(\hat{\zeta}_{2,S};\phi_{2,S}\right)/\left(\hat{\zeta}_{2,N};\phi_{2,N}\right)$	(1.6 m; 23^o)/(1.2 m; 55^o),	(Amp.;Phase) M_2 South(S)/North (N).
	$\left(\hat{\zeta}_{4,S};\phi_{4,S}\right)/\left(\hat{\zeta}_{4,N};\phi_{4,N}\right)$	(0.1 m; -11^o)/(0.1 m; 113^o),	(Amp.;Phase) M_4 South(S)/North (N).
	$\left(\hat{\zeta}_{6,S};\phi_{6,S}\right)/\left(\hat{\zeta}_{6,N};\phi_{6,N}\right)$	(0.05 m; -24^o)/(0.05 m; 77^o),	(Amp.;Phase) M_6 South(S)/North (N).
	ω	1.405$\times 10^{-4}$ s^{-1}	frequency M_2.
Waves	H_s	1 m	Significant height southwesterly waves.
	T_p	5.7 s	Peak period southwesterly waves.
	θ	254^o	Direction southwesterly waves.
Sediment	Van Rijn, 2007		Transport formulation
	Bagnold, 1966		Bedslope formulation
	α	1	Calibration coefficient.
	δ	1.65	Relative density of sediment.
	d_{50}	0.2 mm	Diameter grain size.
	α_{BS}	1	Longitudinal bedslope coefficient.
	α_{BN}	15	Transverse bedslope coefficient.
	p	0.4	Porosity bed.
Numerics	Δt	30 s	Time step.
	α_{MOR}	200/10	Morphological amplification factor.

Figure 3 – Delft3D computational grid. The thick while lines mark the contours of the mouth area, as used in this study.

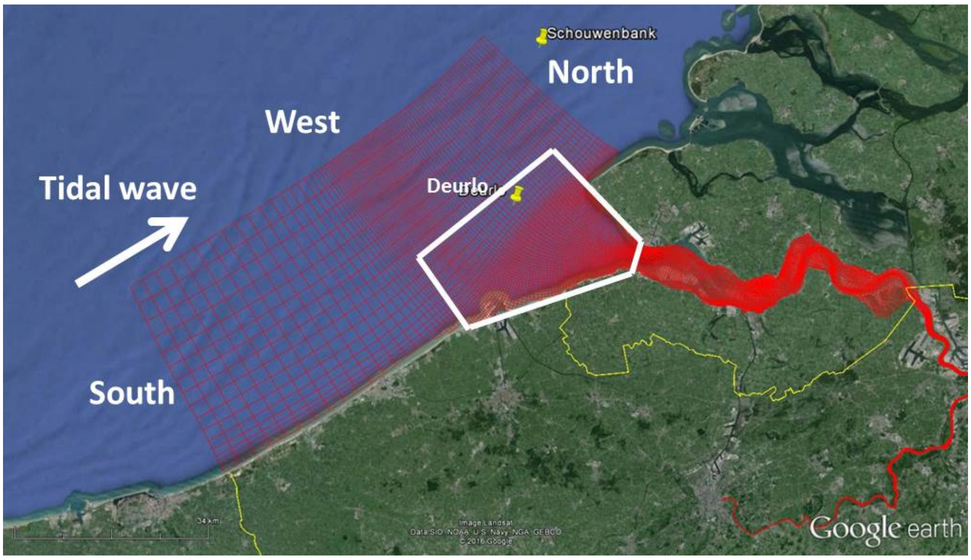
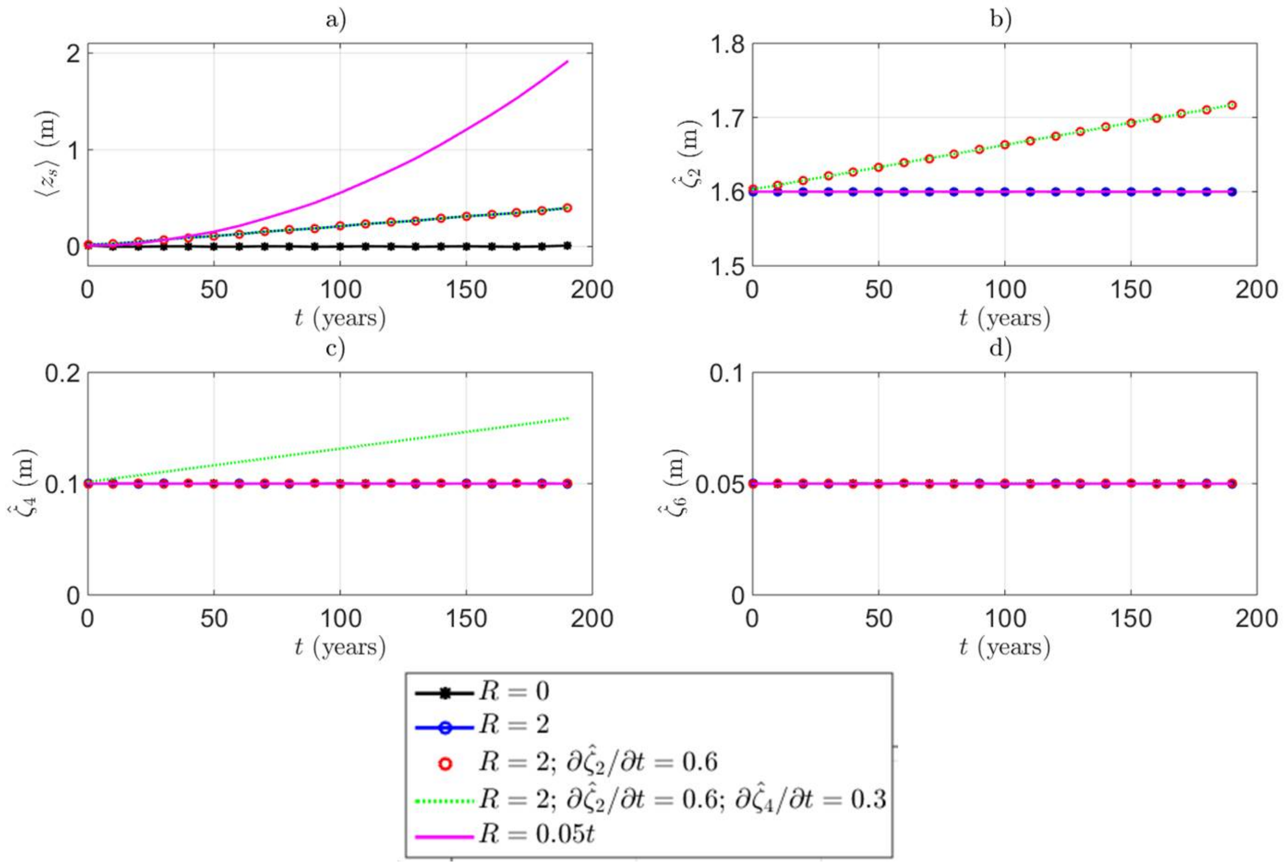


Table 2 – List of model runs.

Name runs	R (mm/yr)	$\hat{\zeta}_2$ (m)	$\hat{\zeta}_4$ (m)
Reference	0	1.6	0.1
SLR-Default	2	1.6	0.1
SensToR	1,3,4,5,10	1.6	0.1
Variable-R	$0.05t$	1.6	0.1
Higher-M2M4	2	1.8	0.18
Variable-M2	2	$\hat{\zeta}_2 = 0.6 \times 10^{-3}t + 1.6$	0.1
Variable-M2M4	2	$\hat{\zeta}_2 = 0.6 \times 10^{-3}t + 1.6$	$\hat{\zeta}_2 = 0.3 \times 10^{-3}t + 0.1$

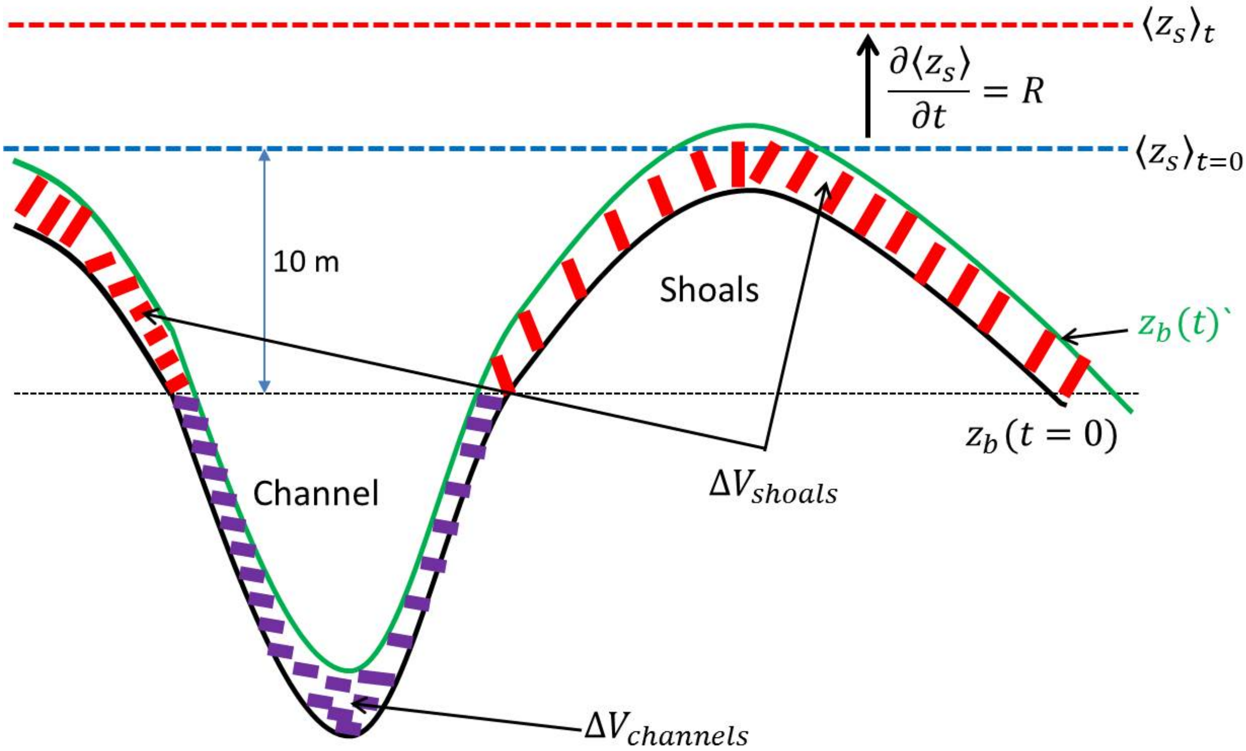
although the changes in the volume of channels are computed using the total volume of water that is in the channels, the additional water volume in the channels induced by SLR is disregarded from the computation of the volume changes. In other words, only changes in the volume of channels that are caused by sedimentation or erosion are considered in this study. Therefore, the comparison between the volumes of the cases with and without SLR are computed with respect to the initial mean sea level $\langle z_s \rangle_{t=0}$. See Figure 5 for a schematic view of these changes. Bedlevel $z_b = -10$ m with respect to the initial mean sea level $\langle z_s \rangle_{t=0}$ is used as a reference bedlevel to distinguish between channels and shoals (Figure 5). Note that a positive (negative) volume change of channels means deepening (sedimentation), while a positive (negative) volume change of shoals indicates sand gain (loss).

Figure 4 – Imposed amplitudes $\hat{\zeta}_i$ of the tidal forcing at the western boundary in the different scenarios: Reference, SLR-Default, Variable-M2, Variable-M2M4 and Variable-R.



Subscript "i" represents the amplitudes of the different tidal components ($\hat{\zeta}_0$, panel a), ($\hat{\zeta}_2$, b), ($\hat{\zeta}_4$, c) and ($\hat{\zeta}_6$, d).

Figure 5 – Schematic view of channel and shoals configurations used to compute changes in the volume of channels and shoals ($\Delta V_{\text{channels}}$ and ΔV_{shoals}, respectively) with respect to their volumes at $t = 0$.



Channels and shoals are defined at bedlevel $z_b = -10$ m with respect to the initial mean sea level $\langle z_s \rangle_{t=0}$.

4 Results and discussion

4.1 SLR-default (R=2)

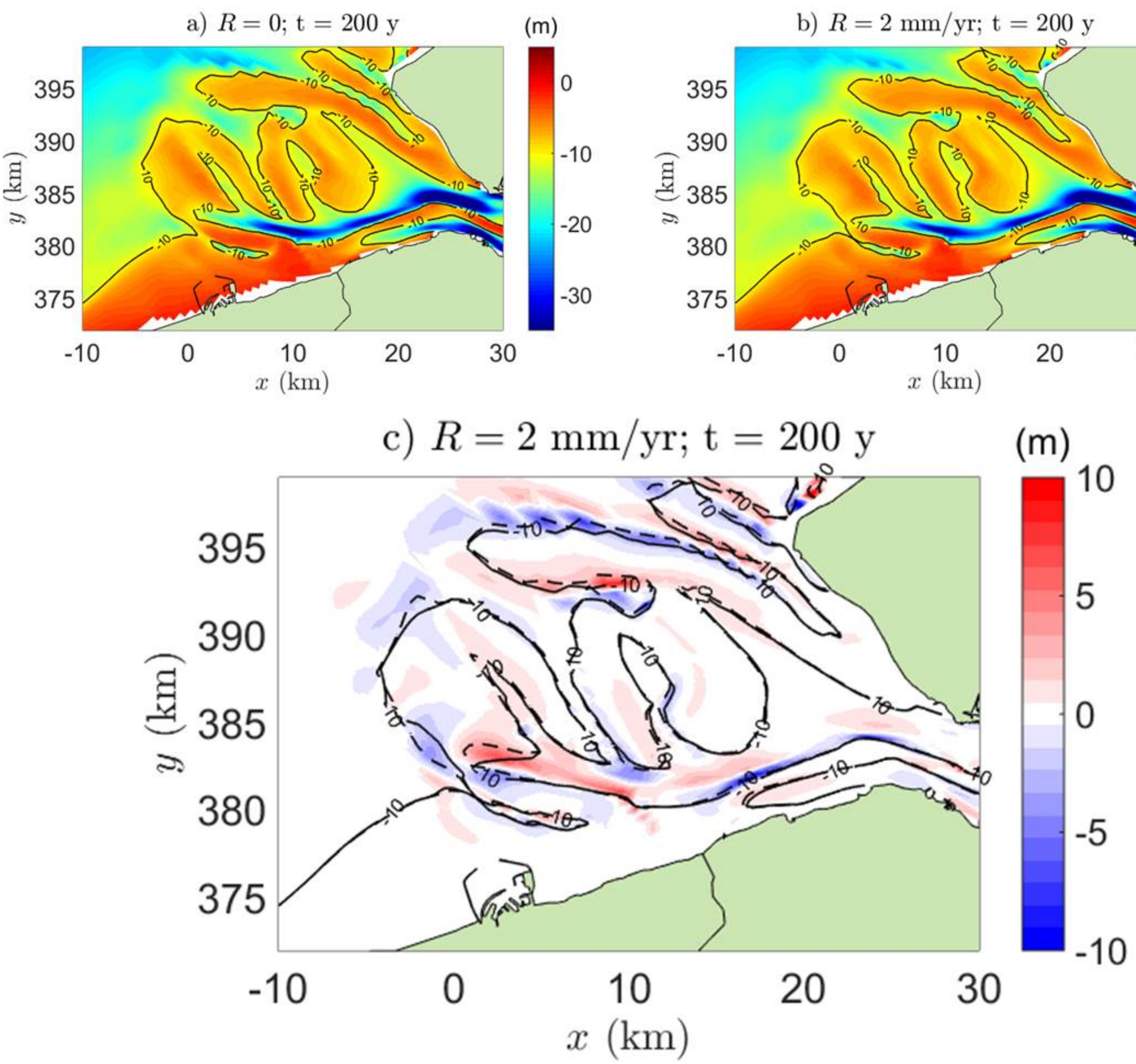
The simulated bedlevels z_b after 200 years of morphodynamic development in the cases without and with SLR ($R = 2$ mm/yr) are presented in Figure 6 (panels a and b, respectively). Overall, no fundamental differences seem to exist between the simulated bottom patterns of the cases. However, by plotting bedlevel difference dz between the two cases (i.e. $dz = (z_b)_{R=2} - (z_b)_{R=0}$), it is seen that on average (panel c), channels and shoals undergo sedimentation (red colors), meaning that channels become shallower and shoals are getting higher in the course of time. The overall shallowing of channels and the sand gain by shoals are also confirmed by Figure 7, which shows that the total volume of channels of the mouth area decreases with time (sedimentation) and the volume of shoals increases (sedimentation) (panels a and b, respectively). It is stressed here that only changes in the volume of channels that are caused by sedimentation or erosion are considered in this study. Therefore, the comparison between the volumes of the cases with and without SLR are computed with respect to the initial mean sea level $\langle z_s \rangle_{t=0}$ (for further details see Section 3.2).

For a quantitative impression of the relative impact of sea level rise on the development of channels and shoals in the mouth area, differences between the volumes of channels and shoals of the cases with and without SLR at $t = 200$ years are indicated in the panel titles as $\Delta|_{t=200\ \mathrm{yr}}$. These differences are also marked by the vertical red arrows. Recall that a positive (negative) volume change of channels $\Delta|_{t=200\ \mathrm{yr}}$ means erosion (sedimentation), while a positive (negative) volume change of shoals indicates sand gain (loss). If these differences are averaged over the total time period, it is found that the amount of sedimentation in the channels and on shoals is $\sim\ 0.1 \cdot 10^6$m^3/yr. The fact that the sand import from the Western Scheldt (WS) reduces in the case with SLR (Figure 7d), whereas more sand is deposited in the mouth area (panel c) means that sedimentation in the latter area is caused by enhanced sand import from the sea. Besides sedimentation of channels and shoals, Figure 6c further shows that the ebb-tidal delta of the mouth area retreats somewhat in the case of SLR. This retreat can clearly be seen when comparing the 10 m isobaths of the cases with and without SLR (solid and dashed lines).

Regarding volume changes in the Western Scheldt estuary, Figure 8 reveals that in the case with SLR, volume of channels (panel a) and shoals (panel b) are relatively larger during almost the entire simulation ($t < 170$ year) time period than those in the case without SLR. This means that most of time, the channels have been deepening and shoals have been rising under the rising sea level. Eventually, after $t \sim 170$ years, the opposite takes place, meaning that volume of channels and shoals in the former case become relatively smaller (i.e., sedimentation and erosion, respectively) than those in the latter case. The sand loss from from WS reduces when adding SLR (panel c). Contrary to the mouth area, the relative volume changes in the channels and shoals of WS induced by SLR are mostly established through sediment redistribution in the estuary. This means that channel erosion (sedimentation) is accompanied with rising (lowering) of shoals.

Finally, to assess the relative contributions of the different channels and shoals to the total volume change, hypsometric curves (amount of surface area A below a specific bedlevel z_b) of the mouth and WS at $t = 200$ years in the cases with and without SLR are depicted in Figure 9 (panel a and b). For the sake of visualization, the differences between hypsometric curves of the two cases are also shown (panels c and d). Almost all the channels and shoals of the mouth area experience sedimentation in the case with SLR (panel c), although lowering of some of high shoals and deepening of some channels

Figure 6 – a-b) Simulated bedlevels z_b at $t = 200$ years in the cases without ($R = 0$ mm/yr, panel a) and with SLR ($R = 2$ mm/yr, panel b) and the difference between these bedlevels ($dz = (z_b)_{R=2} - (z_b)_{R=0}$, panel c).



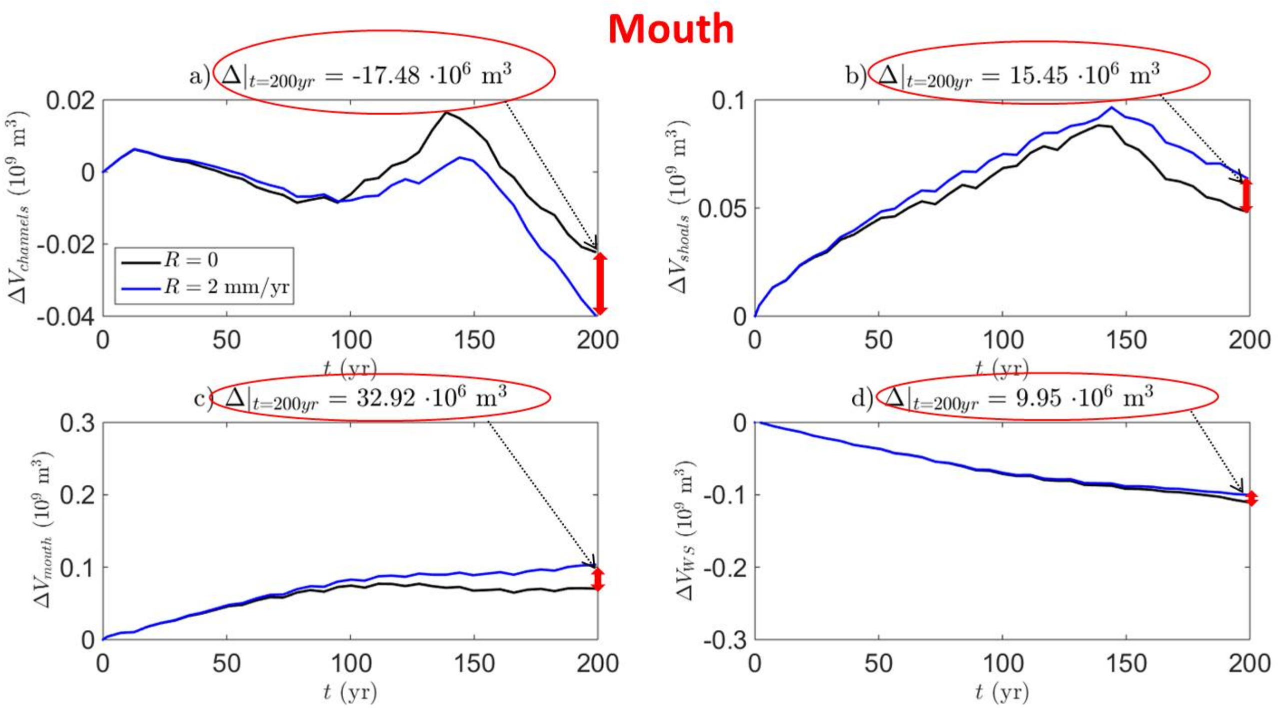
The dashed and solid contour levels indicate the -10 m bedlevel in the cases without and with SLR, respectively.

take place as well. In terms of sedimentation rates, the mouth area experiences a sedimentation rate of roughly 0.25 mm/year, which is a factor of $\sim$10 smaller than the rate of SLR (2 mm/yr). In the estuary (panel d), alternating eroding and accreting channels characterize this area. The highest shoals and tidal flats are higher in the case of SLR. The average sedimentation rate of the entire estuary is about 0.15 mm/yr.

4.2 Sensitivity to rate of SLR

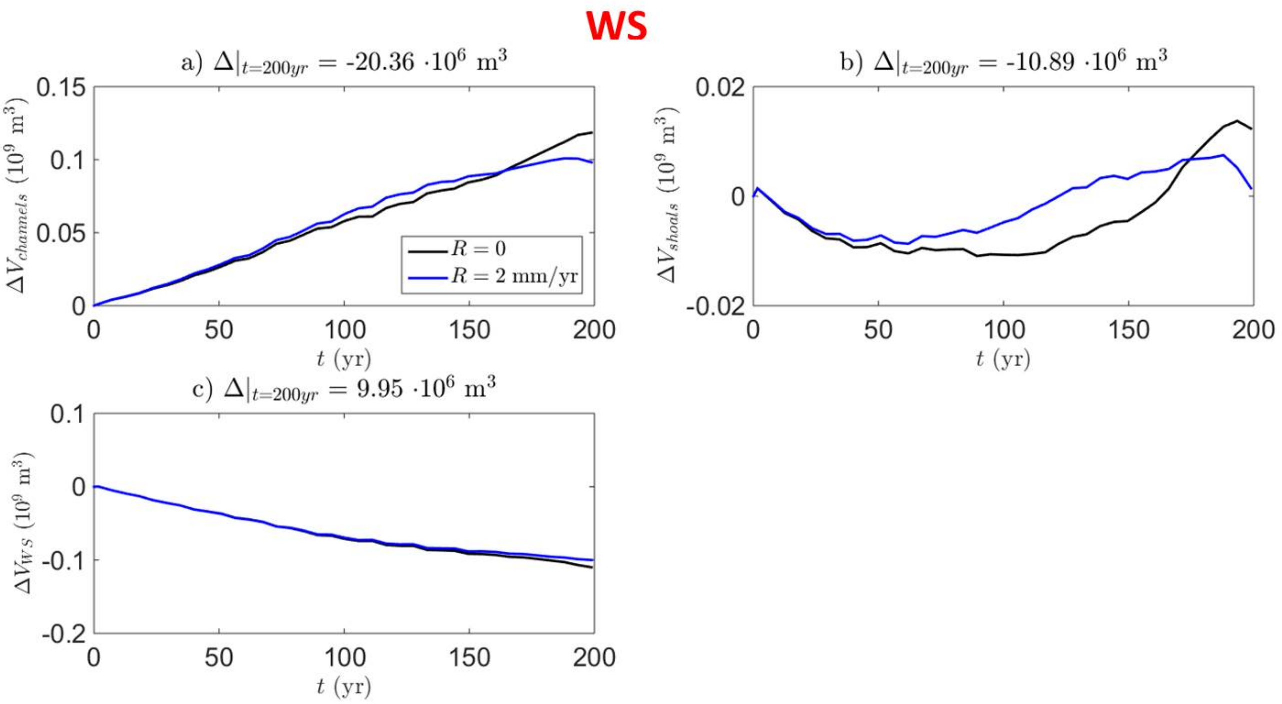
Figure 10 displays the bedlevel differences dz in the mouth area between the cases with different rates of sea level rise and the reference case. The rate of SLR ranges between 1 mm/yr and 10 mm/yr. From this Figure it appears that with increasing rate R, channels and shoals of the mouth area experience more sedimentation, and the ebb-tidal delta is located more landward (solid contour levels) compared with its position in case without SLR (dashed contour level). The increasing sedimentation in channels and on shoals with increasing R is also confirmed by Figure 11 (panels a and b), in which

Figure 7 – a-b) Cumulative change of the total volumes of channels (a) and shoals (b) of the mouth area versus time in the cases without (black) and with (blue) SLR ($R = 2$ mm/yr). c-d) As previously, but for the change of the total volumes of mouth (c) and the Western Scheldt (d).



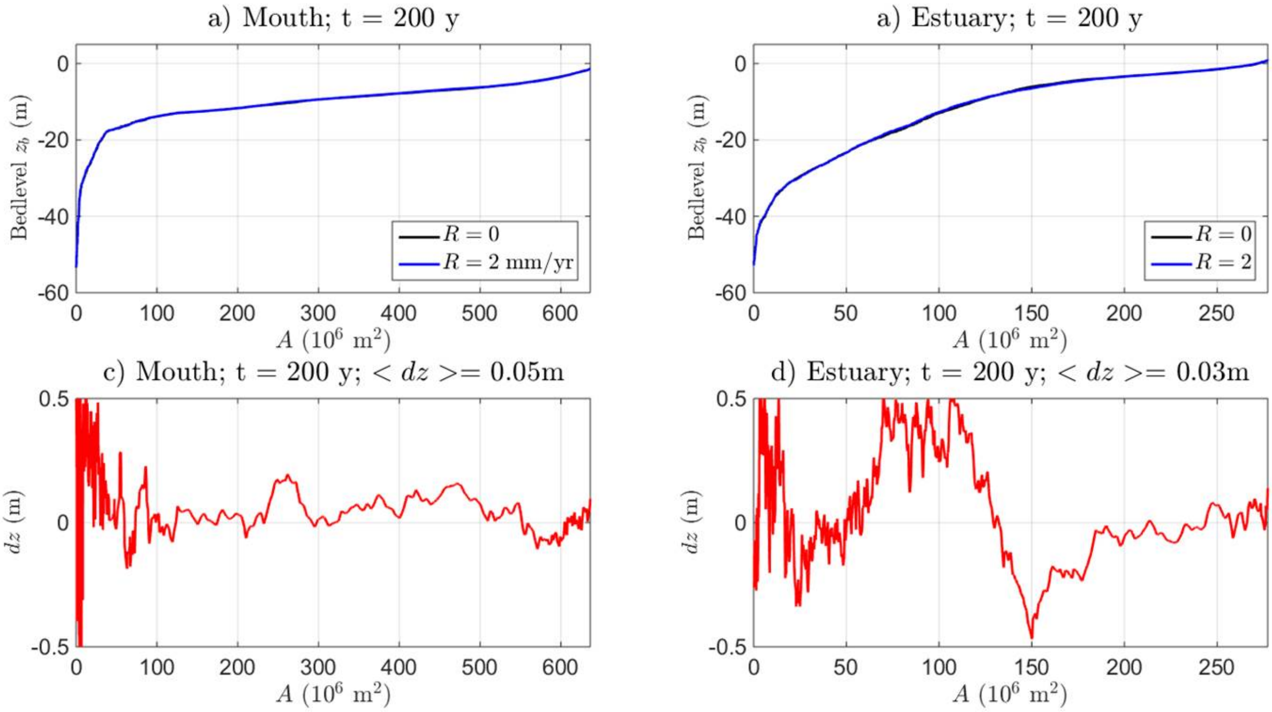
Cumulative volume changes are computed with respect the initial volume ($t = 0$). Values $\Delta|_{t=200\text{ yr}}$ represent differences between the volumes of cases with and without SLR at $t = 200$ years, which are indicated by the red arrows.

Figure 8 – As in Fig. 7, but for the Western Scheldt (WS).



the changes in the total volume of channels (a) and shoals (b) are plotted versus time. For a quantitative impression of how changes in the volumes of channels and shoals scale with the rate R of SLR,

Figure 9 – a-c) Modeled hypsometric curves at $t = 200$ yr of the mouth (a) and WS (b) in the cases without (black) and with SLR (blue). c-d) Bedlevel difference dz between cases with and with SLR as a function of the surface area A (m^2) for the mouth (b) and WS (c).



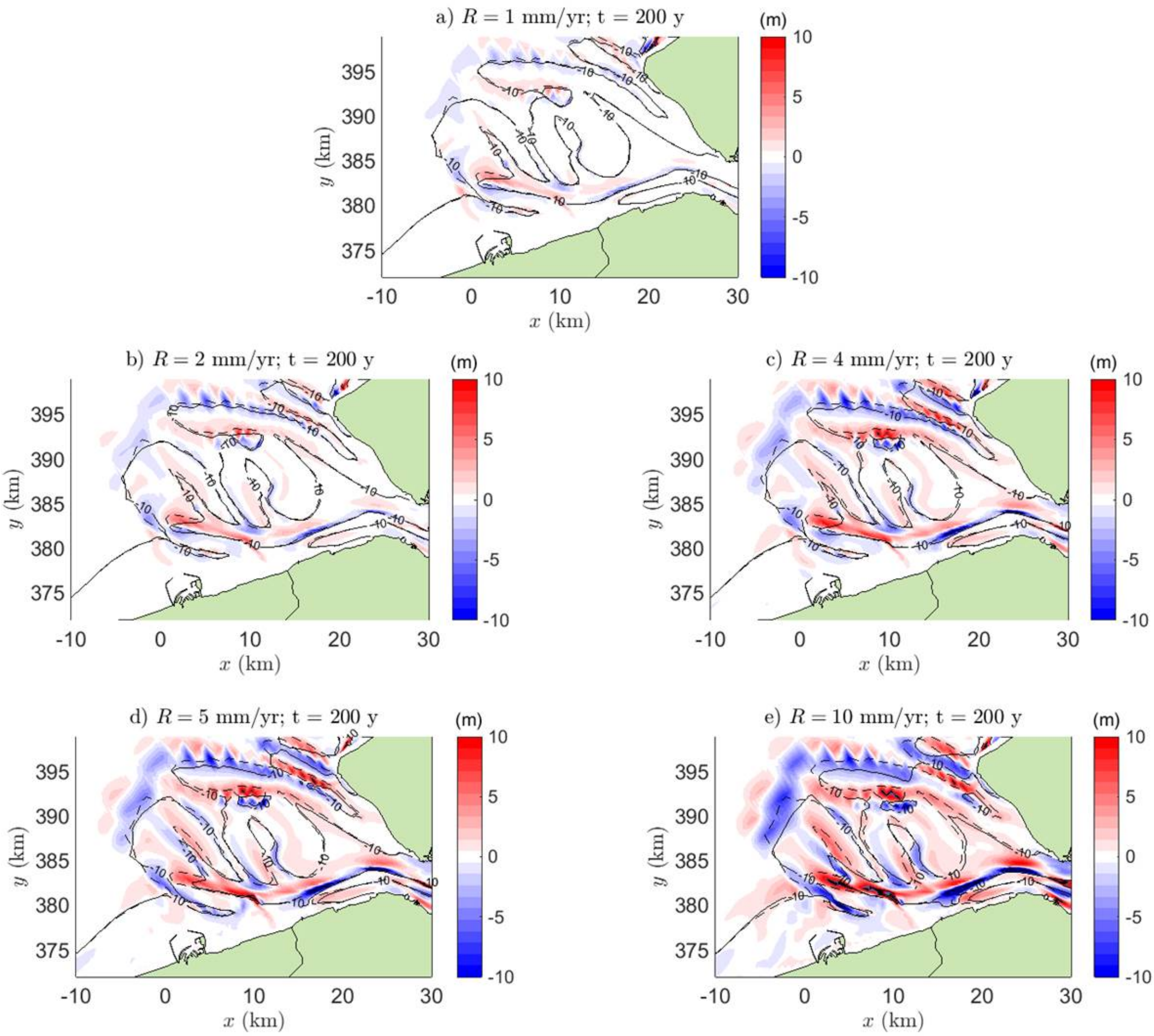
$< dz >$ in panels b and d is the mean bedlevel difference, which is obtained by averaging dz over the total surface area A.

Figure 11 reveals that in the case of $R = 10$ mm/yr, the amounts of sedimentation in the channels and shoals are approximately $0.4 \cdot 10^6$m^3/yr and $0.3 \cdot 10^6$m^3/yr, respectively, which are factors of ~ 4.2 and ~ 4.3 larger than the corresponding amounts of sedimentation obtained in the case of imposing $R = 2$ mm/yr. These results suggest that amount of sand that is deposited in channels and on shoals is approximately proportional to the rate of SLR. Similarly to the case of 'SLR-Default' ($R = 2$ mm/yr), also in the case of different rates of SLR, the overall sand gain by the mouth area is provided by the sea (panel c). The sand exchange between WS and the mouth area reduces with increasing rate of SLR (panel d).

With regard to volume changes in WS, it appears that with increasing R, the overall volumes of channels and shoals are larger than those of the case without SLR (Figure 12, panels a and b). It is interesting to note that for high rates R of SLR, the increased sedimentation on shoals mostly is established by a reduction in the sand loss from WS (panel c). In other words, sand that is lost to the mouth area in the case without SLR is increasingly more used with increasing R to rise the shoals of the estuary. For example, in the case of $R = 10$ mm/yr, almost all of the sand that is deposited on the shoals comes from reduction in the sand loss from the estuary.

Finally, by plotting the differences between hypsometric curves of the cases with and without SLR as a function of the surface area A (Figure 13), it turns out that with increasing rate R, the deepest channels and the high shoals and tidal flats of the mouth area and WS experience increasing sedimentation rates. Besides sedimentation, the intermediate channels of WS seem to deepen more with increasing rate R. In terms of an overall sedimentation rate of the system, model results show that for e.g. $R = 10$ mm/yr, the mouth area and WS are accreting at rates of roughly 1.15 mm/yr and 0.5 mm/yr, which are factors of ~ 10 smaller than the rate of SLR.

Figure 10 – Difference dz at $t = 200$ years between the bedlevels of the cases with different rates of SLR and without SLR.



The dashed and solid contour levels indicate the -10 m bedlevel in the cases without and with SLR, respectively.

4.3 Variability in tidal forcing

The addition of stronger tidal currents turns out to have a major impact on the bedlevel development in the mouth area subject to a rising sea level. This can be seen from Figure 14, showing the bedlevel differences dz (with respect to reference case) obtained from runs 'SLR-Default' (panel a) and 'Higher-M2M4' (panel b). The difference between the bedlevels of the two runs are also shown (panel c). These panels demonstrate that an increase of the amplitudes of tidal constituent M_2 and M_4 at the seaward boundaries ($\hat{\zeta}_2 = 1.8$ m and $\hat{\zeta}_4 = 0.18$ m) seems to increase the volume of the main channels, thereby counteracting the sedimentation of these channels caused by the rising sea level. Also, the landward retreat of the ebb-tidal delta caused by SLR is counteracted by the inclusion of stronger tidal currents. Furthermore, the hypsometric curves depicted in Figure 15 reveal that imposing stronger tidal currents increases the volume of particularly the deep channels ($z_b < -20$ m) of the mouth area and WS (panels c and d, respectively), and it increases the sand volume of their shoals. On average, the sedimentation rate in the mouth (including channels and shoals) is approx-

Figure 11 – As in Figure 7, but for the cases with different rates of SLR.

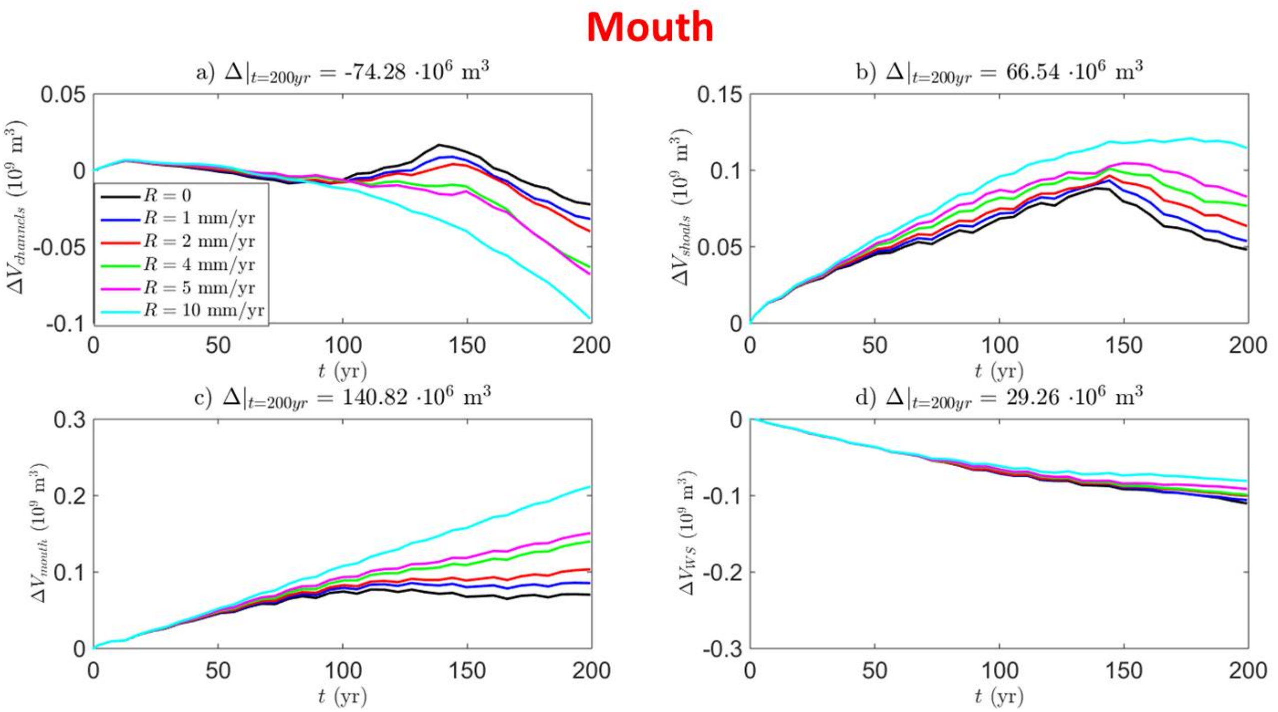
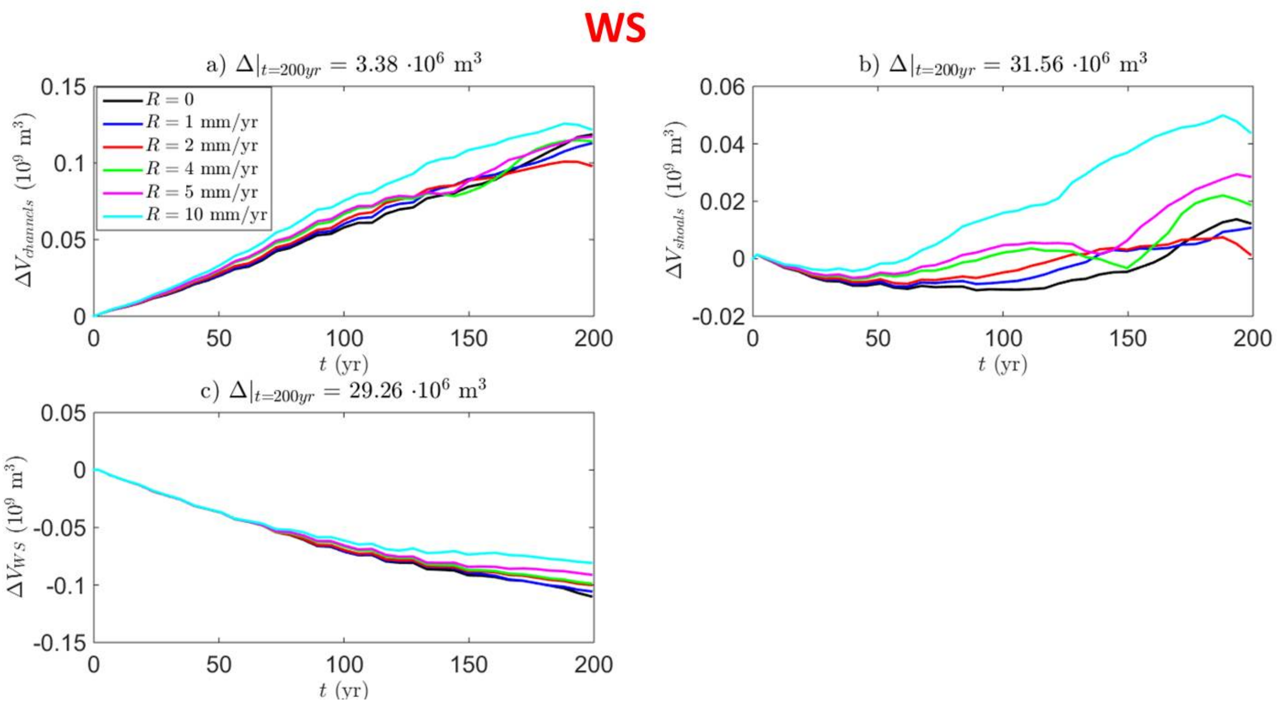


Figure 12 – As in Figure 8, but for the cases with different rates of SLR.



imately 3.5 mm/yr, which is of the same order of magnitude as the rate of SLR. In the estuary, the overall sedimentation rate is -1 mm/yr (erosion), which is caused by the large deepening of the channels. However, the sedimentation rate on the shoals is ~ 5 mm/yr, which even exceeds the rate R of SLR.

Development of channels and shoals in the mouth after 200 years morphodynamic evolution in cases

Figure 13 – As in Figure 9, but for the cases with different rates of SLR.

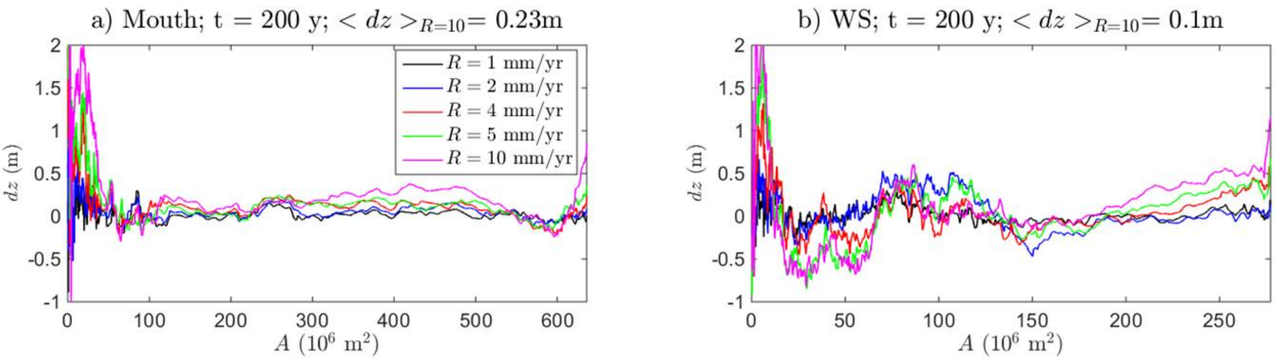
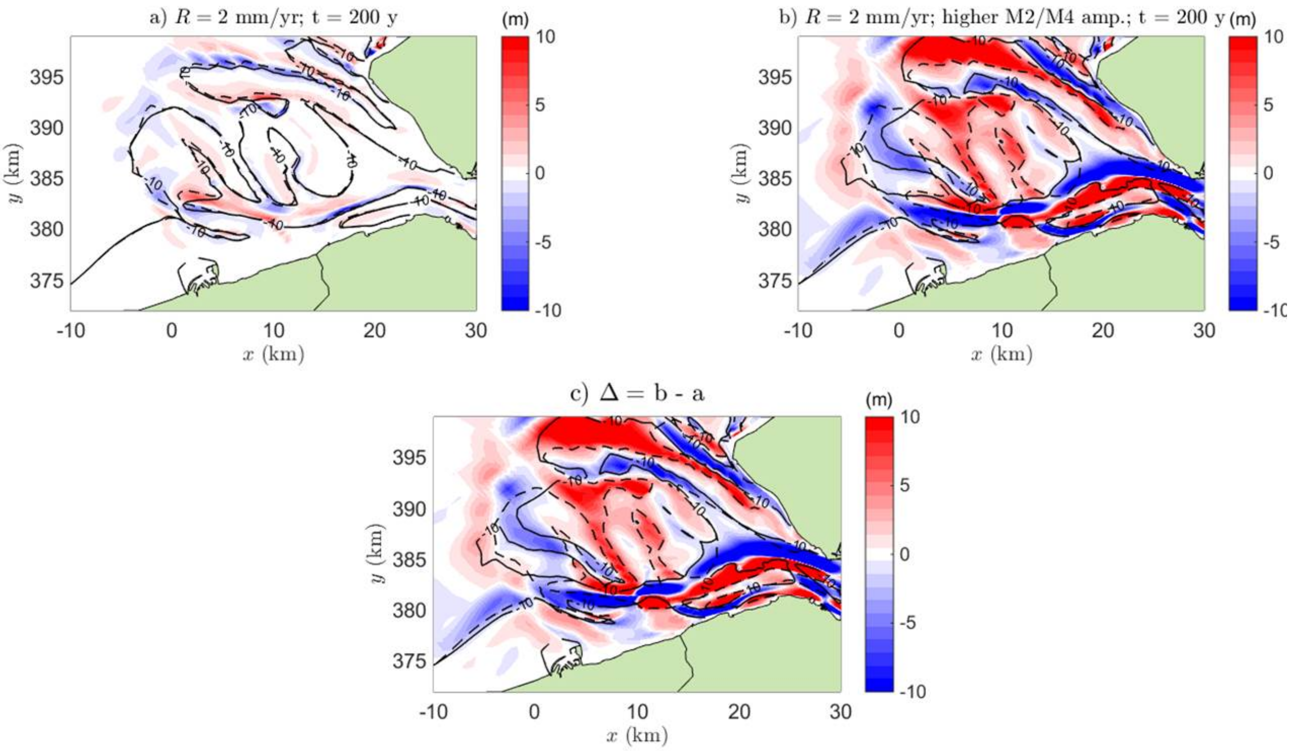


Figure 14 – a-b) As in Figure 6, but comparing the bedlevel differences dz (with respect to the reference case) in the cases of 'SLR-Default' (a) and 'Higher-M2M4' (b). c) Difference between the bedlevels of the two cases.



of the more realistic scenarios 'Variable-M2' and 'Variable-M2M4' are presented in Figure 16 (panels a and b, respectively). Here, the amplitudes $\hat{\zeta}_2$ and $\hat{\zeta}_4$ of tidal components M_2 and M_4 increase with increasing sea level, at rates of 0.6 mm/yr and 0.3 mm/yr, respectively. Similarly to the results obtained in case of a sudden increase of the amplitudes $\hat{\zeta}_2$ and $\hat{\zeta}_4$ at the start of the simulation (run 'Higher-M2M4'), also in the cases of runs 'Variable-M2' and 'Variable-M2M4' a gradual increase of these amplitudes also counteracts sedimentation of the channels in the mouth and WS, and it opposes the landward retreat of the ebb-tidal delta in the mouth area. The main difference between the results of cases of a sudden jump and a gradual increase of the amplitudes of the M_2 and M_4 tidal components is that the volume changes in the channels and shoals are smaller in the latter case. The overall sedimentation in the mouth is $\sim$0.5 mm/yr. The overall WS area experiences erosion, but the shoals accrete at a rate of ~ 1 mm/yr, which is comparable to the rate R of SLR. These results clearly indicate that stronger tidal currents are needed to counteract the sedimentation of channels and to make shoals able to keep up with the rising sea level.

Figure 15 – As in Figure 9, but with the addition of the results from run 'Higher-M2M4'.

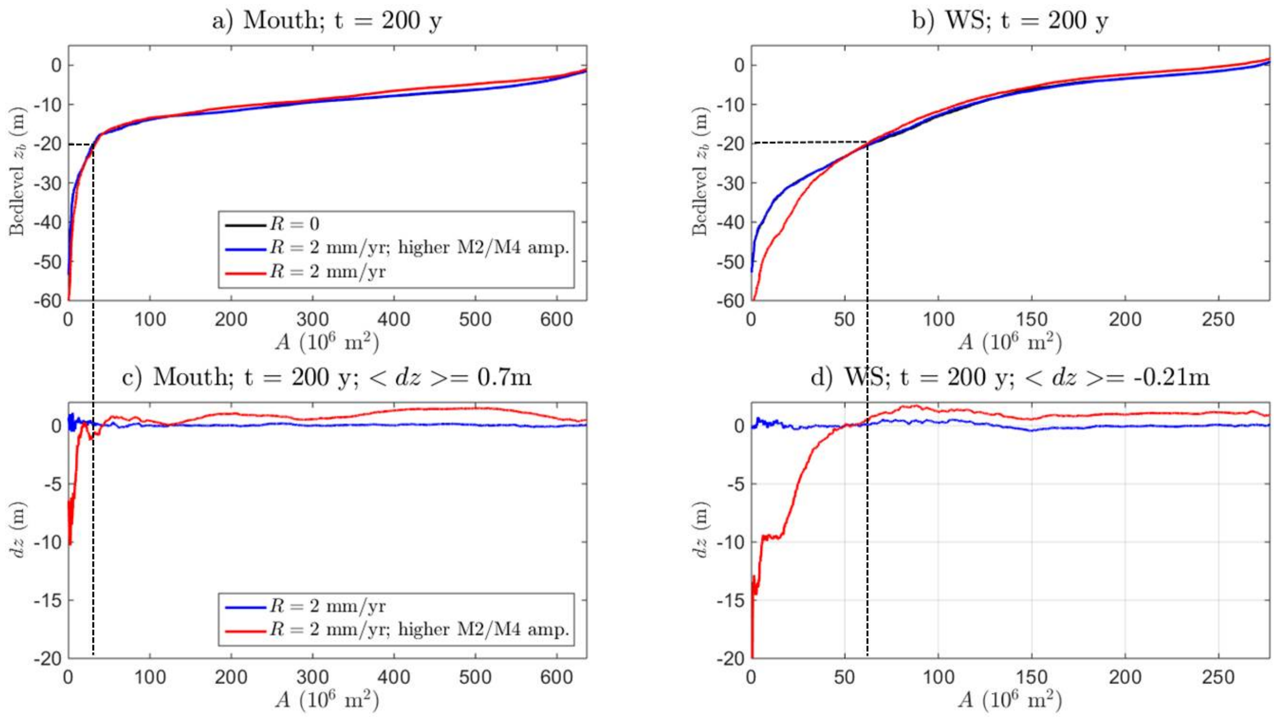
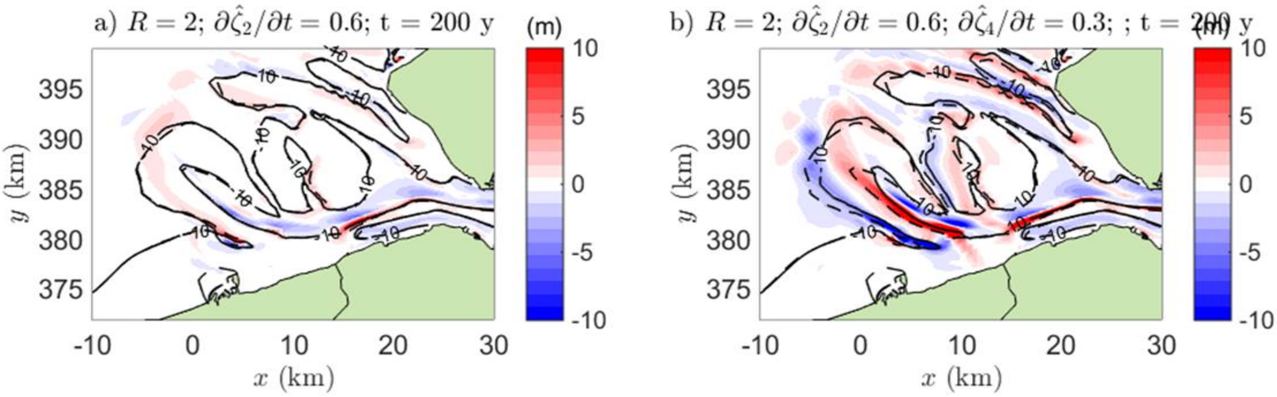


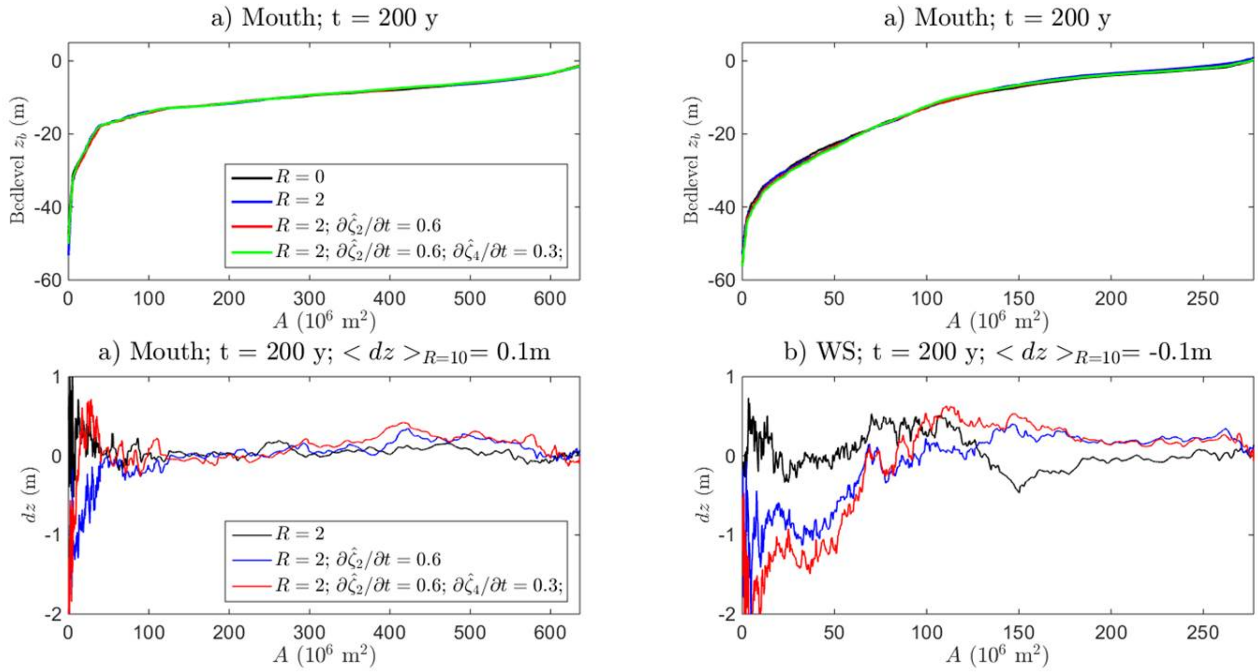
Figure 16 – As in Figure 6, but comparing the bedlevel differences dz (with respect to the reference case) in the cases of 'Variable-M2' (a) and 'Variable-M2M4' (b).



4.4 Physical mechanisms

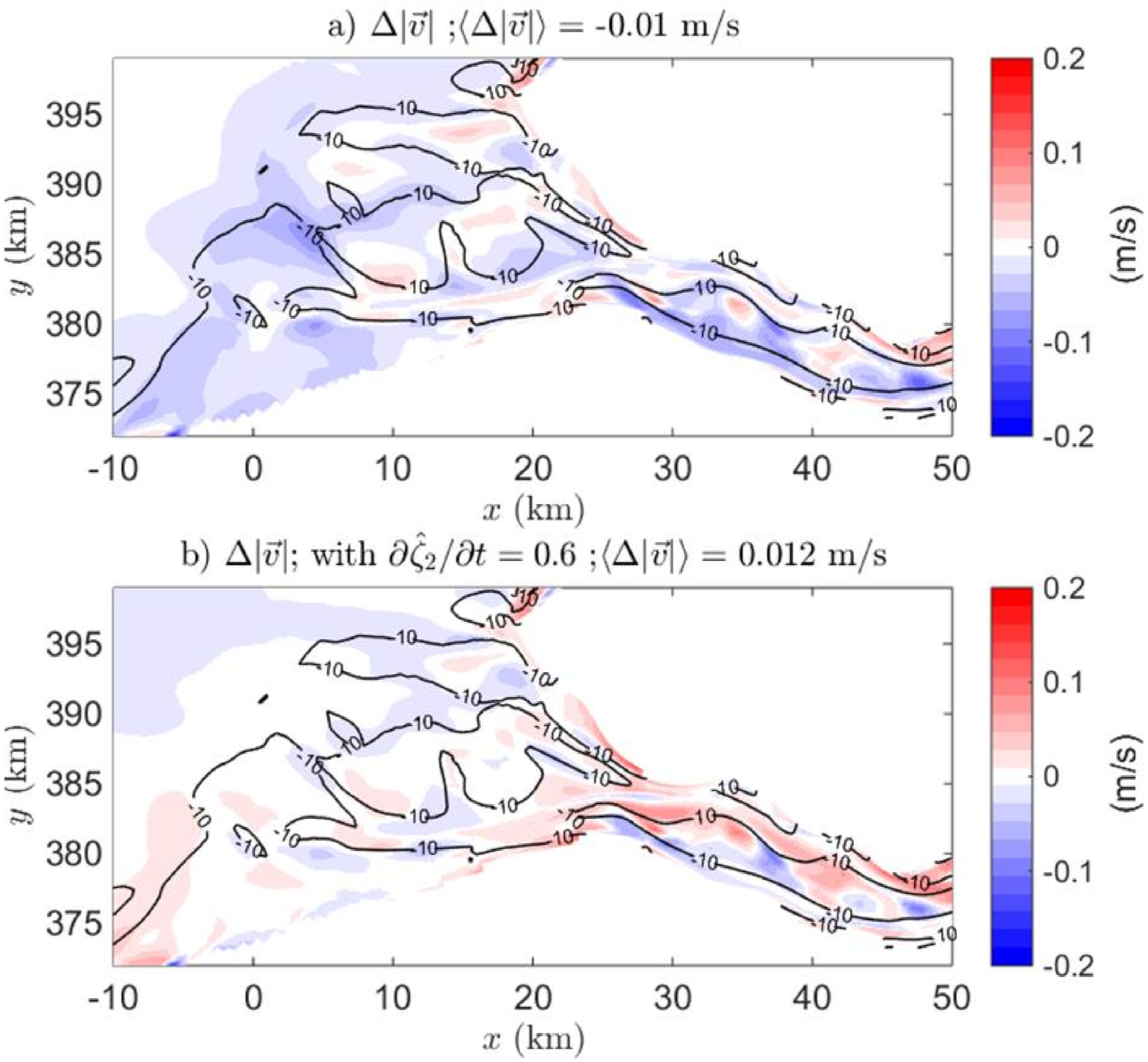
Model results indicate that sea level rise causes the overall sedimentation of channels and shoals of the mouth area with sand that comes from the sea, and it leads to a landward retreat of the ebb-tidal delta. The higher the rate of SLR, the more sedimentation and landward retreat. In the Western Scheldt estuary, a rising sea level causes the redistribution of sand of the entire estuary, such that sand is deposited on the shoals and tidal flats. This sand comes partly from a reduction of the sand export to the mouth area, while the other part is provided through erosion of channels. Rising of shoals and tidal flats with increasing sea level agrees with previous findings by e.g. Madsen *et al.*, 2007; Morris *et al.*, 2002; Wang *et al.*, 2015, stating that tidal basins generally adapt to sea-level rise such that height of their shoals and tidal flats can keep up with the rising sea level. However, in the case that the amplitude of tidal currents remains fixed in time, sedimentation rates on shoals are

Figure 17 – As in Figure 9, but with the addition of the results from runs ’Variable-M2’ and ’Variable-M2M4’.



too small for these shoals to keep up with rising sea level. However, the inclusion of stronger tidal currents increase sedimentations rates on the shoals, and they increase volume of the deep channels, thereby counteracting the weakening of the mechanisms that maintain the estuarine system caused by SLR. Figure 18a reveals that a rising sea level causes an overall weakening of tidal currents in the mouth and WS, which is attributed to the increasing water depth. However, imposing larger tidal amplitudes at the offshore boundaries, which is motivated by observations, results in stonger tidal currents (panel b), thereby opposing the weakening of these currents by SLR. Thus, the joint impact of a rising sea level and stronger tidal currents is crucial to maintain the equilibrium of the estuarine system.

Figure 18 – a) Difference $\Delta|\vec{v}|$ between the magnitude of tidal current $|\vec{v}|$ of the cases with and without SLR. b) as in a), but with addition of gradually increasing amplitude of M_2 tidal components with time.



Blue and red colors represent current reduction and enhancement, respectively. $\langle\Delta|\vec{v}|\rangle$ represents domain averaged values.

5 Summary and conclusions

The specific aims of the present report were threefold. The first was to investigate effects of sea level rise on the morphodynamic evolution of shoals and tidal channels, with particular attention to the development of channels and shoals subject to rising sea level. The second objective was to examine sensitivity of model results to different rates of sea level rise. The third was to examine the joint impact of sea level rise and stronger tidal currents. Use has been made of the coupled Delft3D-SWAN morphodynamic models described in the report by Nnafie *et al.*, 2017b.

Model results indicate that sea level rise causes an overall weakening of the ebb-tidal delta of the mouth area by causing sedimentation in its channels and on its shoals with sand that comes from the sea, and by reducing its seaward extension. In the Western Scheldt estuary, a rising sea level rather causes a redistribution of sand in this area such that sand is deposited on the shoals and tidal flats. This sand comes partly from a reduction of the sand export to the mouth area, while the other part is provided through erosion of particularly the deep channels.

Regarding the impact of different rates of sea level rise on model results, it turns out that especially the deepest channels and the highest shoals and tidal flats in the mouth area experience more sedimentation with increasing rate of SLR. The amount of sedimentation of channels and shoals appears to be approximately proportional to the rate of SLR. Moreover, higher rates of SLR further reduces the seaward extension of the ebb-tidal delta. In the Western Scheldt estuary, sedimentation on shoals increases and the sand exchange between the estuary and the mouth reduces with increasing rate of SLR. In the case of very high rates ($R = 10$ mm/yr), almost all the sand that is deposited on the shoals comes from the reduction in sand export from the estuary to the mouth.

In the case that the amplitude of tidal currents remain fixed in time, sedimentation rates on shoals are too small for these shoals to keep up with rising sea level. However, the inclusion of stronger tidal currents increases sedimentations rates on the shoals, and they increase the volume of the deep channels, thereby counteracting the weakening of the mechanisms that maintain the estuarine system caused by SLR. This is because a rising sea level, and thus larger water depths, causes an overall weakening of tidal currents in the mouth and WS. However, imposing larger tidal amplitudes at the offshore boundaries, which is motivated by observations, results in stonger tidal currents, thereby opposing the weakening of these currents by SLR. Thus, the joint impact of a rising sea level and stronger tidal currents is crucial to maintain the equilibrium of the estuarine system.

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