Scaldis Coast: Numerical modelling of 10 years for long-term morphology in the surf zone of the Belgian coast using the TELEMAC-MASCARET system

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***Abstract* – With the increasing awareness of sea level rise, the Flemish Authorities initiated the *Complex Project Kustvisie* (CPKV) in order to start to define the overall long-term coastal defence strategy for the Belgian Coast together with all involved stakeholders. A flexible coastal model for the Belgian coast and Scheldt mouth area is needed to analyse the impact of sea level rise on the morphology of the coast, and to assess the efficiency of mitigation measures. An integral morphodynamic model for the whole Belgian Coast including the Western Scheldt mouth was built within the TELEMAC- MASCARET models suite.**

Keywords: Coastal modelling, Coastal protection, sediment transport

I. INTRODUCTION

The simulation of the long-term evolution of hydrodynamics and morphodynamics by state-of-the-art numerical modelling tools can give an important contribution to the strategic decision-making for the protection of the Belgian Coast from the climate change hazards. The SCALDIS-COAST model, developed in the present study, aspires to become a valuable tool for the assessment of potential coastal protection measures by predicting the morphological behaviour of the coast driven by the coupled action of currents and waves.

II. SCALDISCOAST

A. Model setup

The model covers the entire Belgian coast and Scheldt mouth area, including the Dunkirk coast, a part of the Dutch coast and the Eastern Scheldt, Figure 1. In order to model the tidal wave propagation correctly, the Western Scheldt is included and the upper part of the Sea Scheldt and its tributary are modelled schematically.

The computational grid is constructed by use of an advanced finite element mesh generator GMSH [4]. The mesh generator does not only allow for an automatic refinement in the vicinity of complex geometries, but also at steep gradients in the bathymetry. This way steep banks, gullies and navigation channels are accurately and efficiently represented in the model, Figure 2. The model resolution reaches from 750 m offshore to 25 m along the Belgian coastline. The resolution in the Western Scheldt estuary varies between 125 to 225 m. In total, the computational mesh consists of 250 000 nodes connecting around 500 000 triangular elements. Along the coastline, the grid is aligned to the crest of the groins which are represented in the bathymetry in combination with a hard layer to prevent the erosion of these structures.

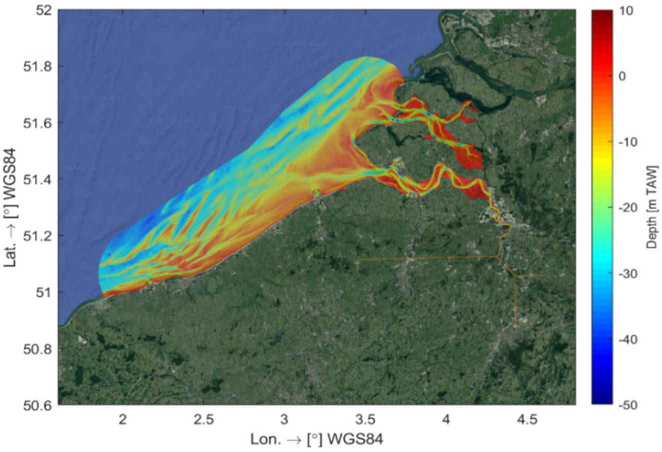

Figure 1. Domain and bathymetry of the Scaldis-Coast model

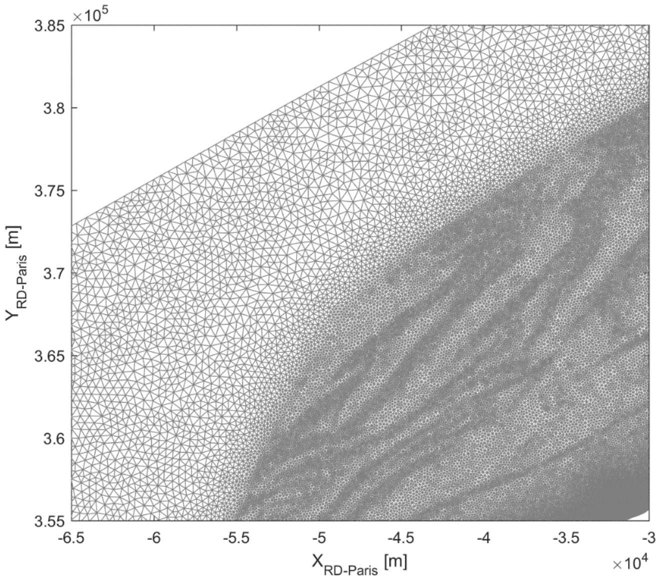

Figure 2. Detail of the mesh: Coarse elements are used offshore and automatic grid refinement is used along the steep bathymetry gradients at the Flemisch banks in the zone of interest

B. Tidal modelling

Water levels and currents are resolved by TELEMAC-2D. Originally the model was built within version v7p2r2, but recently all modules have been updated to v8p4. The offshore boundary conditions of the Scaldis-Coast model come from the regional ZUNOv3 [8] model of the southern North Sea through nesting. Specifically, the nesting procedure consists of numerical simulations conducted at two levels: First a continental shelf model (CSM) is run in order to provide the boundary conditions of the second-level nested model (ZUNO), which includes the southern North Sea and the Channel. The model is forced by 10-minute time series of the water level and velocities calculated by the ZUNOv3 model. The subroutine *bord.f* of TELEMAC was modified properly to allocate water level and velocity values for each boundary node separately. At the upstream boundaries, measured flow discharges at eight tributaries and channels are imposed. For the wind forcing, the measured wind times series at the offshore measurement station *Westhinder* (located at the offshore boundary of the model) was applied uniformly over the model.

The TELEMAC-2D model is validated against 25 tidal gauges along the Belgian coast and Wester Scheldt estuary, eight stationary velocity measurement station, and five sailed ADCP transects: in the vicinity of Zeebrugge port and the fairways, as well as along the Western Scheldt. It was found that the model performs well using a constant bed roughness coefficient (Manning's law) of 0.022 $m^{1/3}/s$. Only in the upper part of the Estuary, the coefficient is gradually reduced to 0.012 $m^{1/3}/s$ and an increased value is applied at the upstream schematized part of the model (0.04 $m^{1/3}/s$).

The RMSE of velocity magnitude is in general around 0.15 m/s. However, the peak flood velocities seem to be underestimated in some of the considered locations.

C. Waves

The wave propagation and transformation from the offshore boundary towards the coast under the influence of tides and wind is modelled using the TOMAWAC module. The waves have a major impact on the coastal morphology of the foreshore and beach. They drive the littoral transport through wave induced currents and steer the sediment up. The wave asymmetry and wave-skewness, Stokes drift, undertow and surface rollers are the main mechanisms for cross-shore sediment transport. In order to include the effect of tide on wave propagation, the TOMAWAC model is coupled to the TELEMAC-2D hydrodynamic model which provides, the water depths and tidal currents. The coupling is a two-way coupling so that TELEMAC-2D on its turn can calculate the wave driven currents.

Computationally, the wave transformation model is by far the most CPU time demanding module, and therefore one of the major limiting factors for long term morphodynamic model runs. Therefore, within the project a module TEL2TOM was developed to couple TOMAWAC with TELEMAC-2D on arbitrary meshes [1]. For the TOMAWAC run, the resolution was reduced by a factor two in the nearshore from 25 m to 50 m, and major parts of the Western and Eastern Scheldt estuaries were omitted. The total number of nodes is reduced from 273 000 to 138 000 nodes and the number of triangular elements from more than 500 000 to nearly 260 000, Figure 3. This way, the computational cost has been reduced by a factor two. For the wave propagation model a time step of 120 seconds and a coupling time with TELEMAC-2D of 30 minutes was used.

The wave boundary conditions are derived from the offshore measurement station Westhinder, which is located on the model boundary. Westhinder is a fixed measurement station part of the monitoring network Flemish Banks (Meetnet Vlaamse Banken, MVB). A JONSWAP spectrum based on the significant wave height, peak wave period and wave direction is applied uniformly on the off-shore boundary. The measured wind speed and direction at Westhinder is applied uniformly over the entire domain.

The wave model was validated against the data obtained within the Broersbank project [7]. In the Broersbank project, wave data was sampled at seven locations during the period between 2013 and 2017, Figure 4. The temporal resolution of the wave data reaches thirty minutes. The other six stations are temporary wave buoys placed for the duration of the Broersbank project. Since they are inside the model at different distances from the coast, they are particularly useful in validating the modelled wave propagation and transformation. For the validation, a seven-day period in November 2015 was selected including two storms, one from the Southwest on November 18, and one from the North on November 21.

The transformation of the significant wave heights and mean wave period from offshore boundary station, Westhinder, to onshore, BRB1GB, are shown in Figure 5 and Figure 6. For comparison both the TEL2TOM coupling and the one-to-one fully coupled version of the model are added to the graph. The wave model predicts the measured wave height and wave period well. The TEL2TOM coupling has hardly any influence on the model quality at the nearshore, even though the resolution is reduced by a factor two.

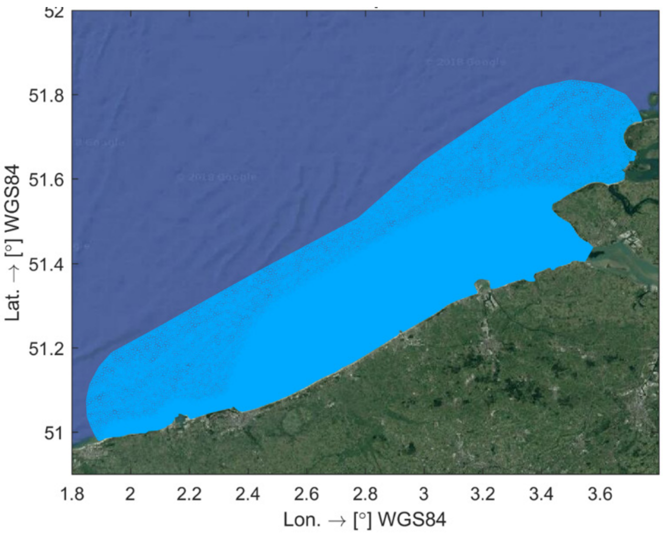

Figure 3. Computational grid of the wave model

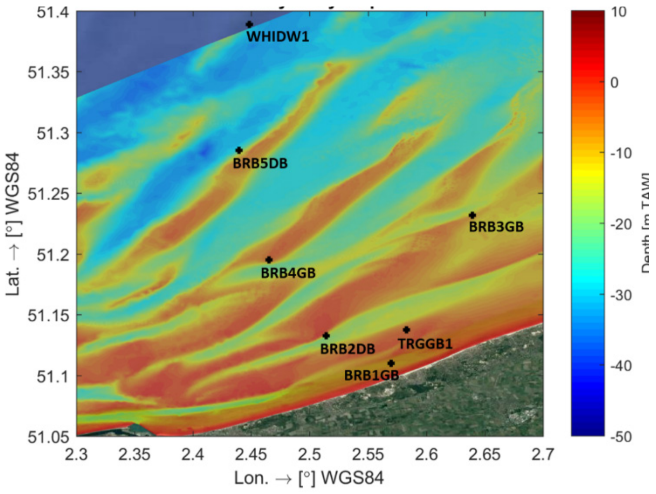

Figure 4. Locations of the Westhinder fixed station (WHIDW1) and the six temporary wave buoys during the Broersbank project.

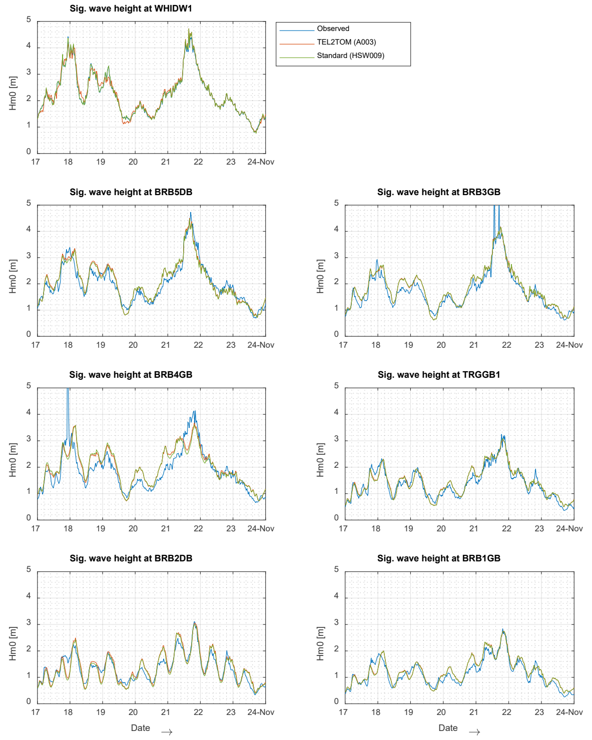

Figure 5. Comparison of significant wave height from offshore to onshore with in blue the observed wave heights, in red the TEL2TOM coupled TELEMAC-2D – TOMAWAC model and in green the standard fully coupled TELEMAC-2D – TOMAWAC model version

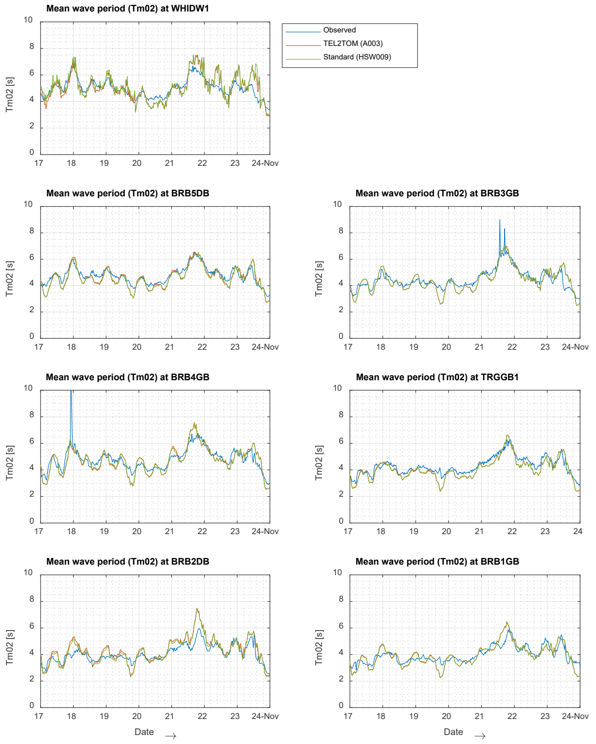

Figure 6. Comparison of mean wave period from offshore to onshore with in blue the observed wave periods, in red the TEL2TOM coupled TELEMAC-2D – TOMAWAC model and in green the standard fully coupled TELEMAC-2D – TOMAWAC model version

D. Sediment transport and morphodynamic model

Finally the TELEMAC-2D hydraulic model and the TOMAWAC wave transformation model are coupled to the sediment transport and bed update model. In the first stage of the project this was the SISYPHE model, recently the model has been updated to GAIA.

An input reduction technique named as 'representative tide' is implemented for the generation of simplified tidal forcing suitable for the long-term morphological simulations using a morphological acceleration factor of 10 to 20 (MORFAC). The reduction of hydrodynamic input data of a tide-dominated numerical model aims to reduce the computational cost by finding a satisfactory way to represent a long tidal period by only one (or a small number of) 'representative' tide(s). The concept of input data reduction in long-term morphological simulations under tidal action followed here, was proposed and successfully implemented by Latteux [7]. According to Latteux, this representative tide must lead to the same elementary (flood and ebb) and residual transport as the actual set of natural tides.

The criterion for the selection of the representative tide of the considered year (2014) is the best agreement between the mean sediment transport, resulting from the tested representative tide and the one from the yearly water level time-series. Specifically, the procedure includes to following steps:

- The coupled hydrodynamic and sediment transport model is run for the considered simulation period of one year, imposing a frozen bottom, i.e. no bed updating.
- The two components of the sediment transport rate, Q_x and Q_y (x and y directions) are calculated at every single node of the domain and summed at every time-step of the calculation.
- The two components of the mean sediment transport rate, Q_{xmean} and Q_{ymean}, are calculated by averaging the instantaneous sediment transport rates for each set of two consecutive tidal cycles covering the full year 2014.

Finally, the set of two tides which best represents the magnitude (lowest RMSE) and the patterns (high correlation) of each of the yearly mean Q_x and Q_y components is selected. Note that two consecutive tides were chosen, because of the daily inequality in the tide, which lead to difference in the low water levels between two consecutive tides. This difference is less between the first and last low water in the selected period.

Generally, analogue to the input reduction for the tide, also the wave input is reduced to a limited set of representative wave conditions in morphodynamic modelling. This is to allow a higher morphological acceleration factor necessary to simulate a long term morphodynamic evolution. The waves have a major impact on the shallow near- and on-shore bed evolution. The Belgian coast is characterised by a mean littoral transport from west to east. The annual alongshore transport will be used as validation parameter for the representative wave climate, i.e. the annual longshore transport modelled by a representative wave climate should be in close agreement to the brute force long term mean longshore transport.

At first, a limited set of schematized wave conditions based on equal wave energy was derived from the measured wave data at Westhinder for a one-year period 2014-2015 and applied as boundary condition [6]. It was shown that the limited set of schematized wave conditions gave a similar annual net longshore transport for the selected period 2014-2015 as the full year timeseries of waves. However, when applying the method in the model to a pre-selected representative one-year period for which the derived schematized wave conditions were similar to the schematized ones obtained from a 10-year times series, it turned out the schematized wave conditions did not give the same annual net transport as the one-year timeseries. From this result, it was concluded that the method was not applicable for the Scaldis-Coast model. The main reason for this is that due to the size of the model, the wind generated waves inside the model, especially during western winds, are dominating the littoral transport. When reducing the wave input, a corresponding reduction of the wind input was needed as well.

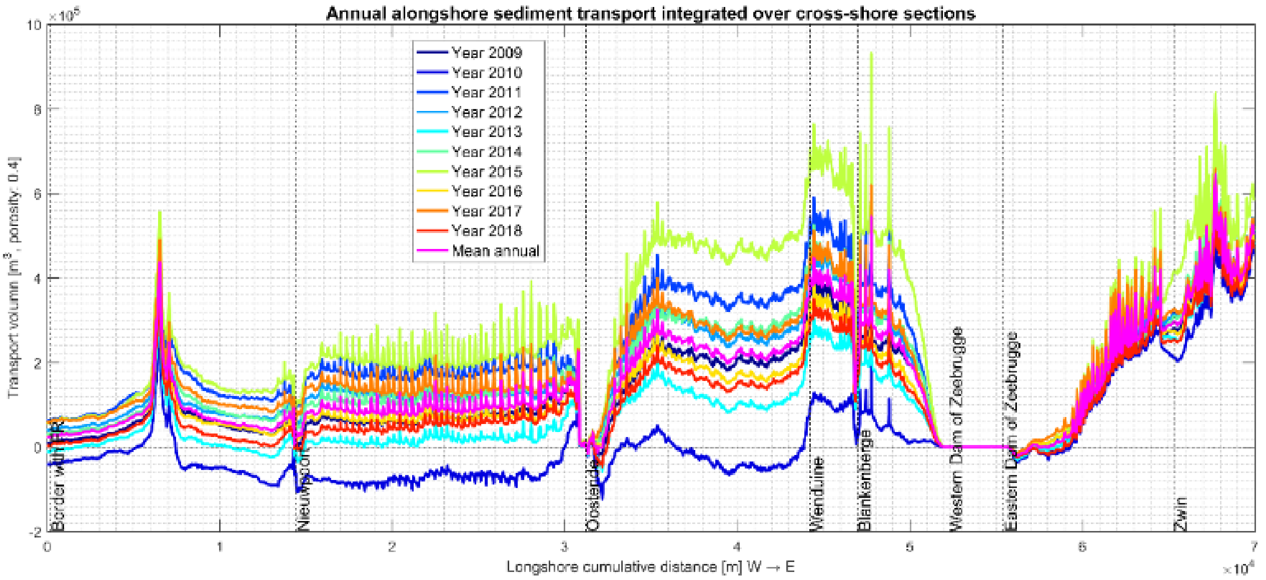

Figure 7. Modelled annual longshore transport rates along the Belgian coastline for ten consecutive years 2009-2018 with in cyan the mean transport rate over the 10-year period

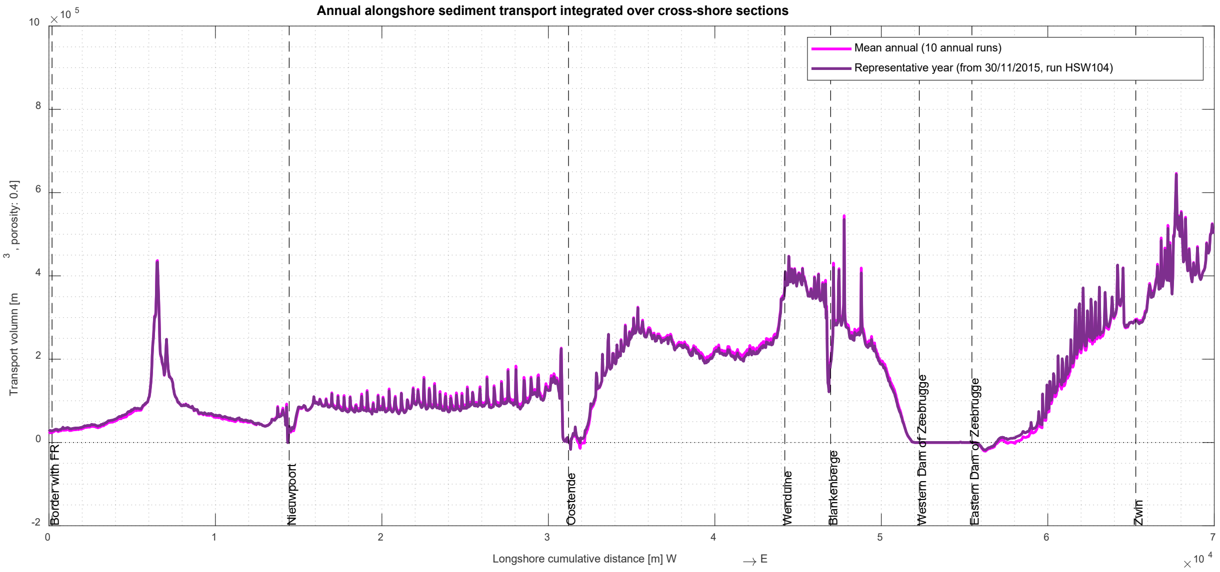

Figure 8. Comparison of the annual mean longshore transport of the brute force 10 year simulation (cyan) and for the representative year (purple)

However, it turned out that is was not appropriate to assume an identical direction for the wave and wind conditions in this study.

Therefore, the model was run for 10-year brute force wind and wave conditions, and the mean annual net alongshore transport was derived, Figure 7. Next, a continuous period of one year observed wave and wind boundary conditions was selected, which represented the long term annual mean longshore transport best, namely November 2015 - November 2016, Figure 8. This period is called the representative year. For the morphodynamic runs, a MORFAC 10 is applied to the one year run in order to model the bed evolution over a 10 year period. In a later phase, the method is repeated to determine a representative half year period, which is applied in combination with MORFAC 20 to simulate a 10 year period.

Different transport formulas and settings have been extensively tested. To evaluate the performance of the model a hindcast of the bed evolution after the extension of the outer port of Zeebrugge in 1986 has been used as testcase. Transport formulas that have been tested were Engelund & Hansen [3], which accounts for steady currents, and formulas that can account for coupled wave- and current-induced transport, i.e. those of Soulsby- Van Rijn [10], Van Rijn 2007, (which was specially implement for the use in this project) [12] and Bijker [2].

The Engeland & Hansen formula tends to perform well at those locations with a tidally driven bed evolution, but does not take the effects of waves on the sediment transport into account, which is crucial in the near-shore area and the shallow areas like *Vlakte van de Raan* in the Scheldt mouth area. The Soulsby-Van Rijn and Van Rijn 2007 formulas tend to overestimate the magnitude of the morphological patterns substantially at deeper areas. Bijker's formula presents many similarities with the formula of Engelund & Hansen, but is also capable of reproducing the morphological patterns close to the coastline when the wave effects are taken into account. Therefore the Bijkers formula was selected as a compromise between the tidally driven off-shore bed evolutions and the nearshore wave driven morphodynamics. The transport formula was further improved by:

- Replacement of the default wave-current bed shear stress, τ_{cw}, formula in Bijker's transport formula with the τ_{cw} formula proposed by Soulsby [10], known as the DATA2 method and based on a fit to laboratory and field measurements:

$$\tau_{cw} = \tau_c \cdot \{1 + 1.2[\tau_w/(\tau_c+\tau_w)]^{3.2}\} \qquad (1)$$

  with τ_c the current shear stress and τ_w the maximum wave shear stress.

- Replacement of the default (fixed) breaking wave parameter (b) in the Bijker's transport formula with a spatio-temporal varying expression that depends on the wave height and water depth ratio H_w/h (Bijker, 1971):

$$\begin{aligned} b &= 2 \;,\; H_w/h < 0.05 \\ b &= 2 + 3(H_w/h - 0.05) \;,\; 0.05 \le H_w/h < 0.4 \qquad (2) \\ b &= 5 \;,\; 0.4 \le H_w/h \end{aligned}$$

- Minimum depth for bed load equal to 0.1 m (instead of 0.01 m)

The concept of the active bed layer with two sediment classes (200 and 500µm) is applied to mimic a spatially varying grainsize. Briefly, the steps followed for the calculation of bed morphology evolution, in case of sediment mixtures, are:

- Sediment transport rates are computed separately for each class by use of one of the provided bed (or total) load transport formulas
- The Exner equation is solved for each sediment class
- The total bed evolution is calculated by summing the individual bed evolutions of each class

- At the end of each time-step the new bed composition of the active layer is computed, ensuring the mass conservation of each class. The new composition is simply calculated based on the ratio of the evolution of each sediment class over the total evolution within one time-step.

However, in order to achieve a spatially-varying d_{50} transport calculation in the ScaldisCoast model, the concept of equivalent sediment transport is implemented. The number of classes in the active bed layer is limited, in this case to two classes, a fine and a coarse class, even though the Continental Shelf is characterized by a broad range of classes. The initial composition of the active layer is calculated in such a way that the total transport of the two classes togethers is equivalent to the transport rate of the actual in situ d_{50} grain size.

Furthermore, the formula for deviation (correction of sediment transport direction due to slope effect) by Talmon et al. (1995) is used instead of the default one (Koch and Flokstra [5])

$$\tan a = \tan \delta - T(\partial Z_f / \partial n) \tag{3}$$

$$T = 1/(\beta_2 \sqrt{\theta}) \tag{4}$$

with β_2=0.85, a is the direction of bed load transport with respect to the flow direction, δ is the direction of bottom shear stress with respect to the flow direction, Z_f is the bed level, n is the coordinate along the axis perpendicular to the flow and θ the Shields number, i.e. the dimensionless shear stress as a combination of the current shear stress and the maximum wave shear stress:

$$\theta = \theta_c + 0.5\theta_w \tag{5}$$

III. CALIBRATION AND VALIDATION

A. *Calibration test case: Hindcast port of Zeebugge*

For the calibration of the model the 10 years bed evolution after the extension of the outer port of Zeebrugge was used. The extension of the port was finished in 1986. By that time the port was extended about 3 km seaward. In the decades after the extension, severe erosion took place northwest and north of the breakwaters and along the fairway to the port, *Pas van het Zand*. The eroded sediments are mainly deposed at the shallow bank east of the port: *Paardemarkt*, and just east of the eastern dam: *Bay of Heist*. Figure 9 shows the observed sedimentation and erosion patterns between 1986 and 1996.

Figure 10 shows the modelled bed evolution around the port of Zeebrugge between 1986 and 1996. Qualitatively one can notice that the erosion pattern at the entrance of the port (pit) is more or less captured by the model. Strong sedimentation east of the port at *Paardemarkt* (and the surroundings are) is predicted by the model as well. However, the pattern differs from the observed sedimentation and erosion patterns. The strong accumulation of sediments at Bay of Heist, in the axillary between the eastern dam and the beach, is not observed in the model. Instead, the sediment tends to accumulate a bit more off-shore east of the eastern harbor breakwater. This has been observed in other models in the past as well [13]. This discrepancy can be attributed to possible differences in the composition of the transferred material, which in reality contains a large fraction of mud, which is currently missing in the model. In Figure 10 accumulation of sand can be observed in the fairway to the port, Pas van het Zand, and the channel towards the Scheldt estuary. This is because no dredging is included in the hindcast. The maintenance dredging of the channels has been added later on to the model for simulation of the present conditions using the Nestor module. A quantitative comparison between the observed and modelled volume changes in the surrounding of the port is made in Table I. The predicted volumes correspond well to the observed values for the erosion areas, but the volume deposited on the east is captured a bit worse by the model.

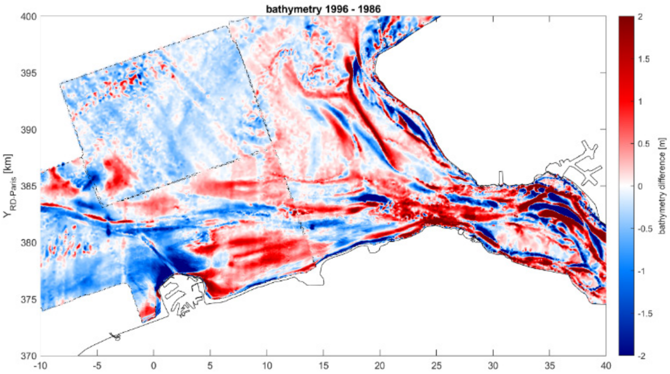

Figure 9. Bathymetric evolution in the first decade after the extension of the outer port in 1986

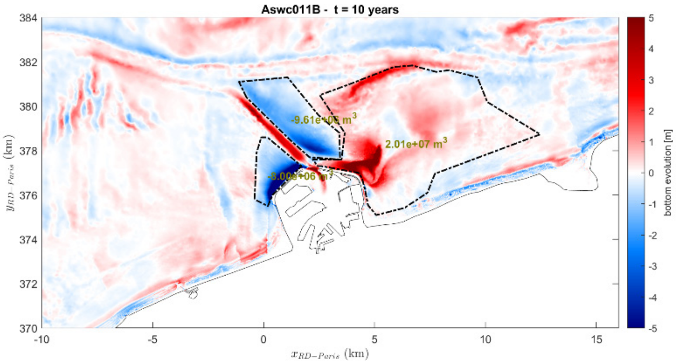

Figure 10. Modelled bed evolution 1986-1996

Table I Observed and modelled volume changes in the polygons of Figure 10

Polygon	**Volume change 1986-1996 (10^6 m³)**	
	Modelled	***Observed***
Erosion area western breakwater	-8.0	-7.4
Erosion area East of the entrance channel	-9.6	-9.0
Sedimentation zone east of the port	+20.1	+14.5

B. *Validation case: Ciara winter storm February 2020*

In February 2020 a single storm event caused an instantaneous sedimentation of the Blankenberge marina access channel. For the preparation of the regular dredging works planned at the end of the winter, the marina entrance and foreshore were surveyed on February 6th, which is only three days before the storm. Shortly after the storm, on February 14th, the survey was repeated, Figure 11. Together with the hydrodynamic and meteorologic measurements of Meetnet Vlaamse Banken, this forms a valuable dataset for model validation.

For this case the model is driven by hydrodynamic boundary conditions from the regional ZUNO model [8]. Wave and wind boundaries are taken from the measurement station Westhinder and applied to the model. No extra model calibration or refinement of the mesh in the vicinity of the marina entrance channel was done, Figure 12.

The pre- and post-storm bathymetric surveys allow to accurately calculate the bed evolution during the storm event. The observed and modelled bed evolution are compared in Figure 13. The sedimentation-erosion patters not only show a good qualitative agreement, but also quantitative there is a good agreement: 44 200 m³ modelled sedimentation versus 43 800 m³ observed. It is understood that the sedimentation of the channel is mainly driven by the littoral alongshore transport. The case shows that the model is capable of representing alongshore littoral transport processes accurately.

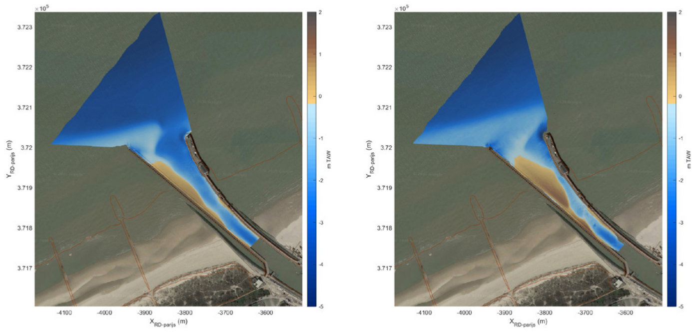

Figure 11. Pre- and post-storm bathymetric surveys

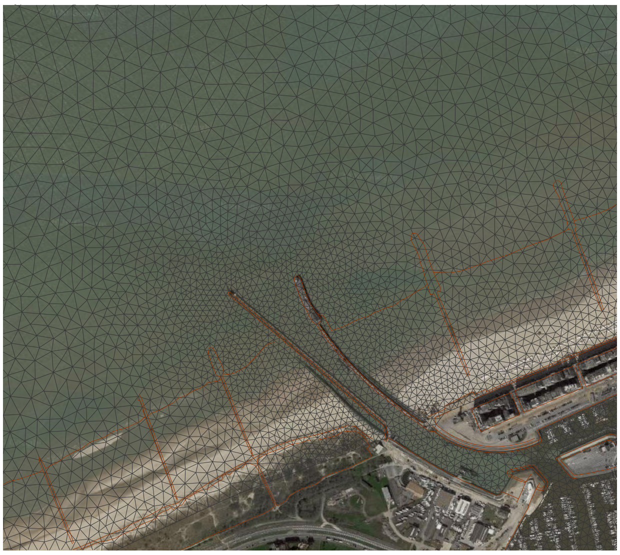

Figure 12. Detail of the ScaldisCoast mesh at the Blankenberge marina entrance channel

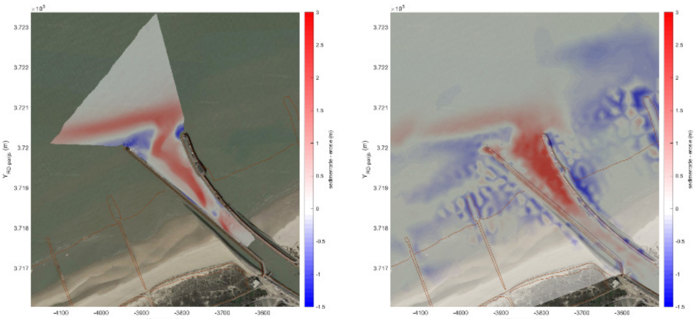

Figure 13. Observed (left) and modelled (right) bed evolution of the Blankenberge marina entrance channel during storm Ciara February 2020

IV. CONCLUSIONS AND FURTHER RESEARCH

An integral morphodynamic model was built for the Belgian coast. The model is capable of modelling long term, decadal scale, bed evolutions, but single storm events are also represented well in the model, at least when the morphological processes are mainly driven by longshore transport processes.

Wave-driven currents are only driven by radiation stresses in the current version of the model. Stokes drift, as well as effects of wave asymmetry and boundary layer streaming are not modelled. This means that the model misses cross-shore processes. The implementation of cross-shore processes is currently under investigation based on the work in [14,15]. The main transport process along the Belgian coast is the longshore transport from west to east. However, cross-shore processes do play a role during storm events and for the long-term natural feeding of the beach during periods of mild wave conditions. Notice however, that the latter are difficult to calibrate because lack of direct and accurate measurements of these processes in situ.

Only sand fractions are modelled. No sand-mud interaction or less erosive clay layers are modelled yet. Mainly in the vicinity of Zeebrugge clay layers are present (Holocene Clay). The extension of the model to sand-mud is another topic of investigation.

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