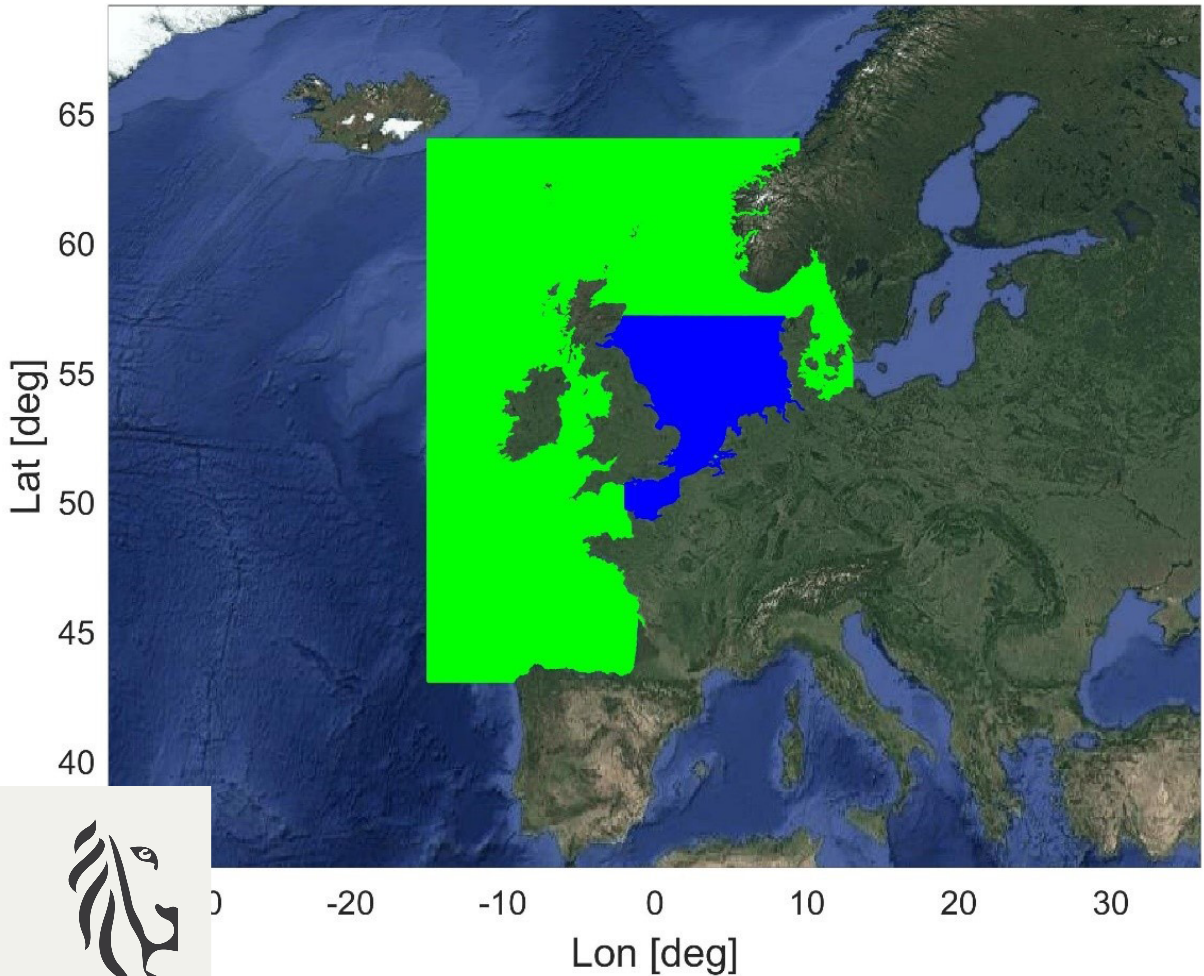

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Validation of North Sea models

Sub report 1
Validation and sensitivity analysis

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Validation of North Sea models

Sub report 1 – Validation and sensitivity analysis

Chu, K.; Vanlede, J.; Decrop, B.; Mostaert, F.

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Abstract

North Sea models are necessary tools to provide boundary conditions for any model that has its boundaries in the North Sea. They solve the physics of the propagating Kelvin wave in the North Sea (harmonics component) and the wind-driven surge.

This report aims to test 4 different schematisations of the North Sea with regards to their hindcasting performance at calculating water levels in the Belgian Coastal Zone.

- DCSMv5-ZUNOv3
- DCSMv6-ZUNOv4
- DCSM-FM-0.5nm
- DCSM-FM-100m

Furthermore, two different data sources for wind data are tested. They both stem from different models:

- HIRLAM
- ECMWF

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1 Introduction

Within the framework of the research programme “Agenda voor de Toekomst II”, Flanders Hydraulics is performing research on the topic of Sea Level Rise (SLR).

As a first step, this report aims to validate the different available North Sea model schematisations for the year 2015 with regards to their hindcasting performance at calculating water levels in the Belgian Coastal Zone.

4 different schematisations are tested:

- DCSMv5-ZUNOv3
- DCSMv6-ZUNOv4
- DCSM-FM-0.5nm
- DCSM-FM-100m

In a first sensitivity analysis, two different data sources for wind data are tested.

- HIRLAM
- ECMWF

In a subsequent sensitivity analysis, some test runs with different scenarios of SLR will be performed to explore the effects of SLR on tidal hydrodynamics in the Belgian part of the North Sea (follow up report).

2 Methodology

In order to perform a decent comparison of the 4 North Sea model, all the models are run for the same period of 2015 with the same wind and pressure fields provided by Hirlam7.2. However the user should note some inevitable differences between the different validation runs:

- Different software platforms (Simona and Delft3D Flexible Mesh, listed in Table 2).
- Different model domains between DCSMv5-ZUNOv3 and the other 3 models (shwn in Figure 1).
- Different model mesh resolution, especially near the Belgian and Dutch coast (listed in Table 3 to Table 6).
- Different tidal boundary conditions. Note that DCSMv5-ZUNOv3 uses only 11 tidal components while the other 3 models use more than 30 tidal components. (listed in Table 3 to Table 6).
- The DCSM-FM models excludes river discharges that are included in the ZUNO models (see details in Chapter 5).

Therefore the comparison is strictly speaking not one-on-one comparison, but more like a model competition because all the 4 models are the 'best' models independently calibrated and validated during the past years (see references in §3.1.1).

In order to quantify the model quality, the water level analysis are performed with:

- Basic analysis: comparing the BIAS, RMSE and RMSE0 of the complete time series of water level and high/low water levels and time.
- Harmonic analysis: comparing the tidal components (e.g. A0 and M2) and the total vector differences.
- Surge analysis: the low-passed averaged error signal is evaluated by applying a three step low-pass filter according to Godin (1972) to a timeseries to remove tidal and higher frequency signals to obtain the residual signal. The filter applies a moving average over periods of 25, 24 and 25 hours respectively. By removing the tidal signal out of the error signal, we get a measure of the non-tidally varying part of the error.
- Analysis for stormy period (including the maximum wind speed of 24 m/s) which is selected based on measured wind data at Vlakte van de Raan (see details in §6.3).
- Sensitivity analysis on using different wind data between Hirlam7.2 and publicly available ERA5 dataset provided by European Centre for Medium-range Weather Forecasting (ECMWF).

3 Previous studies

3.1.1 Deltares North Sea models

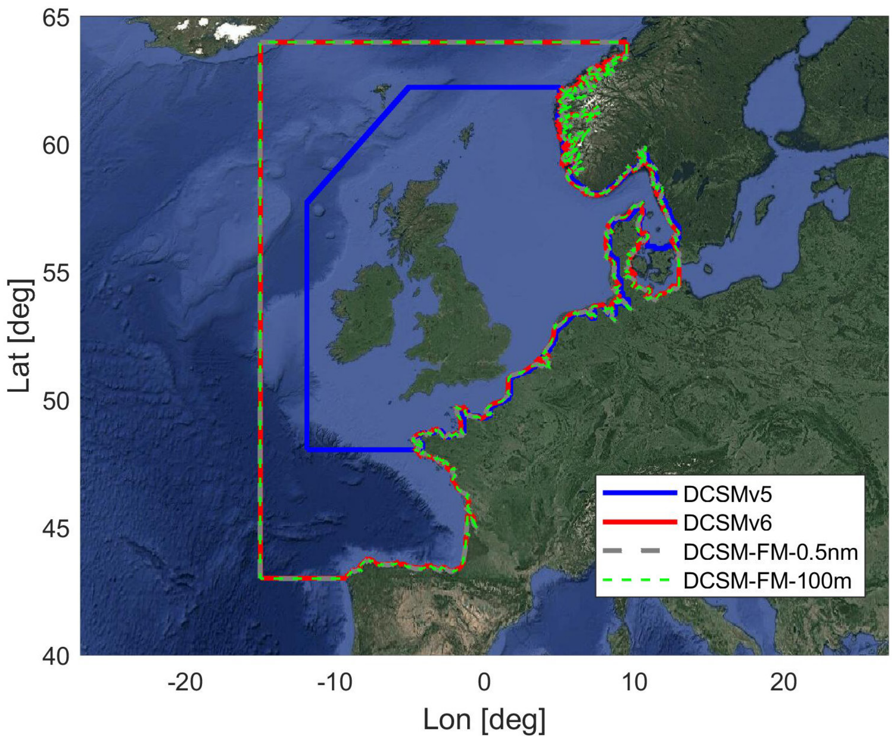
The DCSMv5 – ZUNOv3 has been developed at Deltares as an application of WAQUA in SIMONA, a framework for hydrodynamic modelling of free-surface water systems. These two models were initially provided by Deltares to FHR on 20/05/2010 and has been widely used internally at FHR during the past 10 years. The DCSMv5-ZUNOv3 was recently calibrated and validated for the year 2014 by Maximova et al (2015). The averaged RMSE near the Belgian coast is around 20 cm which is considered as substantial. Therefore during the boundary nesting, the hydrodynamic boundary conditions are corrected based on analysis of model output from ZUNOv3 model. This means that the time series at the boundary locations of the regional model (e.g. NEVLA or SCALDIS) that are obtained out of ZUNO, are decomposed into harmonic components and a residual term. The harmonic components are corrected, and the signal is re-synthesized. The details of the model setup can be found in §5.1.

The DCSMv6 – ZUNOv4 has been developed at Deltares as an application of WAQUA in SIMONA (Zijl, 2013). The calibration results reveal that the DCSMv6-ZUNOv4 model yields an overall RMSE of 9.2 cm for water level, which is decent. The details of the model setup can be found in §5.2.

Two DCSM-FM models have been developed at Deltares as an application of Delft3D Flexible Mesh (Zijl, 2019). The difference of the two models are the mesh resolution near the Belgian and Dutch coast (0.5 nm and 100 m).The details of the model setup can be found in §5.3 and §5.4.

Figure 1 shows the outline of all the different North Sea models.

Figure 1 – Demonstration of the outlines and covered domains of different North Sea models.



3.1.2 Effect of SLR on Zeebrugge

Kolokythas et al (2017) has carried out a modelling study to evaluate the influence of future SLR on the hydrodynamic flow at the Belgian coast and especially on the Zeebrugge port accessibility. The numerical simulations by means of Telemac3D are performed considering 3 different scenarios of future SLR along with the Reference scenario (current situation). The selected scenarios for the SLR are identical to those determined in the framework of the CLIMAR project for the evaluation of climate change impacts, i.e. a moderate SLR of 60 cm by the year 2100, a warm scenario with SLR of 90 cm and a worst case scenario of SLR scenario of 200 cm. The boundary conditions for the Telemac3D model are derived from the DCSMv5-ZUNOv3 model run with the increased water levels superimposed on the CSM continental shelf boundaries.

The model runs show that with increased SLR, not only the mean sea level increases, but also the tidal amplitude increases at the Belgian and Dutch coast and upstream the Scheldt estuary. For the worst case scenario the amplitude during spring tide increases up to about 10 cm at the area around Zeebrugge, while near Antwerp an increase up to 20 cm is observed. Changes in the tidal amplitude are expected to be accompanied by some changes in the tidal phase.

Although the scenarios show an increase in maximum depth-averaged velocities near the mouth area and the coast of Walcheren, mainly during ebb phase, in general the currents in the vicinity of the port of Zeebrugge (Scheur, Wielingen and Pas van het Zand) are lower in case of SLR. However during ebb phase, a local increase along the eastern breakwater and in front of the port can be noticed, ranging from a few cm/s in case of moderate SLR up to locally 30 cm/s in the worst case scenario (but only around 10 to 15 cm/s right in front of the port entrance). As for the currents in the Western Scheldt, it is found that SLR leads to significant increase of maximum velocity in the intertidal areas, where dry areas become wet, and reduction of its magnitude in the navigation channels (about 30 cm/s in the worst case scenario). Furthermore, it is not expected that the SLR will affect substantially the residual flow velocity patterns observed at the coastal area east of Zeebrugge and at the mouth of Scheldt estuary. The residual currents are significant for the estimation of the net sediment transport and thus the morphological development of the bottom.

The impact of SLR on the port accessibility is rather small. SLR has hardly any impact on the time window with respect to the 2 knots cross current limit, i.e. the limit during arrival and departure of container carriers and departure of LNG carriers. On the other hand, the total duration of the window of 1.5 knots limit (arrival of LNG carriers) is reasonably affected by the SLR, which is translated to a maximum increase of about 30% in the worst case scenario.

3.1.3 Effect of SLR on tidal amplitude at the Dutch coast

Taal (2019) studied the tidal changes in the Netherlands due to SLR. The research evaluated the influences of SLR on tide including high water and low water. Two scenarios of SLR are defined:

	RCP4.5	RCP8.5
50 percentile	1.05	1.84
95 percentile	1.77	2.92

Where RCP (Representative Concentration Pathway) represents the greenhouse gas concentration (not emissions) trajectory adopted by the IPCC. For instantce RCP4.5 is a scenario that stabilizes radiative forcing at 4.5 W/m^2 in the year 2100 without ever exceeding that value.

The effect has therefore only been studied for situations in which SLR is at least one meter or higher. The Global Tide and Surge Model (GTSM) takes into account the global differences in water levels and the influence zoomed into the Dutch coast.

The main findings are:

- The North Sea (relatively shallow) shows the greatest changes in tides worldwide with large SLR.

- Along the North Sea coast, the scenarios of SLR lead to an increase in the tidal range along the Zeeland and Wadden coast, in addition to a decrease in the tidal range along the Dutch coast.
- Changes scale generally linearly with SLR scenarios: stronger changes for higher SLR scenarios.
- Looking at the effects on high and low water, it is striking that the change in tidal range is not equally divided into changes in high and low water. The elevation of the high water is stronger near the Wadden than in the delta. On the other hand, the lowering of the low water in the delta is stronger than near the Wadden.

4 Available Data

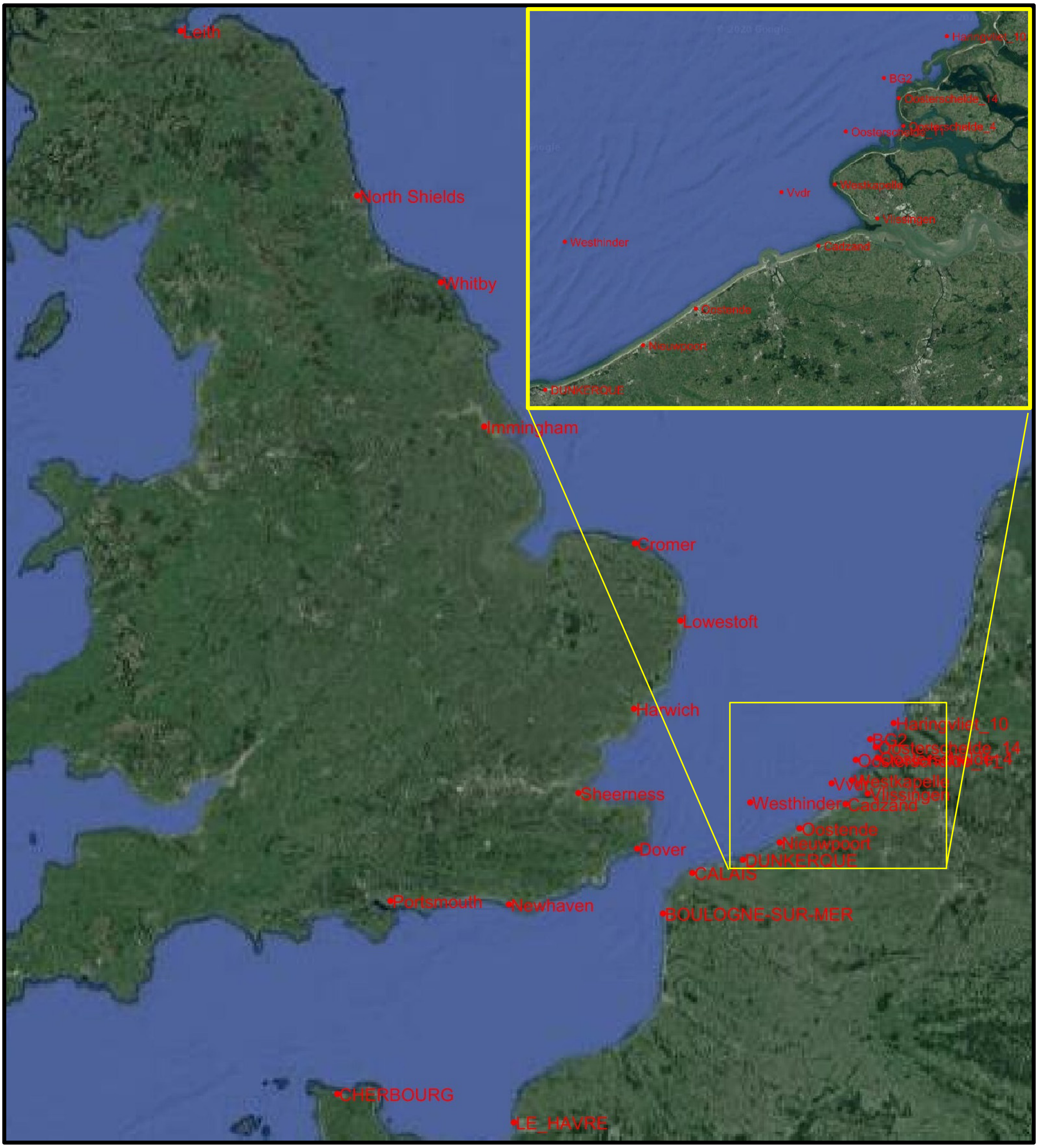
4.1 Water levels

For the year 2015, 28 stations are available with water level measurements every 10 minutes, see Table 1. The stations are also shown in Figure 2. The water levels are used for the validation of different North Sea models.

Table 1 – Available water level measurements for the year 2015.

No.	Station Name	Source	No.	Station Name	Source
1	Leith	BODC	15	Calais	SHOM
2	North Shields	BODC	16	Dunkerque	SHOM
3	Whitby	BODC	17	Westhinder	MVB
4	Immingham	BODC	18	Nieuwpoort	MVB
5	Cromer	BODC	19	Oostende	MVB
6	Lowestoft	BODC	20	Cadzand	HMCZ
7	Harwich	BODC	21	Vlakte van de Raan	HMCZ
8	Sheerness	BODC	22	Westkapelle	HMCZ
9	Dover	BODC	23	Vlissingen	HMCZ
10	Newhaven	BODC	24	OS11	HMCZ
11	Portsmouth	BODC	25	OS04	HMCZ
12	Cherbourg	SHOM	26	OS14	HMCZ
13	Le Havre	SHOM	27	BG2	HMCZ
14	Boulogne-Sur-Mer	SHOM	28	Haringvliet10	HMCZ

Figure 2 – Measurement locations of water level

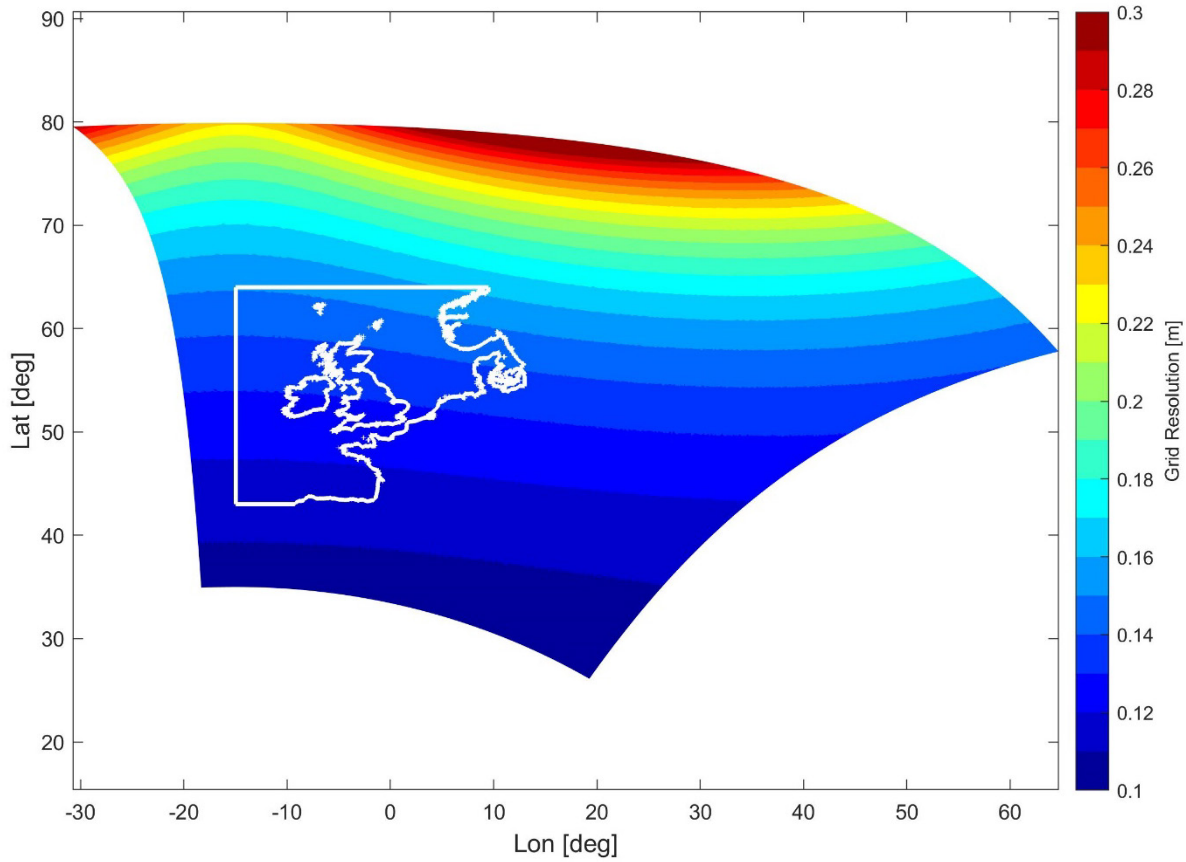


4.2 Wind

4.2.1 Hirlam wind

The wind field data (format: NetCDF) are received from Hirlam (High Resolution Limited Area Model, version 7.2), which is a Numerical Weather Prediction (NWP) forecast system developed by the international HIRLAM programme. The data are converted into a SDS-file (binary format) by means of the Simona script **waqwnd**. The spatial resolution varies from 0.1 to 0.322 degrees (Figure 3). The temporal resolution is one hour. The Hirlam wind field data are utilized to force all the North Sea models.

Figure 3 – Spatial resolution of Hirlam7.2 wind data.
The white line indicates the domain of DCSMv6 model.



4.2.2 ECMWF wind

The space- and time varying wind data are also collected from publicly available ERA5 hourly dataset provided by European Centre for Medium-range Weather Forecasting (ECMWF). The spatial resolution is 0.25 × 0.25 degree. The ERA5 dataset also contains a space- and time varying Charnock drag coefficient for computing the Charnock wind formula. The ERA5 data are used for sensitivity analysis as discussed in §7.

5 North Sea Models

In this chapter, the 4 North Sea models developed at Deltares are compared. Table 2 shows the computational time required for one year simulation of 2015. The DCSM-FM-100m requires most of the computational time which is logical as it has the highest mesh resolution of 100 m and the most computational elements.

Table 2 – Comparison of computational time of each North Sea models.

Model	Software	Computational elements	Number of processors	Time Step	Computation Time for one year simulation of 2015
DCSMv5[1]	WAQUA	Active cells[2] 19,700 (201×173)	1	10 mins	1 hour
ZUNOv3		Active cells 42,200 (486×170)	1	2.5 mins	6 hours
DCSMv6[3]	WAQUA	Active cells 860,000 (1120×1260)	32	1 min	25 hours
ZUNOv4		Active cells 394,000 (1448×637)	16	1 min	
DCSM-FM-0.5nm	Delft3D Flexible Mesh	630,000	1	Dynamic time step, with maximum time step of 2 mins	102 hours
DCSM-FM-100m	Delft3D Flexible Mesh	1,600,000	8	Dynamic time step, with maximum time step of 50 s	212 hours

[1] DCSMv5 and ZUNOv3 are nested offline with modnst.pl.
[2] The active cell count of a structured mesh is less than the (M×N) dimension multiplied.
[3] DCSMv6 and ZUNOv4 are nested online with domain decomposition.

5.1 DCSMv5-ZUNOv3

5.1.1 Introduction

The North Sea model currently used at FHR is the DCSMv5-ZUNOv3 which was recently calibrated and validated for the year 2014 by Maximova et al (2015). These two models (CSMv5 and ZUNOv3) were initially provided by Deltares to FHR on 20/05/2010 and they are property of Rijkswaterstaat (Leyssen et al., 2012). Figure 4 demonstrates the computational model grids. Table 3 lists the parameter settings for the DCSMv5 and ZUNOv3.

Figure 4 – CSMv5 and ZUNOv3 model grid, with the DCSMv5 domain in green and the ZUNOv3 domain in blue.

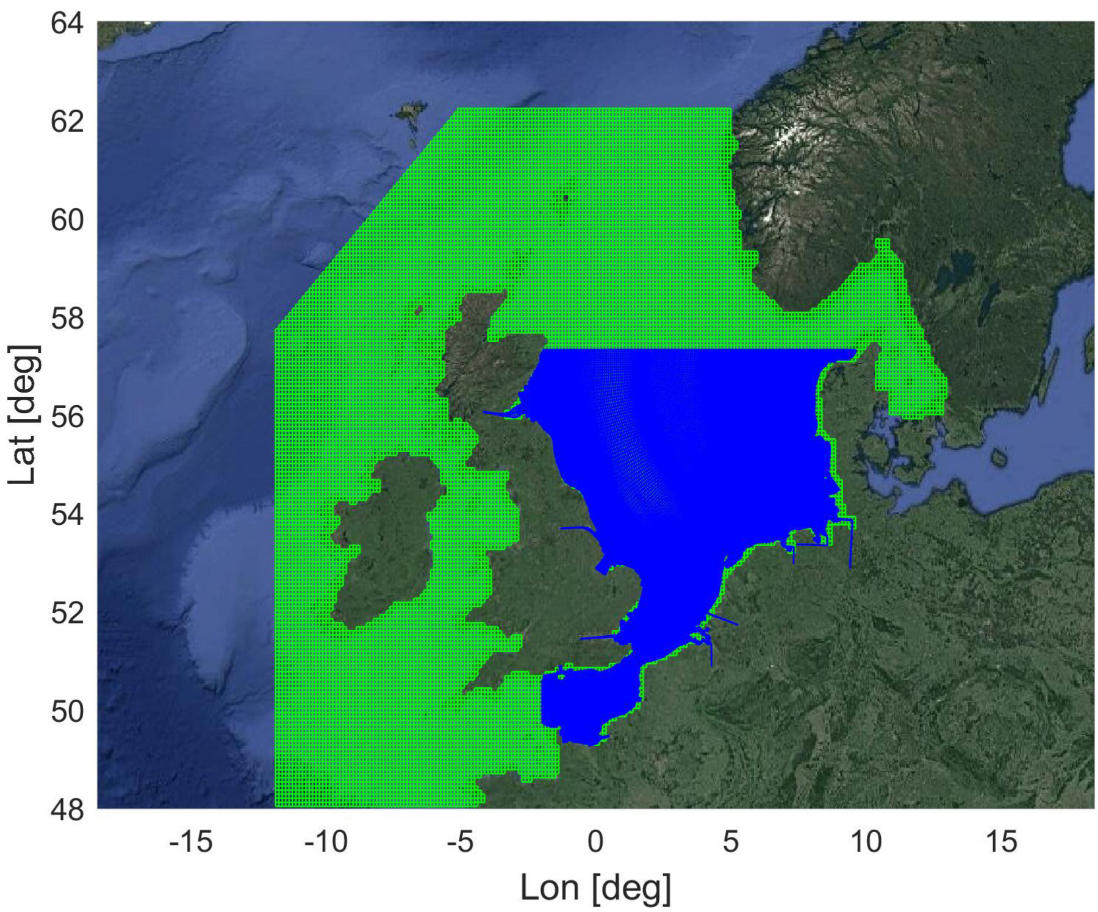


Table 3 – Parameter settings of the DCSMv5 and ZUNOv3.

Settings	DCSM-v5	ZUNO-v3
Grid resolution	9.3 to 6.5 km in the west-east direction and 9.25 km in the south-north direction	about 4.5 to 6 km along the English coast, 2.5 to 4 km in the Channel and the German Bight and 1 to 2 km along the Dutch coast
Number of grids	201 in east-west direction and 173 in north-south direction.	486 in east-west direction and 170 in north-south direction.
Open boundary condition	1. Water level defined by 11 tidal constituents. 2. non-tidal effect of local pressure is considered with inversed barometer correction	Calculated by DCSM-v6 via boundary nesting
Coordinate system	WGS84 geographical	
Time Zone	Changed from MET to GMT for the 2015 run.	
Roughness	Spatial varying Chezy values.	
Wind	Spatial and temporal (3-hourly) varying wind field data from Hirlam (v7.0).	
Drying and flooding	Threshold value of 0.1 m.	
Vertical reference	NAP	
Time step	10 mins	2.5 mins

5.1.2 Model set-up for 2015

As an validation, the existing DCSMv5 – ZUNOv3 model runs for the year 2015 as reported Chu et al (2017), which involves the following updates. The rest model setups are being kept the same.

- Wind forcing: Spatial (~10×10 km) and temporal (hourly) varying wind field data from Hirlam (v7.2).
- Daily discharge at Schelle are collected from HIC and imposed to the model.

5.1.3 Validation results for 2015

Figure 5 shows the comparison of RMSE of complete time series between 2014 (calibration) and 2015 run (validation). Figure 6 shows the corresponding vector differences calculated in the frequency domain. The model quality shows consistency in general.

Figure 5 – RMSE of complete time series of water levels for the year 2014 and 2015.

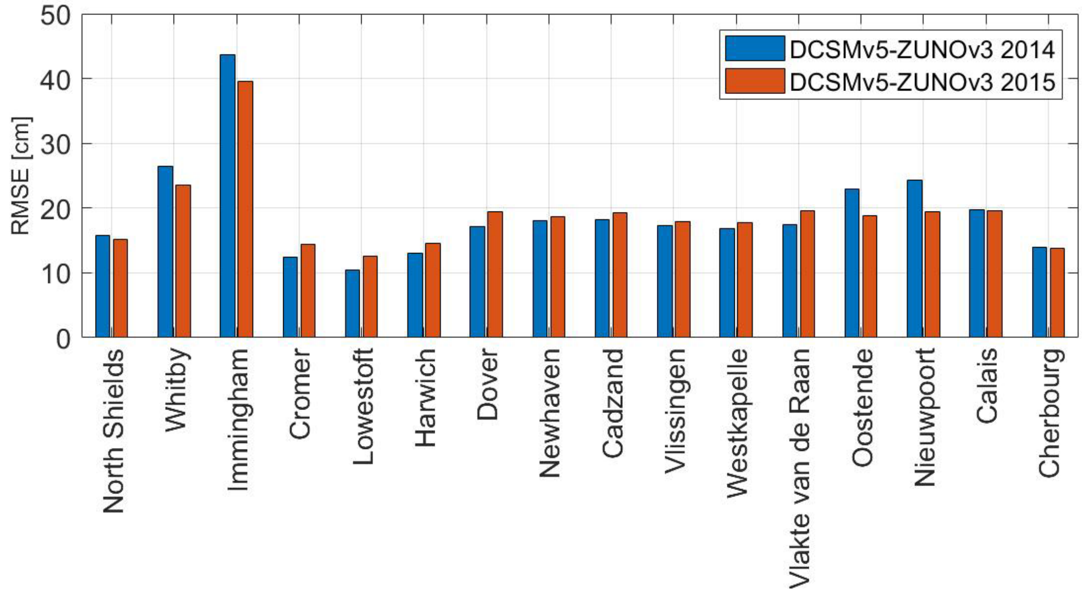
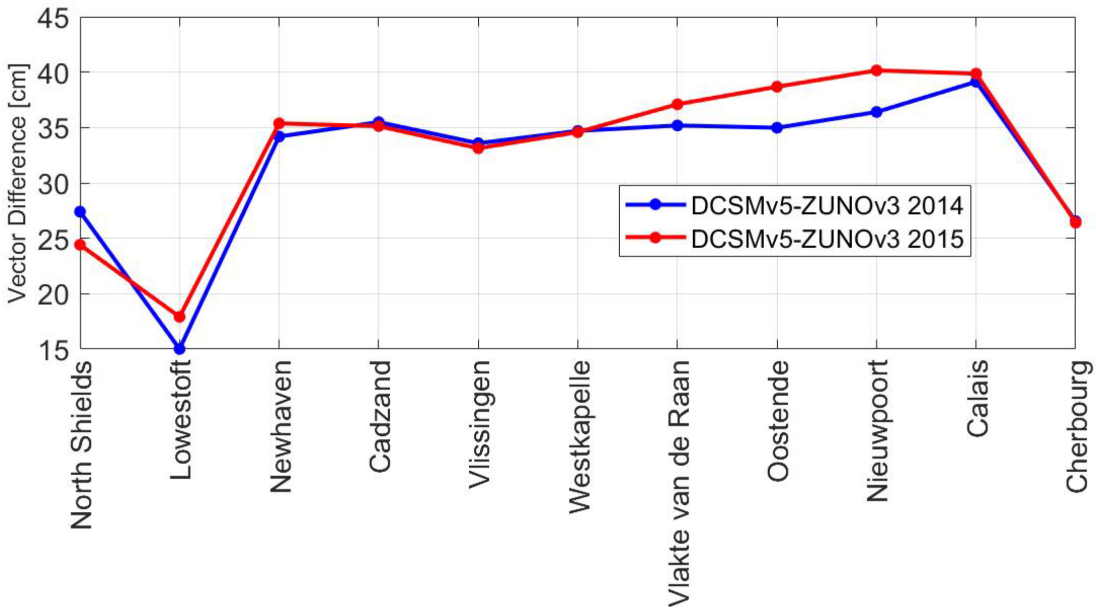


Figure 6 – Vector difference for the year 2014 and 2015.



5.2 DSCMv6-ZUNOv4

5.2.1 Introduction

DCSMv6 – ZUNOv4 has been developed at Deltares as an application of WAQUA in SIMONA, a framework for hydrodynamic modelling of free-surface water systems (Zijl, 2013). The DCSMv6-ZUNOv4 model consists of two separate domains coupled together by means of horizontal domain decomposition.

Figure 7 demonstrates the computational model grid. Table 4 listed the general settings of the DCSMv6 and ZUNOv4. The calibration results reveal that the DCSMv6-ZUNOv4 model yields an overall RMSE of 9.2 cm for water level, which is very decent.

Figure 7 – Overview of the DCSMv6-ZUNOv4 hydrodynamic model grids,
with the DCSMv6 domain in green and the ZUNOv4 domain in blue.

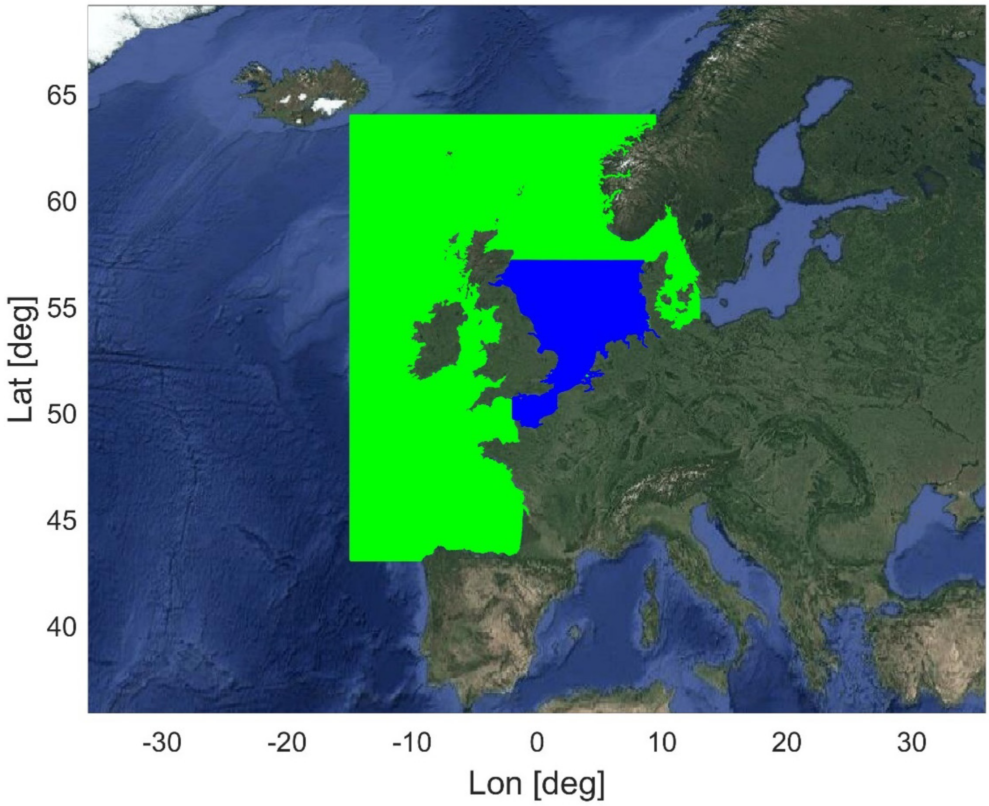


Figure 8 – Grid resolution of ZUNOv4.

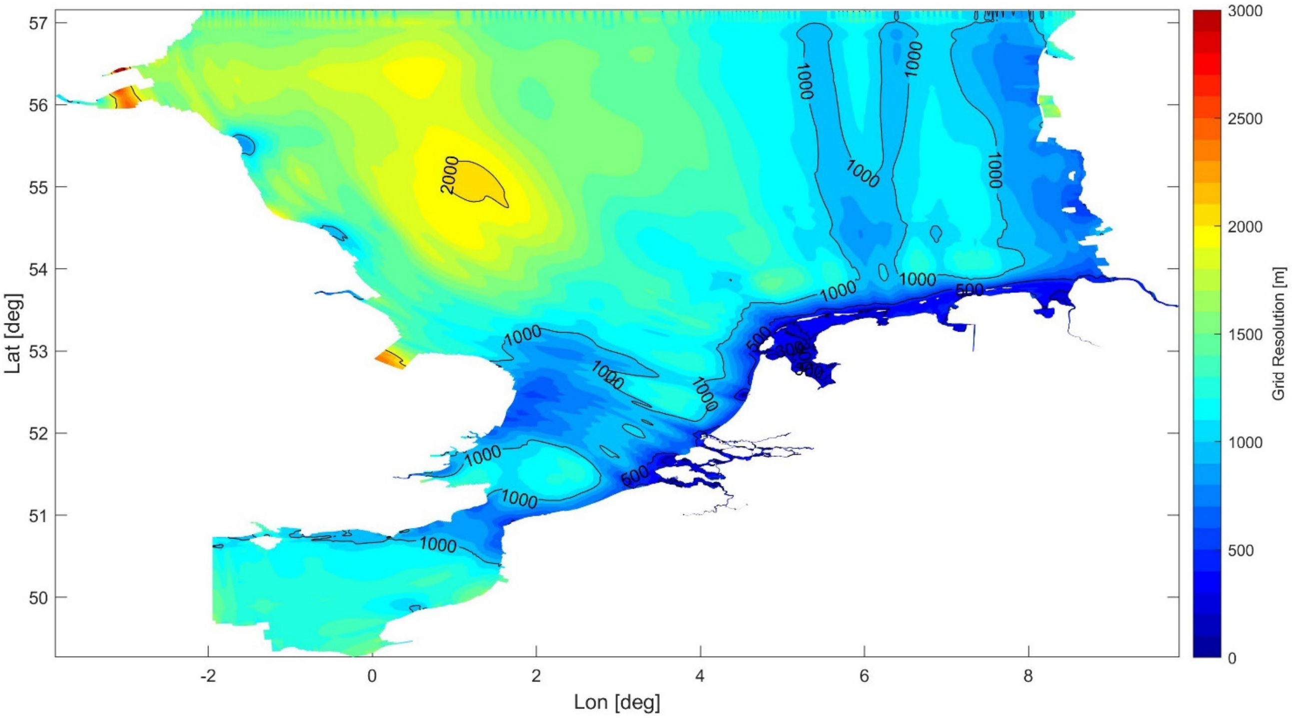


Figure 9 – Grid resolution of ZUNOv4, zoom in to the Belgain coast.

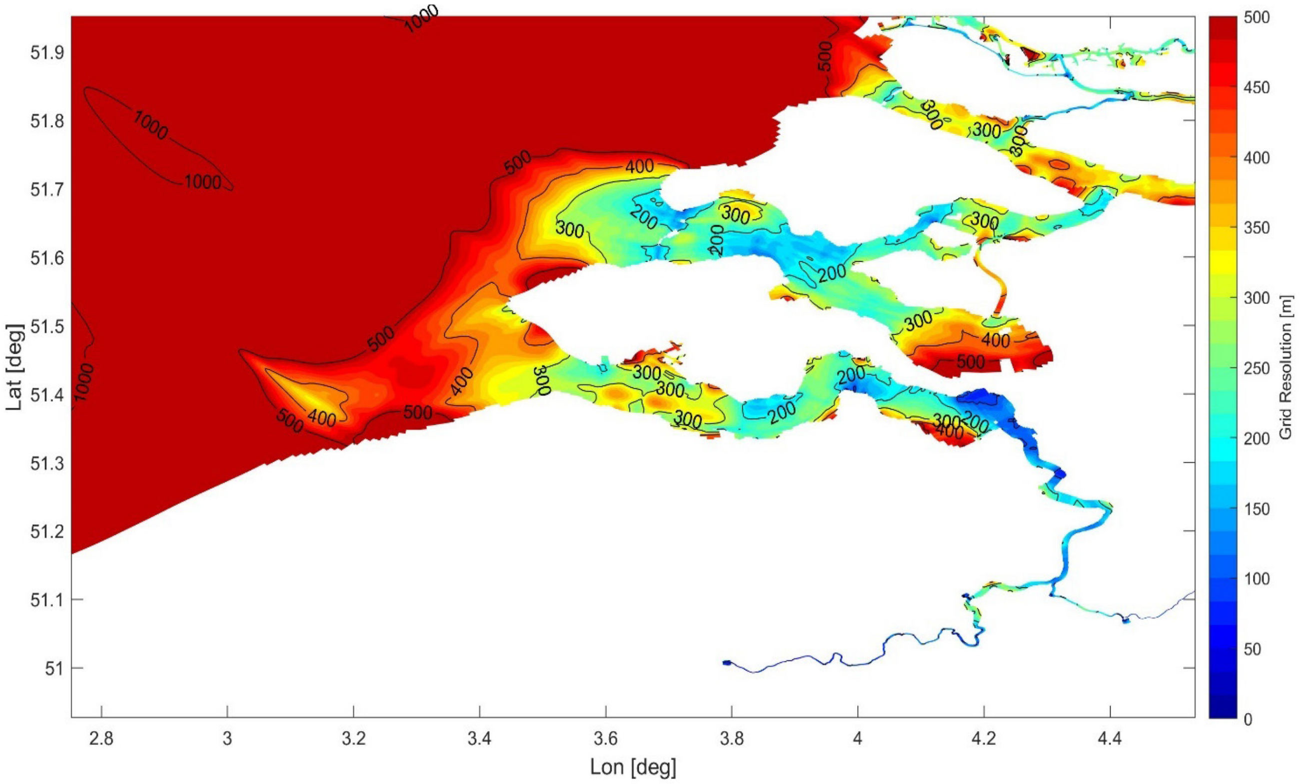


Table 4 – Parameter settings of the DCSM-v6-ZUNOv4.

Settings	DCSM-v6	ZUNO-v4
Grid resolution	1.5' in east-west direction and 1.0' in north-south direction (2×2 km), with a refinement in the southern North Sea and Dutch coastal waters.	25-500 m nearshore and 2-3 km offshore. See details in Figure 8 and Figure 9.
Number of grids	1120 in east-west direction and 1260 in north-south direction.	1448 in east-west direction and 637 in north-south direction.
Open boundary condition	1. Water level defined by 38 tidal constituents. 2. non-tidal effect of local pressure is considered with inversed barometer correction	Calculated by DCSM-v6 via domain decomposition.
Coordinate system	WGS84 geographical	
Time Zone	GMT	
Roughness	Spatial varying Manning values determined by automatic calibration with OpenDA	
Tide generating force	Components of the tide with a Doodson number from 55.565 to 375.575 are included.	
Wind	Spatial (~10×10 km) and temporal (hourly) varying wind field data from Hirlam (v7.2). Charnock coefficient = 0.025.	
Drying and flooding	Threshold value of 0.1 m.	
Vertical reference	MSL	
Time step	1 mins	

5.2.2 Model set-up for 2015

As an validation, the existing DCSMv6 – ZUNOv4 model run for the year 2015 for this study, which involves the following updates. The rest model setups are being kept the same.

- Wind forcing: Spatial (~10×10 km) and temporal (hourly) varying wind field data from Hirlam (v7.2) for the year 2015.
- River discharges at Hagestein, Lith and Tiel are updated to 2015 with Matroos database (every 10 minutes). Constant discharge at Eems, Kornwerderzand, Den Oever and Ijmuiden are imposed. Daily discharge at Schelle are collected from HIC and imposed to the model.
- The four barriers (Maeslant Barrier, Hartel Barrier, Eastern Scheldt Barrier and Ems) are being kept open for the 2015 run.
- The operation of the Haringvliet Sluices is modelled with updated river discharge at Tiel in 2015.

5.2.3 Validation results for 2015

Figure 10 shows the comparison of RMSE of complete time series between 2007 (calibration by Zijl., 2013, and re-ran at FHR) and 2015 run (validation). Figure 11 shows the corresponding vector differences calculated in the frequency domain. The model quality shows consistency in general.

Figure 10 – RMSE of complete time series of water levels for the year 2007 and 2015.

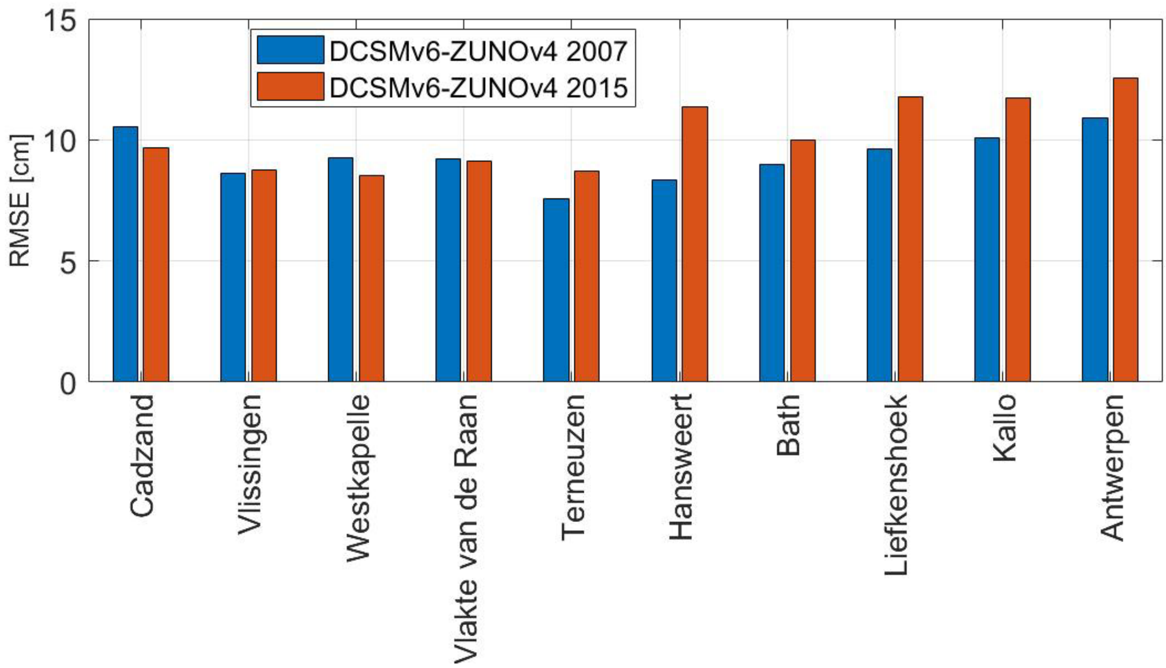
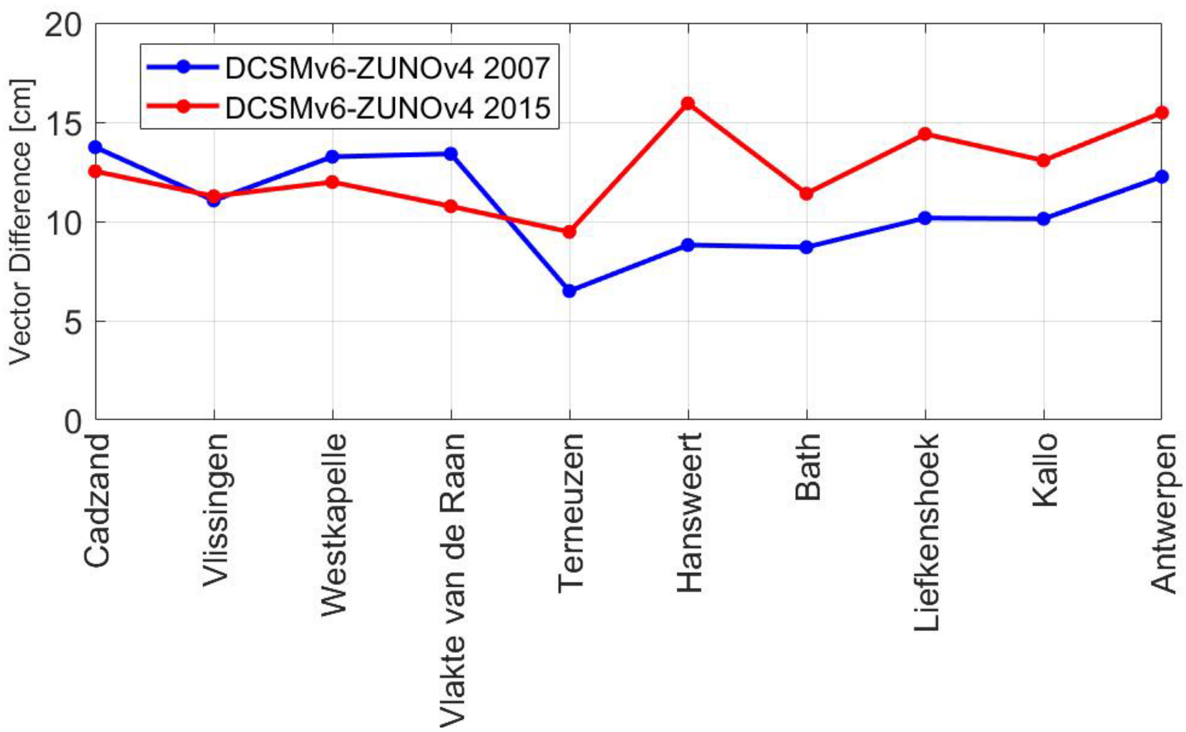


Figure 11 – Vector differences for the year 2007 and 2015.



5.3 DCSM-FM-0.5nm

5.3.1 Introduction

DCSM-FM-0.5nm model has been developed at Deltares as an application of Delft3D-Flexible-Mesh, a framework for hydrodynamic modelling of free-surface water systems. The calculation grid of the DCSM-FM model covers the northwestern part of the European Continental Shelf. The model grid is shown in Figure 12 and consists of approximately 630,000 cells with different resolutions (Figure 13). The largest calculation cells (shown in yellow) measure 1/10° in the longitude direction and 1/15° in the latitude direction, which corresponds to approximately 4 by 4 nautical miles (nm) or 4.9-8.1 by 7.4 km, depending on the latitude. The smallest cells (shown in red) have a resolution of 2/3' in longitude direction and 1/2' in latitude direction. This corresponds to approximately 0.5 by 0.5 nm or 840 by 930 m near the Dutch coast. Table 5 lists the general settings of the DCSM-FM-0.5nm. The calibration results reveal that the DCSM-FM-0.5nm model yields an overall RMSE of 11.1 cm for water level, which is fairly satisfactory.

Figure 12 – Model grid of DCFM-FM-0.5nm.

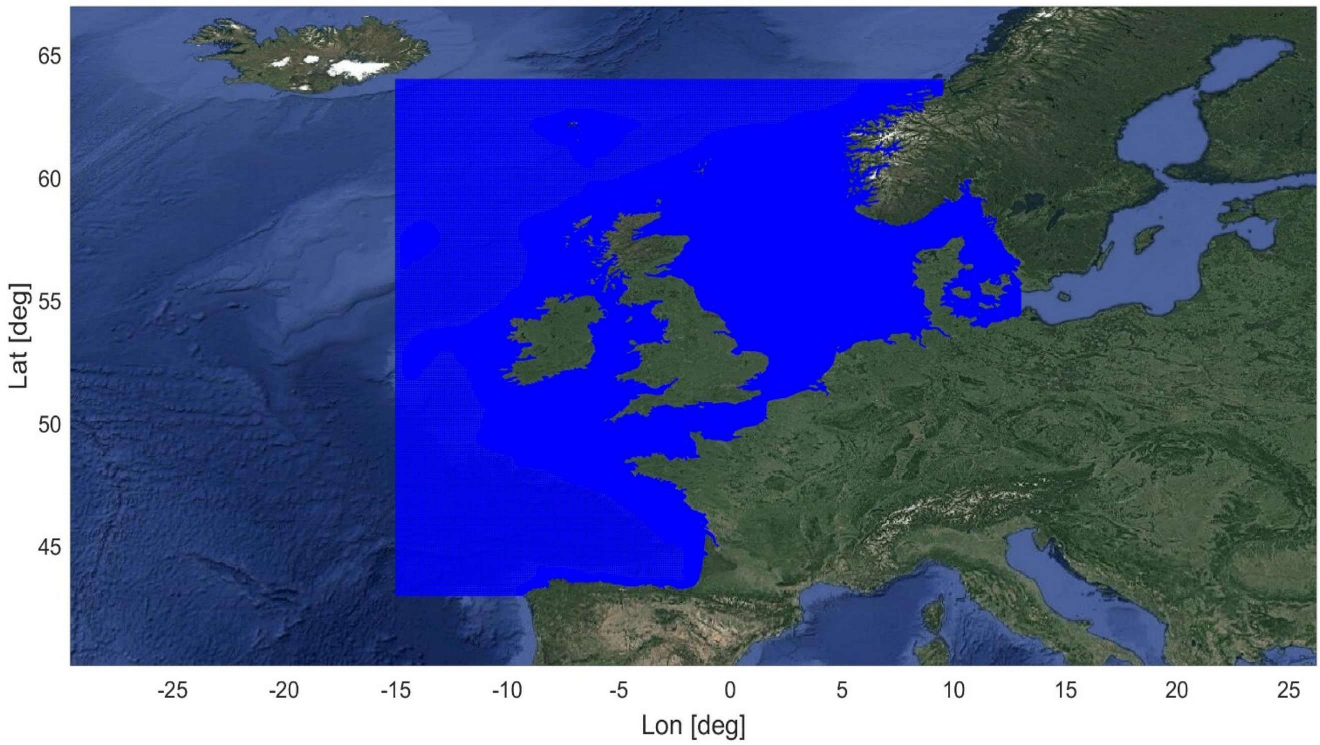


Figure 13 – Overview (left) and detail (right) of the DCSM-FM computational grid in which the colors indicate the resolution (yellow: ~ 4 nm; green: ~ 2 nm; blue: ~ 1nm; red: ~ 0.5 nm).

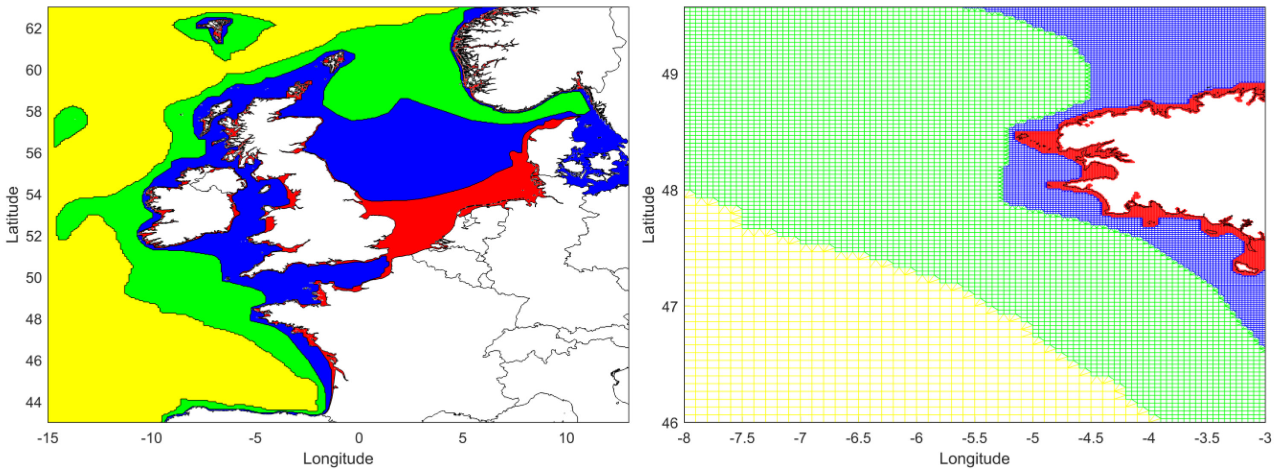


Table 5 – Parameter settings of the DCSM-FM-0.5nm.

Settings	DCSM-FM-0.5nm
Grid resolution	See Figure 13
Number of calculation nodes	630,000
Open boundary condition	1. Water level defined by 33 tidal constituents. 2. non-tidal effect of local pressure is considered with inversed barometer correction
Coordinate system	WGS84 geographical
Time Zone	GMT
Roughness	Spatial varying Manning values determined by automatic calibration with OpenDA
Tide generating force	Components of the tide with a Doodson number from 55.565 to 375.575 are included.
Wind	Spatial (~10×10 km) and temporal (hourly) varying wind field data from Hirlam (v7.2). Charnock coefficient = 0.025.
Drying and flooding	Threshold value of 0.0001 m.
Vertical reference	MSL
Time step	Dynamic time step, with maximum time step of 2 mins

5.3.2 Model set-up for 2015

As validation, the existing DCSM-FM-0.5nm model runs for the year 2015 with wind data of Hirlam7.2. Be aware that river discharges are not considered in this model.

5.4 DCSM-FM-100m

5.4.1 Introduction

DCSM-FM-100m model has been developed at Deltares as an application of Delft3D-Flexible-Mesh, a framework for hydrodynamic modelling of free-surface water systems. The calculation grid of the DCSM-FM-100m model covers the northwestern part of the European Continental Shelf, same as the DCSM-FM-0.5nm model. The model grid is shown in Figure 14 and consists of approximately 1,600,000 computational nodes with different resolutions (Figure 15). The highest mesh resolution of 100-200 meters are found at the Belgian and Dutch coast. Table 6 listed the general settings of the DCSM-FM-100m.

The model results reveal that the DCSM-FM-100m model yields an overall RMSE of 11.5 cm for water level, which is fairly satisfactory.

Figure 14– Model grid of DCFM-FM-100m

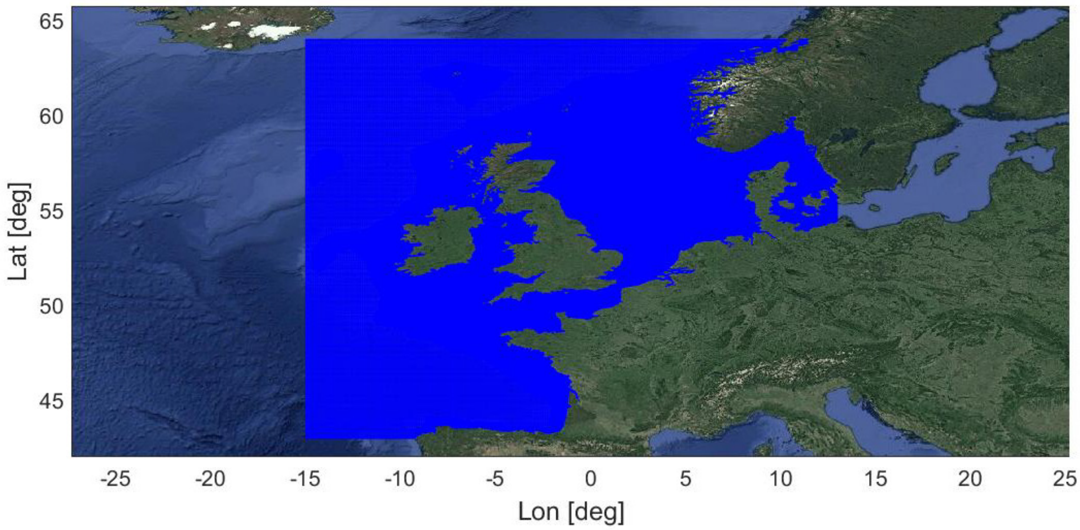
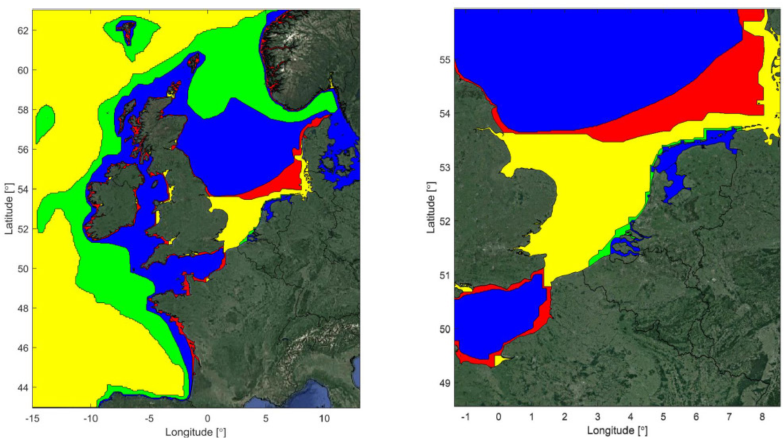


Figure 15 – Overview (left) and detail (right) of the DCSM-FM-100m calculation grid in which the colors indicate the resolution.



naut. miles	4	2	1	0.5	0.25	0.125	0.0625
meter	7200	3600	1800	900	450	200	100

Table 6 – Parameter settings of the DCSM-FM-100m model.

Settings	DCSM-FM-100m
Grid resolution	See Figure 15
Number of calculation nodes	1,600,000
Open boundary condition	1. Water level defined by 33 tidal constituents. 2. non-tidal effect of local pressure is considered with inversed barometer correction
Coordinate system	WGS84 geographical
Time Zone	GMT
Roughness	Spatial varying Manning values determined by automatic calibration with OpenDA
Tide generating force	Components of the tide with a Doodson number from 55.565 to 375.575 are included.
Wind	Spatial (~10×10 km) and temporal (hourly) varying wind field data from Hirlam (v7.2). Charnock coefficient = 0.025.
Drying and flooding	Threshold value of 0.0001 m.
Vertical reference	MSL
Time step	Dynamic time step, with maximum time step of 50 s

5.4.2 Model set-up for 2015

The existing DCSM-FM-100m model runs for the year 2015 with wind data of Hirlam7.2. Be aware that river discharges are not considered in this model.

6 Results of North Sea model comparison for 2015

6.1 Water Level Timeseries

6.1.1 High and Low water analysis

The overview of RMSE in each region for all the North Sea models is presented in Table 8. Table 9 to Table 11 compare the statistics of Bias, RMSE and RMSE0 (see definitions in Appendix A) of the complete time series, high water levels and low water levels respectively. The statistical values are color-coded by the definition shown in Table 7. The statistical values are also visually compared in Figure 26 to Figure 34 (Appendix C).

In general, DCSMv5-ZUNOv3 shows much larger errors which are not comparable with the other 3 models. For instance, the averaged RMSE for all the stations is 18.5 cm while the other 3 models produce RMSE of around 10 cm (see Table 8). This is due to the fact that DCSMv5-ZUNOv3 model uses a much coarser mesh which leads to less accurate representation of bottom gradient, which in turn distorts the tidal propagation. Therefore this model will not be further discussed hereafter.

The DCSMv6-ZUNOv4, DCSM-FM-0.5nm and DCSM-FM-100m produce broadly speaking similar results on water levels, although DCSMv6-ZUNOv4 leads to slightly better result (about 1 cm less on RMSE). At the Belgian coast, DCSMv6-ZUNOv4 gives the best predictions on water level with RMSE of 8.6 cm. At the Dutch coast, all the 3 models gives equally decent result with RMSE of 9 cm. The model errors at the British coast is relatively larger compared with the other regions, DCSMv6-ZUNOv4 gives the lowest RMSE of 12.6 cm while DFM-0.5nm and DFM-100m leads to slightly higher RMSE (14.8 and 15.8 cm respectively). At the French coast all the 3 models leads to similar values of RMSE (9.5-11.4 cm).

Table 7 – Definition of colour code in terms of bias, RMSE and RMSE0.

Legend	|Bias| [cm]	RMSE [cm]	RMSE0 [cm]
	0-5	0-5	0-5
	5-10	5-10	5-10
	10-15	10-15	10-15
	15-20	15-20	15-20
	>20	>20	>20

Table 8 – Summary of RMSE in each region from all the north sea models

Coastal Region	RMSE [cm]			
	ZUNOv3	ZUNOv4	DFM_0.5nm	DFM_100m
British	20.0	12.6	14.8	15.8
French	16.6	9.5	10.6	11.4
Belgian & Scheldt Mouth	18.2	8.6	10.4	9.6
Dutch	19.1	9.2	9.2	9.1
Overall	**18.5**	**9.9**	**11.2**	**11.5**

Table 9 – Comparison of Bias, RMSE and RMSE0 of the complete time series of water level.
The averaged statistics are calculated for the British, French, Belgian and Dutch coast respectively. ,

Region	Stations	Complete TimeSeries											
		BIAS [cm]				RMSE [cm]				RMSE_0 [cm]			
		ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m	ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m	ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m
British	Leith	1.7	-3.0	-2.4	-2.3	24.4	10.6	11.3	12.2	24.4	10.2	11.1	11.9
	North Shields	-8.8	-10.2	-9.9	-9.7	15.2	12.6	13.7	14.6	12.3	7.4	9.4	10.9
	Whitby	-18.1	-20.7	-20.7	-20.7	23.6	22.2	22.8	23.3	15.1	8.1	9.7	10.6
	Immingham	-25.3	-3.6	-3.4	-12.1	39.5	16.4	19.6	19.2	30.4	16.0	19.3	14.9
	Cromer	4.0	3.3	2.7	2.5	14.5	9.6	10.6	10.8	13.9	9.0	10.2	10.5
	Lowestoft	7.2	4.7	6.0	5.5	12.6	8.7	9.4	10.4	10.3	7.2	7.2	8.9
	Harwich	1.7	2.0	3.2	3.3	14.6	8.7	10.8	13.7	14.5	8.4	10.3	13.2
	Sheerness	12.1	13.7	11.7	9.4	19.6	16.5	18.7	25.1	15.4	9.3	14.6	23.3
	Dover	13.3	7.1	4.7	4.9	19.4	11.7	12.3	11.5	14.1	9.3	11.4	10.3
	Newhaven	10.1	9.0	9.6	9.7	18.6	11.4	15.0	15.4	15.6	6.9	11.6	11.9
	Portsmouth	6.9	5.8	8.8	8.8	17.8	9.8	18.5	18.0	16.4	7.9	16.2	15.7
	Absolute Average	**9.9**	**7.6**	**7.6**	**8.1**	**20.0**	**12.6**	**14.8**	**15.8**	**16.6**	**9.1**	**11.9**	**12.9**
French	CHERBOURG	5.2	3.6	3.8	4.3	13.7	8.2	7.6	9.7	12.7	7.4	6.6	8.7
	LEHAVRE	n/a	5.8	5.4	5.8	n/a	11.3	11.7	13.4	n/a	9.7	10.4	12.1
	BOULOGNE-SUR-MER	n/a	4.7	4.2	4.5	n/a	10.4	12.7	13.2	n/a	9.3	12.0	12.4
	CALAIS	4.3	3.2	4.0	3.5	19.5	8.4	9.7	9.4	19.1	7.8	8.8	8.7
	DUNKERQUE	n/a	5.0	6.4	6.6	n/a	9.1	11.2	11.4	n/a	7.6	9.2	9.3
	Absolute Average	**4.7**	**4.5**	**4.7**	**4.9**	**16.6**	**9.5**	**10.6**	**11.4**	**15.9**	**8.3**	**9.4**	**10.2**
Belgian & WES	Westhinder	2.4	0.4	0.9	1.0	14.6	6.7	8.3	8.2	14.4	6.7	8.3	8.2
	Nieuwpoort	5.9	3.0	2.8	3.2	19.4	8.8	11.1	10.9	18.5	8.2	10.7	10.5
	Oostende	7.3	3.7	3.4	3.0	18.8	8.5	10.3	9.1	17.4	7.7	9.7	8.6
	Cadzand	12.7	6.1	7.3	7.0	19.2	9.7	11.7	10.6	14.5	7.5	9.1	8.0
	Vlakte van de Raan	9.3	4.2	4.1	4.5	19.5	9.1	10.0	9.6	17.1	8.1	9.1	8.5
	Westkapelle	10.7	4.5	4.8	5.5	17.8	8.5	10.6	9.4	14.3	7.2	9.5	7.6
	Vlissingen	9.7	4.0	3.5	4.0	17.9	8.8	10.7	9.0	15.0	7.8	10.1	8.0
	Absolute Average	**8.3**	**3.7**	**3.8**	**4.0**	**18.2**	**8.6**	**10.4**	**9.6**	**15.9**	**7.6**	**9.5**	**8.5**
Dutch	OS11	n/a	5.1	4.6	4.9	n/a	8.8	8.8	8.8	n/a	7.1	7.5	7.4
	OS04	n/a	4.4	3.0	4.4	n/a	9.2	8.8	8.5	n/a	8.0	8.2	7.3
	OS14	10.3	3.5	3.5	3.4	19.3	8.3	8.4	8.1	16.3	7.5	7.6	7.4
	BG2	12.1	6.3	6.1	6.5	18.8	10.2	9.9	10.0	14.4	8.0	7.9	7.6
	Haringvliet10	14.0	6.1	6.1	6.6	19.2	9.5	9.9	9.9	13.1	7.3	7.8	7.4
	Absolute Average	**12.1**	**5.1**	**4.6**	**5.2**	**19.1**	**9.2**	**9.2**	**9.1**	**14.6**	**7.6**	**7.8**	**7.4**
Overall		**8.8**	**5.2**	**5.2**	**5.6**	**18.5**	**9.9**	**11.2**	**11.5**	**15.7**	**8.1**	**9.6**	**9.8**

Table 10 – Comparison of Bias, RMSE and RMSE0 of high water levels.
The averaged statistics are calculated for the British, French, Belgian and Dutch coast respectively.

Region	Stations	High Water Levels											
		BIAS [cm]				RMSE [cm]				RMSE_0 [cm]			
		ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m	ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m	ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m
British	Leith	-4.3	-0.5	-0.5	-9.2	16.6	7.7	8.3	12.5	16.0	7.7	8.3	8.5
	North Shields	-13.2	-14.0	-10.2	-15.3	16.6	15.4	12.2	17.1	10.1	6.4	6.8	7.6
	Whitby	-19.3	-24.0	-18.6	-25.2	22.3	25.0	19.9	26.5	11.3	7.2	7.2	8.2
	Immingham	-23.1	0.0	-12.4	-1.4	25.1	7.7	15.0	8.2	9.9	7.7	8.5	8.1
	Cromer	5.0	3.7	11.6	11.1	12.4	8.2	14.1	13.6	11.4	7.3	8.0	7.8
	Lowestoft	10.2	4.2	4.3	6.3	13.4	7.9	7.9	9.3	8.7	6.7	6.6	6.8
	Harwich	-0.8	0.3	-1.6	-6.3	10.5	8.0	9.4	12.0	10.5	8.0	9.2	10.2
	Sheerness	2.4	22.3	28.1	15.5	8.4	23.6	29.0	17.0	8.0	7.8	6.9	7.2
	Dover	17.1	14.8	12.9	11.7	19.9	16.3	14.4	13.4	10.1	6.8	6.5	6.5
	Newhaven	4.9	10.1	11.2	11.7	10.6	11.5	12.5	12.8	9.3	5.5	5.5	5.2
	Portsmouth	10.7	1.8	16.7	13.1	13.4	6.1	17.8	14.1	8.0	5.8	6.3	5.4
	Absolute Average	**10.1**	**8.7**	**11.6**	**11.5**	**15.4**	**12.5**	**14.6**	**14.2**	**10.3**	**7.0**	**7.2**	**7.4**
French	CHERBOURG	6.7	-3.0	0.2	-4.3	10.4	6.5	4.6	6.9	7.9	5.8	4.6	5.3
	LEHAVRE	n/a	2.9	12.4	11.5	n/a	8.4	15.8	15.3	n/a	7.9	9.9	10.1
	BOULOGNE-SUR-MER	n/a	5.6	4.2	6.2	n/a	8.4	6.7	8.2	n/a	6.2	5.3	5.4
	CALAIS	-5.7	2.1	-0.8	2.0	11.3	5.6	5.2	5.6	9.8	5.2	5.1	5.2
	DUNKERQUE	n/a	5.7	4.6	4.8	n/a	7.9	7.0	7.3	n/a	5.6	5.2	5.5
	Absolute Average	**6.2**	**3.9**	**4.4**	**5.7**	**10.8**	**7.4**	**7.9**	**8.6**	**8.9**	**6.1**	**6.0**	**6.3**
Belgian & WES	Westhinder	4.6	1.3	0.6	0.8	9.5	5.7	5.4	5.7	8.4	5.6	5.4	5.6
	Nieuwpoort	6.9	4.2	1.2	3.7	10.9	7.1	5.7	6.8	8.4	5.7	5.5	5.7
	Oostende	8.3	7.5	4.4	3.8	11.6	9.3	6.9	6.7	8.1	5.5	5.4	5.5
	Cadzand	4.6	7.0	-2.7	2.6	12.0	9.4	7.6	6.8	11.0	6.3	7.1	6.2
	Vlakte van de Raan	15.0	3.3	-1.8	1.0	17.9	7.9	7.3	6.9	9.7	7.2	7.1	6.8
	Westkapelle	4.4	5.6	-4.9	1.7	11.5	8.4	8.5	6.3	10.6	6.2	6.9	6.1
	Vlissingen	-5.7	5.8	-6.8	-2.2	14.1	8.6	9.5	6.9	12.9	6.4	6.6	6.5
	Absolute Average	**7.1**	**5.0**	**3.2**	**2.3**	**12.5**	**8.1**	**7.3**	**6.6**	**9.9**	**6.1**	**6.3**	**6.1**
Dutch	OS11	n/a	2.6	-3.8	-1.6	n/a	6.8	8.0	6.8	n/a	6.3	7.0	6.6
	OS04	n/a	6.0	1.2	-0.4	n/a	8.7	7.4	6.9	n/a	6.3	7.3	6.8
	OS14	6.7	4.1	1.1	-1.6	12.2	7.3	6.4	6.4	10.2	6.0	6.4	6.2
	BG2	11.1	8.2	4.5	1.8	15.3	10.9	8.7	7.7	10.5	7.1	7.4	7.5
	Haringvliet10	14.9	7.1	3.6	0.0	17.8	9.6	7.9	7.0	9.7	6.5	7.0	7.0
	Absolute Average	**10.9**	**5.6**	**2.8**	**1.1**	**15.1**	**8.6**	**7.7**	**7.0**	**10.1**	**6.4**	**7.0**	**6.8**
Overall		**8.6**	**5.8**	**5.5**	**5.2**	**13.5**	**9.1**	**9.3**	**9.1**	**9.8**	**6.4**	**6.6**	**6.7**

Table 11 – Comparison of Bias, RMSE and RMSE0 of low water levels.
The averaged statistics are calculated for the British, French, Belgian and Dutch coast respectively.

Region	Stations	Low Water Levels											
		BIAS [cm]				RMSE [cm]				RMSE_0 [cm]			
		ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m	ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m	ZUN Ov3	ZUN Ov4	DFM_0.5nm	DFM_100m
British	Leith	-0.1	-2.5	-6.1	-1.8	14.5	11.0	11.2	10.1	10.7	14.5	9.4	9.9
	North Shields	-8.4	-9.5	-10.2	-5.1	13.4	11.9	12.7	9.8	7.1	10.4	7.6	8.4
	Whitby	-21.6	-19.9	-23.8	-17.6	25.2	21.1	24.7	19.0	7.1	13.0	6.5	7.4
	Immingham	13.4	-18.0	-5.5	-1.1	17.3	19.0	6.7	6.8	6.1	10.8	3.8	6.7
	Cromer	3.6	8.4	4.0	4.1	12.5	11.2	8.5	8.9	7.4	12.0	7.5	7.9
	Lowestoft	2.2	3.8	7.6	4.1	9.5	7.7	9.9	7.6	6.7	9.3	6.5	6.4
	Harwich	-2.6	2.4	2.4	5.9	9.9	8.0	8.2	10.0	7.7	9.5	7.9	8.1
	Sheerness	18.3	4.7	12.8	18.3	19.7	7.1	13.9	19.6	5.2	7.2	5.5	6.9
	Dover	16.8	-0.8	-3.3	-2.6	19.6	6.7	8.2	7.8	6.6	10.0	7.5	7.3
	Newhaven	17.3	7.3	7.2	7.7	19.5	9.7	9.5	9.8	6.4	9.0	6.1	6.1
	Portsmouth	11.4	4.4	15.1	8.8	15.4	7.7	19.5	14.0	6.4	10.3	12.4	10.8
	Absolute Average	**10.5**	**7.4**	**8.9**	**7.0**	**16.0**	**11.0**	**12.1**	**11.2**	**7.0**	**10.5**	**7.3**	**7.8**
French	CHERBOURG	19.0	10.5	9.6	17.2	21.3	13.2	11.6	19.0	8.0	9.5	6.6	8.1
	LEHAVRE	n/a	10.4	8.0	10.1	n/a	13.0	10.7	12.5	7.7	n/a	7.2	7.4
	BOULOGNE-SUR-MER	n/a	3.6	7.4	7.6	n/a	7.8	10.2	10.4	7.0	n/a	7.0	7.2
	CALAIS	23.5	4.4	14.2	9.9	25.8	8.8	16.3	12.5	7.6	10.7	7.9	7.7
	DUNKERQUE	n/a	2.0	10.1	10.4	n/a	7.9	12.6	13.1	7.6	n/a	7.5	8.0
	Absolute Average	**21.3**	**6.2**	**9.9**	**11.0**	**23.5**	**10.1**	**12.3**	**13.5**	**7.6**	**10.1**	**7.2**	**7.6**
Belgian & WES	Westhinder	3.5	-1.1	0.8	1.5	9.3	7.5	7.1	7.3	7.4	8.6	7.0	7.1
	Nieuwpoort	7.2	-1.8	0.8	0.0	11.1	7.9	7.4	7.4	7.7	8.4	7.4	7.4
	Oostende	10.6	0.3	1.2	1.3	13.8	7.6	7.3	7.3	7.6	8.8	7.2	7.2
	Cadzand	14.0	2.8	7.8	6.5	17.1	8.4	11.1	10.0	7.9	9.8	7.9	7.6
	Vlakte van de Raan	-4.2	1.3	0.5	1.5	10.3	8.6	8.1	8.2	8.5	9.4	8.1	8.1
	Westkapelle	9.7	2.8	6.6	5.7	13.2	8.1	9.9	9.2	7.6	9.0	7.3	7.2
	Vlissingen	15.4	-0.1	2.8	3.2	18.5	7.9	8.2	8.2	7.9	10.1	7.7	7.5
	Absolute Average	**9.2**	**1.5**	**2.9**	**2.8**	**13.3**	**8.0**	**8.4**	**8.2**	**7.8**	**9.2**	**7.5**	**7.4**
Dutch	OS11	n/a	5.5	5.7	6.0	n/a	9.8	9.4	9.7	8.1	n/a	7.5	7.5
	OS04	n/a	0.2	-2.5	5.0	n/a	7.3	7.6	8.8	7.3	n/a	7.2	7.2
	OS14	8.0	2.2	1.2	5.5	12.5	7.9	7.5	9.3	7.6	9.6	7.4	7.5
	BG2	5.8	4.2	3.3	7.8	11.0	8.6	8.1	10.8	7.5	9.4	7.4	7.4
	Haringvliet10	5.3	4.9	4.7	9.2	11.3	9.0	8.7	11.8	7.5	10.0	7.3	7.4
	Absolute Average	**6.3**	**3.4**	**3.5**	**6.7**	**11.6**	**8.5**	**8.3**	**10.1**	**7.6**	**9.7**	**7.4**	**7.4**
Overall		**11.8**	**4.6**	**6.3**	**6.9**	**16.1**	**9.4**	**10.3**	**10.8**	**7.5**	**9.9**	**7.4**	**7.6**

6.1.2 Surge analysis

In this section, the low-passed averaged error signal is evaluated. We apply a three step low-pass filter according to Godin (1972) to a timeseries to remove tidal and higher frequency signals to obtain the residual signal. The filter applies a moving average over periods of 25, 24 and 25 hours respectively. By removing the tidal signal out of the error signal, we get a measure of the non-tidally varying part of the error. Surge is an important component of this error.

Table 12 presents the comparison of RMSE of surge between all the North Sea models (see detailed table in Appendix D). Similar to the patterns of RMSE of total water level signal, DCSMv5-ZUNOv3 again produces larger RMSE of surge (10 cm) compared with the rest 3 models (7.2, 7.2 and 7.4 cm).

At the Belgian coast, the lowest RMSE of surge is around 5.5 cm from the DCSMv6-ZUNOv4 model.

Table 12 – Summary of RMSE of surge in each region from all the north sea models

	RMSE [cm]			
Region	ZUNOv3	ZUNOv4	DFM_0.5nm	DFM_100m
British	9.6	9.1	9.2	9.3
French	6.4	5.9	6.1	6.3
Belgian & WES	9.7	5.5	5.7	5.8
Dutch	14.0	6.7	6.2	6.8
Overall	10.0	7.2	7.2	7.4

6.2 Harmonic Analysis of Water Levels

Table 14 compares the bias of M2 amplitude and phase between different models (also shown in Figure 17 and Figure 18). Broadly speaking DCSMv6-ZUNOv4 produces the lowest errors of M2 amplitude (2.1 cm) and phase (0.6 deg) while the largest errors are found with DCSMv5-ZUNOv3 (4.4 cm and 3.7 deg). However at the Belgian and Dutch coast, DFM_100m leads to the best predictions on M2 amplitude with bias of 1.4 cm and 1.8 cm respectively.

Figure 16 presents the comparison of the Z0 component. All the models except DCSMv5-ZUNOv3 produce similar result. At the Belgian coast, the Z0 component is overestimated by about 5 cm. There is no clear reason why Z0 seams to increase along the Belgian coast. Note that the Z0 error is strongly dependant on the period which is analysed. The behaviour of the Z0 error over different choces of analysis period has not been considered in this study.

Figure 19 summarizes the vector difference in the frequency domain, from which DCSMv6-ZUNOv4 leads to the lowest vector difference at Belgian coast (around 11 cm).

Table 13 – Definition of colour code in terms of bias of tidal amplitude and phase.

Legend	|Bias| Amplitude [cm]	|Bias| Phase [deg]
	0-2.5	0-1.5
	2.5-5	1.5-3
	5-7.5	3-4.5
	7.5-10	4.5-6
	>10	>6

Table 14 – Comparison of M2 amplitude and phase between all the models.

	Bias of M2 Amplitude [cm]				Bias of M2 Phase [deg]			
	ZUNOv3	ZUNOv4	DFM_0.5nm	DFM_100m	ZUNOv3	ZUNOv4	DFM_0.5nm	DFM_100m
Leith	1.1	-0.7	-1.5	-5.5	5.2	-0.4	0.0	0.4
North Shields	-4.1	-0.8	1.9	-2.5	1.5	0.2	-2.2	-3.1
Cromer	1.9	-0.3	4.3	4.0	2.1	-1.5	-1.9	-2.2
Lowestoft	2.3	0.4	-0.5	1.7	0.8	1.5	-1.4	-5.3
Harwich	3.1	0.6	0.5	-4.0	-4.3	-0.4	2.9	5.3
Newhaven	-6.8	2.2	1.5	2.9	-3.2	-0.8	-2.8	-2.9
Portsmouth	0.7	1.3	0.5	4.7	-3.6	-0.8	3.1	2.0
Absolute Average	2.9	0.9	1.5	3.6	3.0	0.8	2.0	3.0
CHERBOURG	-6.8	-4.0	-2.0	-7.0	-1.3	-0.2	0.3	0.2
LEHAVRE	NaN	-0.6	2.0	3.3	NaN	0.1	-0.2	-1.6
BOULOGNE-SUR-MER	NaN	2.2	1.3	0.8	NaN	-1.2	-2.0	-2.2
CALAIS	-11.9	0.6	-3.6	-2.5	-3.1	-0.7	-0.6	-1.2
DUNKERQUE	NaN	2.5	-0.3	-3.0	NaN	-0.6	-1.9	-1.7
Absolute Average	9.4	2.0	1.8	3.3	2.2	0.6	1.0	1.4
Westhinder	-0.7	1.5	0.3	-1.2	-4.4	-0.3	-2.1	-2.0
Nieuwpoort	-0.6	3.7	0.7	0.6	-5.5	-0.9	-2.8	-2.7
Oostende	-2.4	4.0	1.1	-0.2	-5.5	-0.4	-2.8	-2.1
Cadzand	-6.9	2.8	-5.9	-3.0	-3.6	-0.4	-0.5	-1.3
Vlakte van de Raan	6.7	2.7	-0.6	0.1	-5.6	0.2	-2.0	-1.7
Westkapelle	-4.2	2.6	-5.6	-2.0	-4.3	0.1	-2.0	-1.6
Vlissingen	-12.2	3.5	-6.7	-2.9	-0.4	-0.2	-0.5	-0.9
Absolute Average	4.8	3.0	3.0	1.4	4.2	0.4	1.8	1.8
OS11	NaN	0.8	-2.4	-2.0	NaN	0.1	-1.0	-1.2
OS04	NaN	4.0	3.0	-1.0	NaN	-0.9	-1.7	-1.0
BG2	1.8	3.9	2.8	-1.6	-6.3	-0.3	-0.3	-1.1
Haringvliet10	4.3	3.1	3.3	-2.5	-5.7	0.6	1.4	-0.1
Absolute Average	3.1	3.0	2.9	1.8	6.0	0.5	1.1	0.9
Overall	4.4	2.1	2.3	2.6	3.7	0.6	1.6	1.9

Figure 16 – Comparison of Z0 component.

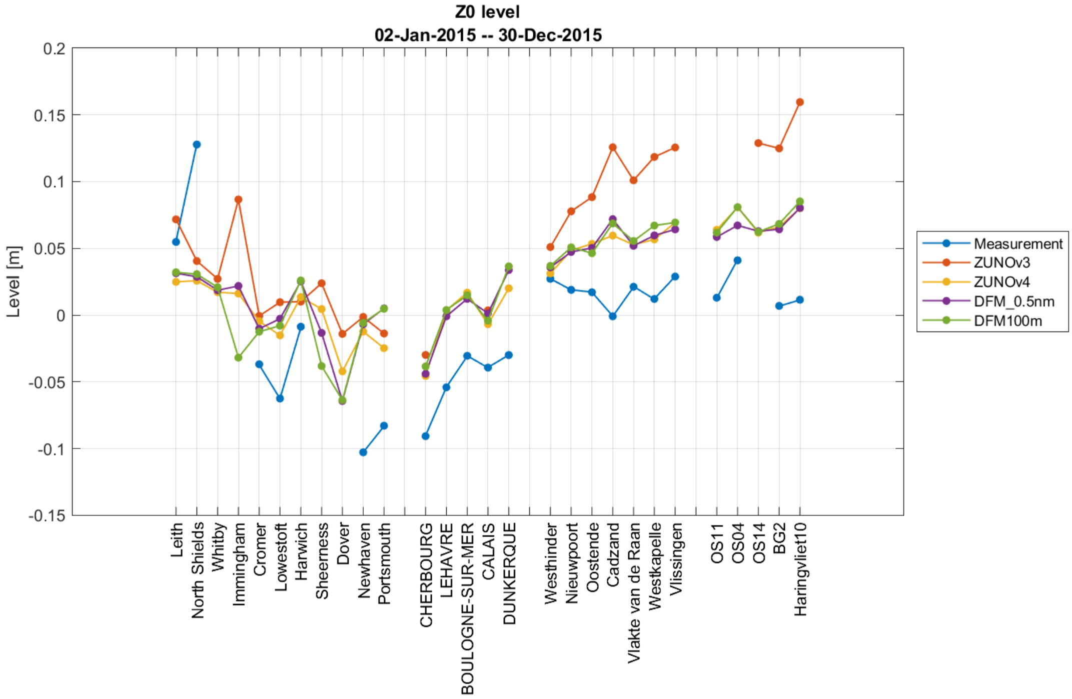


Figure 17 – Comparison of M2 amplitude.

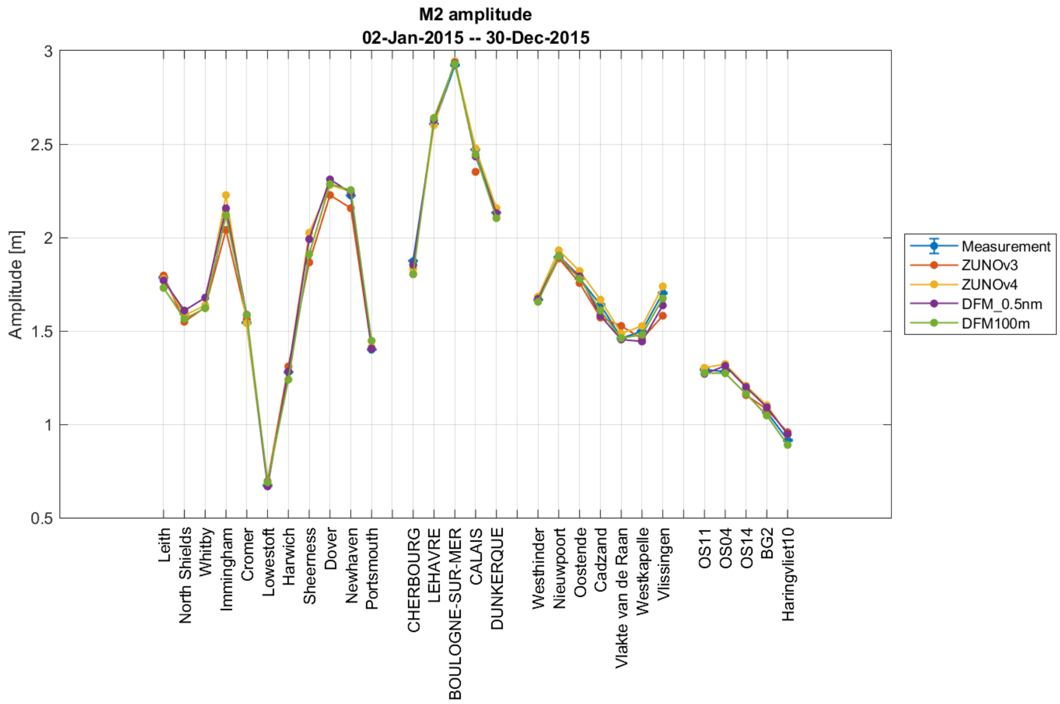


Figure 18 – Comparison of M2 phase.

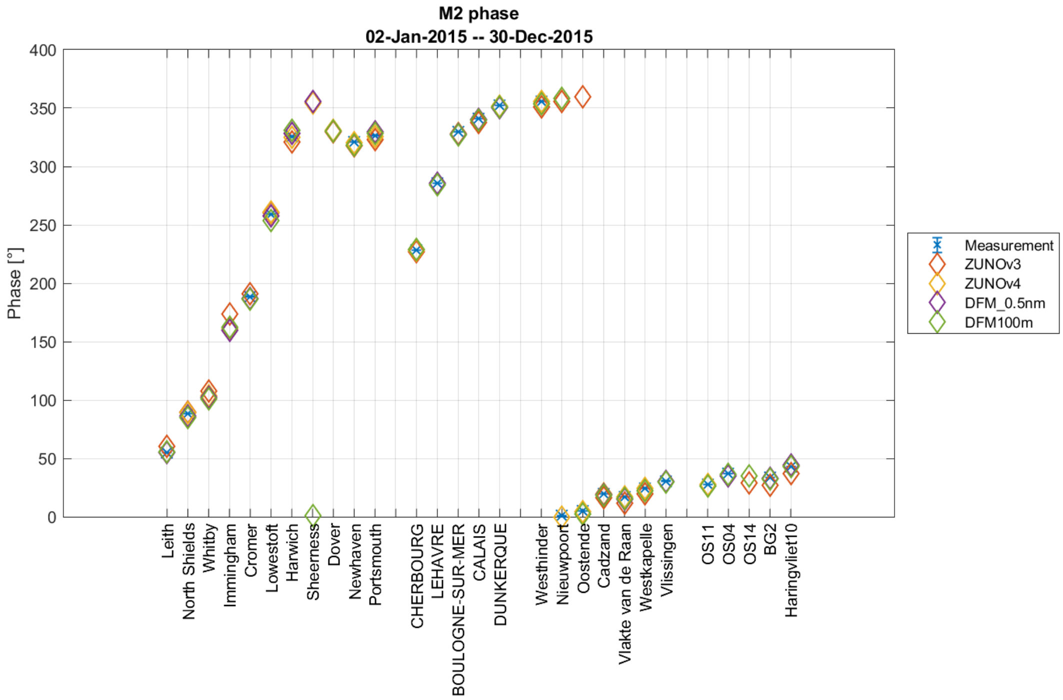
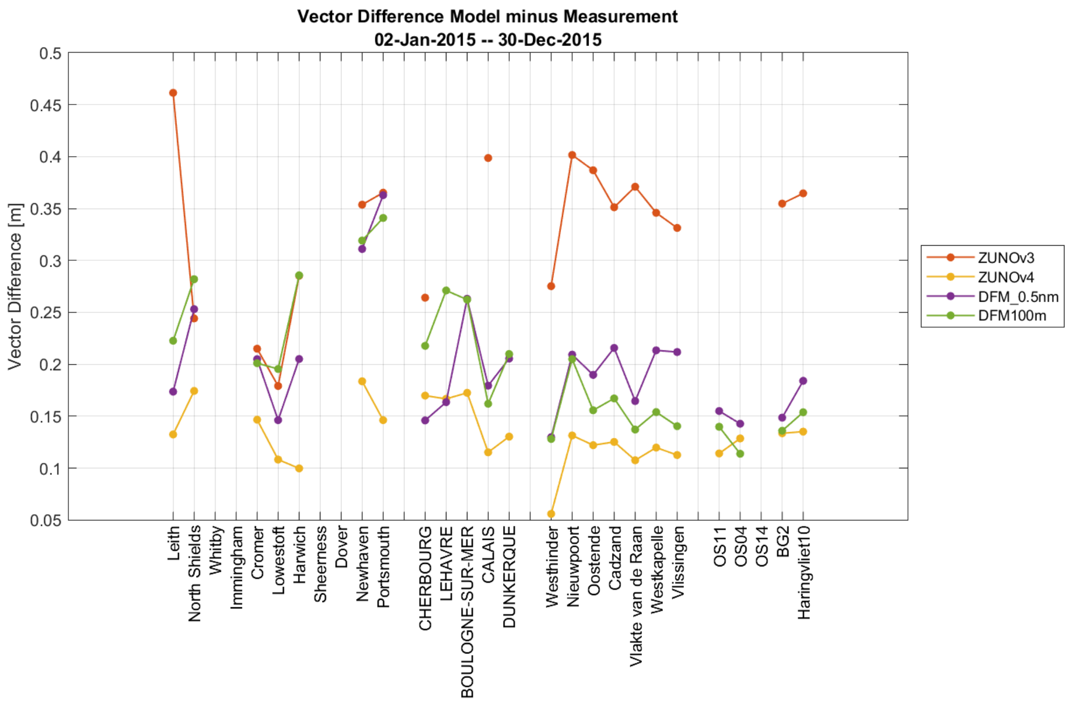


Figure 19 – Comparison of Vector difference.



6.3 Comparison for stormy period

The comparison carried out above is based on the statistics over the entire year of 2015. The model quality for a more stormy period is evaluated in this section. The stormy period (including the maximum wind speed of 24 m/s) is selected based on measured wind data at Vlakte van de Raan (see Figure 20).

Table 15 shows the RMSE for each region. Figure 21 and Figure 22 shows the comparison of RMSE in time domain and vector difference in the frequency domain respectively for a stormy period between 01/11/2015 and 30/12/2015. The DCSM-FM-100m shows the best results at the Belgian coast with averaged RMSE of 8.1 cm. The two DCSM-FM models lead to averaged RMSE of 8.9 cm.

Figure 20 – Wind speed and direction of 2015 at vlakte van de raan (data source: HMCZ).
The green shadow indicate the stormy period between 01/11/2015 and 30/12/2015.

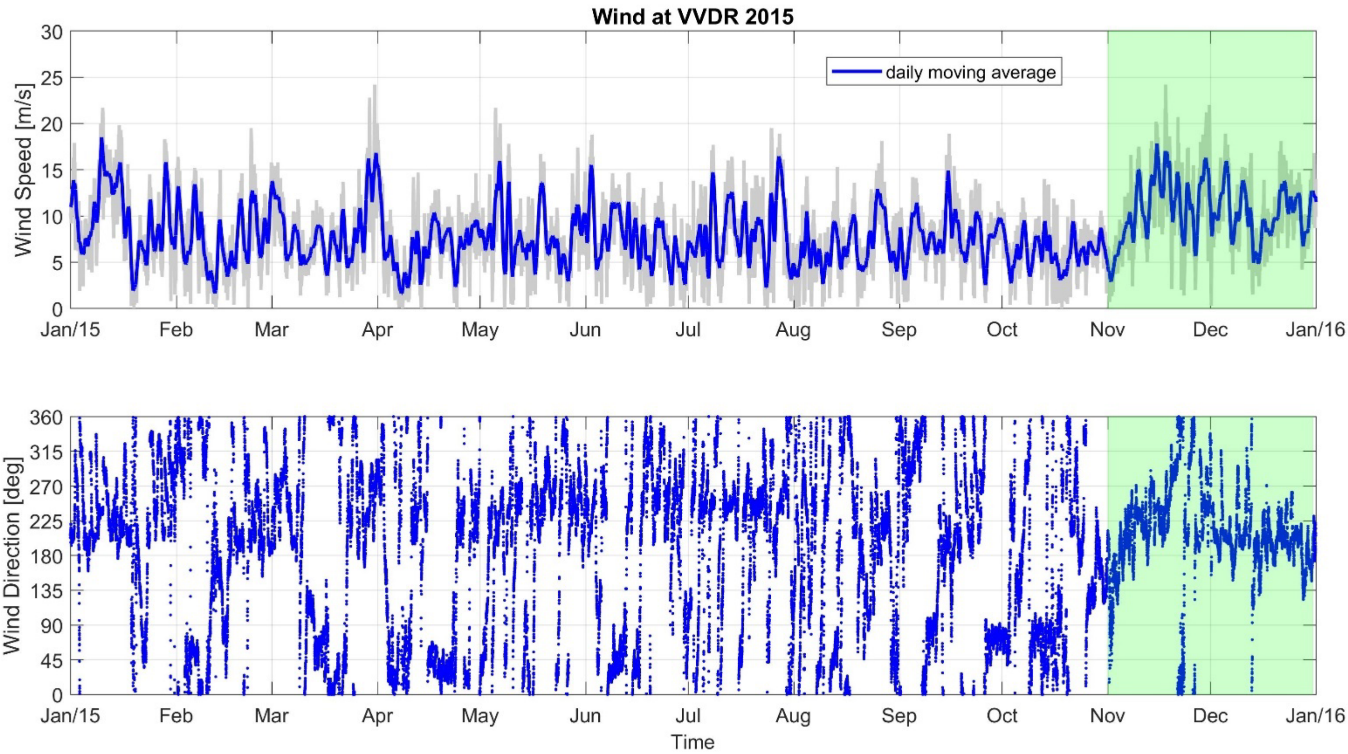


Table 15 – Summary of RMSE in each region from all the north sea models for the stormy period between 01/11/2015 and 30/12/2015.

	RMSE [cm]			
	ZUNOv3	ZUNOv4	DFM_0.5nm	DFM_100m
British	17.5	10.9	12.9	13.5
French	15.5	8.2	8.8	9.5
Belgian & WES	16.7	8.9	8.9	8.1
Dutch	19.5	9.3	9.1	8.7
Overall	17.3	9.3	9.9	9.9

Figure 21 – RMSE during 01/11/2015 to 30/12/2015 (stormy period).

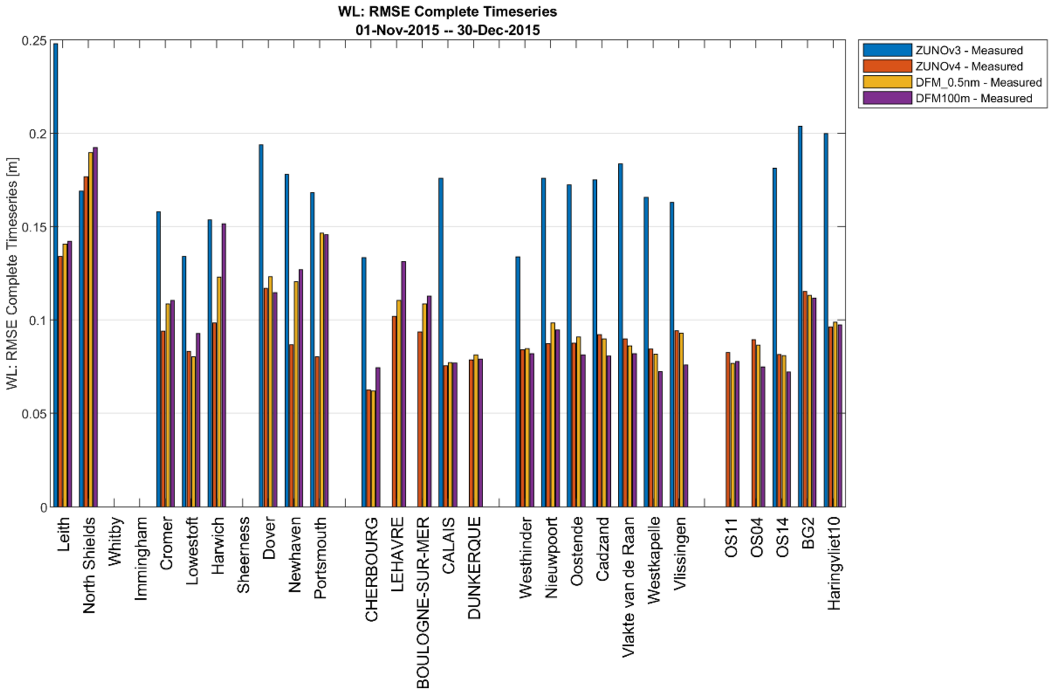
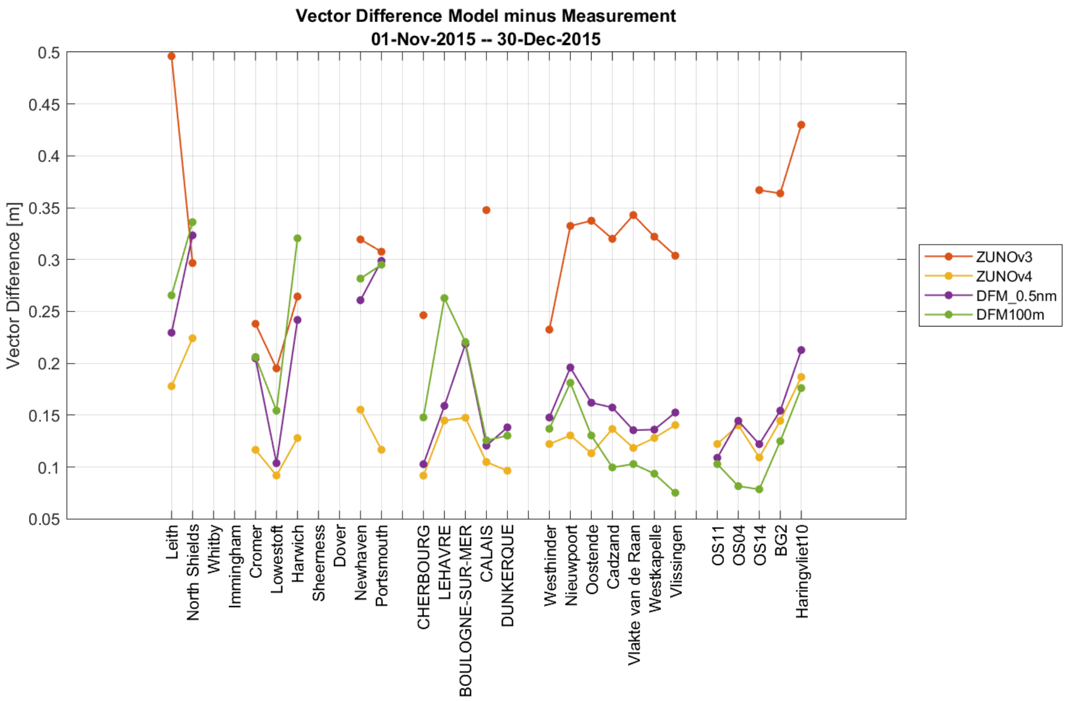


Figure 22 – Vector difference during 01/11/2015 to 30/12/2015 (stormy period).



7 Sensitivity of source of wind data

Currently all the North Sea models are forced with wind data from Hirlam7.2, to which FHR does not have direct access. Therefore in preparation for the long-term modelling at FHR for future, we tested the quality of ERA5 hourly wind and pressure data provided by ECMWF in this section.

The DCSMv6-ZUNOv4 is chosen for the sensitivity analysis. Four model simulations are compared as shown in Table 16. Table 17 and Figure 23 presents the resulted RMSE for the entire year of 2015. As wind forcing are more pronounced during stormy events, Table 18 and Figure 24 shows the comparison of RMSE for a stormy period between 01/11/2015 and 30/12/2015 (see Figure 20).

For the entire year comparison, using ECWMF-ERA5 forcing with a variable Charnock coefficient yields a model quality that is slightly better than using HIRLAM forcing or ECMWF forcing with a constant Charnock coefficient. However, the difference of RMSE are less than 1cm.

For the stormy period, using Hirlam7.2 forcing yields slightly better results for the Belgium coast and Western Scheldt (averaged RMSE 8.9 cm), compared with using ECWMF-ERA5 forcing with a variable Charnock coefficient (averaged RMSE is 9.5 cm at Belgium coast and Western Scheldt). Figure 25 exmplifies the water level predicted at Vlakte van de Raan under stormy conditions.

The above-described findings agree with the conclusions drawn by Zijl (2017). In general using ECMWF-ERA5 wind forcing yields comparable results to using Hirlam wind forcing. In the future, this could be an option to drive the North Sea models at FHR.

Table 16 – Overview of the DCSMv6-ZUNOv4 model runs for sensitivity analysis on various types of meteorological forcing.

Meteorological model	Wind drag parameter (Charnock coefficient)
HIRLAM 7.2	0.025
ECMWF - ERA5	0.025
ECMWF - ERA5	0.041
ECMWF - ERA5	Space and time varying field from ERA5

Table 17 – Summary of RMSE in each region from different wind source for the entire year of 2015.

	RMSE [cm]			
	HIRLAM 7.2	ERA5_0.025	ERA5_0.041	ERA5_Var
British	12.6	12.6	12.5	12.4
French	9.5	9.4	9.3	9.2
Belgian & WES	8.6	8.8	8.5	8.3
Dutch	9.2	9.2	9.1	8.6
Overall	9.9	10.0	9.8	9.6

Table 18 – Summary of RMSE in each region from different wind source for the stormy period between 01/11/2015 and 30/12/2015.

	HIRLAM 7.2	ERA5_0.025	ERA5_0.041	ERA5_Var
British	10.9	10.8	10.4	10.7
French	8.2	8.9	8.2	8.6
Belgian & WES	8.9	10.5	9.1	9.5
Dutch	9.3	10.0	9.2	8.8
Overall	9.3	10.0	9.2	9.4

Figure 23 – RMSE between using different wind sources, for the entire year of 2015.

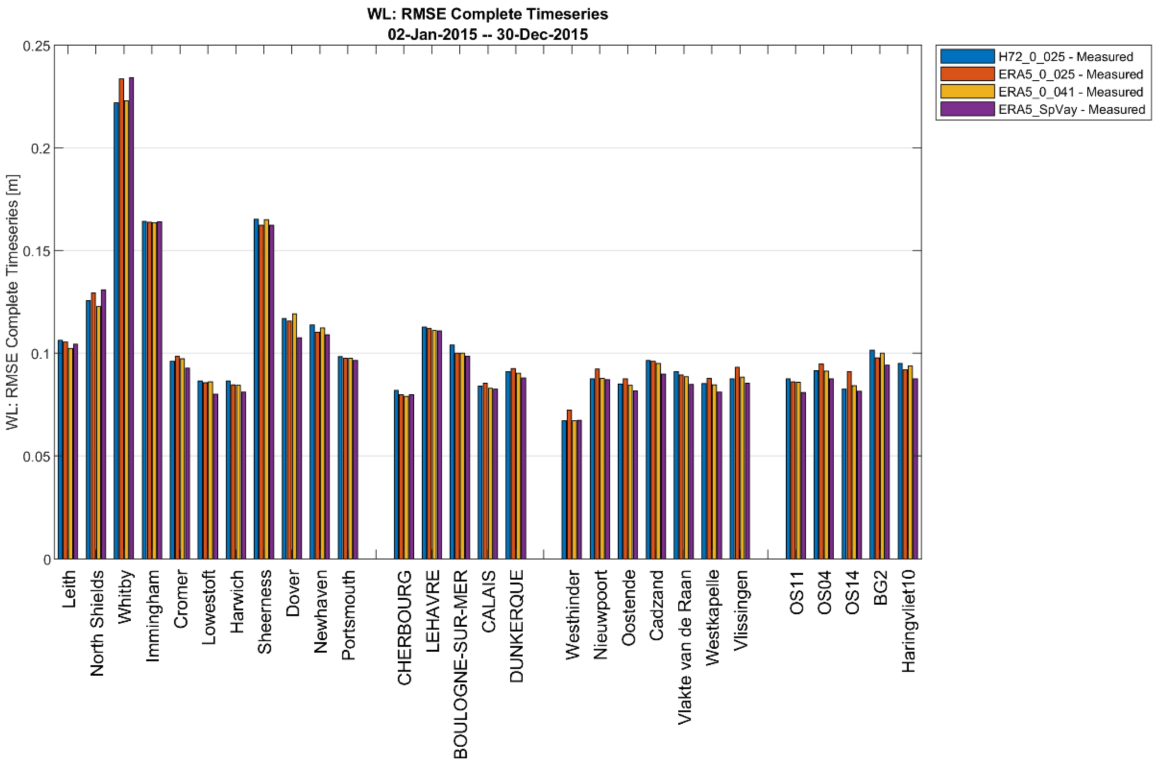


Figure 24 – RMSE between using different wind sources, for November and December 2015 (stormy).

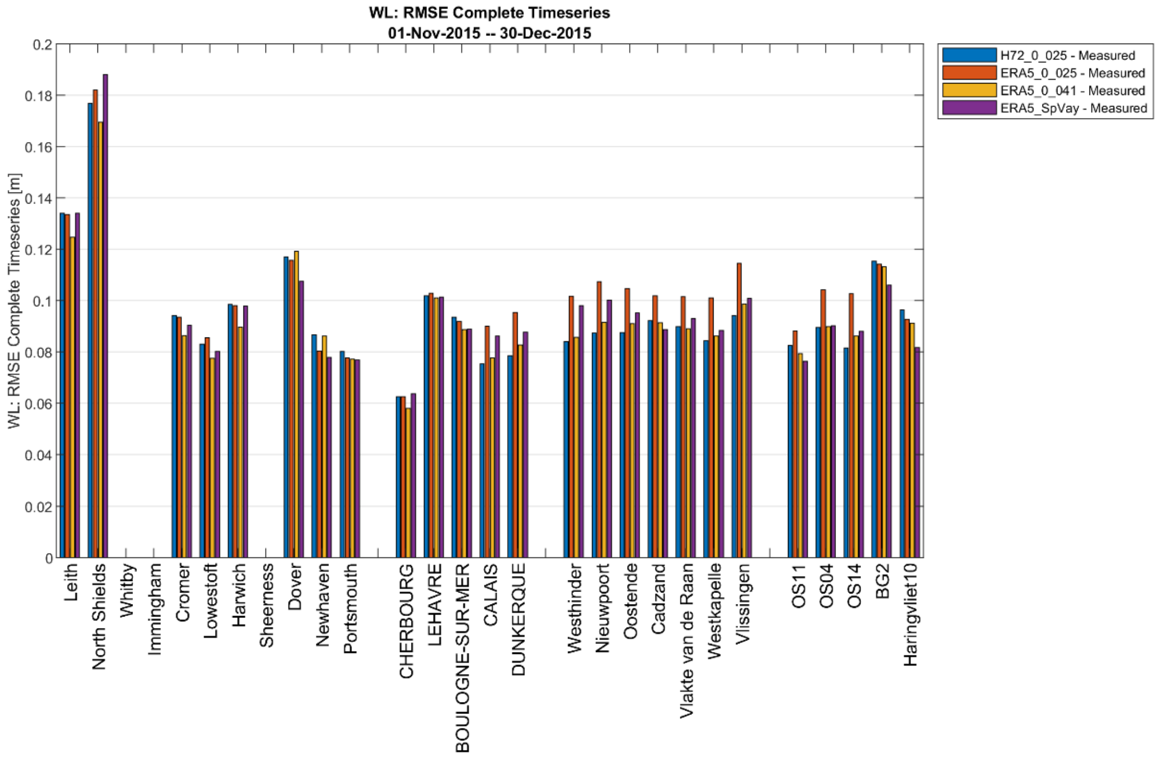
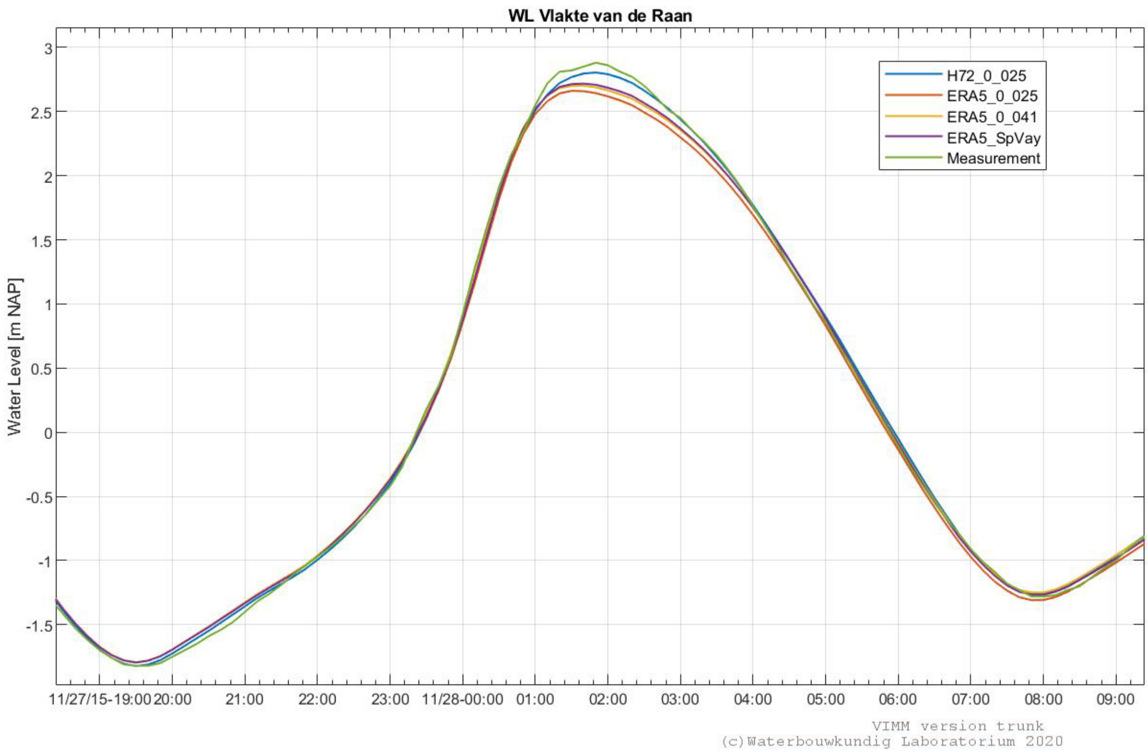


Figure 25 – Example of water level during one tidal cycle at Vlakte van de Raan during storm.



8 Conclusions

This study compares four different North Sea model schematisations (each developed at Deltares) in a hindcast of water levels for 2015. The main findings are:

- In general the DCSMv5-ZUNOv3 model produces the largest RMSE of water level when compared with the other 3 model schematisations. This might be due to the fact that the DCSMv5-ZUNOv3 model uses a much coarser mesh which leads to less accurate representation of the bottom gradient, which distorts the tidal propagations.
- The DCSMv6-ZUNOv4, DCSM-FM-0.5nm and DCSM-FM-100m models produce broadly speaking similar results on water levels, although DCSMv6-ZUNOv4 leads to slightly better results (about 1 cm less on RMSE).
- At the Belgian coast, DCSMv6-ZUNOv4 gives the best predictions on water level with a RMSE of 8.6 cm. The lowest RMSE of surge is around 5.5 cm predicted by the DCSMv6-ZUNOv4 model.
- At the Dutch coast, all the 3 models gives equally decent result with a RMSE of 9 cm.
- The RMSE at the British coast is relatively larger compared with the other regions for all models.
- In the frequency domain, the Z0 component is overestimated by about 5 cm at the Belgian coast. DCSMv6-ZUNOv4 leads to the lowest vector difference at the Belgian coast (around 11 cm). Note that errors in Z0 are strongly dependant on the period which is analysed.
- For a stormy period, the DCSM-FM-100m shows the best results at the Belgian coast with averaged RMSE of 8.1 cm. The DCSMv6-ZUNOv4 and DCSM-FM-0.5nm models lead to averaged RMSE of 8.9 cm. However in the frequency domain, DCSMv6-ZUNOv4 gives the lowest vector difference of 12.2 cm on average for the Belgian territory (Westhinder, Nieuwpoort and Oostende). In the Dutch territory (from Cadzand to Vlissingen), DCSM-FM-100m shows the lowest vector difference with an average value of 9.3 cm.
- A Sensitivity analysis is carried out on using different wind data between Hirlam7.2 and ERA5 dataset with different Charnock coefficient. DCSMv6-ZUNOv4 is chosen for this sensitivity analysis. For the entire year comparison, using ECWMF-ERA5 forcing with a variable Charnock coefficient yields a model quality that is slightly better than using HIRLAM forcing or ECMWF forcing with a constant Charnock coefficient. However, the difference in RMSE is less than 1cm. For the stormy period, using Hirlam7.2 forcing yields slightly better results for the Belgium coast and Western Scheldt (averaged RMSE 8.8 cm), compared with using ECWMF-ERA5 forcing with a variable Charnock coefficient (averaged RMSE is 9.5 cm at Belgium coast and Western Scheldt).

9 References

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Appendix A Definition of Statistics

Water levels

The **Bias** of water level represents the average deviation of the differences between model predicted water level and measurement.

The **RMSE** of water level is a measure of the spread of the predicted values level around the measurement. It corresponds to a sample standard deviation.

The **RMSE0** is the bias corrected root mean square error which describes the forecast errors not associated with the bias.

The **RMSE_ Surge** is the RMSE between two surge signals.

The mathematical expressions are listed below. y and x represent modelled and measured values respectively and n is the number of samples.

$$Bias = \overline{y} - \overline{x}$$

$$RMSE = \sqrt{\frac{\sum_{1}^{n} (y_i - x_i)^2}{n}}$$

$$RMSE\_Surge = \sqrt{\frac{\sum_{1}^{n} (y\_surge_i - x\_surge_i)^2}{n}}$$

$$RMSE0 = \sqrt{\frac{\sum_{1}^{n} ((y_i - x_i) - (\overline{y} - \overline{x}))^2}{n}}$$

Appendix B Definition of Vector Difference

The vector difference analysis combines the results from different tidal components regarding both amplitude and phase. In short vector difference is a unified variable with one value describing the model accuracy from harmonic point of view. The mathematical expression of vector difference is shown as below.

$$e_s = \sum_{i=1}^{N} \sqrt{[A_{c,i} cos(\phi_{c,i}) - A_{m,i} cos(\phi_{m,i})]^2 + [A_{c,i} sin(\phi_{c,i}) - A_{m,i} sin(\phi_{m,i})]^2}$$

where e_s is the vector difference calculated at a certain station. c and m represent the model computed and measured value. A and ϕ represent the tidal amplitude and phase. i represents the number of tidal components.

Appendix C Statistics of water level between all the North Sea models

Figure 26 – Bias of complete time series of water levels.

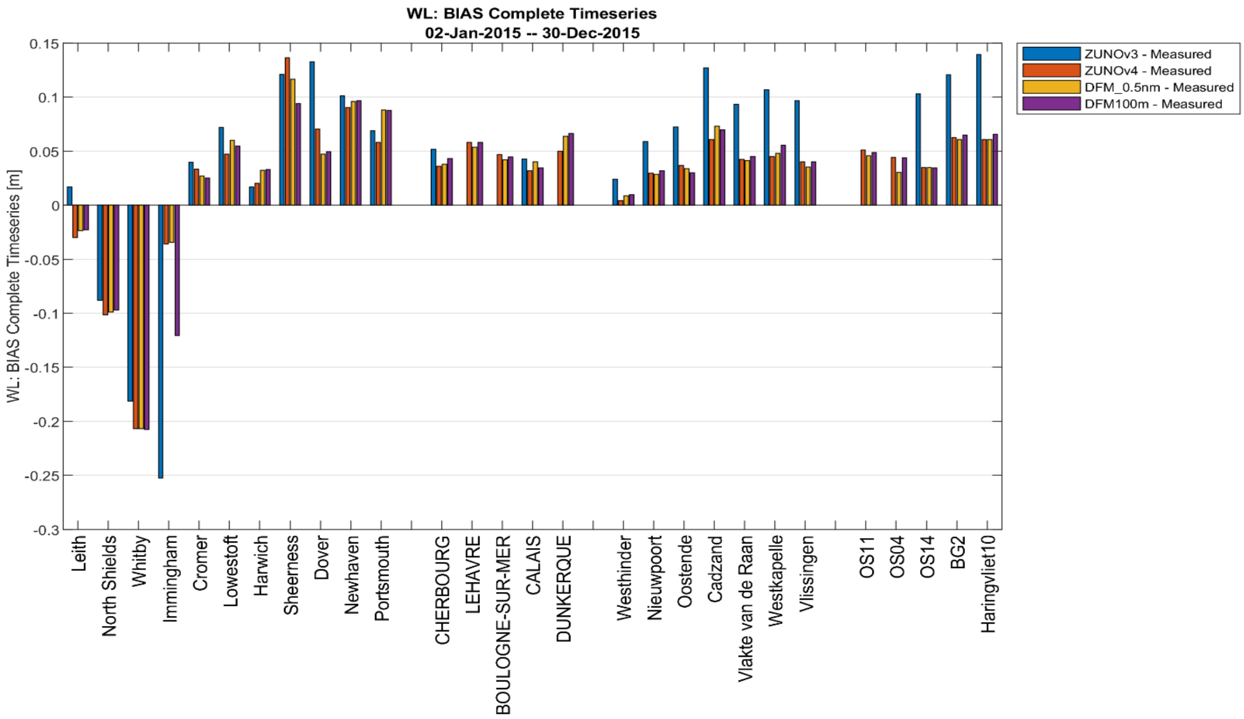


Figure 27 – RMSE of complete time series of water levels.

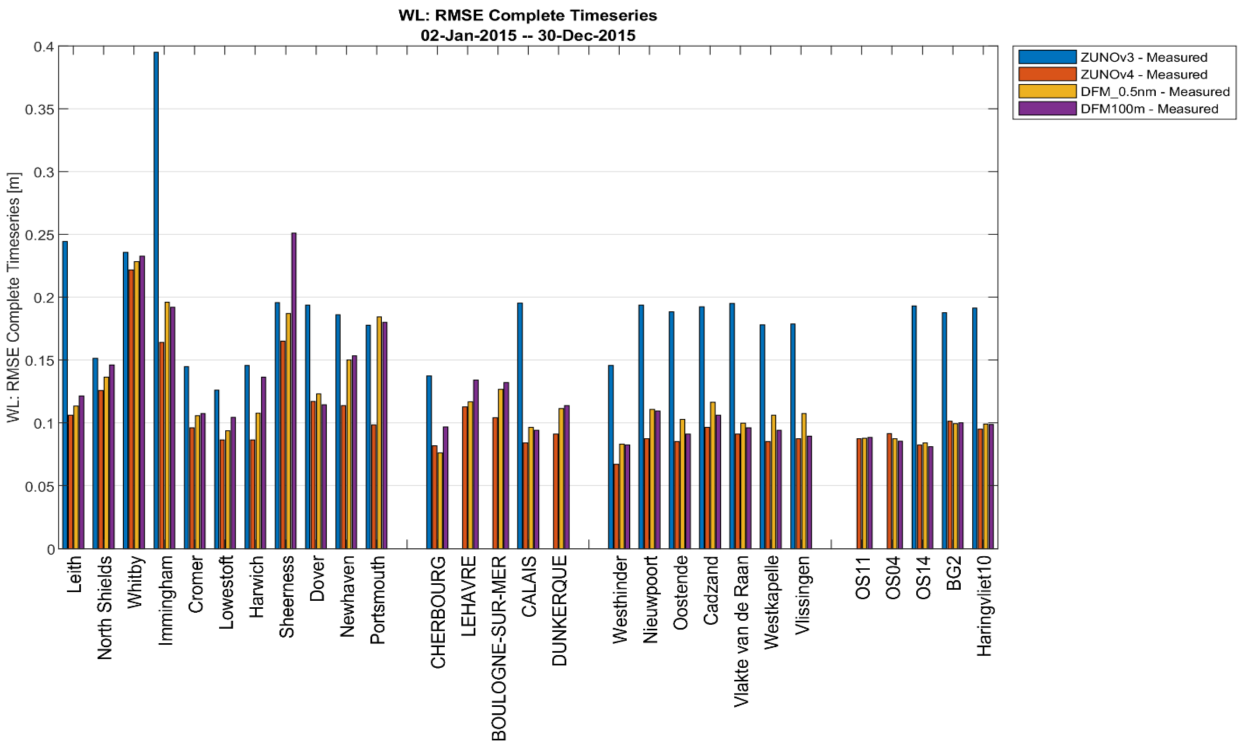


Figure 28 – RMSE0 of complete time series of water levels.

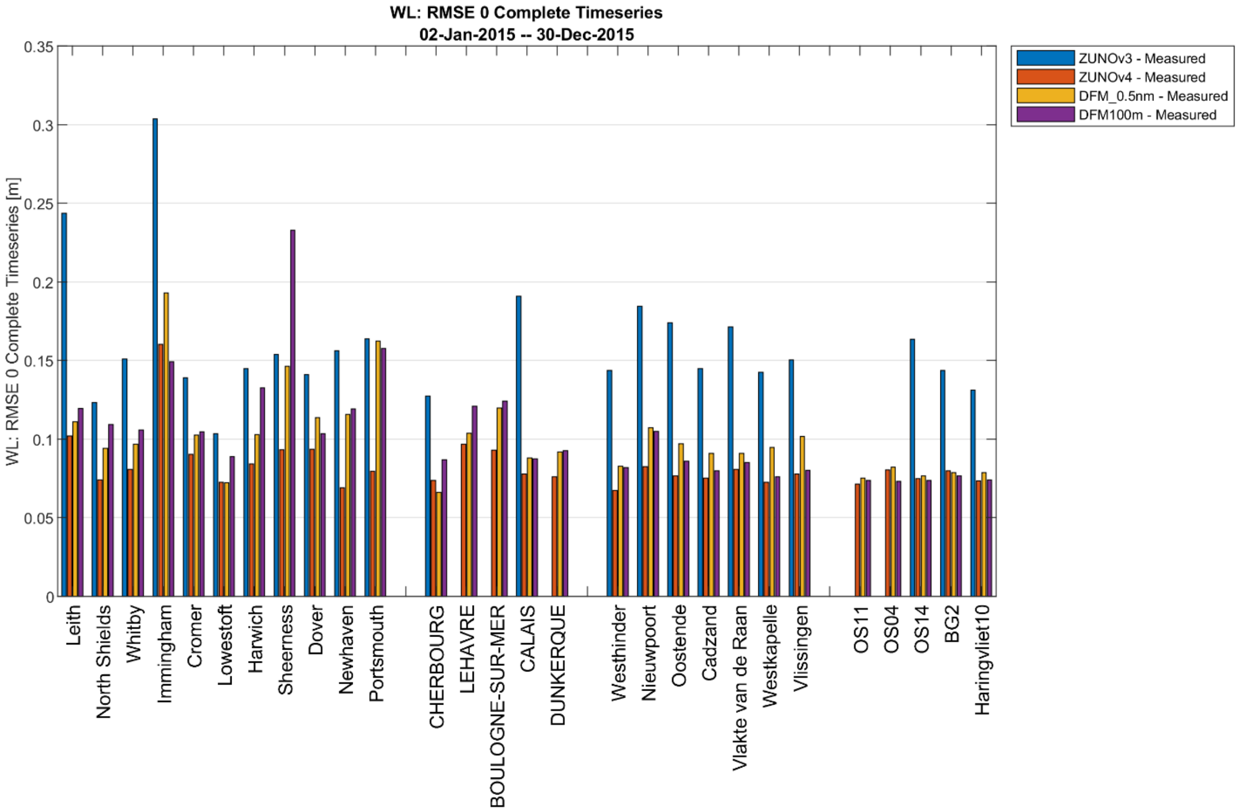


Figure 29 – Bias of high water levels.

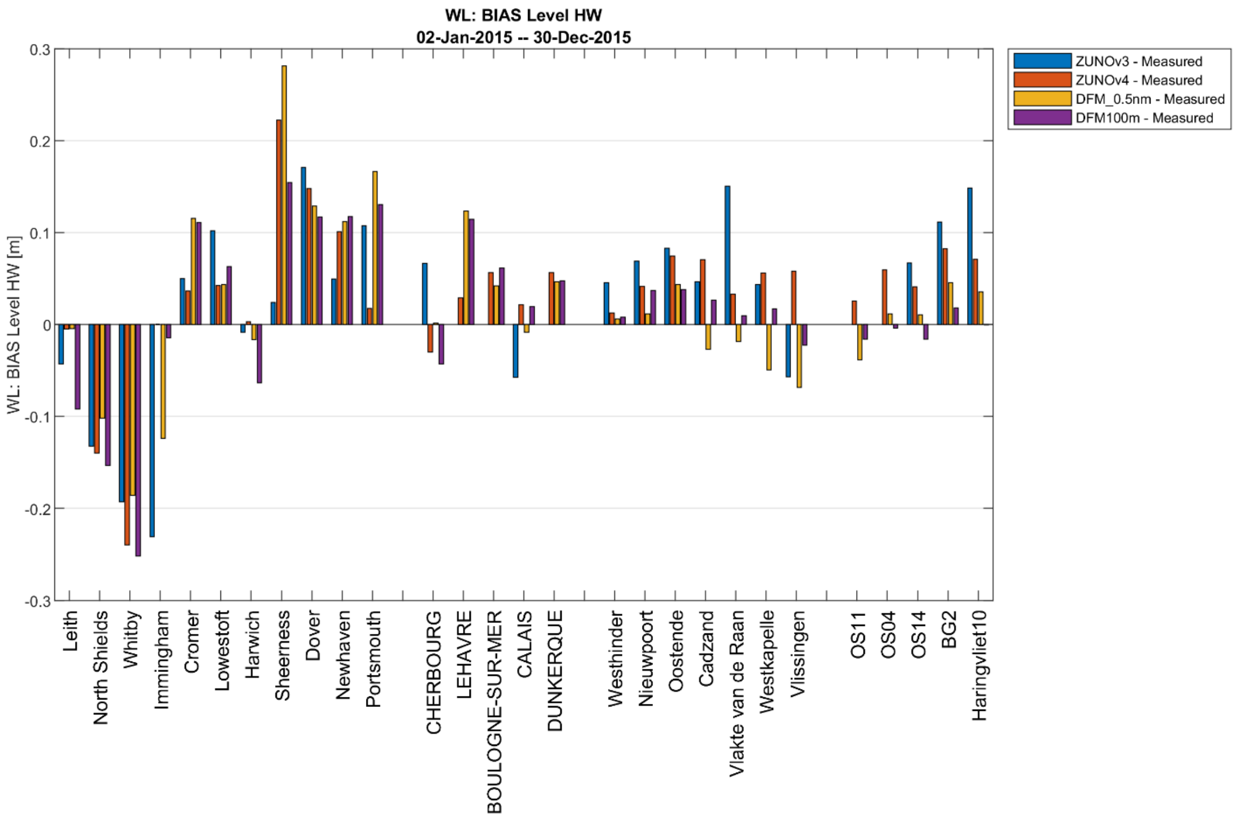


Figure 30 – RMSE of high water levels.

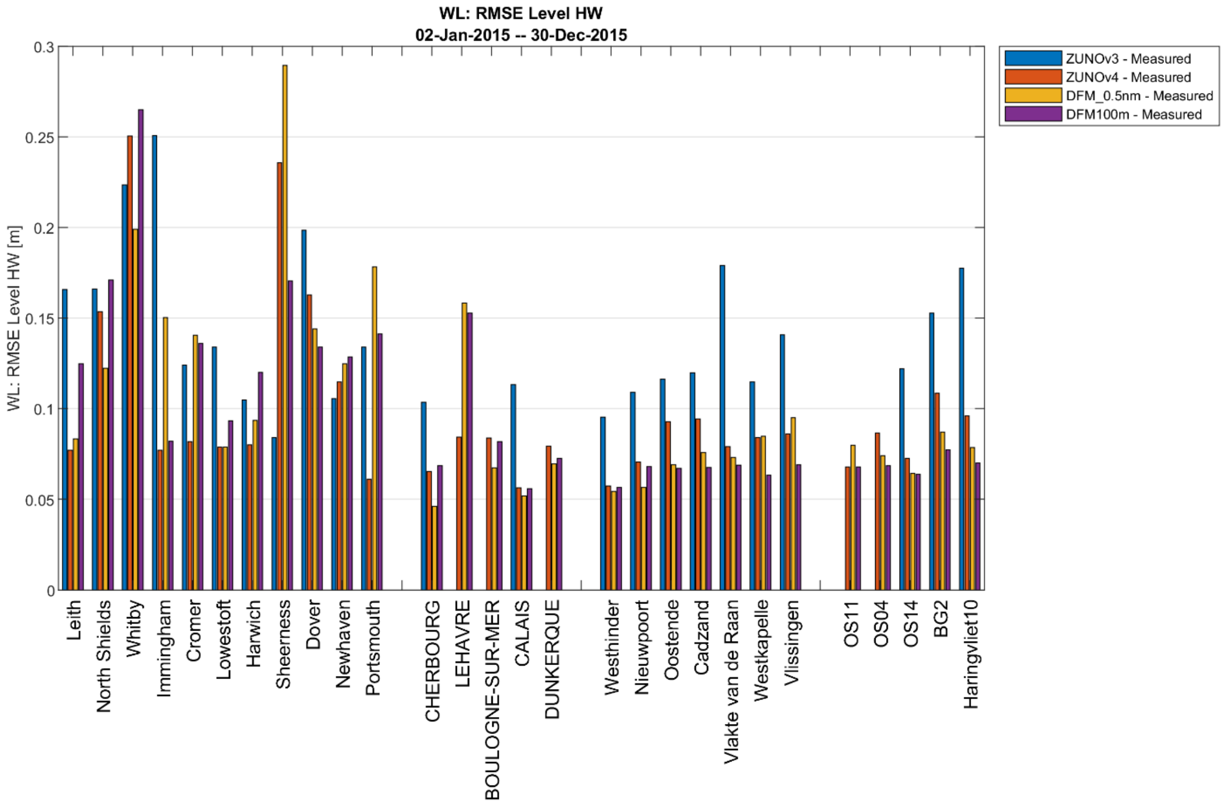


Figure 31 – RMSE0 of high water levels.

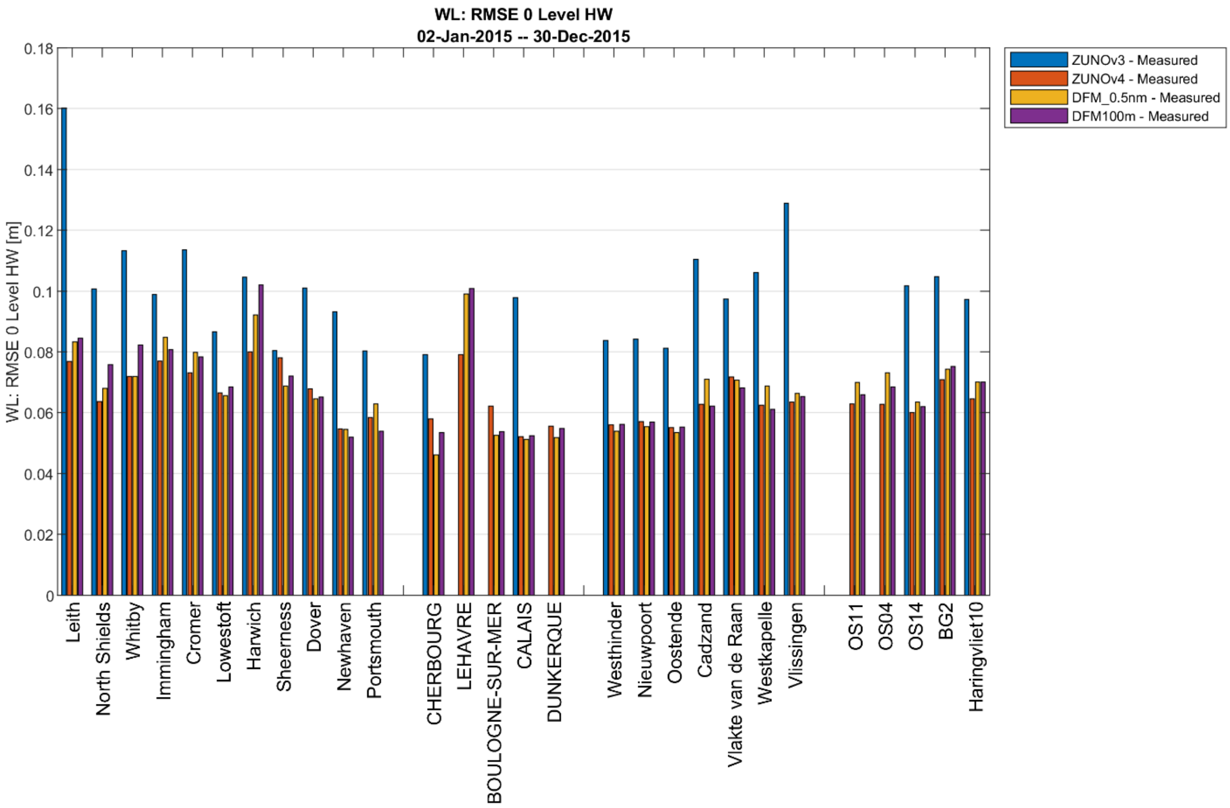


Figure 32 – Bias of low water levels.

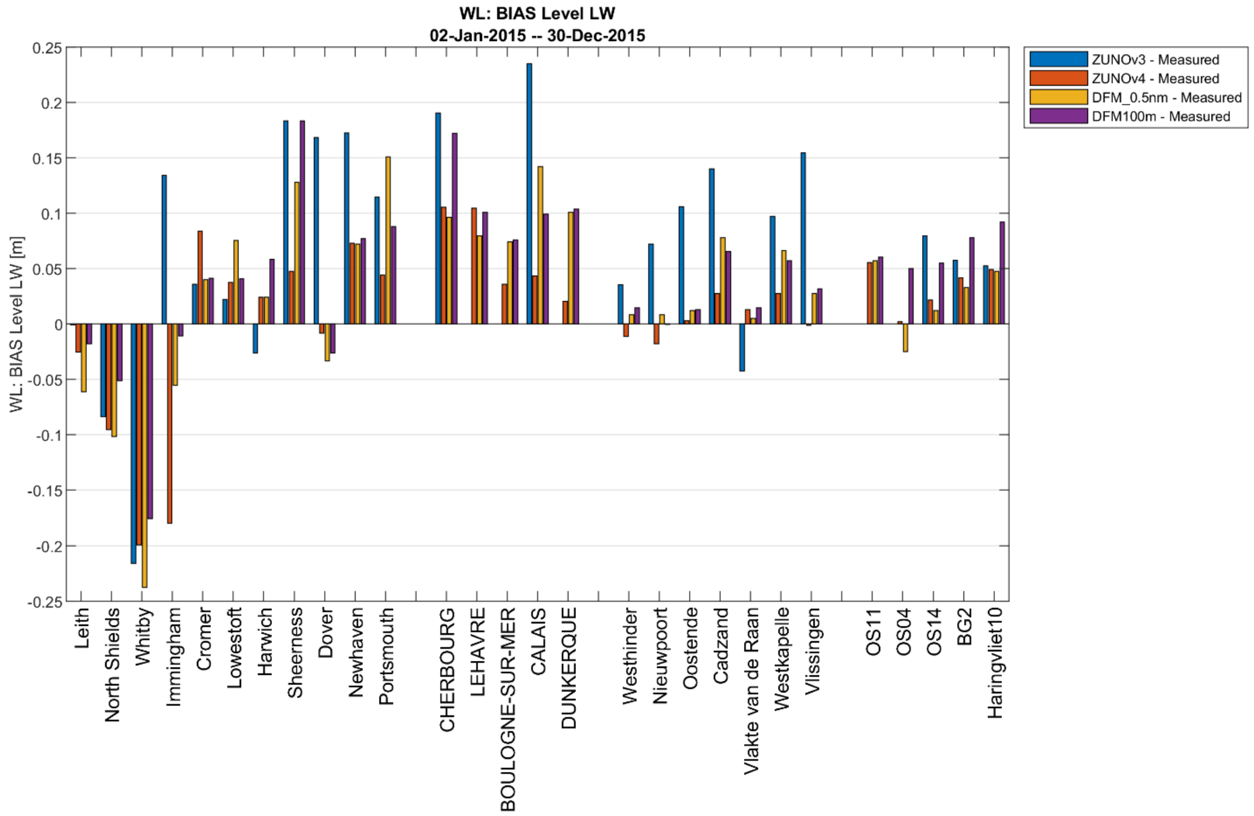


Figure 33 – RMSE of low water levels.

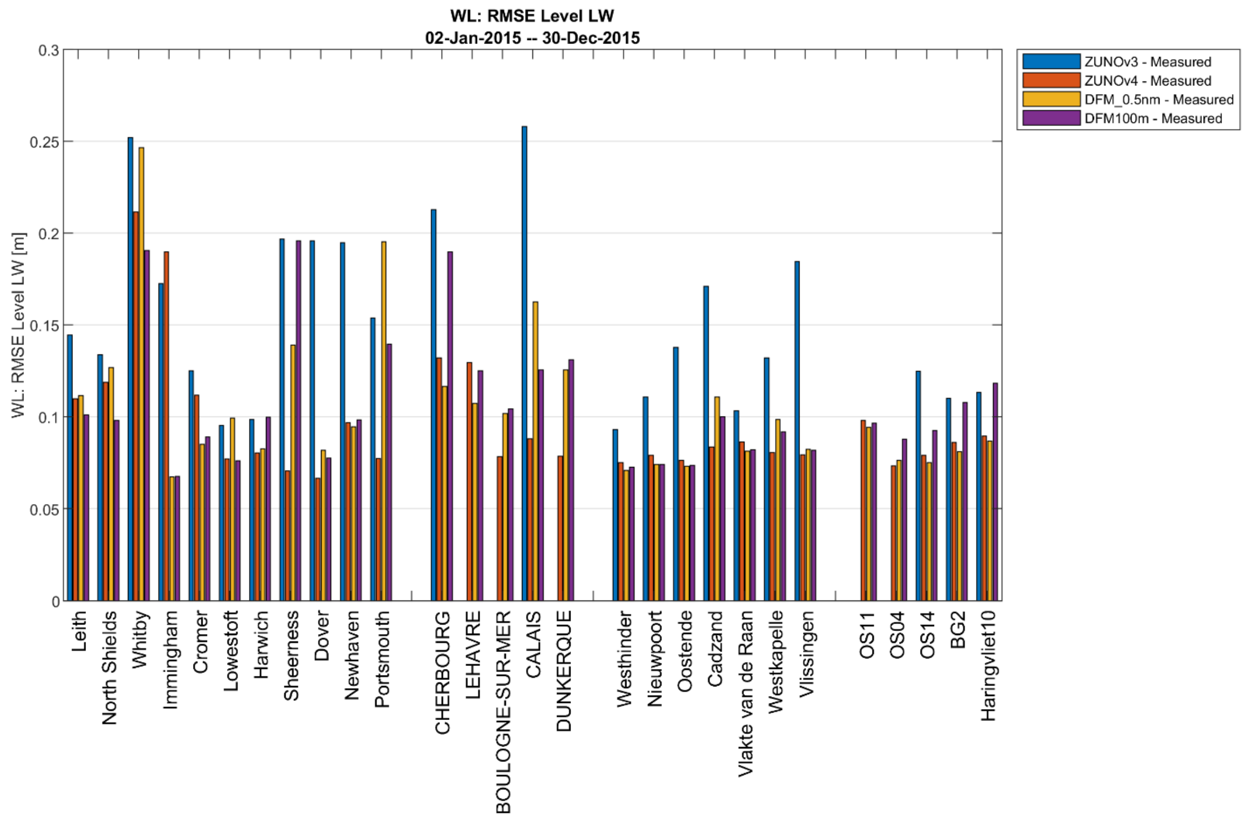
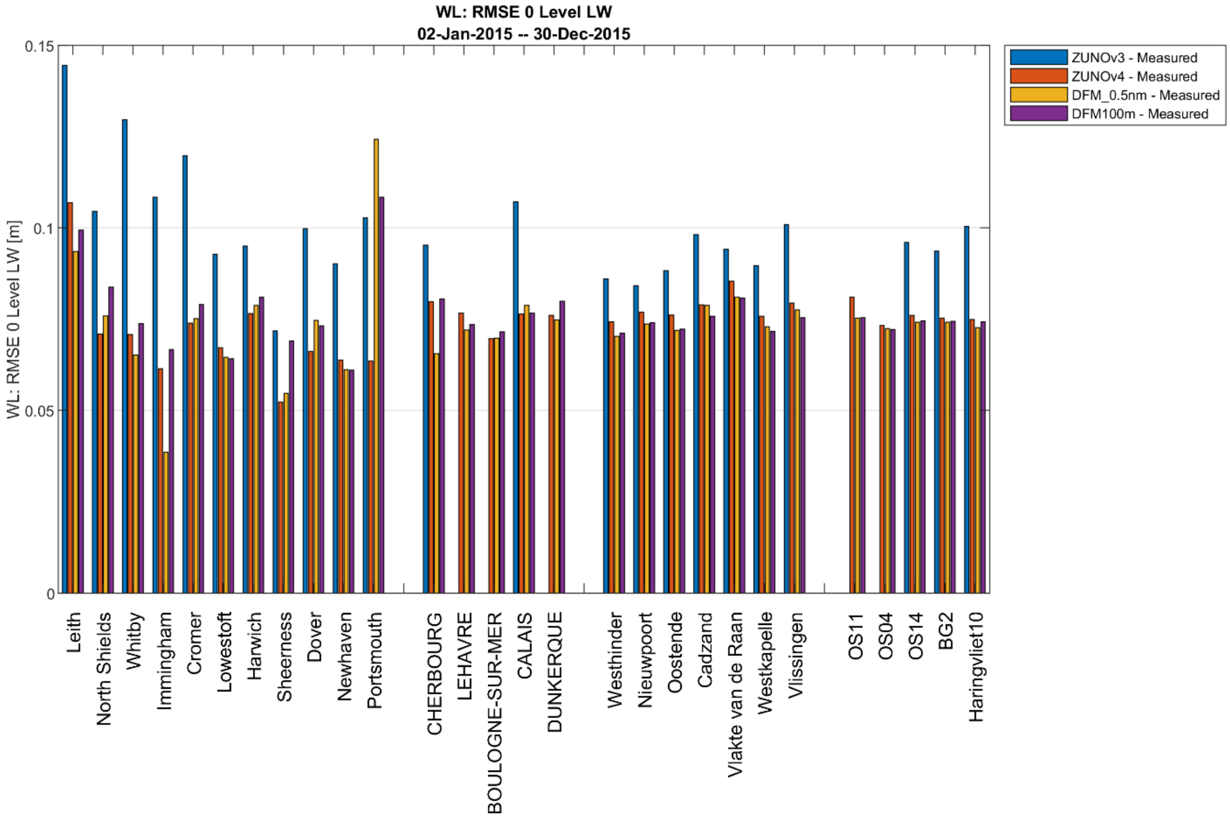


Figure 34 – RMSE0 of low water levels.



Appendix D RMSE of surge

Table 19 – Comparison of RMSE of surge in cm.
The averaged values are calculated for the British, French, Belgian and Dutch coast respectively.

Region	Stations	ZUNOv3	ZUNOv4	DFM_0.5nm	DFM_100m
British	Leith	4.5	4.9	4.7	4.6
	North Shields	9.7	10.7	10.6	10.4
	Whitby	18.6	20.3	20.6	20.5
	Immingham	5.7	6.7	6.3	10.3
	Cromer	6.0	5.6	5.5	5.4
	Lowestoft	9.0	6.5	7.5	7.1
	Harwich	5.6	5.5	6.2	6.2
	Sheerness	12.1	14.1	12.0	9.9
	Dover	15.7	9.5	7.5	7.7
	Newhaven	11.0	9.7	10.2	10.3
	Portsmouth	8.1	6.9	9.9	9.6
	Average	**9.6**	**9.1**	**9.2**	**9.3**
French	CHERBOURG	6.7	5.4	5.5	5.9
	LEHAVRE	n/a	6.8	6.5	6.8
	BOULOGNE-SUR-MER	n/a	6.0	5.6	5.8
	CALAIS	6.2	4.9	5.6	5.1
	DUNKERQUE	n/a	6.3	7.4	7.7
	Average	**6.4**	**5.9**	**6.1**	**6.3**
Belgian & WES	Westhinder	5.2	4.0	4.1	4.2
	Nieuwpoort	7.3	4.9	5.0	5.2
	Oostende	8.5	5.1	4.9	4.7
	Cadzand	13.6	7.2	8.3	8.0
	Vlakte van de Raan	10.8	6.4	6.4	6.6
	Westkapelle	11.9	5.8	6.2	6.7
	Vlissingen	10.7	5.3	5.0	5.3
	Average	**9.7**	**5.5**	**5.7**	**5.8**
Dutch	OS11	n/a	6.8	6.3	6.6
	OS04	n/a	5.5	4.3	5.5
	OS14	11.8	5.2	5.0	5.2
	BG2	13.7	7.9	7.8	8.2
	Haringvliet10	16.5	8.0	7.9	8.6
	Average	**14.0**	**6.7**	**6.2**	**6.8**
Overall		**10.0**	**7.2**	**7.2**	**7.4**

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