Memo

To
Thomas van Walsem

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Subject
IJmond cross-current validation

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1 Introduction

1.1 Context

HMC makes forecasts of the flow transverse to the channel of the port of IJmuiden. This forecast determines when boats may enter the harbor: if the cross-current is too strong, they are advised not to enter. The forecast is currently generated with the help of a neural network developed several decades ago. It uses the moon phase, the expected wind, and expected water level as input. A WAQUA model of the area (IJmond model) also runs operationally and is used for spatial current information but has not been further developed for over a decade and will soon be phased out. The real-time operational sixth generation (2D) DCSM-FM 100m model also covers this area and is considered as a replacement. HMC (Theo van Dam) has indicated that the neural network has consistently shown unreliable results, both in normal circumstances and during strong wind events (most often observed when there are winds ≥6 Beaufort from the Southwest). The question is whether more reliable cross-current forecasts can be made with DCSM-FM 100m. Having accurate spatial current information near the IJmuiden harbor entrance would also be desirable.

1.2 Earlier work with DCSM-FM 100m

In Laan & Zijl (2020) it is shown that DCSM-FM 100m is suitable for calculating depth-averaged currents at the temporary observation point MP19, 6-7 km off the IJmuiden coast (see Figure 2.1). However, this is not the case near the harbor entrance (temporary observation point MP17), especially with respect to non-tidal currents. It is suspected that 3D processes play a role in this, possibly related to the exchange of relatively fresh water from the harbor with the sea (originating from the discharge of fresh water through Rijksgemaal IJmuiden) and the influence of the Rhine ROFI, whose influence extends beyond IJmuiden. As these are three-dimensional, density driven processes, they would not be captured in a two-dimensional (depth averaged) barotropic model.

1.3 Proposed approach

Given the complex dynamics near the IJmuiden harbor entrance, coming up with a solution that provides more accurate cross-currents, including spatial information, is not a trivial task. RWS has expressed a wish to first focus on the possibilities of the already operational 2D model DCSM-FM 100m and see if this would be a good replacement of the WAQUA IJmond model (and possibly the neural network). Compared to the DCSM-FM 100m model version used in the earlier current validation work of Laan & Zijl (2020) - a preliminary version predating the first official release (Zijl et al., 2020) - several model improvements have taken place resulting in the currently operational 2022 release (Zijl et al., 2022). Furthermore, this previous work did not focus specifically on cross currents and did not use measurements from the ‘stroommeetpaal’. This measurement pole (Dutch: ‘stroommeetpaal’) has been taking continuous measurements for years. These data can be used for validation. However, it is located just outside the shipping lane and might therefore not be fully representative of conditions experienced by ships entering IJmuiden harbor. Therefore, the validation will be supplemented by temporary measurements in the shipping lane (MP17).

In summary, the present memo aims to quantify and compare the cross-current quality of three models: the latest version of DCSM-FM 100m, the WAQUA IJmond model and the neural network. This is important input for the decision to replace the WAQUA IJmond model with DCSM-FM 100m.

2 Measurements, models and methods

2.1 Measurements

Measurement data from following locations and periods were used to assess model quality:

- IJgeul observation point 17 (52°28'01,7" N, 4°31'44,0" E), also known as MP17. This is also the location for which the neural network provides cross-current information (email Theo van Dam, dd. 20/02/2024). The closest output location from WAQUA IJmond (Erosieput2) was used. Period: 16/12/2016 – 16/03/2017.
- IJgeul observation point 19 (52°28'06,2"N, 4°27'51,2"E) also known as MP19. Period: 22/03/2017 – 08/06/2017.
- Stroommeetpaal. Period: 01/08/2016 – 31/12/2017.

Note that the measurement data for MP17 and MP19 originally covered a larger period. After thoroughly checking the quality, aided by harmonic analysis, some periods with less reliable data due to e.g. time shifts were omitted in the present validation.

It was indicated that HMC is mostly interested in the depth-averaged currents. Therefore, where possible, the available measurements will be converted to depth-averaged values.

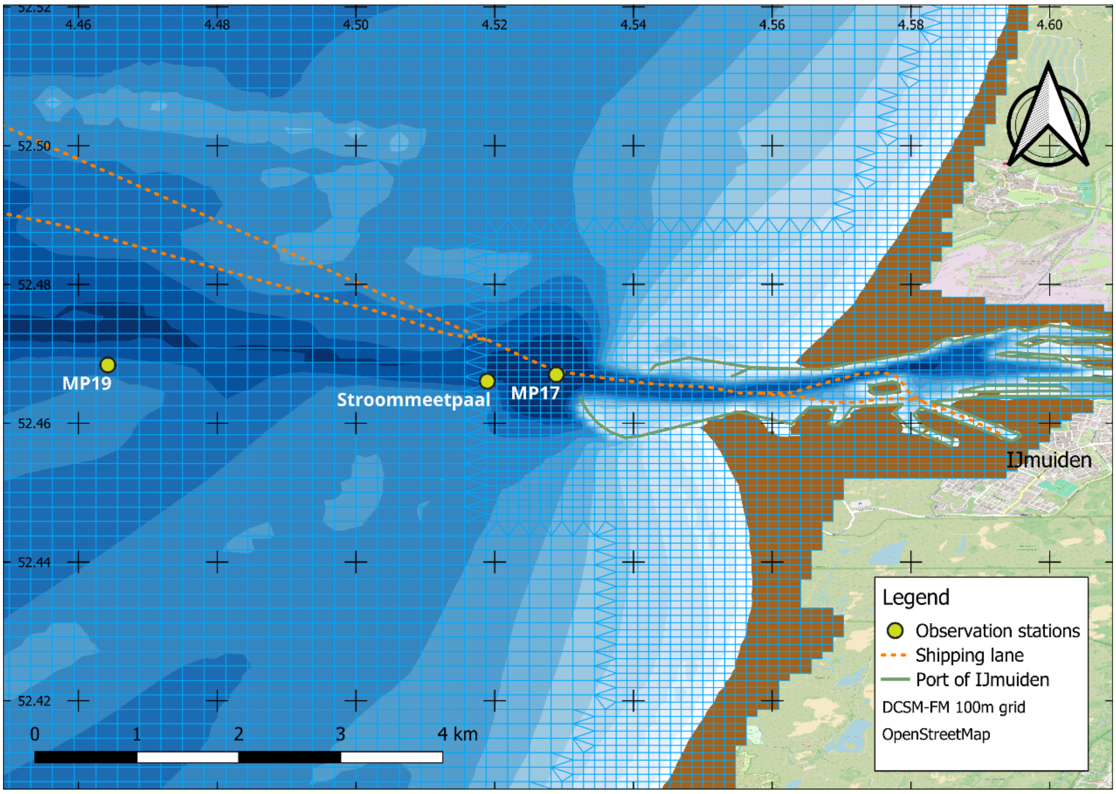

Figure 2.1 – Overview of the study area with model bathymetry and measurement locations.

2.2 Models

2.2.1 DCSM-FM 100m

We apply the 2022 release of the Dutch Continental Shelf Model - Flexible Mesh (DCSM-FM 100m) in our approach (Zijl et al., 2022), also referred to as dflowfm2d-noordzee_100m-j22_6-v1a. DCSM-FM covers the northwest European continental shelf between 15°W to 13°E and 43°N to 64°N (Figure 2.3) and has a spatially varying grid size. Along the Dutch coastline, including the area around Ijmuiden Harbor, the smallest cells occur, with a size of 5.625'' in east-west direction and 3.75'' in north-south direction, which corresponds to about 105 m x 115 m. At the lateral boundaries total water levels are prescribed, consisting of tide and surge. The tidal levels are derived by harmonic expansion using the amplitude and phase of 39 harmonic constituents, based on a blend of three different global sources, namely FES2014 (Lyard et al., 2021), GTSMv4.1 (Muis et al., 2016) and EOT20 (Hart-Davis et al., 2021).

To make sure the model data has sufficient temporal resolution, the data set is homogeneous, and we are not limited to the relatively recent data stored in Matroos, we decided to rerun the hydrodynamic model. This is done for the years 2016-2017 (using the last days of 2015 as spin-up) with meteorological forcing obtained from the ECMWF HRES model. Meteorological forcing parameters consist of neutral wind and mean level pressure. The wind speed is converted to wind stress using the Charnock drag formulation, applying the time- and space-varying Charnock coefficient provided by ECMWF HRES, considering the water velocity computed by the model and using a time- and space-varying air density computed from meteorological model parameters.

This model version differs slightly from the version that is running operationally since 2023, since it already incorporates the following recent developments not yet operationalized.

- The use of the neutral wind speed instead of the 'regular' wind speed, to consider the effect of atmospheric stability on the wind stress.
- The use of a time- and space-varying air density instead of a constant, uniform air density. The air density is computed in a pre-processing step, using air pressure, air temperature and dew point temperature from the meteorological model (see Zijl & Veenstra, 2024).
- The addition of periodic surface forcing with (semi-)annual periodicity, to consider effects of spatial and temporal water density variations which cannot be explicitly modelled in this two-dimensional barotropic model (see Zijlker & Zijl, 2023).

The computations were performed with D-Flow FM version 2.26.12.78884, which is the version that became part of the D-HYDRO Suite 2024.02 release.

2.2.2 WAQUA IJmond

The WAQUA IJmond model is a two-dimensional fourth-generation WAQUA model running operationally in the HMC operational system. This model has a space-varying grid spacing of around 300-400 m along its open boundary 30-35 km off the coast. Just off the IJmuiden breakwaters, near the location of the Stroommeetpaal and MP17, the grid size is approximately 100 m, whereas the smallest cells of around 50 m can be found within IJmuiden harbor.

The depth-averaged current data from the WAQUA IJmond model have been obtained from the Rijkswaterstaat MATROOS operational database.

2.2.3 Neural Network

The neural network predicts cross-currents at location MP17, based on the following input:

- Measured waterlevel IJmuiden [cm NAP]
- Astronomical tide IJmuiden [cm NAP]
- Moonfase [-1….1]
- Windspeed Ijmuiden [m/s] (measurement/forecast)
- Winddirection IJmuiden [deg] (measurement/forecast)
- Windspeed Europlatform [m/s] (measurement/forecast)
- Winddirection Europlatform [deg] (measurement/forecast)
- Windspeed K13 [m/s] (measurement/forecast)
- Winddirection K13 [deg (measurement/forecast)

The neural network cross-current results for 2016-2017 were provided by Rijkswaterstaat (Theo van Dam) and are assumed to be representative of depth-averaged values at location MP17.

2.3 Methods

2.3.1 Comparisons

Currents from all three models will be quantitatively validated against measurements, after which the quality of these models can be compared. Only DCSM-FM 100m generates output at all three locations where measurements are available. The neutral network only generates output at MP17, whereas for the MATROOS history information from the WAQUA IJmond model this is the case for MP17 and the Stroommeetpaal. The possible combinations with both modelling and measurement data available are indicated with a cross in Table 2.1.

Table 2.1 Possible combinations with both modelling and measurement data available (indicated with a cross).

	MP17	Stroommeetpaal	MP19
DCSM-FM 100m	**X**	**X**	**X**
Neuraal Network	**X**		
WAQUA IJmond	**X**	**X**	

2.3.2 Cross-current conversion

For this study, current values will be presented in the direction perpendicular to the entrance of the IJmuiden harbor, as also used in the Neural Network model. To this end, the x- and y-components of flow velocity have been recomputed using the following formulas:

$y_2 = x_1 \cdot \sin \alpha - y_1 \cdot \cos \alpha$ $\qquad$ $x_2 = x_1 \cdot \cos \alpha + y_1 \cdot \sin \alpha$

The axes were shifted by 10.5 degrees in clockwise direction as shown in Figure 2.2. The cross-current is defined as the velocity along axis Y2.

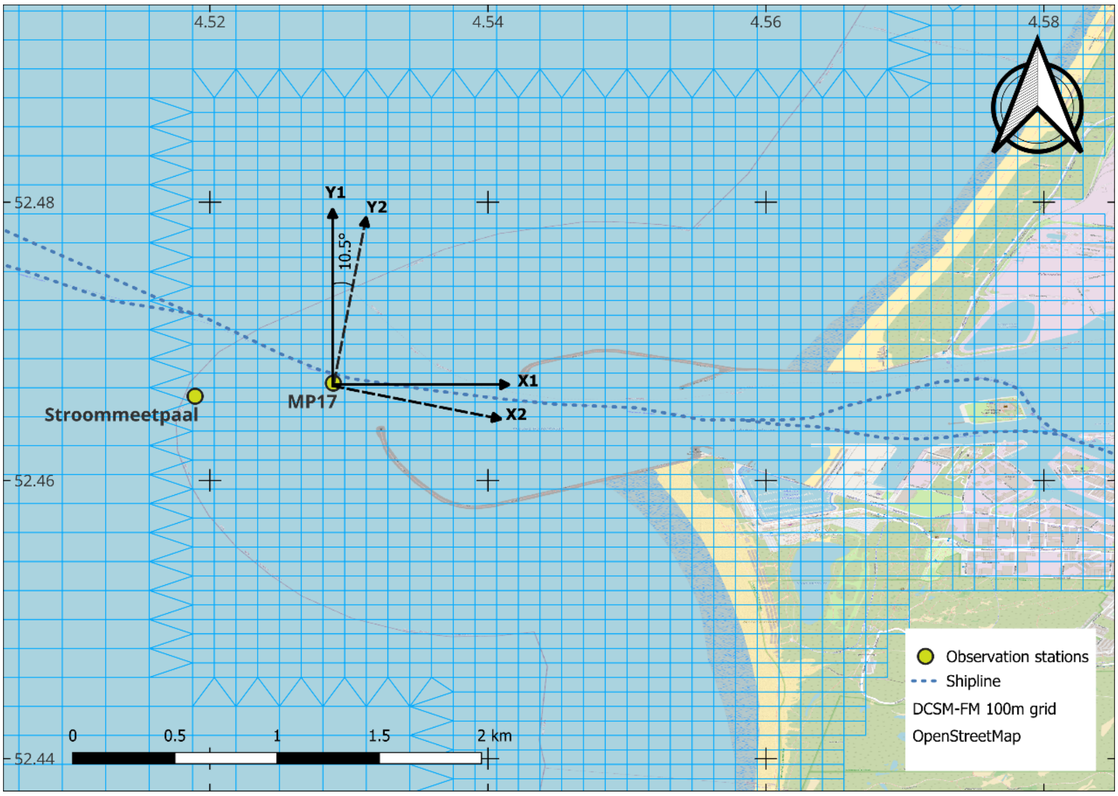

Figure 2.2 – Definition of the cross-current axis (Y2).

2.3.3 Quantitative evaluation method

The quantitative evaluation will be performed with a set of in-house developed Matlab scripts called the ‘current validation toolbox’. The results consist of time series and scatter plots. In the latter, the following error statistics are presented: bias, standard deviation (std), root-mean-square error (RMSE) and correlation coefficient. The modelled and measured currents are also split in a tidal and non-tidal part by means of harmonic analysis of currents in both horizontal directions. This is done with the t_tide package in Matlab.

Model output is available for the years 2016-2017. The error statistics will be determined for the period where measurements are available within these two years.

2.3.4 Sensitivity discharge Rijksgemaal IJmuiden

DCSM-FM 100m does currently not make use of discharge information. However, a sensitivity computation including the discharge from Rijksgemaal IJmuiden was performed. The results of this run will be compared to the results without these discharges, to test the impact on cross currents. The daily discharge data was obtained from an old extraction from the Waterbase database and is presented in Figure 2.3.

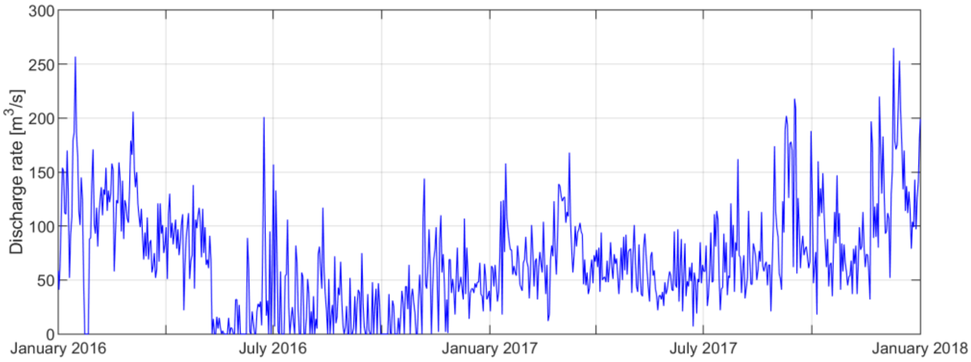

Figure 2.3 Discharge Rijksgemaal IJmuiden for the year 2016-2017, obtained from the Waterbase database.

3 Results

3.1 Comparison of model quality

3.1.1 Error statistics

The cross-current error statistics at location MP17 (in a deep pit off the Ijmuiden port entrance) are presented in Table 3.1, for DCSM-FM, WAQUA IJmond and the neural network model. The emphasis in this chapter is on MP17, since all three models are available at this location. The statistics for the other two locations can be found in the Appendix A.1.

The results in Table 3.1 show that the quality of the tidal cross-currents is similar in all three models, with an RMSE of 8-9 cm/s. This also holds for the standard deviation of the non-tidal cross-current of 10 cm/s. However, the bias of the non-tidal cross-current more than doubles in the neural network model (12 cm/s) compared to DCSM-FM 100m and the WAQUA IJmond model (5 cm/s). This difference also shows up in the RMSE of the non-tidal current, with 15 cm/s for the neural network model and 11 cm/s for both DCSM-FM 100m and the WAQUA IJmond model. Since the tidal quality is similar in all three models, the relative performance in non-tidal cross-current also shows up in the quality of the total cross current: 17 cm/s for the neural network model and 14 cm/s for both DCSM-FM 100m and the WAQUA IJmond model.

Table 3.1 Statistics for tidal, non-tidal and total cross-current flow velocity in comparison to ADCP measurements at station MP17.

	bias (cm/s)			std (cm/s)			RMSE (cm/s)		
	tidal	non-tidal	total	tidal	non-tidal	total	tidal	non-tidal	total
DCSM	0	-5	-5	9	10	13	9	11	14
WAQUA	0	-5	-5	8	10	13	8	11	14
NN	0	-12	-12	8	10	13	8	15	17

3.1.2 Time series and non-tidal events

A close-up of the DCSM-FM 100m time series of total, tidal, and non-tidal cross-current flow velocity at station MP17 is presented in Figure 3.1. This shows that the shape of the tide is generally well represented, even though the magnitude is underestimated by 10-20%. Also, the variability of the non-tidal cross-current is severely underestimated, in particular during the event on January 13-14, 2017. There, the measured non-tidal cross-current exceeds 0.5 m/s in (more or less) southern direction, which is hardly picked up by the model.

In Figure 3.2 the non-tidal cross-current durign the same period is plotted for the WAQUA IJmond and neural network models. This shows that the respons of the WAQUA IJmond model is qualitatively very similar to DCSM-FM 100m. In contrast, the neural network model reacts differently, exhibiting more variability before the event, but not necessarily with the same timing, resulting in even larger errors compared to the other models. While the peak of the event (just after midnight) is picked up well, the performance in the day leading up to the peak and in the two days after the peak is worse.

Another example of an event where all three model perform poorly with respect to cross-currents is on February 23, 2017 (see Figure 3.3). All three models severely underestimate the peak of the northgoing current. Thereafter, just before midnight they predict a flow reversal with a mild southgoing cross-current. Instead, the measurements show a north-going current of up to 1 m/s.

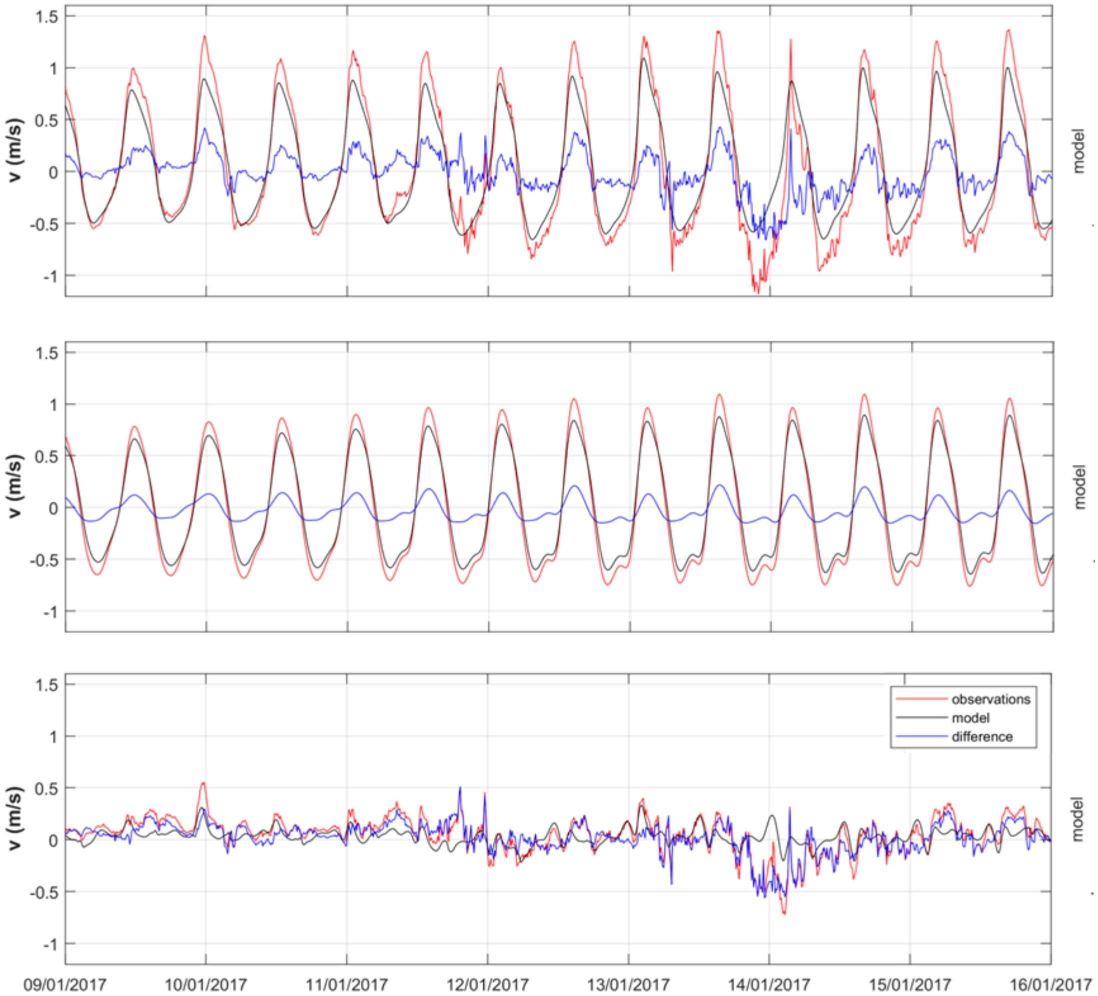

Figure 3.1 Timeseries of total (top), tidal (middle), and non-tidal (bottom) cross-current flow velocity at MP17 station, based on DCSM-FM 100m results.

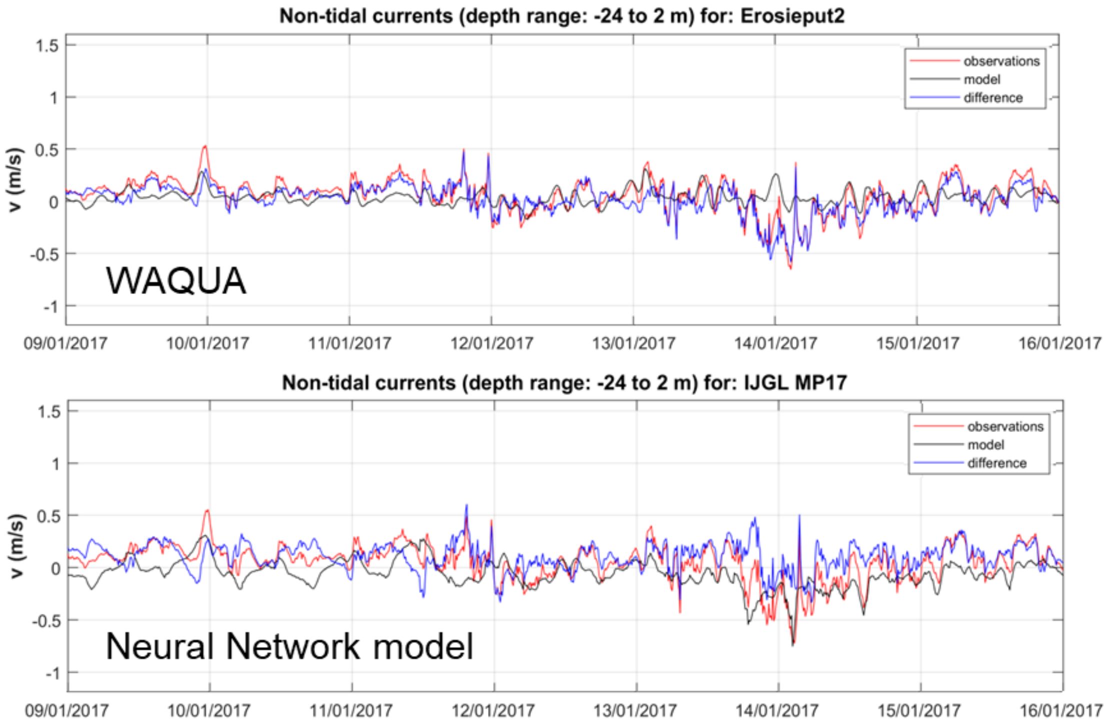

Figure 3.2 Timeseries of non-tidal cross-current flow velocity at MP17 station based on WAQUA IJmond (up) and Neural Network (down) model results.

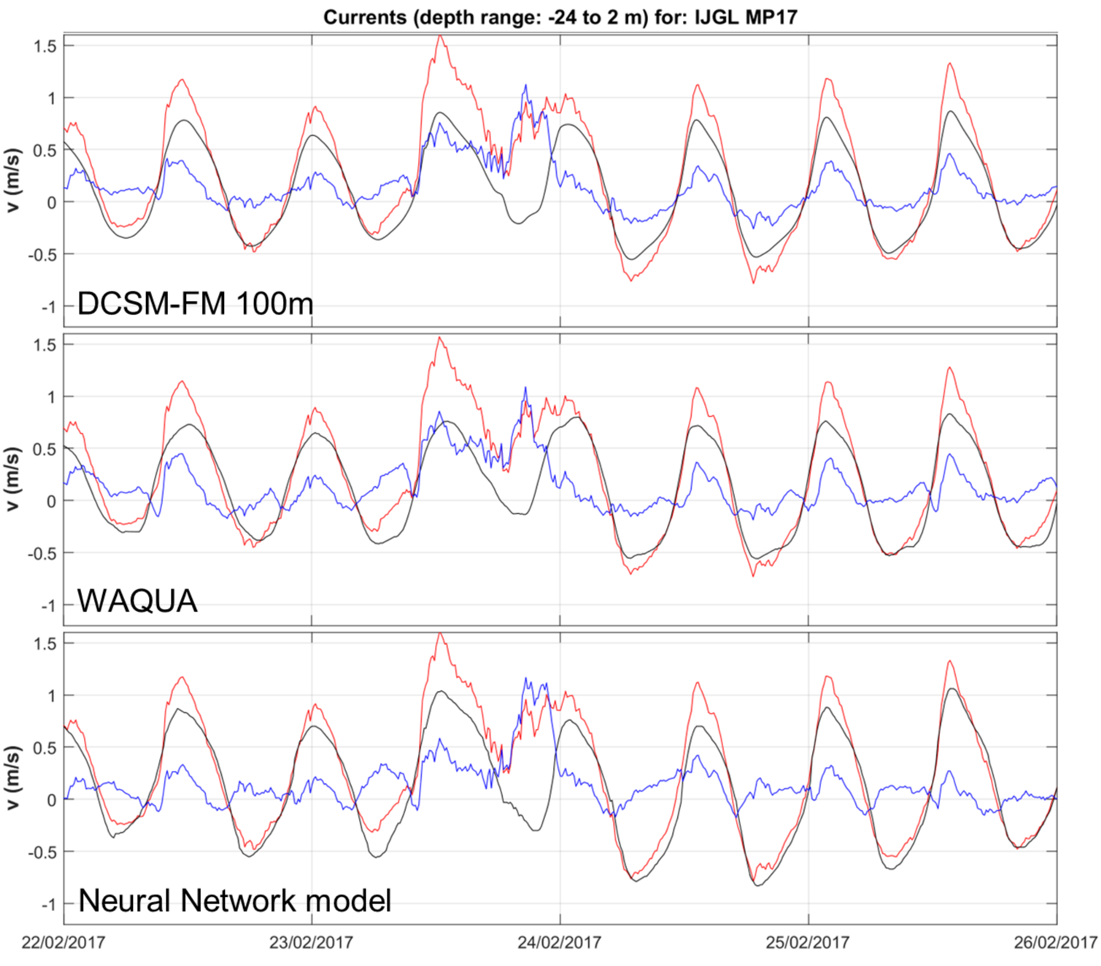

Figure 3.3 Timeseries of cross-current flow velocity at station MP17, compared to model results from DCSM-FM 100m (top), WAQUA (middle) and Neural Network model (bottom).

3.1.3 Scatter plots

Correlation plots of modelled and measured values are presented in Figure 3.4 – Figure 3.6, for the total, tidal and non-tidal cross-currents, respectively. Regarding the total cross-currents, DCSM-FM 100m shows the largest correlation coefficient (0.98), compared to the slightly lower 0.97 fro WAQUA IJmond and the neural network. However, in the case of DCSM-FM 100m, the relative bias (indicated by the red line) is also larger, showing an underestimation of the variability. This is less the case for the other models.

Looking at the tidal results, the correlation coefficient is excellent with values of 1.00 for DCSM-FM 100m and 0.99 for the other two models. The linear fit of all models is less steep than the diagonal, although this is less severe for the neural network model and most severe for DCSM-FM 100m. However, the scatter around the linear fit is least pronouonced in DCSM-FM 100m and most pronounced in theneural network results. The neural network shows an overprediction of the lower cross-current mangitudes, while the magnitude of the current peaks in both directions is underestimated.

The correlation coefficients for the non-tidal cross-currents are much lower, with values between 0.70 (WAQUA IJmond) and 0.76 (DCSM-FM 100m). The neural network shows larger variability than the other two models, which is closer in line with the measured variability. However, this comes with a much more severe systematic underprediction, representing a residual current in southern direction.

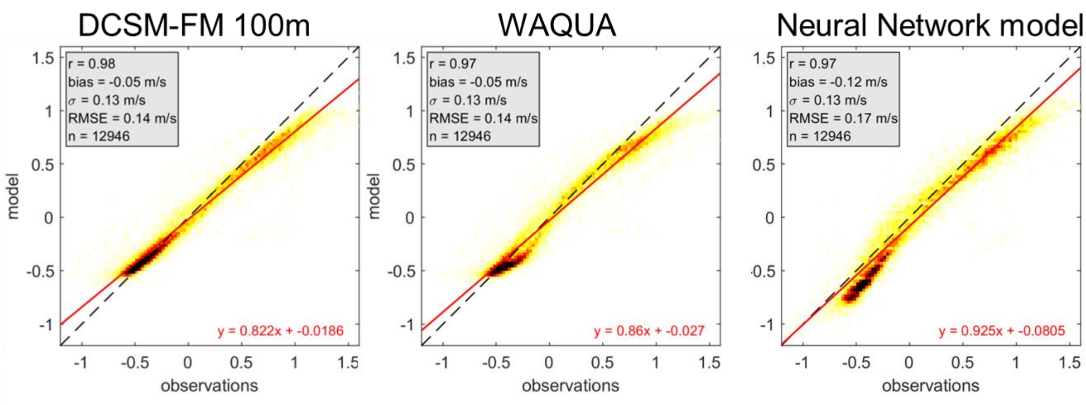

Figure 3.4 Scatter plot of model and measurement values of total cross-current at station MP17, for DCSM-FM 100m, WAQUA IJmond and neural network models.

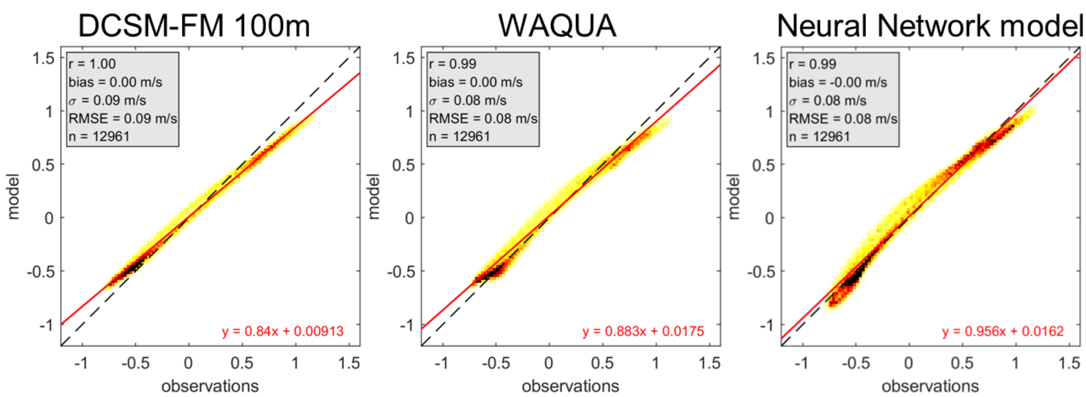

Figure 3.5 Scatter plot of model and measurement values of tidal cross-current at station MP17, for DCSM-FM 100m, WAQUA IJmond and neural network models.

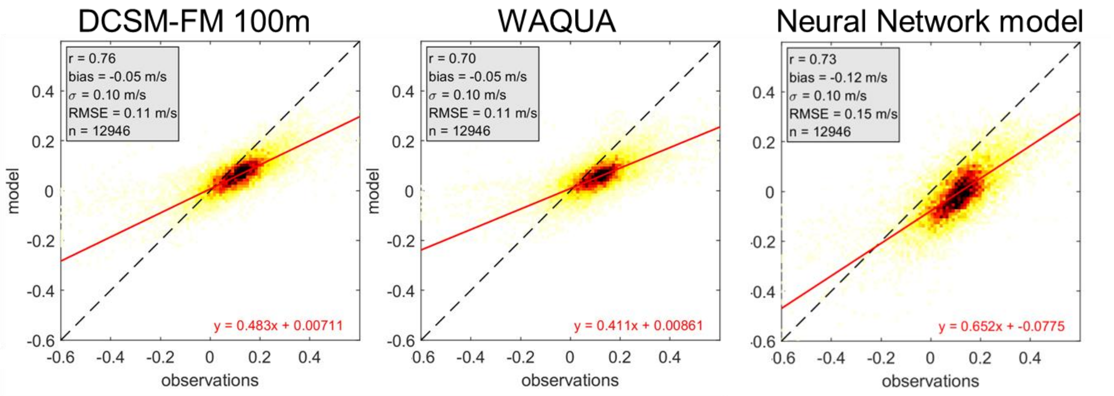

Figure 3.6 Scatter plot of model and measurement values of non-tidal cross-current at station MP17, for DCSM-FM 100m, WAQUA IJmond and neural network models.

3.2 Comparison to previous study

Compared to the DCSM-FM 100m model version used in the earlier current validation work of Laan & Zijl (2020) - a preliminary version predating the first official release (Zijl et al., 2020) - several model improvements have taken place. To check whether this has also led to an improvement in IJmond current predictions, a comparison of model quality has been made for station MP17 and MP19. Since the raw model output used in Laan & Zijl (2020) is not available anymore, it was not possible to compute cross-currents. Instead, the earlier post-processing has been repeated for the new model. The comparison is made for the velocity magnitude, while considering a longer period than used for the other analyses in the present memo. This implies that some erroneous data have been included. Nonetheless, we think a comparison of model quality is still relevant.

The results of the comparison to previous results in presented in Table 3.2. This shows that most metrics have slightly deteriorated or remained the same. In terms of total current magnitudes, both model versions have an RMSE of 6 cm/s at MP19, while the RMSE at MP17 has slightly increased from 19 to 20 cm/s.

Table 3.2 Statistics for the tidal, non-tidal and total current velocity magnitude in comparison to ADCP measurements for different versions of DCSM-FM 100m, at station MP17 and MP19.

	bias (cm/s)			std (cm/s)			RMSE (cm/s)		
	tidal	non-tidal	total	tidal	non-tidal	total	tidal	non-tidal	total
MP17									
old	-3	-10	-7	7	13	17	8	16	19
new	-5	-11	-9	9	13	18	10	17	20
MP19									
old	0	-2	-2	2	4	5	2	4	6
new	-2	-3	-3	2	3	5	3	4	6

3.3 Impact discharge Rijksgemaal IJmuiden

DCSM-FM 100m does currently not make use of discharge information. However, a test computation including the discharge from Rijksgemaal IJmuiden was performed to test the impact on cross currents. Figure 3.7 presents the comparison between simulated cross-current current series at station MP17, with and without the discharge at Rijksgemaal IJmuiden included. These results show that the inclusion of the discharge has virtually no effect on the modelled cross-currents at the selected location.

Note that the model, with and without additional discharge, assumes a constant, uniform density (salinity, temperature), which implies that only the volumetric effect of the discharge is considered and the effect of density gradients introduced by this discharge, and resulting stratified flows, are not accounted for. It remains possible or even likely that the freshwater discharges from Rijksgemaal IJmuiden play a role in the exchange current with the North Sea, especially during high discharge event. However, it is unclear to what extent these exchange flows influence the depth-averaged current in the direction perpendicular to the shipping channel.

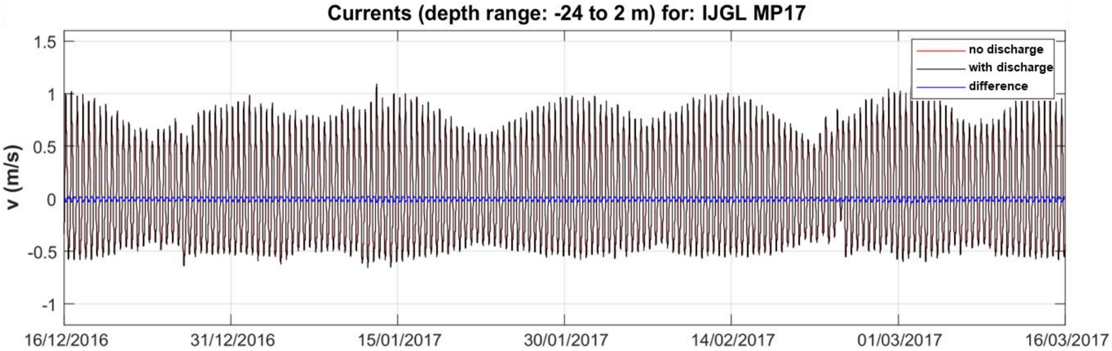

Figure 3.7: Timeseries of total cross-current flow velocity at MP17 station based on DCSM-FM 100m model results with and without discharge from Rijksgemaal IJmuiden included.

4 Conclusions and recommendations

4.1 Conclusions

HMC currently runs the WAQUA IJmond model and a neural network model to forecast cross-currents in the shipping channel towards the harbor of IJmuiden. The WAQUA IJmond model has not been further developed for over a decade and will soon be phased out. The neural network model is perceived to be unreliable and does not provide spatial information. The real-time operational sixth generation (2D) DCSM-FM 100m model also covers this area and is considered as a replacement. To support a decision on using DCSM-FM 100m as a replacement, a quantitative validation of depth-averaged cross-currents near the IJmuiden harbor entrance was performed for the above-mentioned models. The results of this validation are presented and compared in the present memo. Based on this, the following can be concluded:

- The quality of the tidal, non-tidal and total cross-currents at station MP17 is very similar in DCSM-FM 100m and the WAQUA IJmond model, with an RMSE of 8-9 cm/s, 11 cm/s and 14 cm/s, respectively. In the neural network, the bias more than doubles from 5 cm/s to 12 cm/s (representing an overestimation of the residual south-going current), leading to a larger RMSE of the total cross-current of 17 cm/s (compared to 14 cm/s in the other models).
- With an RMSE of 0.14 – 0.17 m/s, none of the models considered is capable of accurately representing the cross-currents near the IJmuiden harbor entrance (measurement location MP17). For comparison, further offshore at location MP19 an RMSE of 0.05 m/s is achieved with DCSM-FM 100m.
- Focusing on events with large non-tidal cross-currents, the performance of the models is even poorer. During an event on January 13-14, 2017 the measured non-tidal cross-current exceeds 0.5 m/s, while both DCSM-FM 100m and the WAQUA IJmond model show hardly any (non-tidal) response. The neural network model reacts differently, but not necessarily better: while the non-tidal peak of the event is picked up well, the performance in the day leading up to the peak and in the two days after the peak are worse.
- The inclusion of the discharge from Rijksgemaal IJmuiden in DCSM-FM 100m has virtually no effect on the modelled cross-currents. Since in these tests only the volumetric effect of the discharge is accounted for, it still remains possible or even likely that the freshwater discharges from Rijksgemaal IJmuiden plays a role in the exchange current with the North Sea, especially during a high discharge event.
- Compared to Laan & Zijl (2020), which used a preliminary version of the previous release of DCSM-FM 100m, the quality to represent current magnitudes at location MP17 (and MP19) has not improved.

4.2 Recommendations

- The fact that more extreme non-tidal current events are hardly represented in both DCSM-FM 100m and the WAQUA IJmond model implies that the phenomena driving these events are missing from the model altogether. It is recommended to investigate both the role of density effects in the Rhine ROFI and the influence of density differences between the harbor and the North Sea area just outside the breakwaters. These processes cannot be captured in a two-dimension barotropic model. Instead, it is recommended to use a three-dimensional model with salinity and temperature as state-variables. As a first attempt, a local cut-out from DCSM-FM, with boundary conditions and 3D settings from 3D DCSM-FM could be used. Fresh water discharges into IJmuiden harbor would also need to be included. In addition, it is possible that currents generated by breaking surface waves and Stokes drift play a role in the residual current along the coast and just off the breakwaters. To investigate this, a test computation including coupling to the SWAN Kuststrook model is recommended.
- The depth-averaged tidal current quality near the harbor entrance is relatively poor compared to locations further offshore. It is therefore recommended to investigate the origin of these errors. Besides the above-mentioned density effects now ignored in this 2D barotropic model, possible causes might include the lack of resolution (relative to the large gradients in bathymetry and current velocity) and possible poor representation of local bathymetry.

References

Hart-Davis, M. G., Piccioni, G., Dettmering, D., Schwatke, C., Passaro, M., & Seitz, F. (2021). EOT20: a global ocean tide model from multi-mission satellite altimetry. Earth System Science Data, 13(8), 3869-3884.

Laan, S. & Zijl, F. (2020). Stromingsvalidatie dieptegemiddelde Noordzee modellen. Deltares, memo 11203715-004-ZKS-0002_v0.2, Versie 1.0

Lyard, F., D. Allain, M. Cancet, L. Carrere, N. Picot (2021). FES2014 global ocean tides atlas: design and performances. Ocean Science 17, 3, 615–649.

Muis, S., M. Verlaan, H.C. Winsemius, J.C.J.H. Aerts, P.J. Ward (2016). A global reanalysis of storm surges and extreme sea levels. Nature Communications 7, 11969.

Zijl, F. & Groenenboom, J. (2020). Development of a sixth-generation model for the NW European Shelf (DCSM-FM 100m). Deltares, report 11205259-004-ZKS-0001, Delft.

Zijl, F., Zijlker, T., Laan, S., Groenenboom, J. (2022). DCSM-FM 100m: a sixth-generation model for the NW European Shelf (2022 release). Deltares, report 11208054-004-ZKS-0002, Delft.

Zijlker, T. & Zijl, F. (2023) Ontwikkeling periodieke oppervlakteforcering voor DCSM-FM. Deltares, memo 11209278-004-ZKS-0002.

Zijl, F. & Veenstra, J. (2024) Varying air density in DCSM-FM. Deltares, memo 11209278-004-ZKS-0003, Delft.

A Appendix

A.1 Error statistics

Table 4.1 Statistics for tidal, non-tidal and total cross-current flow velocity for DCSM-FM 100m, WAQUA IJmond, and Neural Network models in comparison to ADCP measurements at location MP17, MP19 and Stroommeetpaal.

	bias (cm/s)			**std (cm/s)**			**RMSE (cm/s)**		
	tidal	non-tidal	total	tidal	non-tidal	total	tidal	non-tidal	total
MP17									
DCSM	0	-5	-5	9	10	13	9	11	14
WAQUA	0	-5	-5	8	10	13	8	11	14
NN	0	-12	-12	8	10	13	8	15	17
MP19									
DCSM	-2	0	-2	3	4	5	3	4	5
Stroommeetpaal									
DCSM	-3	0	-3	11	7	13	11	8	14
WAQUA	-3	0	-3	5	8	10	5	8	10

A.2 Correlation plots

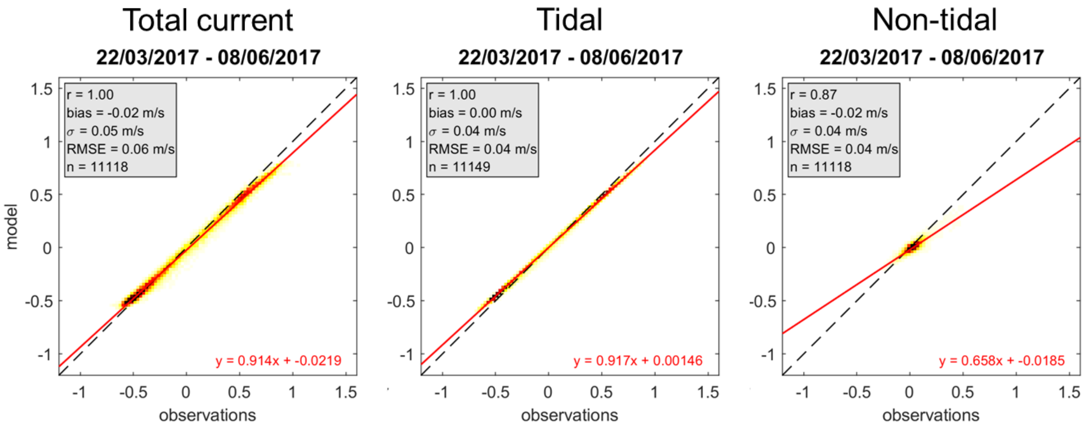

Figure 4.1 – Scatter plot of model and measurement values of total, tidal, and non-tidal cross-current at MP19 station for 2D DCSM-FM 100m model.

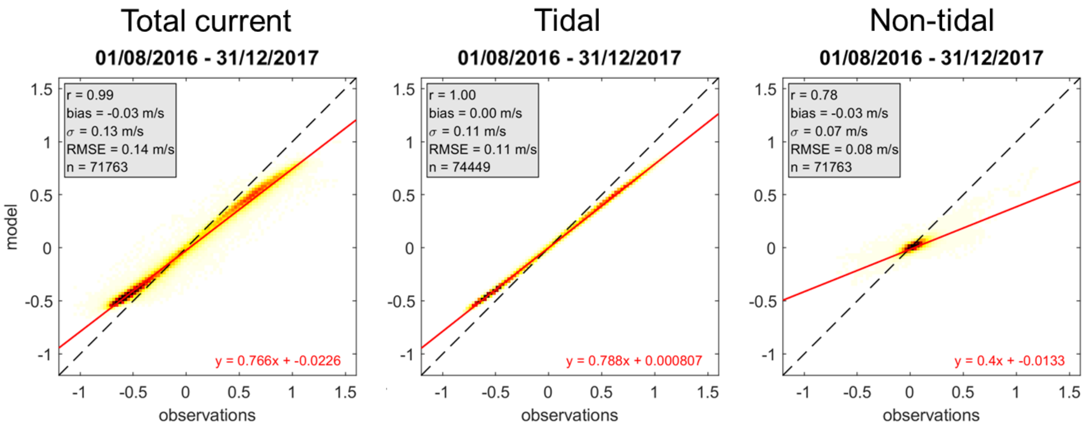

Figure 4.2 – Scatter plot of model and measurement values of total, tidal, and non-tidal cross-current at Stroommeetpaal station for 2D DCSM-FM 100m model.

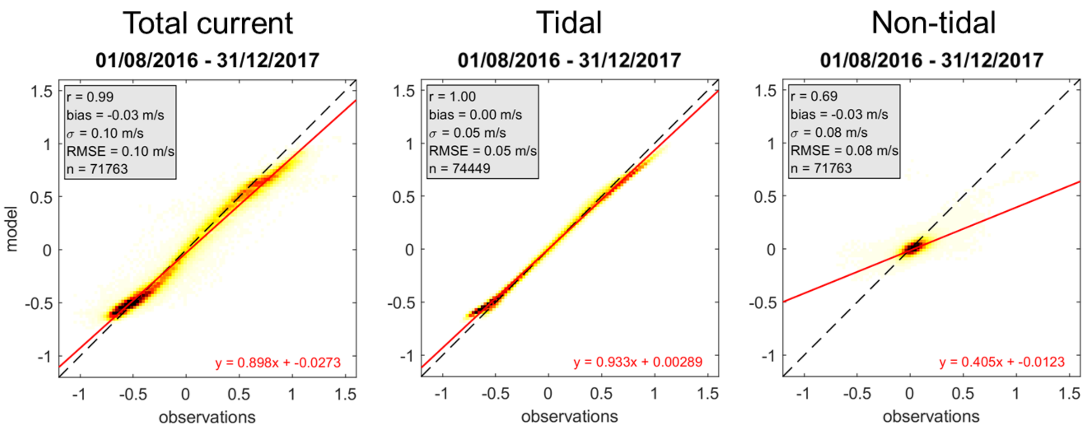

Figure 4.3 – Scatter plot of model and measurement values of total, tidal, and non-tidal cross-current at Stroommeetpaal station for WAQUA IJmond model.