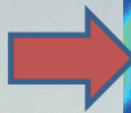


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Effects of extreme wave and wind events

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Morphodynamic modeling of the Scheldt mouth

Effects of extreme wave and wind events

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

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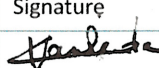
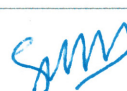
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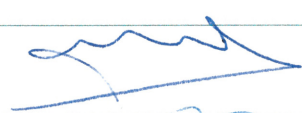
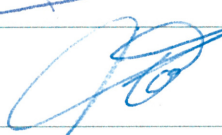
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Abstract

The overall aim of this study is to increase fundamental knowledge of effects of extreme wave and wind events on the morphodynamic evolution of the Scheldt mouth area, using a coupled Delft3D-SWAN morphodynamic model. Different scenarios are examined: relative effect of extreme wave events versus the combined effects of extreme wave and wind events, number and chronology of extreme events, and wave growth by wind.

Model outcomes show that the joint action of extreme wave and wind events causes an increase of sand volume of the mouth area in the course of time, thereby leading to smaller volume of channels (channels infill, in the order of 0.1 cm/yr) and larger volume of shoals (higher shoals, in the order of 0.1 cm/yr), particularly in the offshore part of the mouth area. These volume changes are larger with increasing number of extreme events. Moreover, when adding extreme events, the orientation of the offshore parts of channels changes as well. Increased shoal volume and channel infill with time also occurs in case of only extreme wave events, but these volume changes are much smaller than those in case that extreme wave and wind events are added to the model. The Western Scheldt estuary experiences relatively minor changes in its sand volume over time when including wave and extreme events. Results further show that a different chronology of extreme events influences the morphodynamic evolution of the mouth. However, the tendency of increased channel infill and sand gain by shoals in the mouth area with sand that is imported from the North Sea remains qualitatively the same. In case of including additional wave growth by wind, wave action during extreme wave events becomes stronger, and thus more sediment is resuspended in the water column, which is subsequently imported into the mouth area, resulting in enhanced infilling of channels and sand gain by shoals.

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Nederlandse samenvatting

Het doel van dit rapport is om fundamenteel inzicht te verschaffen hoe de morfodynamische evolutie van de Scheldemonding beïnvloed wordt door extreme golf- en windcondities. Hierbij wordt gebruikt gemaakt van een gekoppelde Delft3D-SWAN model. In deze studie wordt onder meer aandacht besteed aan de relatieve effecten van extreme golfcondities alleen, de effecten van het aantal en chronologie van de extreme condities, en de effecten van het meenemen van extra golfgroei door de wind.

Model resultaten laten zien dat met name de aanwezigheid van zowel extreme golf- als extreme windcondities leidt tot een toename van het zandvolume van de monding, waarbij het volume van de geulen afneemt (verzanding, ordegrootte 0.1 cm per jaar) en het volume van de banken toeneemt (verhoging, ordegrootte 0.1 cm per jaar). De toename van zandvolume in de monding wordt veroorzaakt door een toename van invoer van zand uit het zuidwestelijk deel van de Noordzee. Hoe frequenter extreme condities voorkomen, des te meer de geulen verzanden en de banken hoger worden. Extreme golfcondities alleen tonen minder effecten dan wanneer het model geforceerd wordt met gecombineerde golf- en windcondities. Geulverzanding en bankverhoging nemen af wanneer het model geforceerd wordt met alleen extreme golven. In tegenstelling tot de monding, ondergaat de Westerschelde relatief weinig volumeveranderingen onder invloed van extreme golf- en windcondities. Resultaten laten verder zien dat chronologie van extreme condities de model resultaten beïnvloeden, maar geulverzanding en bankverhoging vertonen wel steeds dezelfde trend. Geulverzanding en bankverhoging nemen toe wanneer de extra golfgroei door wind in het model wordt meegenomen. Dit is omdat er dan meer zand terechtkomt in de waterkolom als gevolg van een toename van zandopwoeling, waardoor meer zand door de windgedreven stroming naar de monding getransporteerd wordt.

1 Introduction

Extreme storm events, which are defined in this study as those events that are much stronger than the regular storm events occurring each year, have the potential of producing the equivalent of several years of sediment movement within one day (Benavente *et al.*, 2002), thereby substantially contributing to the long-term (order decades to centuries) morphological evolution of estuaries and coastal seas. During extreme storm events, the combined strong currents and waves might cause significant erosion of tidal flats and shoals and major or even complete infilling of tidal channels. The study by Yang and Dachu, 1983, reported that net erosion of up to 60 cm was measured on tidal flats after a single storm, where the long-term average sedimentation rate was on the order of several centimeters per year. Moreover, individual extreme storm events might induce considerable changes in the reorientation of channels and shoals. Morphological changes in estuaries resulting from these events have consequences on navigation, fishery and other estuarine values.

The overall aim of this report is to increase fundamental knowledge of effects of extreme wave and wind events on the morphodynamic evolution of the Scheldt mouth area, following an idealized modeling approach by schematizing forcing conditions, initial bathymetry and excluding as many processes as possible. To our knowledge, no systematic research has been conducted to assess the impact of extreme wind and wave events on the morphological evolution of this area.

The specific aims of the present report are twofold. The first is to investigate effects of extreme wave and wind events (including their relative importance) on the morphodynamic evolution of shoals and tidal channels. Particular attention will be paid to the impact of these events on time evolution of volume of channels and shoals. The second objective is to examine sensitivity of model results to the number and order of occurrence (chronology) of extreme events. To this end, the coupled Delft3D-SWAN morphodynamic models described in the previous report by Nnafie *et al.*, 2017, are used in this study. Further details can be found in the latter report.

In the next chapter, an analysis of wave and wind data collected in the Scheldt mouth is presented, with specific focus on wave and wind characteristics during extreme events. In Chapter 3, the methodology and set-up of the model experiments are outlined. Results from these experiments are presented in Chapter 4. Finally, Chapter 5 contains a summary and the conclusions.

2 Observed extreme events in the Scheldt mouth

Time series of significant wave height (H_s , in m), wave direction (θ , in degrees with respect to North, positive clockwise), peak wave period (T_p , in s), wind velocity (v_{wind} , in m/s; measured at 10 m above MSL) and wind direction (θ_{wind} , in degrees with respect to North) collected by Rijkswaterstaat at Deurlo station (see Figure 1 between 2003 and 2015 are presented in Figure 2. From these time series wave and wind roses are constructed, which are presented in Figure 3. As can be seen from the latter figure, the wind generally blows from the southwest, with a mean velocity (averaged over the entire time period) $v_{wind} = 8.6$ m/s and direction $\theta_{wind} = 224^\circ$. Waves are coming mostly from southwest and northwest. The southwesterly waves have a mean (averaged over the entire time period) significant wave height $H_s = 1$ m, a mean peak wave period $T_p = 5.7$ s and a mean wave direction $\theta = 254^\circ$, and the northwesterly waves have $H_s = 0.9$ m, $T_p = 7.1$ s and $\theta = 345^\circ$.

Extreme wave events, which are defined in this study as those with significant wave height $H_s > 4$ m, occurred 4 times between 2003 and 2015 (indicated by red circles in the top three panels in Figure 2). These events have a mean wave height $H_s = 4.1$ m, a peak wave period $T_p = 11.7$ s and a wave direction $\theta = 316^\circ$. Note that all these events have a northwestern direction. Extreme wind events, defined here as those with wind velocity $v_{wind} > 25$ m/s, occurred 2 times between 2003 and 2015 (indicated by red circles in the bottom two panels in Figure 2). One extreme wind event has a northwestern direction ($\theta_{wind} = 316^\circ$) and a maximum velocity v_{wind} of 26.9 m/s, while the other event has a southwestern direction ($\theta_{wind} = 238^\circ$) and a maximum velocity v_{wind} of 25.4 m/s. It is worthwhile to note that the latter velocity lasted about three hours, while the extreme velocity of 26.9 m/s lasted half an hour.

Interestingly, extreme wave events do not necessarily coincide with extreme wind events, as can be seen from Figure 2 (red circles). When zooming in on the extreme wind event that occurred on 18 January of 2007 (Figure 4), it is seen that the wave height did not exceed 4 m on this day, although wave heights between 3.5 and 4 m were observed. Another example is the extreme wave event of 21 October, 2014 (Figure 5), which reached a wave height $H_s = 4.2$ m. The latter event was not accompanied by an extreme wind event on the same day. By plotting the significant wave height (H_s) and wave direction (θ_{wave}) of all wave events that occurred between 2003 and 2015 as a function of wind velocity (v_{wind}) and wind direction (θ_{wind}) of all wind events (Figure 6), it turns out that (panel a) the highest waves ($H_s > 4$ m) do not coincide with the highest wind velocities ($v_{wind} > 25$ m/s), implying that the highest waves are not locally generated by wind, but they are rather swell waves coming from elsewhere. The latter is also confirmed by the fact that wind and wave directions are poorly correlated, as can be seen from panel b in Figure 6. In addition, panel c shows that the highest waves generally have a larger peak wave period.

Figure 1 – Delft3D computational grid. The thick white lines mark the contours of the mouth area, as used in this study.

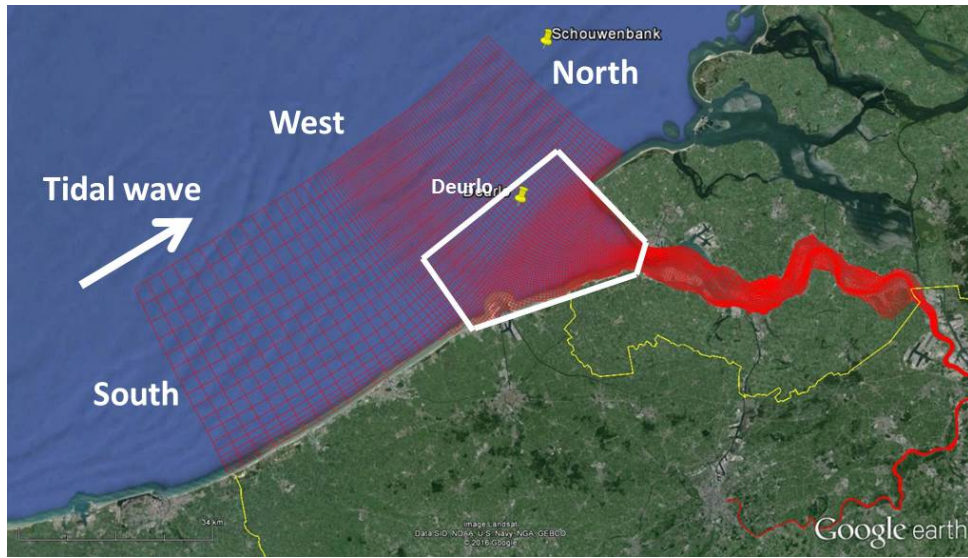
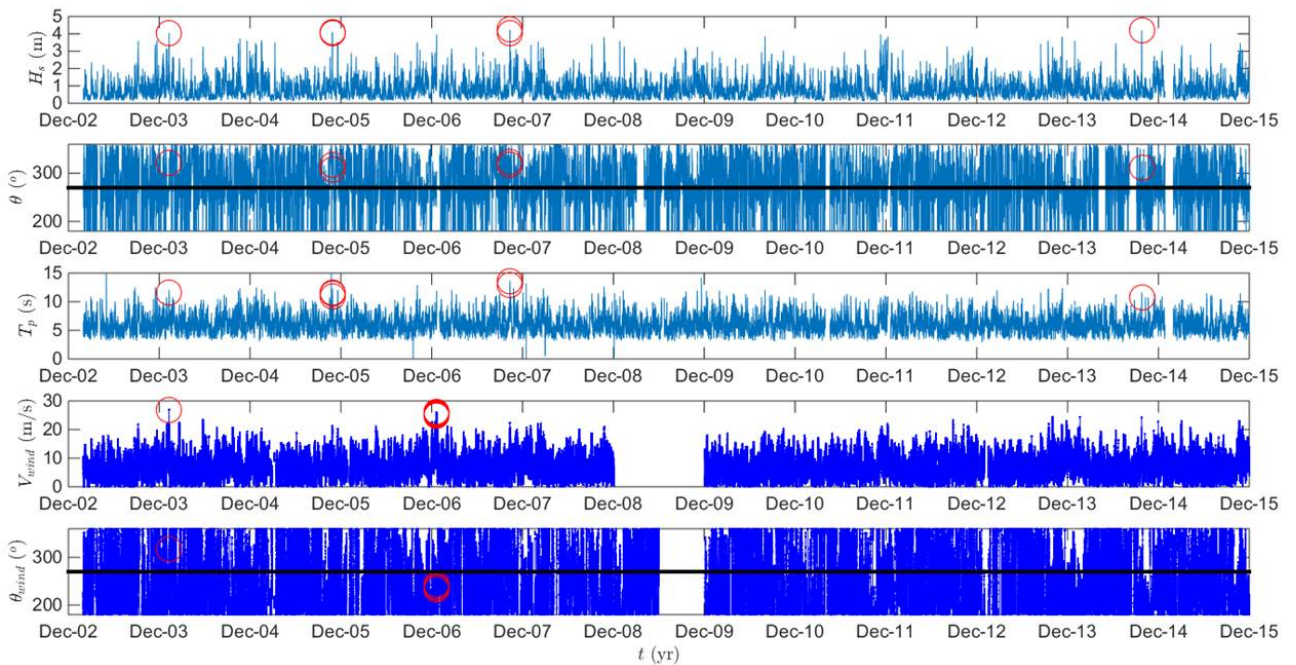
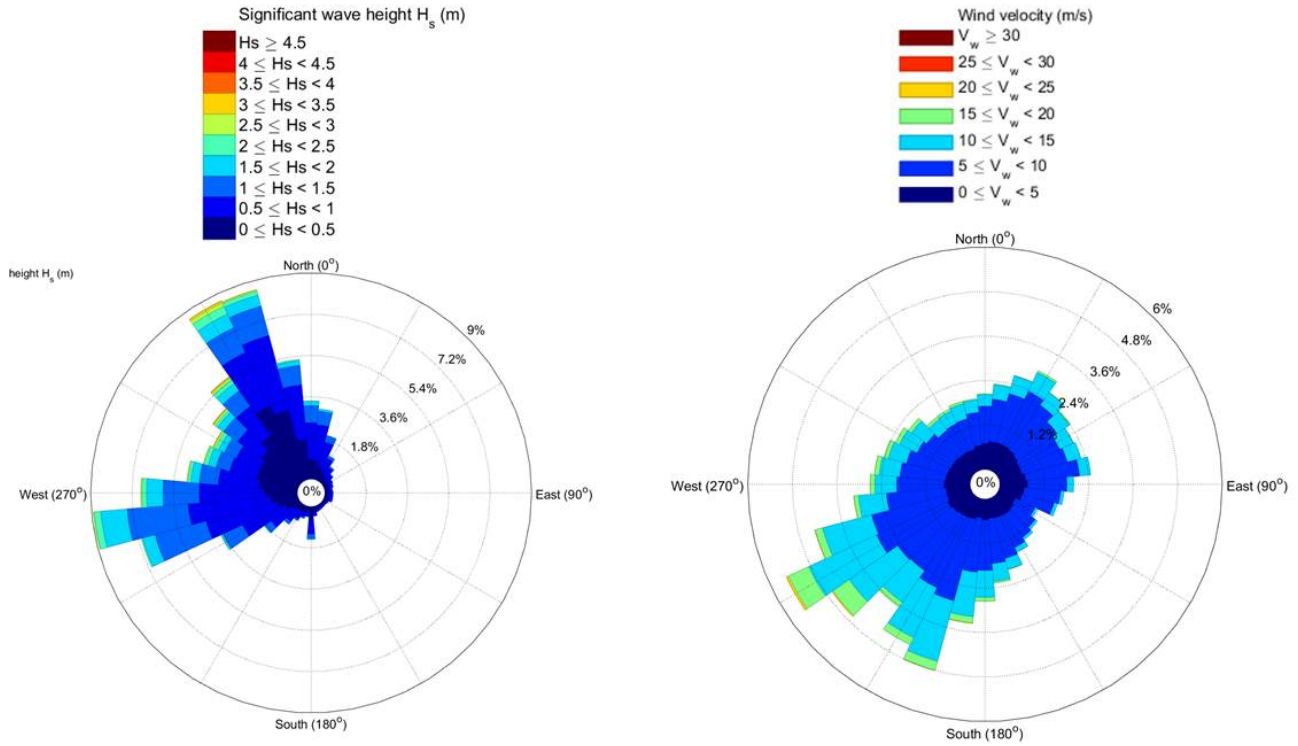


Figure 2 – Time series of significant wave height H_s (m), wave direction θ (degrees with respect to North), and peak wave period T_p (s), wind velocity v_{wind} (m/s) and wind direction θ_{wind} (degrees with respect to North).



Data are collected by Rijkswaterstaat at station Deurlon (see Figure 1) between 2003 and 2015. Red circles indicate extreme wave and wind events ($H_s > 4$ m; $v_{wind} > 25$ m/s) that occurred within this time period. The thick black line denotes the western direction (270°).

Figure 3 – Wave (left) and wind (right) roses showing measured significant wave heights H_s versus wave directions θ and measured wind velocities v_{wind} versus wind directions θ_{wind} .



Wave and wind directions are measured in degrees with respect to North axis. The radial values in these roses are the percentages of occurrence.

Figure 4 – Time series wave and wind climate during the extreme wind event of January 18, 2007.

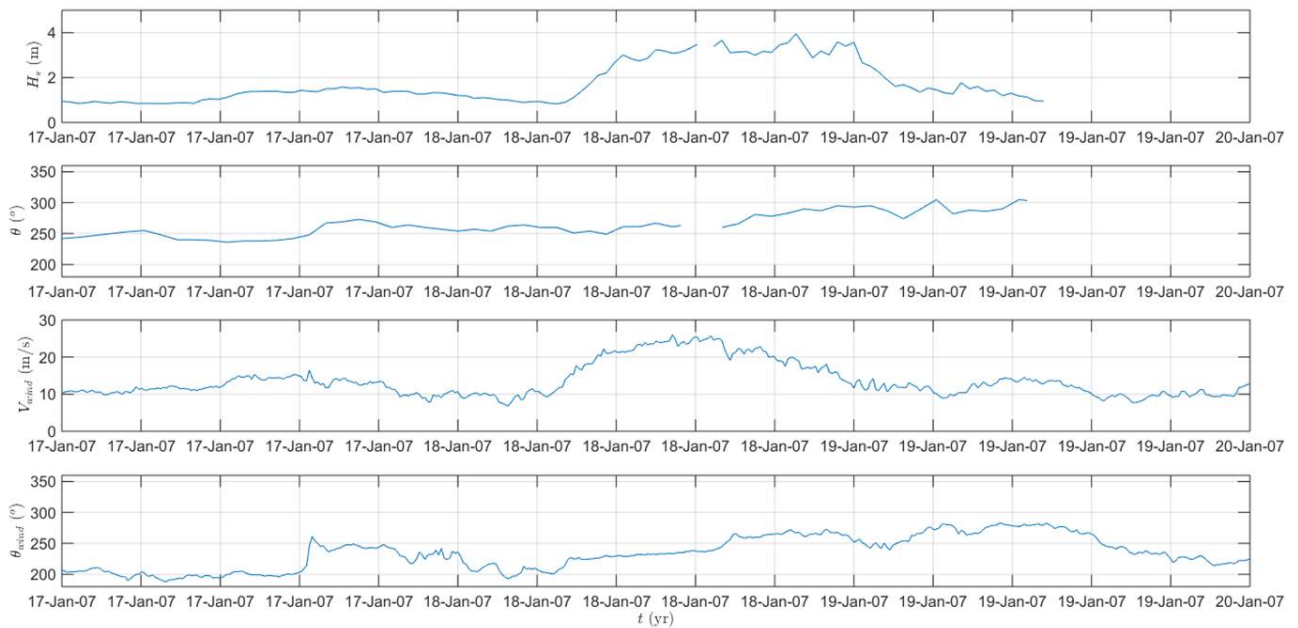


Figure 5 – Time series wave and wind climate during the extreme wave event of October 21, 2014.

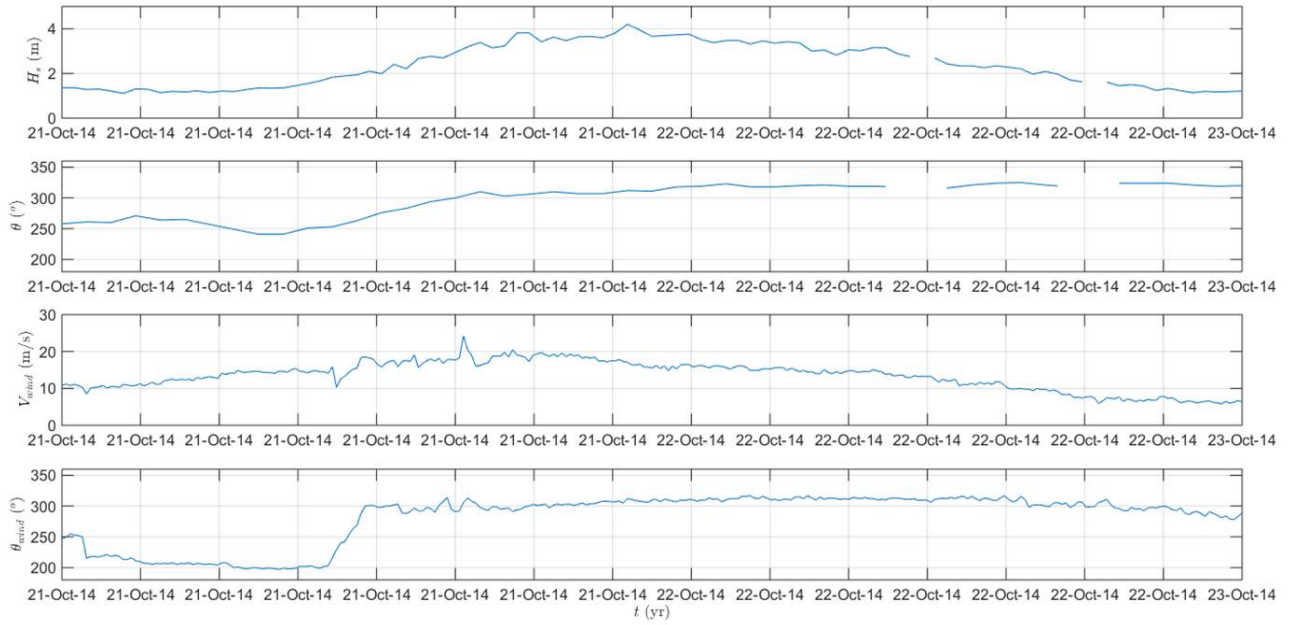
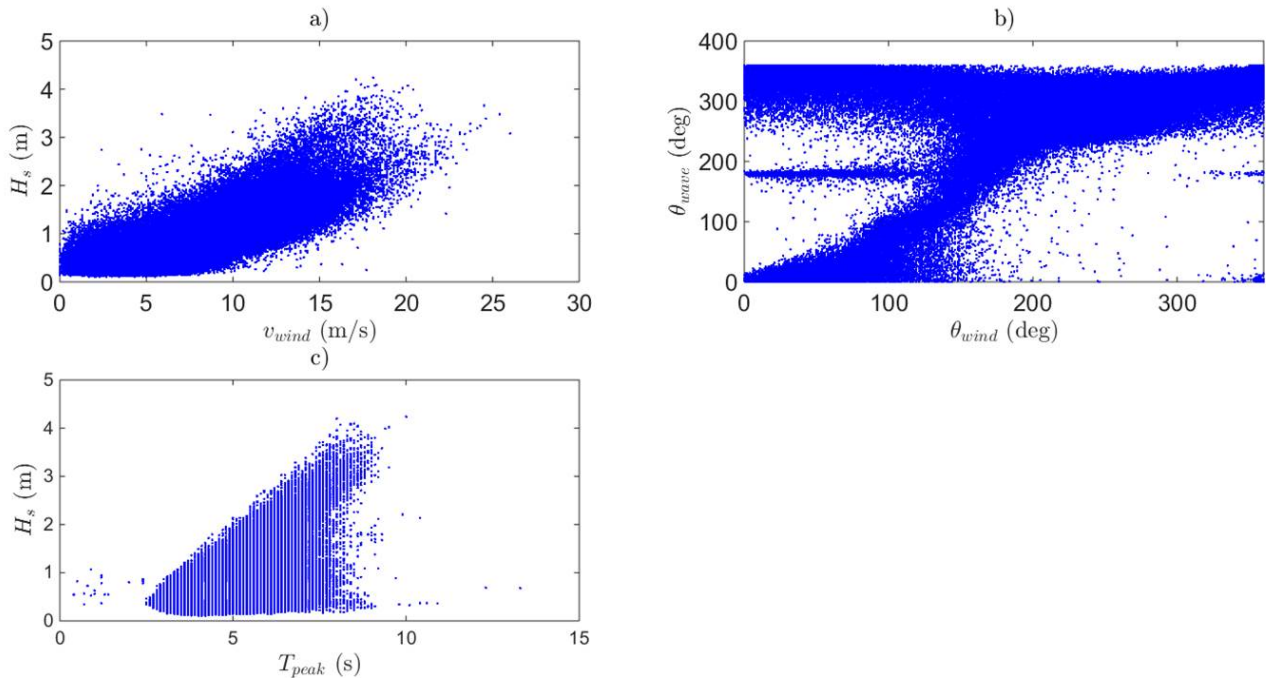


Figure 6 – Significant wave height versus wind velocity (a), wind direction (b) and peak wave period (c).



3 Experimental setup

3.1 Implementing extreme events in the model

The analysis of wave and wind data collected in the Scheldt mouth area between 2003 and 2015 revealed that 4 and 2 extreme wave and wind events occurred during this period. In the present study, due to lack of data over long periods, it is assumed that the period 2003-2015 represents well the wave and wind climate of the mouth area. Based on this assumption, extreme wave and wind events are estimated to have a probability of occurrence (P) of about ~ 3 and ~ 1.5 events per 10 year, respectively. Moreover, in view of the idealized modeling approach applied in this study, the probability of occurrence of extreme wind events is chosen equal to that of extreme wave events (i.e., $P = 3$ events per 10 year). Based on these probabilities, schematized wave and wind forcings are constructed as follows: First, wave and wind time series with a length of 500 years are generated. To fulfill a probability of occurrence of 3 events per 10 year, the time series contain 150 extreme wave and wind events with each event lasting 1 day. Next, to mimic the irregular occurrence of extreme events, the MATLAB intrinsic random function is used to create a random ordering of the extreme events. Here, extreme wind and wave events occur at the same time points. Result of this construction is presented in Figure 7. The blue lines represent average climate condition, featuring southwesterly waves with wave height $H_s = 1$ m, peak wave period $T_p = 5.7$ s and wave direction $\theta = 254^\circ$, and southwesterly wind having a velocity $v_{wind} = 8.6$ m/s and direction $\theta_{wind} = 224^\circ$. The red lines indicate values of the wave and wind characteristics during days of extreme events ($H_s = 4.1$ m, $T_p = 11.7$ s, $\theta = 316^\circ$, $v_{wind} = 25.4$ m/s and $\theta_{wind} = 238^\circ$). To avoid numerical instabilities, values of wave and wind characteristics are linearly increased to their corresponding values during days of extreme events, as can be seen from the zoom-in panel in Figure 7. Furthermore, as sediment activity strongly increases during stormy conditions, a variable morphological amplification factor α_{mor} is imposed in this study, which has values $\alpha_{mor} = 10$ during extreme wave and wind events and $\alpha_{mor} = 200$ during average climate conditions. This means that the morphological time in the model is slowed down by a factor of $200/10 = 20$ during extreme events.

Due to lack of wave and wind data sets in the Scheldt mouth area that cover longer time periods, it is rather uncertain whether the derived probability P ($= 3$ events per 10 year) also holds for longer time periods. Therefore, additional time series are generated where lower and higher values of P are used (Figures 8 and 9). These figures show time series of wave and wind forcings where extreme events have a probability of occurrence of 1 and 5 events per 10 year, respectively. Furthermore, to investigate the dependence of model results on the order of occurrence of extreme events (chronology), the MATLAB random function is re-run to generate a wave and wind time series with $P = 3$ extreme events per 10 year, with the difference that these events have a different chronology of occurrence compared with the time series depicted in Figure 10.

3.2 Model configuration

The model described in the report by Nnafie *et al.*, 2017, is also used in the present study, but with the following adjustments: 1) the SWAN grid is refined by a factor of 2 (Figure 11), and 2) the spinup experiment starts from an initial bed level where a more realistic bathymetry of the coastal area is implemented, as depicted in Figure 12. Specifically, the bed level decreases from 30 m at the offshore

boundary to 0 m at the shore. The refinement of the SWAN grid is needed in order to ensure that wave characteristics are correctly resolved during extreme events. Other model settings described in Nnafie *et al.*, 2017, are kept the same in the present model. See Table 1 for an overview of all model parameters.

3.3 Overview experiments

In order to investigate effects of extreme wave and wind events on the morphodynamic evolution of the mouth area, first, a spinup experiment is conducted starting from a initially flat bed until a more or less stable state is reached (run 'Spinup' in Table 2). The latter state lasts about 300 years. For further details on how this state is defined, the reader is referred to the report by Nnafie *et al.*, 2017. The spinup experiment is run with only climate average conditions, thus without the presence of any extreme wave or wind events (see Figure 13).

Subsequently, the obtained bedlevel from the spinup experiment is used as an initial bathymetry in the following runs. Firstly, as analysis of experiments conducted in this study focuses on the relative importance of extreme events with respect to the case without these events, a reference experiment is performed which, in principle, is a continuation of the spinup experiment. Secondly, a series of runs (run series 'ExtremeWaves' in Table 2) are carried out in the presence of only extreme wave events, having a probability of occurrence P ranging between 1 and 5 events per 10 year, which are represented by the time series displayed in Figures 8, 7 and 9. Thirdly, in run series 'ExtremeWavesWinds',

Table 1 – Overview model parameters.

	Parameter	Value	Description
Flow	f	$1.43 \times 10^{-4} \text{ s}^{-1}$	Coriolis parameter.
	C	$65 \text{ m}^{1/2} \text{ s}^{-1}$	Chézy coefficient.
	ν	$1 \text{ m}^2 \text{ s}^{-1}$	Eddy viscosity.
	$(\hat{\xi}_{2,S}; \phi_{2,S}) / (\hat{\xi}_{2,N}; \phi_{2,N})$	$(1.6 \text{ m}; 23^\circ) / (1.2 \text{ m}; 55^\circ)$,	(Amp.;Phase) M_2 South(S)/North (N).
	$(\hat{\xi}_{4,S}; \phi_{4,S}) / (\hat{\xi}_{4,N}; \phi_{4,N})$	$(0.1 \text{ m}; -11^\circ) / (0.1 \text{ m}; 113^\circ)$,	(Amp.;Phase) M_4 South(S)/North (N).
	$(\hat{\xi}_{6,S}; \phi_{6,S}) / (\hat{\xi}_{6,N}; \phi_{6,N})$	$(0.05 \text{ m}; -24^\circ) / (0.05 \text{ m}; 77^\circ)$,	(Amp.;Phase) M_6 South(S)/North (N).
	ω	$1.405 \times 10^{-4} \text{ s}^{-1}$	frequency M_2 .
Waves	H_s	1 m	Significant height southwesterly waves.
	T_p	5.7 s	Peak period southwesterly waves.
	θ	254°	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.
Numerics	p	0.4	Porosity bed.
	Δt	30 s	Time step.
	α_{MOR}	200/10	Morphological amplification factor.

Table 2 – List of model runs.

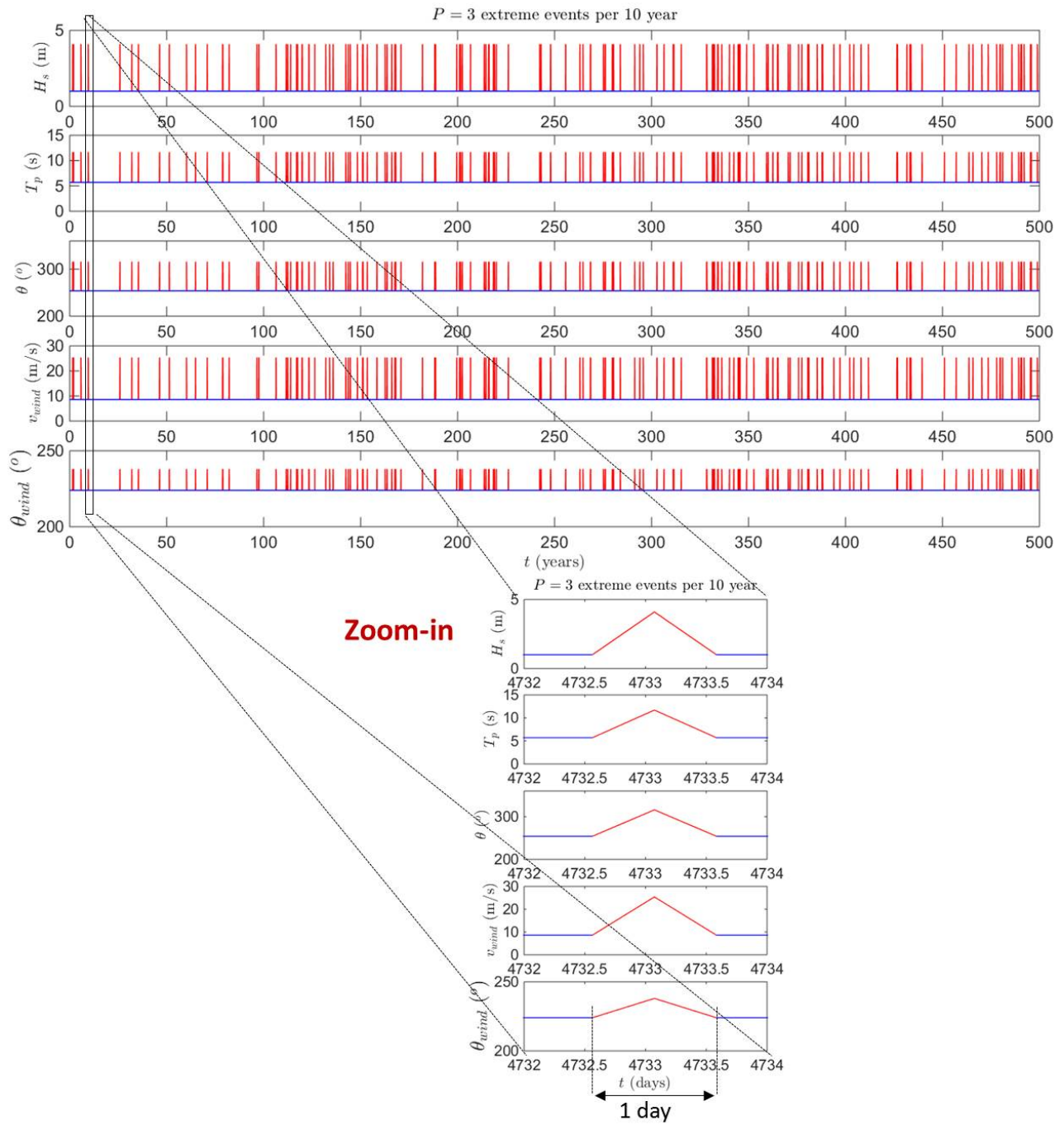
Name runs	Av. waves Av. winds	Extreme waves	P	α_{MOR}	Wave growth
Spinup	Waves:[1m-5.7s-254°] Wind:[8.6m/s-224°]	No	–	200/10	No
Reference	Waves:[1m-5.7s-254°] Wind:[8.6m/s-224°]	No	–	200/10	No
ExtremeWaves	Waves:[1m-5.7s-254°] Wind:[8.6m/s-224°]	Waves:[4.1m-11.7s-316°] Winds: No	1, 3, 5	200/10	No
ExtremeWavesWinds	Waves:[1m-5.7s-254°] Wind:[8.6m/s-224°]	Waves:[4.1m-11.7s-316°] Winds:[25.4m/s-238°]	1, 3, 5	200/10	No
DifferentChronology	Waves:[1m-5.7s-254°] Wind:[8.6m/s-224°]	Waves:[4.1m-11.7s-316°] Winds:[25.4m/s-238°]	1, 3, 5	200/10	No
LocalWaveGrowth	Waves:[1m-5.7s-254°] Wind:[8.6m/s-224°]	Waves:[4.1m-11.7s-316°] Winds:[25.4m/s-238°]	3	200/10	Yes
MorfacStorm	Waves:[1m-5.7s-254°] Wind:[8.6m/s-224°]	NW:[4.1m-11.7s-316°] Winds: SW:[25.4m/s-238°]	3	200/1	No

Abbreviation 'Av.' refers to climate average conditions. Symbol P indicates probability of occurrence of extreme events (in number of events per 10 year). Morphological amplification factor (α_{MOR}) during climate average as well as extreme conditions is also indicated.

sensitivity of model results to the combined effect of extreme wave and wind events is studied. Note that additional wave growth by wind is neglected, meaning that wind influences only the flow field. Fourthly, as the order of occurrence of extreme events (chronology) might have an impact on the morphodynamic evolution of the mouth area, a run is carried out using the wave and wind forcing depicted in Figure 10, where extreme events have the same probability of occurrence as those shown in Figure 7, but a different chronology (run 'DifferentChronology'). Fifthly, in run 'LocalWaveGrowth', transfer of wind energy to the waves is activated, which is described by the resonance mechanism of Phillips, 1957, and the feedback mechanism by Miles, 1957. Finally, as sediment activity strongly increases during stormy conditions, a variable morphological amplification factor α_{mor} is imposed in this study, which has values $\alpha_{\text{MOR}} = 10$ during extreme wave and wind events and $\alpha_{\text{MOR}} = 200$ during regular events. To test whether the use of $\alpha_{\text{MOR}} = 10$ is a valid approximation during stormy conditions, a run is conducted ('MorfacStorm') without a morphological amplification factor (i.e., $\alpha_{\text{MOR}} = 1$), which means that morphodynamic and hydrodynamic time steps are equal ($= 30$ s) during extreme events.

All experiments have a maximum simulation period of 500 years, but in view of the engineering time scales, results from these experiments are showed only for the first 150 years. Analysis of most these experiments focuses 1) on differences Δz_b between the cases with and without extreme events, and 2) on time evolution of the total volume of the mouth area (marked by the thick white lines in Figure 1) and the Western Scheldt estuary. Additionally, specific attention will be paid to time evolution of the total volume of channels and shoals of the mouth area, which are defined with respect to a certain reference bedlevel. In this study, $z_b = -10$ m is used as a reference bedlevel (Figure 14). Note that a positive (negative) volume change of channels means deepening (infilling), while a positive (negative) volume change of shoals indicates sand gain (loss).

Figure 7 – Wave and wind time series that are used as input in the model.



Extreme events have a probability of occurrence P of 3 events per 10 year. A zoom-in on an extreme event is depicted in the lower panel.

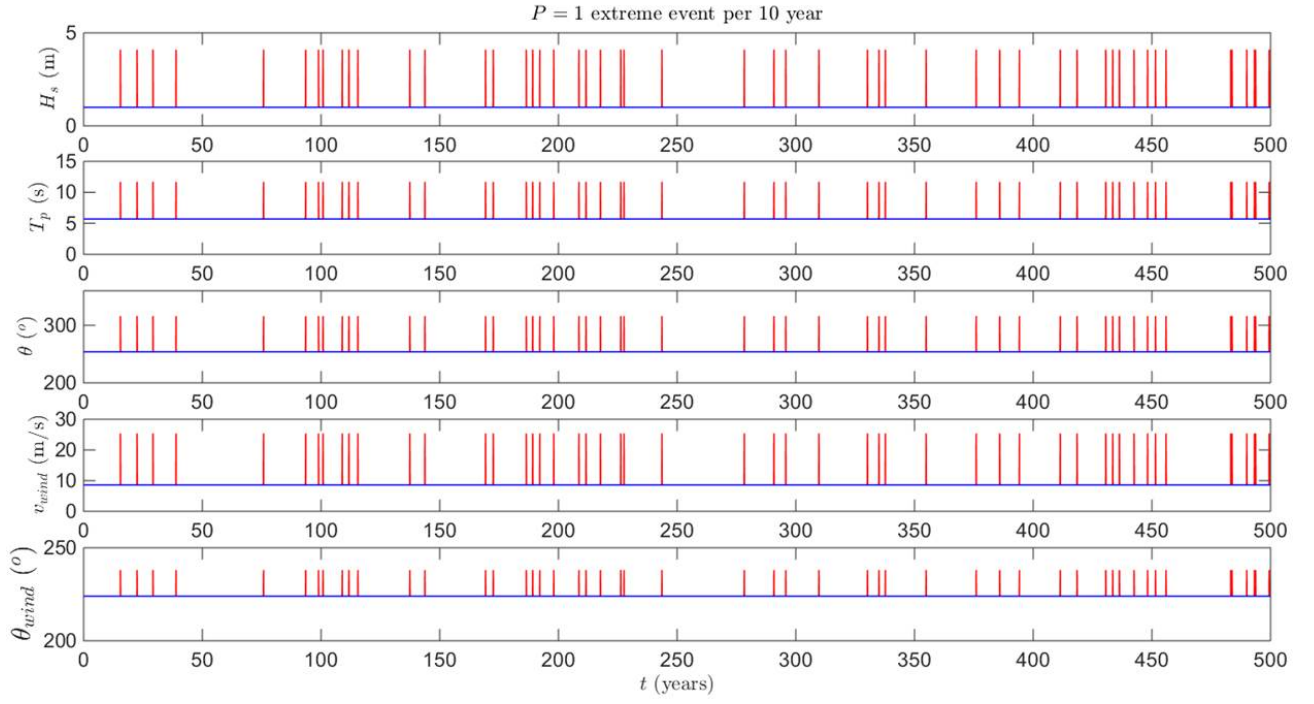
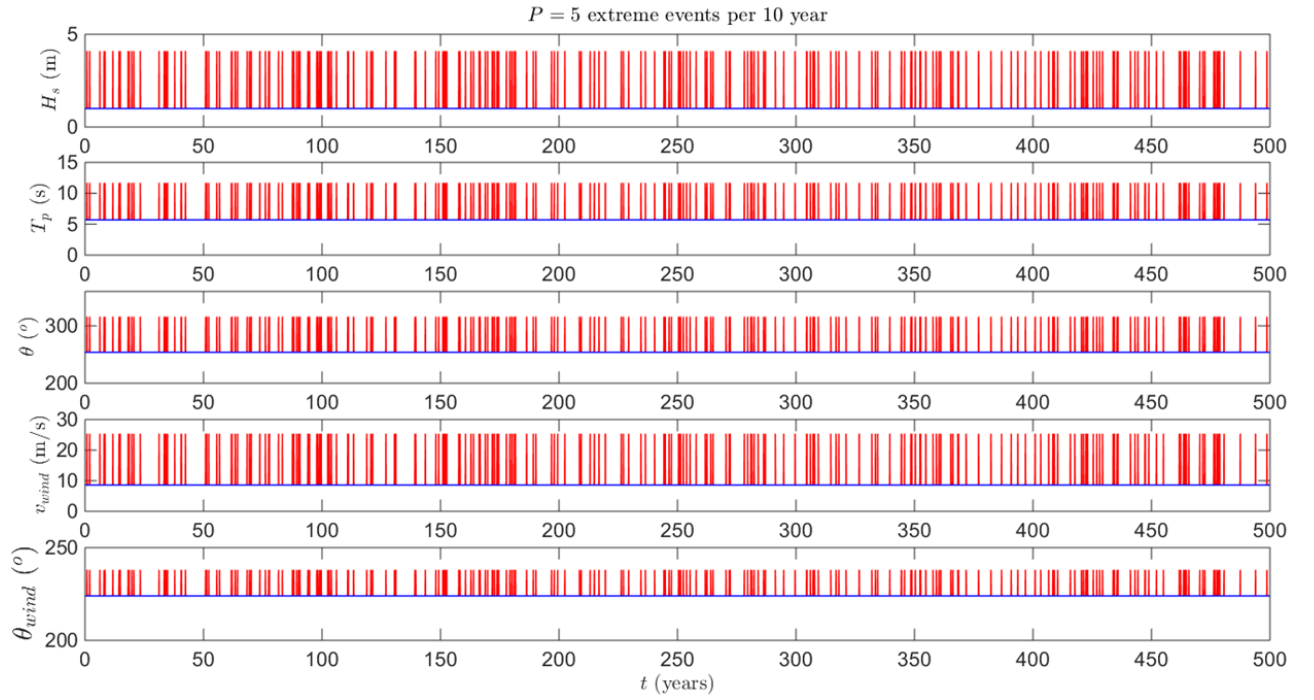
Figure 8 – As in Figure 7, but in case that $P = 1$ event per 10 year.Figure 9 – As in Figure 7, but in case that $P = 5$ events per 10 year.

Figure 10 – As in Figure 7, but in case that extreme events have a different chronology of occurrence.

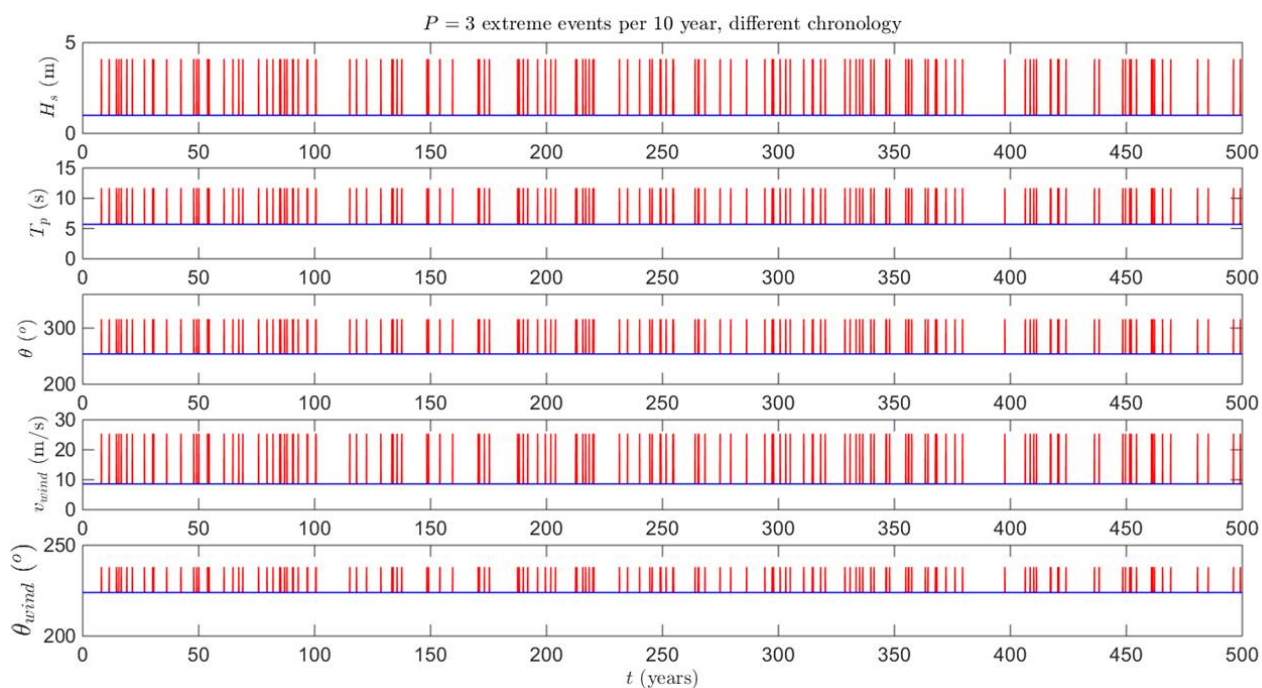


Figure 11 – SWAN computational grid used in this study.

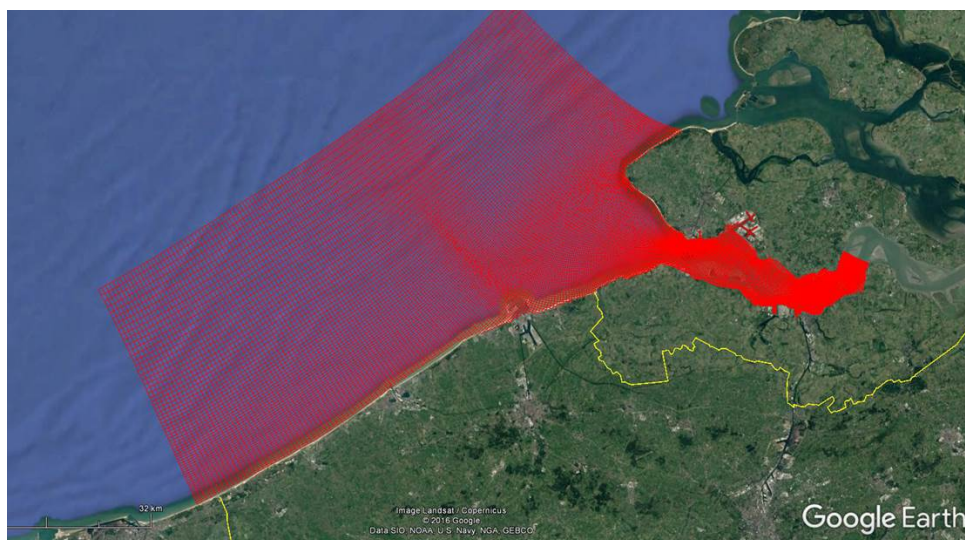


Figure 12 – Initial bed level used in the spin-up experiment, where a more realistic bathymetry of the coastal area is used.

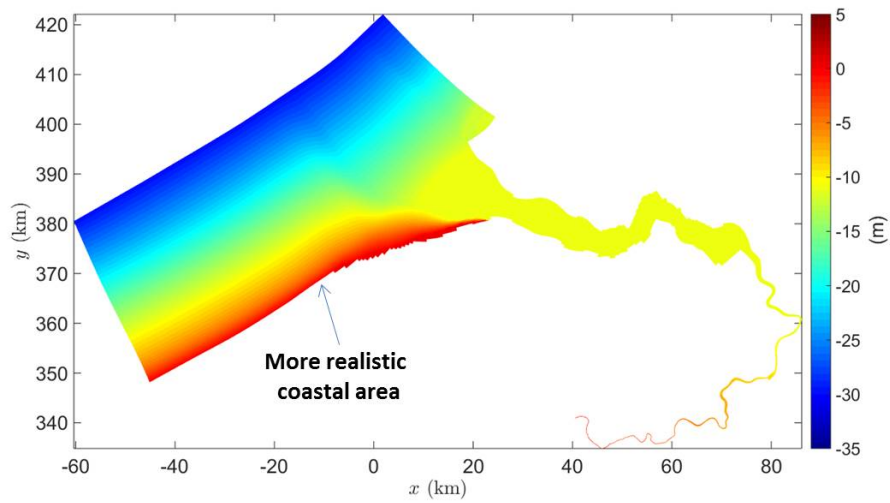


Figure 13 – Wave and wind time series representing average climate conditions.

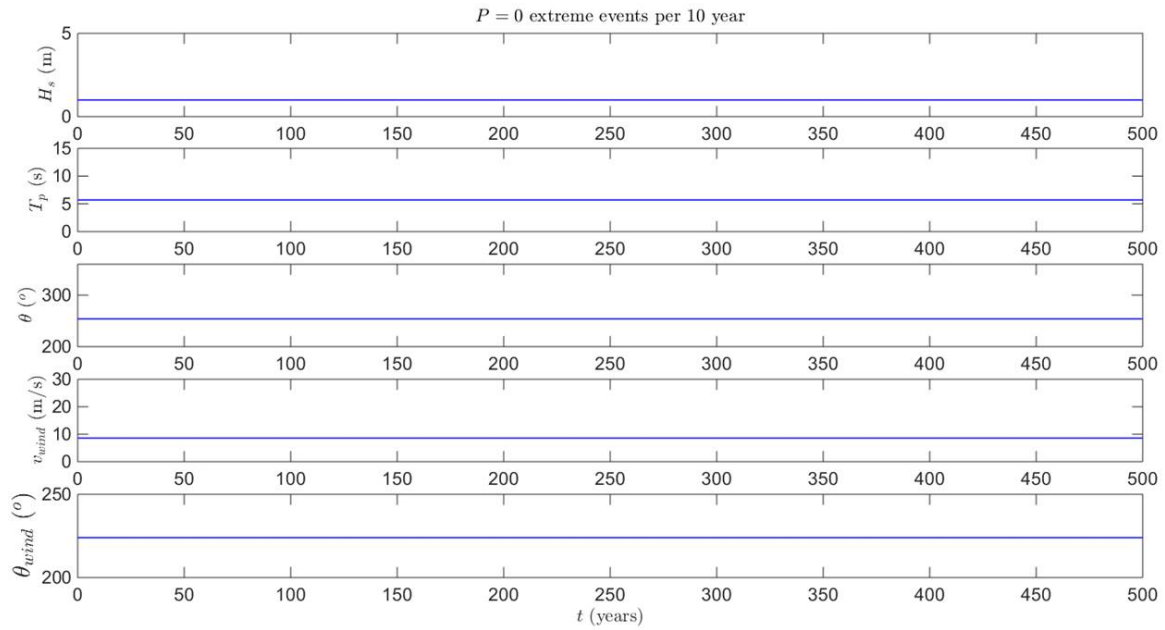
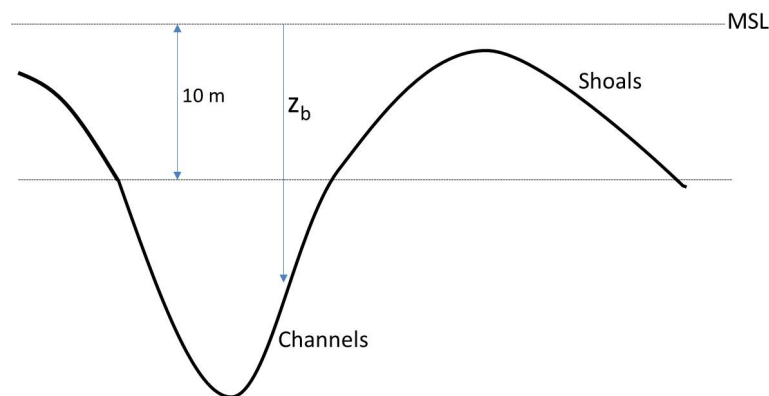


Figure 14 – Schematic view of channels and shoals in the model, which are defined with respect to the reference bedlevel $z_b = -10$ m.



4 Results and discussion

4.1 Model spinup

Results obtained from the spinup experiment are presented in Figure 15 (panels b-d). For comparison, the measured 2011 bathymetry as well as the modeled bedlevel of the mouth area in case of excluding the initially more realistic coastal area (Nnafie *et al.*, 2017) are also shown (panels a and e, respectively). The inclusion of a more realistic coastal area at the start of the simulation seems to improve comparison between model results and observations regarding the location of the southern channel (panel d). From the latter panel it appears that the southern channel is located more southward compared with the channel displayed in the bottom panel (e). However, the channel along the northern coast seems to be less pronounced in the case of a more realistic coastal area. All following run series that consider extreme events start with the bedlevel shown in panel d.

4.2 Effect of extreme wave and wind events

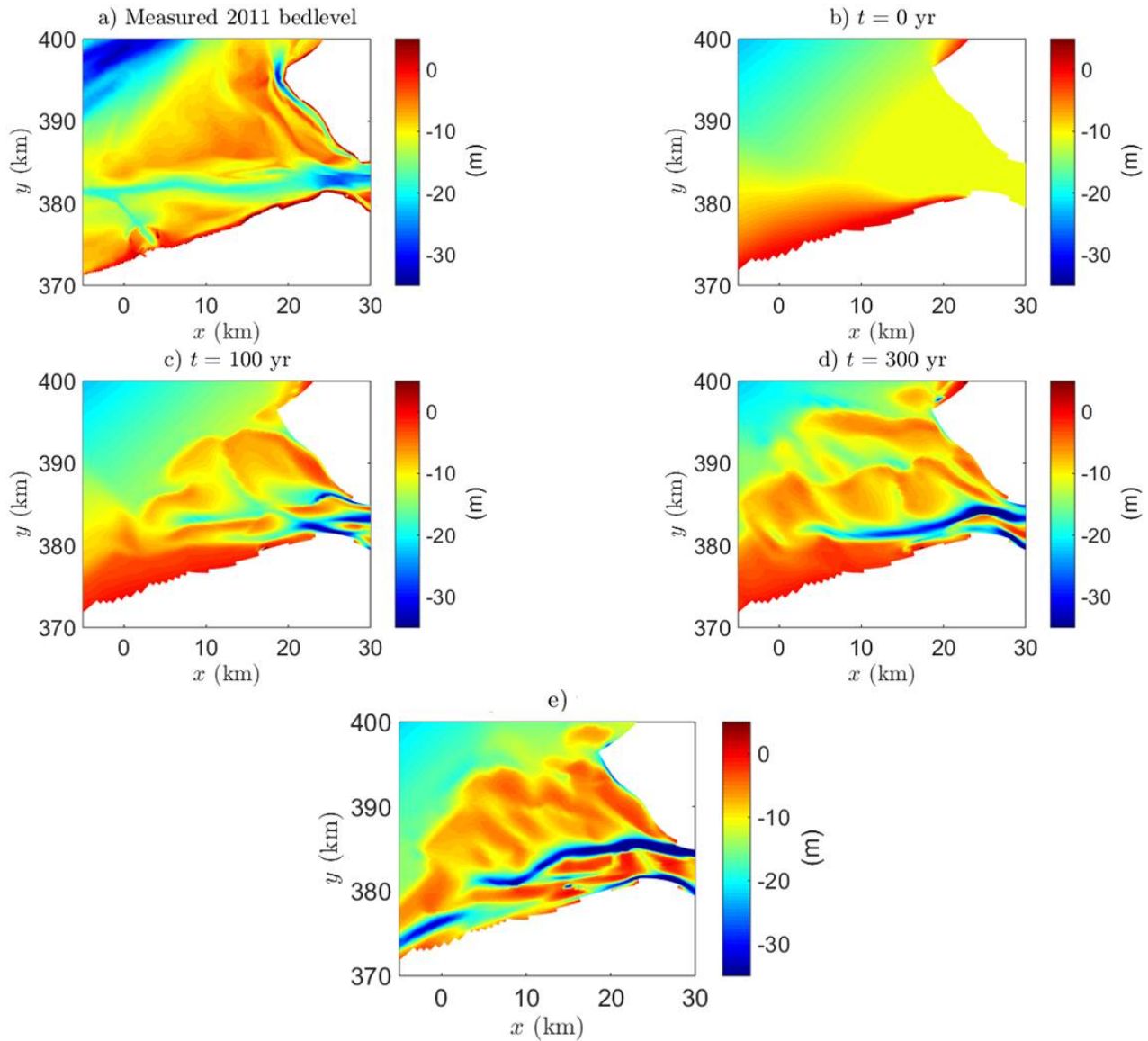
4.2.1 Extreme waves only

Figure 16 (panels a and b) shows snapshots of bedlevel development in the first 100 years in cases without and with extreme wave events, having a probability of occurrence $P = 3$ events per 10 year (run 'Reference' and 'ExtremeWaves' in Table 2, respectively). Overall, the large scale bottom patterns, featuring a shallow area flanked by a southern main channel and a narrow channel near the northern coast, do not qualitatively differ between the cases without and with extreme wave events. Regarding the bedlevel evolution in the case of extreme wave events relative to that in the reference case (hereafter referred to as bedlevel difference), it turns out that the inclusion of extreme wave events causes erosion and sedimentation of particularly the offshore parts of channel margins (Figure 17a). As a result, channels tend to migrate in these areas (Figure 17b), as can be seen from the slightly shifted -10 m depth-contour level in the case with extreme wave events compared to that in the reference case (solid and dashed contour lines, respectively).

Furthermore, analysis of the total volume of channels and shoals of the mouth area versus time (Figure 18) demonstrates that with respect to the reference case, the inclusion of extreme wave events causes a relative increase of shoal volume in the course of time, resulting in an overall increase of sand volume of the mouth (panel d). Channel volume experiences relatively minor changes when adding extreme wave events, although channels undergo weak infilling in the first 100 years (panel a). For an impression of orders of magnitudes of these volume changes, differences between channel and shoal volumes of cases with and without extreme wave events at $t = 100$ yr are indicated in the panels as $\Delta|_{t=100 \text{ yr}}$. The fact that the total sand volume of Western Scheldt is hardly affected by the inclusion of extreme events (panel d) implies that the relatively higher sand volume of the mouth area in the latter case with respect to the reference case is caused by increased sand import from the North Sea.

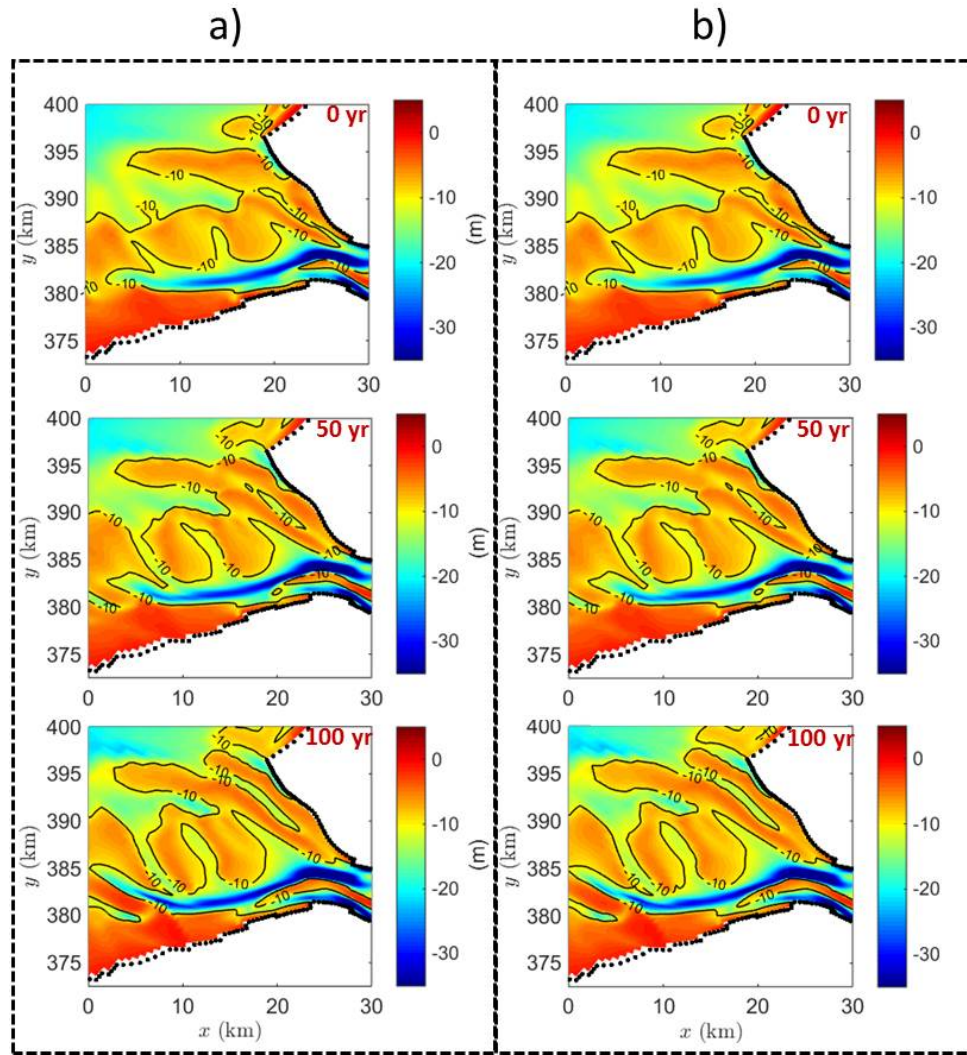
With regard to sensitivity of model results to the presence of extreme wave events with different probabilities of occurrence (P), it appears that higher values of P do not change the overall bottom pattern in the mouth area (Figure 19a). However, from panel b in the latter figure, it appears that

Figure 15 – b-d) Snapshots of bedlevel development during the model spinup.



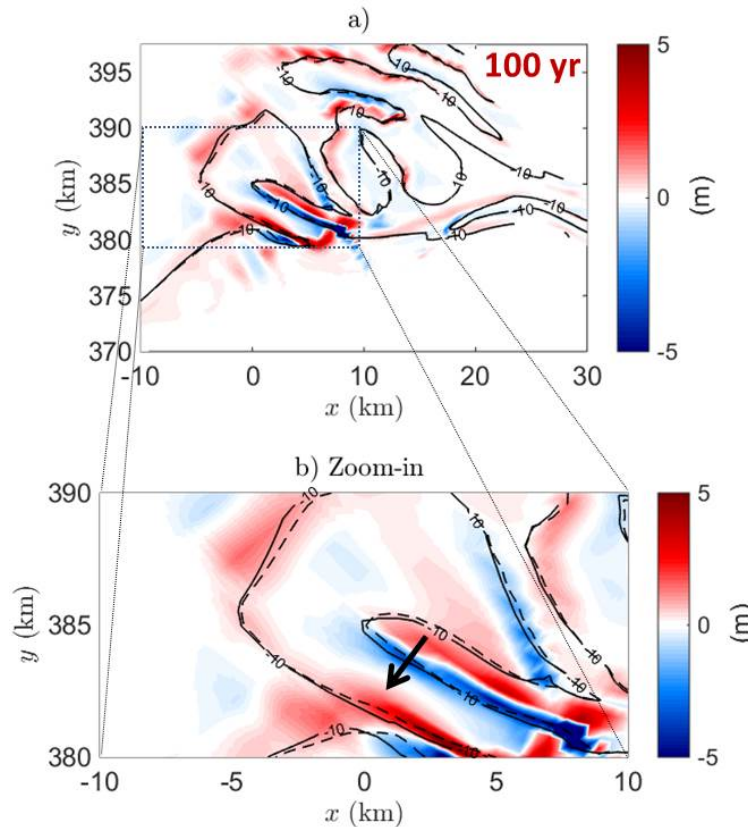
For comparison, measured 2011 bathymetry of the mouth area (a) as well as the simulated bedlevel in the case without a initially realistic coastal area (Nnafie *et al.*, 2017) are also shown (e).

with increasing P , orientation of the offshore parts of channels changes more due to increased sedimentation and erosion of channel margins. Moreover, with increasing P , channels experience more infilling and shoals gain more volume (Figure 20, panels a-b) with sand that comes mostly from the North Sea (panel c, d). The Western Scheldt loses more sand for higher values of P (panel d). Interestingly, only for $P > 1$ event per 10 year, time evolution of total volume of channels and shoals starts to deviate from those in the reference case. Finally, to get an impression of order of magnitudes of the volume changes, volume differences between cases of $P = 5$ events per 10 year and the reference case at $t = 100$ yr ($\Delta|_{t=100 \text{ yr}}$) are also indicated.

Figure 16 – Bedlevel development in cases without (a) and with (b) extreme wave events between $t = 0$ and $t = 100$ years.Probability $P = 3$ events per 10 year.

4.2.2 Adding extreme wind events

Results in case of adding extreme wind events (run series 'ExtremeWavesWinds') are presented in Figure 21a. Clearly, the joint action of extreme wave and wind events has a stronger impact on the morphological evolution of the mouth area compared with extreme wave action only. The simultaneous presence of extreme waves and wind significantly weakens the southern main channel due to increased channel infill, particularly for high values of P . Note the seaward breaching of the main channel for high values of P . Moreover, the bedlevel differences between cases with and without extreme and wind events (Figure 22b) reveal that sedimentation and erosion occurs in particularly the offshore part of the mouth area. It is important to note here that bedlevel differences in this figure reflect more the impact of extreme events on migration of channels and shoals, rather than on changes in sand volumes of the latter bottom features, as can be seen from the large spatial differences that exist between the -10 m contour levels of cases with and without extreme wave and wind events. With regard to the impact of extreme events on the sand volume of channels and shoals, Figure 22 shows that the addition of extreme wind events enhances the overall channel infill in the mouth area (panel a), and it further increases the shoal volume. For a more quantitative indication of volume changes that occur in case of adding extreme wind events, values $\Delta|_{t=100 \text{ yr}}$ shown in the

Figure 17 – a) Difference Δz_b between bedlevels of cases with and without extreme wave events after 100 years.

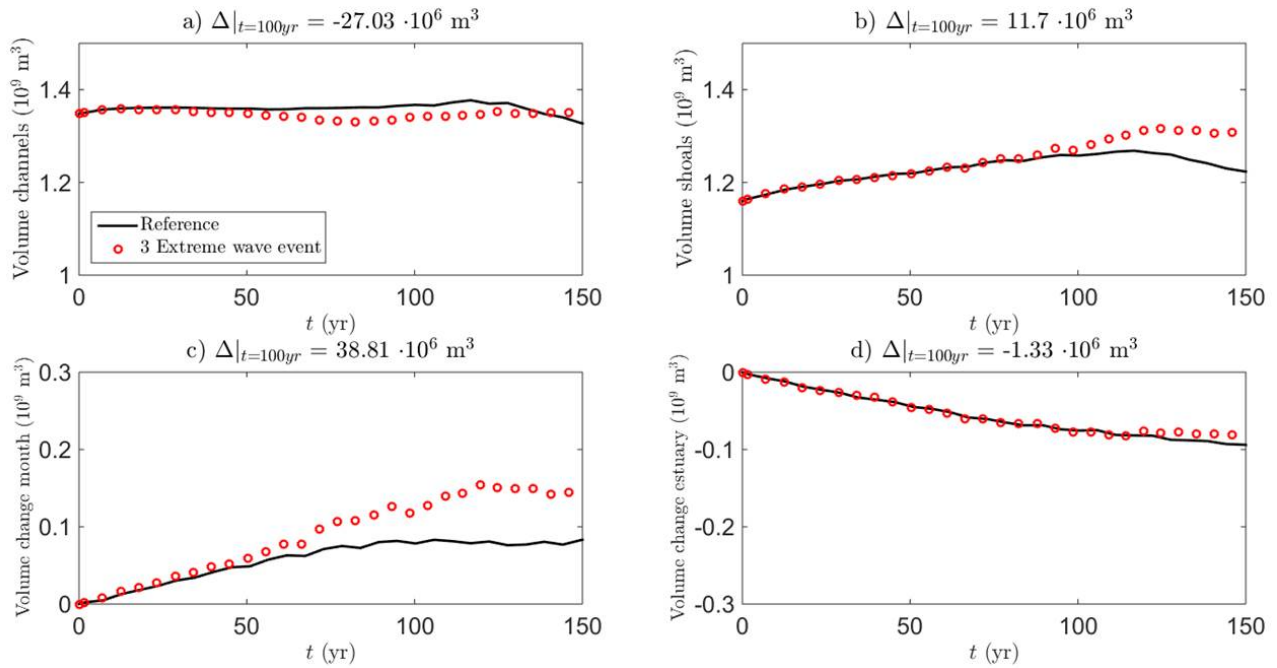
A zoom-in on the offshore part of the mouth is provided in panel b. Solid and dashed lines in panel a represent the -10 m depth-contour lines of the latter cases, respectively. Blue and red colors represent erosion and sedimentation, respectively. Black arrow in panel b indicates migration of the main channel in this area.

panels indicate that with respect to the case of extreme wave events only ($P = 5$ events per 10 year) (Figure 22), channel infill increases by a factor of 4, while sand gain by shoals is 1.6 times larger. In terms of the mean depth of channels and shoals (averaged on the entire mouth, with a total horizontal surface area of roughly $600 \cdot 10^6 \text{ m}^2$), the joint action of extreme wave and wind events with $P = 5$ decreases the overall channel and shoal depths with ~ 0.3 m after 100 years (or, 0.3 cm/year), while in the presence of only extreme wave events ($P = 5$), the infilling of channels is $\sim 0.1 \text{ cm/yr}$, and the sand gain by shoals is 0.2 cm/yr . This comparison clearly proves that the simultaneous action of extreme wave and wind events is necessary when modeling the impact of extreme storms on the morphodynamic evolution of particularly channels in the mouth area.

4.2.3 Physical mechanisms

Model outcomes reveal that particularly the joint action of extreme wave and wind events causes a strong increase of sand volume of the mouth area, featuring increased infill of channels and sand gain by shoals. The sand volume of the Western Scheldt experiences relatively minor changes compared with that of the mouth area. This section addresses the physical mechanisms responsible for the increase of the sand volume of the mouth area when adding extreme events. To this end, residual velocity and sediment transport (i.e., averaged over one tidal cycle) are compared between cases without and with extreme events at the start of the simulation ($t = 0$). Results are presented in Figures 23 and 24. These figures show that particularly in the case that both extreme wave and wind

Figure 18 – a-b) Time evolution of total channel (a) and shoal (b) volumes in the mouth area, and the cumulative volume change of the mouth (c) and the Western Scheldt (d) in cases without (black) and with (red) extreme wave events.



Cumulative volume changes are computed with respect the initial situation ($t = 0$). Probability $P = 3$ events per 10 year. Values $\Delta|_{t=100 \text{ yr}}$ indicate volume differences at $t = 100 \text{ yr}$ between the two cases.

events are present in the climate forcing, a strong increase of residual velocity and sediment transport occurs in the mouth area, resulting from increased sediment resuspension in the water column by stronger wave action, which is subsequently transported by the strong current (wind-induced currents superimposed on tidal currents). Interestingly, offshore of the mouth area, the currents are predominantly alongshore aligned (bidirectional) in the former case (Figure 23, panel d) compared with those in the latter one, which are more rotary (i.e., increased tidal eccentricity, panel c). This is related to the direction of the extreme wind event (southwest), which induces alongshore currents pointing in the northeastern direction. In contrast, in the case that extreme wind events are excluded, the resuspended sediment in the water column due to increased wave action is transported by the relatively weaker and more rotary tidal currents. The relatively larger magnitude and stronger bidirectionality of currents in the case with both extreme wave and wind events compared with those in case with only extreme waves means that relatively more sediment is transported from the southern part of the North Sea (particularly the southern coastal area) into the mouth in the former case compared with the latter one (Figure 24). This explains the relatively larger sand accumulation in the mouth area in the former case. However, it must be stressed that the model used in this study underestimates the wave-driven currents related to wave radiation stresses, due to insufficient grid resolution in the model (see next chapter for further details). Particularly in shallow areas of the mouth, where wave breaking often occurs, the inclusion of wave-driven currents would enhance sediment transport and thus morphological changes in these areas.

Figure 24 further displays that the more landward part of the mouth area experiences relatively smaller changes in sediment activity during extreme events, compared with its more offshore part. In the Western Scheldt (results not shown), the increase in sediment activity due to the presence of extreme events is much weaker than that in the mouth area, explaining the relatively smaller changes in sand volume of channels and shoals in the former area compared with the latter one. Moreover, the presence of extreme events in the climate forcing hardly changes sediment exchanges between

the Western Scheldt and the mouth.

4.3 Results of other sensitivity runs

4.3.1 Chronology extreme events

Results regarding effects of a different order of occurrence of extreme events (chronology) on the morphodynamic evolution of the mouth area are presented in Figure 25. Panels a and b in this figure show bedlevels obtained after 100 year of morphodynamic evolution in cases of using the forcings of Figure 7 and Figure 10, respectively, where extreme events have the same probability of occurrence (i.e., $P = 3$ events per 10 year), but a different chronology. Although the large scale bottom patterns are qualitatively the same, Figure 25c reveals that a different chronology of the extreme events does induce different bedlevel changes in the mouth area, resulting in differences in the time evolution of sand volume of the this area (Figure 26). Nevertheless, the tendency of channel infill and sand gain by shoals in the mouth with sand that is imported from the North Sea does not change in case that extreme events have a different chronology, as can be seen from Figure 26.

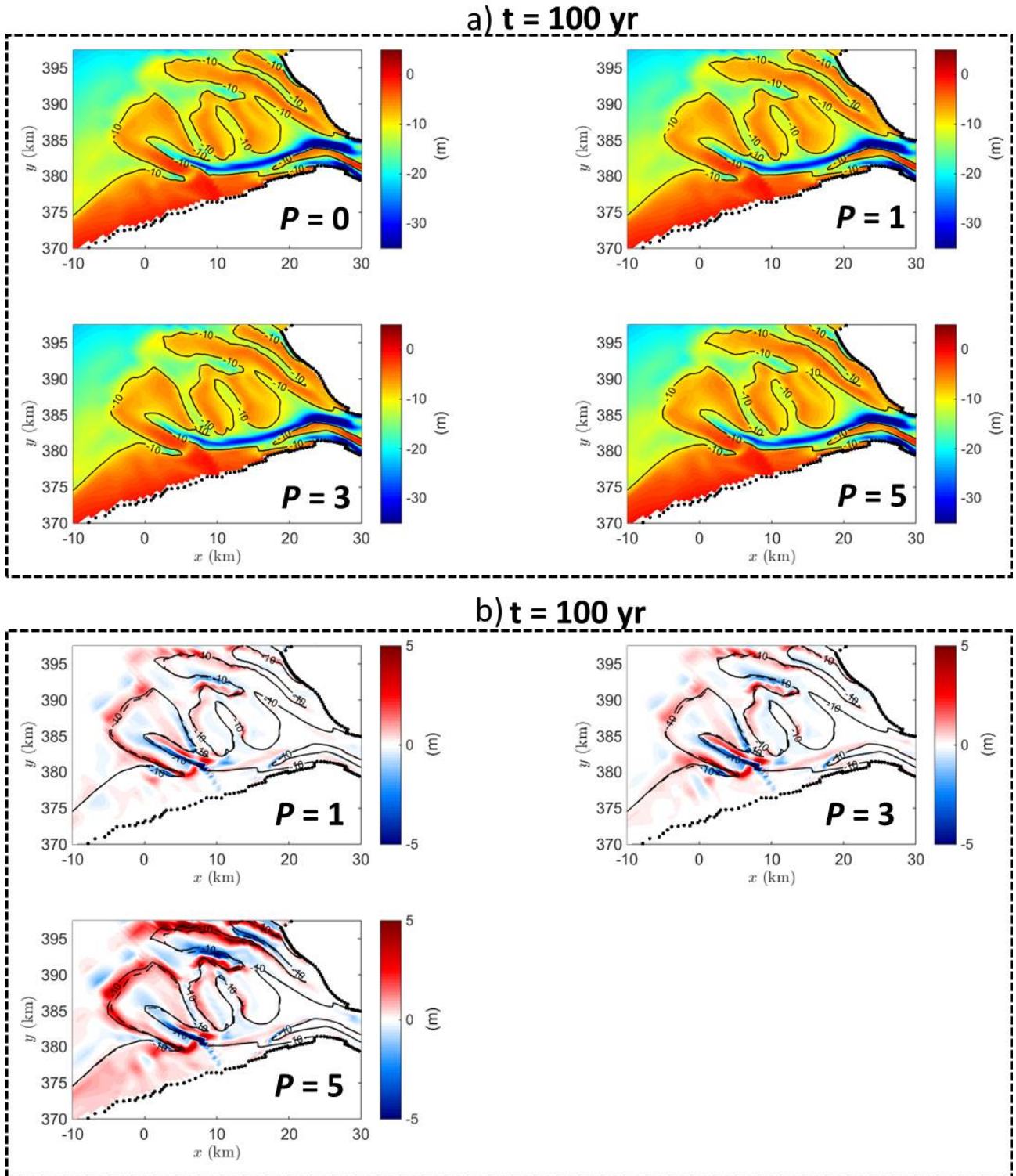
4.3.2 Local wave energy generation by wind

In view of the idealized modeling approach applied in this study, additional wave growth by wind has been neglected in the results discussed so far, where the latter influences only the flow field by generating additional (wind-induced) currents. Figure 27 shows that in case of accounting for additional wave growth by wind, results are qualitatively similar to those of case that growth is neglected. Quantitatively, however, in case of additional wave energy input by wind, channels experience more infilling (Figure 28, panel a) and shoals gain more sand (panel b) due to a larger sand gain by the mouth area (panel c). The reason of the relatively more sand gain by the mouth area in case of accounting for additional wave growth by wind is the fact that more sediment is resuspended in the water column compared with the case that wave growth is absent. As a result, more sand is imported into the mouth area in the former case. Figure 28d further displays that the Western Scheldt loses a bit more sand over time if additional wave energy input by wind is activated.

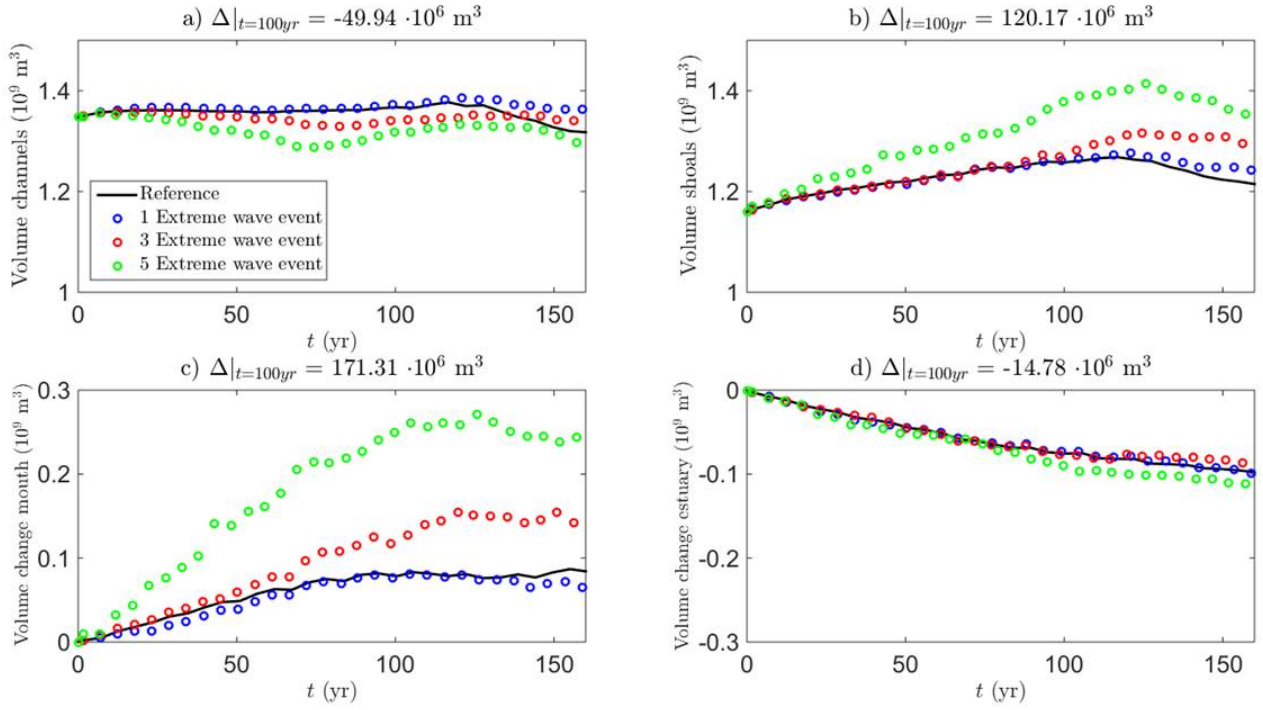
4.3.3 Sensitivity to morfac

As sediment activity strongly increases during stormy conditions, a variable morphological amplification factor (α_{mor}) is imposed in this study, which has values $\alpha_{mor} = 10$ during extreme wave and wind events and $\alpha_{mor} = 200$ during average conditions. From Figure 29, which compares the bedlevels obtained after 100 year of morphodynamic evolution between cases that $\alpha_{mor} = 10$ (panel a) and $\alpha_{mor} = 1$ (pane b), it is seen that a further decrease of the amplification factor during extreme events does not result in qualitatively different sediment and erosion patterns (panel c). Regarding time evolution of the total volume of the study area, the use of a value $\alpha_{mor} = 0$ still produces infilling of channels and sand gain by shoals with sand that is provided mostly by the North Sea (Figure 30). Quantitative differences are that the model seems to overestimate channel infill and sand gain by the shoals in case of using $\alpha_{mor} = 10$. Nevertheless, in view of the idealized nature of the model used in this study, these results prove that the use of $\alpha_{mor} = 10$ during extreme events is a reasonable assumption.

Figure 19 – Comparison of bedlevels (a) and bedlevel difference Δz_b (b) between cases of different probabilities of occurrence of extreme wave events ($P = 1, 3, 5$ events per 10 year).



Reference case is indicated as $P = 0$. Difference Δz_b is computed with respect to the reference case.

Figure 20 – Same as Figure 18, but in cases of different values of P of extreme wave events.


Values $\Delta|_{t=100\text{yr}}$ indicate volume differences at $t = 100$ yr between case of $P = 5$ events per 10 year (green) and the reference case (black).

Figure 21 – Same as Figure 19, but in case of adding extreme wind events.

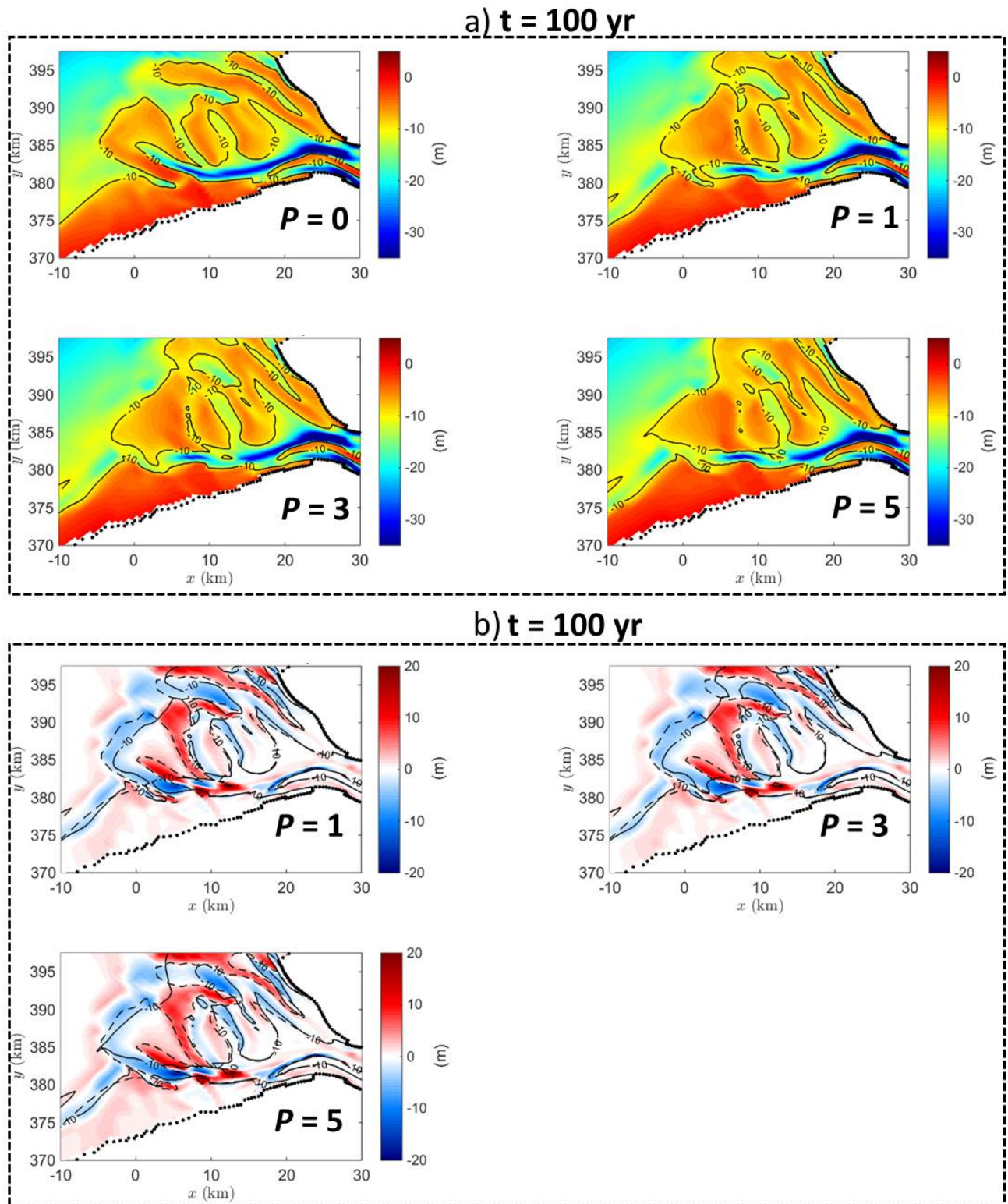


Figure 22 – Same as Figure 20, but in case of adding extreme wind events.

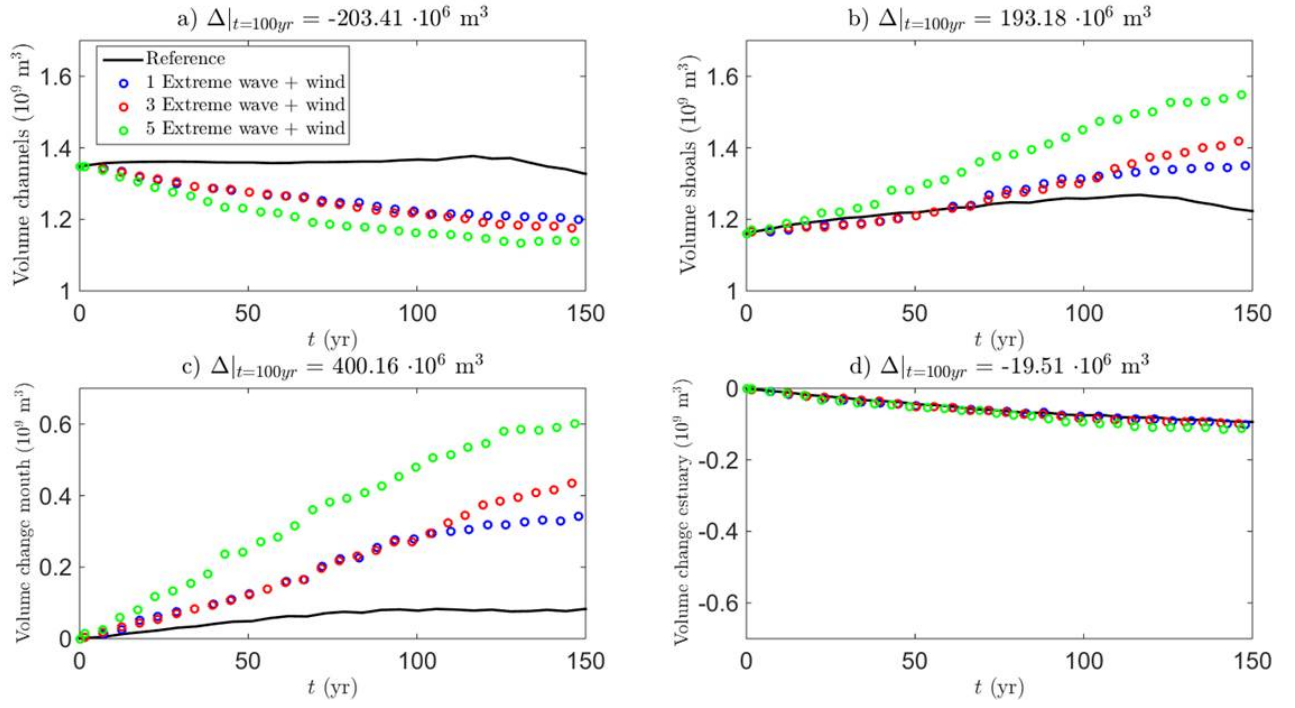
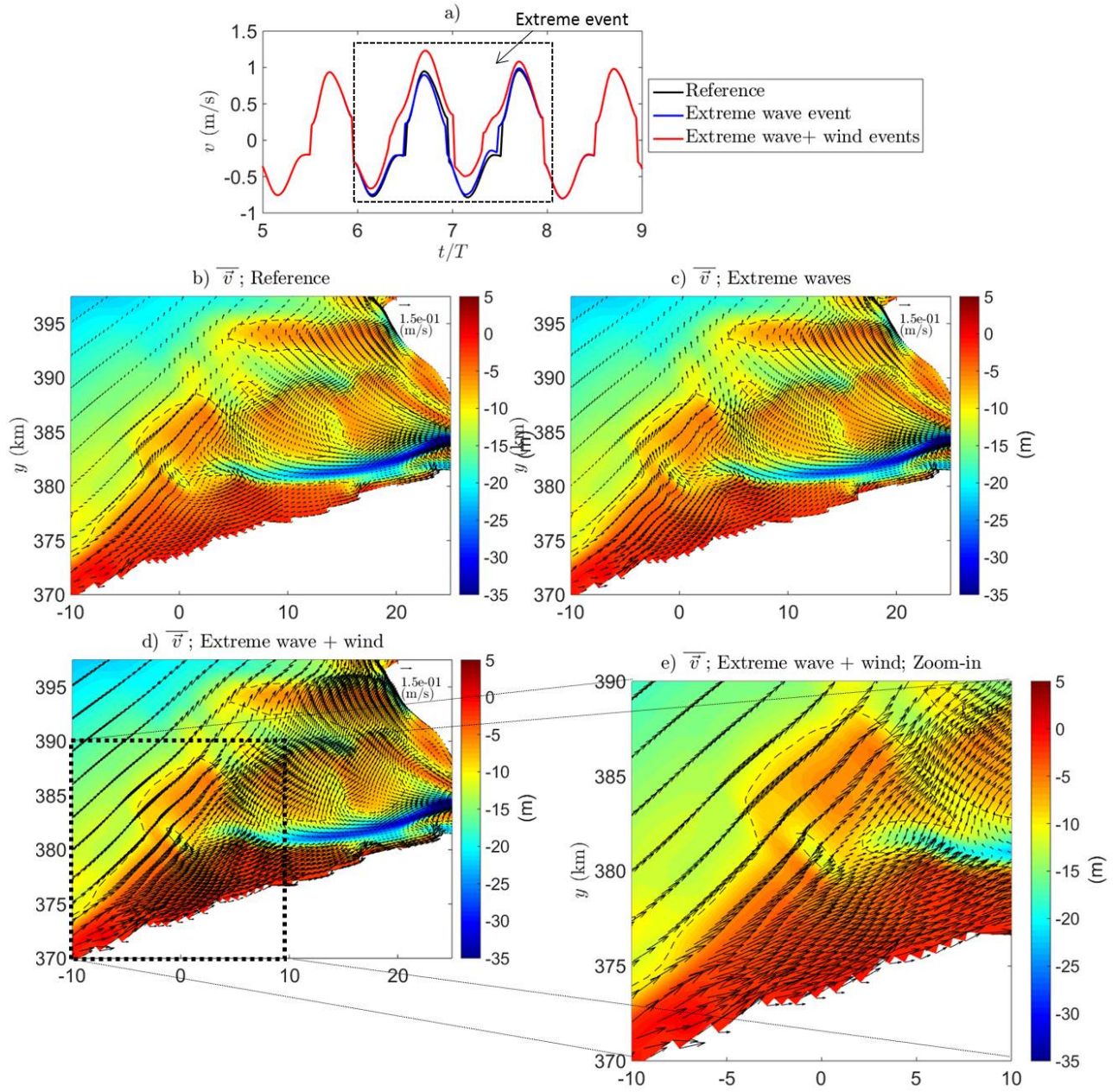


Figure 23 – a) Modeled velocity v versus time at station Deurlo in the reference case (black), in the case with one extreme wave event (blue), and in the case with one extreme wave and wind events (red). b-d) Comparison of bedlevels z_b (colors) and residual velocities $\bar{v}$ (arrows) in the mouth area at the start of the simulation between the different cases.



A zoom-in on the coastal area in case of extreme wave and wind events is shown in panel e. Time in panel a is scaled by tidal period T . Overbar indicates averaging over T .

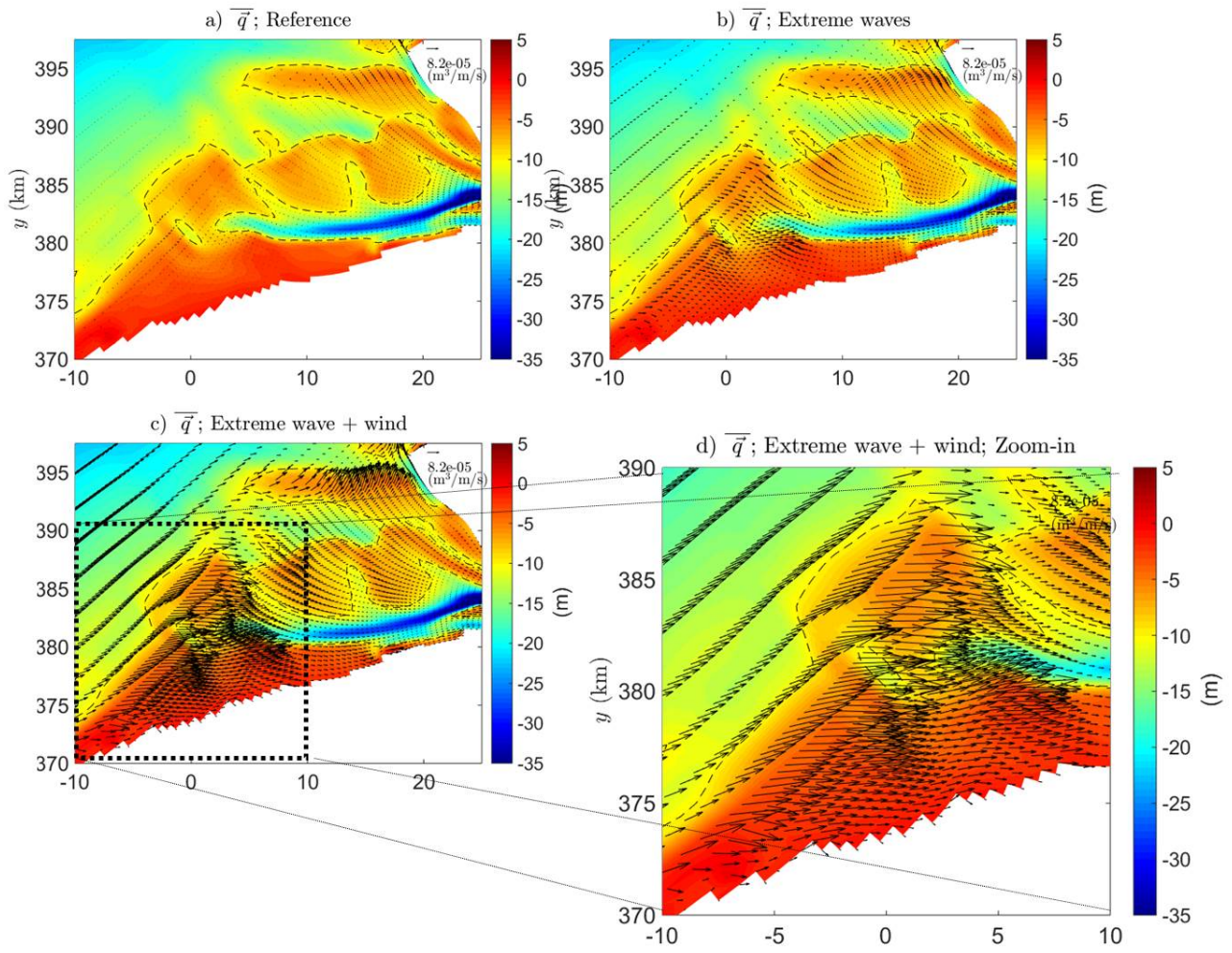
Figure 24 – Same as Figure 23, but showing residual sediment transport $\bar{q}$.


Figure 25 – a-b) Simulated bed levels in case that extreme wave and wind events have a different chronology of appearance ($P = 3$ events per 10 year).

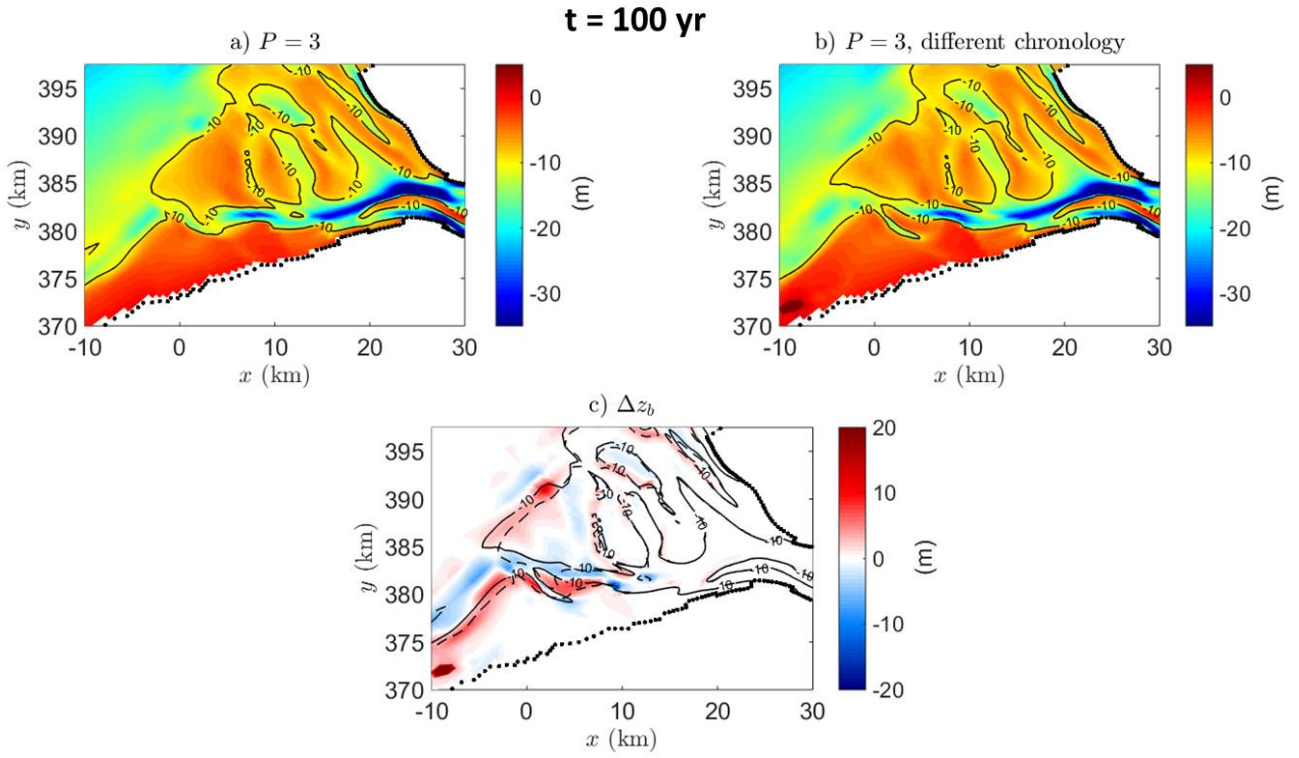
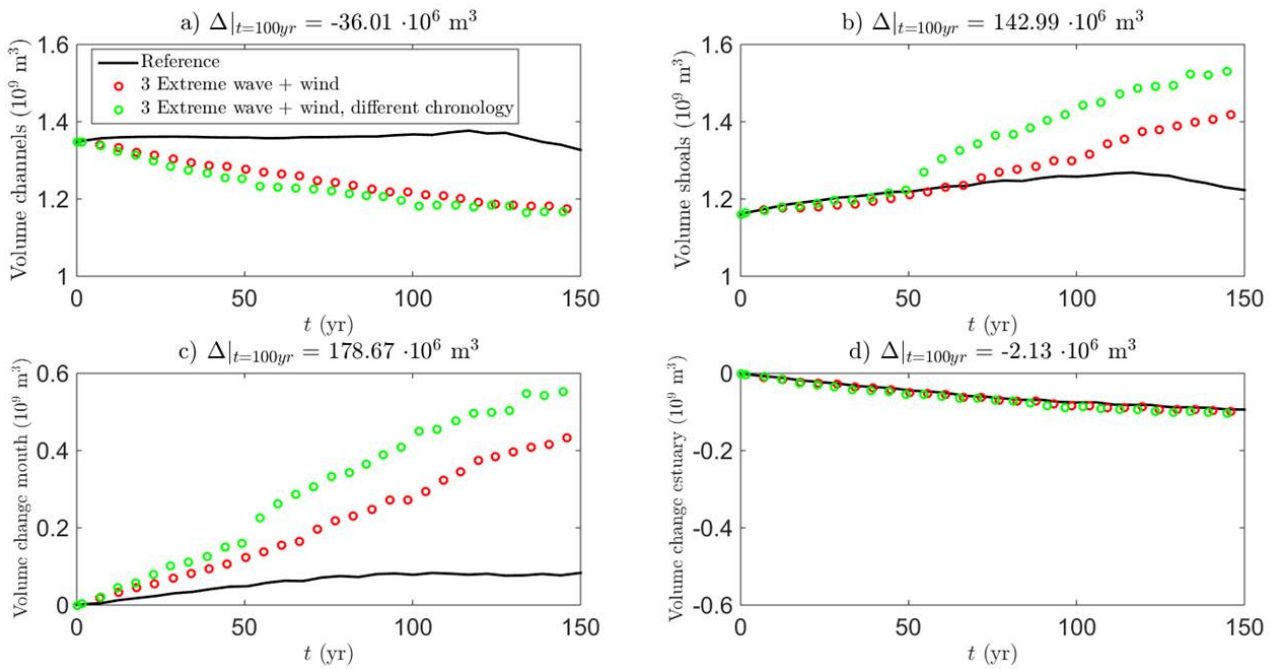


Figure 26 – Same as Figure 18, but including the case that extreme events have a different chronology of occurrence (green).



Values $\Delta|_{t=100yr}$ indicate volume differences at $t = 100$ yr between the cases of different chronology of the extreme events (green and red).

Figure 27 – Same as Figure 25, but comparing the simulated bedlevels between cases without and with wave growth by wind.

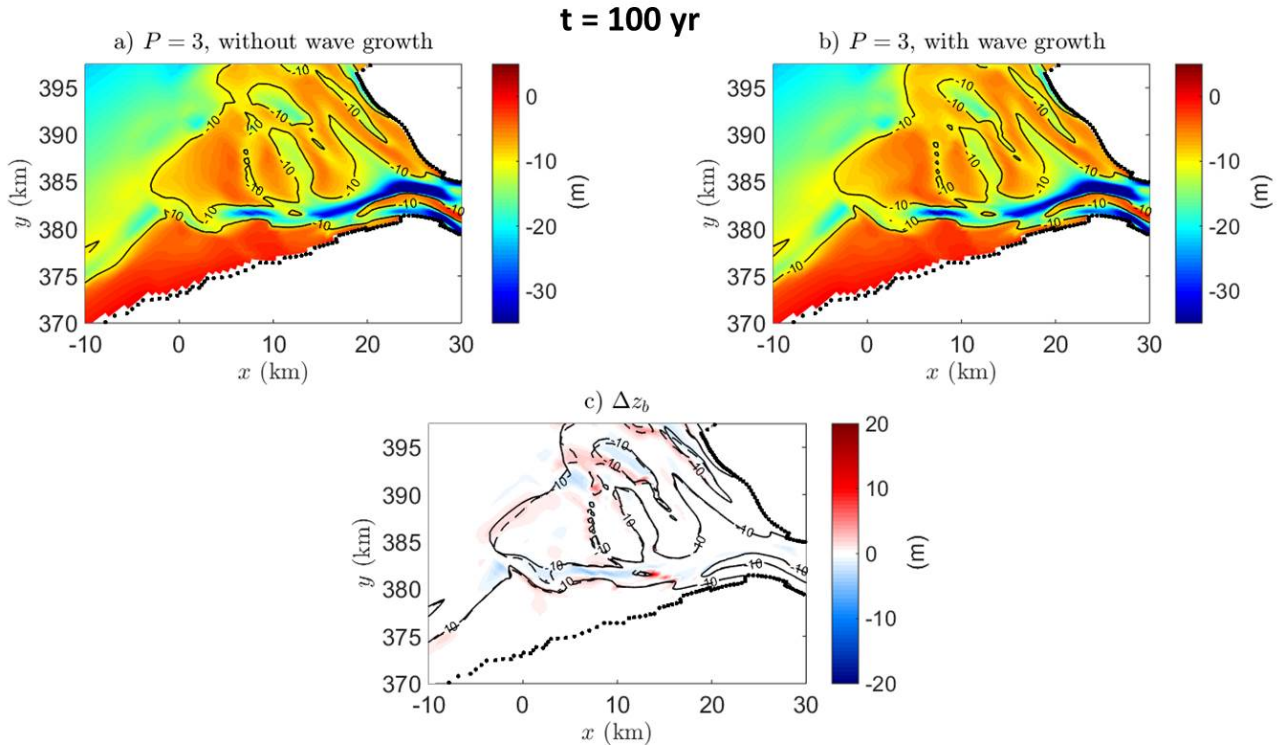
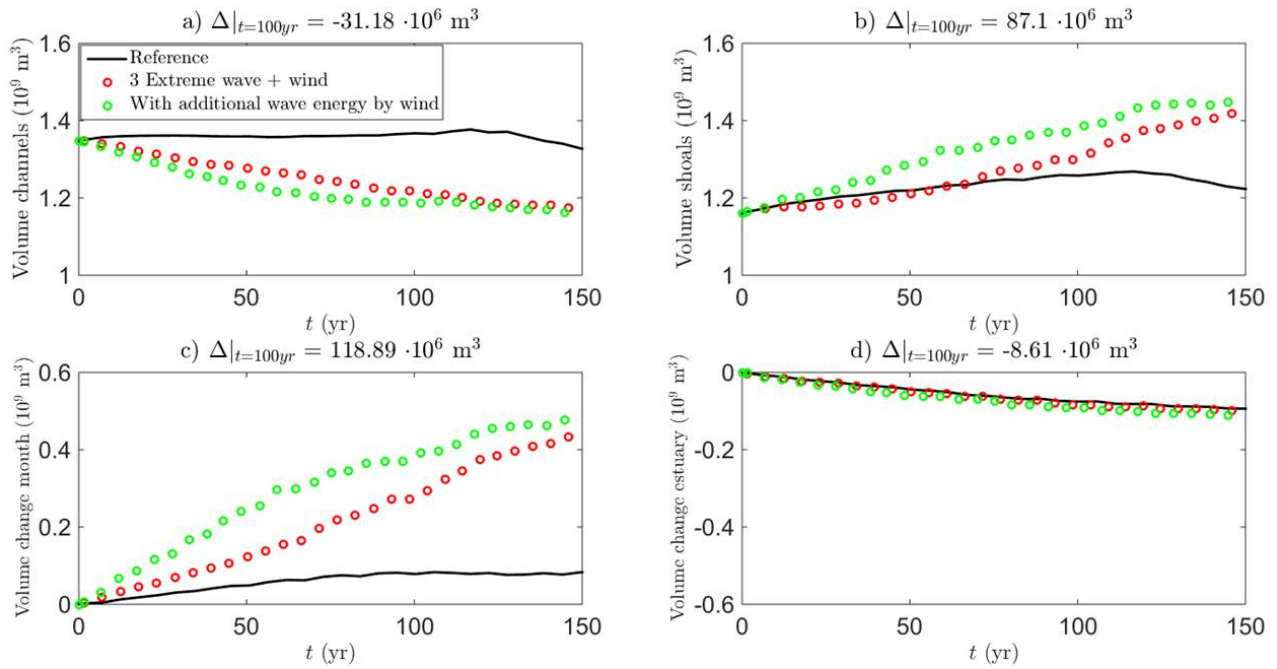


Figure 28 – Same as Figure 18, but including the case with additional wave energy input by wind (green).



Values $\Delta|_{t=100 \text{ yr}}$ indicate volume differences at $t = 100 \text{ yr}$ between cases with and without additional wave energy generation by wind (green and red, respectively).

Figure 29 – Same as Figure 25, but comparing bedlevels between cases of morfac values of 10 and 1.

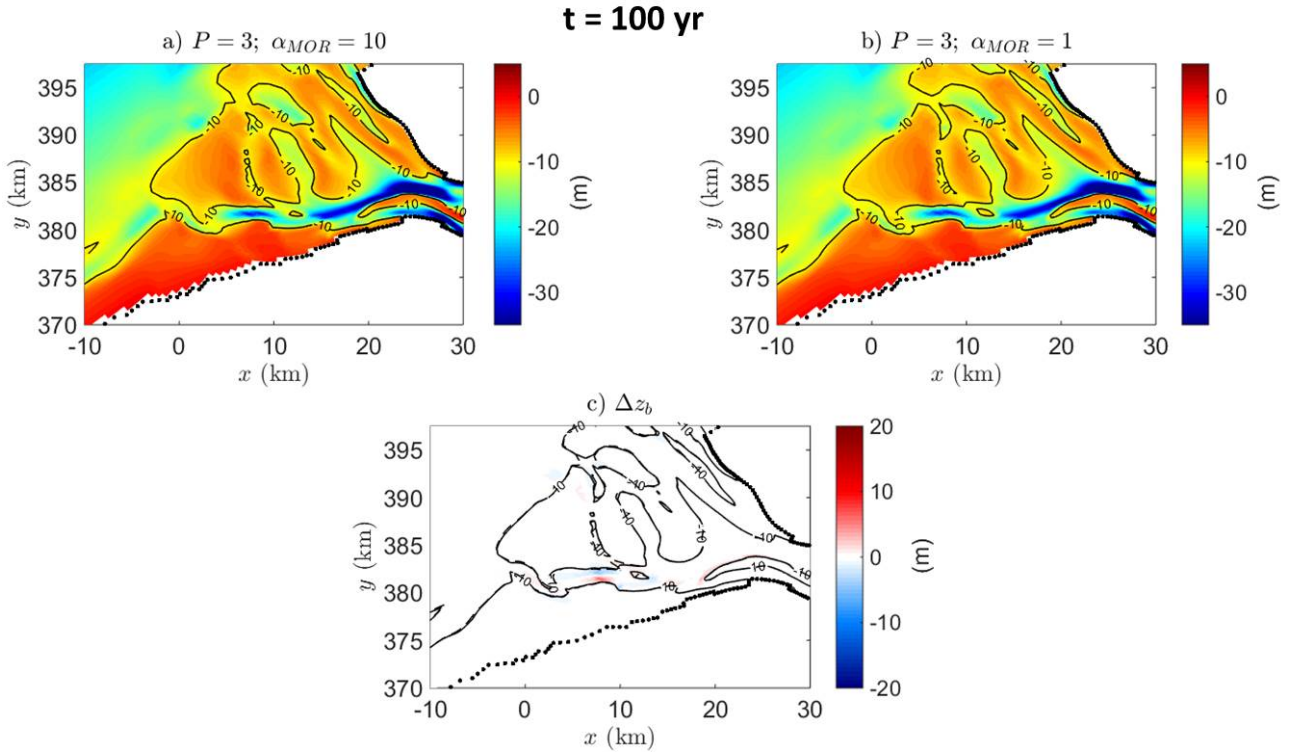
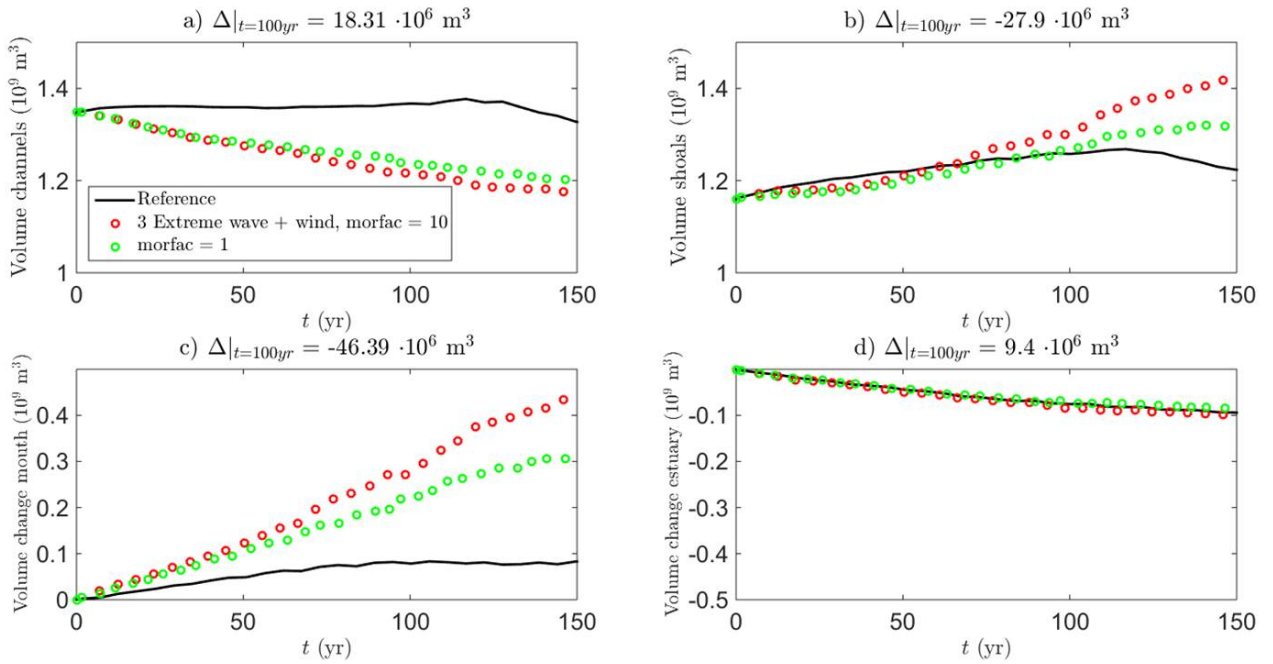


Figure 30 – Sames as Figure 18, but including the case of morfac = 1 during extreme events (green).



Values $\Delta|_{t=100 \text{ yr}}$ indicate volume differences at $t = 100 \text{ yr}$ between cases with morfac = 1 and morfac = 10 (green and red, respectively).

5 Summary and conclusions

The specific aims of the present report were twofold. The first was to investigate effects of extreme wave and wind events (including their relative importance) on the morphodynamic evolution of shoals and tidal channels. Specific focus was on the impact of these events on time evolution of volume of channels and shoals. The second objective was to examine sensitivity of model results to the number and chronology of extreme events.

As a first step, wave and wind data collected in the Scheldt mouth area between 2003 and 2015 were analyzed, from which wave and wind characteristics were derived during average as well as extreme conditions. Based on these data, the probability of occurrence (P) of extreme wave and wind events was estimated to be roughly 3 and 1.5 events per 10 year, respectively. As a climate forcing in the model, the MATLAB intrinsic random function was used to generate wave and wind time series with a length of 500 years, consisting of average wave and wind conditions and a random ordering of alternating extreme events, with the latter having a probability $P = 3$ events per 10 year. Other wave and wind time series with smaller and larger values of P were also considered. Extreme wave and wind events were assumed to occur at the same points in time. Next, starting from an initially flat bed, a spinup experiment was run with only climate average conditions. Finally, the obtained bathymetry from the spinup experiment after 300 years was used as an initial bathymetry in subsequent runs that consider extreme wave and wind events.

Model outcomes show that the joint action of both extreme wave and wind events causes an increase of sand volume of the mouth area, thereby leading to increased sand gain by shoals (i.e., higher shoals, in the order of 0.1 cm per year) and increased infill of channels (i.e., shallower channels, in the order of 0.1 cm per year), particularly in the offshore part of the mouth area. These volume changes are larger with increasing values of P . Also, the offshore parts of channels tend to migrate with the addition of extreme events. Increased shoal volume and channel infill also occurs in case of only extreme wave events, but these volume changes are much smaller than those in case that both extreme events are present. The Western Scheldt estuary experiences relatively minor changes in its sand volume. Analysis of the residual velocity and sediment transport fields in the mouth area reveals that particularly in the case that both extreme wave and wind events are present in the climate forcing, strong residual currents (tidal currents reinforced by storm-driven currents) are generated offshore of the mouth area, which are predominantly alongshore aligned in the northeastern direction. The increased sediment resuspension in the water column by strong wave action, which is subsequently transported by strong currents, causes a large transport of sand from the southern North Sea to the mouth area. The relatively smaller volume changes that occur in the mouth area in case of only extreme wave events is because the resuspended sediment in the water column due to increased wave action is transported by relatively weaker and more rotary tidal currents.

Results further show that a different chronology of extreme events influences morphodynamic evolution of the mouth. However, the tendency of channel infill and sand gain by shoals in the mouth area with sand that is imported from the North Sea remains qualitatively the same. In case of including additional wave growth by wind, wave action during extreme wave events becomes stronger, and thus more sediment is resuspended in the water column, which is subsequently imported into the mouth area, resulting in enhanced infilling of channels and sand gain by shoals.

Due to longer computation times in the case of extreme wave and wind events compared with the case of only average climate conditions, resulting from the use of a variable morphologic factor in

the former case, the question rises to what extent the inclusion of these events is crucial when modeling the morphodynamic evolution of the mouth area. Although extreme events cause shallower channels and higher shoals, the overall changes are in the order of 0.1 cm per year, which seem to be small. Moreover, the overall morphologic patterns that evolve in the presence of these events are not fundamentally different from those in case without, suggesting that inclusion of these events is not crucial. From a small-scale morphodynamic point of view, however, the inclusion of these events might have a significant impact on model results, as is demonstrated by De Maerschalck *et al.*, 2016, in their study of the long-term evolution of a new navigation channel in the Scheldt mouth area. Therefore, when modeling the morphodynamic evolution of the mouth area, it is recommended to examine at least the impact of one single extreme event on model results by conducting a limited set of additional model runs.

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