Improvement of a Continental Shelf Model of the North Sea

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***Abstract*— A continental shelf model (iCSM) was developed in TELEMAC-2D at IMDC. The model domain covers the North Sea, the Irish Sea, the Celtic Sea and the Bay of Biscay. This paper presents the stepwise improvement of the iCSM model. The model predictive skills on water levels are significantly improved with several new features implemented. The averaged root-mean-square-error (RMSE) at the Belgian coast is reduced to 13 cm after calibration. The Storm Xaver in December 2013 is well reproduced. The model also shows good predictive skills on velocities (both stationary and ADCP sailed) near the Belgian coast.**

I. INTRODUCTION

During the past decades the attention to global climate change and its local effects have highlighted the significance of providing accurate information on the natural evolution of coastal hydrodynamics and morphology, human intervention assessment and natural disaster predictions. The Belgian Coastal Zone has important environmental and commercial values due to the presence of large harbours and wind farms. An accurate prediction of the tidal propagation is important for both planning purposes (e.g. coastal zone management) and for the nautical accessibility (e.g. navigation to the harbour of Zeebrugge and the Scheldt river estuary). Process-based numerical models, including the most important processes and parameters for tidal predictions, have been widely adopted for this purpose. The numerical model shall be reliable to perform accurate predictions during normal conditions, in which the main forcing for the water levels and velocities are coming from the tidal wave that enters the North Sea from the Norwegian Sea in the north, with a secondary influence of the tidal wave entering through the Dover Strait from the South. In addition, the model shall also be able to produce adequate predictions during extreme conditions when strong winds and large atmospheric pressure gradients are present.

A continental shelf model (iCSM) was developed in TELEMAC-2D at IMDC [1]. The model generally showed decent tidal propagations in the North Sea, albeit room for further improvement was possible along the coast of the Southern Bight, in particular in the Belgian Coastal Zone. This paper presents the stepwise improvement of the iCSM model by including several relevant physical processes and improving the model parameter calibration. The model predictive skills on both water levels and velocities are significantly improved.

II. MODEL SETUP

The iCSM domain covers the North Sea, the Irish Sea, the Celtic Sea and the Bay of Biscay (Figure 1).

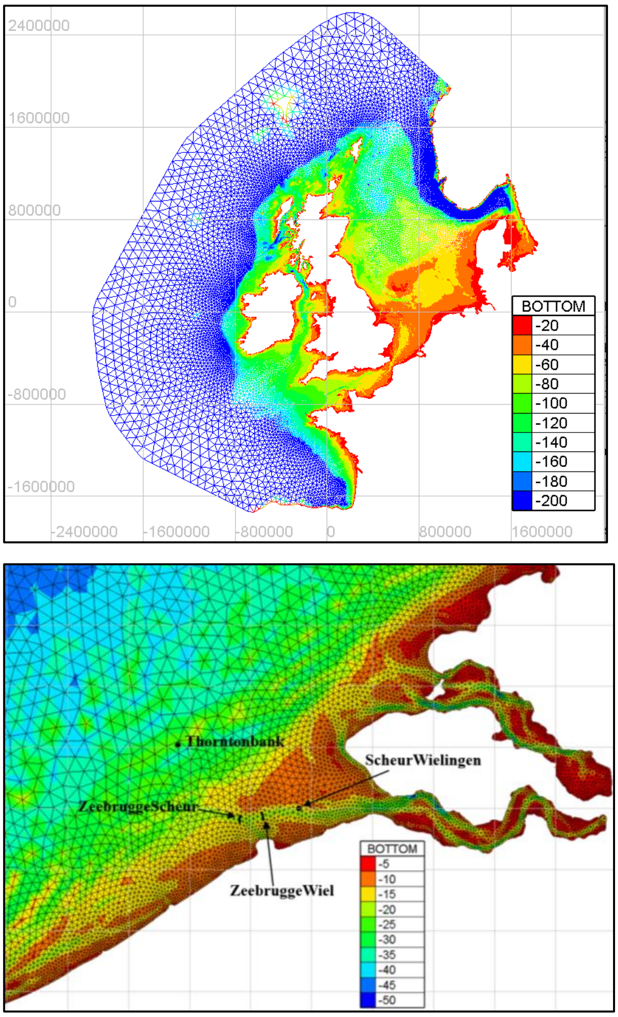

Figure 1. Upper panel: Bathymetry and computational mesh of iCSM. Lower panel: Detailed view of the Belgian Coastal Zone (horizontal system: Spherical Mercator projection. Vertical datum: MSL). The measurement locations of stationary and ADCP sailed velocities are also indicated.

The model is built in a spherical Mercator projection with Coriolis effect included. The computational mesh consists of approximately 150,000 nodes and 292,000 elements. The unstructured mesh is refined near the coastal zones, e.g. with a minimal resolution of 500 m at Belgian coast. Mesh refinement is also applied along the coastlines of UK, France and The Netherlands as well as in the Wadden Sea and the English Channel. The Scheldt river estuary is partly included in the model, thus allowing the tidal wave to propagate sufficiently up into the estuary, such that the influence of the estuary on the tide in the coastal zone is considered. The freshwater discharge from the rivers is neglected, since its magnitude is rather small compared to the discharge from the tidal flow in the estuary.

The model bathymetry is adopted from the latest EMODNET 2018 dataset with a spatial resolution of 1/16 × 1/16 arc minutes (circa 115 × 115 meters).

The model is driven by both tidal and nontidal forcing. The tidal water levels at the open boundaries are specified in the frequency domain with 14 harmonic constituents (M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, MN4, MF, MM and 2N2) from the TPXO9 global tidal inversion [2]. In addition, 16 minor harmonic constituents (2Q1, SIGMA1, RO1, M1, CHI1, PI1, PHI1, THETA1, J1, OO1, 2N2, MU2, NU2, L2, T2, LAMBDA2) are added at the open boundaries by switching on the 'MINOR CONSTITUENTS INFERENCE' in TELEMAC. Although wind setup at the open boundaries are negligible due to the deep water locally, the non-tidal effect of local pressure is considered important and therefore are added at the open boundaries by means of Inverse Barometer Correction (IBC) [3]. It is an isostatic response of the oceans to atmospheric pressure, i.e. with increase in pressure the sea level goes down and vice versa. In simple terms, 100 Pa decrease in atmospheric pressure with result in 1 cm increase in sea surface height.

$$IBC\ (x,y,t) = \frac{-(P(x,y,t)-P_0)}{\rangle_0 \times \gamma} \tag{1}$$

where P_0 represents the standard atmospheric pressure of 101,325 Pascal.

The meteorological surface forcing includes the space- and time varying wind (at 10-meter height) and air pressure at MSL from the ERA5 hourly dataset provided by European Centre for Medium-range Weather Forecasting (ECMWF). The use of Flather [4] and Charnock formula [5] (Figure 2) for the wind drag coefficient are evaluated. The optimal setting is found with a dimensionless Charnock coefficient of 0.04 which accurately captures the peak high-water levels on a stormy event. Using the Flather formula leads to ~ 5 cm underestimation of the water levels (details are not shown in this paper).

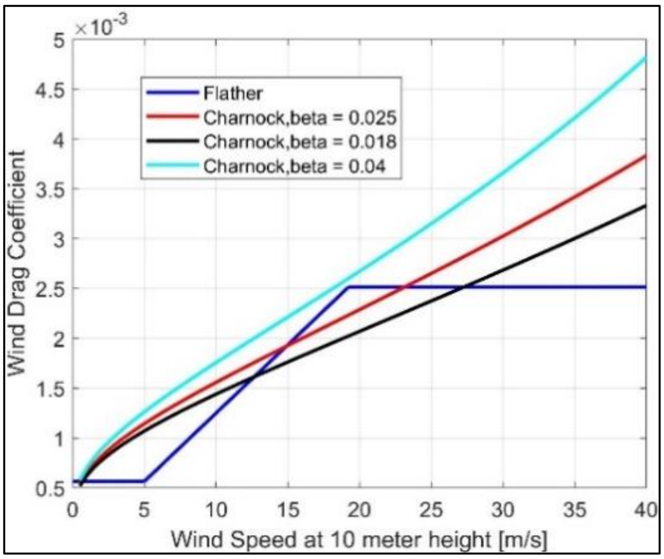

Figure 2. Relation between wind speed at 10 m height and wind drag coefficient using Flather formula and Charnock formula with different Charnock coefficients (beta).

The global tidal dissipation consists of two terms. In shallow waters the tidal dissipation through bottom friction is the primary mechanism. However, the dissipation of tidal energy through generation of internal tides is the dominant mechanism when tides propagate over steep topography in deep stratified waters. The global energy conversion rate from external to internal tides is 25-30%, amounts to about 1 TW, mainly occurs in areas of rough topography [6]. The parameterization of internal tide dissipation has been implemented to TELEMAC-2D and successfully applied to the in-house IMDC South Asian Model (iSAM) where the internal tide dissipation is a dominant process. The model predictive skill on water levels is significantly improved. Inside of the iCSM domain, Bay of Biscay is well-known for pronounced internal tidal dissipation in summer. Therefore, this process is included as well and its impact on tidal propagations in the Belgian Coastal Zone is evaluated. For a 2D barotropic model, the internal-tide stress τ_{IT} is parameterized as below and added to the momentum equation [7].

$$\tau_{IT} = (1/2)\kappa h^2 N \mathbf{u} \tag{2}$$

The implementation is only applied in water depths greater than 200 m. $\mathbf{u}$ = (u, v) represents the horizontal velocity vector. κ represents the wave number which is set to be spatially constant of 2π/(10 km). h^2 represents the standard deviation of the bathymetry in a certain area, computed based on EMODNET 2018 dataset interpolated on a 0.01° × 0.01° rectangular grid. Over each grid cell, a polynomial sloping surface is fit to the bottom topography (given by H = a + bx + cy + dxy), and the residual heights are used to compute h^2 by mean-square averaging over the grid cell. The depth averaged buoyancy frequency (Brunt-Väisälä frequency) N accounts for the stratification which is calculated based on the annual means of water density adopted from World Ocean Atlas (WOA) 2013-V2 dataset provided by NOAA. The buoyancy frequency N is implemented as a spatially varying scalar field but constant both in the vertical and in time.

$$N = \sqrt{\frac{g}{\rho}\frac{d\rho}{dz}} \qquad (3)$$

Another physical process often neglected in regional models but of remarkable importance at oceanic scale is the self-attraction and loading effect (SAL). This phenomenon consists of three effects: the deformation of the seafloor under the weight of the water column (Earth is an elastic body); the redistribution of Earth mass and its corresponding changes in the gravitational field; the gravitational attraction induced by the water body on itself. As SAL has a well-acknowledged impact on the tidal phases [8], therefore we included it in the iCSM using a simple beta (β) approximation approach which utilizes a proportionality constant between SAL elevation and surface elevation, with typical values of β ~10% on a global scale. One can consider it as a reduction factor of the barotropic pressure gradient. In the North Sea, the representative value of β is found to be 1.5% [9] which is parameterized in iCSM by reducing the gravity $\boldsymbol{g}$ by 1.5%. The full form of momentum equation applied on iCSM is expressed as:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} - fv = -g(1-\beta)\frac{\partial \zeta}{\partial x} - \frac{1}{\rho}\frac{\partial P_{atm}}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) - \frac{\tau_{xbot}}{h} - \frac{\tau_{xIT}}{h} + \frac{\tau_{xwind}}{h} \qquad (4)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + fu = -g(1-\beta)\frac{\partial \zeta}{\partial y} - \frac{1}{\rho}\frac{\partial P_{atm}}{\partial y} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) - \frac{\tau_{ybot}}{h} - \frac{\tau_{yIT}}{h} + \frac{\tau_{ywind}}{h} \qquad (5)$$

To account for the effect of bottom friction, a spatially varying roughness field of Nikuradse value is determined by manual calibration (Figure 3). The calibrated bottom friction map shows higher value in the west side of the Dover Straight. However, this large variation on Nikuradse values does not lead to substantial variations on the bed drag force (logarithmic relation).

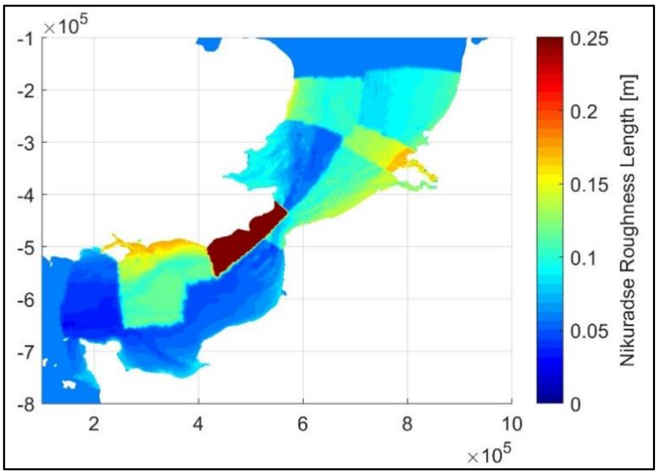

Figure 3. Spatial varying bottom friction of Nikuradse roughness length applied in iCSM.

III. CALIBRATION RESULTS

The model is calibrated for the entire year of 2015, with time step of 2 minutes. The computation takes 3 hours with 48 cores, which is sufficiently efficient. During the calibration, the focus is made on improving the water level representation at 28 stations along the coasts of UK, France, Belgium and the Netherlands.

The stepwise calibration is summarized in Table 1. The Reference model (Run01) includes the use of EMODNET 2018 bathymetry data; TPXO9 tidal boundary with minor harmonic components switched on; ERA5 hourly wind and pressure data and Charnock coefficient of 0.04, as described in the previous section. The remaining processes are taken as separate calibration steps; thus the contribution of each step can be evaluated. Figure 4 shows the RMSE of each calibration step. The detailed statistics are averaged over each coastal region and summarized in Table 2. VIMM (Visualization of Model and Measurements) is adopted for comparison between model and measurements in this study [10].

It is noteworthy that the inverse barometer correction (Run02) effectively reduces the bias of water level in general. This is more pronounced in the Belgian Coastal Zone where it is reduced from 6.9 cm to 1.1 cm and the model accuracy holds till the end of the calibration. Subsequently the RMSE of the water level also decreases by 20% on average. An exception is found along the British coast where, according to literatures [11], the inverse barometer correction accounts for only one-third of the observed variability of MSL in UK, whereas larger-scale atmospheric or ocean processes (e.g. gyre-scale circulations) may play important roles as well. However, successful modelling of such processes is still a major challenge.

Including internal tide dissipation (Run03) hardly modify the tidal propagation in the North Sea. For instance, the RMSE of water level is reduced by less than 1 cm on average. This is probably because the tidal wave entering the North Sea is primarily coming from the North, while the tidal wave coming from the South via Dover Strait has only a secondary influence. The impact of internal tide dissipation in the Bay of Biscay requires further evaluation in future studies.

Including SAL (Run04) effectively reduces the bias of M2 tidal phase which is decreased e.g. from 5.4° to 1.5° in the Belgian Coastal Zone. Nevertheless, it shows limited improvement in the UK, which implies that the beta approximation may not be sufficient to represent the spatial characteristics of the SAL field. A more decent way of modelling the SAL effect using the spherical harmonics approach [9] will be considered in future studies.

Finally tuning the bottom roughness (Run05) leads to better predictions on M2 amplitude. This is more noticeable in the Belgian and Dutch coastal zone where the bottom roughness adjustments are focused on.

TABLE 1. OVERVIEW OF ICSM CALIBRATION STEPS.

Run ID	***Description***
Run01	Reference
Run02	Run01+ inverse barometer correction
Run03	Run02 + internal tide dissipation
Run04	Run03 + self-attraction and loading
Run05	Run04 + spatially-varying bottom roughness

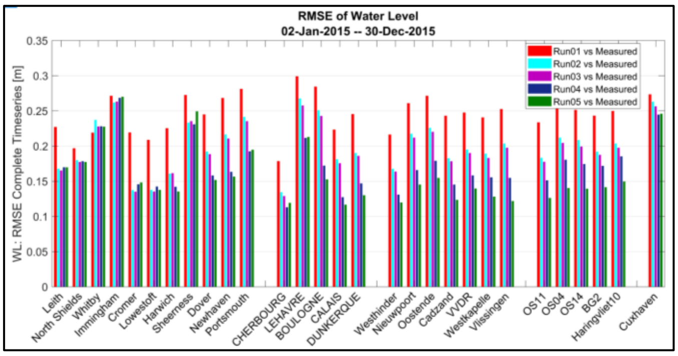

Figure 4. RMSE of water levels during model calibration.

TABLE 2. STATISTICS OF CALIBRATION RESULTS. THE VALUES ARE LINEARLY COLOR-CODED FROm red (largest errors) to green (lowest errors).

Statistics	*Zone*	*Run01*	*Run02*	*Run03*	*Run04*	*Run05*
RMSE of water level [cm]	UK	23.9	19.7	19.4	18.4	18.4
	France	24.6	20.5	19.8	15.4	14.6
	Belgium	24.7	19.7	19.2	15.6	13.3
	Netherlands	24.6	20	19.3	17.3	14
	Average	24.5	20	19.4	16.7	15.1
|Bias| of water level [cm]	UK	8.1	6.6	6.5	6.6	6.7
	France	7.9	1.4	1.5	1.6	1.5
	Belgium	6.9	1.1	1.3	1.3	1.5
	Netherlands	7.8	1	1.7	1.9	2.1
	Average	7.7	2.5	2.8	2.9	3
|Bias| of M2 Amplitude [cm]	UK	3.7	3.6	3.5	3.5	3.3
	France	6.2	6.5	5.9	8.4	7.2
	Belgium	13.1	13.8	12.9	13.4	8.2
	Netherlands	17.7	18.4	17.5	17.7	11.6
	Average	10.2	10.6	10	10.8	7.6
|Bias| of M2 Phase [deg]	UK	4.2	4.5	4.3	4	3.7
	France	4.7	4.4	4.3	2.2	2
	Belgium	5.4	4.8	4.9	1.5	1.1
	Netherlands	5.5	4.9	5	1	1.2
	Average	5	4.7	4.6	2.2	2

IV. VALIDATION RESULTS

After calibration, the iCSM is validated on water level during the Storm Xaver. The model predictive skills on stationary and ADCP sailed velocities are also evaluated. The M2 tide from the model is compared to OSU/TPXO data [2]. Afterwards, the iCSM is used to force a regional model of the Scheldt Estuary via boundary nesting.

K. Hindcast of the Storm Xaver

The Storm Xaver is an extratropical storm that occurred from December 4th to December 10th, 2013. It formed in Greenland and grew while travelling North of Scotland up to the Baltic Sea. During the storm, the air pressures decreased to 962 mb and wind velocities up to 130 km/h were observed. The storm led to increased water levels around the North Sea and even to inundations in England and Wales.

In order to perform a hindcast of the storm, the model was run for the period 4th-10th December 2013. Figure 5 exemplifies the water level comparison at Cadzand. The peak water level on 06-Dec-2013 is well captured by the model with a discrepancy less than 10 cm. Table 3 implies that the water level predicted by the model during the Storm Xaver is slightly worse than the calibration results (e.g. the RMSE in the Belgian Coastal Zone is increased from 13.3 cm to 17.5 cm). The meteorological surface forcing of wind and air pressure play more dominant roles during stormy events. This suggests that the use of a constant Charnock coefficient in space and time is insufficient for modelling extreme storms. The space- and time varying Charnock coefficient are available in the ERA5 dataset. This parameter accounts for increased aerodynamic roughness as wave heights grow due to increasing surface stress. It depends on the wind speed, wave age and other aspects of the sea state and is used to calculate how much the waves slow down the wind. They are computed by the ECMWF wave model and used in the air-sea boundary layer parameterization of the ECWMF meteorological model. Using these variable Charnock values could be a reasonable solution to improve the model performance for stormy periods. Hence it will be considered for future studies.

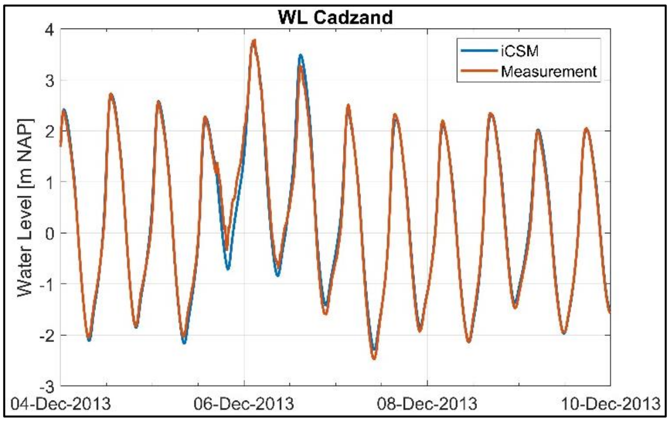

Figure 5. Modelled and measured water levels at Cadzand during the Storm Xaver.

TABLE 3. RMES AND BIAS OF THE WATER LEVEL DURING THE STORM XAVER.

Statistics	*Zone*	*Calibration (Run05)*	*Validation (Xaver Storm)*
RMSE of water level [cm]	UK	18.4	22.5
	France	14.6	19.3
	Belgium	13.3	17.5
	Netherlands	14	18.7
	Average	15.1	19.5
|Bias| of water level [cm]	UK	6.7	8.6
	France	1.5	1.7
	Belgium	1.5	2.1
	Netherlands	2.1	3.4
	Average	3	3.9

L. Validation on velocities

The modelled velocities are compared with measurements at the stations Scheur/Wielingen (Figure 6) and Thorntonbank (Figure 7), the latter of which is slightly more offshore. In general, the model reproduces the flow patterns decently for both velocity magnitude and direction. The RMSE of flow magnitude are 16 cm/s and 13 cm/s at those two stations. The bias of flow magnitude is -2 cm/s and 0 cm/s respectively.

There is a slight discrepancy on the flow direction at Scheur/Wielingen, probably due to the uncertainty of the local bathymetry interpolated on relatively coarse mesh.

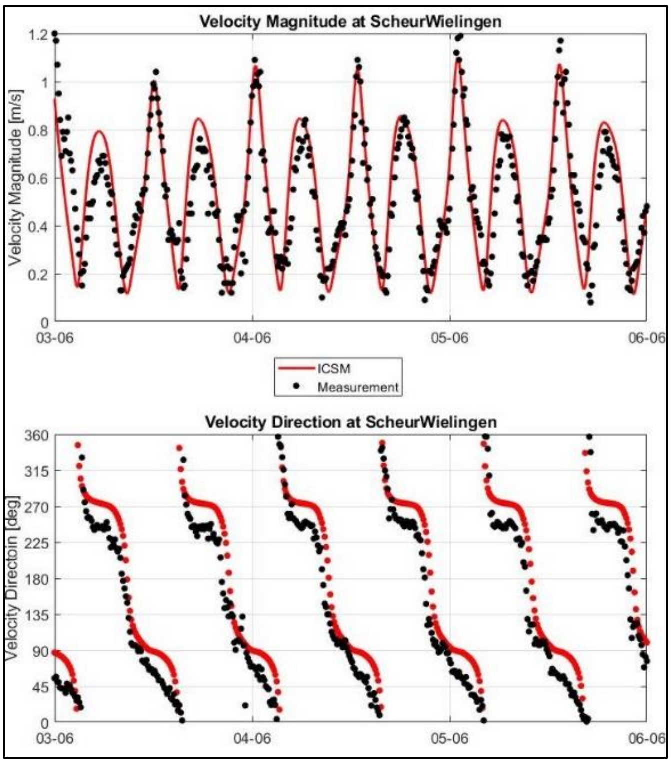

Figure 6. Modelled and measured velocity at Scheur/Wielingen.

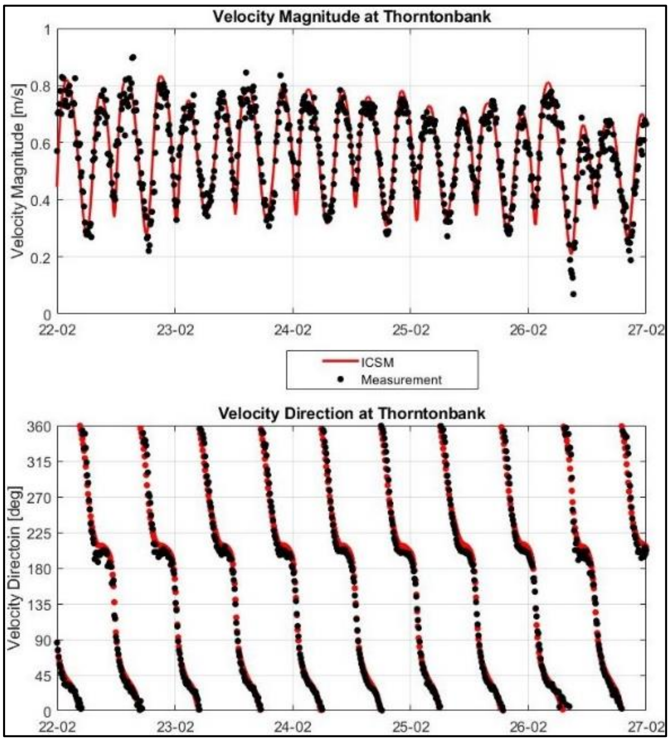

Figure 7. Modelled and measured velocity at the Thorntonbank.

The modelled flow patterns are also validated against 13-hour ADCP sailed velocities near Zeebrugge (see locations in Figure 1). Figure 8 and Figure 9 exemplify the comparison during maximum flood. Both flow magnitude and direction are well reproduced by the model, despite of the rather coarse mesh used locally. For the complete 13-hour period, an averaged RMSE of 16.3 cm/s and 17.5 cm/s are observed at Scheur and Wielingen respectively. The corresponding relative-mean-absolute-error (RMAE) which measures the model performance on both velocity magnitude and directions, is 0.33 and 0.31 respectively. Therefore, the model performance is categorized as *good* [12].

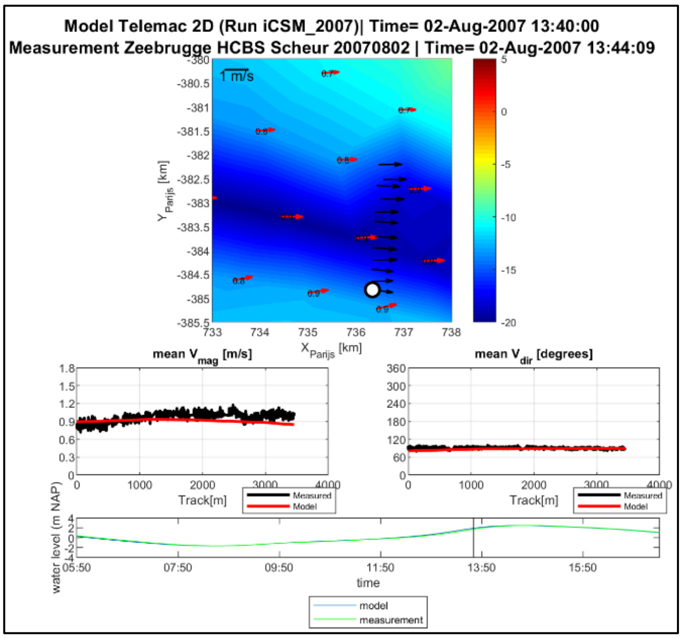

Figure 8. Modelled and measured ADCP velocity at Zeebrugge Scheur during flood.

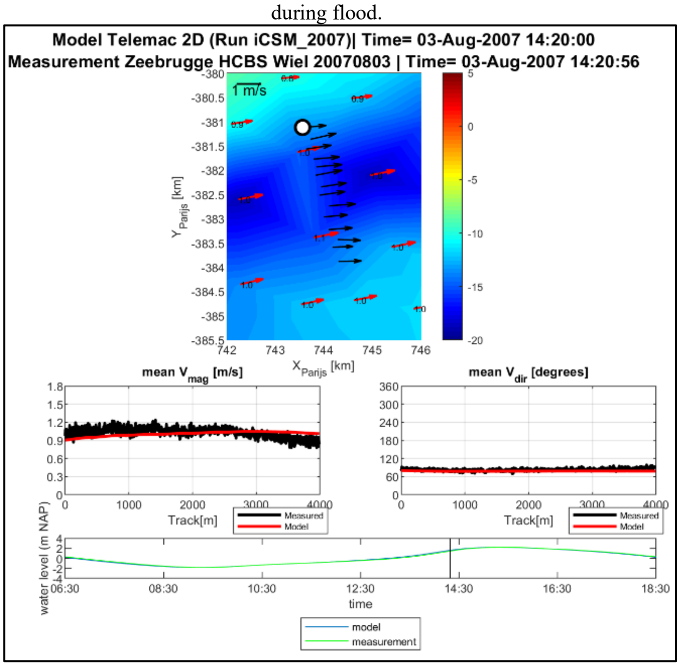

Figure 9. Modelled and measured ADCP velocity at Zeebrugge Wielingen during flood.

M. Validation on M2 tide

The iCSM runs for the entire year of 2015 again without meteorological forcing. The tidal amplitude and phase of the tidal constituents computed by the model are then compared to those from OSU/TPXO [2]. The most dominant tidal constituent in the North Sea is the M2-tide, which is therefore the only one presented in this paper.

Figure 10 presents the map of the calculated M2 amplitude in the model area and the differences from TPXO, which are below 10 cm in a large part of the model domain. The differences tend to be larger in shallow areas and close to the coast (e.g. ~40 cm in the Southern Bight). However, the iCSM is expected to be more accurate than TPXO in these regions, because the model resolution is higher and the physical processes occurring in shallow water are better included in the model than in TPXO. The co-tidal map for the M2 component is shown in Figure 11. The lines of equal tidal phase show good agreement between the model and TPXO. The locations of the amphidromic points in the North Sea are well reproduced by the model.

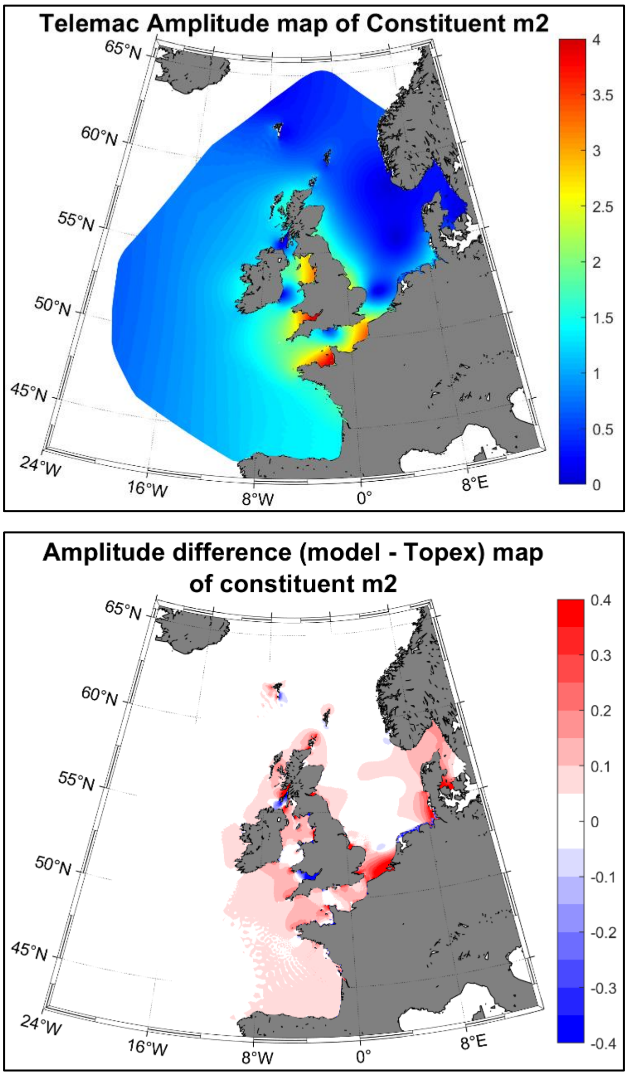

Figure 10. Co-range maps of the M2 tide from the model (top) and the difference from TPXO (bottom).

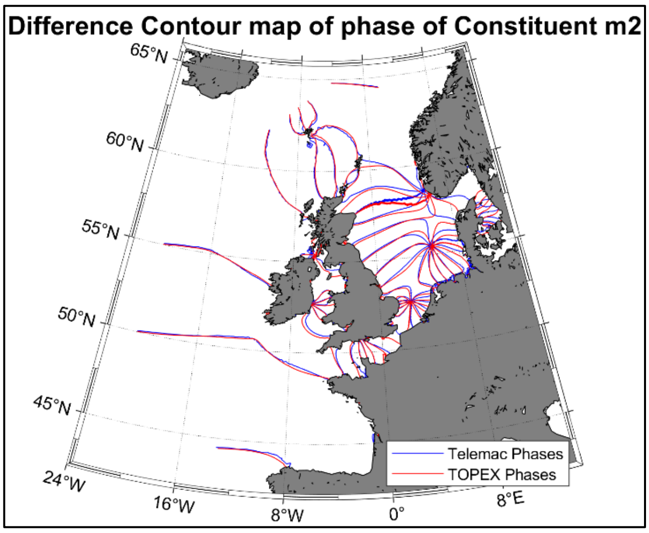

Figure 11. Co-tidal maps of M2 phase from the model and TPXO.

N. Validation on a regional Scheldt model

Boundary nesting is a common practice for modelling phenomenon on different scales e.g. from oceanic to coastal and estuarine scale. The calibrated iCSM is a useful tool to provide boundary conditions for any model that has its boundaries inside of the iCSM domain. Figure 12 exemplifies the application of boundary nesting between iCSM and a regional model of the Scheldt Estuary. The two models are nested in the vicinity of Vlissingen, which is near the mouth the Scheldt river. The boundary nesting is performed with an in-house MATLAB toolbox which drives the calculation of flow conditions (e.g. water level and velocities) in iCSM. The results are interpolated onto the open boundary locations of the Scheldt model; thus the time-dependent flow conditions can be transported from the iCSM to the regional Scheldt model.

Figure 13 presents the RMSE of water levels in the Belgian Coastal Zone calculated from iCSM and in the Scheldt Estuary calculated from the Scheldt model. The water levels predicted by both models show decent consistency, which implies that the tidal flow is well transferred from iCSM to the Scheldt model. The averaged RMSE calculated for the Scheldt Estuary is around 10 cm. The lower RMSE at Vlissingen from the Scheldt model is obtained from the more detailed representation of the geometry and bathymetry on a finer mesh.

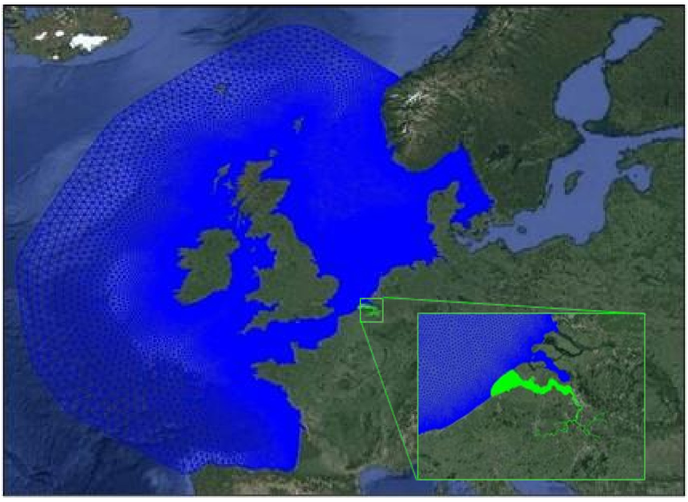

Figure 12. Boundary nesting between iCSM (blue) and the Scheldt model (green).

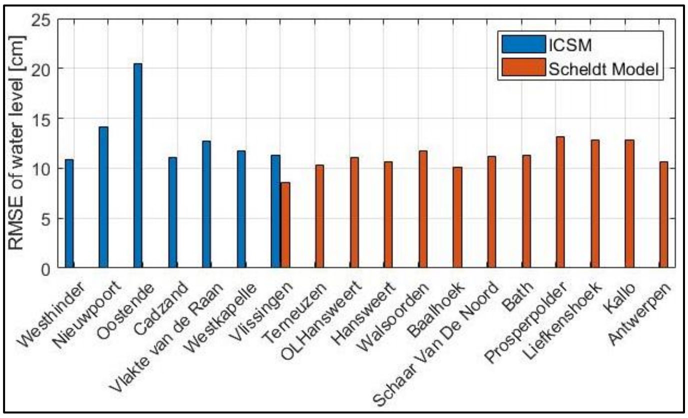

Figure 13. RMSE of water level calculated for one spring-neap cycle in 2017 from iCSM and the Scheldt Model.

V. SUMMARY AND CONCLUSIONS

The stepwise improvement of the in-house continental shelf model of the North Sea is presented in this paper. The model is driven by the latest bathymetric and meteorological data. Using the Charnock wind drag formula with a coefficient of 0.04 leads to better predictions on peak water level during storms. Several physical processes often neglected in regional models, but of substantial importance at oceanic scale are included into iCSM.

Focusing on the Belgian coastal zone, it is noticed that the inverse barometer correction significantly reduced the bias of the water level to ~1 cm. Including self-attraction and loading leads to a much lower bias of the M2 phase (~1°). Internal tide dissipation occurring in the Bay of Biscay hardly influences the tidal characteristics. In the end, tuning the bottom roughness decreases the averaged RMSE of the water level to 13 cm.

As validation, the iCSM shows capability to predict the peak water levels during Storm Xaver. Both near-shore (near harbour of Zeebrugge) and off-shore velocities are also predicted reasonably well. The co-range and co-tidal maps generally show a good agreement with TPXO. The improved iCSM model is used to force a regional model of the Scheldt Estuary via boundary nesting. The averaged RMSE calculated for the Scheldt Estuary is around 10 cm.

Therefore, it is concluded that the iCSM is a decent tool fulfilling both scientific and engineering needs.

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