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Sub report 4 – Hindcast with 2D NEVLA

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Sub report 4 – Hindcast with 2D NEVLA

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IMDC International Marine & Dredging Consultants

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Abstract

This study investigates the causes of under prediction of high water levels by the operational forecasting system during two recent storm periods. Sensitivity analysis has shown wind forcing is of great importance. Hirlam wind with forecast horizon of 6 hours does not necessarily possess the best quality. Salinity shows potential positive impact on model performance, however extensive model calibration and validation are recommended before including it on the operational forecasting system (VSSKS). The river discharge and different nesting scripts show limited impact on water level predictions.

Contents

List of tables

List of figures

1 Introduction

In November 2015 and January 2016, two high water levels along the river Scheldt were underestimated significantly by the online operational forecasting system (VSSKS). The main objective of this study is to reveal the possible causes of the malfunction and to provide insights for the management, maintenance and improvement of the VSSKS.

This study is performed under the framework of project ’16-016 Model- en data-analyse ten behoove van betere tij-verwachtingen’. The online forecasting system is converted to an offline hindcast model which runs on the research cluster. The overall performance of Nevla2D has been evaluated both for the two storm periods and a longer period of 3 months covering ordinary conditions as well. The predictive quality of the Nevla2D model is cross-checked with a sophisticated Nevla3D model and a simpler 1D operational model (“sigma-model” which runs in the 1D operational forecasting system).

Sensitivity analysis has been carried out with respect to different nesting approaches, functionality of Kalman Filtering, different driving forces of river discharge and wind, and also with inclusion of salinity.

Knowing the importance of wind forcing to the model predictive abilities, Hirlam wind forecasts with different forecast horizons are extensively analyzed and compared with measurement at Vlakte van de Raan. The overall quality of Hirlam wind forecasts is therefore systematically evaluated. Subsequently water levels predicted by Nevla2D models with different wind forecast horizons are assessed.

The first chapter of this report contains the general assignment description. The second chapter describes the VSSKS model trains. The two storms are briefly described in the third chapter, where the simulation period is defined. The fourth chapter describes the available data. The fifth chapter contains a description of the hindcast model performance. Sensitivity analysis is elaborated in chapter 6. The report ends with conclusions, references and annexes.

2 Model Description

2.1 The VSSKS forecasting system

The forecast system for the Belgian Coast and Scheldt (*Voorspellingssysteem voor kust en Schelde*; VSSKS) is an operational hydrodynamic prediction system in charge of the forecast of the water levels along the Dutch and Belgian Scheldt. The predictions of water levels are carried out by means of a sequence of shallow water 2D models (a ‘model train’). These simulations are carried out using the Waqua/SIMONA numerical simulation engine.

The train of models cascades from a rough hydrodynamic continental shelf model to fine estuary/river models. The models extend from the Belgian and Dutch North Sea until the tidal border of the Scheldt, Dijle, Nete Durme and Zenne rivers. This cascade is controlled by software that arranges automatic setup of the execution environment of each cascade run (i.e. the Nautboom-script).

The whole simulation domain is discretized by 5 models:

- CSM8 – Continental shelf Model of the North Sea
- ZUNO – Zuidelijke Noordzee Model (Sourthern North Sea model)
- KUSTGROF – Kuststrook Grof (Coarse coastal model)
- KUSTFIJN – Kuststrook Fijn (Fine coastal model)
- Kustzuid Model (Southern coast model, Western Scheldt and Scheldt up to Antwerp)
- NEVLA 2D (Belgian coast and entire Scheldt Estuary including flood control areas)

For more details of the VSSKS, the reader is referred to (Depreiter et al., 2012a).

The main operational train runs every 6 hours, after receiving new wind forecasts (HIRLAM wind). Forecasts (results) are stored in an internal database (WTZ) from which data are exported to the different end-users (HIC-databases, Afdeling Kust).

2.2 NEVLA 2D model

The Nevla version implemented in the VSSKS model train is based on ‘Run 5’ as described by Maximova et al (2009). This is linked to the versioning system with https://wl-subversion.vlaanderen.be/!/#repoSpNumMod/view/head/SIMONA/NEVLA2D/004_753_09_DR4_Extra%20aanpassingen%20ZS.

The grid was extended by inclusion of the **flood control areas.** The bathymetry was updated in the Sea Scheldt and Western Scheldt areas based on more recent 2013 survey data. Afterwards the model was extensively calibrated in terms of local adaptations on bottom roughness. The details of the NEVLA model calibration are reported by Chu et al. (2016).

2.3 Model settings

The main features of the CSM, ZUNO and Nevla2D models on the VSSKS forecasting system are listed in Table 2-1.

Table 2-1: Model settings of CSM, ZUNO and Nevla2D.

Parameter Settings	CSM	ZUNO	NEVLA2D
Time step [min]	10	2.5	0.125
Kalman Filter	Yes	Yes	No
Space varying wind	Hirlam	Hirlam	Hirlam
Salinity	No	No	No
Downstream boundary condition	Water level constructed from 11 Harmonic tidal components (M2, S2, N2, K2, O1, K1, Q1, P1 , NU2, L2, SA)	Water level nested from CSM	Current-Riemann-Current (perpendicular to Nederland – offshore section – perpendicular to France)

2.4 SIMONA version

On VSSKS the software version was updated from SIMONA2006 to SIMONA2011 on 23/11/2015. The changes made on the Nevla model include introduction of Waqua (SIMONA) keywords that only appear with version 2011. The details of the migration are described in Chu et al (2016). The shifting of the software versions indicates that the two storms discussed in this study were simulated with SIMONA2011.

2.5 Migration from VSSKS to hindcast model on Linux cluster

The primary principle of migration from VSSKS to model hindcast on the research cluster is to keep the model settings/configurations as similar as possible.

The first aim of the project is to run the most detailed / best model (NEVLA 2D) with ideal boundaries. This to see what the model is capable of with perfect information (boundaries, measurements, etc.). So a reconstruction in hindcast of the operational environment was not really a “must have”. But of course for the sensitivity analysis and to draw conclusions this setup was very convenient.

To be specific:

- All the model parameters are being unchanged;
- For models of CSM and ZUNO, Kalman Filter is implemented by writing water level measurement into a SDS file with a SIMONA script **obs2sds.pl**;
- Boundary nesting between models of CSM, ZUNO and Nevla is carried out by means of a SIMONA nesting script **modnst.pl**;

- Nevla model receives river discharge predicted by a hydrological model instead of measurements;
- SIMONA version **2011-64** is employed to perform model hindcast on the Linux cluster, which is the same as **SIMONA2011** installed on VSSKS;
- The model hindcast uses the same Hirlam wind data as used on VSSKS. Each model train runs for a complete period of 51 hours. The operational train 'reboots' every 6 hours with new wind forecasts from Hirlam (see sketch in Figure 2-1). These six-hour interval Hirlam wind fields (marked as red) are combined and reconstructed to a complete dataset covering the period from 16-11-2015 to 31-01-2016, which is subsequently applied on the model hindcast. However wind data are not successfully stored at the following time points (Table 2-2) due to technical reasons. Nevertheless, these time gaps are rather scattered and random without showing substantial regularity. In addition these time gaps are not corresponding to the two selected storm periods. Therefore using the Hirlam data is not problematic for this study.

Figure 2-1: Schematisation of the restarting of VSSKS.

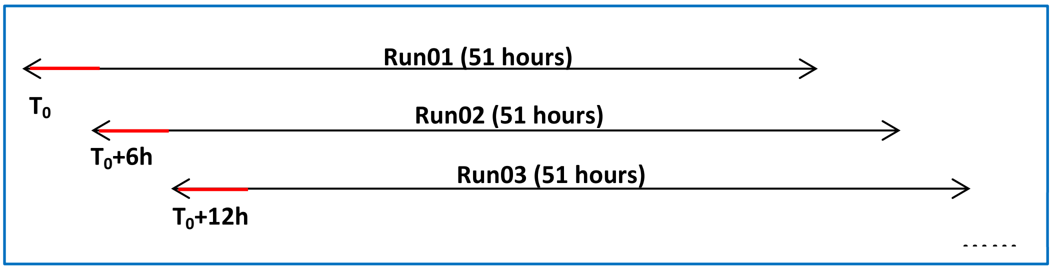


Table 2-2: Time points when Hirlam wind data are missing.

Date [yyyy-mm-dd]	Time [hh:mm]
2015-11-19	00:00
2015-11-20	06:00
2015-12-22	06:00
2015-11-23	00:00; 12:00; 18:00
2015-11-24	00:00; 06:00; 12:00
2015-12-06	00:00
2015-12-07	00:00
2015-12-26	00:00
2016-01-11	00:00

3 STORMEVENTS

On Saturday 28/11/2015 at 5:10 MET an extreme high water level of 4.44 m NAP (6.77 m TAW) was observed at Antwerp. Figure 3-1 shows the short-term forecasting of water level at Antwerp by the operational models of the HIC. All of the last four predictions of the 2D model (VSSKS – NEVLA) show underestimation of the maximum high water level by 20-50 cm. By analysing the wind measurement at Vlakte van de Raan and Hansweert, a possible explanation is that the strong wind forcing was exerted at the time of high tide on the coast. Under unstable (stormy) weather conditions, the significant rotation of wind direction and changes of wind speed occurred around the time of high tide, bring great uncertainty to the forecasting system. Because the rapid changes of wind often last over a short period such that it could be easily overlooked by the wind forecast in use which contains coarser time interval. This is more problematic during high water from the forecasting point of view when handling flood management issues.

On Friday 15/1/2016 at 7:06 MET an extreme high water level of 4.39 m NAP (6.72 m TAW) was observed at Antwerp. This storm occurred just after a spring tide on 11-13 January 2016. Figure 3-2 shows the short-term forecasting of water level at Antwerp by the operational models of the HIC. All predictions of the 2D models (VSSKS – NEVLA) show underestimation of the maximum high water level by 20-60 cm. Similar to the previous storm, a possible cause is the significant rotation of wind direction and changes of wind speed occurred around the time of high tide.

The detailed description and analysis of the two storms are referred to Boeckx et al (2016) and Nossent et al (2016).

In order to include both storms and to ensure sufficient time both before and after storms for results analysis, the model hindcast is performed from 16-Nov-2015 to 31-Jan-2016.

Figure 3-1: Short-term forecasting in Antwerp on 28/11/2015 (adopted from Boeckx et al., 2016)

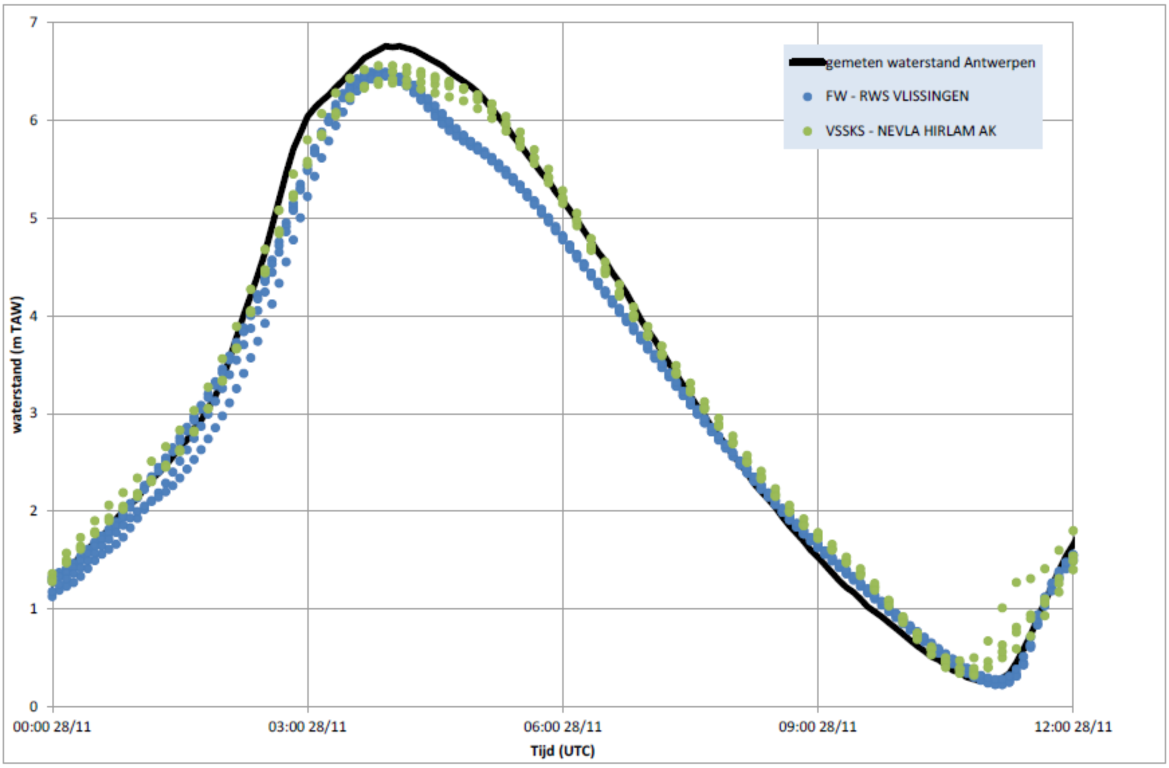
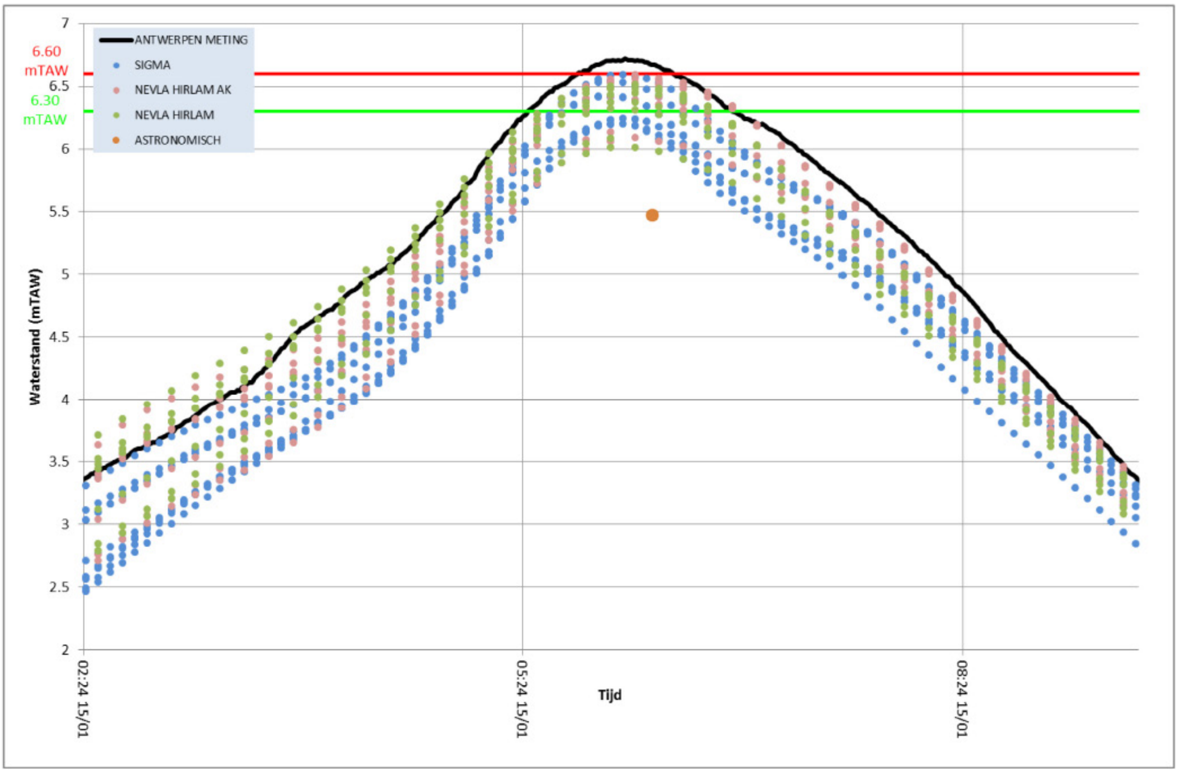


Figure 3-2: Short-term forecasting in Antwerp on 15/01/2016 (adopted from Nossent et al., 2016)



4 DATA

4.1 Water Level

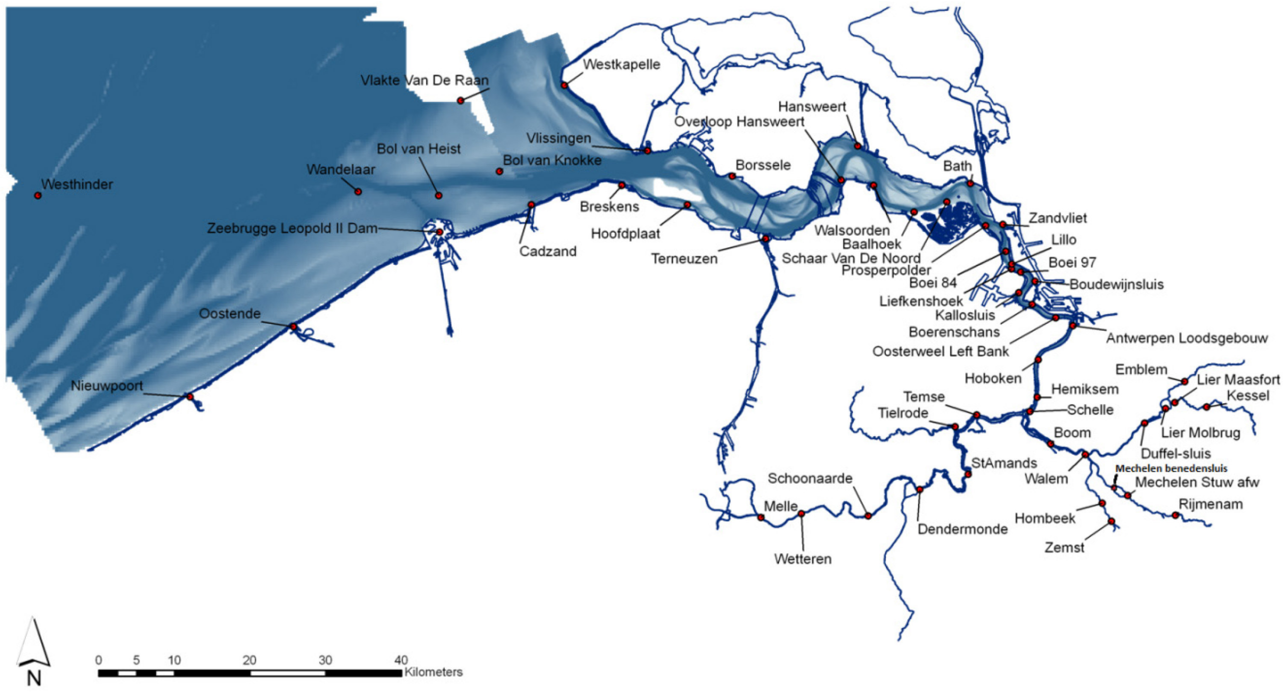
For the period from 16-11-2015 to 31-01-2016, 36 stations are available with water level measurements every 10 minutes, see Table 4-1. The locations of these stations are represented in Figure 4-1. The data are obtained from HMCZ and HIC.

Table 4-1: Available water level measurements.

Nr	Station	Data source
1	Vlakte van de Raan	HMCZ
2	Westkapelle	HMCZ
3	Cadzand	HMCZ
4	Breskens	HMCZ
5	Vlissingen	HMCZ
6	Borssele	HMCZ
7	Terneuzen	HMCZ
8	Hansweert	HMCZ
9	Walsoorden	HMCZ
10	Bath	HMCZ
11	Liefkenshoek	HMCZ
12	Kallo	HMCZ
13	Duffel	HIC
14	Lier_Molbrug	HIC
15	Mechelen_benedensluis	HIC
16	Mechelen_opw_stuw	HIC
17	Rijmenam	HIC
18	Tielrode	HIC

Nr	Station	Data source
19	Waasmunster	HIC
20	Lier_Maasfort	HIC
21	Kessel	HIC
22	Emblem	HIC
23	Walem	HIC
24	Hombeek	HIC
25	Zemst	HIC
26	Prosperpolder	HIC
27	Zandvliet	HIC
28	Antwerpen	HIC
29	Hemiksem	HIC
30	Temse	HIC
31	StAmands	HIC
32	Dendermonde	HIC
33	Schoonaarde	HIC
34	Wetteren	HIC
35	Melle	HIC
36	Grobbendonk	HIC

Figure 4-1: Overview of measurement stations.



4.2 Wind

4.2.1 Hirlam wind

The wind field data (format: Grib) are received from Hirlam (High Resolution Limited Area Model), which is a Numerical Weather Prediction (NWP) forecast system developed by the international HIRLAM programme. The Grib data are converted into a SDS-file (binary format) by means of the 2011 version of **waqwnd**.

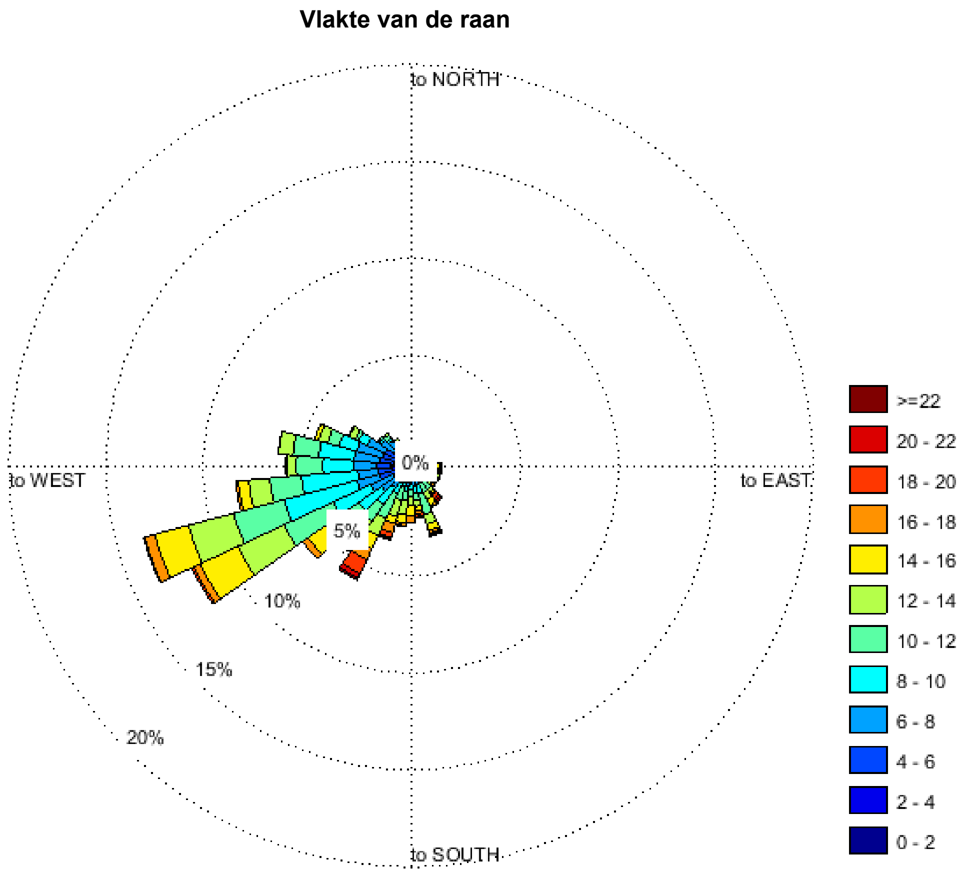
The spatial resolution is 1/12° latitudinal and 1/8° longitudinal, corresponding to the grid resolution of the Continental Shelf Model (CSM). The temporal resolution is 3 hours.

As discussed in §2.5, the VSSKS uses the latest forecasts (6 hours) of Hirlam wind.

4.2.2 Measurement

Wind measurements are available at Vlakte van de Raan with time interval of 10 minutes (HMCZ). Vlakte van de Raan is a representative station as surge development proxy on the North Sea. The wind rose (Figure 4-2) indicates that winds mostly come from the SW with magnitudes generally smaller than 20 m/s.

Figure 4-2: Wind rose at Vlakte van de Raan from measurements (analysis period: 01-11-2015 to 31-01-2016).



4.2.3 Analysis: 01/11/2015 – 31/01/2016

Figure 4-3 shows the comparison of wind measurements and Hirlam forecasts at Vlakte van de Raan. The Hirlam forecasts at Vlakte van de Raan are extracted from the wind field (SDS) data by linear interpolation. Figure 4-4 presents the scatter plot of wind speed. Table 4-2 presents the statistics in terms of correlation coefficient and RMSE.

In general the Hirlam wind forecasts show reasonable agreement with measurements, although the Hirlam forecasts slightly underestimate the wind speed. The correlation coefficients are around 0.93 for both wind speed and direction. The RMSE of wind speed is 3.4 m/s while the circular standard deviation of wind direction is 48°.

In addition, the measurements show more variations with more peaks of wind speed which are not captured by the Hirlam forecasts due to its coarser time interval.

Figure 4-3: Time series of wind speed and direction at Vlakte van de Raan from 01-11-2015 to 31-01-2016.

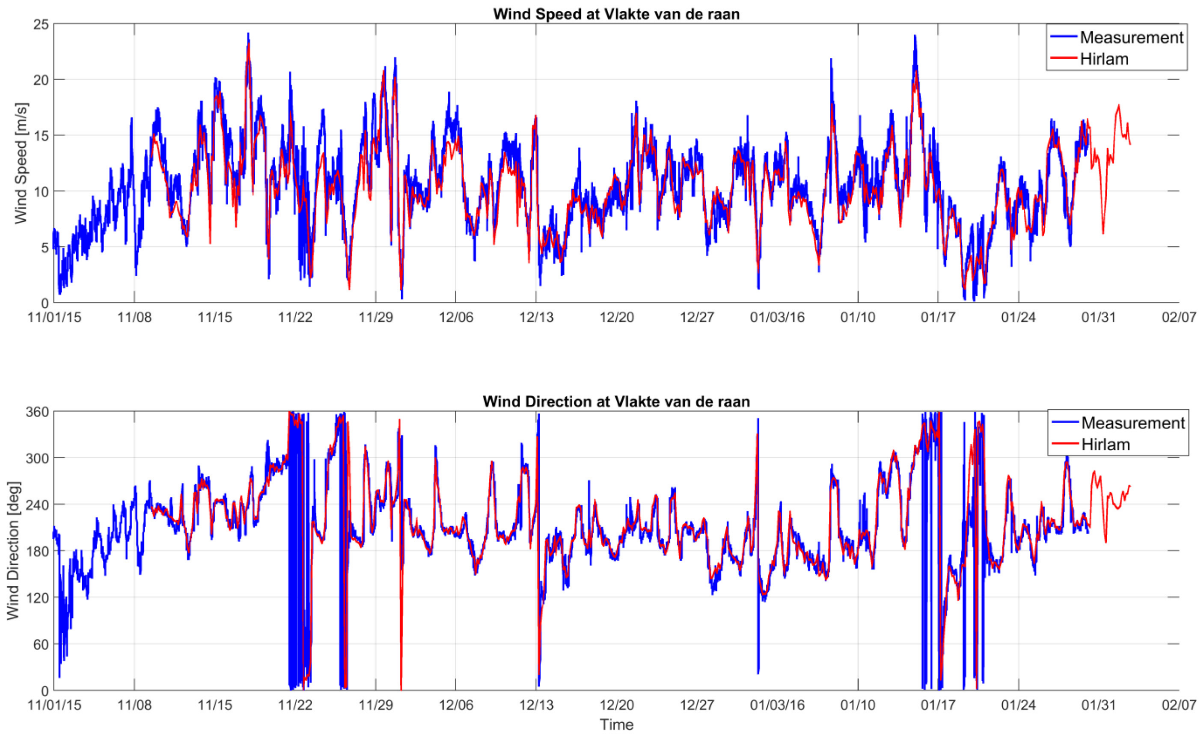


Figure 4-4: Scatter plot of wind speed from measurement and Hirlam forecasts at Vlakte van de Raan from 01-11-2015 to 31-01-2016.

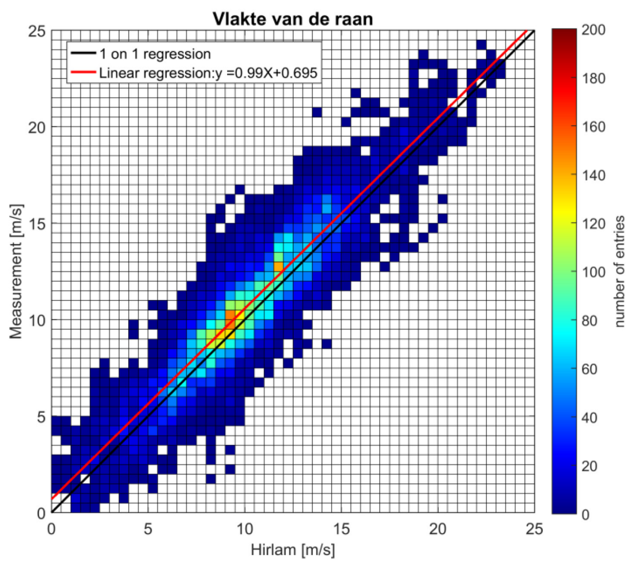


Table 4-2: Statistics of wind speed and direction at Vlakte van de Raan.

Period	Variables	Statistics	Vlakte van de Raan
01-11-2015 to 31-01-2016	Wind speed	Correlation coefficient [-]	0.92
		RMSE [m/s]	3.4
	Wind direction	*Circular Correlation coefficient [-]	0.93
		*Circular standard deviation [deg]	48

* Refer to the Circular Statistics Toolbox for Matlab.

4.2.4 Analysis Storm: 27/11/2015 – 02/12/2015

Figure 4-5 shows the comparison of wind measurements and Hirlam forecasts at Vlakte van de Raan for the storm period from 27-11-2015 to 02-12-2015. Figure 4-6 shows the scatter plot of wind speed. Table 4-3 presents the statistics in terms of correlation coefficient and RMSE.

In general the Hirlam wind forecast underestimates the wind speed, especially at the moment when the storm occurred (28-11-2015 05:00). Meanwhile Hirlam forecasts show earlier changes of wind direction compared with measurements, which is mainly due to its coarser time interval such that the changes of direction could not be fully resolved.

Figure 4-5: Time series of wind speed and direction at Vlakte van de Raan from 27-11-2015 to 02-12-2015.

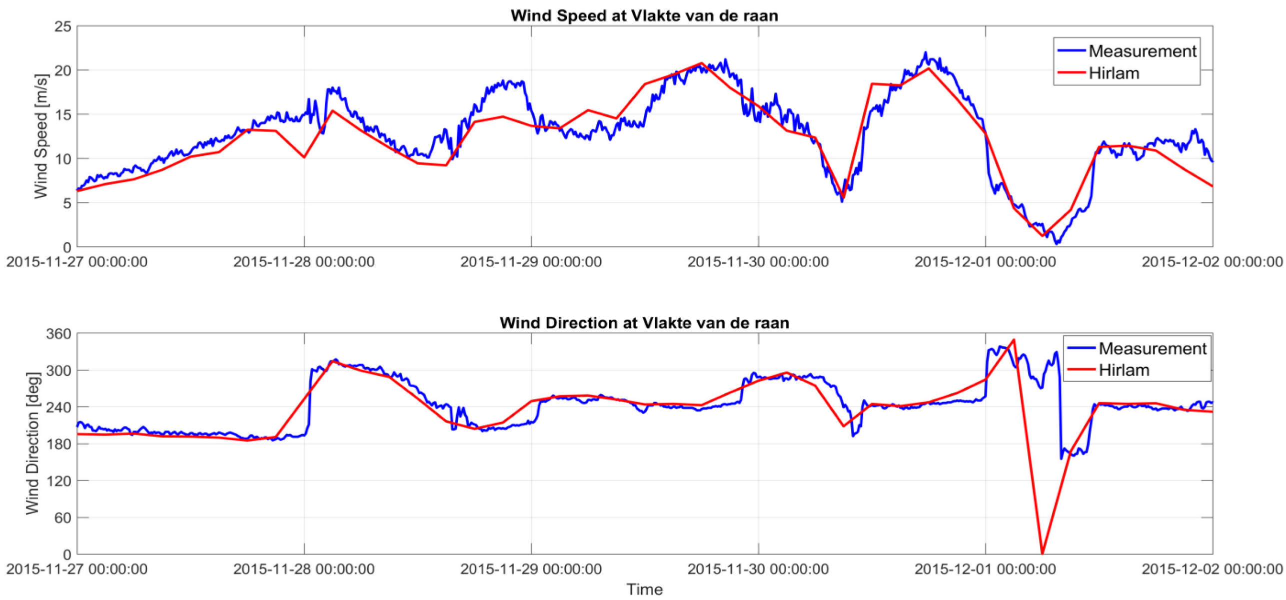


Figure 4-6: Scatter plot of wind speed from measurement and Hirlam forecasts at Vlakte van de Raan from 27-11-2015 to 02-12-2015.

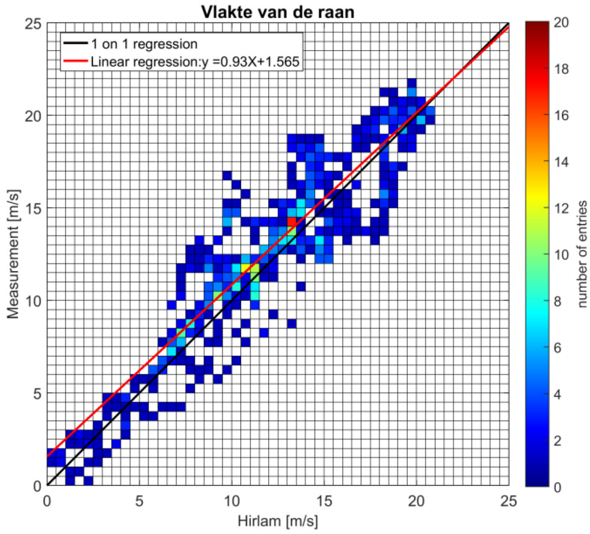


Table 4-3: Statistics of wind speed and direction at Vlakte van de Raan.

Period	Variables	Statistics	Vlakte van de Raan
27-11-2015 to 02-12-2015	Wind speed	Correlation coefficient [-]	0.92
		RMSE [m/s]	4.0
	Wind direction	Circular correlation coefficient [-]	0.86
		Circular standard deviation [deg]	38.6

4.2.5 Analysis Storm: 11/01/2016 – 17/01/2016

Figure 4-7 shows the comparison of wind measurements and Hirlam forecasts at Vlakte van de Raan for the stormy period from 11-01-2016 to 17-01-2015. Figure 4-8 shows the scatter plot of wind speed. Table 4-4 presents the statistics in terms of correlation coefficient and RMSE.

The Hirlam wind forecast again underestimates the wind speed in general, especially before the storm (15-01-2016 07:00) by about 5 m/s. Meanwhile the wind direction from Hirlam shows quite good agreement with measurements.

Figure 4-7: Time sereis of wind speed and direction at Vlakte van de Raan from 11-01-2016 to 17-01-2016.

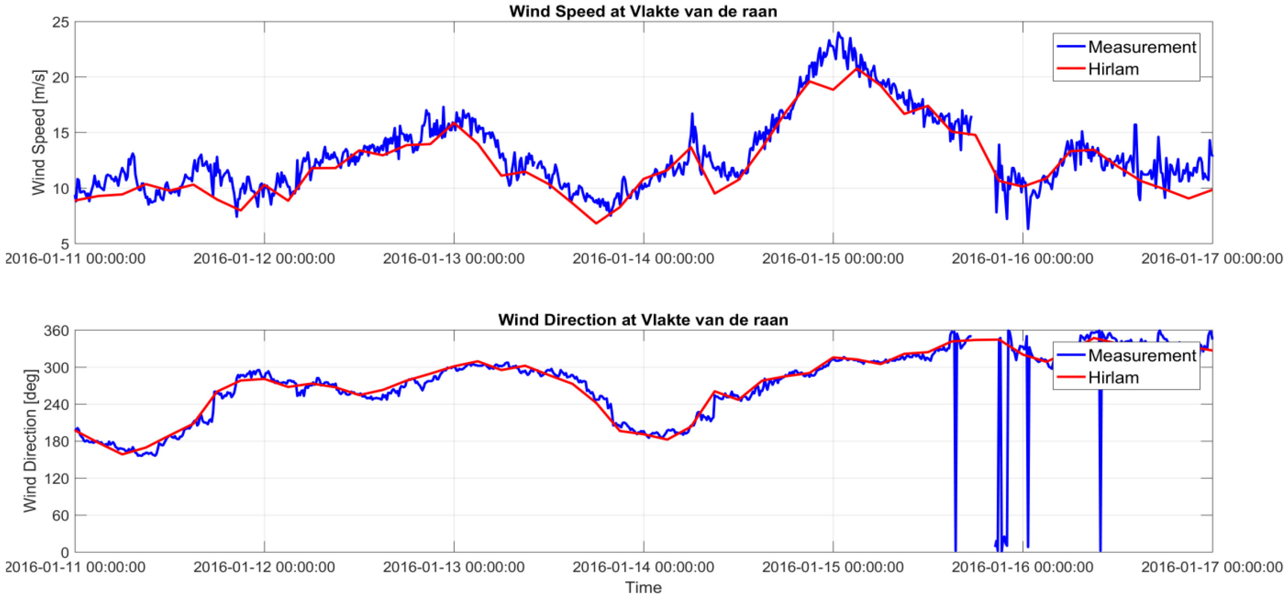


Figure 4-8: Scatter plot of wind speed from measurement and Hirlam forecasts at Vlakte van de Raan from 11-01-2016 to 17-01-2016.

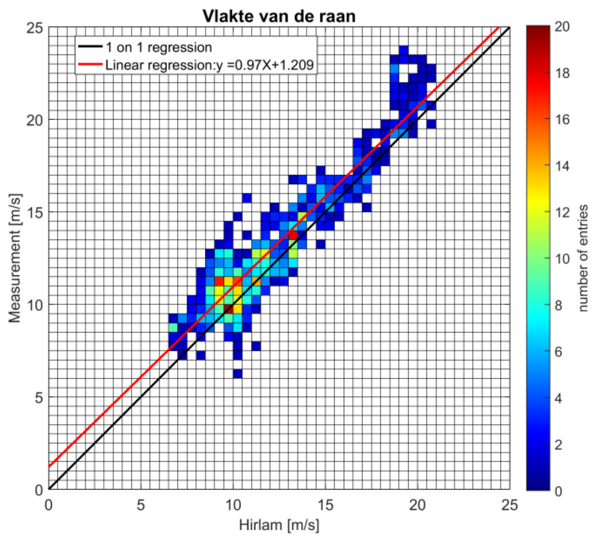


Table 4-4: Statistics of wind speed and direction at Vlakte van de Raan.

Period	Variables	Statistics	Vlakte van de Raan
11-01-2016 to 17-01-2016	Wind speed	Correlation coefficient [-]	0.93
		RMSE [m/s]	3.5
	Wind direction	Circular correlation coefficient [-]	0.98
		Circular standard deviation [deg]	43

4.2.6 Quality check of Hirlam wind forecasts

In this section the quality of Hirlam wind data with different forecast horizons is investigated. Figure 4-9 and Figure 4-10 show comparison of the Hirlam forecasts at Vlakte van de Raan with forecast horizons of 36, 24, 18, 12 and 6 hours for the two storms respectively. The 6 hours ahead forecast (T0-6) is essentially utilized on VSSKS and model hindcast.

Hirlam model adopts data assimilation to determine the best possible meteorological state using observations and short range forecasts, therefore the quality of wind forecast should ideally increase over forecast horizons from 36 hours to 6 hours.

This is roughly verified for the first storm (Figure 4-9). The wind forecast over horizon of 36 hours shows considerable discrepancies on both wind speed and direction compared with measurements. The forecasts get closer to the measurements at 28/11/2015 03:00 with 12 and 6 hours forecast ahead, however still with underestimation of wind speed by 2 m/s (~10%). At 28/11/2015 00:00, the 24 hours ahead forecast shows ‘best’ estimation while the forecast with horizon of 6 hours underestimates the wind speed by about 40-50%. This is considerable since it leads to a wind shear stress in the model of only 25% of the realistic value.

For the second storm (Figure 4-10), the wind forecast over horizon of 12 hours shows considerable discrepancies on both wind speed and direction compared with measurements. Before reaching the peak of wind speed at 15/01/2016 00:00 the forecast with horizon of 24 hours shows ‘best’ estimation while the forecast with horizon of 6 hours underestimates the wind speed by about 4 m/s (~20%). Afterwards the forecast with horizon of 18 hours shows better estimation.

The description above implies that the quality of Hirlam forecast diverges with progression of forecast horizons, which is not as ideally expected. It is therefore difficult to determine an optimal forecast horizon for the forecasting system.

An extensive sensitivity analysis of the effect of wind speed on the generation of a water level setup in the NEVLA model has been carried out (see§6.3).

Figure 4-9: Comparison of Hirlam forecasts at Vlakte van de Raan with different forecast horizons for the storm occurred at 28/11/2015 5:00 (left: wind speed; right: wind direction).

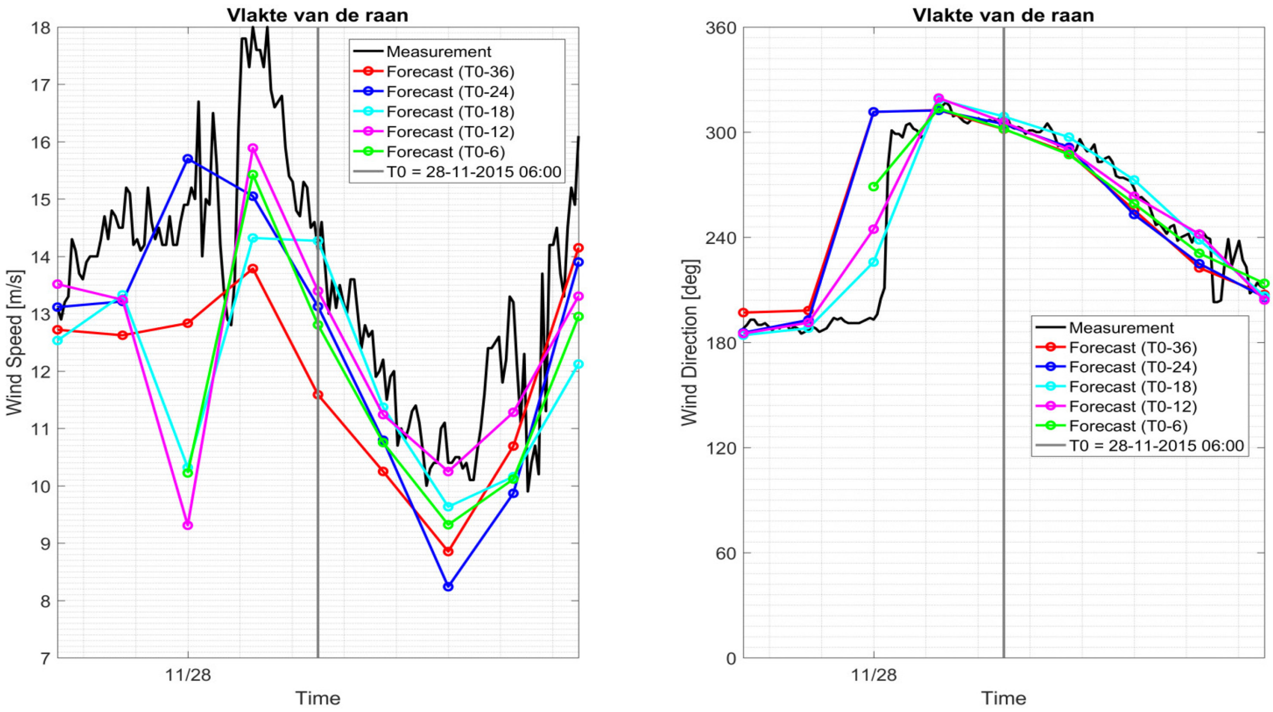
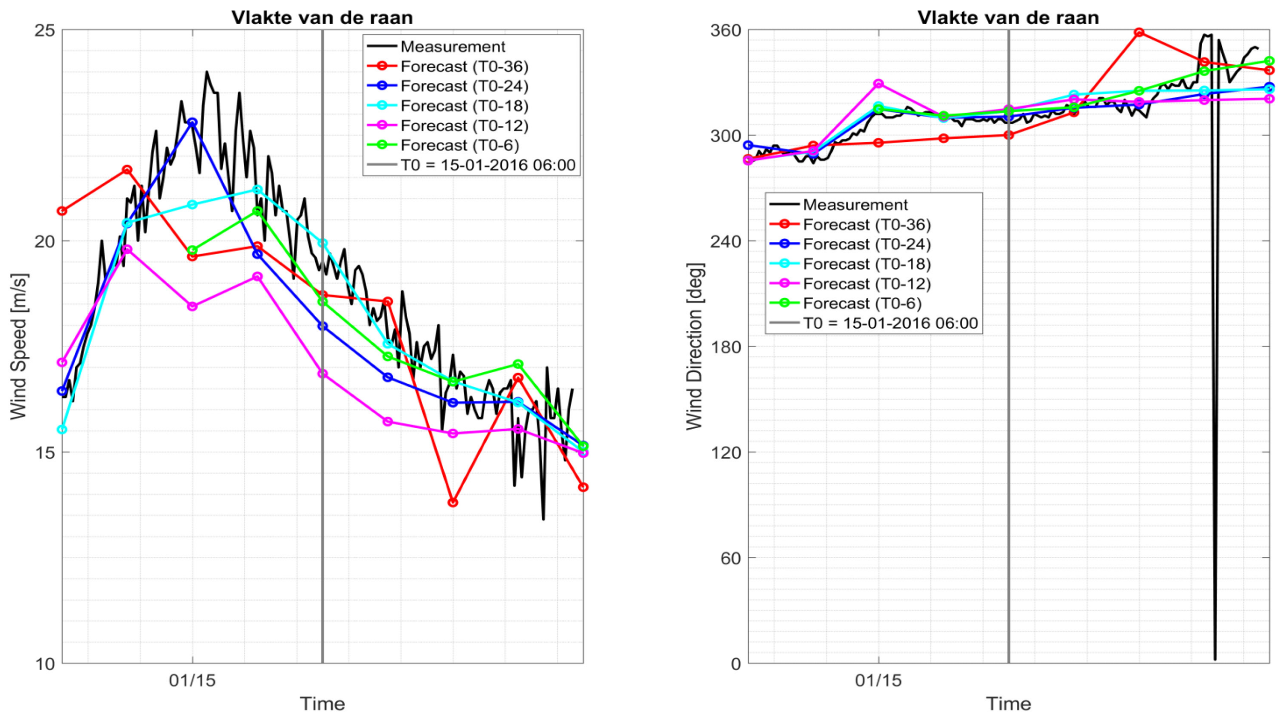


Figure 4-10: Comparison of Hirlam forecasts at Vlakte van de Raan with different forecast horizons for the storm occurred at 15/01/2016 07:00 (left: wind speed; right: wind direction).



4.3 Salinity

Salinity measurements are prepared for this study to perform sensitivity analysis (see §6.4). Salinity measurements are available at seven stations (see locations in Figure 6-24) with time interval of 10 minutes and are listed in Table 4-5.

Table 4-5: Overview of available stations with salinity measurements.

Nr	Measuring station	Data source
1	Vlakte Van De Raan	HMCZ
2	Baalhoek	HMCZ
3	Hemiksem	HIC
4	Liefkenshoek	HIC
5	Lillo	HIC
6	Oosterweel	HIC
7	Prosperpolder	HIC

4.4 River Discharge

River discharge is imposed at 6 stations (Merelbeke, Zemst, Grobbendonk, Dendermonde, Haacht and Hulshout) in the Nevla2D model. Measurements are available with time interval of 10 minutes (from HIC) except at Haacht. However measurements are not being available for real-time forecasting, which alternatively uses forecast data from a hydrological model.

Figure 4-11 shows the comparison of measurements and model forecasts. In general the hydrological model predicts river discharge fairly well at Grobbendonk, Dendermonde and Hulshout. Both of the curve patterns and peaks are captured reasonably well. Although the model forecast shows more variations at Zemst compared with the measurement, both magnitudes are still within a similar range. At Merelbeke the hydrological model substantially underestimates the river discharge.

Table 4-6 shows the maximum and average values of river discharge measurements (prediction data at Haacht). Most of the fresh water is imported from Merelbeke while river discharges from rest stations are less significant.

A sensitivity analysis of different river discharges on water level predictions is discussed in §6.5.

Figure 4-11: Time series of river discharge from 15-11-2015 to 31-01-2016 at Merelbeke, Zemst, Grobbendonk, Dendermonde, Haacht and Hulshout respectively.

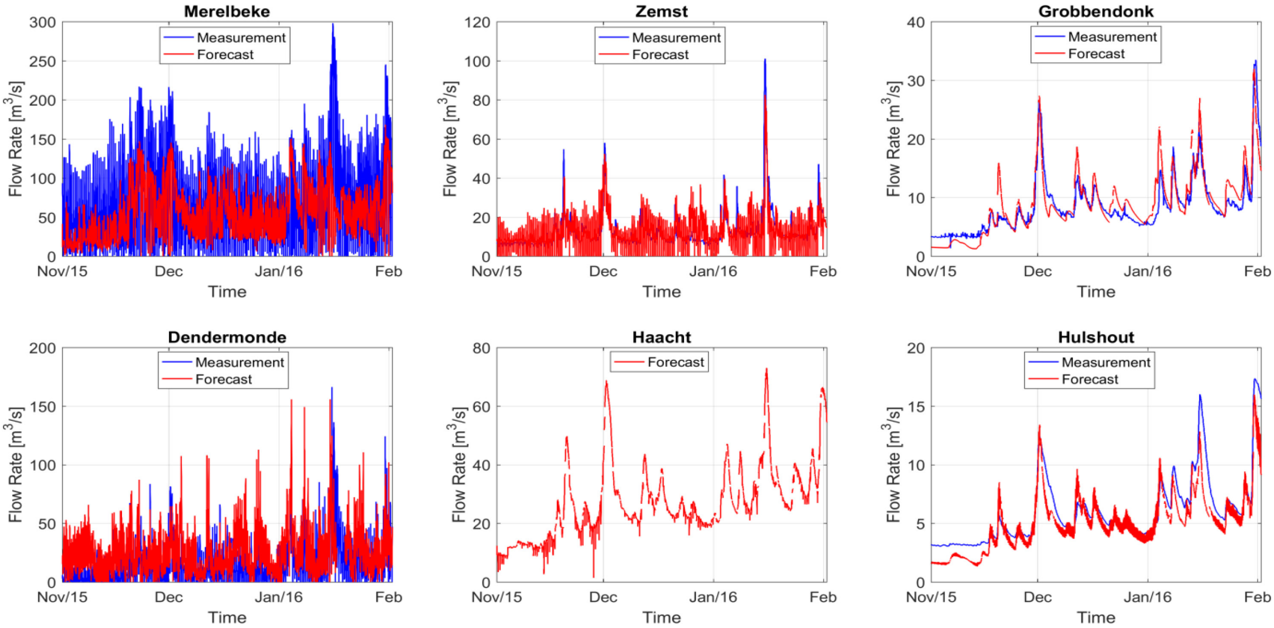


Table 4-6: Statistics of river discharge measurements.

	Merelbeke	Zemst	Grobbendonk	Dendermonde	Haacht	Hulshout
Maximum [m^3/s]	298	101	33	166	73	17
Mean [m^3/s]	74	12	9	15	27	6

5 Model Hindcast

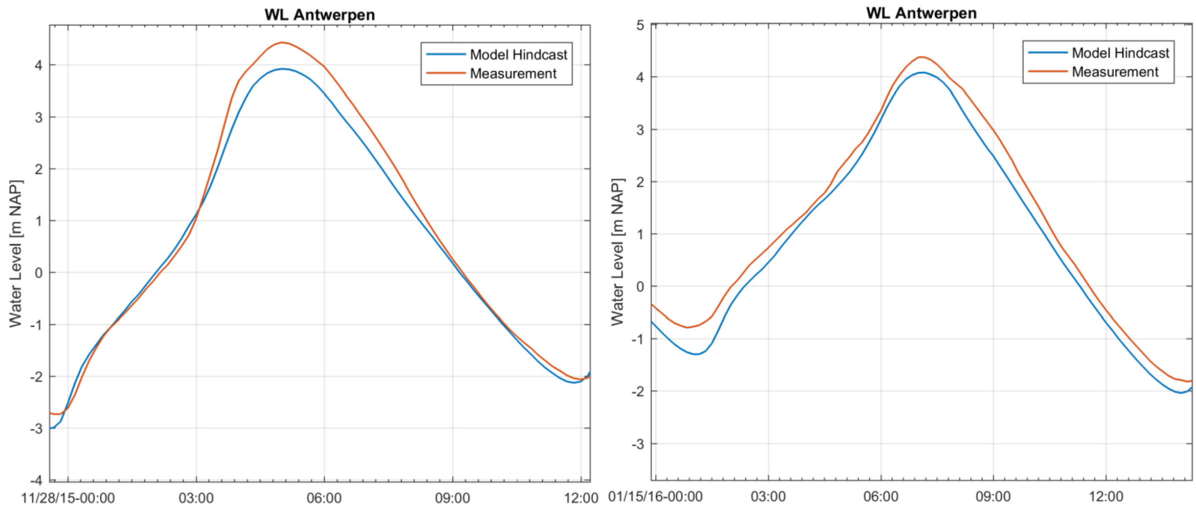
5.1 Forcings

The forcings applied on the hindcast model are identical to that on VSSKS. The details are presented in §2.5.

5.2 Model Quality: Water Level

Figure 5-1 exemplifies the predicted water level during the two stormy periods at Antwerp by the hindcast model. The high water levels are substantially underestimated by 50 cm (12%) and 30 cm (7%) for the two storms respectively.

Figure 5-1: Comparison of water level at Antwerp at 28/11/2015 05:00 (left panel) and 15/01/2016 07:00 (right panel).



5.2.1 Basic Analysis

Figure 5-2 to Figure 5-7 present the results of the basic analysis on high water and the complete time series of water level for the entire simulation period from 16-11-2015 to 30-01-2016. The definition of bias, RMSE and RMSE0 can be found in §Annex1.

The model predictions in general underestimate the high water along the estuary. The high water level at Sint-Amands and Schoonaarde are poorly predicted due to the coarse/poor quality of the local model grid on the one hand, and on the other hand due to the less accurate upstream river discharges. At Western Scheldt and Lower Sea Scheldt (up to Temse), the bias of high water is mostly limited to -15 cm. Both of the magnitudes and distribution patterns of the bias along the estuary are similar to the latest validation results of the run which was performed also over a storm period from 30-11-2013 to 13-12-2013 (Chu et al., 2016). The bias of the complete time series of waterlevel is on average about -10 cm from offshore till upstream station of Dendermonde, and significantly distorted further upstream until Melle.

The RMSE of high water level is on average about 10-15 cm at the Western Scheldt and Lower Sea Scheldt (up to Temse). It increases to maximum 25 cm at upstream stations (e.g. Sint Amands and Schoonaarde). The RMSE of the complete time series of water level shows similar patterns.

The RMSE0 of high water level is on average about 5-10 cm at the Western Scheldt and Lower Sea Scheldt. It increases to maximum 25 cm at upstream stations (e.g. Wetteren). The RMSE0 of the complete time series of water level shows similar patterns.

The basic analysis is also performed for the two stormy periods (27/11/2015 – 02/12/2015 and 11/01/2016 – 17/01/2016) respectively. Figures are not shown in this section for the sake of concision. Similar patterns of bias, RMSE and RMSE0 are observed for both high water and the complete time series. However the predictions are slightly worse (by about 3-5 cm at Western Scheldt and Lower Sea Scheldt) due to the bad predictions of high water level during the storm periods.

The complete set of VIMM basic analysis files is presented in a CD in annex.

Figure 5-2: Bias of high water level (model - measurement) along the estuary from 16-11-2015 to 30-01-2016.

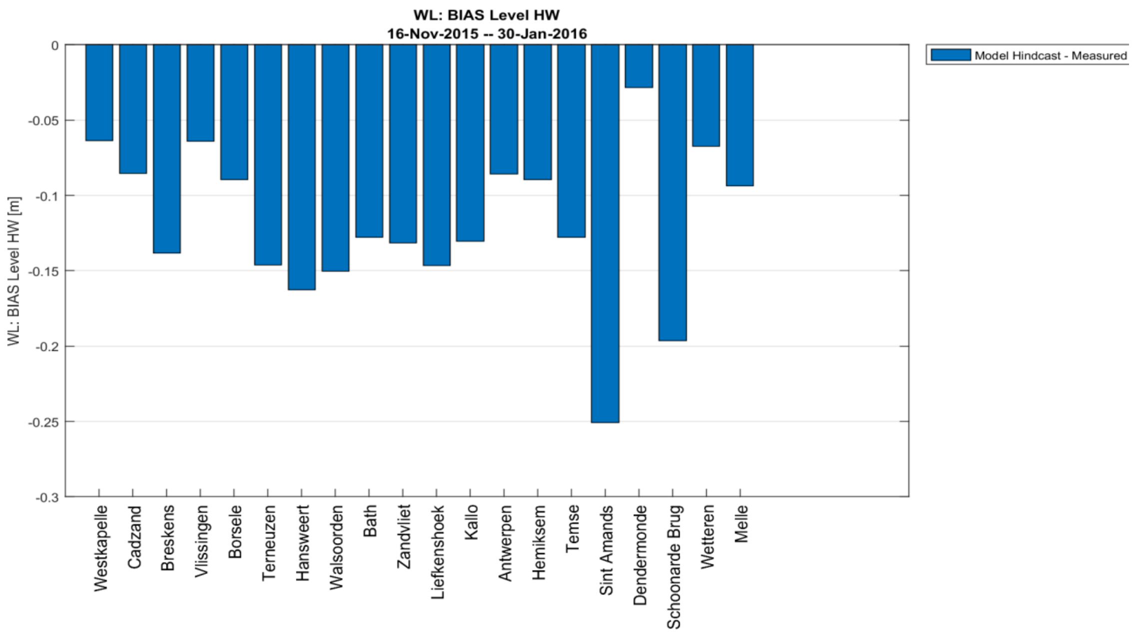


Figure 5-3: Bias of complete time series (model - measurement) along the estuary from 16-11-2015 to 30-01-2016.

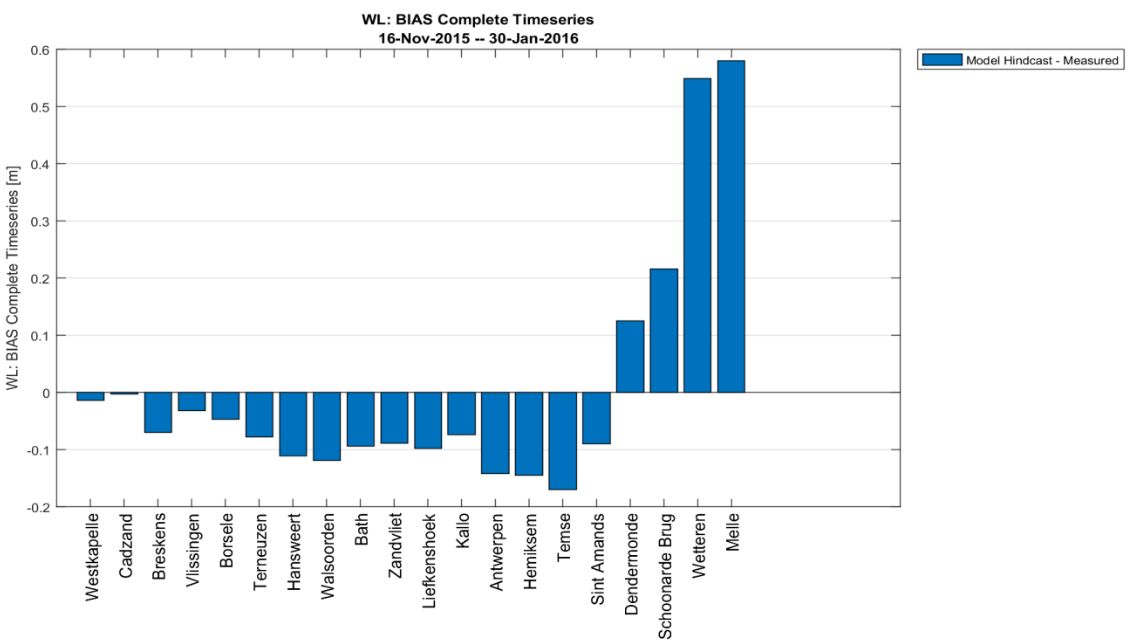


Figure 5-4: RMSE of high water level along the estuary from 16-11-2015 to 30-01-2016.

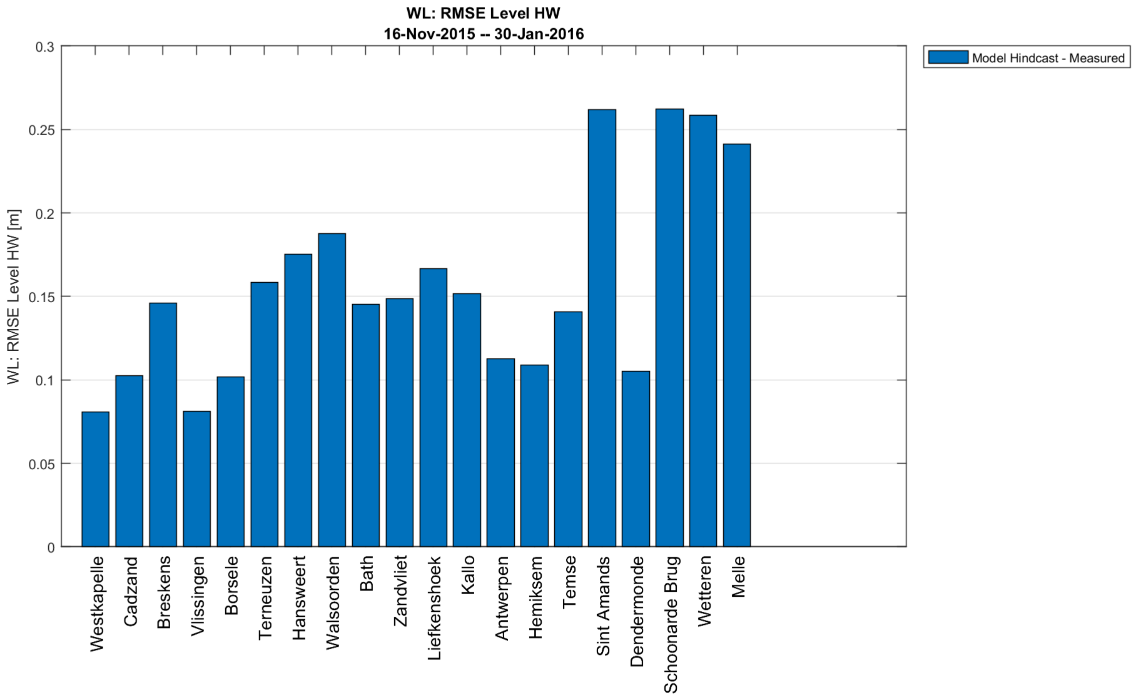


Figure 5-5: RMSE of complete time series along the estuary from 16-11-2015 to 30-01-2016.

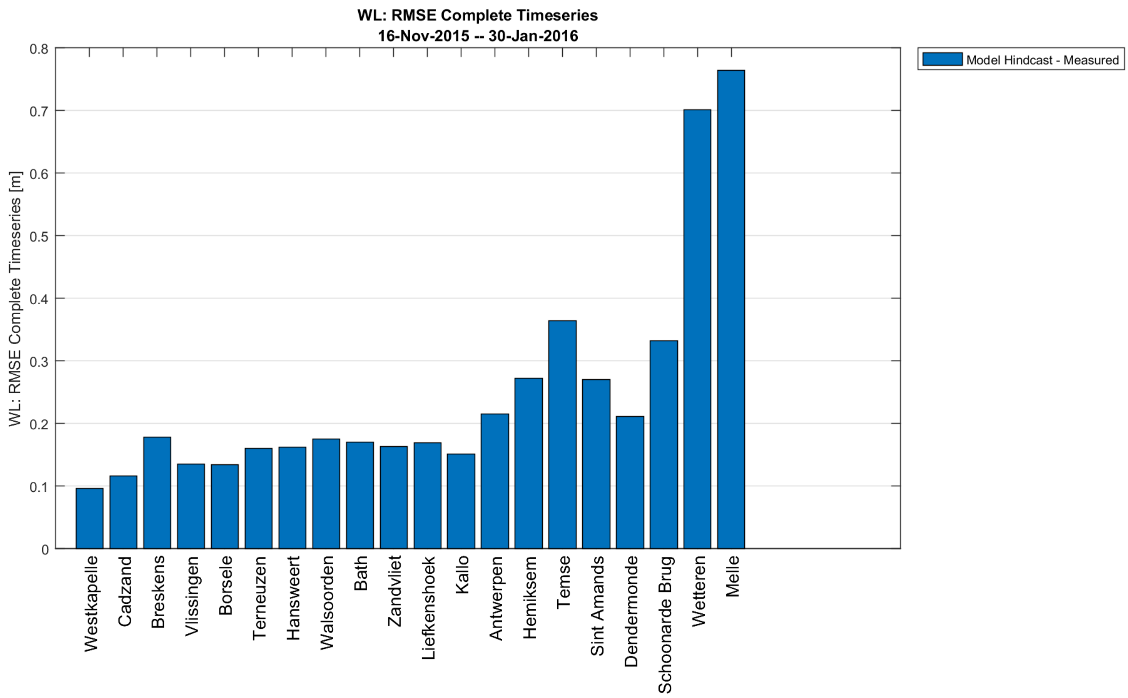


Figure 5-6: RMSE0 of high water level along the estuary from 16-11-2015 to 30-01-2016.

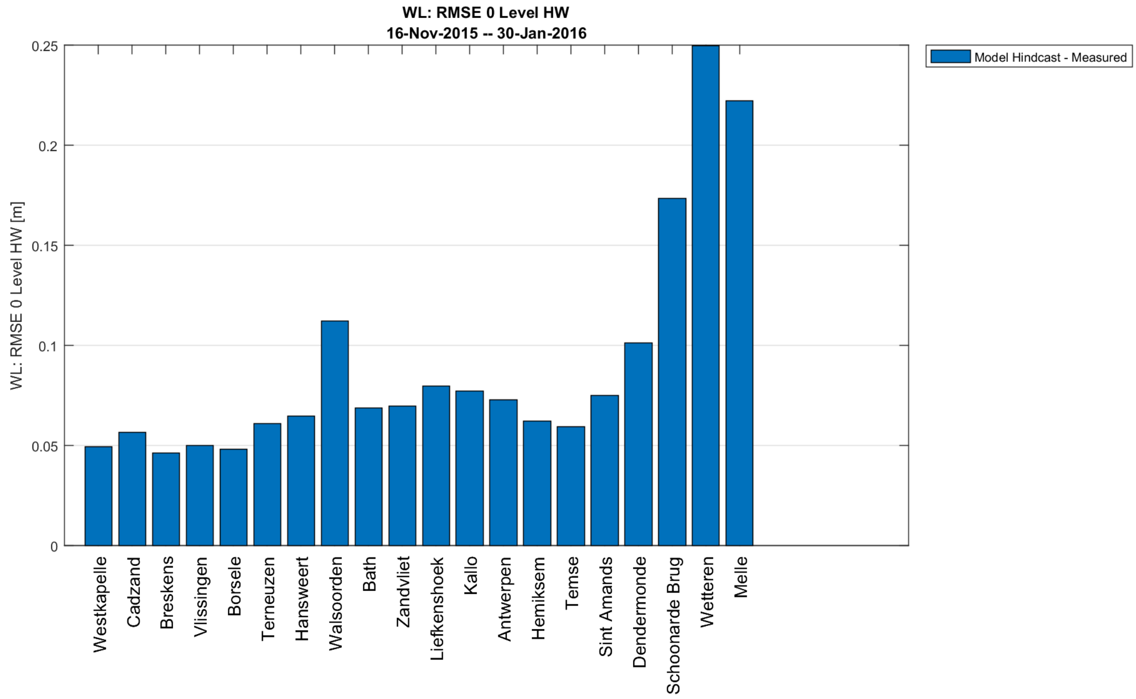
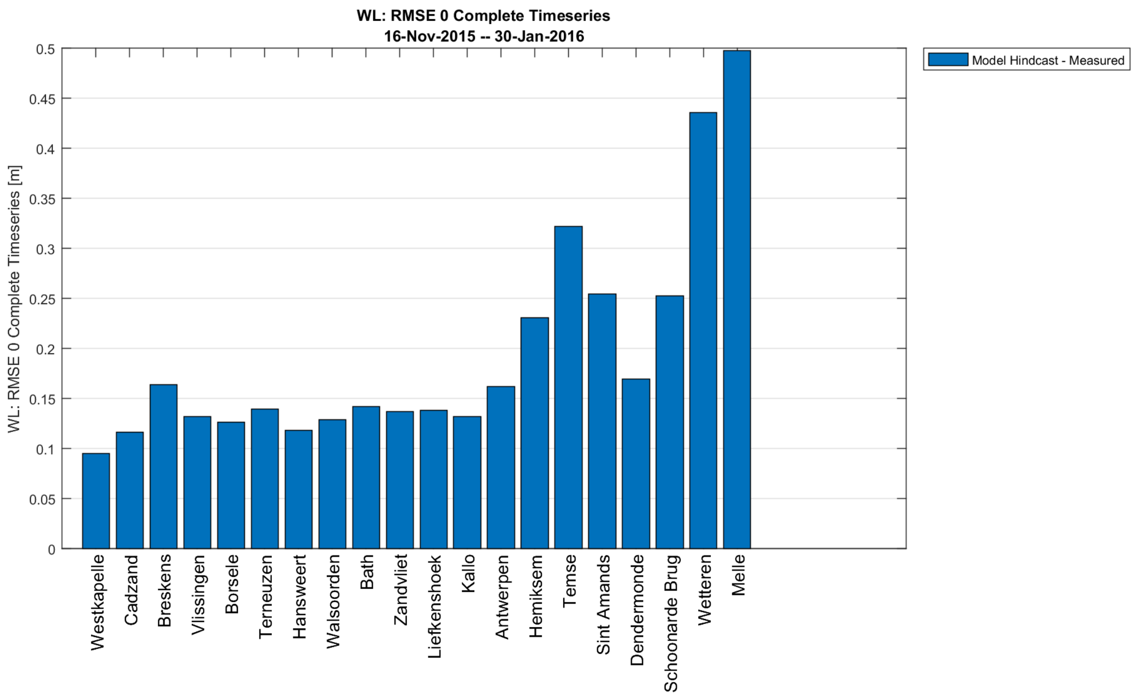


Figure 5-7: RMSE0 of complete time series along the estuary from 16-11-2015 to 30-01-2016.



5.2.2 Harmonic Analysis

The vector differences (see definition in §Annex2) from the harmonic analysis give an overview of the model performance from a harmonic point of view (Figure 5-8). The vector differences are about 40 cm from offshore till Kallo. The amplitude and phase of the harmonic constant M2 is presented in Figure 5-9 and Figure 5-10. And the amplitude and phase of the harmonic constant S2 is presented in Figure 5-11 and Figure 5-12. The M2 and S2 amplitudes are slightly underestimated by about 10 cm and 5 cm respectivly from offshore till Antwerp. The M2 and S2 phases are relatively well reproduced.

Similar patterns have been found for the two storm periods (27/11/2015 – 02/12/2015 and 11/01/2016 – 17/01/2016) as well. Figures are not shown in this section for the sake of concision.

The complete set of VIMM harmonic analysis files is presented in a CD in annex.

Figure 5-8: Vector difference harmonic analysis.

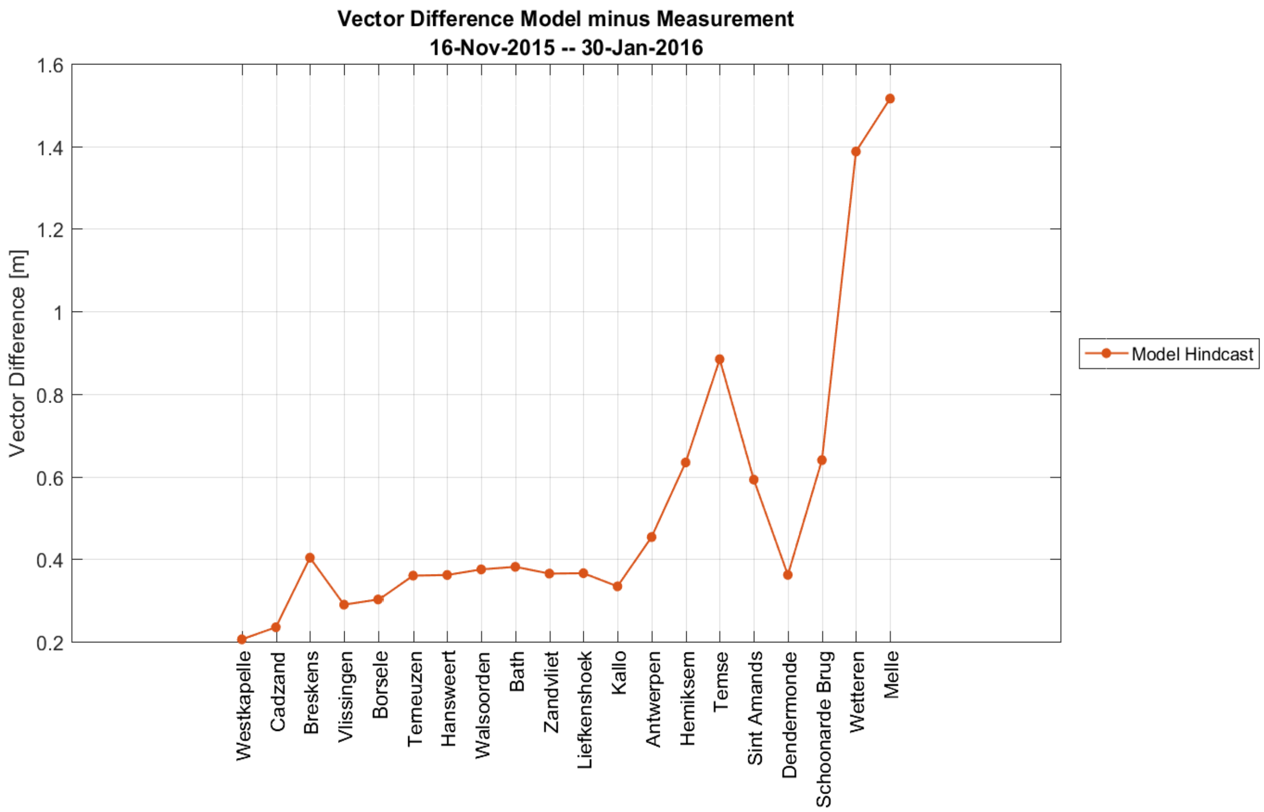


Figure 5-9: M2 amplitude comparison.

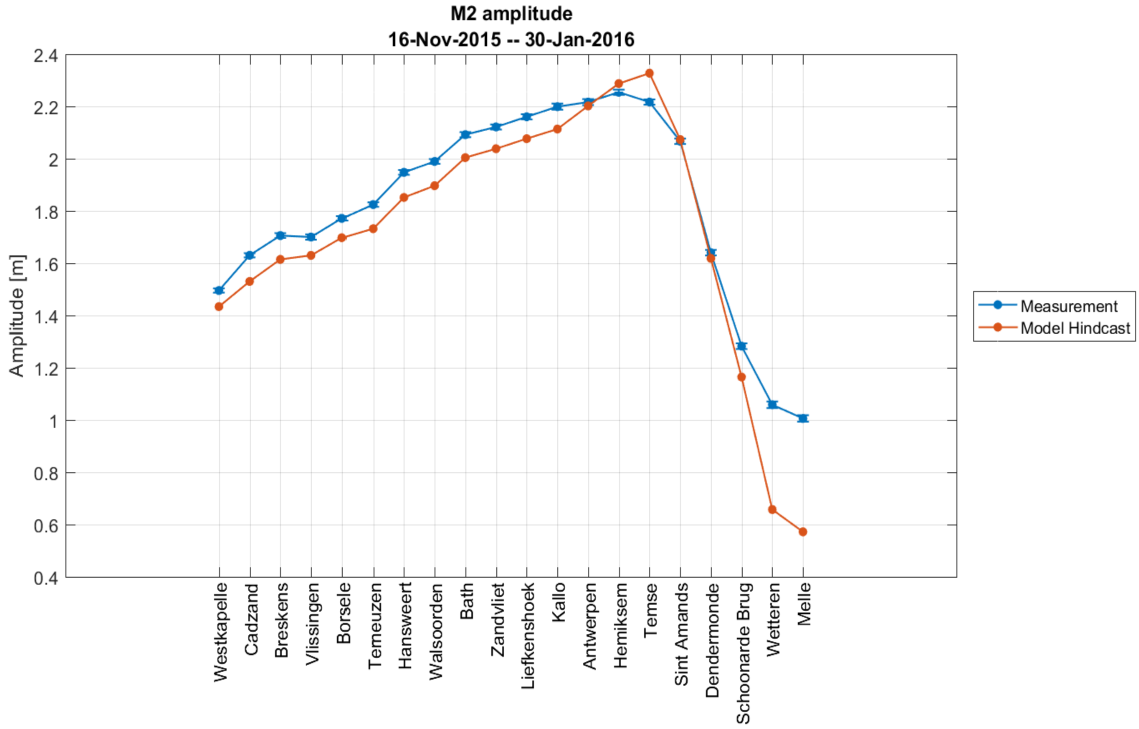


Figure 5-10: M2 phase comparison.

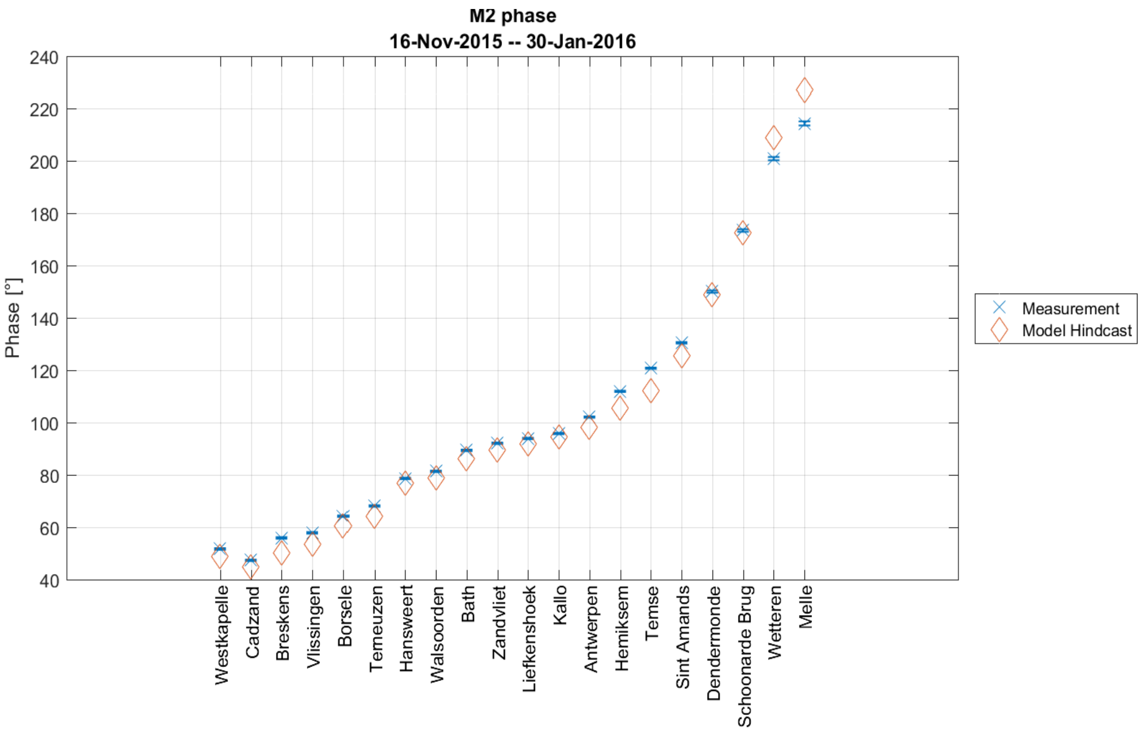


Figure 5-11: S2 amplitude comparison.

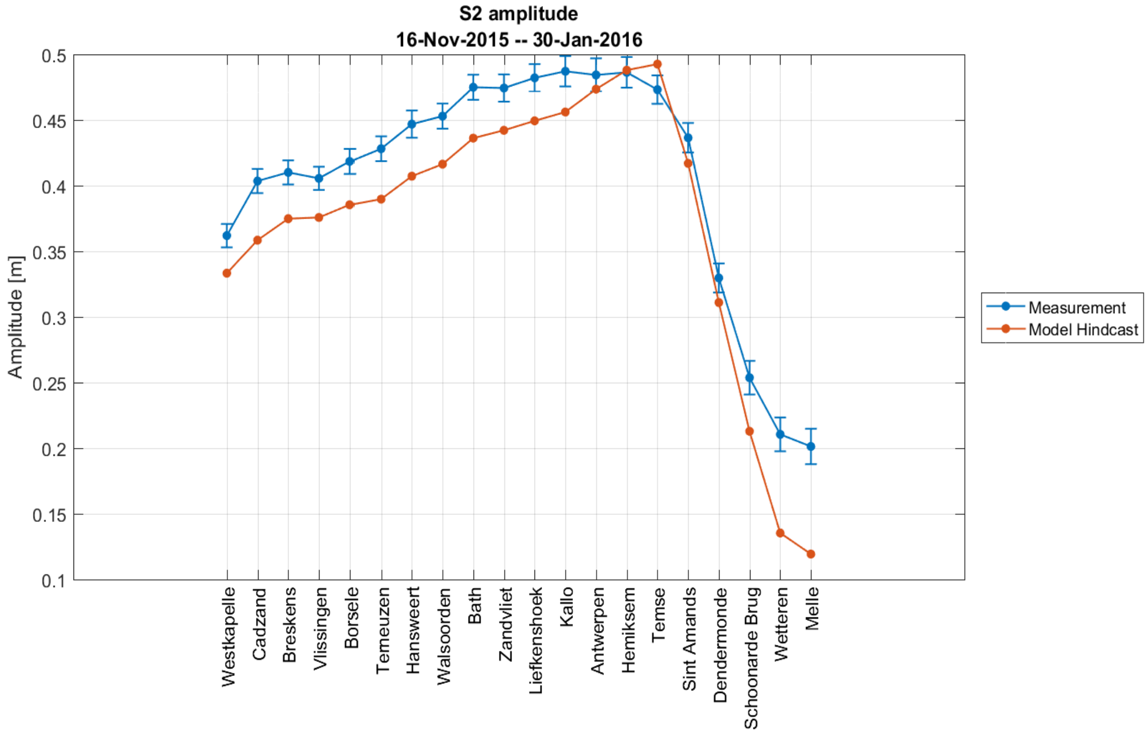
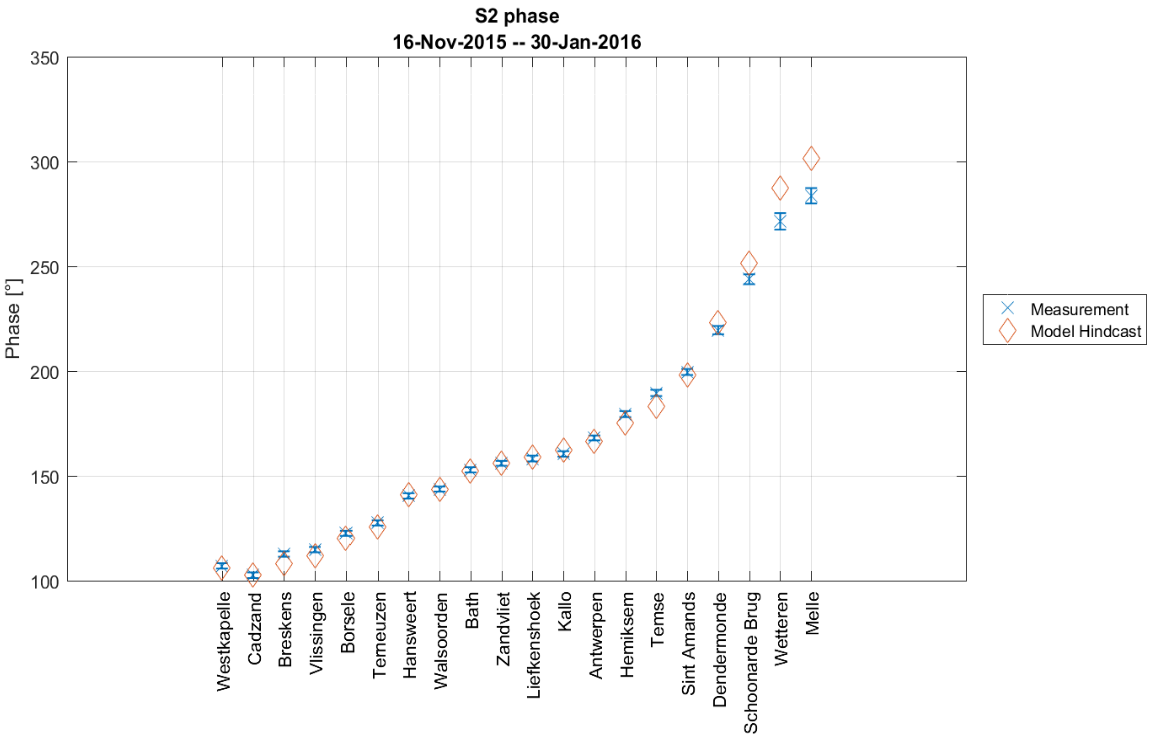


Figure 5-12: S2 phase comparison.



5.3 Benchmark of Water Level performance

In this section, the predictive abilities of the Nevla2D model are systematically evaluated by comparing water level predictions from the existing Nevla3D model and the 1D operational model.

5.3.1 NEVLA3D

The existing Nevla3D model was recently calibrated and validated by Vanlede et al (2015). A full year (2009) run simulation (simG146) was selected as a validation experiment, since it allows to determine the model quality in a period for which the model has not been overly calibrated. The period is long enough for it to cover all kinds of seasonal effects, tidal variations and possible extreme events. The year 2009 was selected based on the large amount of measurement data readily available to compare the simulated results. After analysing the relevant statistical parameters for the full year run of 2009 and comparing them to those found for calibration, it can be concluded that the 3D NEVLA model retains its overall good model performance also outside its calibration period. It can therefore be concluded that model validation was successful, and the model can be used to simulate time periods that lie outside of its calibration period.

In this study, post processing is performed with VIMM for a 3 months of winter period (01-10-2009 to 31-12-2009) out of the full year simulation results from simG146. This is considered to be consistent with the hindcast period from 16-11-2015 to 30-01-2016 in a sense. Although this is not an essentially one-on-one comparison (different months from different years), the comparisons of water levels along the estuary are quantitatively compared to provide impressions/inspirations of the overall model performance.

Figure 5-13 presents the comparison of bias, RMSE and RMSE0 of high water levels along the estuary. The Nevla3D model in general leads to positive bias of high water (overestimation) whereas the Nevla2D model produces negative bias of high water (underestimation). The absolute values of high water bias are generally decreased by 50% on average (6 cm vs 12 cm) with Nevla3D model. There is no significant reduction on the RMSE of high water on average (15 cm vs 16 cm) with Nevla3D model. The Nevla3D model leads to substantially larger RMSE0 on average (12 cm vs 9 cm) compared with Nevla2D model.

Figure 5-14 presents the comparison of bias, RMSE and RMSE0 of the complete time series of water levels along the estuary. Similar patterns have been found. The absolute values of bias are generally decreased by 50% on average (7 cm vs 14 cm) with Nevla3D model. Both of RMSE and RMSE0 decrease from Antwerp to further upstream with Nevla3D model whereas the decrease of RMSE and RMSE0 is less considerable at downstream stations.

Figure 5-15 presents the comparison of vector differences along the estuary. The vector differences are 5-15 cm smaller with Nevla3D model at most of the stations, especially at Western Scheldt stations of Hemiksem and Temse.

The basic analysis and harmonic analysis results imply that the Nevla3D model leads to overall better performance compared with Nevla2D model. This is justified because the Nevla3D includes more physical processes which are not considered in the Nevla2D model, such as vertical and near-bed flows, salinity mixing/stratification due to gravitational circulation, secondary flow etc. Nevertheless the Nevla2D model leads to fairly good water level predictions. The discrepancies are all within reasonable ranges.

Figure 5-13: Comparison of bias, RMSE and RMSE0 of high water level
from Nevla2D model and Nevla3D model (simG146).

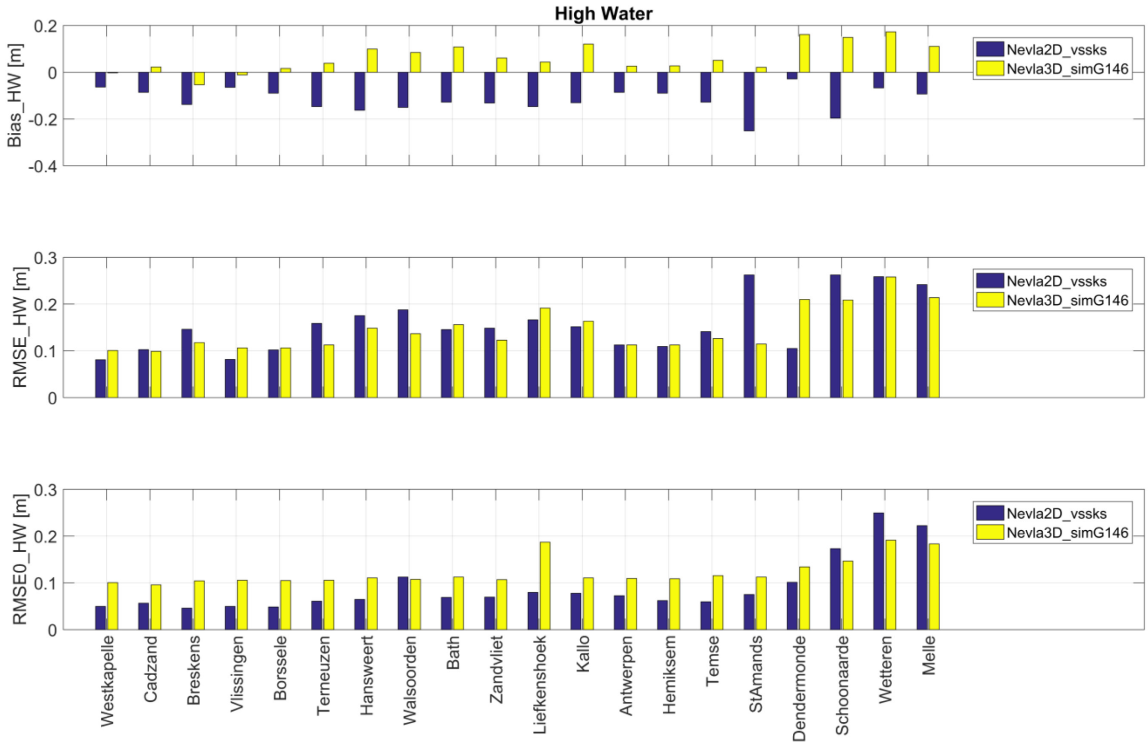


Figure 5-14: Comparison of bias, RMSE and RMSE0 of complete time series of water level
from Nevla2D model and Nevla3D model (simG146).

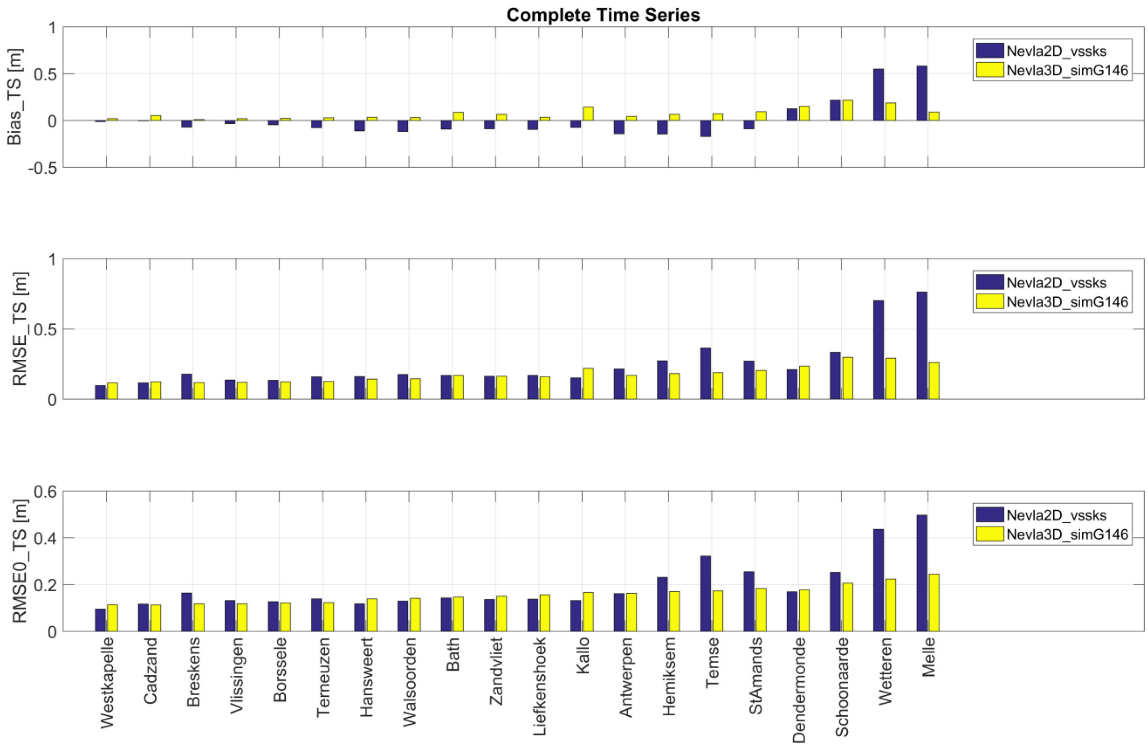
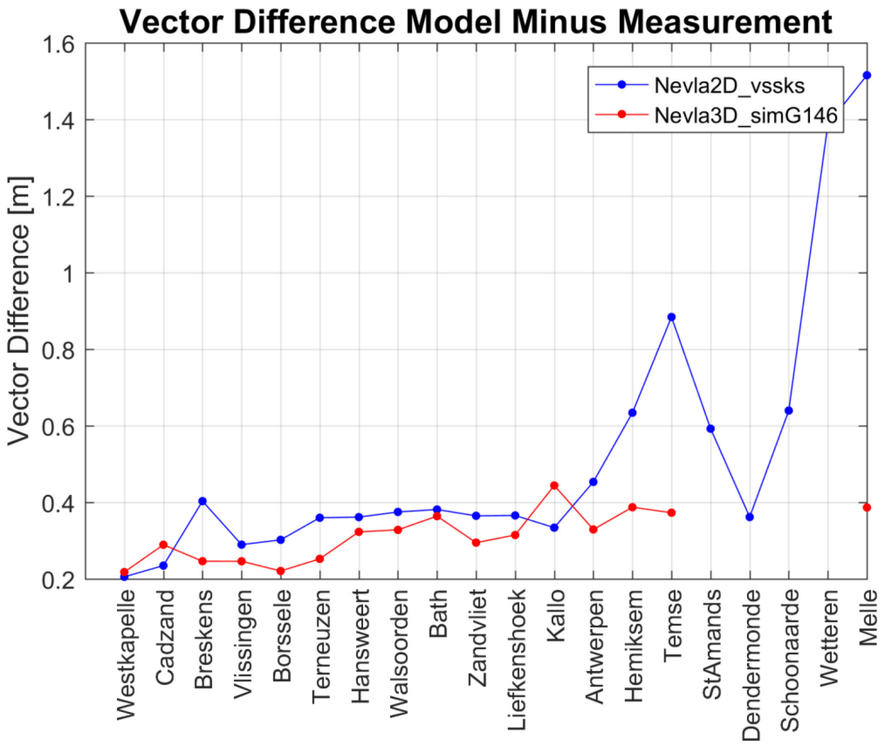


Figure 5-15: Vector difference harmonic analysis.



5.3.2 1D operational model

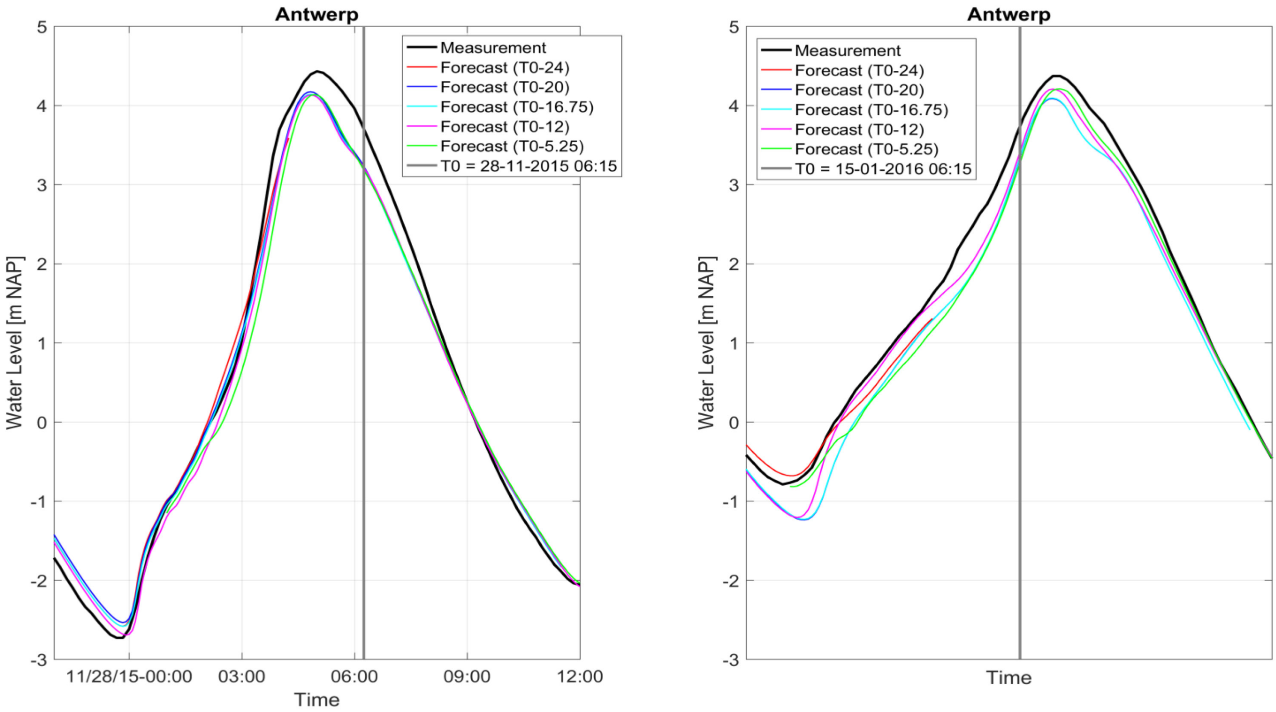
The 1D online operational model (SIGMA) is a tidal water model including the main water courses of river Scheldt. Similar to VSSKS, the SIGMA model is also a restarting system with forecast period of 2 days and 'reboots' frequently (e.g. 5.5 hours or 6.75 hours) when model inputs are available from new forecasts. Astro-correction is not performed on 1D operational model. The downstream boundary of the 1D model is set at Vlissingen where the forecasts from the Netherlands are imposed as boundary conditions.

Figure 5-16 shows the water levels predicted by the 1D forecast models at Antwerp with forecast horizons of 24, 20, 16.75, 12 and 5.25 hours for the two storms respectively. The time series dataset is extracted from the Hydra database. In general the 1D operational model leads to better predictions of the maximum high water at the two stormy periods compared with Nevla2D model (see results in Figure 5-1).

For the first storm, water level predictions with different forecast horizons are very similar in both patterns and magnitudes. The maximum water level is however still underestimated by about 30 cm. Compared with predictions from Nevla2D model, the phase of the water level is poorly reproduced by the 1D forecast model. The period is much shorter during high water, this is more so at the moment immediately after the maximum high water.

For the second storm, model forecasts with 5.25 and 12 hours ahead show best predictions, which however still underestimate the maximum high water level by about 20 cm. The phase of high water level is better predicted with forecast horizon of 5.25 hours. The model run with forecast horizon of 16.75, 20 and 24 hours leads to underestimation of maximum high water by 30 cm.

Figure 5-16: Comparison of water level at Antwerp at 28/11/2015 05:00 (left panel) and 15/01/2016 07:00 (right panel) predicted by the 1D operational model.



A complete time series of water level at Antwerp (15/11/2015 to 31/01/2016) was reconstructed from each 1D model run with the shortest forecast horizon (e.g. 5.5 hours at the two stormy period as described in Figure 5-16). It inherently represents the water level predicted by the most recent 1D forecast model when applicable. Figure 5-17, Figure 5-18 and Figure 5-19 show the comparison of bias, RMSE and RMSE0 calculated at Antwerp between the 1D forecast model and Nevla2D model.

The 1D model in general overestimates the high water levels by about 16 cm, which explains why the 1D model leads to better predictions of high water during the two storm periods. Although Nevla2D fails in predicting the two storms, it on average underestimates the high water level only by 8 cm. The 1D model leads to smaller bias of low water and the complete time series of water level. The Nelva2D model leads to smaller RMSE0 on both high water, low water and complete time series, compared with the 1D operational model.

In addition, Coen (2016) performed 3 hindcast runs with different downstream boundary conditions of wind and different wind factors. The 1D operational model performance improved significantly when the model is driven by wind measurements at downstream boundary edge.

Figure 5-17: Bias of high water, high water time, low water, low water time and complete time series at Antwerp from the 1D forecast model and Nevla2D model

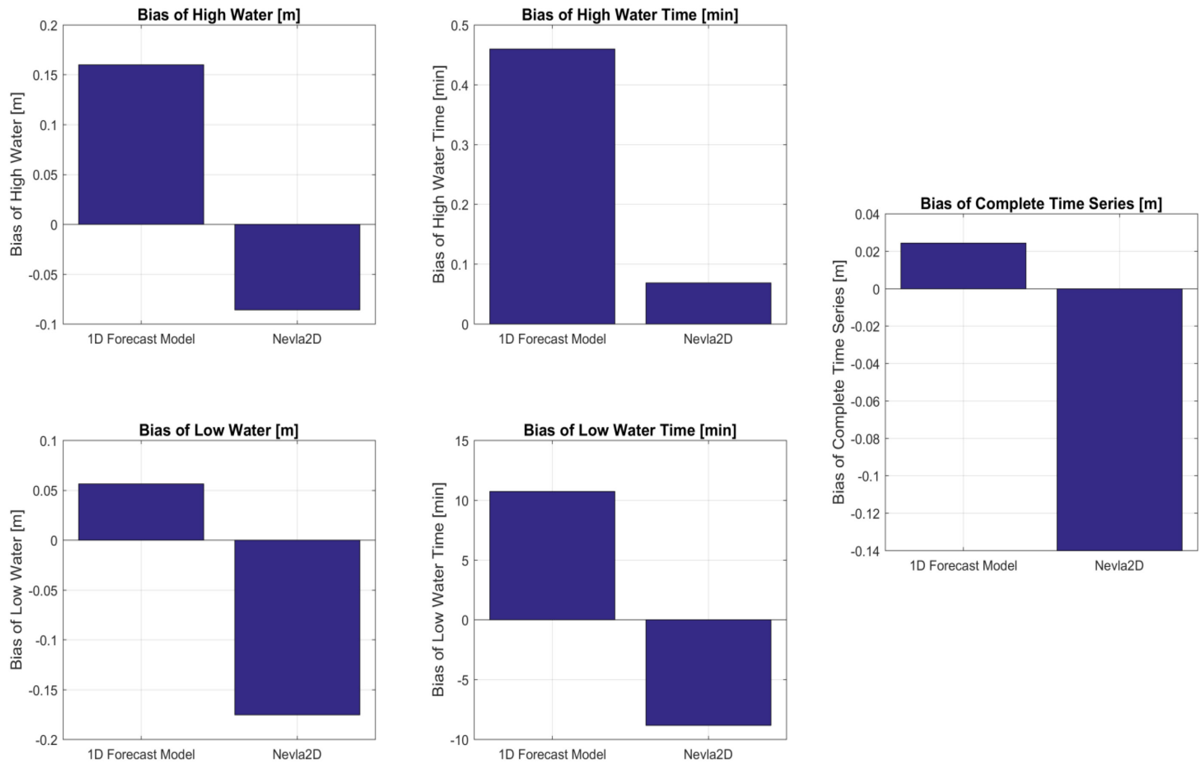


Figure 5-18: RMSE of high water, high water time, low water, low water time and complete time series at Antwerp from the 1D forecast model and Nevla2D model

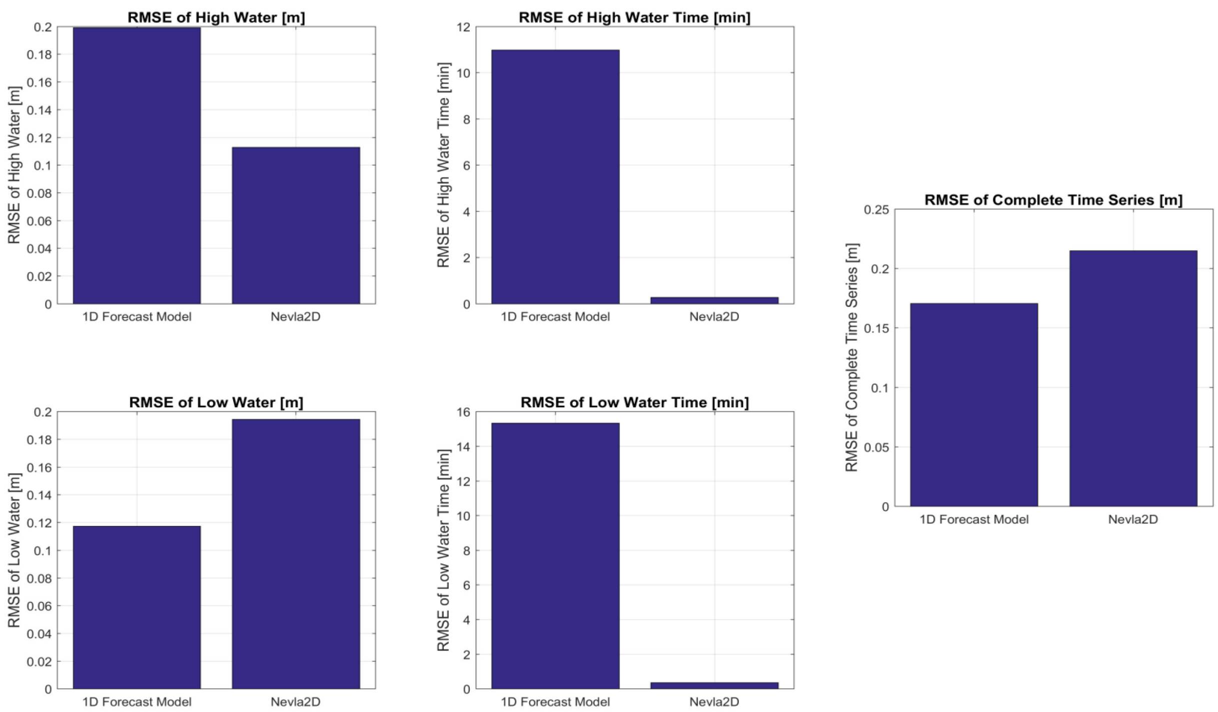


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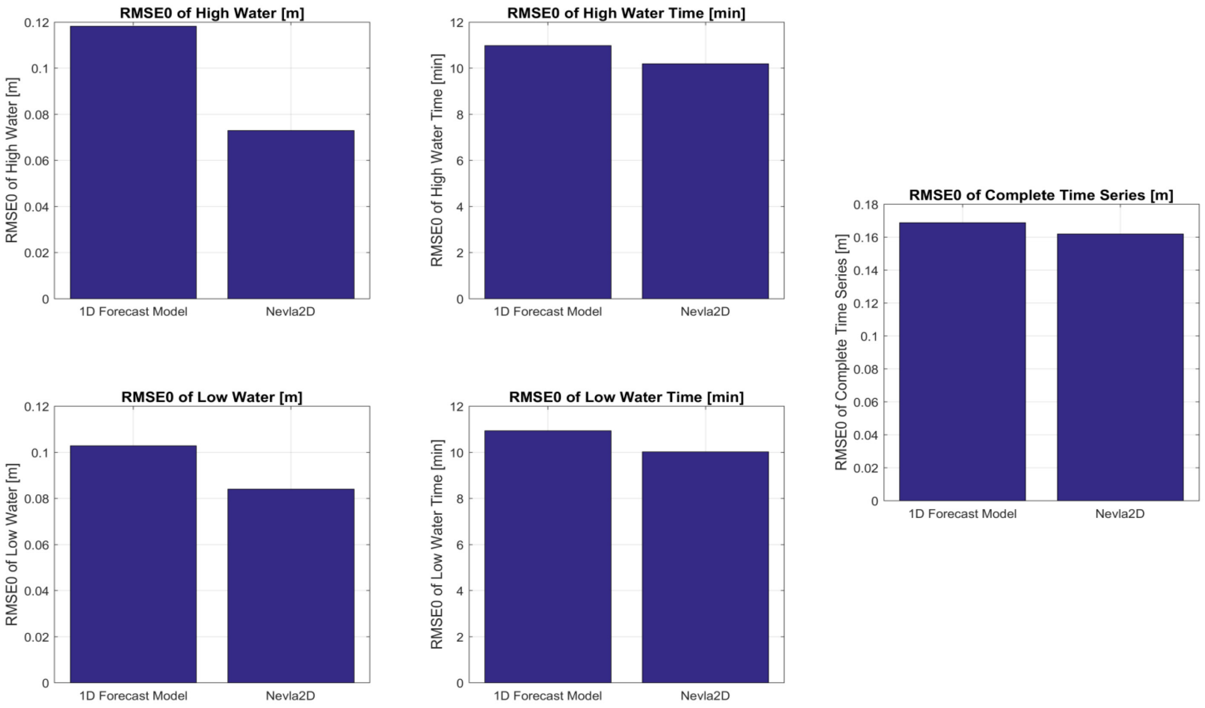
Figure 5-19: RMSE0 of high water, high water time, low water, low water time and complete time series at Antwerp from the 1D forecast model and Nevla2D model

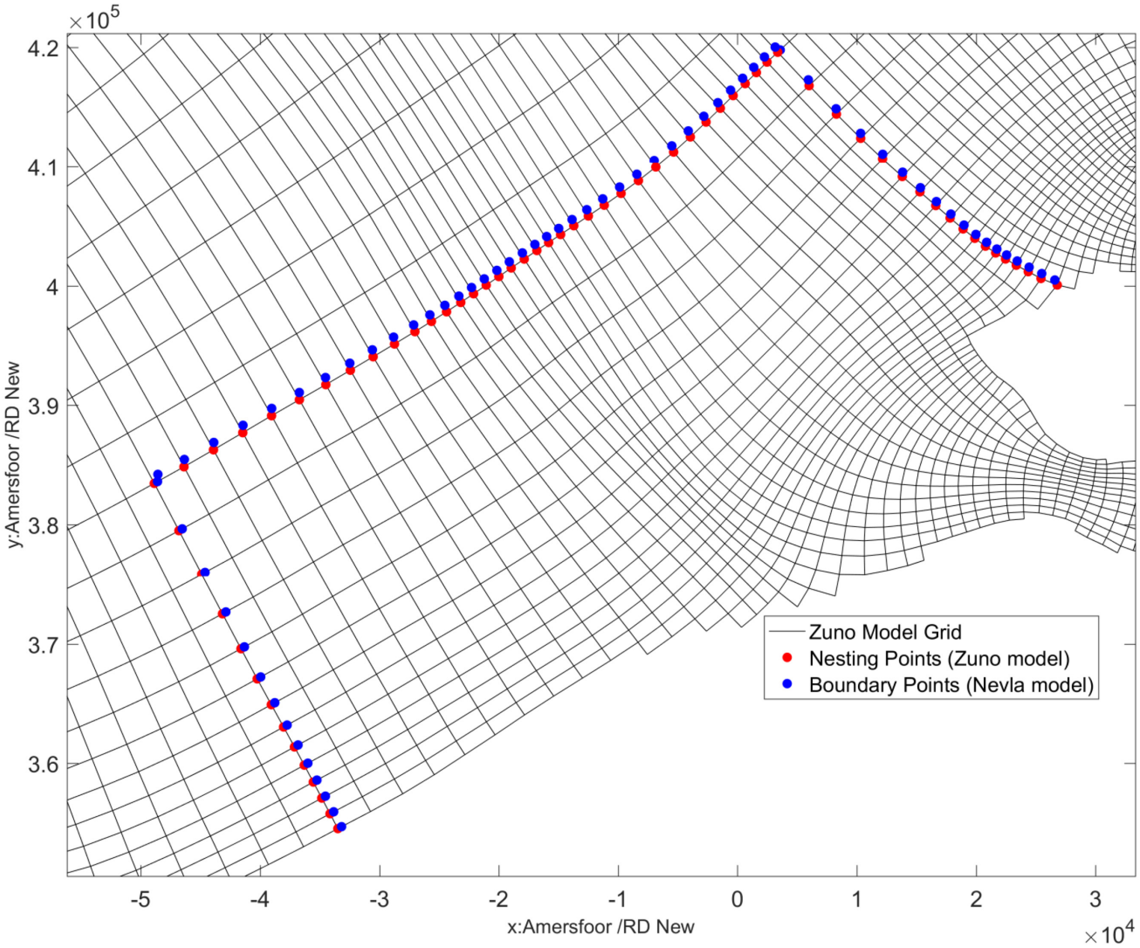


6 Sensitivity Analysis

6.1 Nesting script

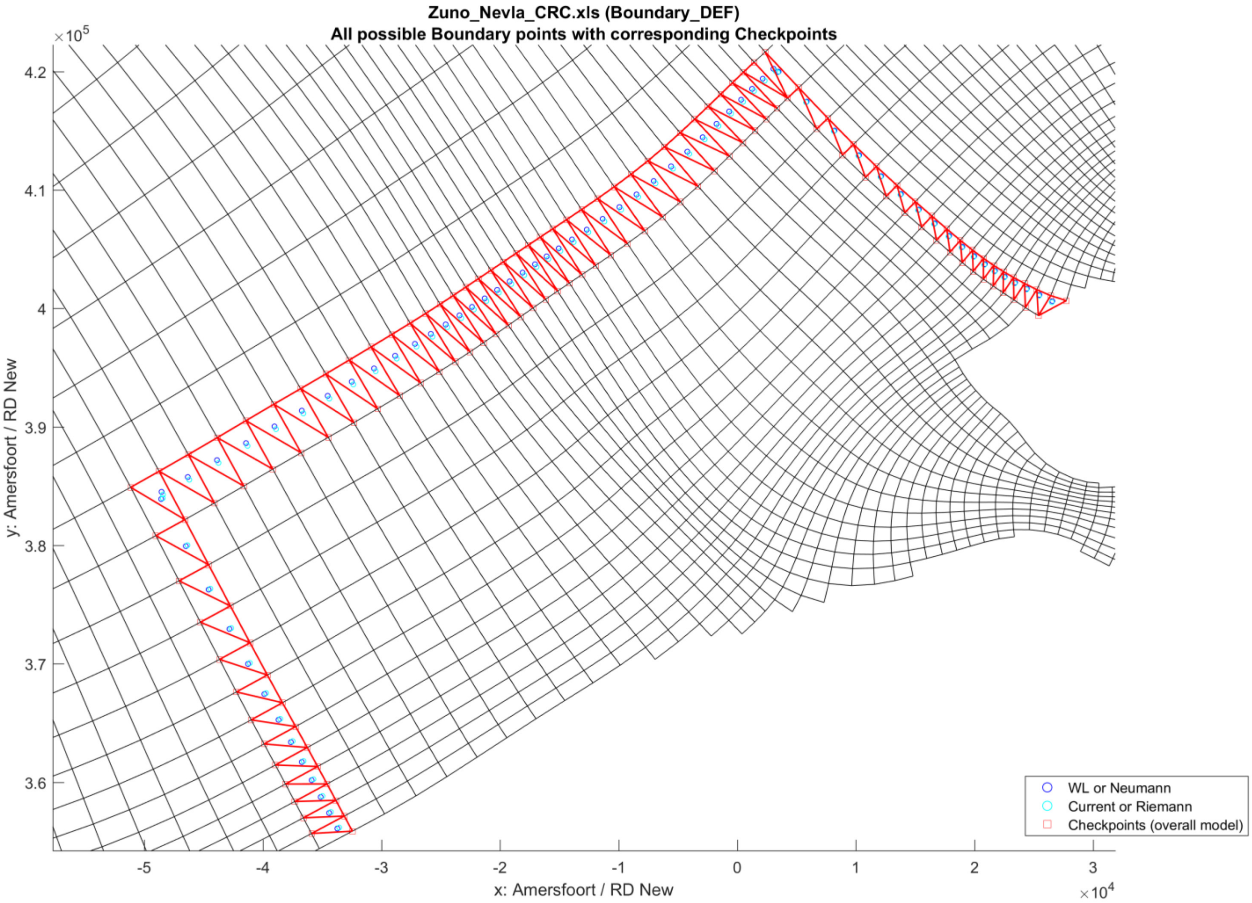
As mentioned in §2.5, the boundary nesting between models of CSM, ZUNO and Nevla2D is carried out by means of a SIMONA nesting script **modnst.pl**, which nests the boundary points from the smaller (daughter) model into the larger (mother) model by copying the values of the nearest grid point. Figure 6-1 exemplifies the nesting between ZUNO and Nevla model with the SIMONA nesting script. The spatial distance between the corresponding points is around 50-500 m, which might create deviations of hydrodynamic information received from the larger model, albeit limited.

Figure 6-1: Demonstration of nesting between ZUNO and Nevla model with SIMONA nesting script of modnst.pl.



An alternative way is to use the in-house matlab script which was initially developed in the framework of project Modellentrein CSM-ZUNO (Leyssen et al., 2011) and has been commonly used by many projects (e.g. Vanlede et al., 2015). Instead of searching the nearest point, it performs spatial interpolation with hydrodynamic information from three surrounding points of the larger (mother) model by means of a Delaunay triangulation. This script is linked to the versioning system with https://wl-subversion.vlaanderen.be/svn/repoSpNumMod/Matlab/Nesting. Figure 6-2 exemplifies the nesting between ZUNO and Nevla model with in-house matlab script.

Figure 6-2: Demonstration of nesting between ZUNO and Nevla model with in-house matlab nesting script.



The two different nesting approaches might impose different boundary conditions on the smaller model, especially in terms of phasing of water wave propagation, which might consequently lead to different water levels predicted along the Scheldt. The sensitivity of the two nesting scripts is therefore investigated in this section.

Three points are selected close by the offshore boundaries of the Nevla model (see Figure 6-3). The hydrodynamics at these 3 stations (e.g. water level) in a way represent the boundary conditions received from the Zuno model. Therefore the water level predicted by the Nevla model should be ideally the same as that predicted by the Zuno model at these 3 locations. Any discrepancies of water level predictions are attribute to the boundary nesting.

Post-processing of water levels with VIMM has shown that the two different nesting approaches indeed contribute to different boundary conditions of the Nevla model, however to a rather limited extent.

Figure 6-4 and Figure 6-5 present the bias of high water and bias of high water time respectively. Near the northeast boundary of the Nevla model (indicated by 'NorthC'), using the in-house nesting script leads to slightly larger bias of high water (9 cm) compared with using the SIMONA nesting script (5 cm). The differences of high water bias are neglectable near the northwest ('WestR') and southwest boundaries ('SouthC'). The bias of high water time is not sensitive to different nesting scripts (order of 1 minute). Similar patterns have been found for the RMSE (Figure 6-6 and Figure 6-7) and RMSE0 (Figure 6-8 and Figure 6-9) as well.

The complete set of VIMM analysis files is presented in a CD in annex.

Figure 6-3: Check points imposed close by the offshore boundary sections of the Nevla model.

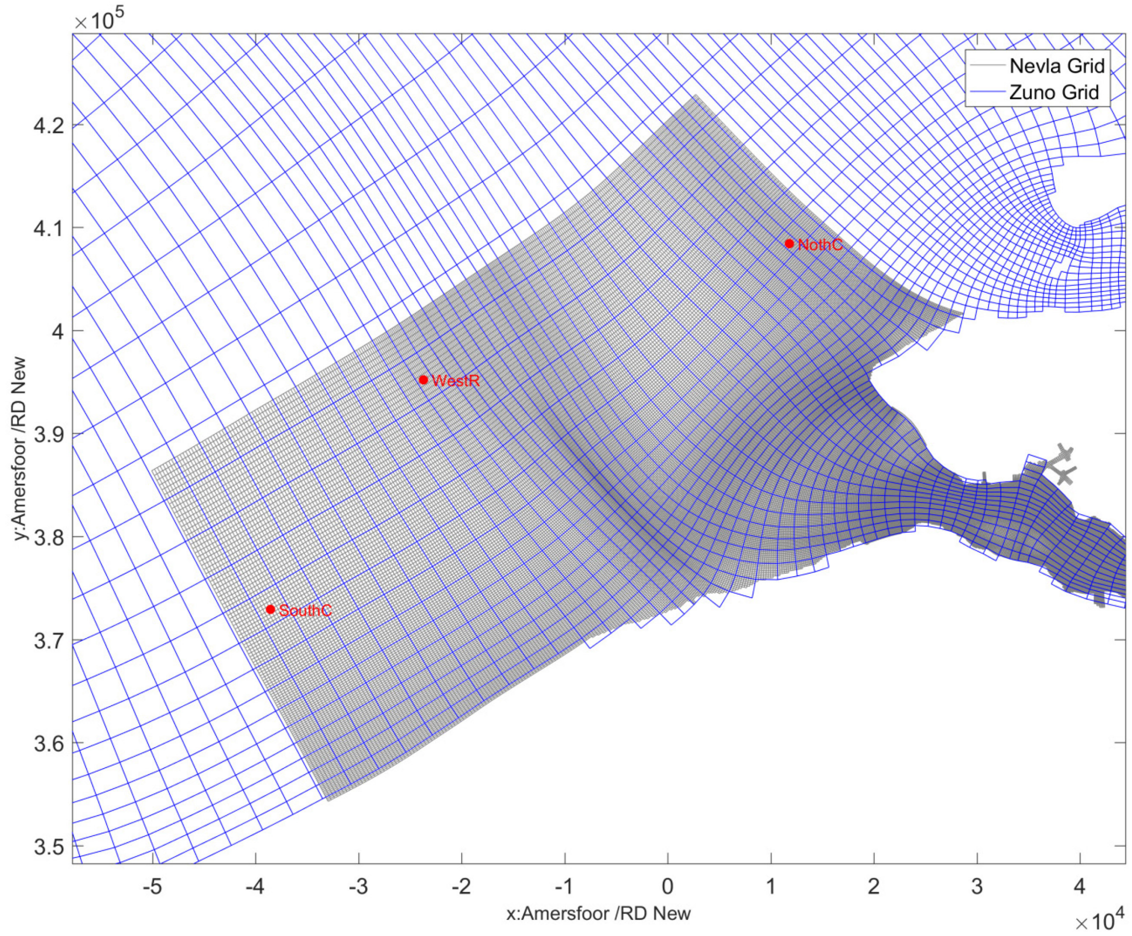


Figure 6-4: Bias of high water (model - measurement) from 16-Nov-2015 to 30-01-2016.

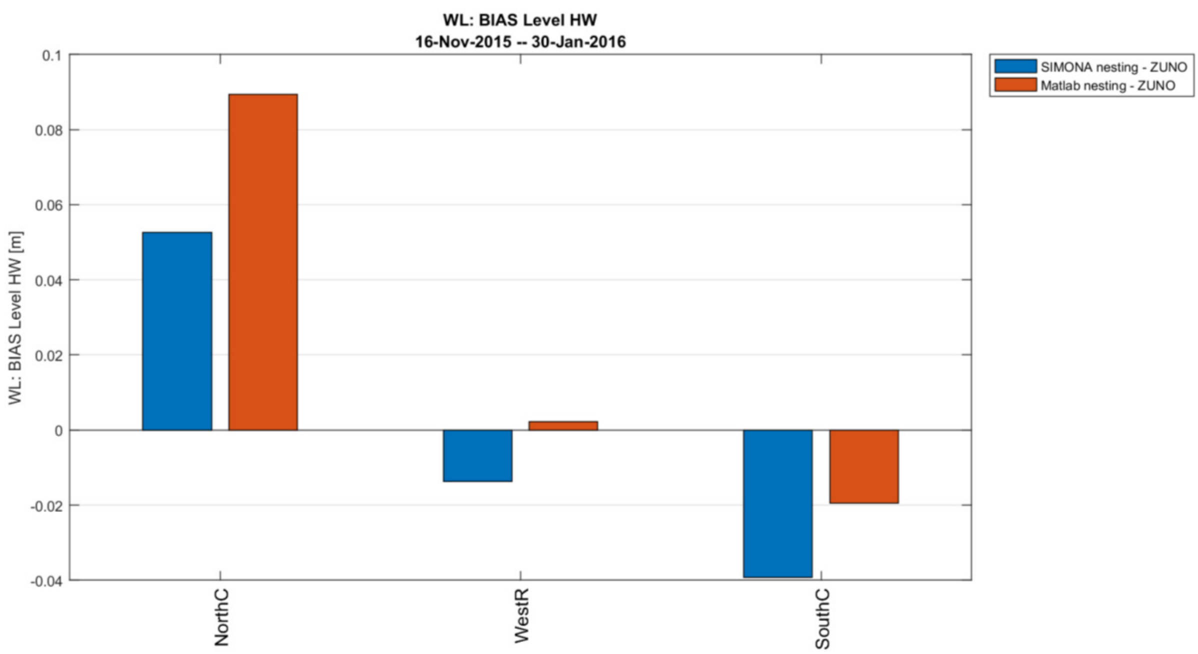


Figure 6-5: Bias of high water time (model - measurement) from 16-Nov-2015 to 30-01-2016.

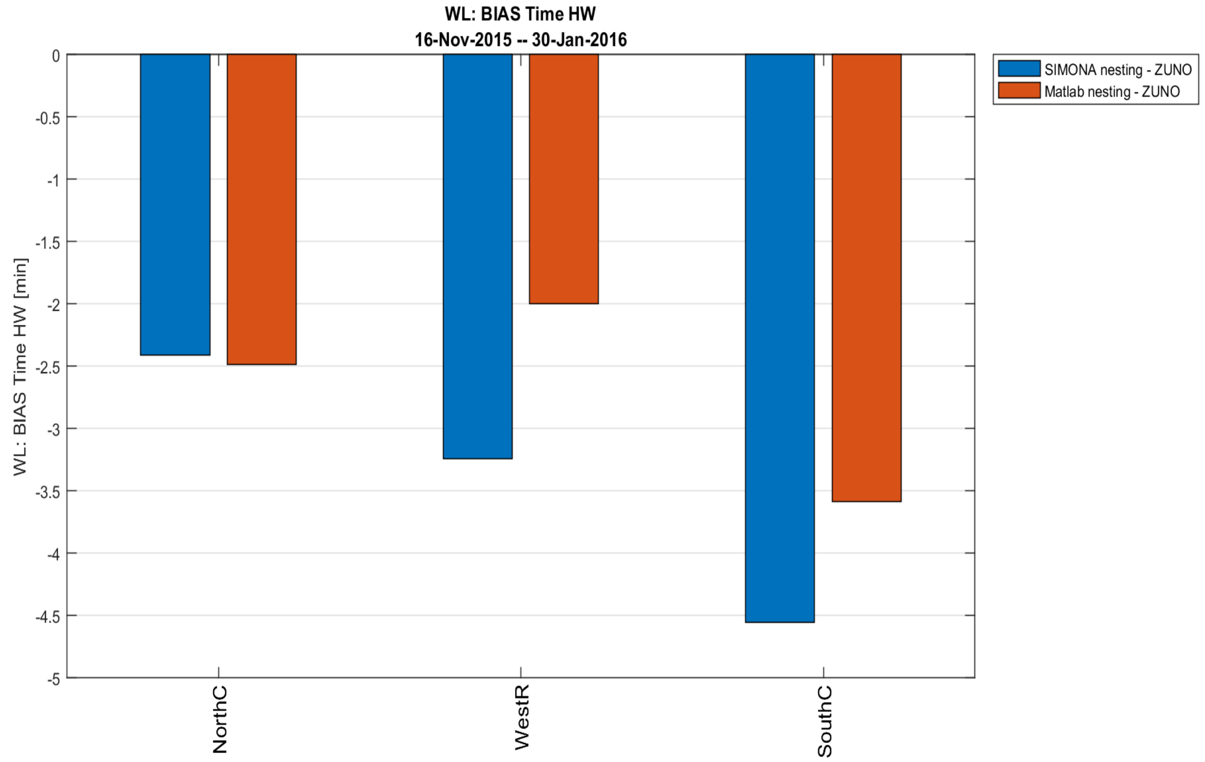


Figure 6-6: RMSE of high water from 16-Nov-2015 to 30-01-2016.

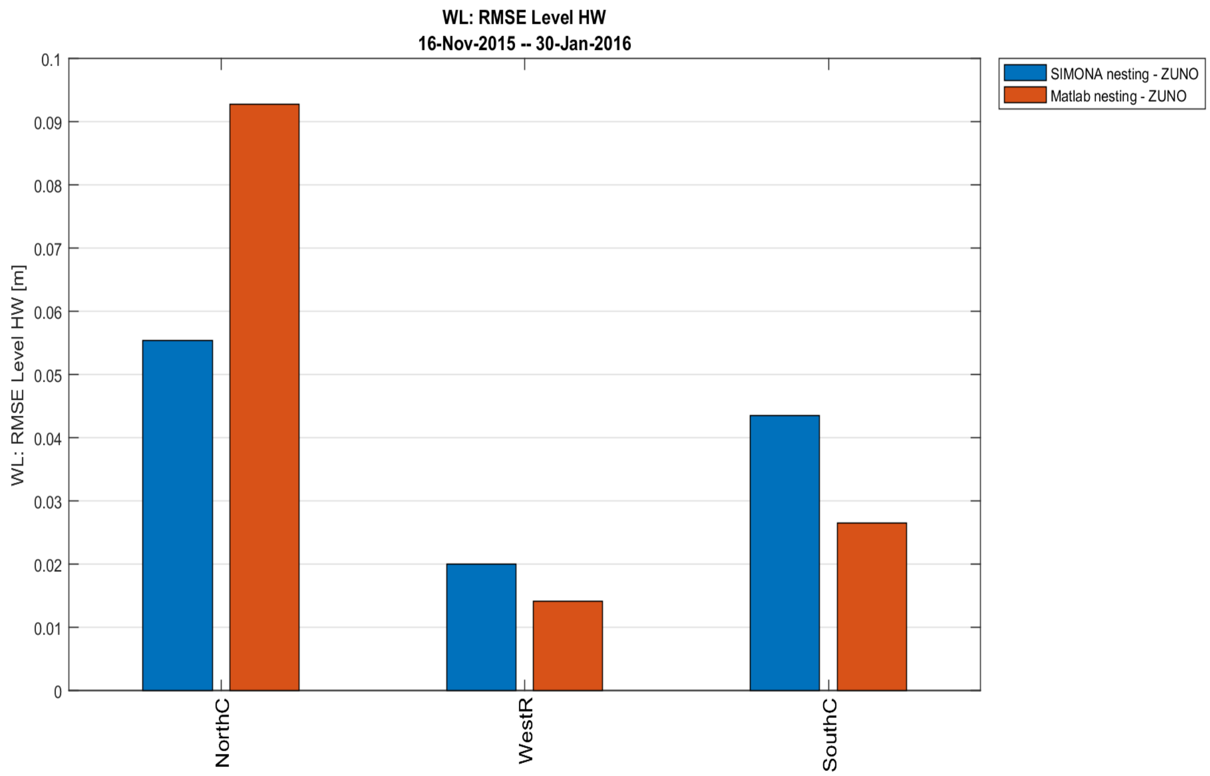


Figure 6-7: RMSE of high water time from 16-Nov-2015 to 30-01-2016.

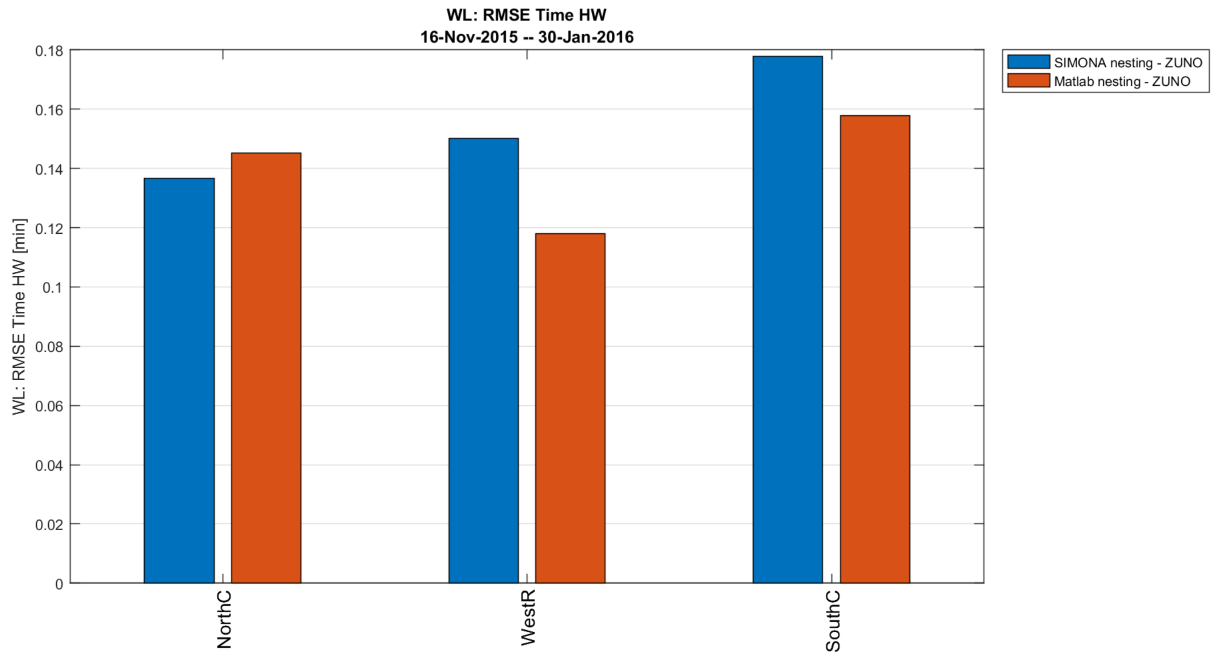


Figure 6-8: RMSE0 of high water from 16-Nov-2015 to 30-01-2016.

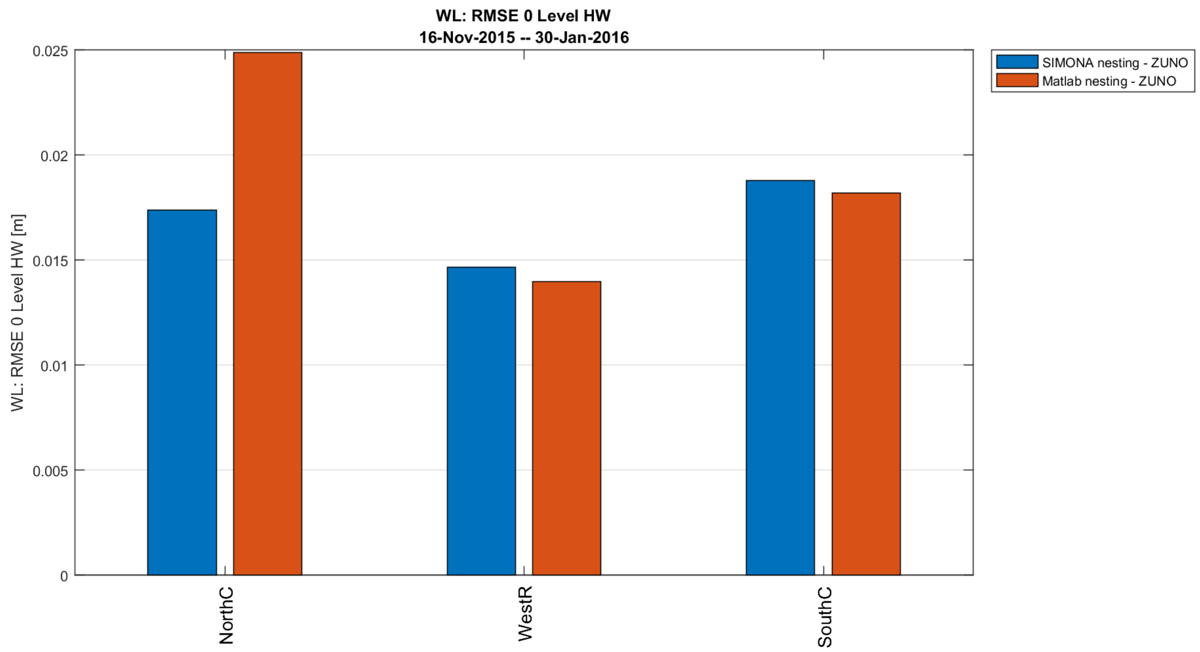
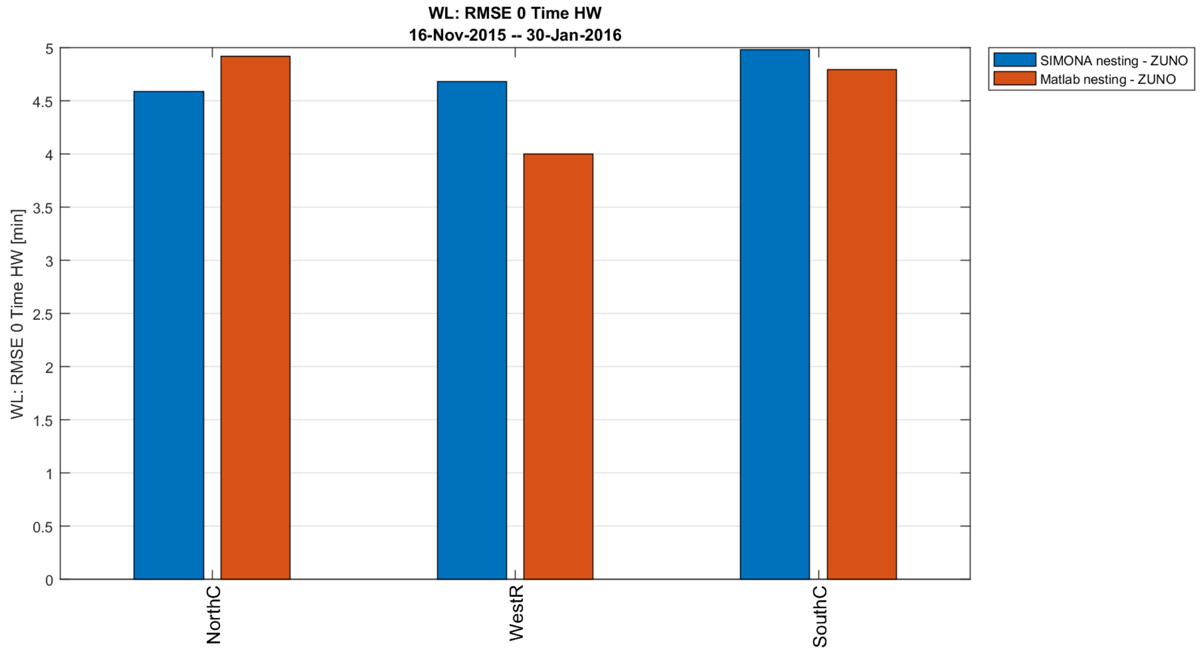


Figure 6-9: RMSE0 of high water time from 16-Nov-2015 to 30-01-2016.



6.2 Kalman Filter

Kalman filtering is a mathematical method that provides efficient computational (recursive) means to estimate the state of a process, in a way that minimizes the mean of the squared errors. On VSSKS Kalman filtering is used to improve predictions for locations where measurements are available (mainly at the English coast). For this purpose, the measurements are compared with the hindcast produced by the model. The statistical information on the deviation is then used to adjust the forecast.

On VSSKS Kalman Filter is implemented on the CSM and ZUNO model (not on Nevla). In order to investigate whether the Kalman Filter is still functional on VSSKS, a sensitivity analysis has been carried out for the period of 01-Nov-2015 to 31-01-2016. To be specific, water levels predicted by CSM model with and without Kalman Filter are compared with water level measurements at Vlissingen and Dover respectively.

The results in terms of bias, RMSE and RMSE0 of water levels are demonstrated in Figure 6-10, Figure 6-11 and Figure 6-12. The Kalman Filter does not reduce the bias of water level significantly. However in terms of RMSE and RMSE0, the Kalman Filter improves the predictions of water levels by 10-20%. Therefore the Kalman Filter implemented on the VSSKS is still functional in terms of improvement on model predictive abilities.

Figure 6-10: Bias of high water, high water time, low water, low water time and complete time series at Vlissingen and Dover.

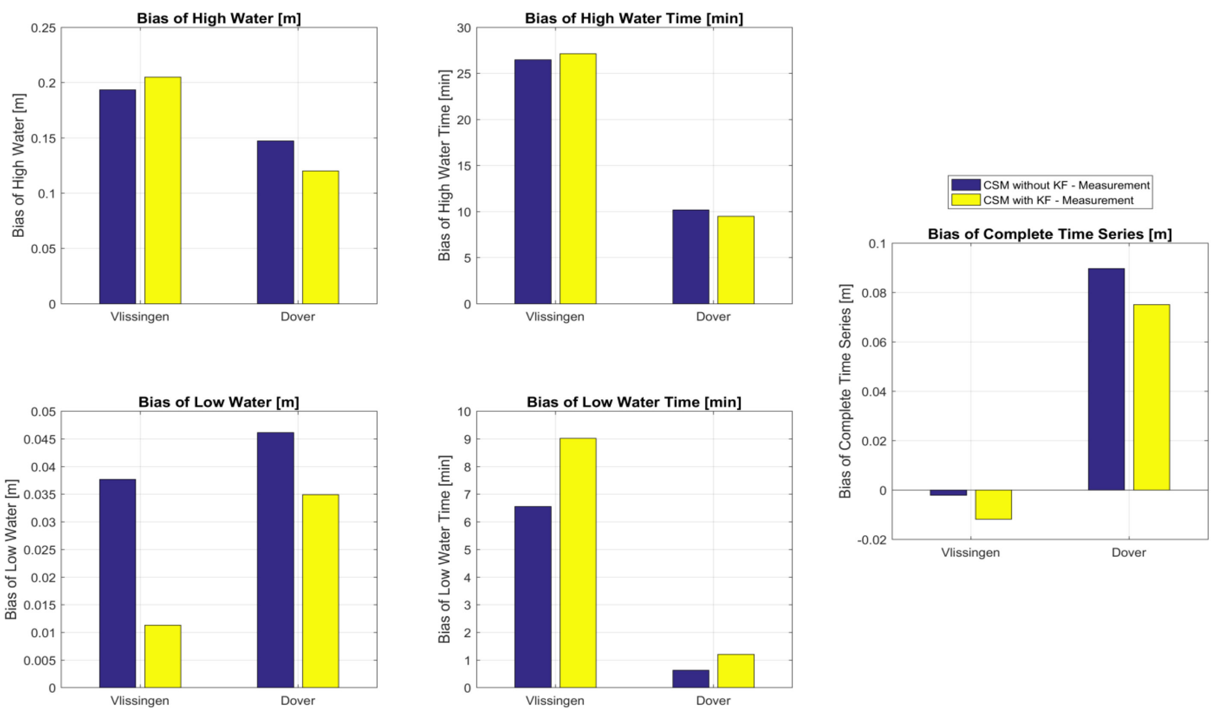


Figure 6-11: RMSE of high water, high water time, low water, low water time and complete time series at Vlissingen and Dover.

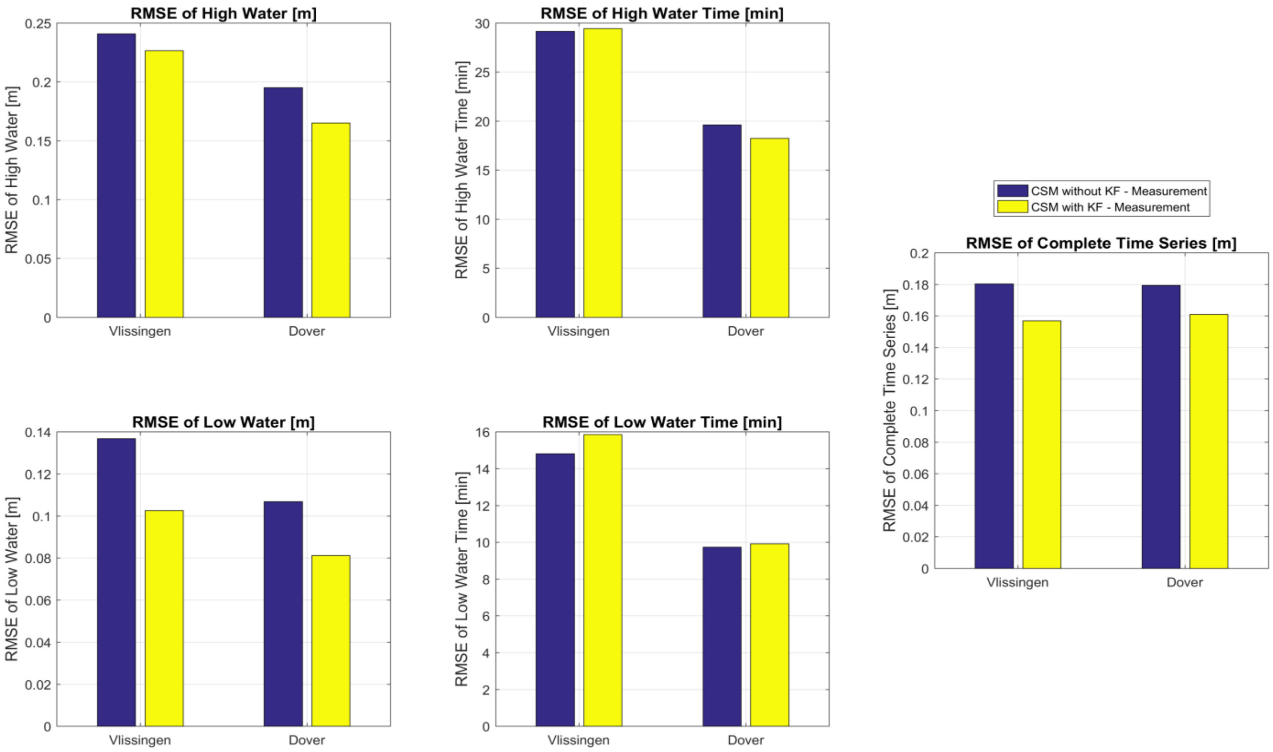
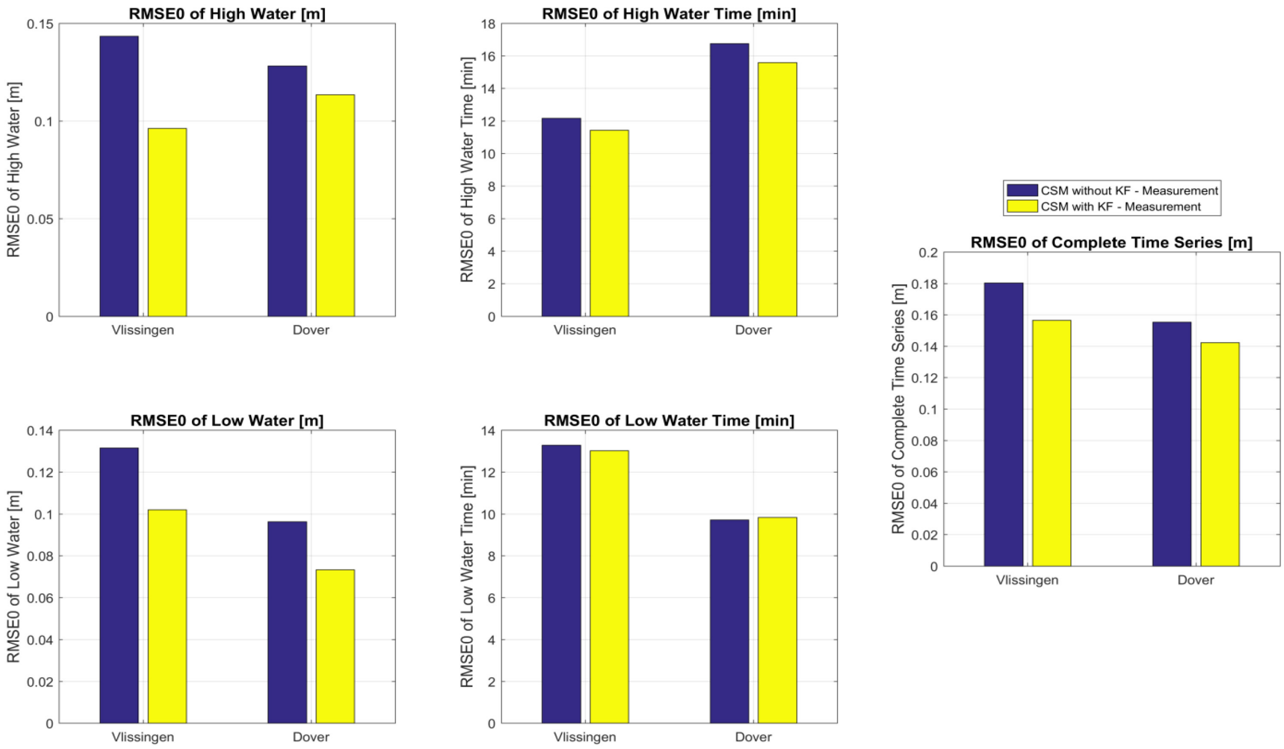


Figure 6-12: RMSE0 of high water, high water time, low water, low water time and complete time series at Vlissingen and Dover.



6.3 Wind on NEVLA domain

Wind measurements and Hirlam forecasts are extensively analysed and described in §4.2. In this section series of sensitivity runs are carried out (Table 6-1) to investigate how sensitive the model predictive abilities are for wind forcing on NEVLA. Run01 is forced by Hirlam wind forecasts with horizon of 6 hours, identical to the settings of VSSKS and the hindcast model. Run02 is a simulation without wind. Run03 is forced by spatial-constant and time-varying (see time series in Figure 4-3) wind measurement at Vlakte van de Raan.

Table 6-1: Overview of sensitivity analysis on wind.

Nr.	Description
Run 01 (Model Hindcast)	Nevla with Hirlam wind forecast (horizon of 6 hours)
Run 02	Nevla without wind
Run 03	Nevla with spatial constant wind from measurement at Vlakte van de Raan.

Figure 6-13 exemplifies the model predicted water levels at Antwerp during the two storm periods. The water level predicted by Run 01 has been discussed in §5. Run 02 shows that without wind forcing the maximum water level is decreased by 19 cm and 48 cm for the two storms respectively. Forced by wind measurements at Vlakte van de Raan (Run 03), the maximum water levels are lifted up by 26 cm for both of the two storms.

Figure 6-13: Comparison of water level at Antwerp at 28/11/2015 05:00 (left panel) and 15/01/2016 07:00 (right panel).

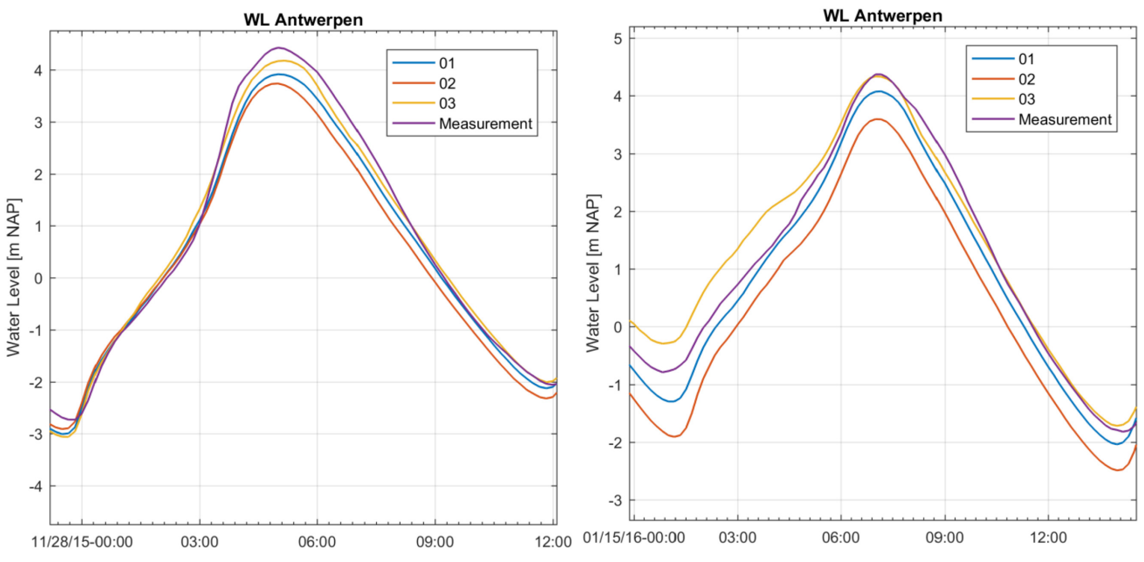


Figure 6-14 to Figure 6-16 present the bias of high water, low water and complete time series of water level. In general the water levels are relatively sensitive to the different wind forcings (changes are within 10 cm).

Compared with the reference run (Run 01), the high water levels at Western Scheldt and Lower Sea Scheldt decrease on average by about 3 cm without wind forcing (Run 02) and increase by 2-4 cm with forcing of wind measurements at Vlakte van de Raan (Run 03).

The basic analyses are also performed for the two storm periods (27/11/2015 – 02/12/2015 and 11/01/2016 – 17/01/2016) respectively. Figures are not shown in this section for the sake of concision. Similar patterns of bias are observed for both high water, low water and complete time series.

The complete set of VIMM analysis files is presented in a CD in annex.

Figure 6-14: Bias of high water level along the estuary from 16-Nov-2015 to 30-Jan-2016.

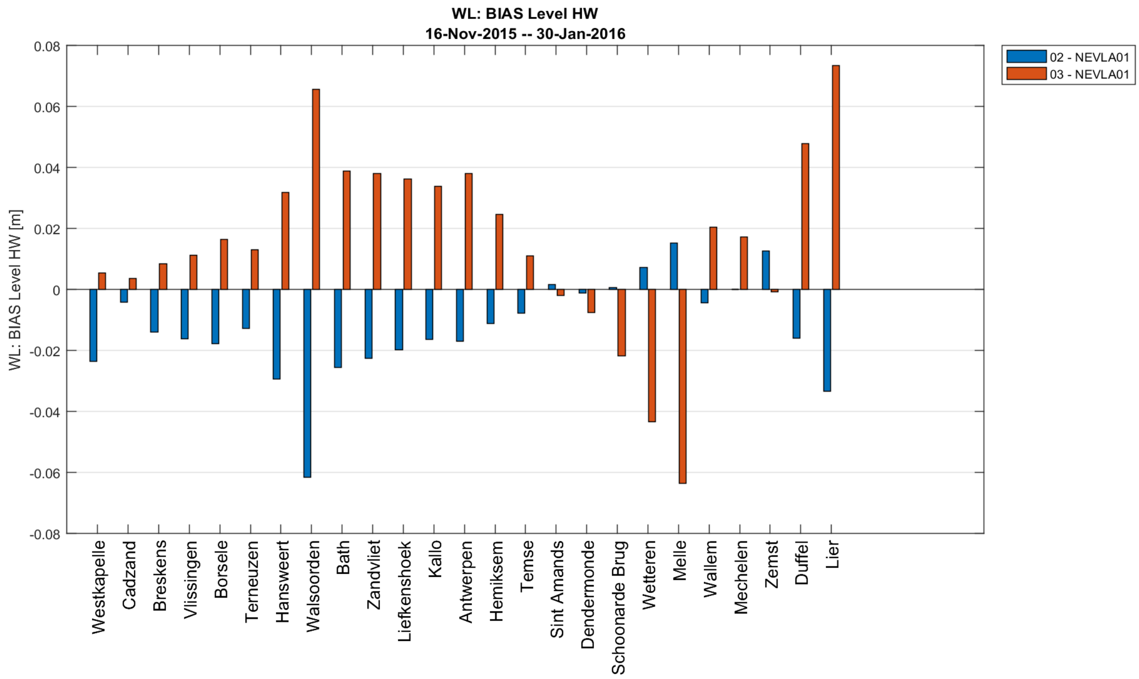


Figure 6-15: Bias of low water level along the estuary from 16-Nov-2015 to 30-Jan-2016.

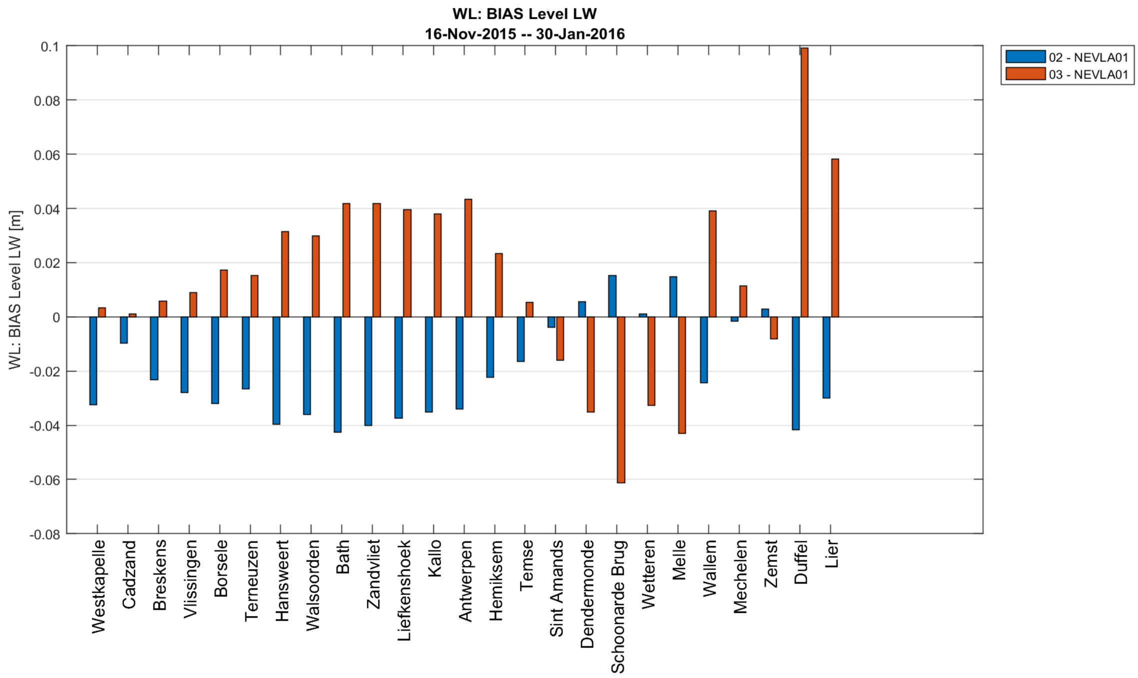


Figure 6-16: Bias of complete time series of water level along the estuary from 16-Nov-2015 to 30-Jan-2016.

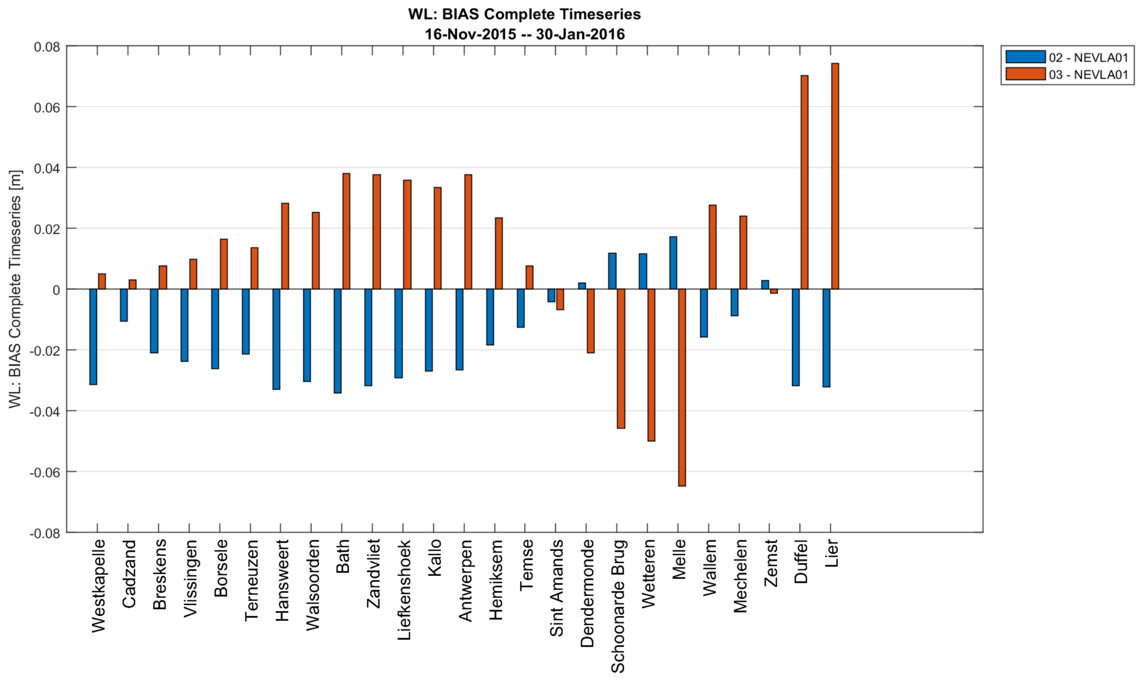


Figure 6-17 shows that the vector differences increase without wind forcing and decrease when the model is driven by wind measurements. There is less impact of wind forcings on M2 and S2 tidal amplitude and phase (Figure 6-18 to Figure 6-21).

Similar patterns have been found for the two storm periods (27/11/2015 – 02/12/2015 and 11/01/2016 – 17/01/2016) as well. Figures are not shown in this section for the sake of concision.

The complete set of VIMM harmonic analysis files is presented in a CD in annex.

Figure 6-17: Comparison of vector differences from harmonic analysis.

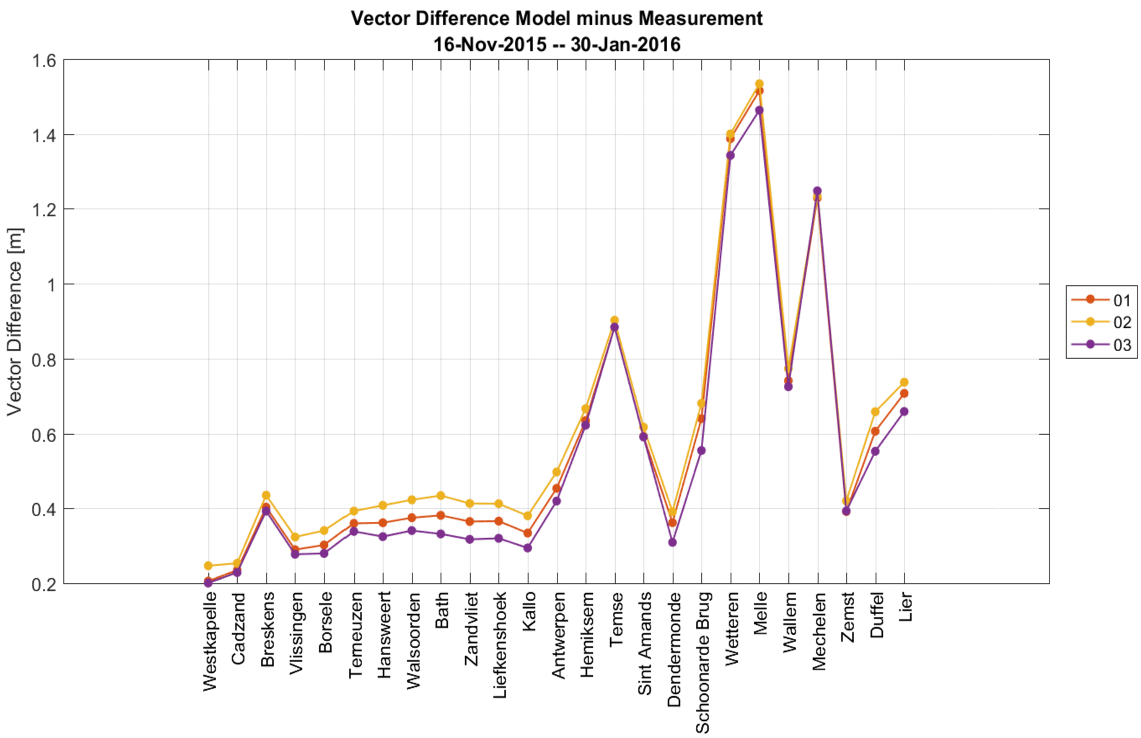


Figure 6-18: Comparison of M2 amplitude from harmonic analysis.

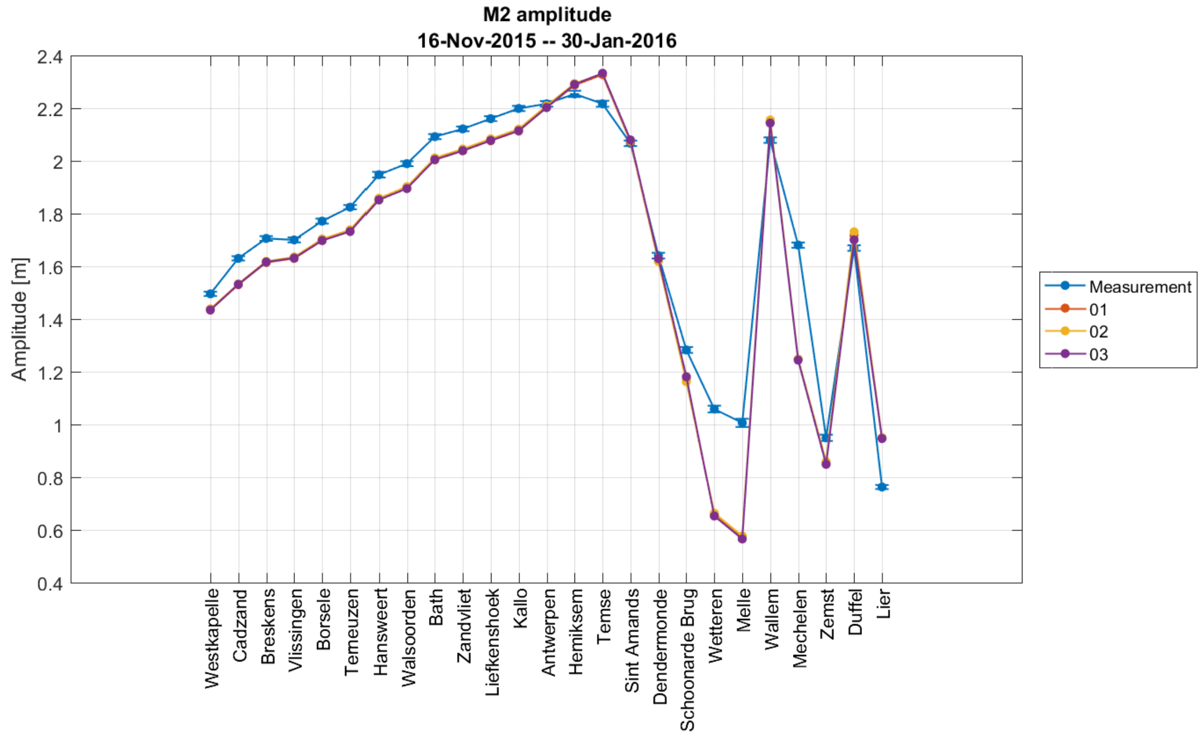


Figure 6-19: Comparison of M2 phase from harmonic analysis.

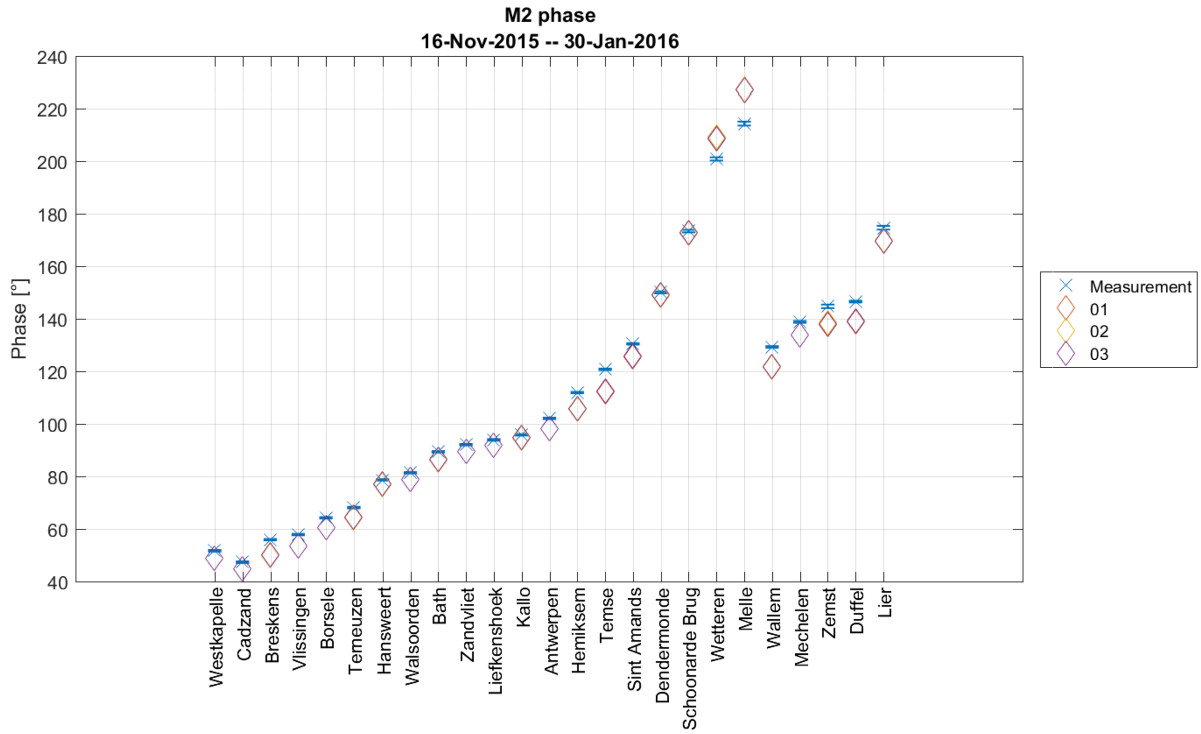


Figure 6-20: Comparison of S2 amplitude from harmonic analysis.

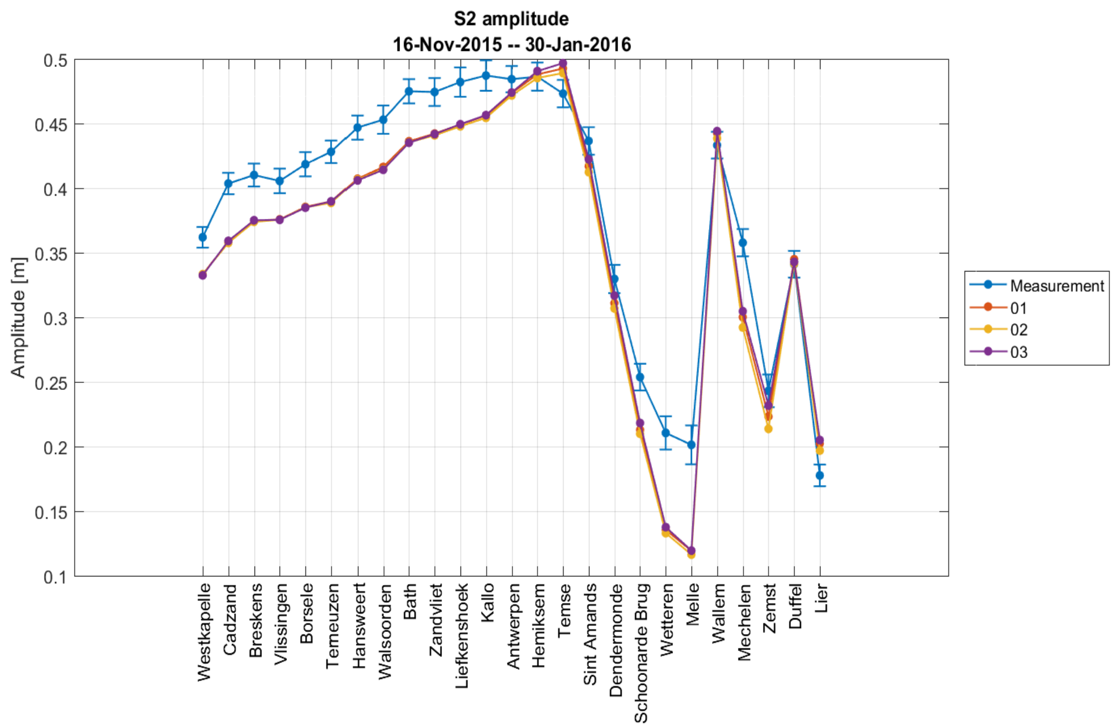
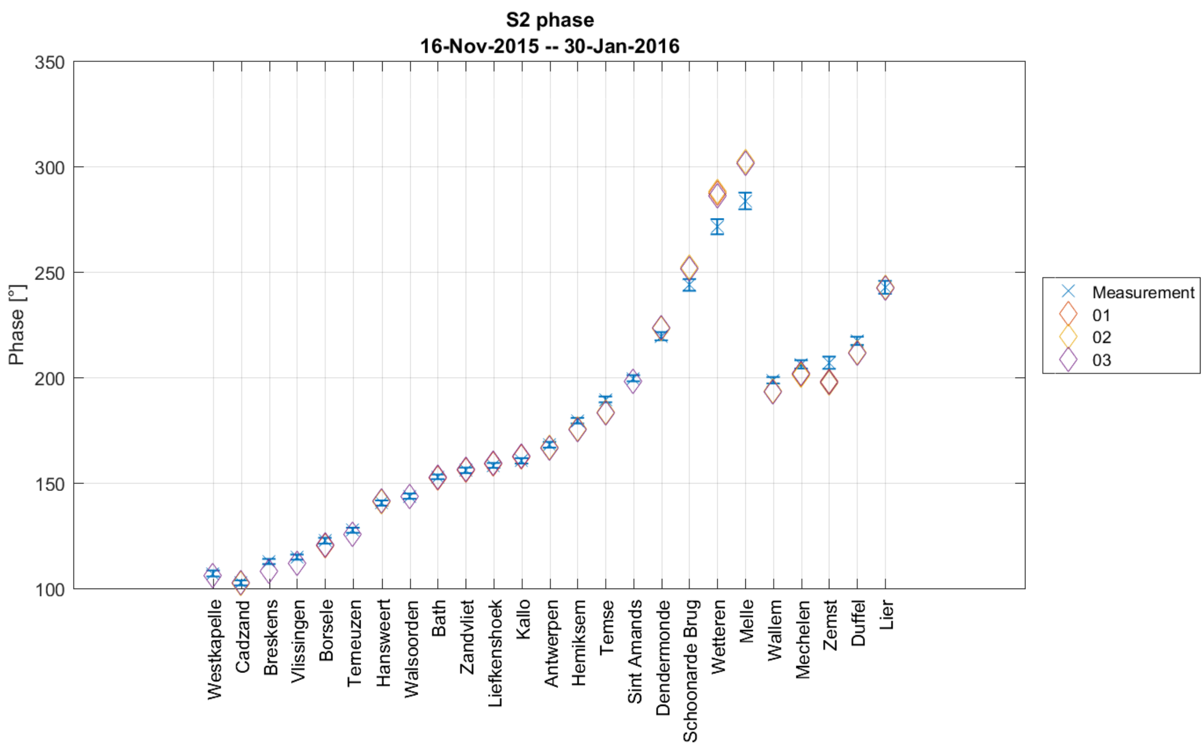


Figure 6-21: Comparison of S2 phase from harmonic analysis.



As mentioned in §2.5, a restarting system is implemented on VSSKS. Each model train runs for a complete period of 51 hours, a new model train starts every 6 hours (Figure 2-1) when the latest Hirlam wind forecasts (updated every 6 hours) are available. The way of the restarting system on VSSKS is in a sense similar to a Monte-Carlo simulation. The different model trains essentially represent different forecast horizons, with different Hirlam forecast horizons. A sensitivity analysis of different Hirlam forecast horizons on water level predictions is investigated in this section.

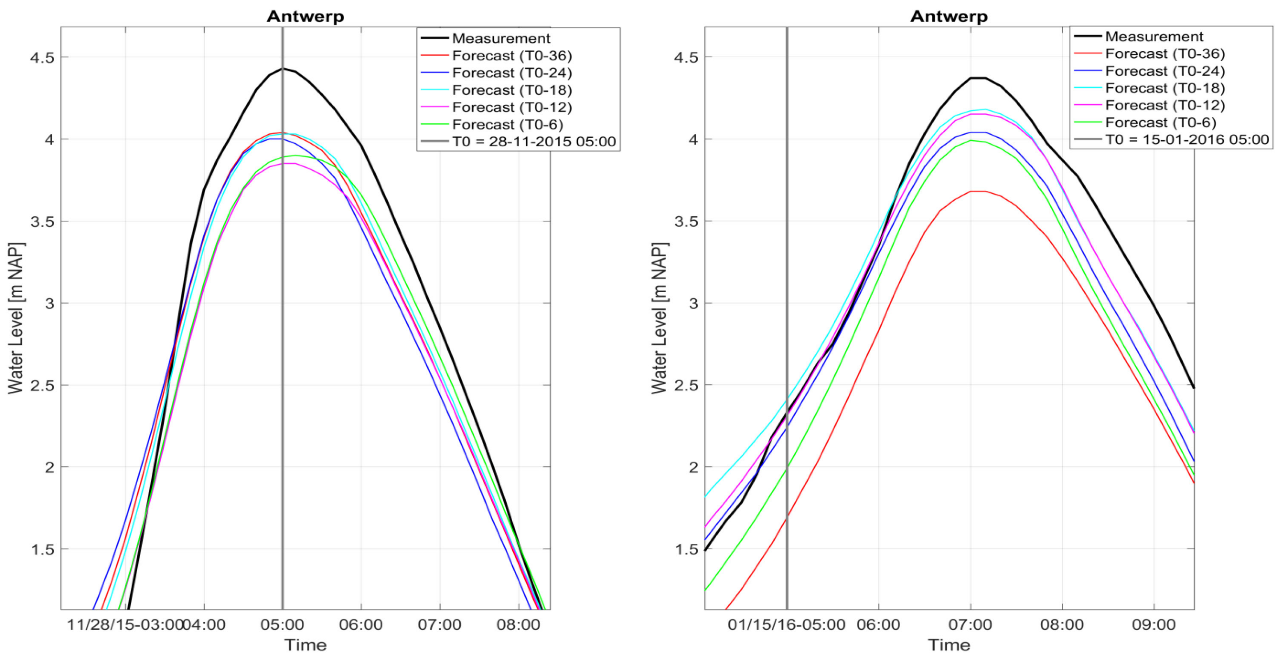
Figure 6-22 shows the water levels predicted by Nevla2D models at Antwerp with forecast horizons of 36, 24, 18, 12 and 6 hours for the two storms respectively. The time series dataset is extracted from Hydra database.

For the first storm, model forecast with 12 hours ahead shows the worst prediction of high water level (underestimation of 60 cm). The predictions are improved by 20 cm with forecast horizons of 18 and 36 hours. The model run with the latest Hirlam wind forecast (forecast horizon of 6 hours) substantially underestimates the high water level by 50 cm compared with measurement.

For the second storm, model forecast with 36 hours ahead underestimates the maximum high water level significantly (by 70 cm). The prediction is improved by 30 cm with forecast horizons of 6 hours. The model run with forecast horizon of 18 hours leads to best estimation of high water level, however still with underestimation of 20 cm.

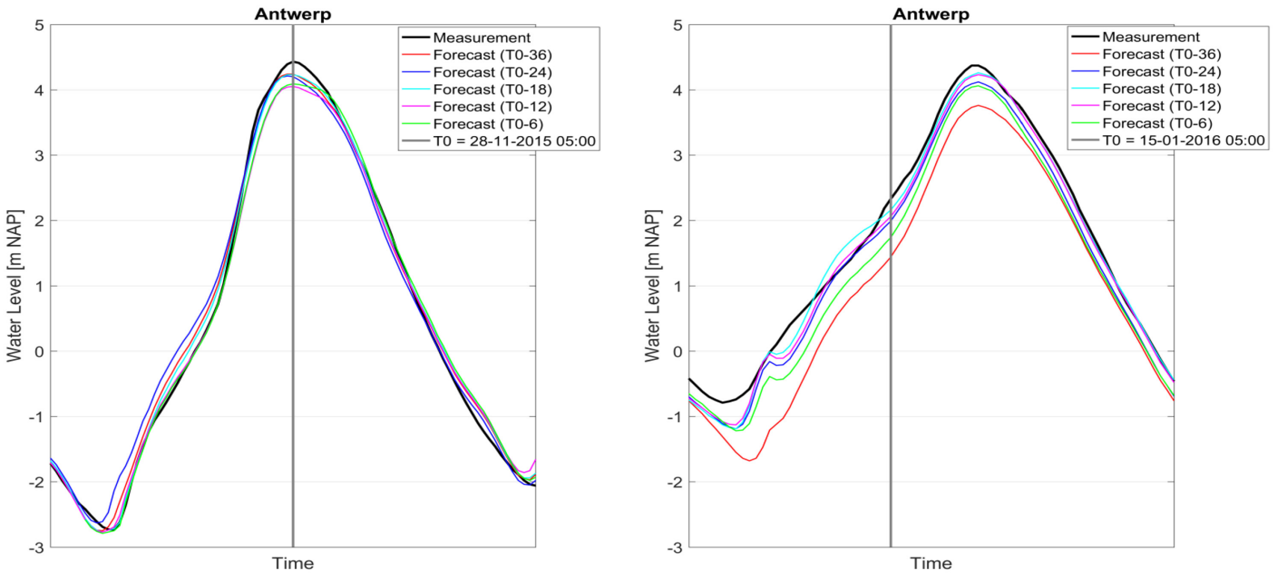
The water level predicted with different forecast horizons can vary by 20-30cm. There are no clear trends/patterns found between the quality of predictions and different forecast horizons. It is therefore not necessarily the best option to rely most on the forecast with 6 hours ahead.

Figure 6-22: Water level predicted by Nevla2D models with different forecast horizons at Antwerp for the storms occurred at 28/11/2015 05:00 (left panel) and 15/01/2016 07:00 (right panel).



For the purpose of operational forecasting, astro-corrections on water levels are executed at different stations (e.g. Antwerp). Essentially astro correction is a postprocessing procedure which superimposes meteorological surge signals on astronomic tidal water levels. The meteorological surge signal is obtained by subtracting water levels predictions without meteorological force (wind) from water level predictions with meteorological force (wind). The astronomical tidal water level is (re-)constructed from tidal constituents decomposed from harmonic analysis of measurements. Figure 6-23 shows the water levels predicted by Nevla2D models (with astro-correction) at Antwerp with forecast horizons of 36, 24, 18, 12 and 6 hours for the two storms respectively. The time series dataset is extracted from Hydra database. Compared with water level predictions without astro-correction (Figure 6-22), the water level predictions are significantly improved by 20 cm and 10 cm respectively for the 2 storms. However the water level patterns with different forecast horizons remain the same.

Figure 6-23: Water level predicted by Nevla2D models with astro-correction with different forecast horizons at Antwerp for the storms occurred at 28/11/2015 05:00 (left panel) and 15/01/2016 07:00 (right panel).



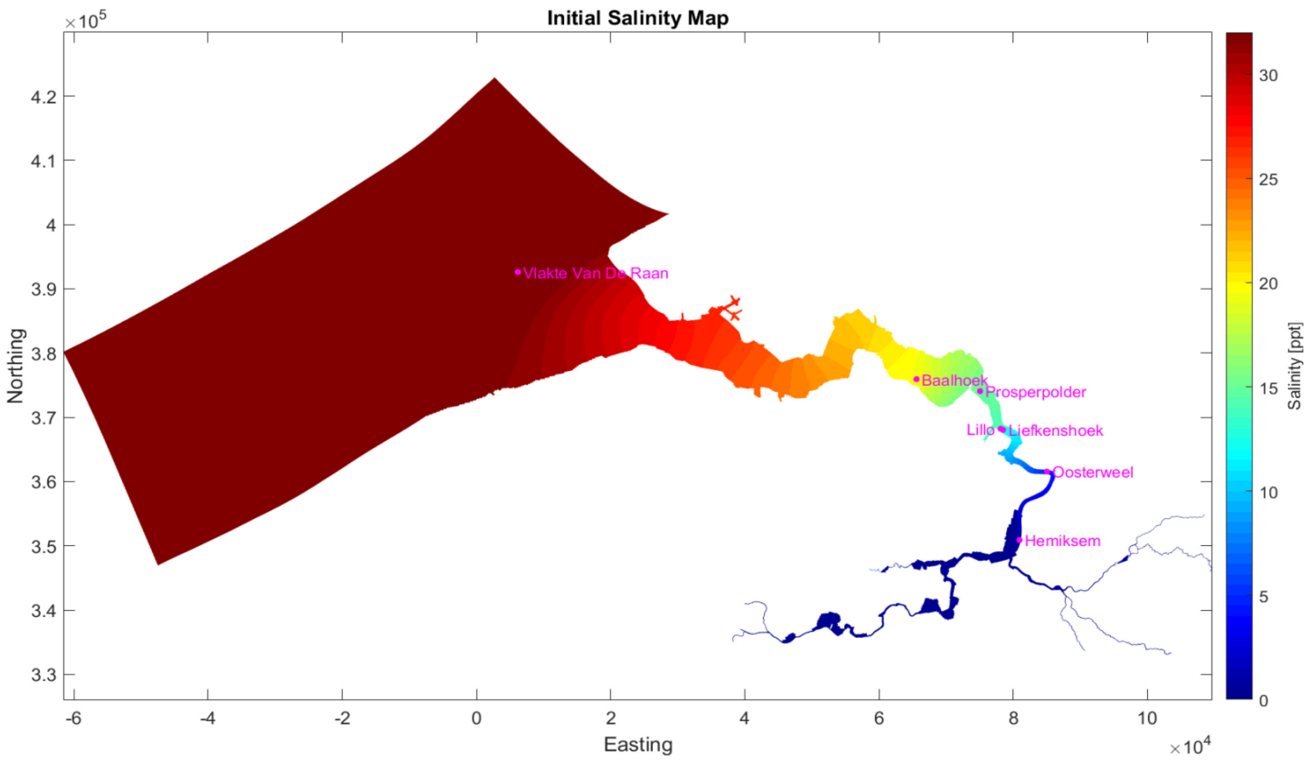
6.4 Salinity

Salinity is not taken into account by VSSKS, water density is set to 1023 kg/m^3 constant. However Van der Kaaij (2016) addressed that inclusion of salinity in Nevla2D model could potentially influence the water level predictions by about 10 cm. In addition, the wind setup is influenced by the weight of the water column and thus by the water density. Therefore it is worthy to investigate the potential influence of salinity on the model predictive abilities. A sensitivity run is performed with salinity switched on.

The initial salinity map at 16/11/2015 00:00 is constructed (Figure 6-24) by linear interpolation along the estuary with measured salinity from seven stations (see §4.3). Be aware that due to unavailability of measurement data, there is a large gap in space between Vlakte Van De Raan and Baalhoek. As such the constructed initial salinity between those two stations might be deviated from reality. In addition the salinity boundary conditions are set to constant value of 32.8 ppt which is not perfect, especially at the northeast boundary where salinity is potentially influenced by river discharge from river Rhine. In addition, salinity is inherently a 3D process, a 2D model has limitations to resolve accurate salt transportation. Although the present model settings with salinity are not optimal, it is however not problematic to simply assess the sensitivity of salinity on water level predictions. Following the settings of Maximova et al (2009), the diffusion coefficient is set to be spatially varying (from 75 to 200 m^2/s).

Figure 6-25 exemplifies the predicted water level with and without salinity at Antwerp during the two storm periods. Switching on salinity lifts up the maximum high water level by 12 cm (3%) and 14 cm (3.5%) for the two storms respectively.

Figure 6-24: Initial salinity map applied on Nevla model for a sensitivity run.



Salinity measurements are available at seven stations shown above.

Figure 6-25: Comparison of water level at Antwerp at 28/11/2015 05:00 (left panel) and 15/01/2016 07:00 (right panel).

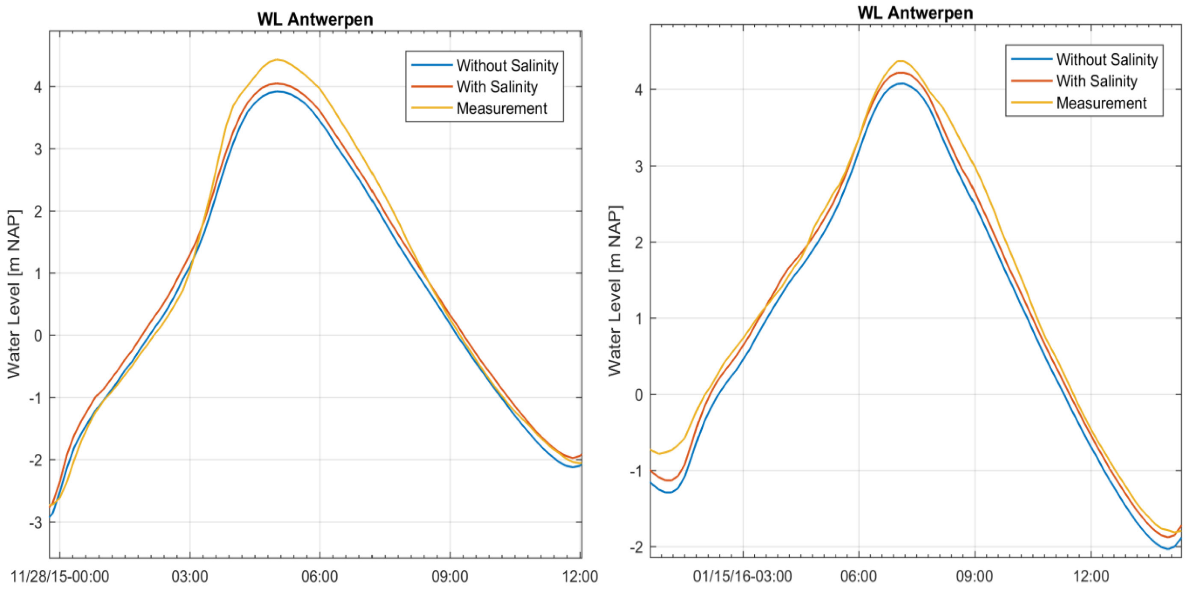


Figure 6-26 to Figure 6-28 present the bias of high water, low water and complete time series of water level. In general the water levels are sensitive to salinity. Compared with the reference run without salinity (NEVLA01), the high water levels increase from 2 cm at the Western Scheldt to 17-18 cm at the Lower Sea Scheldt (e.g. Temse), and 14-15 cm at the Upper Sea Scheldt.

The basic analysis is also performed for the two storm periods (27/11/2015 – 02/12/2015 and 11/01/2016 – 17/01/2016) respectively. Figures are not shown in this section for the sake of concision. Similar patterns of bias are observed for both high water, low water and complete time series.

The complete set of VIMM analysis files is presented in a CD in annex.

Figure 6-26: Bias of high water level along the estuary from 16-Nov-2015 to 30-Jan-2016.

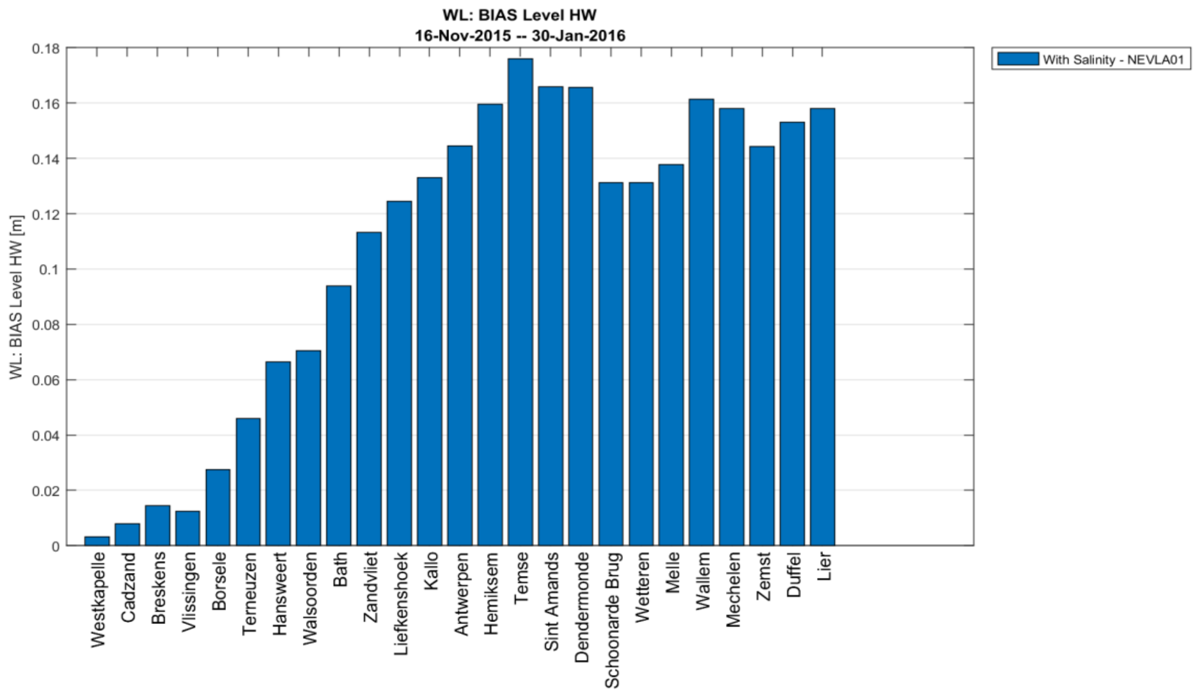


Figure 6-27: Bias of low water level along the estuary from 16-Nov-2015 to 30-Jan-2016.

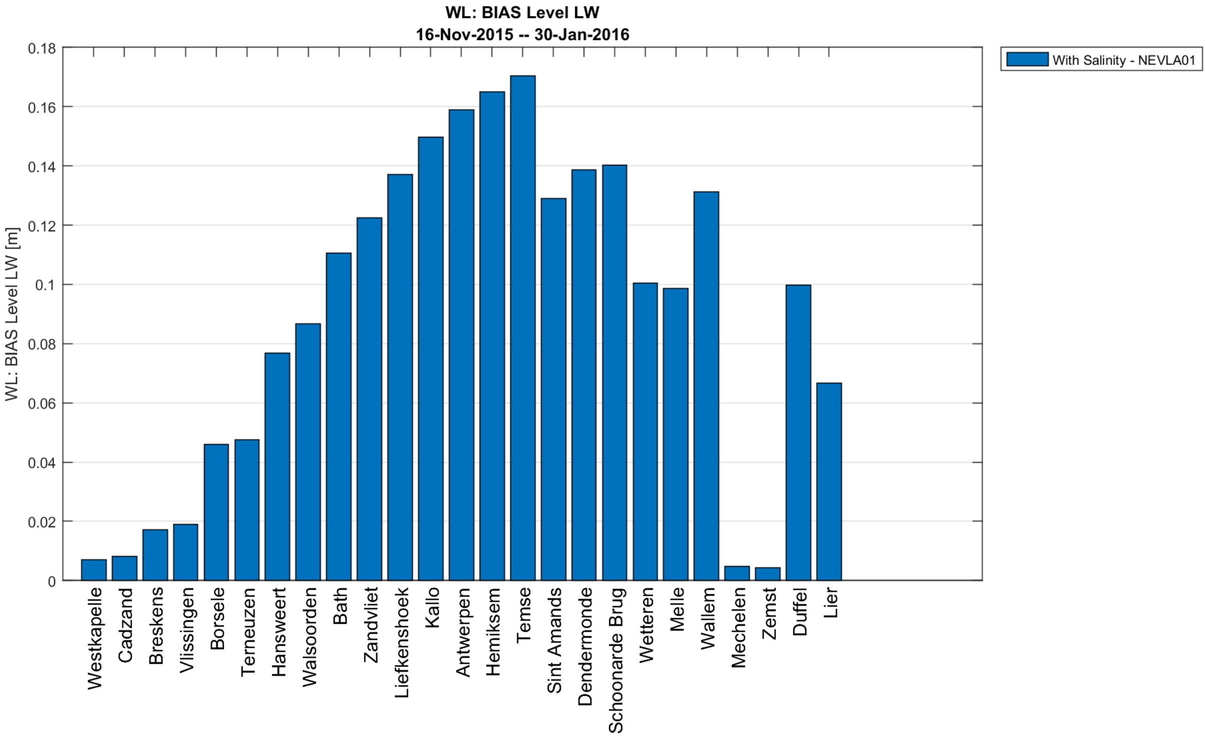


Figure 6-28: Bias of complete time series (model - measurement) of water level along the estuary from 16-Nov-2015 to 30-Jan-2016.

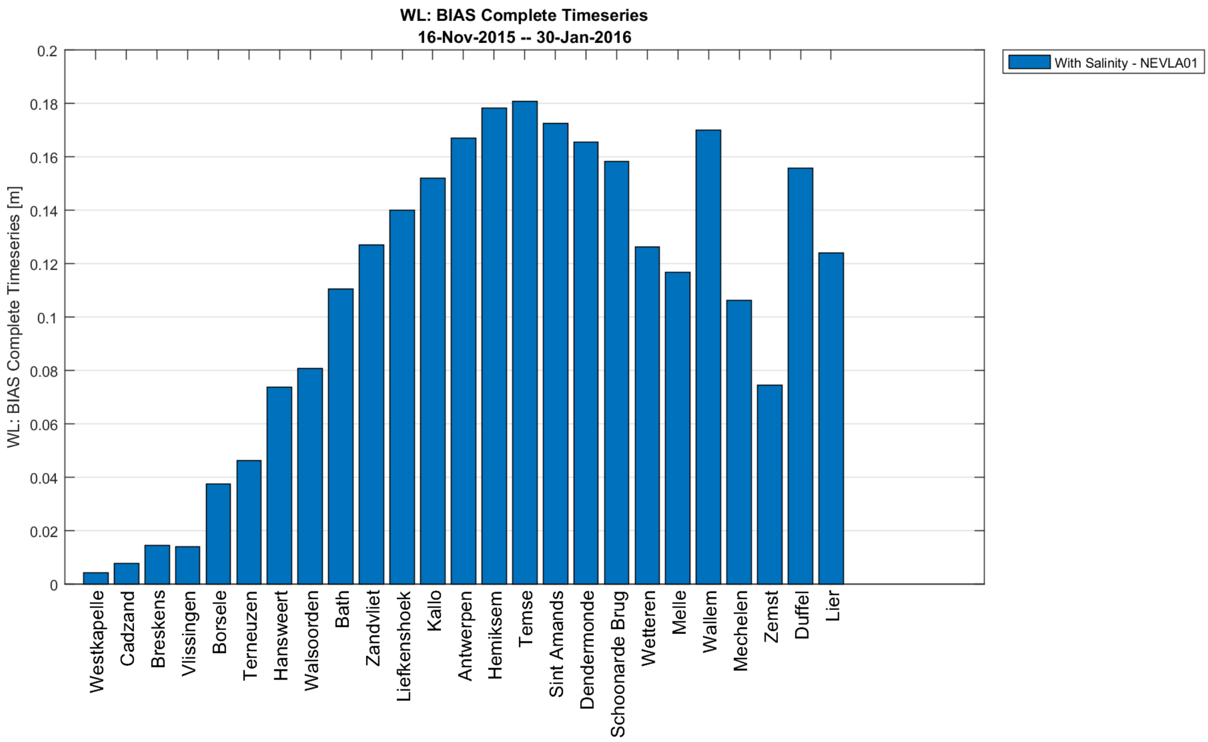


Figure 6-29 shows that the vector differences slightly decrease with salinity switched on. There is less impact of salinity on M2 and S2 tidal amplitude and phase (Figure 6-30 to Figure 6-33).

Similar patterns have been found for the two storm periods (27/11/2015 – 02/12/2015 and 11/01/2016 – 17/01/2016) as well. Figures are not shown in this section for the sake of concision.

The complete set of VIMM harmonic analysis files is presented in a CD in annex.

It needs to be pointed out that although switching on salinity leads to potential improvement on water level predictions, the way of implementation of salinity on the Nevla model is only made for sensitivity analysis rather than model calibration. Before drawing conclusive remarks, an extensive model calibration/validation on salinity is recommended. To proceed, an accurate definition of initial and boundary conditions of salinity is necessary. It may also involve a re-calibration of the Nevla2D model on the bottom roughness.

Being noted that switching on salinity increases computation time by 15%.

Figure 6-29: Comparison of vector difference from harmonic analysis.

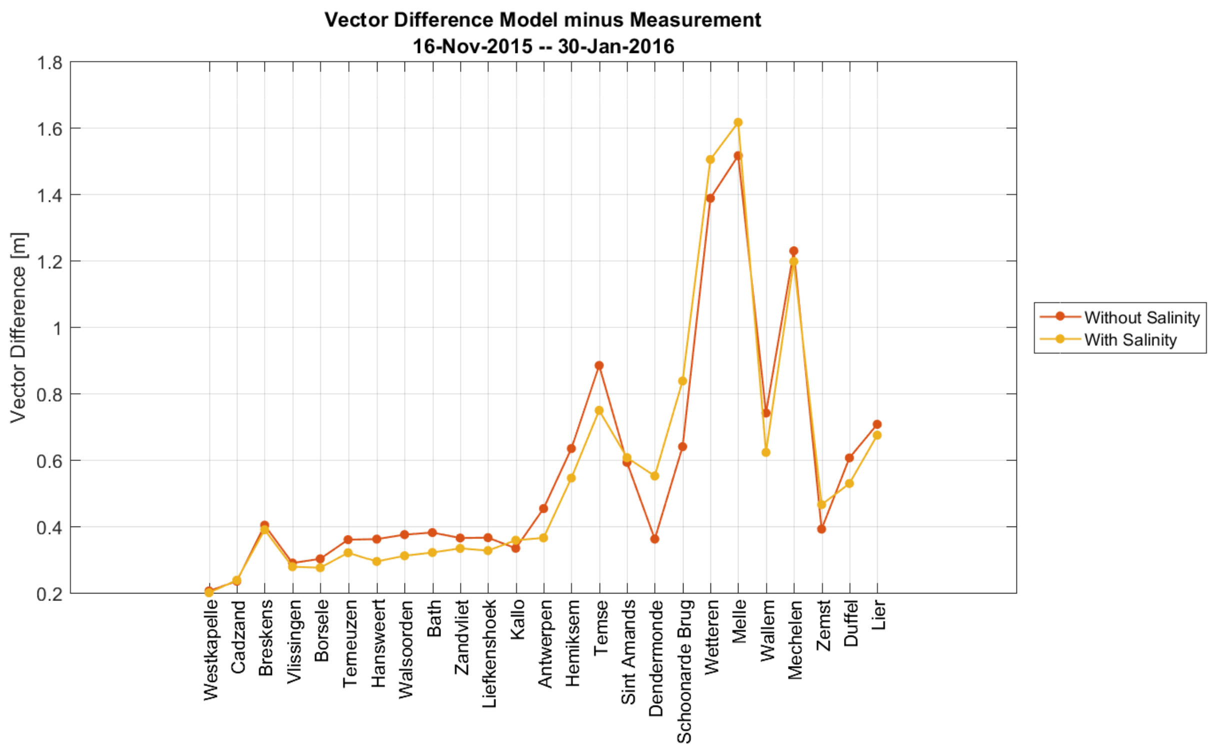


Figure 6-30: Comparison of M2 amplitude from harmonic analysis.

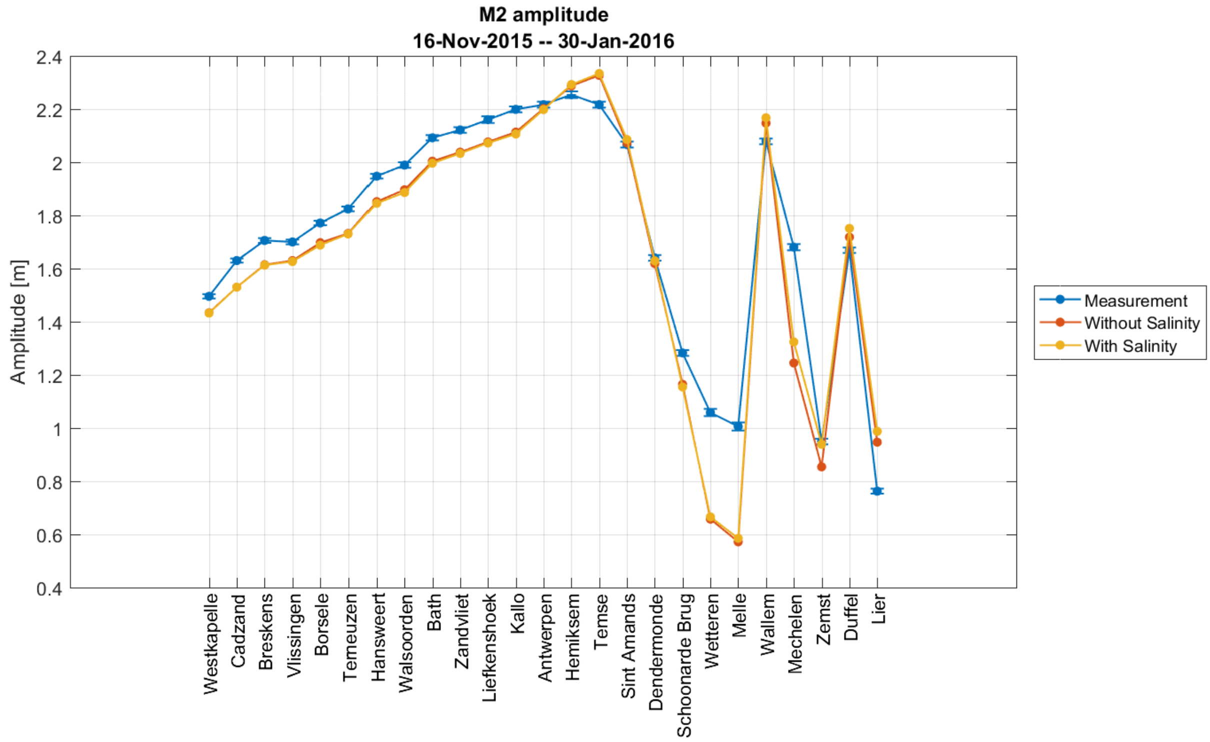


Figure 6-31: Comparison of M2 phase from harmonic analysis.

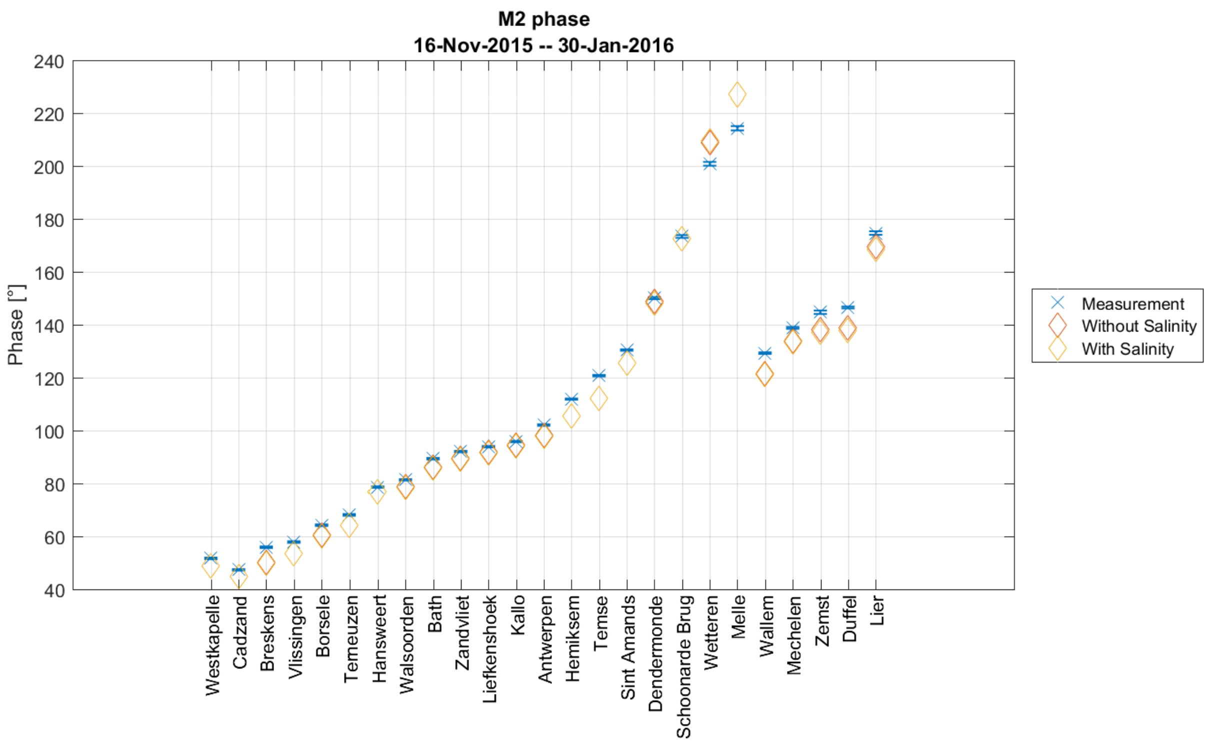


Figure 6-32: Comparison of S2 amplitude from harmonic analysis.

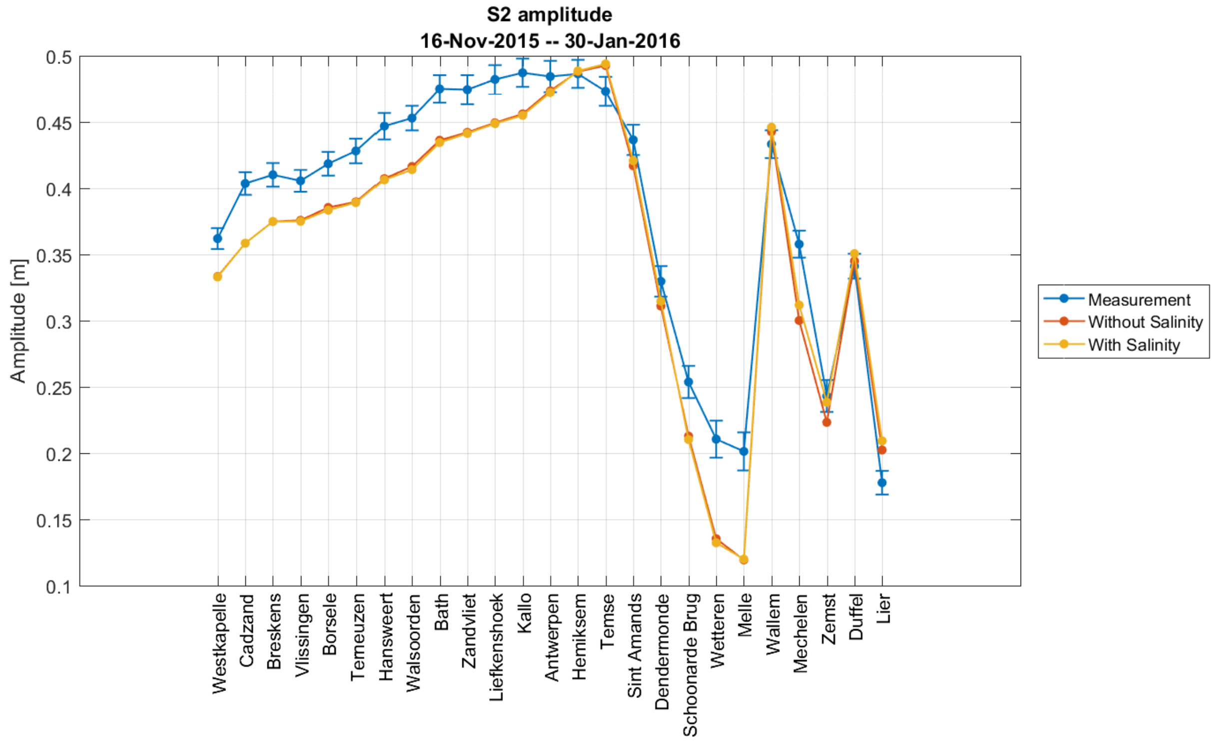
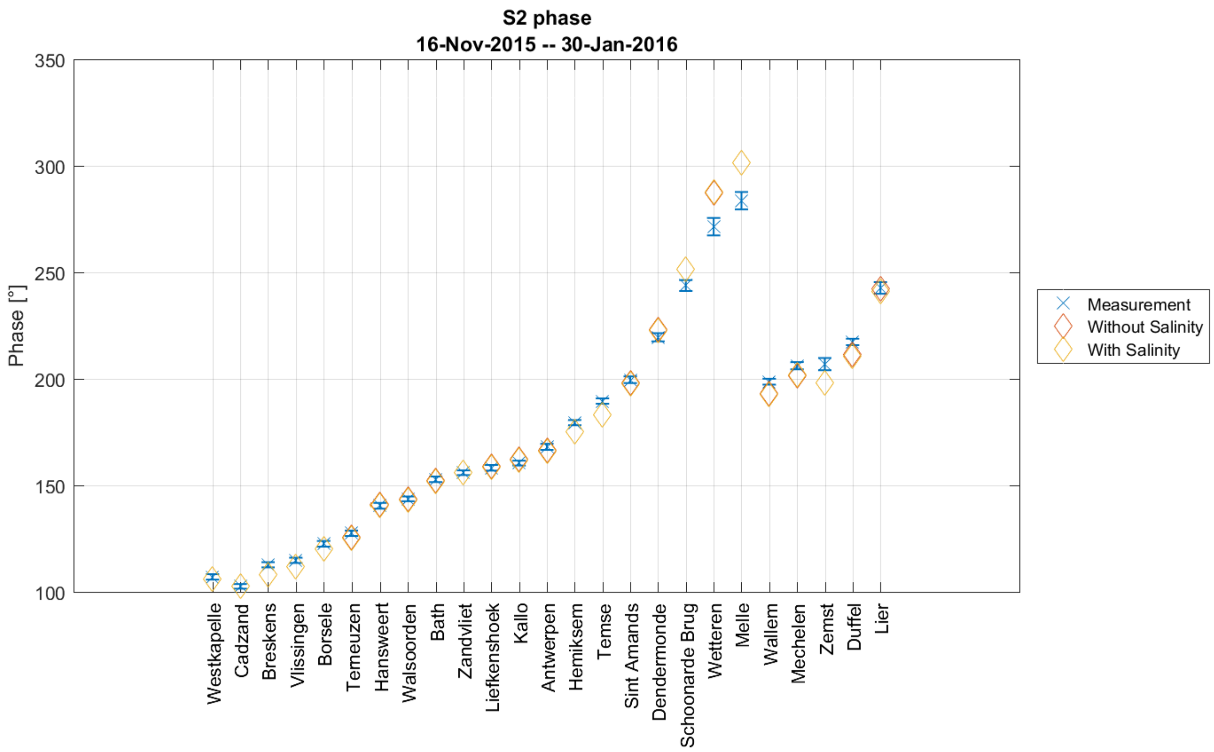


Figure 6-33: Comparison of S2 phase from harmonic analysis.



6.5 Discharge

As described in §4.4, the hindcast model uses river discharge predicted by upstream operation hydrologic and hydrodynamic models. Figure 4-11 shows that themodel forecasts deviate from the field measurements substantially (e.g. at Merelbeke). In order to investigate whether the forcing of river discharge is essential to the Nevla model, a sensitivity run with measured river discharge is executed.

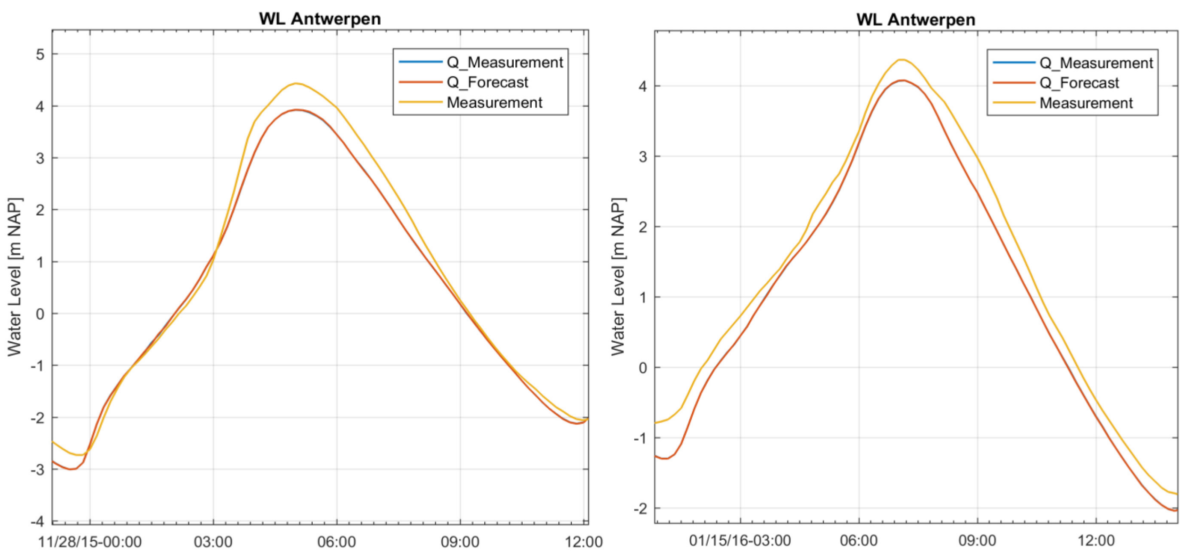
Figure 6-34 exemplifies the predicted water level at Antwerp with river discharge from measurement and model forecast. Different sources of river discharge hardly change the water level predictions at Antwerp.

Figure 6-35 to Figure 6-37 present the bias of high water, low water and complete time series of water level along the estuary. In general the high water levels are not sensitive to different river discharges at most of the stations along the Scheldt except at Melle where the high water increases by 9 cm and Wetteren where the high water decreases by 6 cm. This is justified because Melle and Wetteren are the closest stations to Merelbeke where the forecast is substantially deviated from measurements. Therefore measured fresh water inflow at Merelbeke mainly modified the water level predictions at Melle and Wetteren. And it leads to localized effects (only up to Dendermonde) which hardly influence the water levels predicted in the Western Scheldt and Lower Sea Scheldt. Being noted that the measured discharge leads to more influences on low water and complete time series of water level locally at Schoonaarde, Wetteren and Melle.

Similar patterns have been found for the two stormy periods (27/11/2015 – 02/12/2015 and 11/01/2016 – 17/01/2016) as well. Figures are not shown in this section for the sake of concision.

The complete set of VIMM analysis files are presented in a CD in annex.

Figure 6-34: Comparison of water level at Antwerp at 28/11/2015 05:00 (left panel) and 15/01/2016 07:00 (right panel).



Note: the blue line is beneath the rea line.

Figure 6-35: Bias of high water from 16-Nov-2015 to 30-Jan-2016.

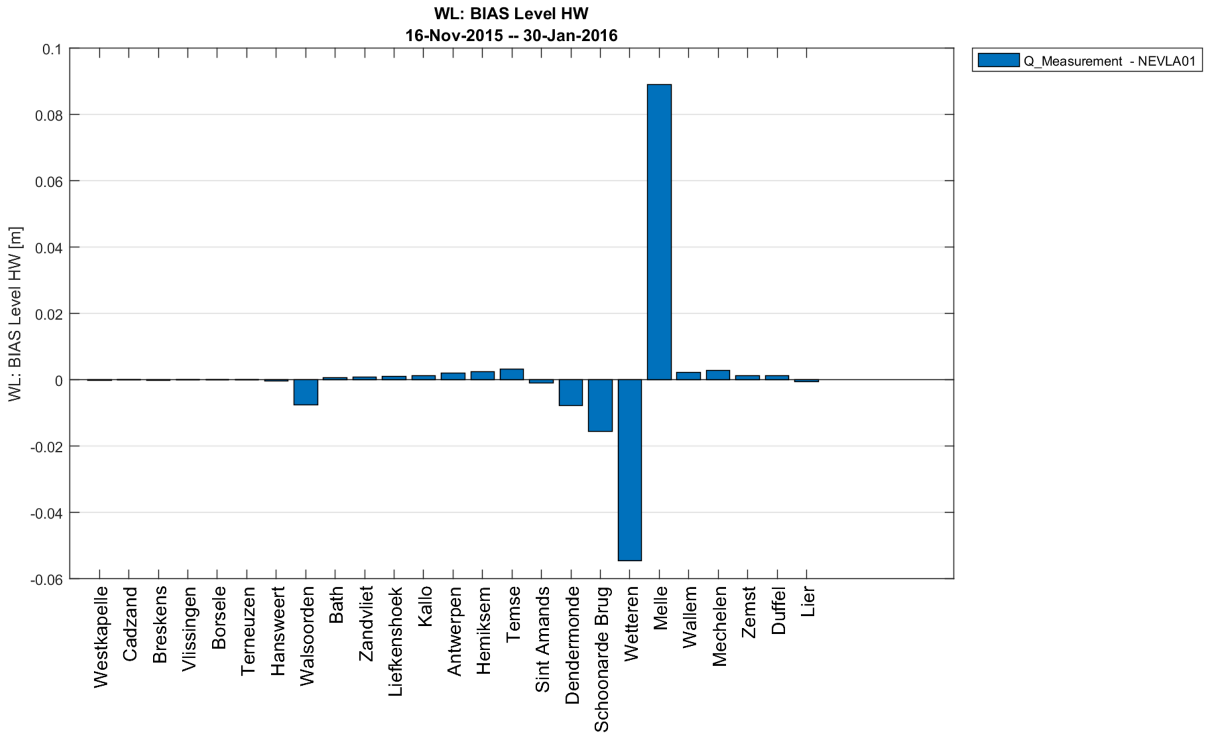


Figure 6-36: Bias of low water from 16-Nov-2015 to 30-Jan-2016.

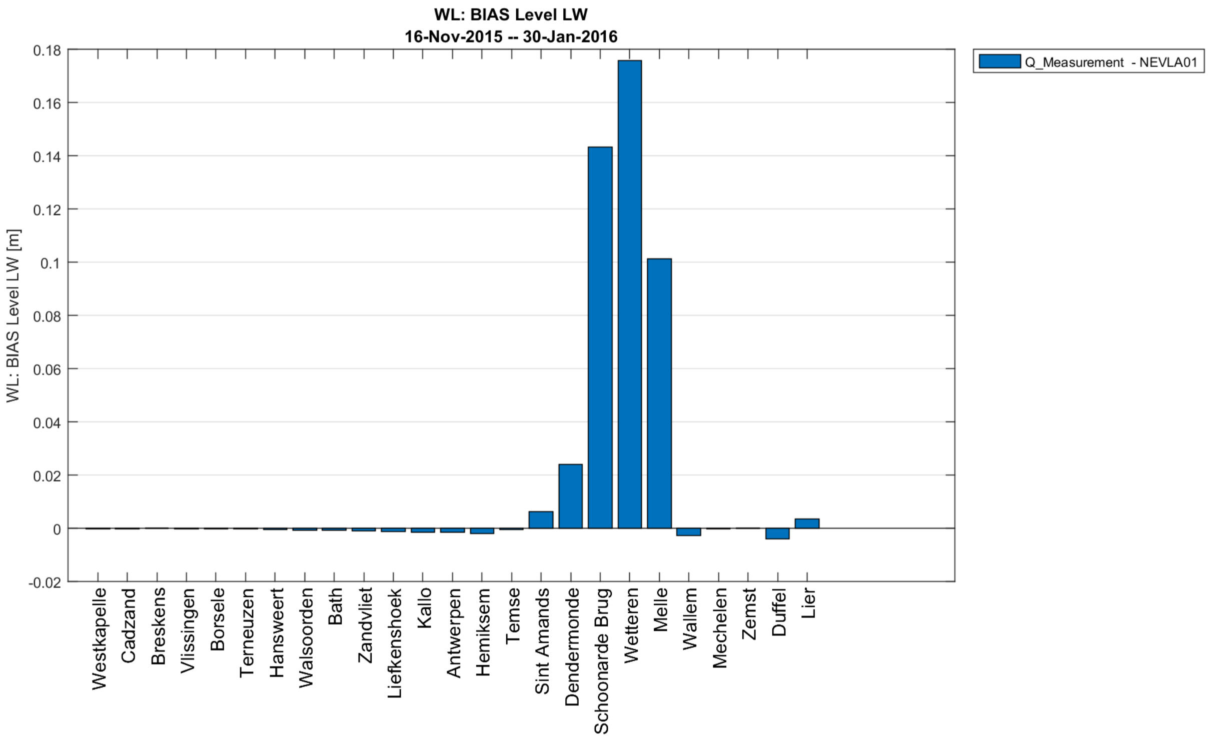
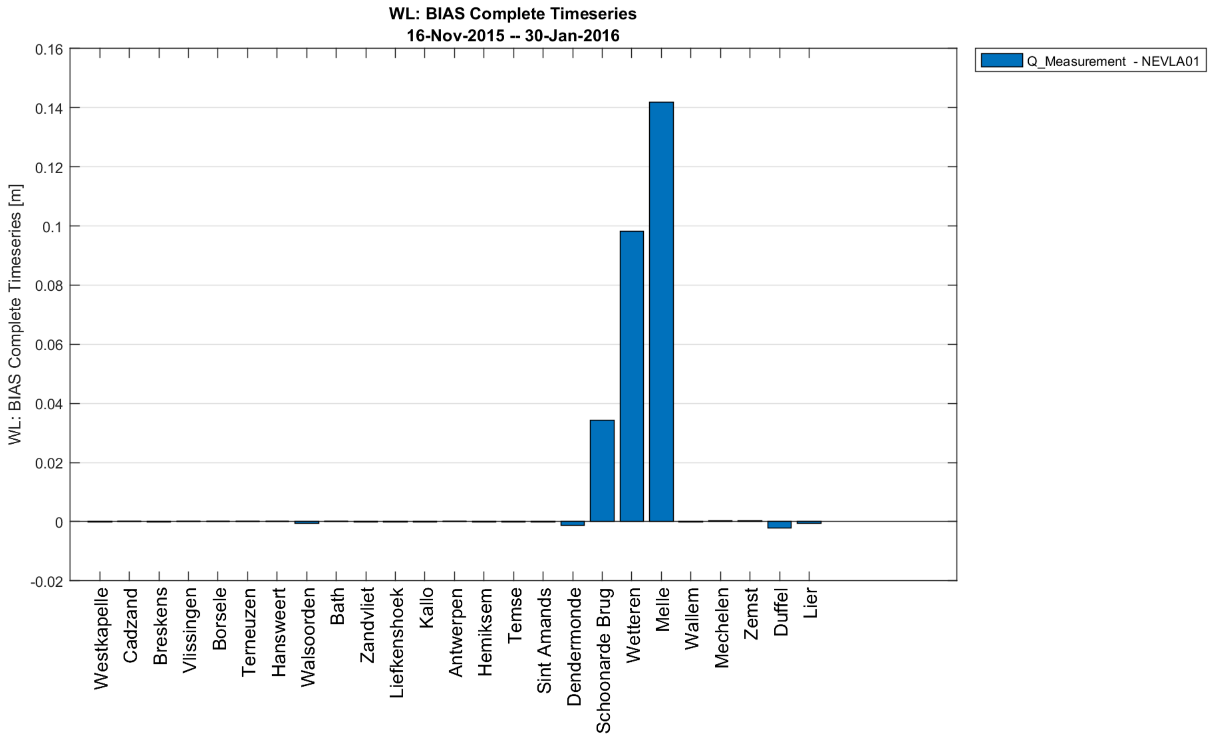


Figure 6-37: Bias of complete time series of water level from 16-Nov-2015 to 30-Jan-2016.



7 Conclusions & Recommendations

In November 2015 and January 2016, two high water levels along the Scheldt were poorly predicted by the online operational forecasting system (VSSKS). The Nevla2D model forecasts substantially underestimated two “storm”-high water levels by about 20 – 60 cm at Antwerp.

This study is therefore motivated to investigate the possible causes of the malfunction. One of the aims of this study is to investigate what models are capable of with perfect information, such that we know what to expect. The online automatic modelling procedures on VSSKS are firstly reconstructed to an offline hindcast model which runs on the research cluster. This migration provides degrees of freedom to evaluate the sensitivity of different parameters and processes on the model predictive abilities.

A series of sensitivity analysis has been carried out in this study. The main findings are listed as below:

- The Nevla2D model reproduces the bad predictions of water level during the two storm periods, despite of which, the overall model performance over a period of 3 months remains rather good. The RMSE0 of HW at downstream stations (e.g. Cadzand and Vlissingen) is about 5 cm, which represents the uncertainty received from the model boundaries. During the water wave propagation to upstream, the RMSE0 of HW slightly increases to 7-8 cm at Kallo and Antwerp and further increases to 10-25 cm at upstream stations from Dendermonde to Melle. Therefore in general the Nevla2D model performs well at the Western Scheldt and Lower Sea Scheldt. The discrepancies at Upper Sea Scheldt are mainly attribute to the coarse/poor quality of the local model grid.

- The existing Nevla2D model shows less accurate predictions on water level compared with the existing Nevla3D model which includes more physical processes such as vertical and near-bed flows, salinity mixing/stratification due to gravitational circulation, secondary flow etc.

- Compared with Nevla2D, the 1D operational model leads to better predictions on the high water at the two storm periods, by sacrificing the accuracy of water level predictions outside of the storm periods. Nevla2D leads to overall better performance.

- Using different boundary nesting scripts (Simona script modnst.pl and in-house matlab script) leads to limited impact on water level predictions.

- Using river discharge measurements modifies water level predictions at upstream stations (e.g. Melle). The impact is however rather local. The water levels predicted in the Western Scheldt and Lower Sea Scheldt are hardly influenced.

- Switching on salinity shows potential improvement on water level predictions, although the high water levels during the two storm periods are still being underestimated. Due to limited data availability, the applied initial and boundary conditions of salinity in this study are not optimal. In addition, salinity is inherently a 3D process, a 2D model has limitations to resolve accurate salt transportation. Before drawing conclusive remarks, an extensive model calibration/validation on salinity is recommended. Being noted that the computation time increases by 15% with inclusion of salinity.

- Kalman Filter is still serviceable by comparing water level predicted by CSM with and without Kalman Filter.

- Wind input is of great importance to the model predictions on water level. Model hindcast forced by wind measurements from Vlakte van de Raan shows great potentials in improving model predictions on water level. However this is impossible to be implemented on real-time forecasting system.

- Data quality of Hirlam wind forecasts diverges with progression of forecast horizons. The forecast with 6 hours ahead is not guaranteed with the best data quality. It is difficult to determine an optimal forecast horizon for the forecasting system.

- Water levels predicted by Nevla2D model with different forecast horizons (of wind) can vary up to 20 to 30 cm. It is difficult to find clear trends/patterns between predictive quality and different forecast horizons. It is therefore not necessarily the best option to rely most on the forecast with 6 hours ahead.

- An astro-correction shows improvement on water level predictions during the two stormy periods.

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Annex 1: Definition of Bias, RMSE and RMSE0

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

The RMSE of water level represents the sample standard deviation of the differences between predicted water level and measurement.

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

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

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

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

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

Annex 2: 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.

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