Development of a sixth-generation model for the NW European Shelf (DCSM-FM 100m)

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Model setup, calibration and validation

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11205259-004

Deltares

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Client	**Project**	**Attribute**	**Pages**
RWS-WVL	11205259-004	11205259-004-ZKS-0001	112

Keywords
D-HYDRO, Delft3D Flexible Mesh, North Sea, Northwest European Continental Shelf, sixth-generation

Summary

Upon request of Rijkswaterstaat (RWS), Deltares has developed a sixth-generation hydrodynamic model of the Northwest European Shelf. Specifically, this model covers the North Sea and adjacent shallow seas and estuaries in the Netherlands, such as the Wadden Sea, the Ems-Dollard estuary, the Western Scheldt and the Eastern Scheldt. The development of this model (DCSM-FM) is part of a more comprehensive project in which sixth-generation models are developed for all waters managed and maintained by RWS. An important difference with the previous fifth-generation models is the use of the D-HYDRO Suite, the new software framework for modelling free surface flows, which was first released in 2015 and allows for the use of unstructured grids.

While the previous generation models for the same area were specifically aimed at an optimal representation of water levels for operational forecasting under daily and storm surge conditions, for the sixth-generation model(s) the scope is wider. This model should also be suitable to use for e.g. water quality and ecology studies, oil spill modelling, search and rescue and to provide three-dimensional (3D) boundary conditions (including temperature and salinity) for detailed models of e.g. the Haringvliet and Rhine-Meuse Delta (RMM).

The above applications pose a wide range and sometimes mutually exclusive demands on a model. Therefore, two horizontal schematizations were proposed:

1. DCSM-FM 0.5nm: a relatively coarse schematization (minimum grid size of 800-900 m in Dutch waters), primarily aimed at ensemble-based probability forecasting, but also forming a sound basis for a three-dimensional model development including temperature and salinity as state parameters.
2. DCSM-FM 100m: a relatively fine schematization with a minimum mesh size of ~100 m in some Dutch waters (such as the Wadden Sea) to be used, amongst others, for accurate (operational) water level forecasting. This model will be a based on the model in item 1, but with refinement where required.

The first schematization (DCSM-FM 0.5nm) has recently been developed, see Zijl & Groenenboom (2019). The present report deals with the development of the relatively fine two-dimensional DCSM-FM model (DCSM-FM 100m).

Version	Date	Author	Initials	Review	Initials	Approval	Initials
V0.1	13-08-2020	Firmijn Zijl		Martin Verlaan		Toon Segeren	
V1.0	30-10-2020	Firmijn Zijl	FZ	Martin Verlaan		Toon Segeren	

Status
final

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Appendices

1 Introduction

1.1 Background

Upon request of Rijkswaterstaat (RWS), Deltares has developed a sixth-generation hydrodynamic model of the Northwest European Shelf. Specifically, this model should cover the North Sea and adjacent shallow seas and estuaries in the Netherlands, such as the Wadden Sea, the Ems-Dollard estuary, the Western Scheldt and the Eastern Scheldt. The development of this model is part of a more comprehensive project in which sixth-generation models are developed for all waters maintained by RWS. An important difference with the previous fifth-generation models is the use of the D-HYDRO Suite (known as the Delft3D Flexible Mesh Suite internationally), the new software framework for modelling free surface flows, which was first released in 2015 and allows for the use of unstructured grids.

While the previous generation models (DCSMv6 and DCSMv6-ZUNOv4, see Zijl et al. (2013)) for the same area were specifically aimed at an optimal representation of water levels for operational forecasting under daily and storm surge conditions, for the sixth-generation model(s) the scope is wider. The model should also be suitable to use for e.g. water quality and ecology studies, oil spill modelling, search and rescue and to provide three-dimensional (3D) boundary conditions (including temperature and salinity) for detailed models of e.g. the Haringvliet and Rhine-Meuse Delta (RMM).

The above applications pose a wide range and sometimes mutually exclusive demands on a model. This is because both the relative importance of representing certain phenomena as well as the allowed computational time varies per application. Since the demands are impossible to meet with one model, two horizontal schematizations (resulting in 3 models) were proposed:

1. DCSM-FM 0.5nm: a relatively coarse schematization (minimum grid size of 800-900 m in Dutch waters). The corresponding computational time makes it possible to use for the following models:
   a. a 3D transport model, including temperature and salinity as state variables
   b. A 2D tide-surge model that is fast enough used to produce probability forecasts with a 2 – 10 day lead-time. These forecasts will be based on meteorology of the ECMWF Ensemble Prediction System (EPS) and will replace the fourth-generation model DCSMv5 that is currently used for this application.
2. DCSM-FM 100m: a relatively fine schematization with a minimum mesh size of ~100 m in some Dutch waters (such as the Wadden Sea) to be used, amongst others, for accurate (operational) water level forecasting. This model will be a based on the schematization in item 1, but with refinement where required.

The first schematization has recently been developed, see Zijl & Groenenboom (2019). The present report deals with the development of the relatively fine two-dimensional DCSM-FM 100m model primarily aimed at deterministic water level forecasting (item 2 above). For reference purposes, this version of the model will also be referred to as dflowfm2d-noordzee_100m-j17_6-v1.

To ensure that all sixth-generation models are compatible, the guidelines with generic technical and functional specifications as specified in (Minns et al., 2019) were used during the setup of this model.

1.2 Guide to this report

The next chapters describe the setup of DCSM-FM 100m (Chapter 2). Chapter 3 describes the tide gauge data that is used to calibrate and validate the model, while in Chapter 4 and Chapter 5 the calibration and the validation are presented. The report ends with conclusions and recommendations in Chapter 6.

2 Model setup

2.1 Network

2.1.1 Network coverage, horizontal extent

The model network of DCSM-FM covers the northwest European continental shelf, specifically the area between 15° W to 13° E and 43° N to 64° N (see Figure 2.1). This means that the open boundary locations are the same as in the fifth-generation model DCSMv6 (Zijl et al., 2013). An extension of the model domain was considered as this might have a beneficial impact on the surge representation, since a larger part of the surge signal is then generated inside the model by means of wind stress and atmospheric pressure gradients. Consequently, a smaller part has to enter the domain through an approximated surge boundary condition based on air pressure alone. Even though tests computations with the coarser DCSM-FM 0.5nm model showed an improvement during the highest storm surge events, this was considered too limited to justify the additional computations cost of an extended domain. The results of these test computations are described in Appendix A of the DCSM-FM 0.5nm report (Zijl & Groenenboom, 2019).

2.1.2 Grid size

The computational grid of the previous generation WAQUA-DCSMv6 model has rectangular cells with a uniform resolution. One of the advantages of D-HYDRO Flexible Mesh above WAQUA is the enhanced possibility to better match resolution with relevant local spatial scales. In Zijl et al. (2016) a test is reported where, starting from a grid with uniform resolution, the deep areas off the shelf were refined by a factor of up to 4 x 4. The advantage of coarsening in deep areas in particular is twofold: firstly, it reduces the number of cells in areas where local spatial scales allow it and secondly, it eases the numerical time step restriction. The combination of both led to a reduction in computational time with a factor ~4, while - crucially - maintaining accuracy. On the other hand, in shallow areas, resolution plays an important role in accurately representing tide and surge, including its enhanced non-linear interaction (Zijl, 2016a).

Given the above considerations, the DCSM-FM network was designed to have a resolution that increases with decreasing water depth. The starting point was a network with a uniform cell size of 1/10° in east-west direction and 1/15° in north-south direction. This course network was refined in six steps with a factor of 2 by 2. The coarsest areas of refinement were initially specified with smooth polygons that were approximately aligned with the 800 m, 200 m, 50 misobaths (i.e., lines with equal depth). Areas with different resolution are connected with triangles (see right-hand side panel of Figure 2.2). The choice of isobaths ensures that the cell size scales with the square root of the depth, resulting in relatively limited variations of wave Courant number within the model domain.

As the focus of DCSM-FM 100m is on the accurate modelling of water levels in Dutch coastal waters, the refinements to a resolution of approximately 0.25 nm, 200 m and 100 m were only applied in the southern North Sea. As a result, the model schematization outside the southern North Sea, or more specifically outside the refinement polygon (to a resolution of 0.25 nm) at the 50 m isobath, is exactly the same as DCSM-FM 0.5nm.

Apart from applying the refinements based on local bathymetry, another consideration in positioning the refinements were the number of cells between transitions (at least a few). Also, it was ensured that all coastlines, except very small islands, were covered by a few rows of at least 0.5 nm-resolution cells. This implies that in areas with steep coasts the transition to the highest resolution takes place in deeper water. Another exception was made for the southern North Sea, where mainly a resolution of 0.25 nm is used. This was done to ensure that the highly variable features in the bathymetry can properly be represented on the network. A few hundreds of metres off the Dutch coast, the transition to a resolution of approximately 200 m is made. This resolution covers the area where bathymetric data with sufficient spatial resolution was available (i.e. the area covered by Baseline, see section 2.4). The highest resolution of 100 m is applied along the entire Dutch coast, including the Dutch estuaries and the Dutch part of the Wadden Sea (see left panel of Figure 2.2).

The resulting network is shown in Figure 2.1 and has approximately 1,600,000 computational cells with a variable resolution. The largest cells (shown in yellow) have a size of 1/10° in east-west direction and 1/15° in north-south direction, which corresponds to about 4 x 4 nautical miles (nm) or 4.9-8.1 km by 7.4 km, depending on the latitude. The smallest cells (shown in orange) have a size of 5.625’’ in east-west direction and 3.75’’ in north-south direction. This corresponds to about 105 m x 115 m along the Dutch coast.

The network is specified in WGS 84 geographical coordinates.

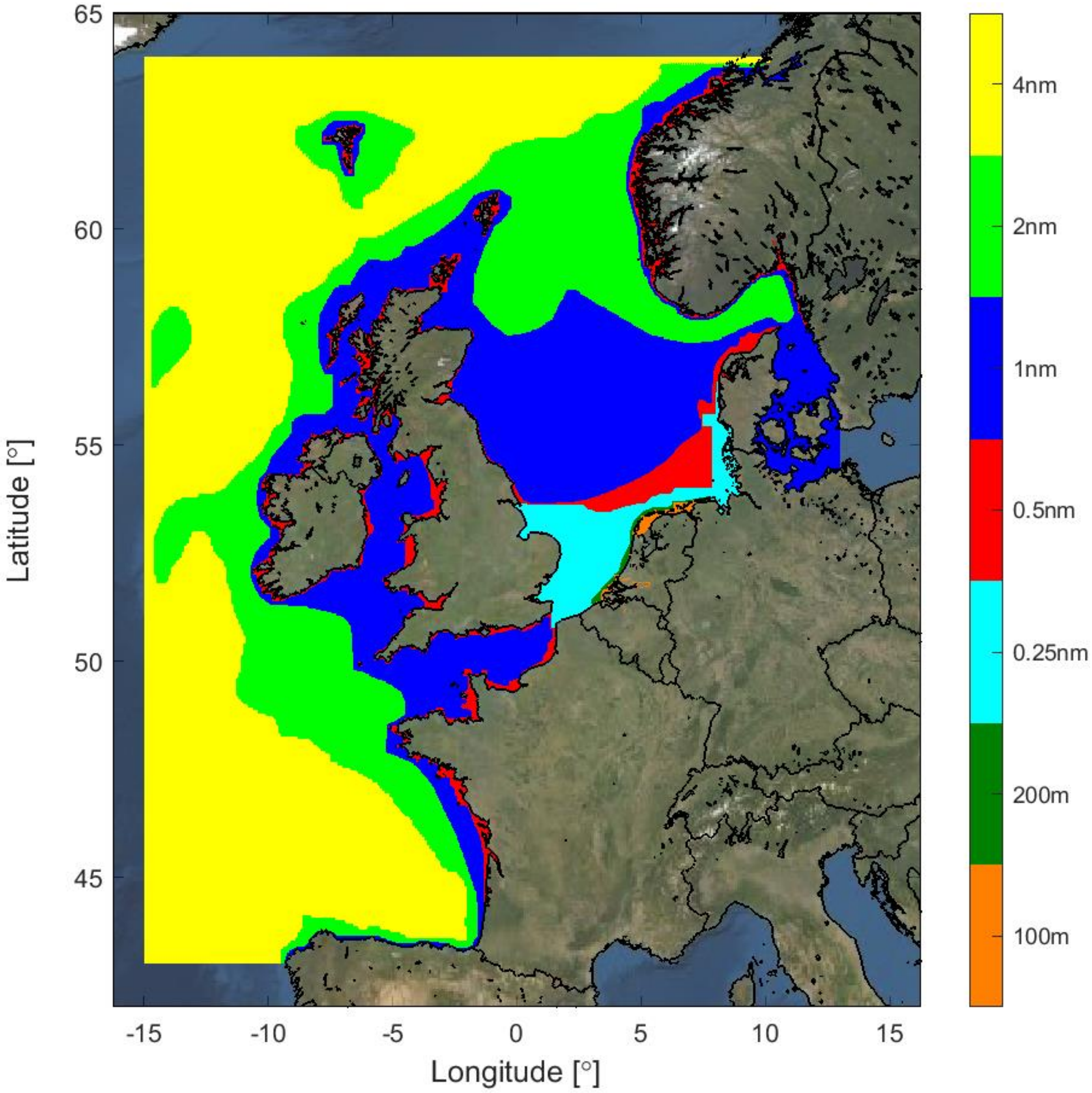

Figure 2.1 Overview of the DCSM-FM 100m network with the colours indicating the grid size (yellow: ~4 nm; light green: ~2 nm; blue: ~1 nm; red: ~0.5 nm, cyan: ~0.25 nm, dark green: ~200 m and orange ~100 m).

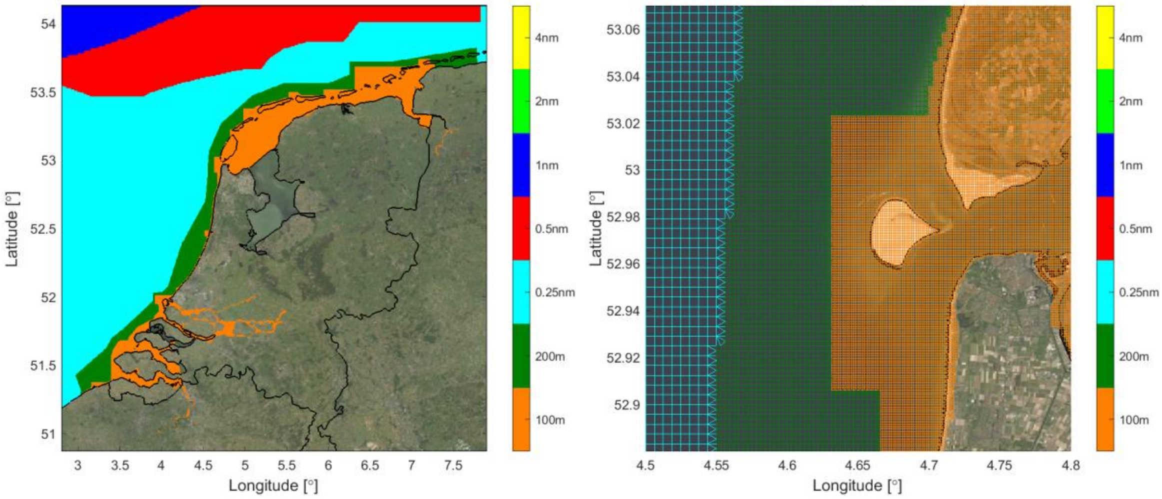

Figure 2.2 Detail of the DCSM-FM 100m network with the colours indicating the grid size (blue: ~1 nm; red: ~0.5 nm, cyan: ~0.25 nm, dark green: ~200 m and orange ~100 m).

2.2 Network optimization

The computational time step used is automatically limited by D-Flow FM (the hydrodynamic module of the D-HYDRO Suite) based on a Courant criterium. This means that parts of the network with a combination of small flow links and high velocities are most likely to restrict the time-varying computational time step and consequently increase the computational time. Figure 2.3 displays an example of the maximum occurring flow velocity during an arbitrary neap-spring cycle in colour, whereas the black dots indicate the locations of computational cells that are responsible for limiting the time step at least once during this period.

From the example in Figure 2.3, it also becomes clear that the time step restricting cells are located in areas with high flow velocities and mostly at the triangles used for the transition in resolution. These triangles have flow links (the connection between two circumcentres or so-called water level points) that are shorter than in the highest resolution rectangles.

To allow for a larger time step and consequently a faster computation, the grid was improved at the locations of the restricting cells. By extending the refinement of the grid more offshore, the transition of the two resolutions is moved outside the region of high flow velocities. Even though this measure slightly increases the amount of computational cells, the net effect is a decrease in computational time (see paragraph 2.9.9), because of the increase in the average time step.

After a few repetitions of manually changing the location of the transition in resolution, many restricting cells in triangles were removed. The left panel of Figure 2.3 shows the initial grid (in red) with the maximum flow velocities (as background colour) and restricting cells (black dots) near Maasvlakte II before the grid adjustments, whereas the right-hand side panel shows the final grid. At some point it was not possible to noticeably further increase the average timestep in this manner, since some remaining restricting cells are not on the transition of resolution but are within the area covered by the higher resolution rectangles (see right-hand side of Figure 2.3). This means that removing these restrictions is not possible with the above described method. Note that, dependent on the flow velocities, the restricting cells vary over time and space and are associated with a varying degree of time step reduction. Beside the restricting cells in this example near Maasvlakte II, time step limiting cells can also be found around other regions of high flow velocities, such as tidal inlets.

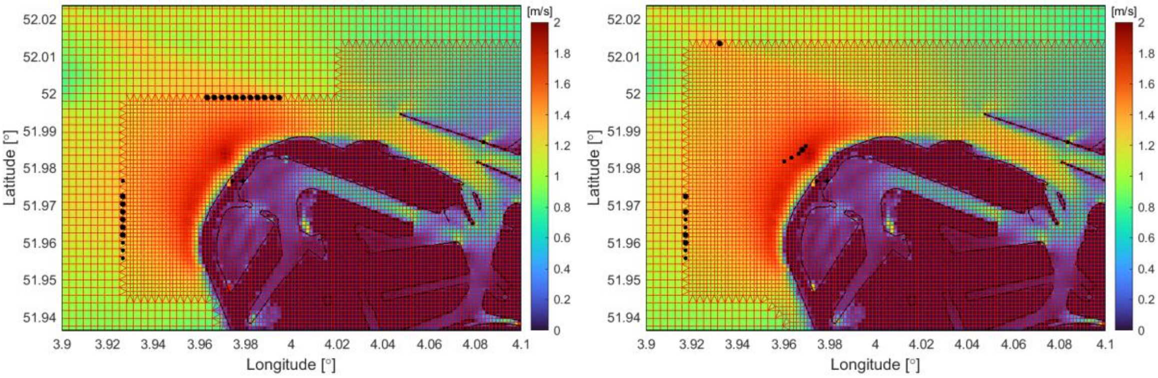

Figure 2.3 Maximum flow velocities in flow element centre during a neap-spring cycle near the Maasvlakte II. The black dots indicate computational cells that are limiting the time step (left: before optimization; right: after optimization)

2.3 Land-sea boundary, dry points and thin dams

2.3.1 Outside the Dutch coastal waters

After the local refinement of the network, the cells that covered land were removed from the computational domain. The first step was to interpolate the EMODnet bathymetric data to the grid and to delete all cells that do not have EMODnet data in its vicinity. Subsequently, a land-sea boundary obtained from the World Vector Shoreline (https://shoreline.noaa.gov/) was used to distinguish between land and water. All cells that, according to this land-sea boundary, were covered by more than 40% land were made inactive by specifying so-called *dry points*. The creation of these dry points was done automatically by a MATLAB-script. Figure 2.4 shows an overview of the resulting computational domain near the entrance of the Humber Estuary (in which tide gauge station Immingham is located). The black line indicates the land-sea boundary and the red crosses within the grid illustrate the dry points.

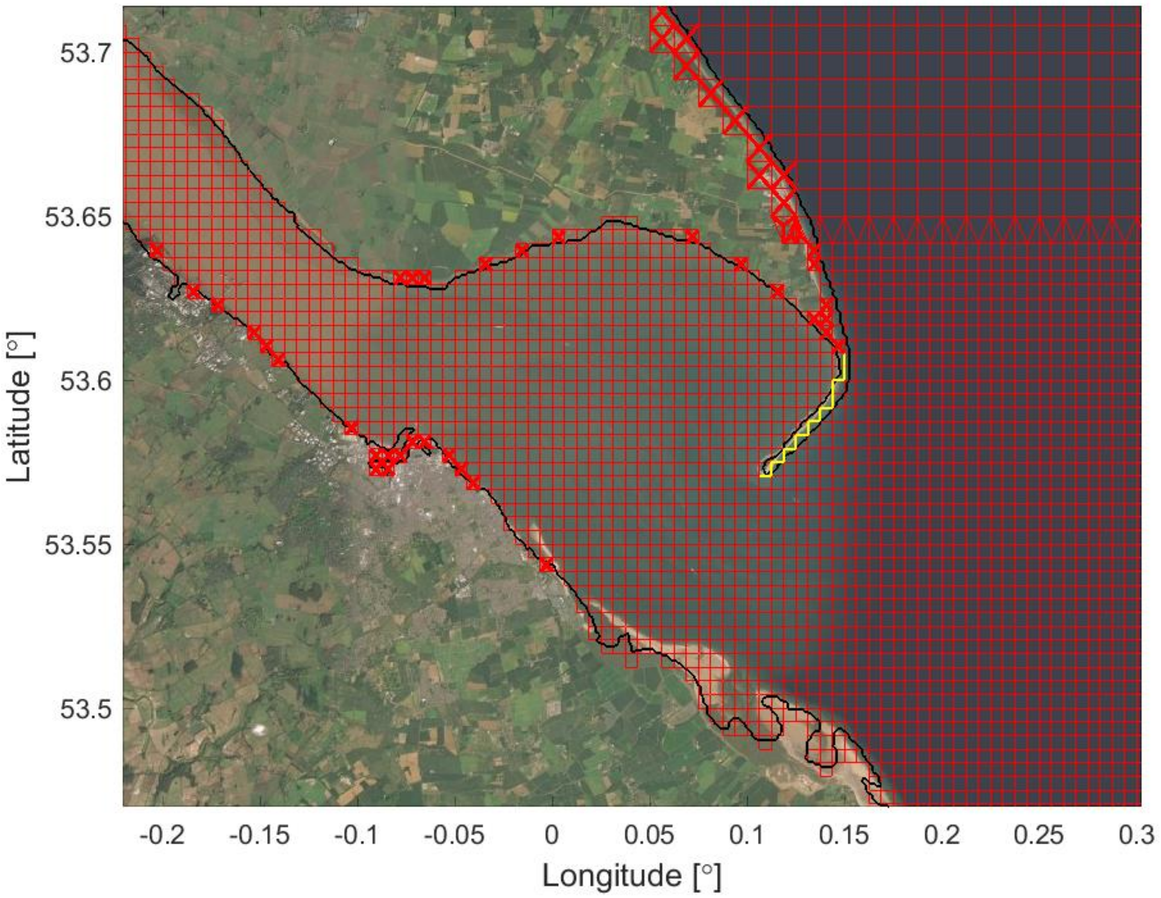

Figure 2.4 Overview of the computational grid (red), land-sea boundary (black), dry points (red crosses) and thin dams (yellow) near the Humber Estuary.

After this automated creation of a first set of dry points, manual work was required to get to the final version of the model geometry. During visual inspection of the shorelines, dry cells were added or removed where necessary. In addition, features that are relatively small compared to the area of a cell, are captured in the model schematisation by specifying so-called *thin dams*. These thin dams prohibit flow exchange through cell edges. The thick, yellow lines in Figure 2.4 illustrate how the breakwater at the entrance to the Humber Estuary is represented by thin dams (weirs with an infinite height).

Another example of manual adjustments is in the fjords of Norway. Some fjords consist of very small inlets that are connected to relatively large upstream basins. In some fjords, large bodies of water were excluded from the model because of a single dry point blocking the entire channel. Also, these erroneously created dry points were removed from the model schematisation to prevent the blockage of flow further upstream. The resulting geometry near one of the many fjords in Norway is shown in Figure 2.5.

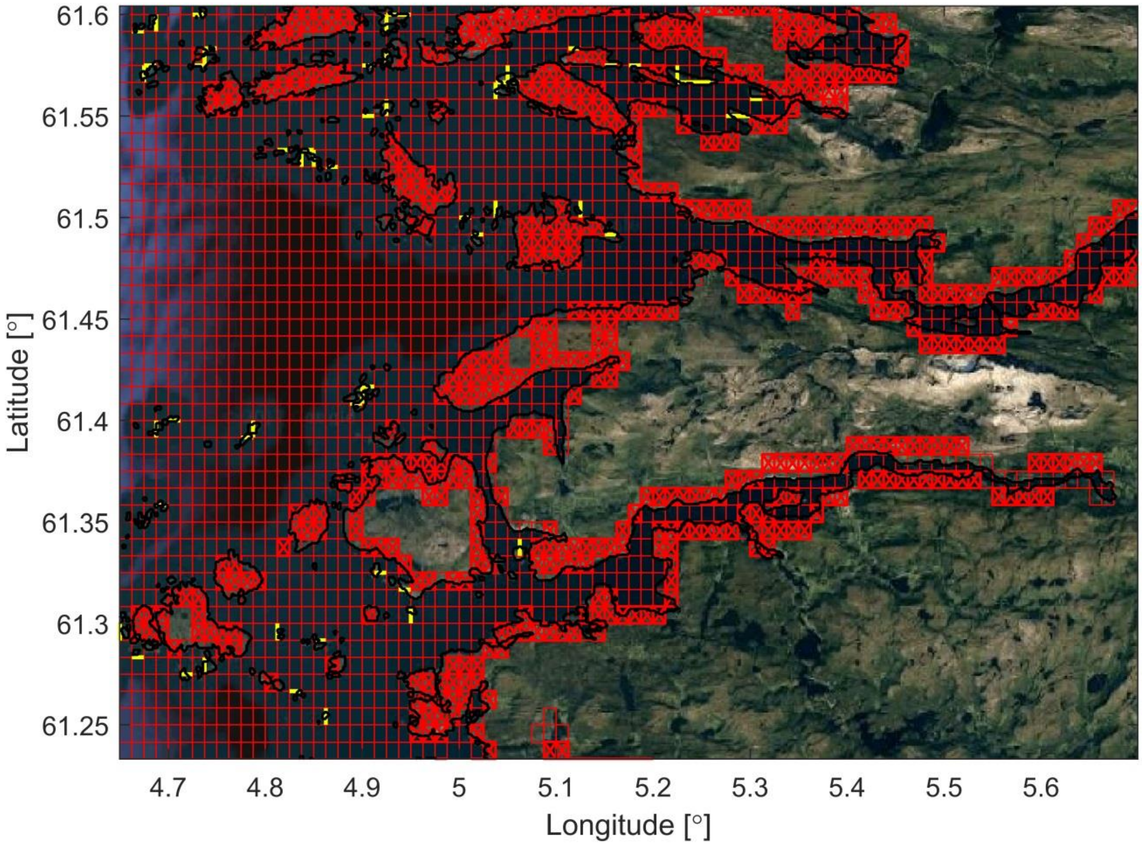

Figure 2.5 Overview of the computational grid (red), land-sea boundary (black), dry points (red crosses) and thin dams (yellow) in Norway.

In order to simulate the correct effect of estuaries on the hydrodynamics, not only certain automatically created dry points had to be removed but also additional grid cells were added to the model domain. Since the removal of grid cells outside the Dutch coastal waters was based on the availability of EMODnet data in the vicinity of the grid cell, some estuaries were not included in the model domain as no bathymetry data was available at these locations. Based on the land-sea boundary and Google Earth, the computational grid at the largest and most important estuaries that were not automatically incorporated in the model domain were manually added.

2.3.2 Dutch coastal waters

Within the Dutch coastal waters and some adjacent parts of the Belgian and German waters, the computational network, dry points, thin dams and fixed weirs (weirs with a constant crest level) are based on Baseline[1]. A so-called Baseline-projection was performed in which the geographical data from Baseline (*Nederland_6/j16_6-w4*) is projected on the computational grid. The resulting enclosure-file (an inverse dry-points-polygon), dry-points-polygons, thin dams and fixed weirs are used in the DCSM-FM 100m model schematization.

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[1] *Baseline is an ArcGIS plugin from Rijkswaterstaat (RWS), which is used by RWS to manage geographical data used in their numerical models.*

An example of the resulting computational grid (red), enclosure-polygon (thick red line), land-sea boundary (black), thin dams (yellow), fixed weirs (green) and general structures (blue) near Ijmuiden and the Eastern Scheldt are shown in resp. Figure 2.6 and Figure 2.7.

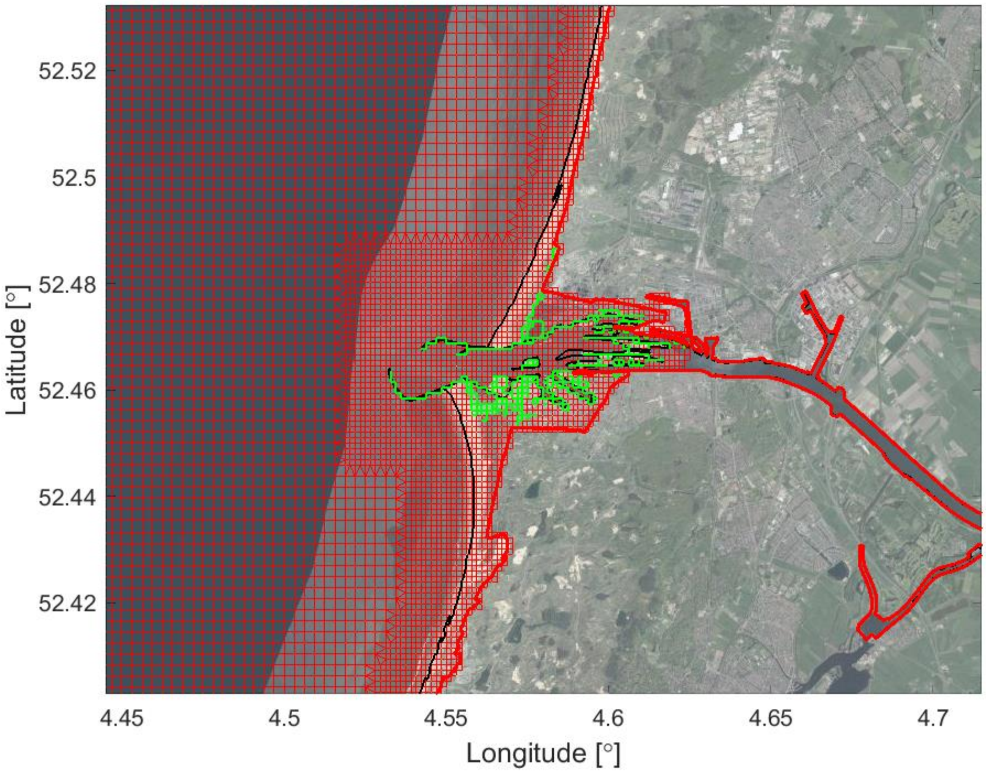

Figure 2.6 Overview of the computational grid (red), enclosure-polygon (thick red line), land-sea boundary (black), and fixed weirs (green) near IJmuiden.

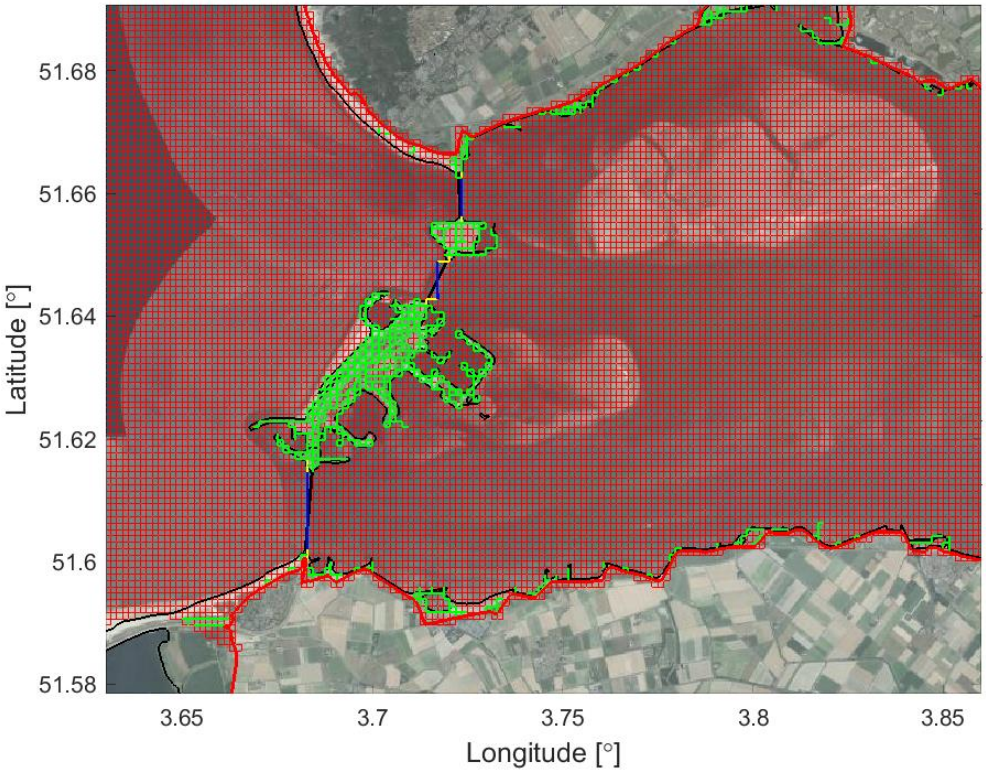

Figure 2.7 Overview of the computational grid (red), enclosure-polygon (thick red line), land-sea boundary (black), thin dams (yellow), fixed weirs (green) and general structures (blue) in the Eastern Scheldt.

Within the Dutch coastal waters, only minor adjustments have been made in the horizontal schematisation. As hydraulic structures are present in this model (see section 2.9.3), a few additional thin dams (indicated by yellow lines) were placed to prevent artificial leakage during a closure of one of the hydraulic structures. This can also be seen in the figure above, were the middle/second gate (structure Schaar) in the Eastern Scheldt Barrier would not correctly block the flow (together with the fixed weirs) without the imposed thin dams. While the actual barrier runs diagonally through the grid, it has been schematized in north-south direction, since diagonal barriers are not allowed in D-Flow FM.

Apart from the Eastern Scheldt Barrier, a few thin dams have been added to improve the schematisation of the breakwaters of the harbour of Zeebrugge, the Haringvliet sluices and the Maeslant Barrier.

2.4 Bathymetry

2.4.1 Outside the Dutch coastal waters

The DCSM-FM model bathymetry outside the Dutch coastal waters has been derived from a gridded bathymetric dataset (October 2016 version) from the European Marine Observation and Data Network (EMODnet; EMODnet Bathymetry Consortium, 2016), a consortium of organisations assembling European marine data, metadata and data products from diverse sources. The data are compounded from selected bathymetric survey data sets (single and multi-beam surveys) and composite DTMs, while gaps with no data coverage are completed by integrating the GEBCO 30’’ gridded bathymetry. The resolution of the gridded EMODnet dataset is 1/8’ x 1/8’ (approx. 160 x 230 m).

As the EMODnet bathymetry data (October 2016 version) is only provided relative to Lowest Astronomical Tide (LAT), this data needed to be converted to the Mean Sea Level (MSL) vertical reference plane to make it applicable for DCSM-FM. The LAT-MSL relation was derived from a 19-year tide-only simulation (calendar years 2005 to 2023) with the previous generation DCSMv6. The long duration is required to capture an entire 18.6-year nodal cycle. More information on the LAT-MSL realization and the bathymetry-interpolation procedure can be found in the DCSM-FM 0.5nm report (Zijl & Groenenboom, 2019).

2.4.2 Dutch coastal waters

The bathymetry in the Dutch coastal waters is, were available, based on Baseline-data. The result of the bathymetry-interpolation procedure as described in section 2.4.1 and the Baseline-projection are merged using a few processing and scripting steps. This was needed since the Baseline application only works with a network in the local Dutch coordinate system (Amersfoort / RD New, EPSG: 28992) whereas the DCSM-FM grid is in spherical WGS84 coordinates. Next to this, there was no complete coverage of available bathymetry data in offshore Dutch waters. The applied procedure results in a model bathymetry that is, where available, based on Baseline (vertically referenced to NAP) in the Dutch coastal waters and on EMODnet (referenced to MSL) elsewhere.

2.4.3 Adjustments and final bathymetry

In some locations the lower water levels where erroneously affected by the local model bathymetry. This can result in artificial drying during low waters (upper plot Figure 2.8), but also when this is not the case the impact of schematization errors in the bathymetry (due to e.g. local coarseness of the network) can be noticeable (lower plot Figure 2.8). Where this cannot be resolved by moving the station location by one or two cells, the local bathymetry has been adjusted in the immediate vicinity. These manual steps were only performed in foreign stations where a solution was possible with the adjustment of only a few cells.

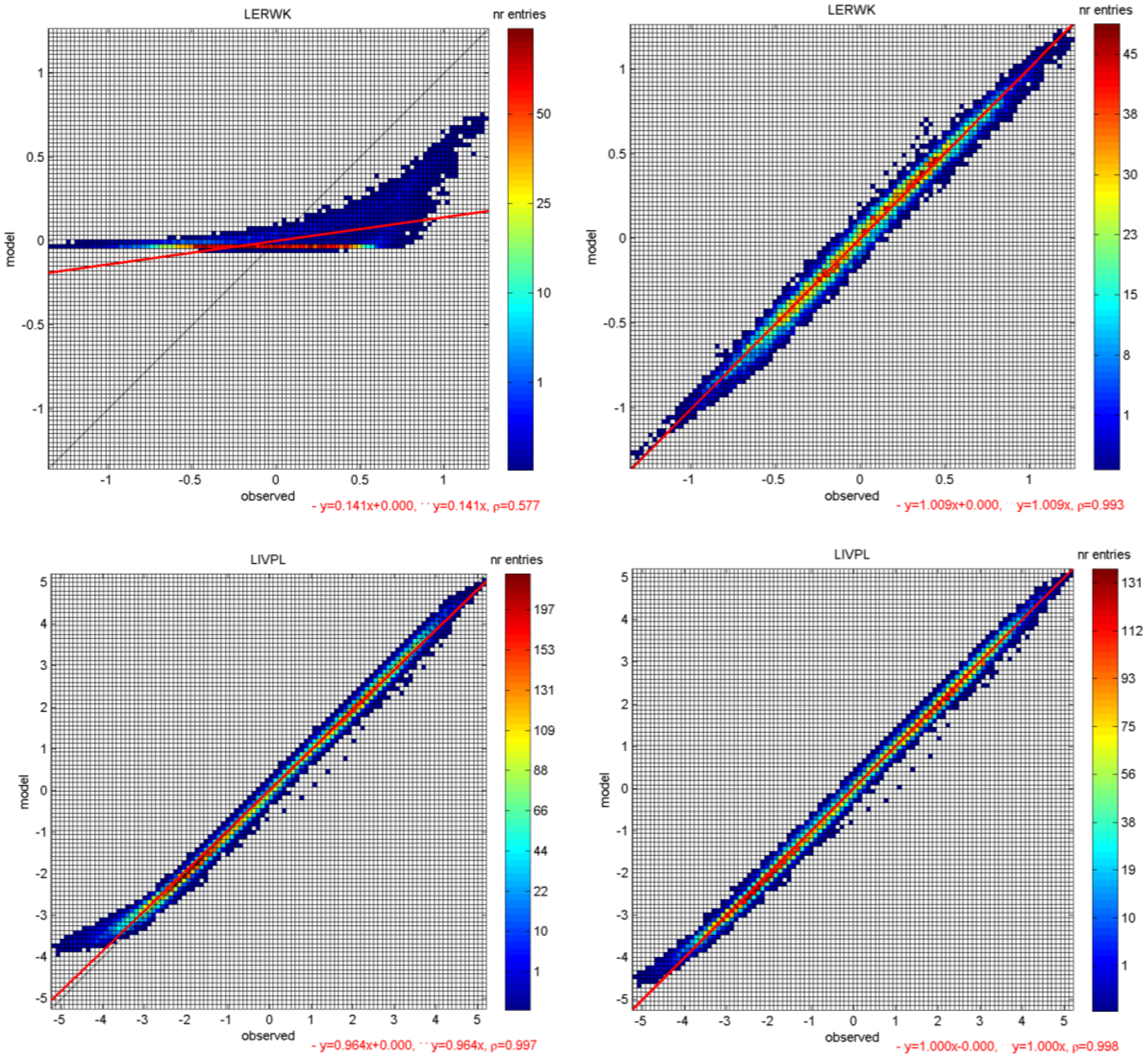

Figure 2.8 Scatter plots of the measured (horizontal) and modelled (vertical) water level before (left) and after (right) manual adjustment of the local bathymetry (upper plot: Lerwick; lower plot: Liverpool)

All net nodes that are still missing a z-coordinate are assigned the value prescribed with the keyword *Bedlevuni*, in this case prescribed to be 5 m.

The model bathymetry is specified on the net nodes. Depths at the middle of the cell edges (the velocity points) are set to be determined as the mean value of the depth at the adjacent nodes. Depths at the location of the cell face (the water level points) are specified to be determined as the minimum of the depth in the surrounding cell edges. These bathymetry interpolations options are prescribed by setting *bedlevtype=3*.

An overview of the resulting DCSM-FM model bathymetry is presented in Figure 2.9. This shows that depths of more than 2000 m occur in the northern parts of the model domain, with depths exceeding 5000 m in the south-western part. The North Sea is much shallower with depths rarely exceeding 100 m in the central and southern part (Figure 2.10). In Figure 2.11 a detail of the DCSM-FM model bathymetry is shown focussing on the southern North Sea. In the southern North Sea depths are generally less than 50 m.

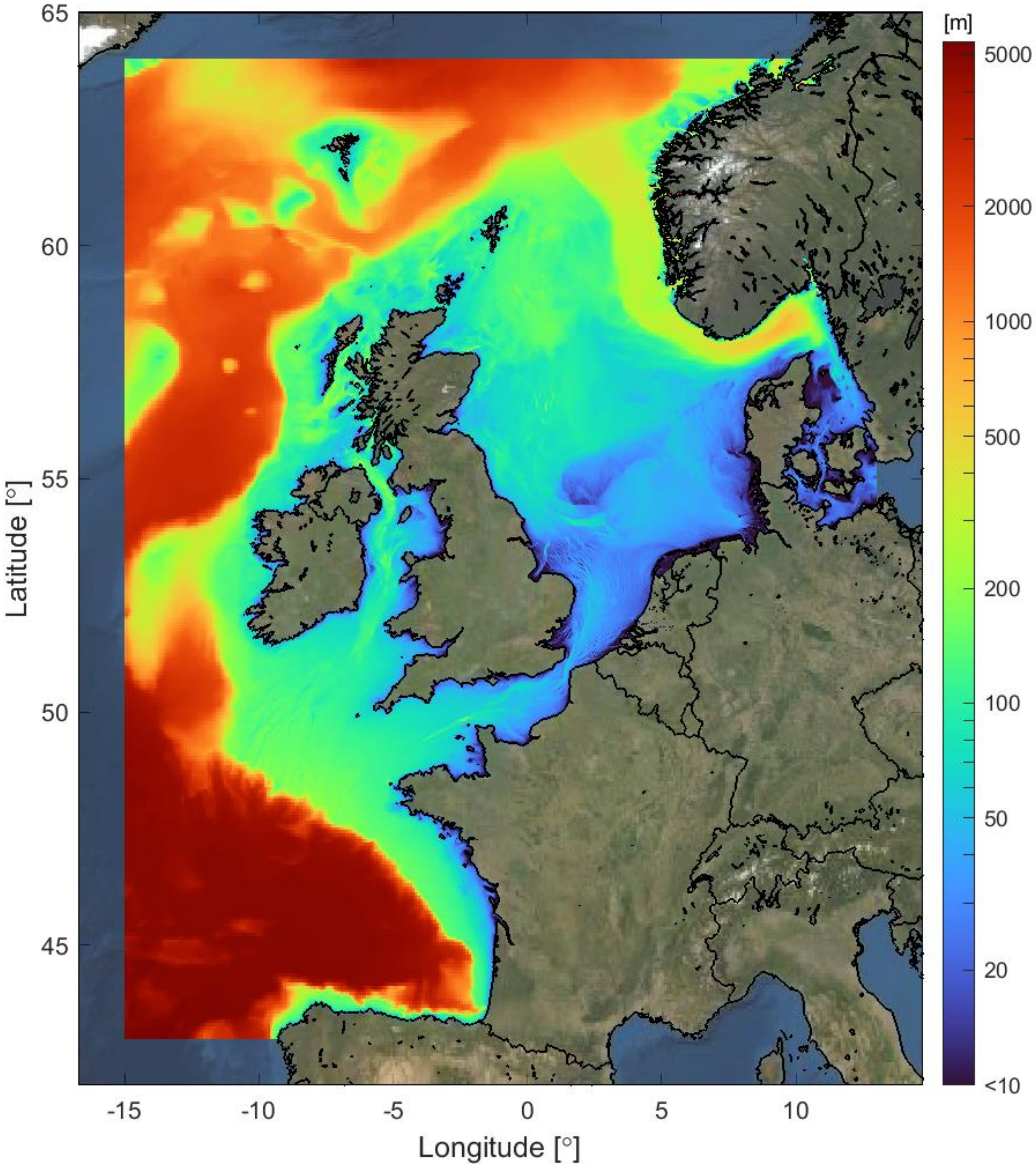

Figure 2.9 Overview of the DCSM-FM model bathymetry (depths relative to MSL on a logarithmic scale).

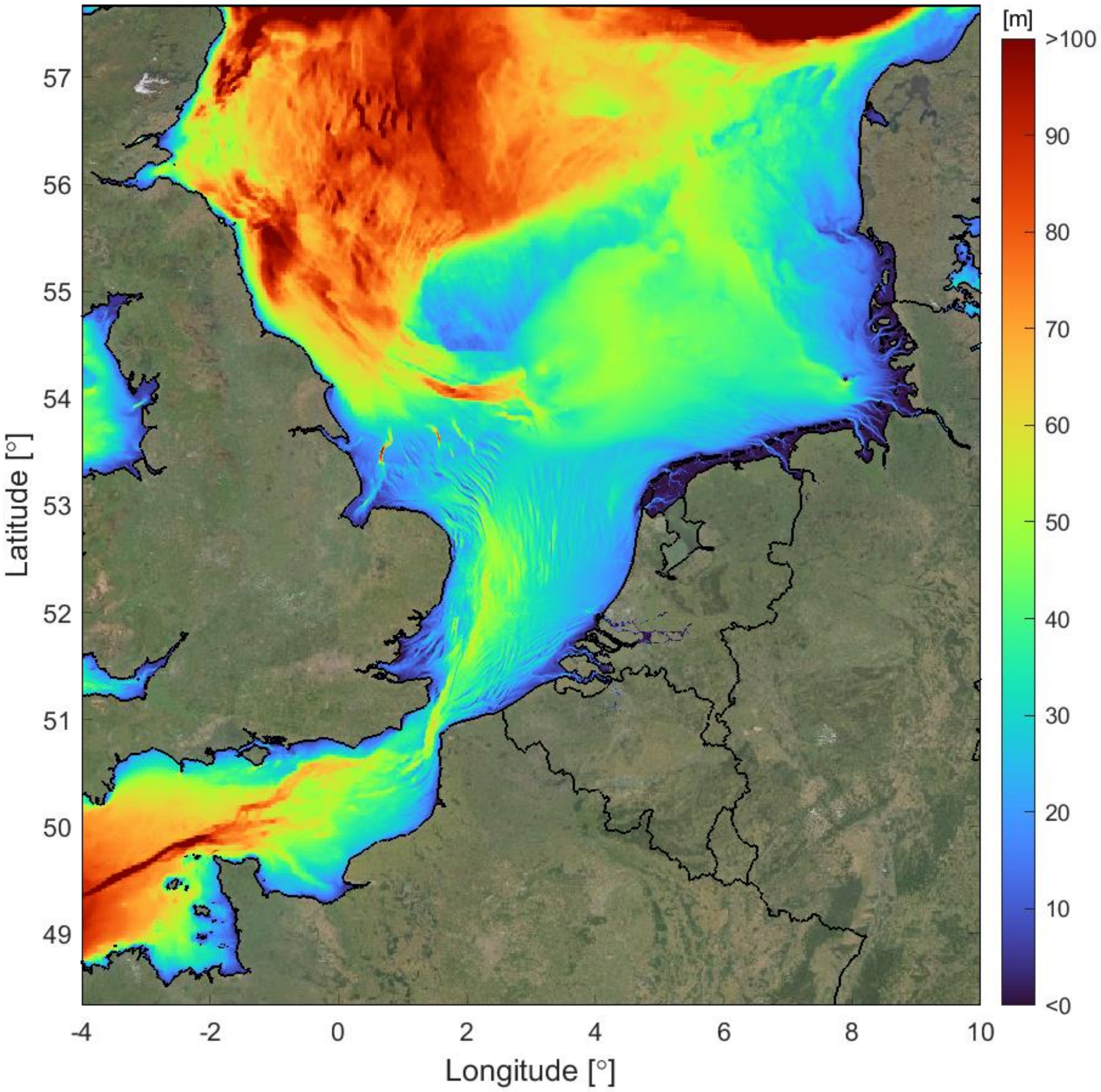

Figure 2.10 DCSM-FM model bathymetry in the central and southern North Sea (depths relative to MSL).

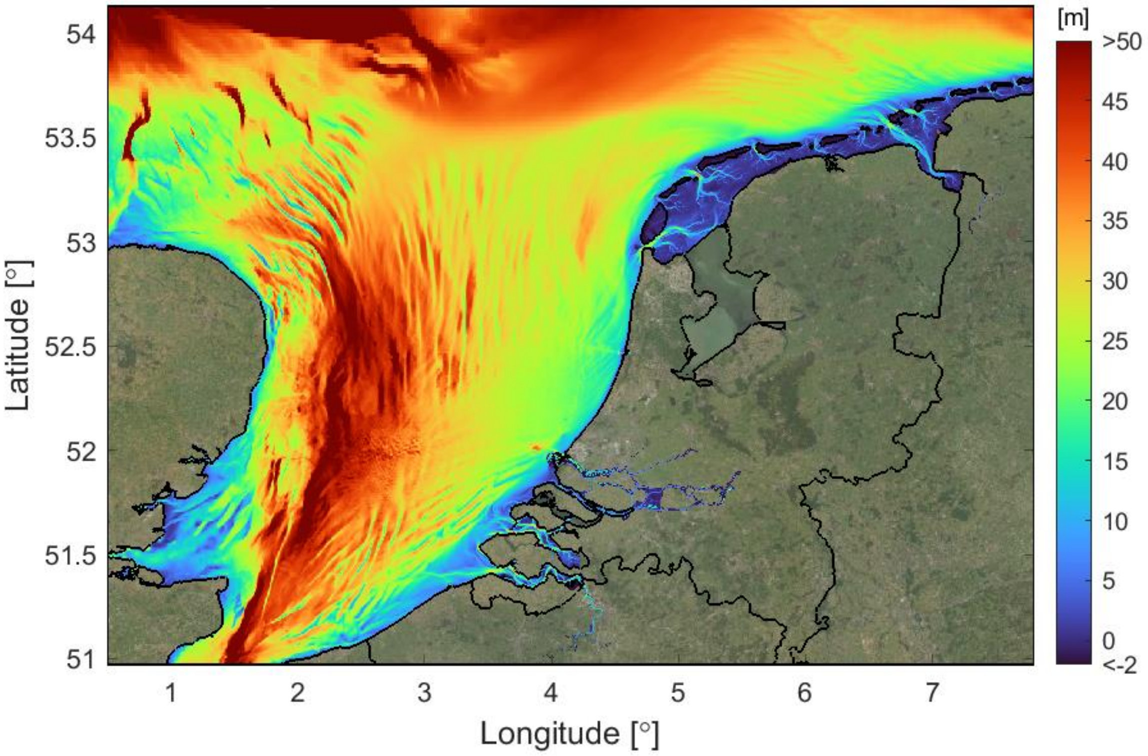

Figure 2.11 DCSM-FM model bathymetry in the southern North Sea (depths relative to MSL).

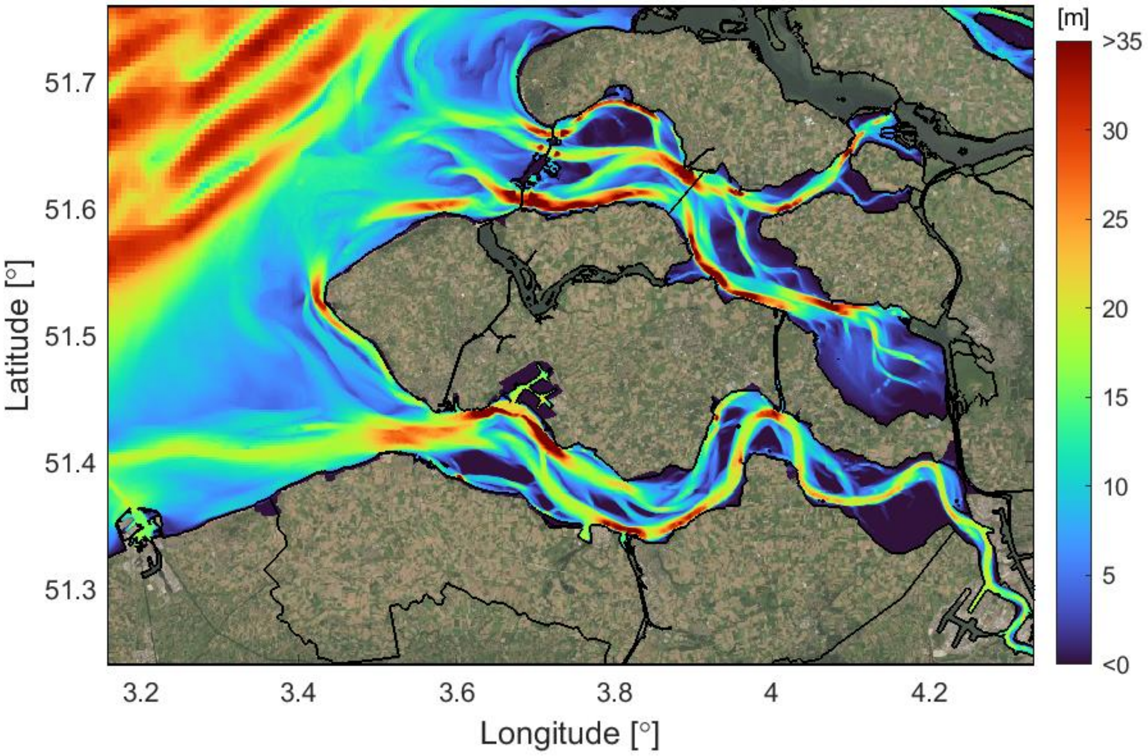

Figure 2.12 DCSM-FM model bathymetry in the South-western Delta (depths relative to MSL).

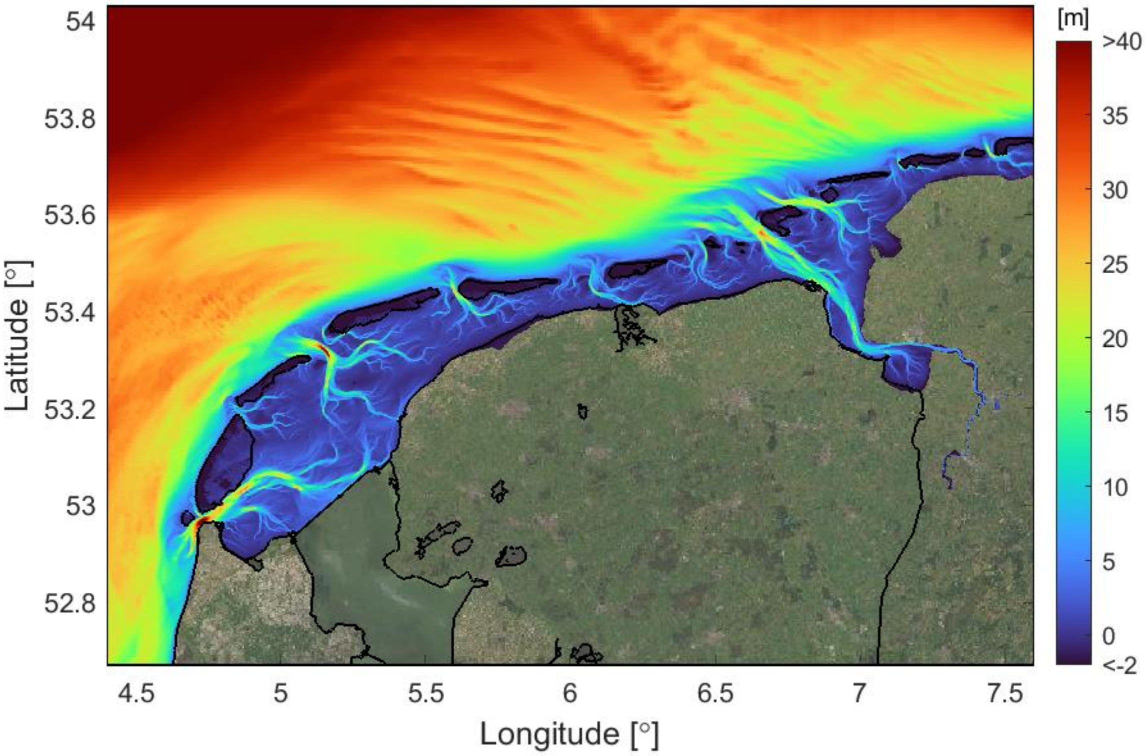

Figure 2.13 DCSM-FM model bathymetry in the Wadden Sea and Ems-Dollard (depths relative to MSL).

2.5 Bottom roughness

To account for the effect of bottom friction, a uniform Manning roughness coefficient of 0.028 s/m$^{1/3}$ was initially applied. During the model calibration (see Chapter 4) this value was adjusted to obtain optimal water level representation. The resulting roughness fields are presented in Figure 2.14 and Figure 2.15. The minimum and maximum bottom roughness values applied are 0.012 s/m$^{1/3}$ and 0.050 s/m$^{1/3}$.

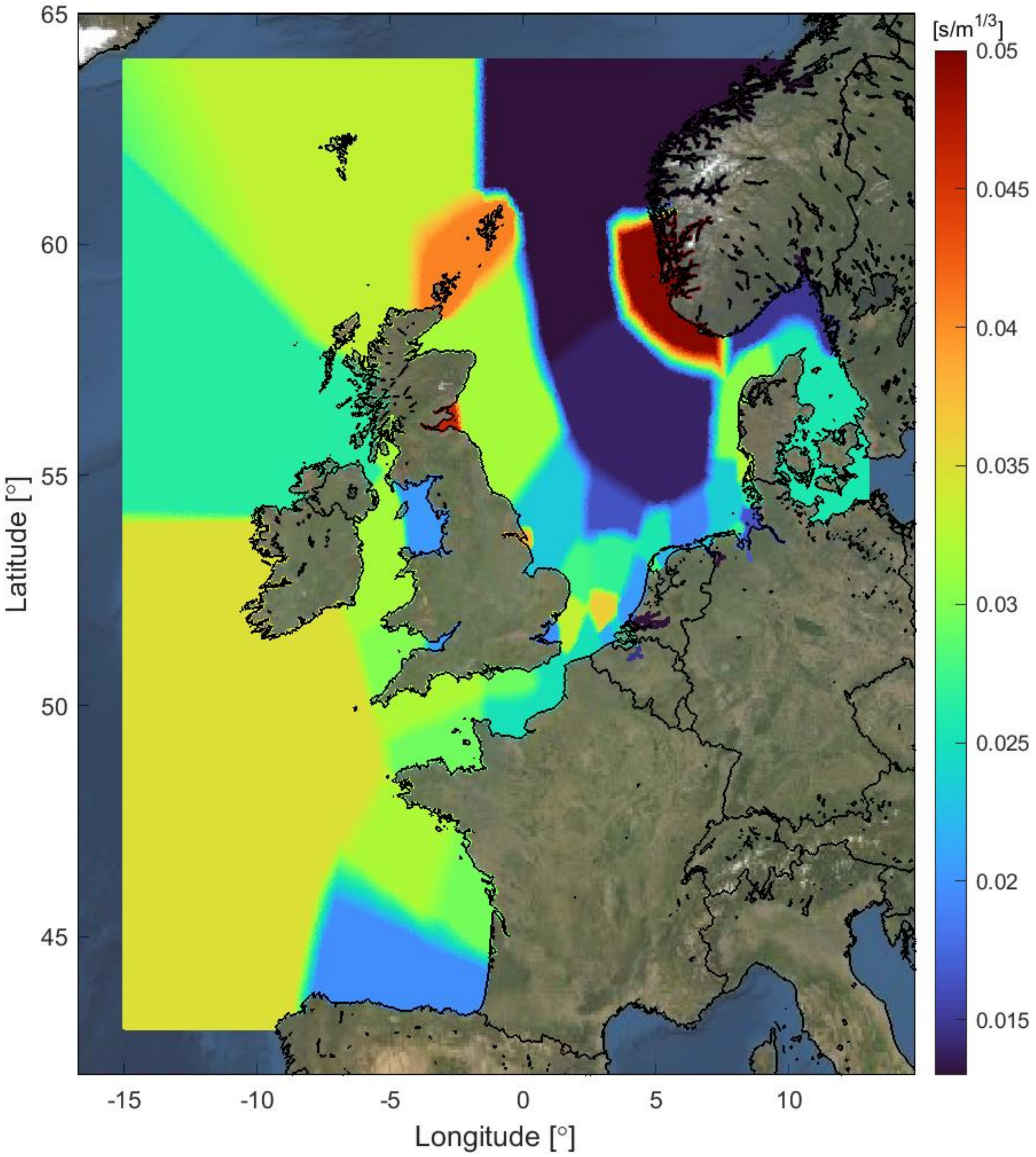

Figure 2.14 Overview of the space-varying Manning bottom roughness field of DCSM-FM 100m.

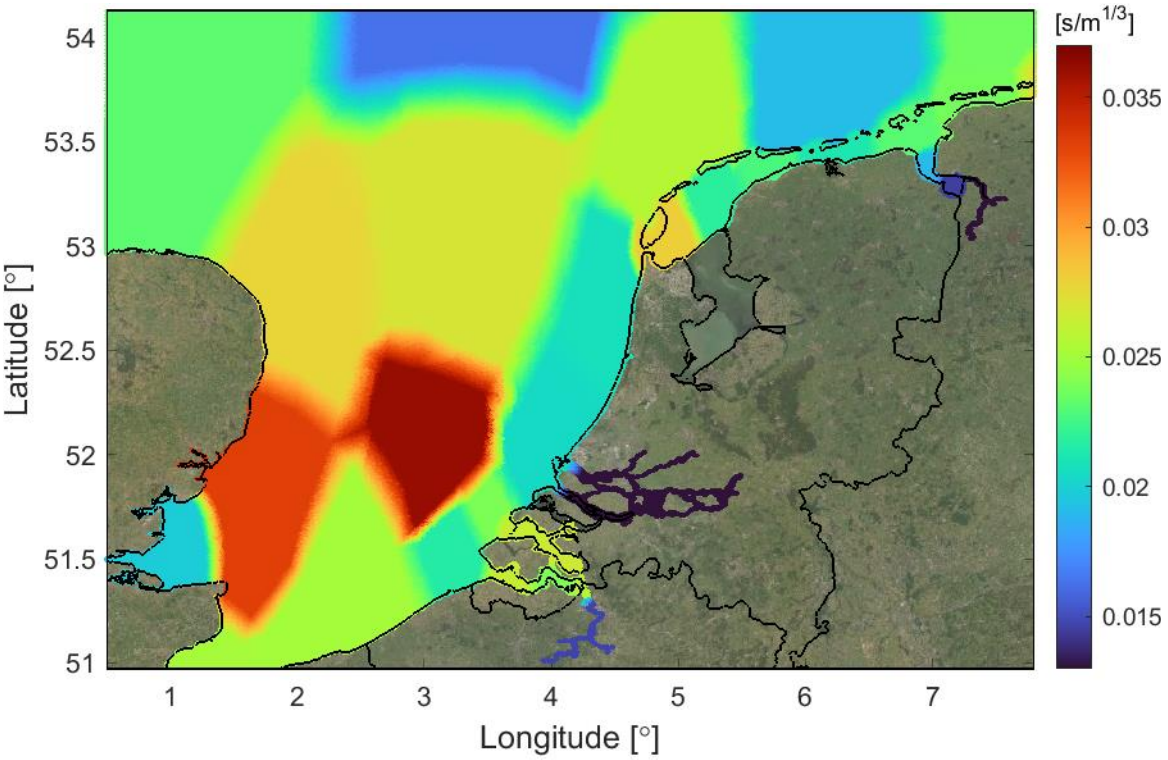

Figure 2.15 Detail of space-varying Manning bottom roughness field of DCSM-FM in Dutch waters.

Vegetation-based bed roughness

In some Dutch and Belgian waters roughness values have been based on detailed land use and resistance classes from the Baseline database. These roughness values are unaffected by the calibration. The trachytope-codes that would describe a uniform value in the deeper waters (with e.g. description ‘diepe bedding’ and ‘diepe getijdewater’) have been removed from the model input.

The trachytopes used depicted in Figure 2.16. Figure 2.17 shows the trachytopes in the Southwestern Delta in more detail. Note that in the Western Scheldt, only the roughness at the intertidal areas and land are now determined based on the prescribed trachytopes.

The land use in each computational cell can be described by a combination of several trachytope-codes. In case a cell uses a trachytope-code that was removed from the dataset, a uniform roughness value of 0.028 s/m$^{1/3}$ is used to complete the input for this cell. Trachytope-codes that indicate ‘buildings’ were found at the location of the Eastern Scheldt Barrier and this resulted in significant decrease of flow through this structure. These values were also removed from the model input.

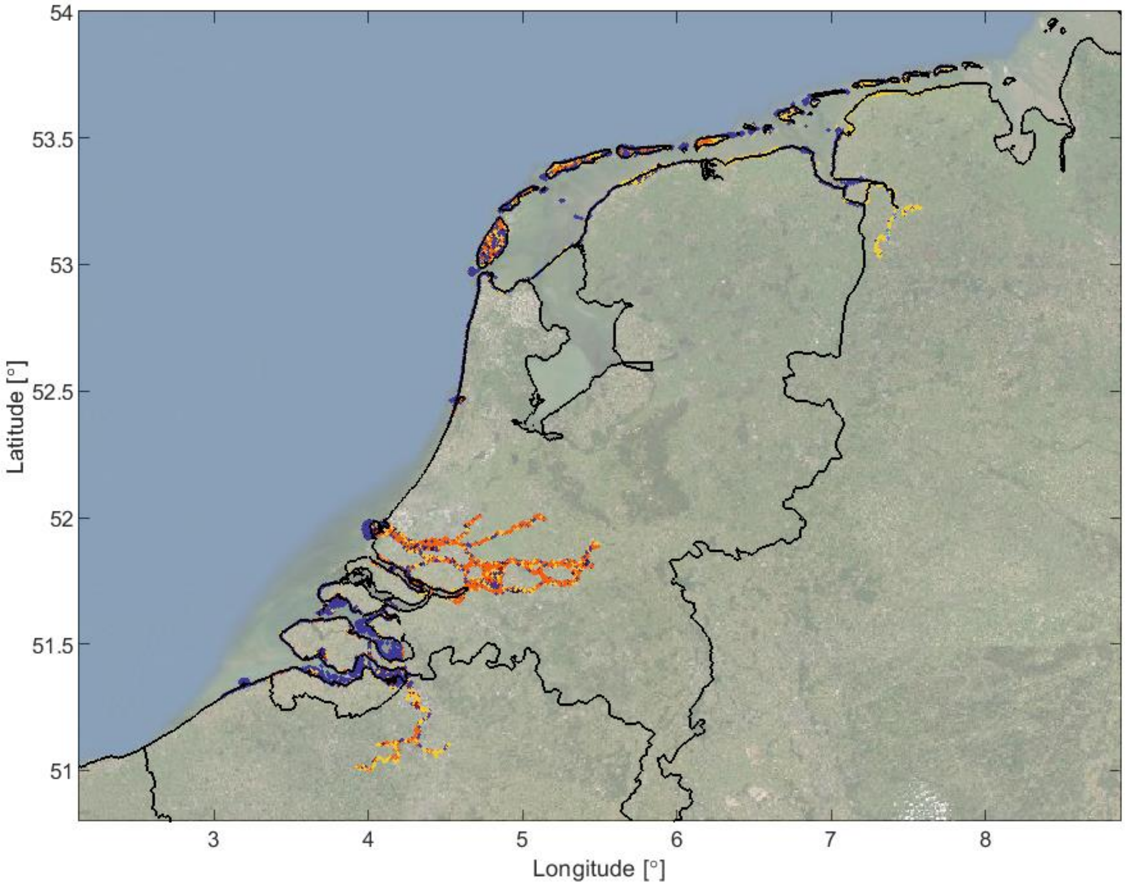

Figure 2.16 Overview of trachytopes codes used (indicated by colour) in DCSM-FM 100m

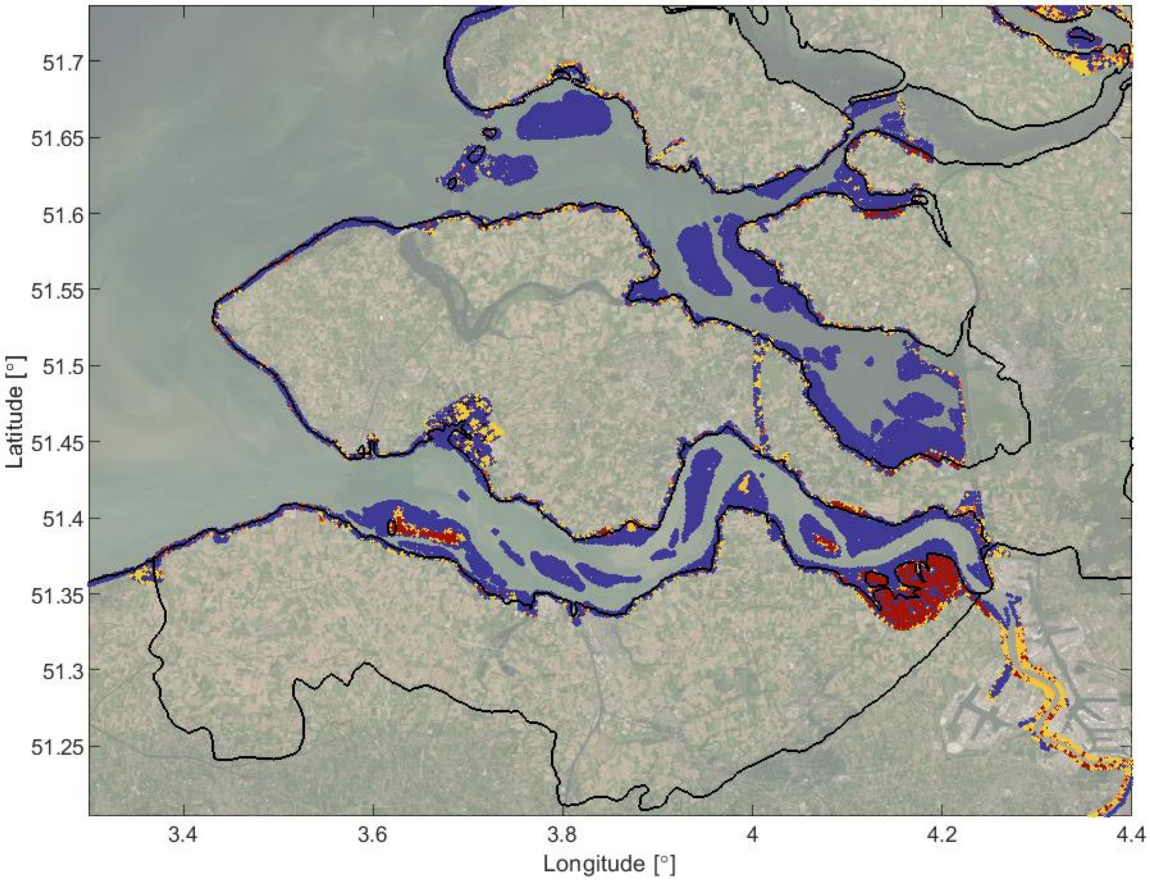

Figure 2.17 Overview of trachytopes codes used (indicated by colour) in DCSM-FM 100m in the Southwestern Delta

2.6 Open boundary conditions

At the northern, western and southern sides of the model domain, open water level boundaries are defined. Water levels are specified at 209 different locations along those boundaries. In between these locations the imposed water levels are interpolated linearly.

Tide

At the northern, western and southern sides of the model domain, open water level boundaries are defined. The tidal water levels at the open boundaries are derived by harmonic expansion using the amplitudes and phases of 32 harmonic constituents (Table 2.1). All except one were obtained from the global tide model FES2012[2], which provides amplitudes and phases of 32 constituents on a 1/16° grid. Of these only MKS2 is not used, since inclusion in the boundary forcing resulted in a deterioration of results.

In addition to the above, the solar annual constituent Sa has also been added based on what was used in DCSMv6 (see Figure 2.18). Even though in the ocean Sa is much less gravitational than meteorological and baroclinic in nature, in the absence of baroclinic forcing it is required to reproduce the observed residual annual cycle, i.e. the signal not captured by annual mean

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[2] More information on the Finite Element Solution (FES) tide model can be found on: https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2012.html

sea-level pressure and wind variations and notably the seasonal temperature cycle. While this is negligible on the shelf, this is less so in the deep ocean.

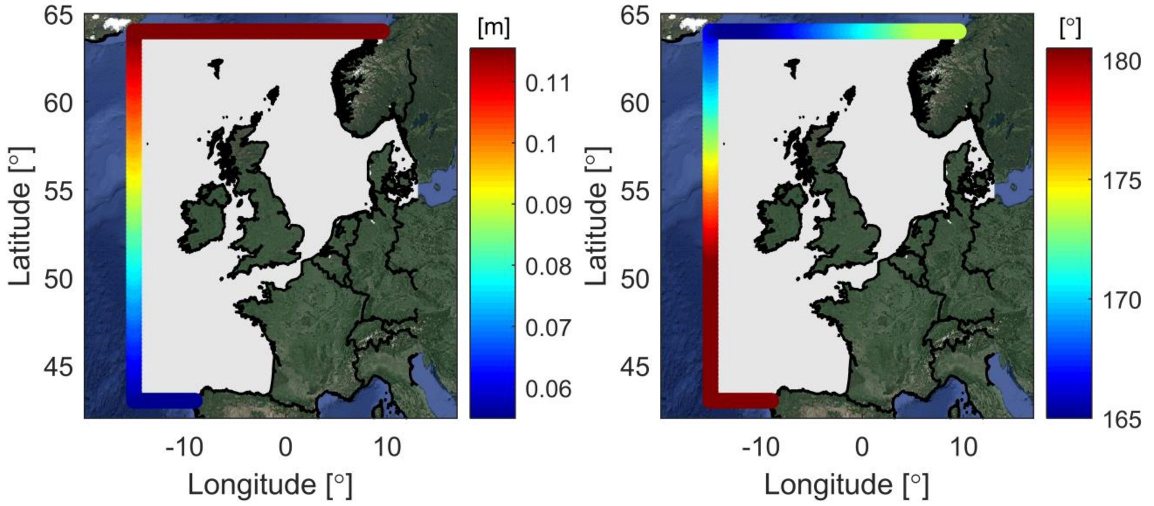

Figure 2.18 Amplitude (left panel) and phase (right panel) of the Sa-component along the open boundaries of the model domain

Table 2.1 Overview of the tidal components prescribed at the open boundaries of DCSM-FM, including their angular frequency (°/h).

Component name	Angular frequency (°/h)	Component name	Angular frequency (°/h)
SA	0.0410686	M2	28.9841042
SSA	0.0821373	LABDA2	29.4556253
MM	0.5443747	NU2	28.5125831
MF	1.0980331	L2	29.5284789
MSF	1.0158958	T2	29.9589333
MFM	1.6424078	S2	30.0000000
Q1	13.3986609	R2	30.0410667
O1	13.9430356	K2	30.0821373
P1	14.9589314	M3	43.4761563
S1	15.0000000	M4	57.9682084
K1	15.0410686	MN4	57.4238337
J1	15.5854433	MS4	58.9841042
MNS2	27.4238337	S4	60.0000000
2N2	27.8953548	M6	86.9523126
MU2	27.9682084	M8	115.9364168
N2	28.4397295		

In the D-HYDRO software the specified amplitudes and phases are converted into timeseries covering the required period by means of harmonic prediction. Implicitly it is assumed that the nodal cycle at the location of the open boundaries can be obtained from the equilibrium tide. The validity of this assumption is corroborated by Zijl (2016b).

Surge

While wind setup at the open boundary can arguably be neglected because of the deep water locally (except near the shoreline), the (non-tidal) effect of local pressure will be significant. The impact of this is approximated by adding an Inverse Barometer Correction (IBC) to the tidal water levels prescribed at the open boundaries. This correction is a function of the time- and space-varying local air pressure.

One can also consider nesting in a model with a larger domain, e.g. a global model. This would also account for the differences due to the mean pressure over the global ocean, which is now assumed to be constant (PavBnd = 101330 N/m^2), but in reality varies in time.

2.7 Meteorological forcing

For meteorological surface forcing of the model the KNMI provided time- and space-varying wind speed (at 10 m height) and air pressure (at MSL) from the Numerical Weather Prediction (NWP) high-resolution limited area model (HiRLAM v7.2). This meteorological model has a spatial resolution of approximately 11 km by 11 km, and a temporal output interval of 1 hour. The wind stress at the surface, associated with the air-sea momentum flux, depends on the square of the local U10 wind speed and the wind drag coefficient, which is a measure of the surface roughness.

To translate wind speed to surface stresses, the local wind speed dependent wind drag coefficient is calculated using the Charnock formulation (Charnock, 1955). The empirically derived dimensionless Charnock coefficient has been set to a constant value of 0.025, which corresponds to the value used in the HiRLAM meteorological model. The resulting wind drag coefficients are shown in Figure 2.19 as a function of the 10 m wind speed.

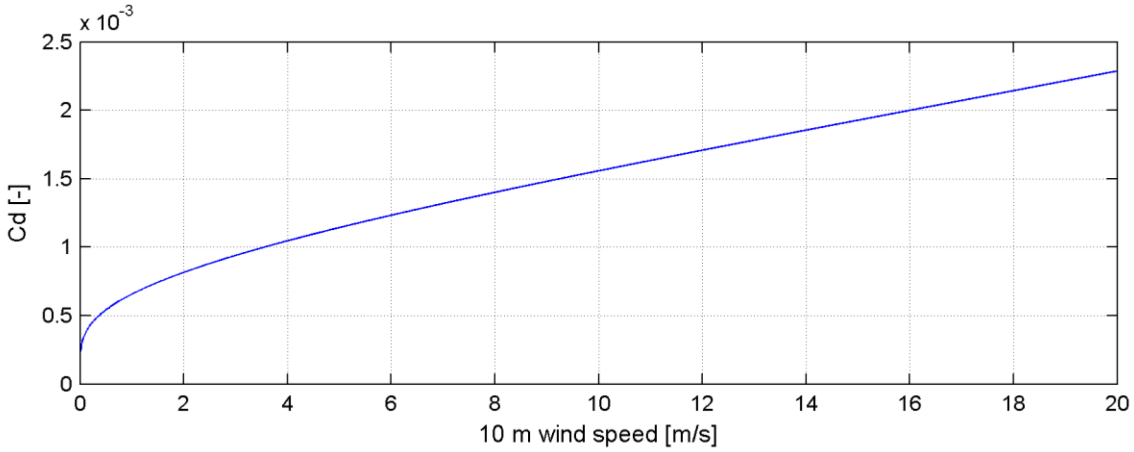

Figure 2.19 Wind drag coefficient (Cd) as a function of the 10 m wind speed, using a Charnock relation with a Charnock parameter of 0.025.

While the calibration and validation as presented in the present report have been performed with HiRLAM v7.2 meteorological forcing, the model can be forced with different meteorological model output. The forcing parameters have then to be adjusted accordingly. For example, in the operational ECMWF meteorological model (IFS or HRES), the Charnock coefficient is dependent on wind waves (as forecasted with the ECMWF WAM model) and consequently time and space dependent. This implies that when using ECMWF IFS forcing, the Charnock coefficient also has to be prescribed in a time-and space dependent manner.

Relative wind effect
In most wind drag formulations the flow velocity is not taken into account in determining the wind shear stress (i.e., the water is assumed to be stagnant). Even though the assumption of a stagnant water surface is common because it makes computing stresses easier, from a physical perspective the use of relative wind speed makes more sense since all physical laws deal with relative changes. In case the flow of water is in opposite direction to the wind speed, this would contribute to higher wind stresses (and vice-versa). The impact of the water velocity on the wind stress at the surface, and consequently also on computed water levels, is indicated with the name ‘Relative Wind Effect’ (RWE).

In general, including RWE leads to a meaningful improvement in (skew) surge quality during calm conditions (see Appendix C of the DCSM-FM 0.5nm report (Zijl & Groenenboom, 2019)). Apparently, RWE adds an effect that cannot fully be incorporated by adjusting the bottom roughness instead. Even though inclusion comes at a cost of an increased systematic underestimation during the two most extreme skew surge events of 1-3 cm, it was decided to include RWE in the final DCSM-FM model schematization. Note that when the wind stress is prescribed directly, this requires switching off the RWE, which would have an adverse effect on the quality of both the surge and tide representation.

2.8 Numerical settings

2.8.1 Theta0

The implicitness of the numerical time integration is specified with the parameter *Teta0*, with *Teta0=1* being fully implicit and *Teta0=0* fully explicit. In accordance with Minns et al. (2019) the value of *Teta0* is set to 0.55.

2.8.2 Time step

D-Flow FM automatically limits the time step to prevent numerical instabilities. Since the computation of the advective term is done explicitly in D-Flow FM, the time step limitation is related to the Courant criterion. In accordance with Minns et al. (2019) the maximum Courant number is set to 0.7. The maximum computational time step has been set to 50 s.

2.9 Miscellaneous

2.9.1 Tidal potential

The tidal potential representing the direct body force of the gravitational attraction of the moon and sun on the mass of water has been switched on. It is estimated that the effect of these Tide Generating Forces (TGF) has an amplitude in the order of 10 cm throughout the model domain. Components of the tide with a Doodson number from 55.565 to 375.575 have been included.

2.9.2 Horizontal viscosity

The horizontal viscosity is computed with the Smagorinsky sub-grid model, with the coefficient set to 0.2. The use of a Smagorinsky model implies that the viscosity varies in time and space and is dependent on the local cell size. With the exception of a two nodes wide strip along the open boundaries a background value of 0.1 m^2/s is specified. Along the open boundaries a background value of 2000 m^2/s has been used (see Appendix D of the DCSM-FM 0.5nm report (Zijl & Groenenboom, 2019)).

In Zijl et al. (2016) it is concluded that the computed water levels in the North Sea are hardly affected by the use of the Smagorinsky sub-grid model. It is therefore expected that the sensitivity of the water level for the Smagorinsky coefficient is negligible. The impact on currents or the salinity distribution can be larger. The latter is not taken into account in the present model setup.

2.9.3 Movable barriers

There are several movable barriers in the model area, such as the Thames Barrier, the Ems Barrier, the Eastern Scheldt Barrier and the Maeslant Barrier. These barriers protect the hinterland from flooding by closing in case of high water is forecasted. The barriers currently implemented in the model are the Eastern Scheldt Barrier (see Figure 2.20), the Hartel Barrier, the Maeslant Barrier and the Ems Barrier. The Thames Barrier is not included as it has a negligible effect on water levels in the Netherlands and doesn’t have the area upstream of the barrier sufficiently included in this model.

2.9.3.1 Eastern Scheldt Barrier

The Eastern Scheldt Barrier consists of 62 separate gates divided over three sections (from north to south: Hammen, Schaar van Roggenplaat and Roompot). These sections are separately schematized in the model. While in reality the Schaar van Roggenplaat section runs diagonally through the network, it has been schematized in north-south direction, since diagonal barriers are not allowed in D-Flow FM (see also section 2.3.2).

The modelled sill height in each of these three sections is taken to be the average of the sill heights within this section: NAP -5.75 m, NAP -6.32 m and NAP -8.60 m. The energy loss coefficients are taken from the sixth-generation Oosterschelde model (Tiessen et al., 2019) and have a value of 0.93 and 1.03 for ebb and flood currents, respectively. Next to the crest level, additional vertical levels are needed for the general structure description (keywords *Upstream1Level*, *Upstream2Level*, *Downstream1Level* and *Downstream2Level*). Directly upstream/downstream of the structure, a level of “crest level minus 5 cm” is applied. One step further upstream/downstream a level of “crest level minus 10 cm” is used.

The schematization of the three sections of the Eastern Scheldt Barrier on the model grid are shown in Figure 2.20. In this figure, the computational network (red), enclosure-polygon (thick red line), thin dams (yellow), fixed weirs (green) and the barrier sections (blue) are shown. The cross-sectional area of the barriers follows from a prescribed gate door height and width. These values are listed in Table 2.2. The width of each of the sections is the summed width of the individual gates in each section.

Table 2.2 Gate door height, width and sill height of the three sections of the Eastern Scheldt Barrier

Section	Gate door height [m]	Width [m]	Sill height [m MSL]
Schaar	11.27	632.00	-5.75
Hammen	11.63	592.50	-6.32
Roompot	14.11	1224.50	-8.60

In the coarser DCSM-FM 0.5nm, the width of the sections needed to be adjusted as the desired results could not be achieved by only adjusting the bottom friction during the calibration. The expectation was that this was related to the coarseness of the model schematization in this area. In the DCSM-FM 100m model, with a much higher resolution at the eastern Scheldt Barrier, adjusting the width of the sections was not required to obtain the desired model results.

The effect of the structures on the cross-sectional area at each of the structures is controlled by a timeseries of the gate lower edge level of the three sections (data provided by Rijkswaterstaat). These timeseries are corrected for the presence of a horizontal concrete beam at 1.0 m (Roompot en Schaar) and 0.8 m (Hammen) above NAP. As the water level at this location sometimes exceeds this vertical level, the flow is partially blocked near the surface. During a closure, see Figure 2.21, the gate lower edge level is almost lowered to the sill height. The timeseries of the gate lower edge level are averaged over the individual gates in each section. The data is corrected for leakage of the hydraulic structure and therefore the gate lower edge level remains above the sill height.

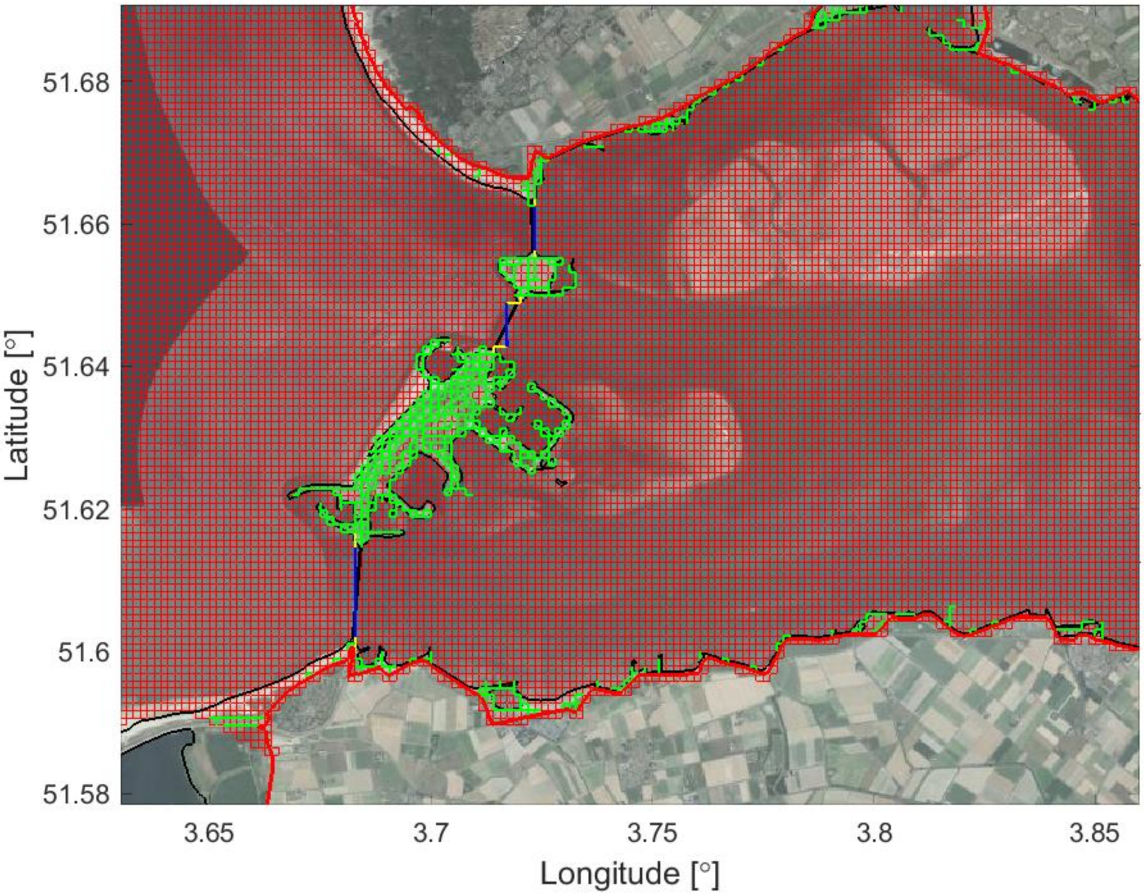

Figure 2.20 Implementation of the Eastern Scheldt Barrier in DCSM-FM 100m (red lines: computational network; red thick line: enclosure-polygon; yellow lines: thin dams; green lines: fixed weirs and blue lines: movable barriers).

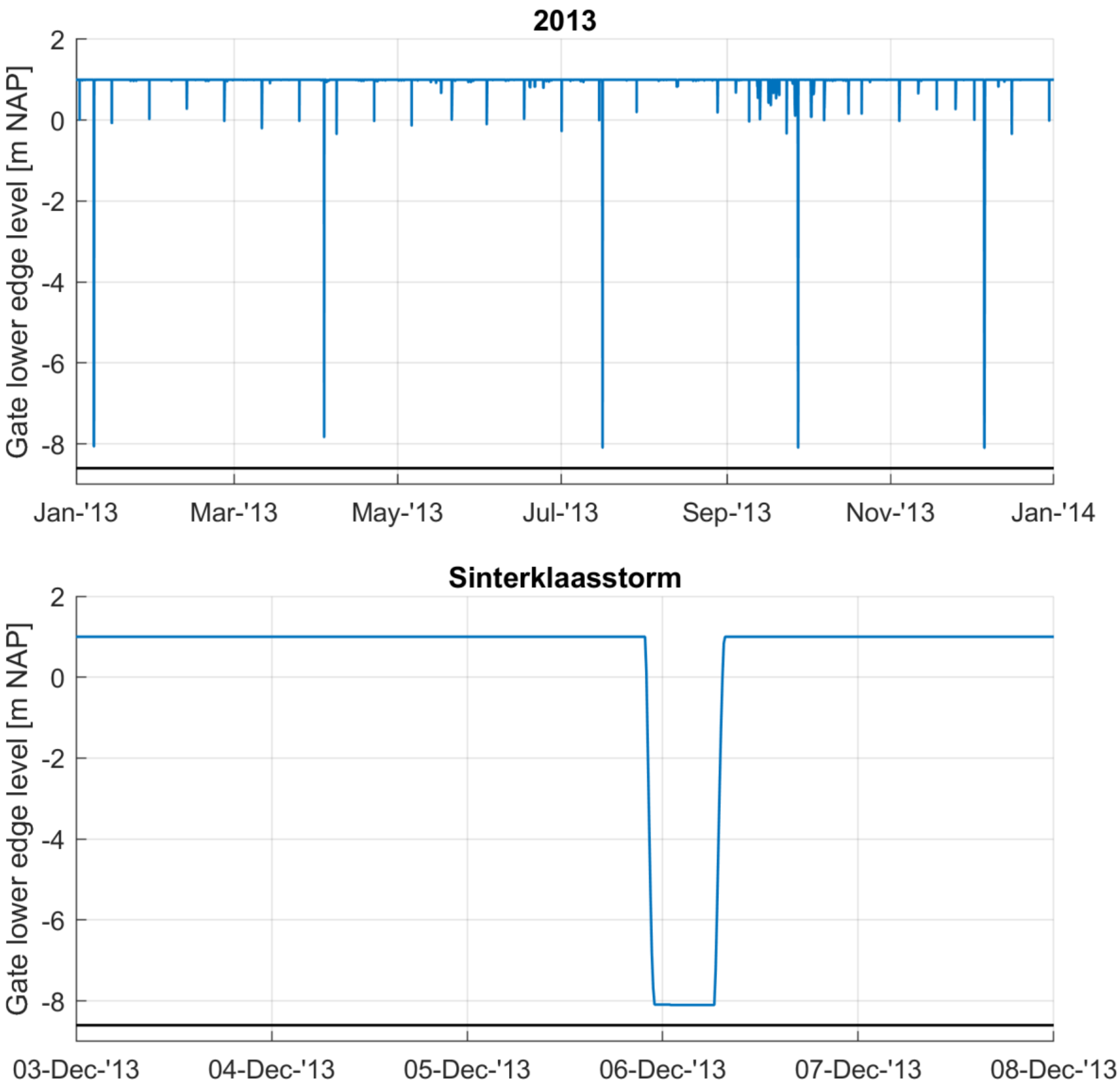

Figure 2.21 Timeseries of the gate lower edge level (in m NAP) of the Eastern Scheldt Barrier section Roompot for year 2013 (top panel) and during the so-called Sinterklaasstorm (lower panel). The black line indicates the sill height of the structure (-8.60 m NAP)

2.9.3.2 Hartel Barrier, Maeslant Barrier and Ems Barrier

The gate door height, width and sill height of the Hartel Barrier, Maeslant Barrier and Ems Barrier are shown in Table 2.3. The prescribed width of the structure is the sum of the individual gates.

Table 2.3 Gate door height, width and sill height of the three sections of the Hartel Barrier, Maeslant Barrier and Ems Barrier

Structure	Gate door height [m]	Width [m]	Sill height [m MSL]
Hartel Barrier	9.50	142.30	-6.50
Maeslant Barrier	22.00	360.00	-17.00
Ems Barrier	15.00	414.00	-7.00

The doors of the Maeslant Barrier can move in multiple directions. The doors will move horizontally during turning into the canal and vertically when lowering into the water. Therefore, both the gate lower edge level and gate opening width are described by a timeseries.

The timeseries of the closure of the Ems Barrier were not available and are therefore derived from the observed water levels upstream of this structure.

2.9.4 Initial conditions and spin-up period

As the spin-up period for tidal models of this scale are not prohibitively large (10 days is assumed to be sufficient), a uniform initial water level of zero elevation has been specified for the calibration and validation computations. For the initial velocity, stagnant flow conditions have been prescribed. Operationally, the initial model state will be taken from previous hindcast computations (i.e., a so-called warm state).

2.9.5 Time zone

The time zone of DCSM-FM is GMT+0 hr. This means that the phases of the harmonic boundary conditions and the tidal potential are prescribed relative to GMT+0 hr. As a result, the model output is in the same time zone. This time zone is the same as in the previous (fifth) generation DCSMv6 and DCSMv6-ZUNOv4 models.

2.9.6 Observation points

Since the North Sea is one of the most intensively monitored seas in the world, water level observations are readily available. An overview of the more than 200 tide gauge stations available for calibration and validation are presented in Figure 2.22 (for the entire domain) and Figure 2.23 (Dutch and Belgian stations).

If locations are just outside the model grid, they are manually placed in the closest cell with sufficient depth.

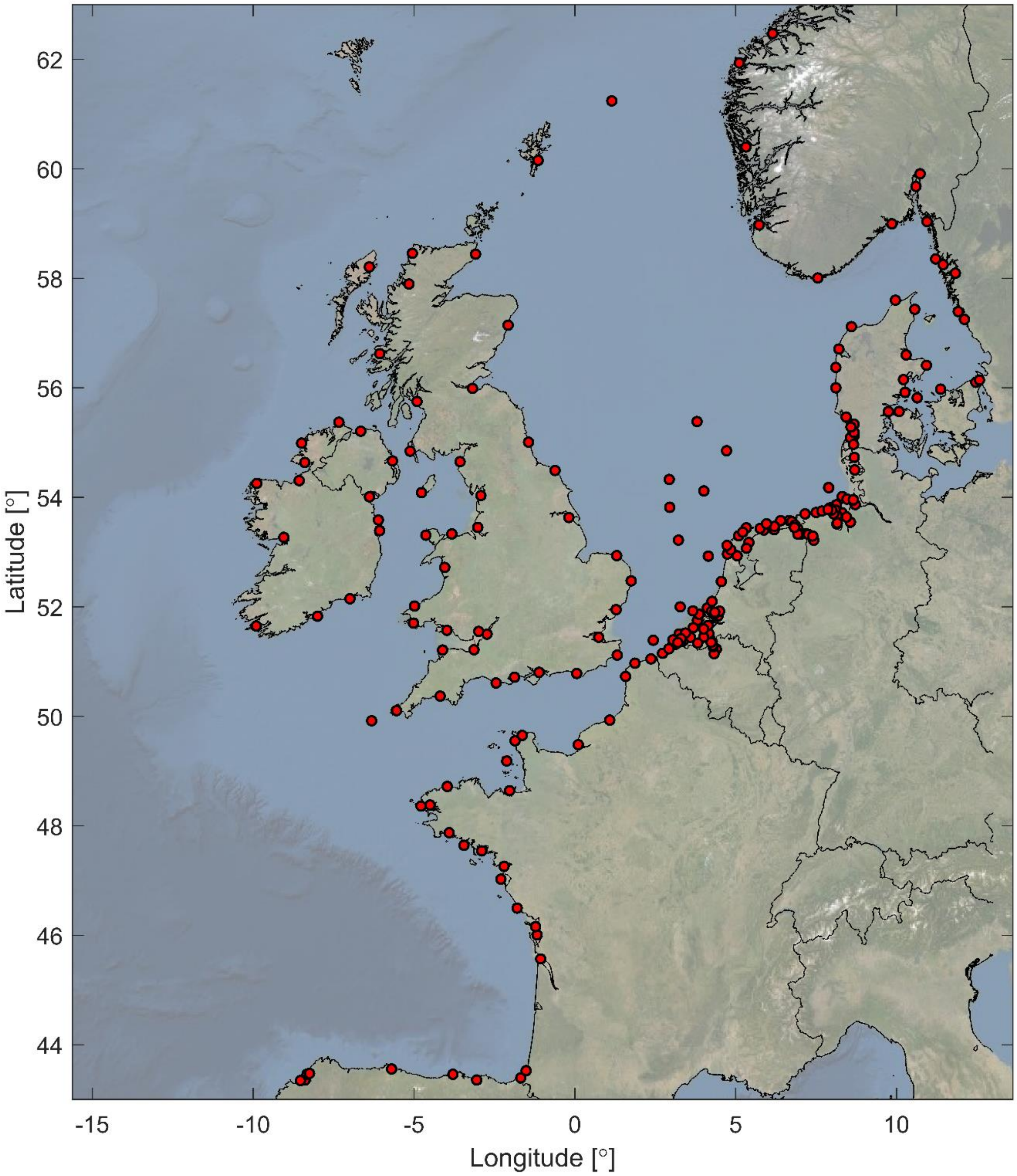

Figure 2.22 Overview of the tide gauge locations used for the model calibration and validation (for Dutch and Belgian locations, see Figure 2.23).

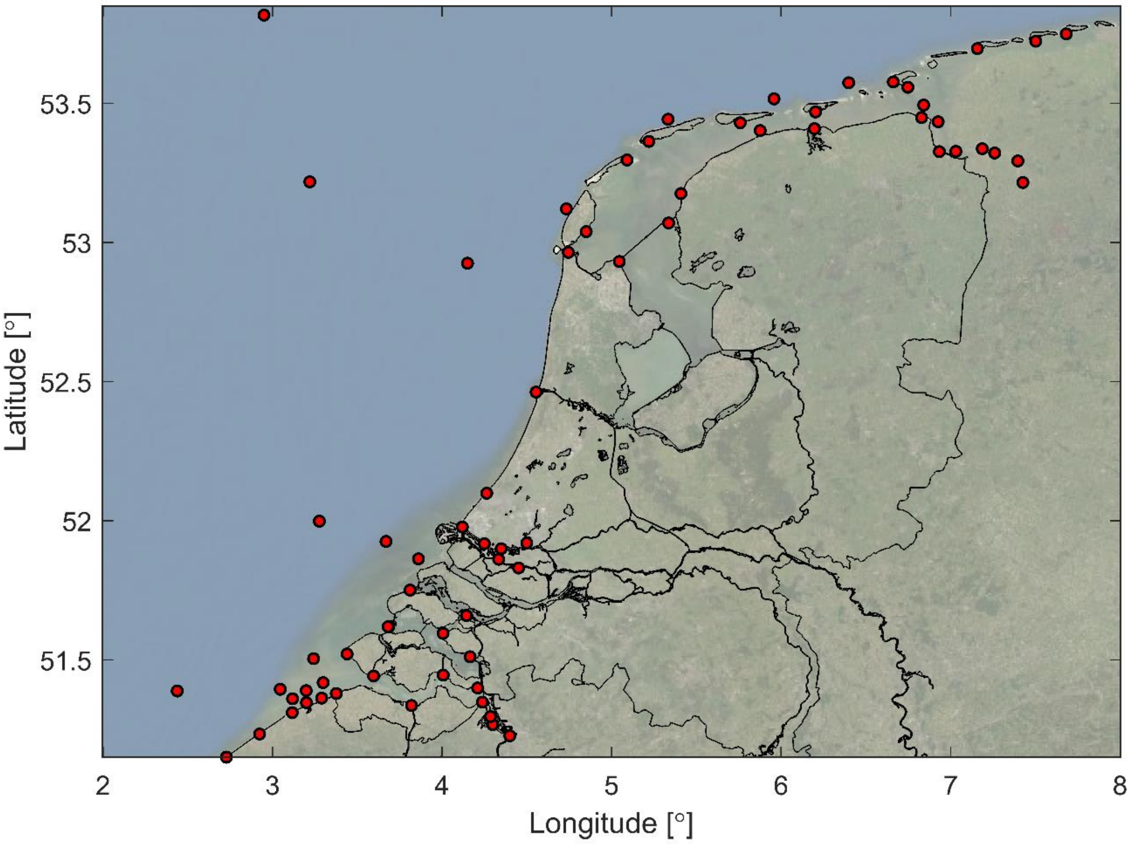

Figure 2.23 Overview of the Dutch and Belgian tide gauge locations used for the model calibration and validation.

2.9.7 Breaking of internal waves

The generation of internal waves on the slope towards the continental shelf precipitates barotropic energy dissipation. Even though the 2D barotropic DCSM-FM model cannot explicitly model internal waves, the energy dissipation this causes can be taken into account through a parametrization that is dependent on the local bathymetry gradient, the local flow velocity perpendicular to the continental slope and the local depth-averaged Brunt–Väisälä frequency. The latter quantity is computed as a pre-processing step on the basis of 3D monthly-averaged temperature and salinity fields.

In Appendix B of the DCSM-FM 0.5nm report (Zijl & Groenenboom, 2019) the impact of taking energy dissipation at the shelf edge into account is quantified. Considering the general improvement in surge quality in both the uncalibrated and calibrated model, it was decided to include the parametrization of energy dissipation by generation of internal waves into the final DCSM-FM 100m model schematization.

2.9.8 Software version

DCSM-FM has been developed as an application of the D-Flow Flexible Mesh (D-Flow FM) module of the D-HYDRO Suite. With this module is suitable for one-, two-, and three-dimensional hydrodynamic modelling of free surface flows on unstructured grids. Various versions of D-Flow FM have been used during the development of DCSM-FM. For the final validation presented in this report, use has been made of D-Flow FM version 1.2.88.65582 (Dec 11, 2019).

2.9.9 Computational time

In Table 2.4 the computational time of DCSM-FM 100m is presented together with the (average) time step and cell size and the number of network nodes. This is also done for DCSM-FM 0.5nm as well as the fifth-generation North Sea models, with all computations performed on Deltares' h6 cluster using 5 nodes with 4 cores each.

These results show that DCSM-FM 100m takes slightly more than 2 days per simulation-year, or 8-9 minutes per simulation-day. This is around six times slower than DCSM-FM 0.5nm, which is caused by the larger number of nodes and the smaller time step.

DCSM-FM 100m is around 30% slower than DCSMv6-ZUNOv4. However, this comes with the advantage of significantly higher resolution in the Southern North Sea and the Dutch estuaries and Wadden Sea in particular (~100m vs. ~300m). Also note that at the time of development of the fifth-generation models, these models were considerably slower than mentioned here because of advances in computational hardware.

Table 2.4 Overview of grid cell size, number of net nodes, maximum and average numerical time step and computational time for various 2D models. The computations were performed on Deltares' h6 cluster using 5 nodes with 4 cores each.

Model	cell size	# nodes	Maximum time step (s)	Average time step (s)	Comp. time (min/day)	Comp. time (hr/year)
Fifth-generation						
DCSMv6	1 nm	859,217	120	120.0	1.6	10.0
DCSMv6-ZUNOv4	4nm – 0.15nm	1,119,106	60	60.0	6.5	40.2
Sixth-generation						
DCSM-FM 0.5nm	4nm – 0.5nm	629,187	120	118.7	1.36	8.3
DCSM-FM 100m	4nm – 100m	1,601,714	50	35.4	8.67	52.8

3 Water level data

3.1 Collection of water level data

Compared to the dataset available for the calibration and validation of the fifth-generation models of the North Sea, availability of time series of water level from tide gauges in the model domain has increased significantly. This extended dataset can be used to further improve the model as it will be used in the calibration procedure and for the validation of the model. Various data sources have been used; national organisations of several countries were contacted and water level data from European data networks has been retrieved. Water level data is obtained from the following sources:

- Rijkswaterstaat (RWS) - Waterbase, The Netherlands;
- Meetnet Vlaamse Banken (VB), Belgium;
- Flanders Hydraulics Research (WL-B), Belgium;
- British Oceanographic Data Centre (BODC), Great Britain;
- Bundesanstalt für Gewässerkunde (BAFG), Germany;
- Copernicus Marine Environment Monitoring Service (CMEMS);
- European Marine Observation and Data Network (EMODnet).

The result was a collection of a few hundred raw data files.

3.2 Quality assurance

First, the available data was processed and a first selection of monitoring stations suitable for model calibration and validation was made. Next, an extensive procedure was performed to merge, carefully check and remove erroneous data from the dataset. This procedure is elaborated on in Chapter 3 of the DCSM-FM 0.5nm report (Zijl & Groenenboom, 2019).

3.3 Tide gauge locations used for the model calibration and validation

After collecting, selecting, merging and quality checking of the water level data, the resulting dataset consists of water level data from 221 tide gauge locations. In these stations water level data is available in the validation period 2013-2017. Furthermore, the model resolution is sufficient to at least reasonably represent these water levels after calibration.

Compared to the stations used in calibration and validation of DCSM-FM 0.5nm (Zijl & Groenenboom, 2019), stations further upstream have been added in the Western Scheldt (Bath, Prosperpolder, Liefkenshoek, Kallo, Antwerpen and Hemiksem), the Rhine-Meuse Delta (Maassluis, Vlaardingen, Spijkenisse, Rotterdam and Goidschalxoord) and Ems-Dollard (Emden, Pogum, Leerort and Terborg). Another difference compared to DCSM-FM 0.5nm, is that data of station Ferring is not used during the validation due to erroneous data. Data from Galway Port and Zeebrugge have been excluded from the validation, due to shifts in datum prior to the validation year (2017).

3.3.1 Geographical locations of observation stations

An overview of the 221 tide gauge locations considered for the model calibration and validation is depicted in Figure 3.1. Figure 3.2 shows the observation locations along the Dutch and German Wadden Sea, Skagerrak and Kattegat in more detail. A more detailed overview of the monitoring stations used near the Netherlands can be found in Figure 3.3.

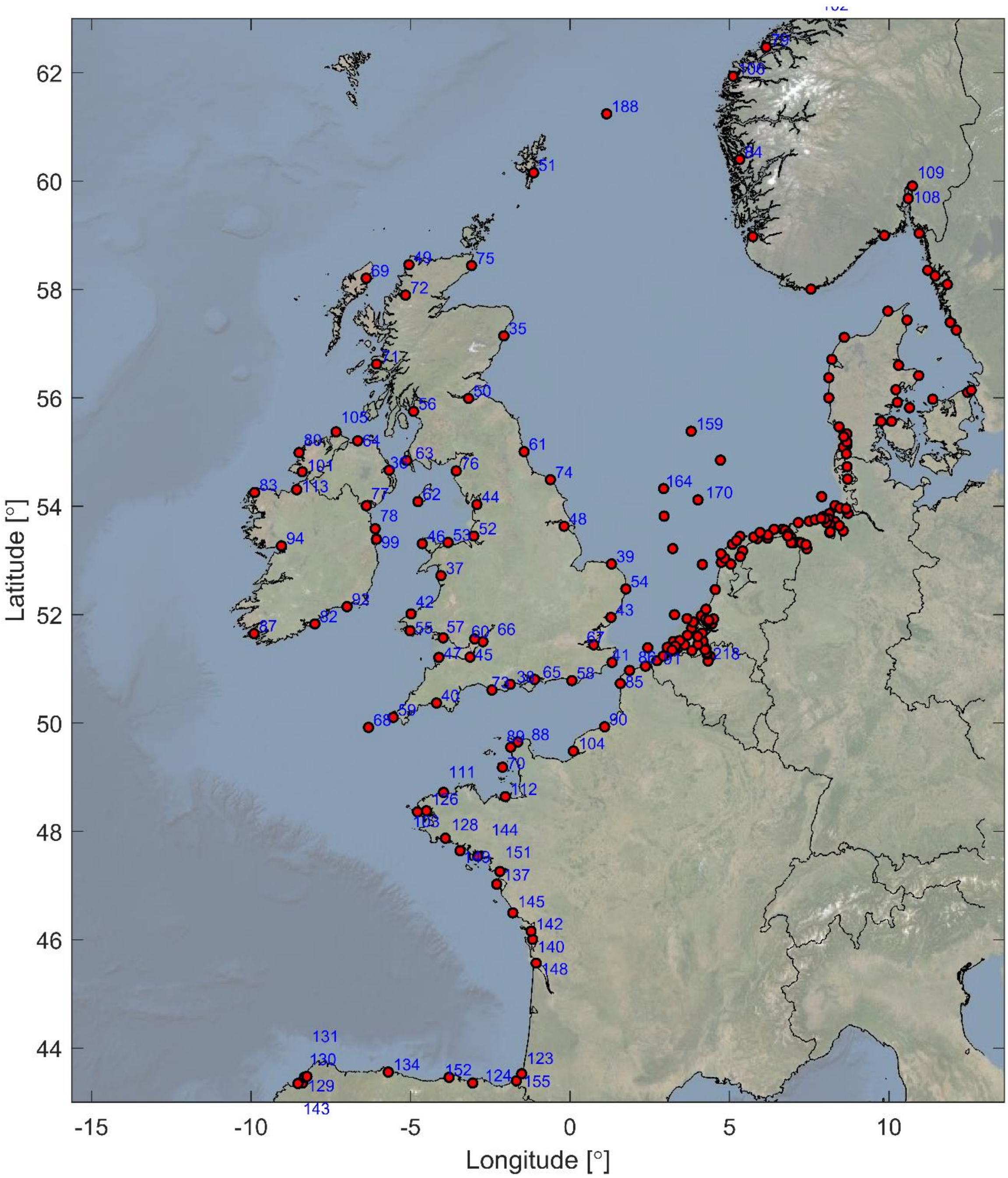

Figure 3.1 Overview of the 221 tide gauge locations used for the model calibration and validation (for the station numbers that are not shown in this figure, see Figure 3.3 and Figure 3.2)

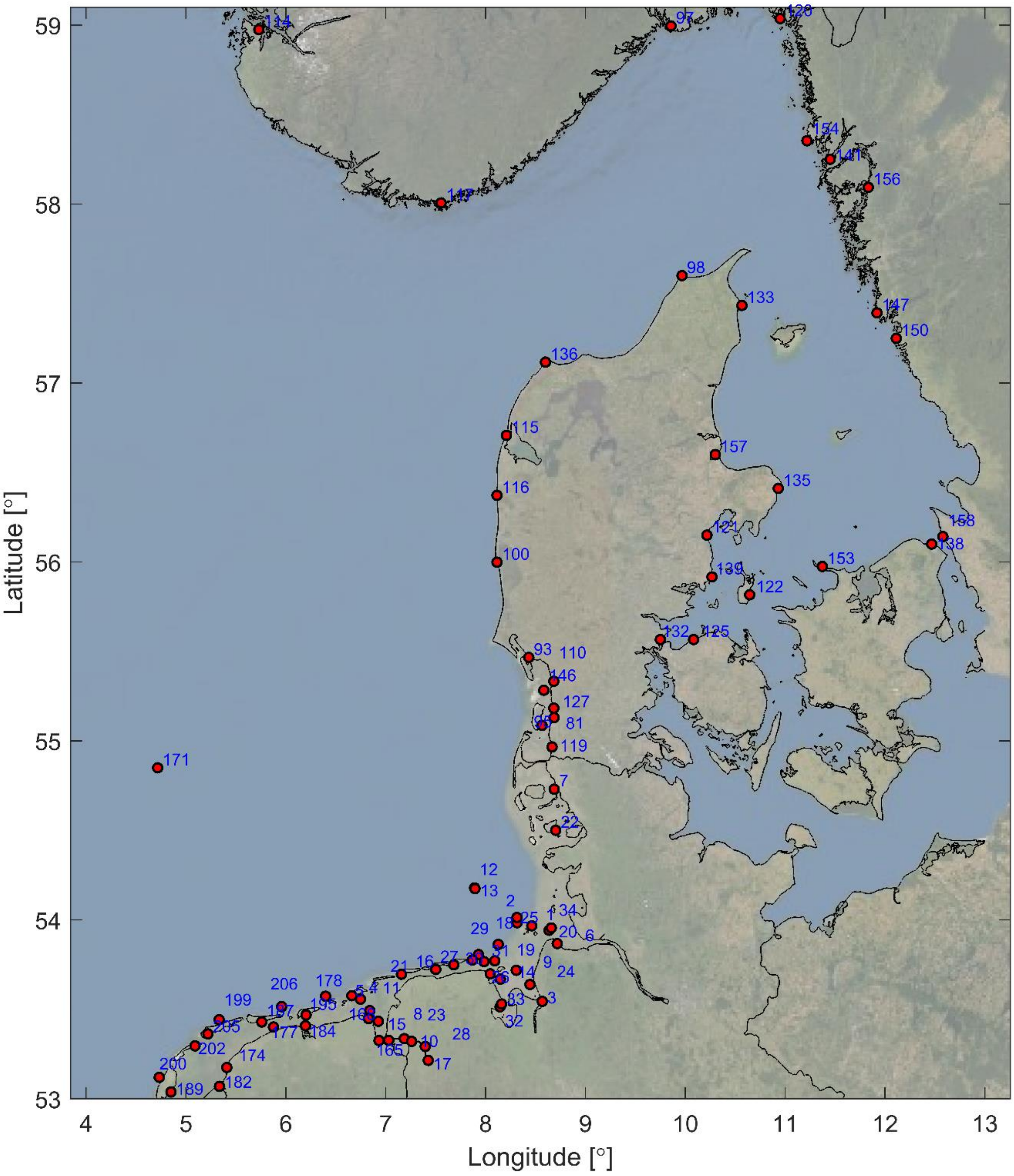

Figure 3.2 Overview of the tide gauge locations used for the model calibration and validation

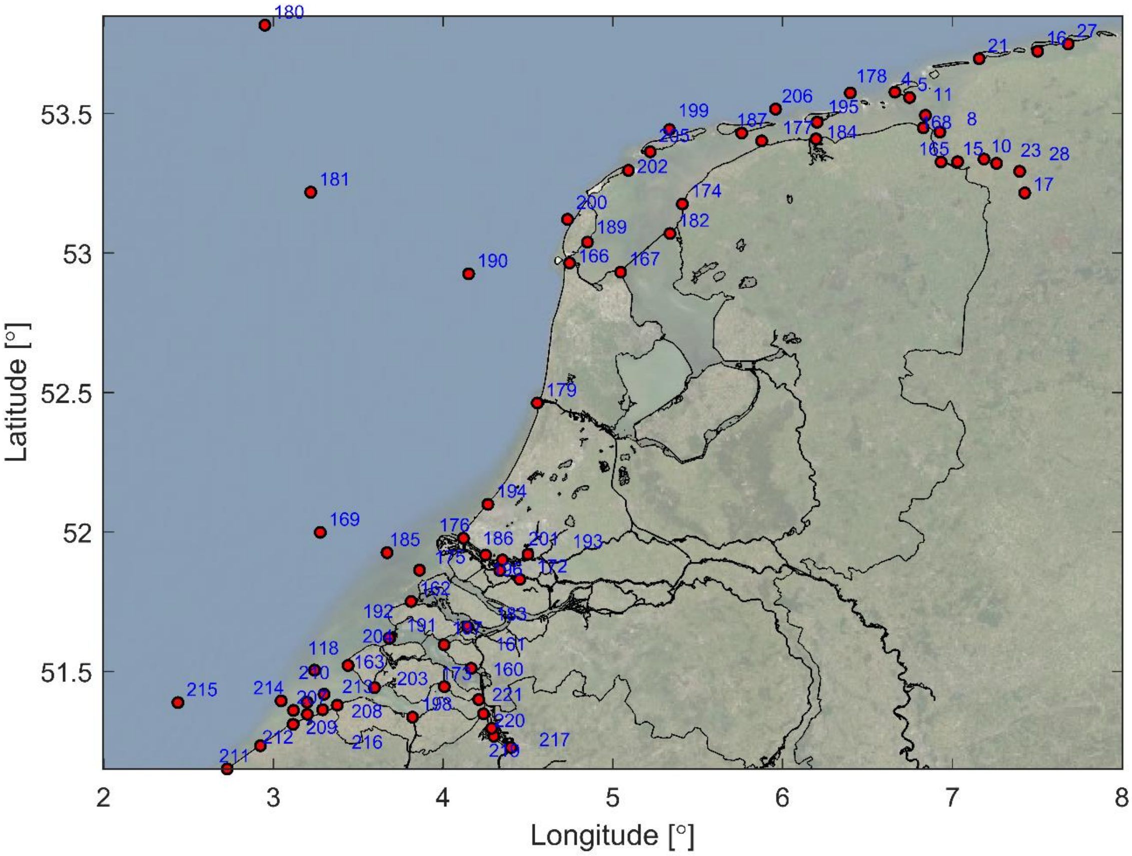

Figure 3.3 Overview of the tide gauge locations used for the model calibration and validation

3.3.2 Temporal availability

The red line in the following figures (Figure 3.4, Figure 3.5, Figure 3.6 and Figure 3.7) shows the temporal availability of data for all tide gauge locations. Each line consists of the station name, data source, station number and availability in the period 2013 – 2017.

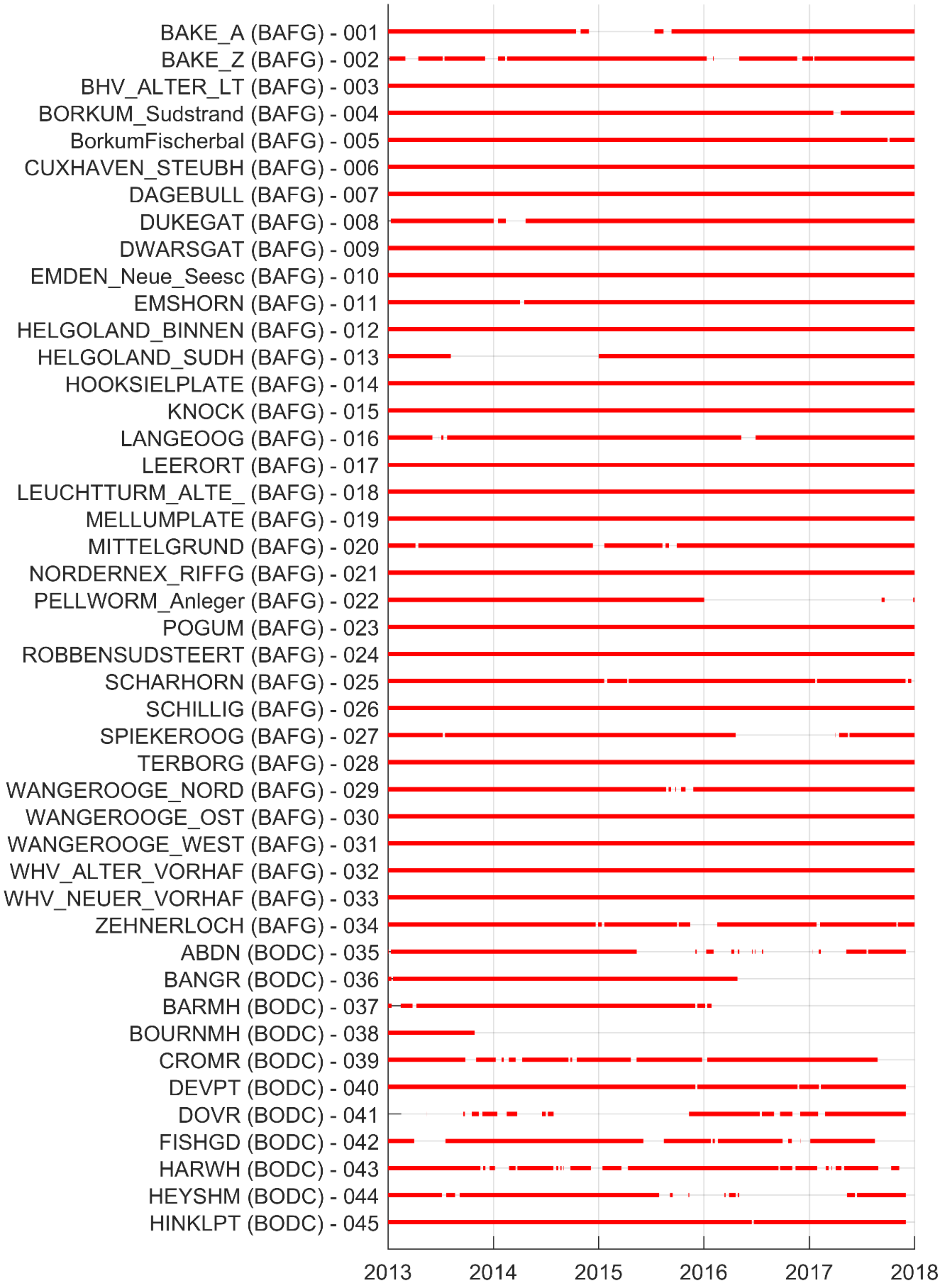

Figure 3.4 Overview of temporal availability of water level data in the period 2013 – 2017 for station numbers 001 – 045

Figure 3.5 Overview of temporal availability of water level data in the period 2013 – 2017 for station numbers 046 – 090 (CM=CMEMS, EN=EMODnet)

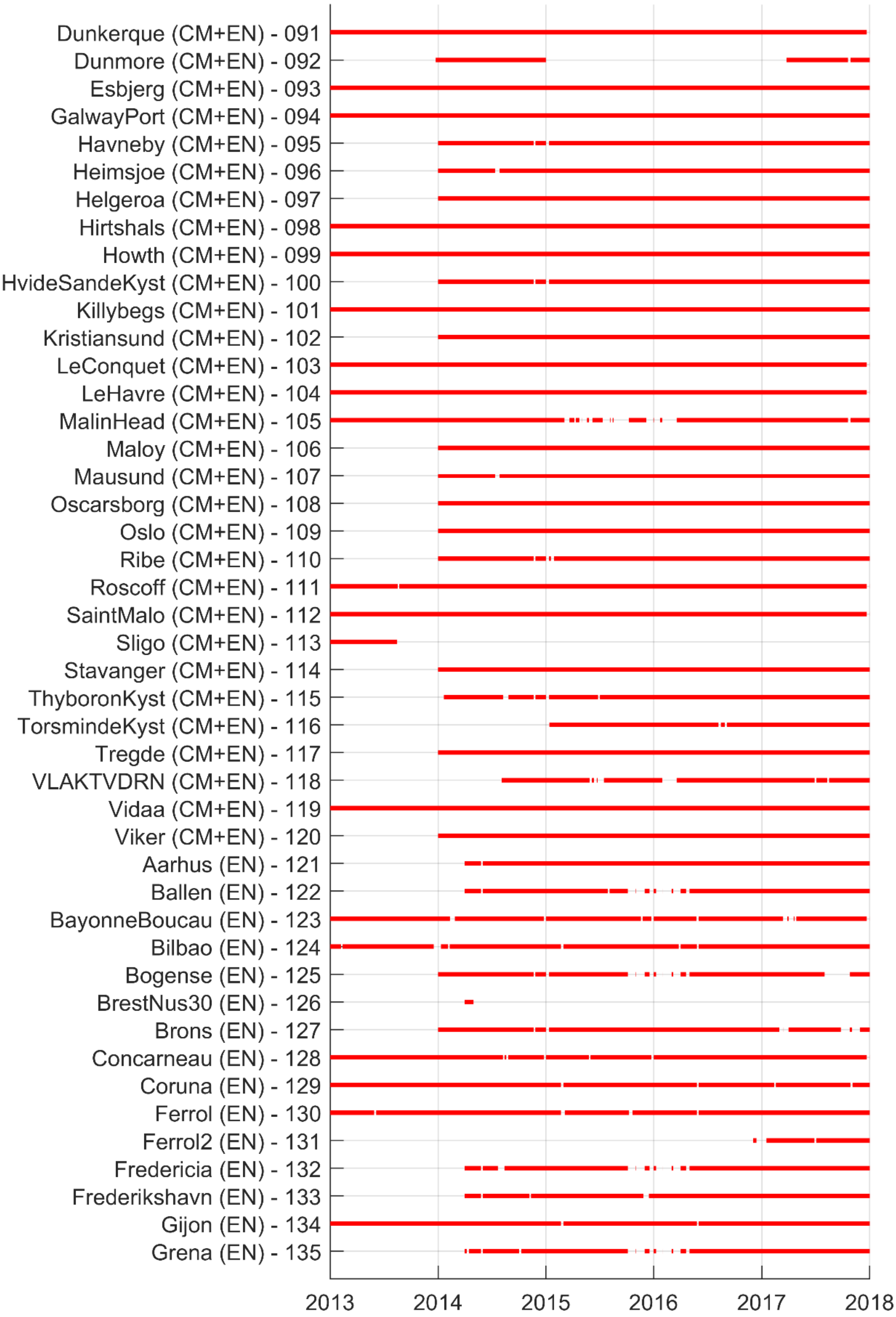

Figure 3.6 Overview of temporal availability of water level data in the period 2013 – 2017 for station numbers 091 – 135 (CM=CMEMS, EN=EMODnet)

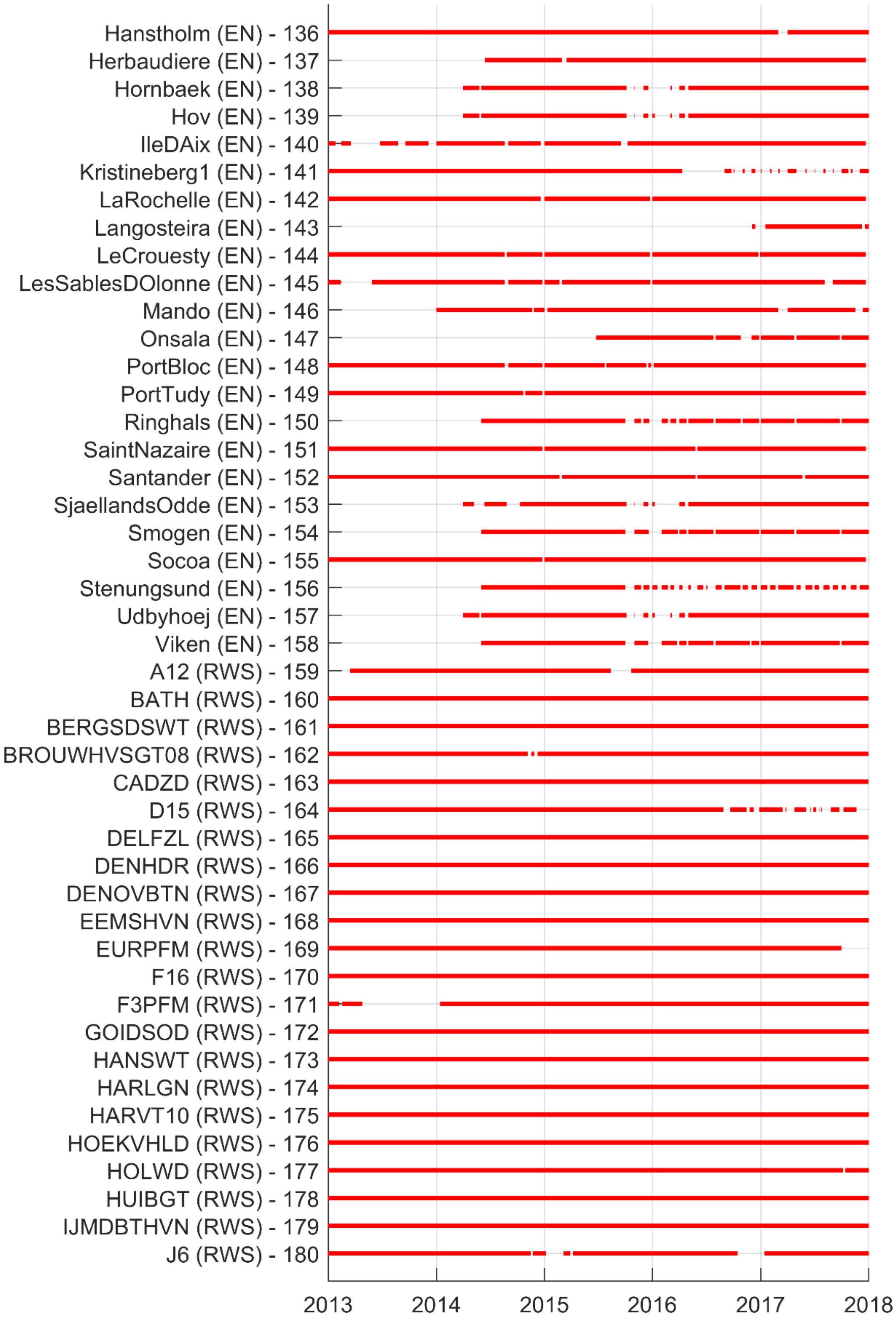

Figure 3.7 Overview Overview of temporal availability of water level data in the period 2013 – 2017 for station numbers 136 – 180 (EN=EMODnet, RWS=Rijkswaterstaat)

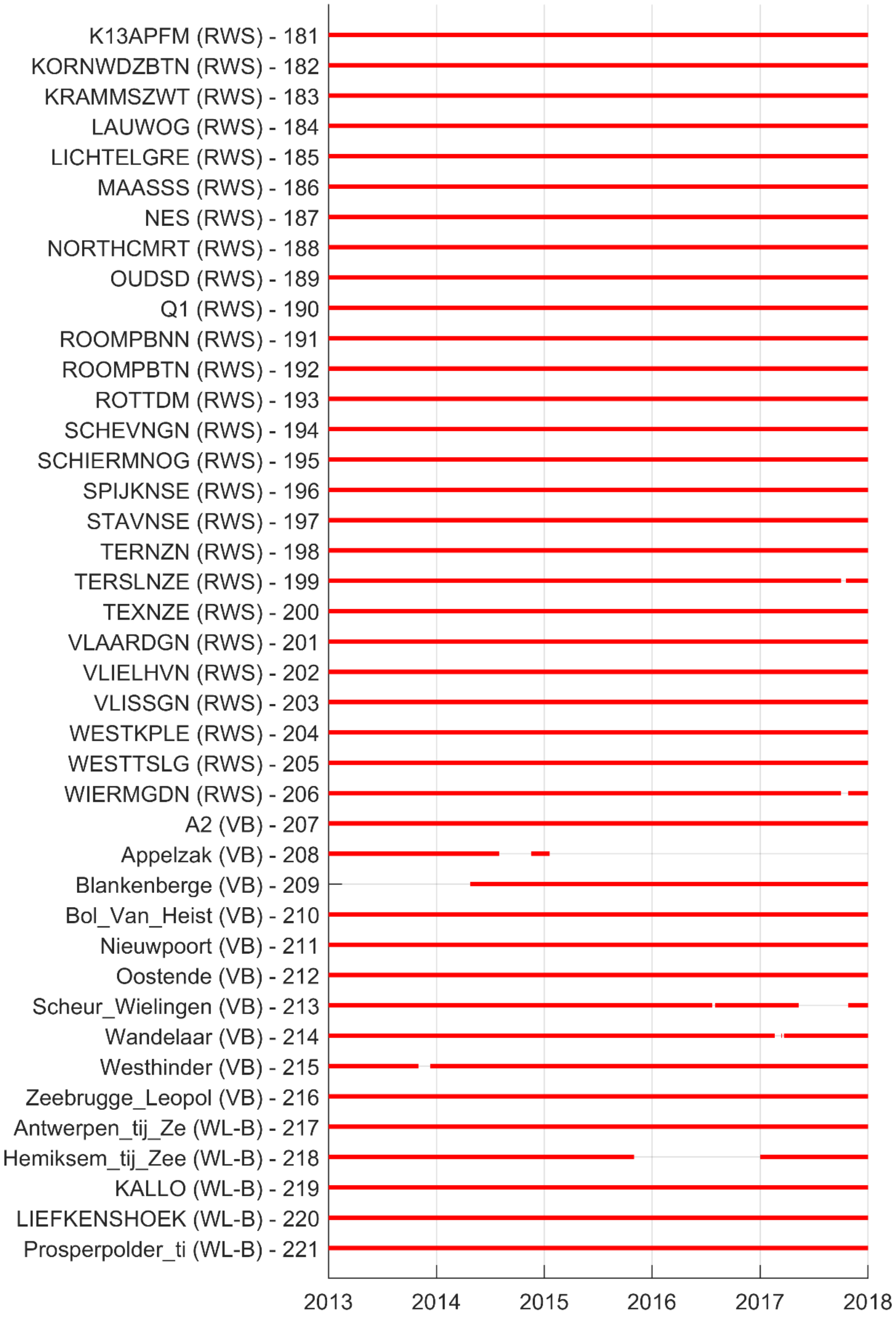

Figure 3.8 Overview of temporal availability of water level data in the period 2013 – 2017 for station numbers 181 – 221 (RWS=Rijkswaterstaat, VB=Vlaamse Banken)

4 Calibration

4.1 Approach

4.1.1 Introduction

Generally, a first simulation with an initial model definition will not lead to an optimal representation of the required parameter (in this case water levels), such as known from measurements. Models contain errors that are generated mainly by errors in the forcing terms (e.g. boundary conditions and meteorological forcing terms), uncertainty in the bathymetry, the model parameters (e.g. bottom friction) and the poorly described or neglected physical processes in the system equations as well as mathematical approximations (e.g. unresolved sub-grid scale motions and exchange of momentum with the atmosphere). In order to reduce the uncertainty of the model parameters and parameterisations used, an automated calibration using the DUD (Doesn't Use Derivative) algorithm (Ralston and Jennrich, 1978) available in the open source data assimilation toolbox OpenDA (version 2.3.1.834) has been performed. This derivative-free algorithm for non-linear least squares transforms a non-linear least square problem onto a well-known least square problem. DUD evaluates and optimizes uncertain model parameters by minimizing a cost function. The parameter values corresponding to the minimum value of the cost function are considered as the optimal parameter values for the given problem. The general methodology followed is similar to the one used for the calibration of the previous generation models DCSMv6 and DCSMv6-ZUNOv4 (Zijl et al., 2013).

4.1.2 Period

It is important to assess model results against sufficiently long measurement series which include all relevant physical processes: e.g. spring and neap tide, various (seasonal) wind patterns, etc. Computing longer periods prevents optimization for specific, unrepresentative events, which would lead to a deterioration of the predictive value of the model.

For the final calibration the entire year of 2017 is therefore used, preceded by a 10-day spin-up period. The use of an entire year is required since the annual modulation of the M2 tide cannot be properly represented in a 2D barotropic model. Optimization for a shorter period would result in an over- or underestimation of dissipation through bottom friction.

4.1.3 Observation data used

The measurement stations described in Chapter 3, with data in the calibration period, have been used for calibration. Accounting for stations without measurements data in the calibration period, a total of 211 stations were eventually used. The measurements (and model output) were provided with a 60-minute interval because of computer memory restrictions.

Removal of data (thresholds)

In some tide gauge stations, the representation of especially the low waters is negatively affected by the poor resolution of the model in some areas. If these measurements are included in the calibration, this would negatively influence the results. An option could be to exclude these stations altogether from the calibration. While this is done for some stations, for others where the higher water levels are well represented in the model, it was decided to just remove the water level measurements below a certain threshold. This threshold is determined by making scatter plots of the modelled and measured total water levels, and visually determining from which level the model accuracy is sufficiently accurate. An example for station Holwerd is presented in Figure 4.1.

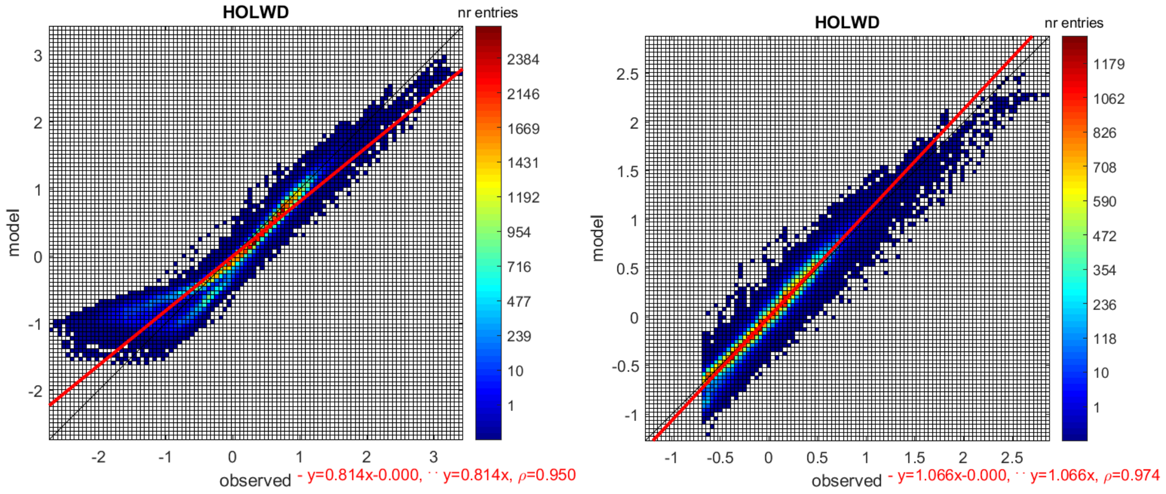

Figure 4.1 Scatter plots of the measured (horizontal) and modelled (vertical) water level at station Holwerd before (left) and after (right) water levels below the provided threshold are removed.

The resulting thresholds, which will be taken into account in both the calibration and validation, are presented in Table 4.1 and visually shown in Figure 4.2. Note that the thresholds are prescribed relative to MSL, which is determined before the removal of the water levels below the threshold. This causes an apparent mismatch between the threshold in Table 4.1 (Holwerd: 0.0 m +MSL) and the lowest observed water level in the Figure 4.1 (right; around -1.5 m +MSL);

Table 4.1 Threshold values relative to MSL below which water level measurements are not taken into account during calibration or validation.

Station name	Threshold (m +MSL)	Station name	Threshold (m +MSL)
BERGSDSWT	-1.5	HARLGN	-1.0
Ballum	0.0	HOLWD	0.0
BayonneBoucau	-1.0	Havneby	0.0
Brons	0.0	NEWPT	-1.0
DENOVBTN	-0.5	PORTSMH	0.0
DEVPT	-2.0	PortBury	1.0
Dagebull	-1.0	SaintNazaire	-2.0
Dundalk	-0.5	Vidaa	-1.0
Esbjerg	-0.5		

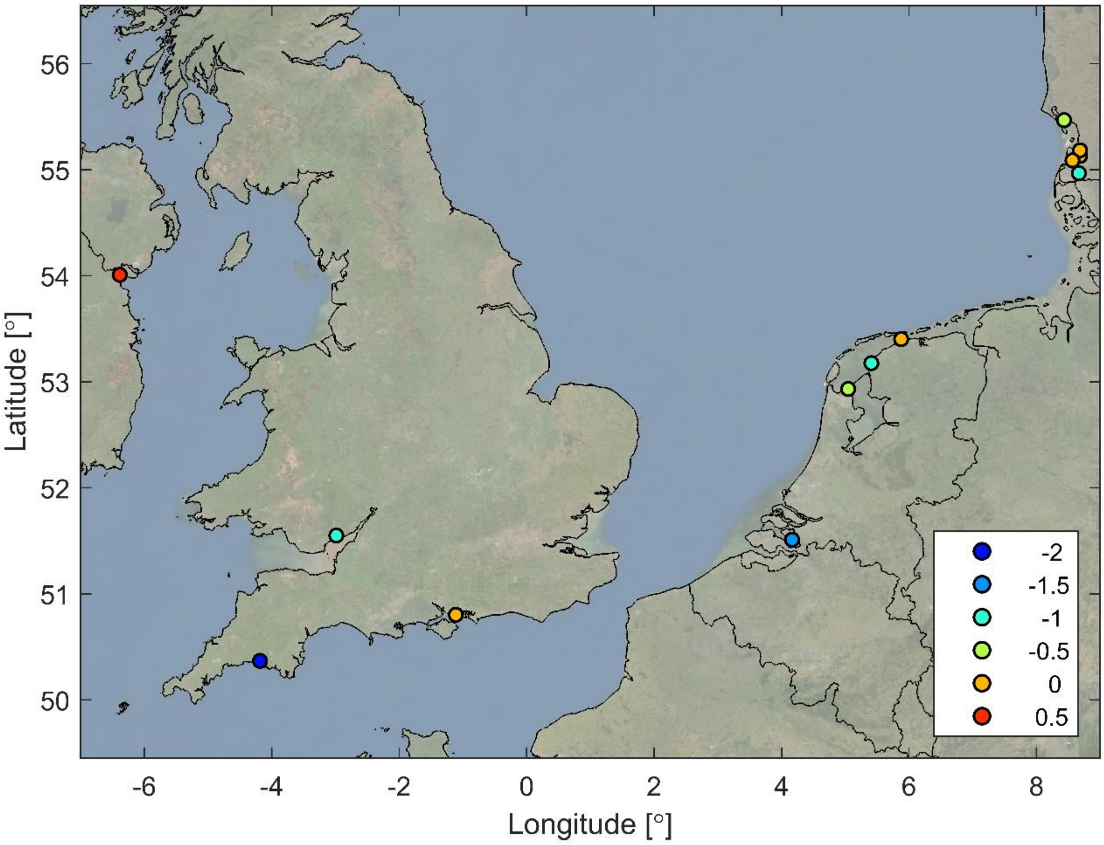

Figure 4.2 Threshold values relative to MSL below which water level measurements are not taken into account during calibration or validation (thresholds for station Bayonne Boucau and Saint Nazaire are not shown).

4.1.4 Cost function and weights

DUD is a derivative-free algorithm for nonlinear least squares that minimises a quadratic cost function by adjusting model parameters. DUD should be initialised with one unperturbed run and n sensitivity run, where n is the number of control parameters.

For the present calibration we have used a quadratic cost function over the complete total water level time series. It is essentially the total sum of squares, made dimensionless with the measurement uncertainty.

In the quadratic cost function minimised during the experiments, the bias between computed and measured water levels is ignored, since this bias is hardly related to the uncertainty in the control parameters, but mostly caused by physical (e.g. baroclinic) processes not considered in this model.

Since the primary focus of this model is the accurate representation of water levels in Dutch waters, additional weight in the cost function has been given to Dutch coastal stations (by a factor 16). This is done by decreasing the uncertainty of the measurements that is specified for each station in the OpenDA-DUD input files. Stations along the North Sea coast of the UK have their weight increased by a factor 2. This is because of the importance of this region for the correct propagation of the tide towards the Dutch coast. In addition; the WMCN-kust main locations have their weight increased by a factor 4. Station in the Skagerrak and Kattegat on the other hand have been given a reduced weight (by a factor 0.5). In addition, stations which are poorly represented in the model compared to neighbouring stations (but nonetheless retained in the calibration) have also been given a reduced weight. This holds for example for the Dutch Wadden Sea and estuarine stations, as well as stations like Sheerness, where the generation of the complex higher harmonics is hampered by a poor representation of the relatively variable bathymetry. Stations located upstream in e.g. the Scheldt River and Ems-Dollard estuary were also given a reduced weight. The resulting weights are visually presented in Figure 4.3 for the entire model area, and in Figure 4.4 focussing on Dutch waters.

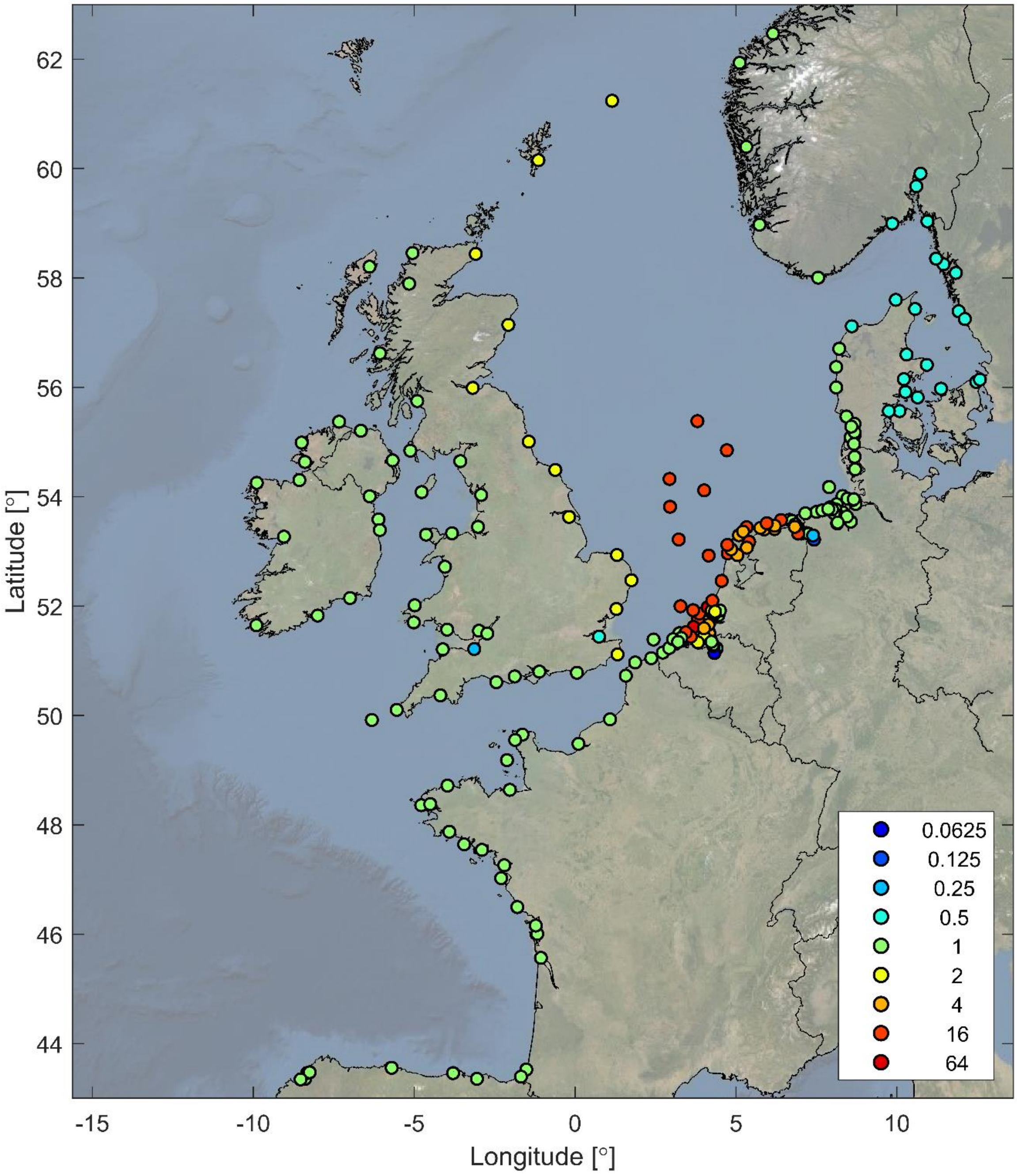

Figure 4.3 Relative weight given to a station in the OpenDA-DUD cost function

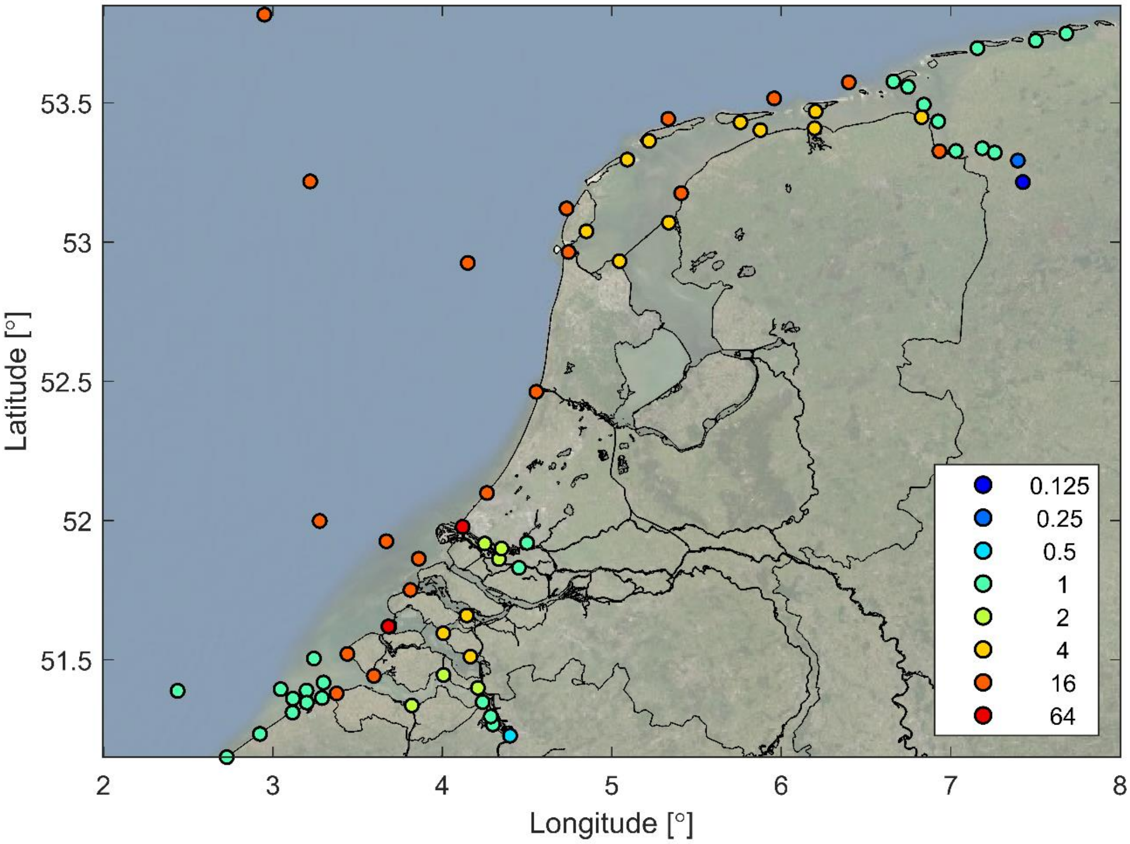

Figure 4.4 Relative weight given to a station in the OpenDA-DUD cost function

4.1.5 Calibration parameters

During the development of the previous generation models for the North Sea uncertainty in both bathymetry and bed roughness coefficients has been reduced during calibration to achieve optimal model representation of water levels (Zijl et al., 2013). At the time, the adjustment of bathymetry was necessary because an M2 phase lag of 15-20° occurred in the uncalibrated model. This phase lag could not be reduced sufficiently by adjusting the bottom roughness.

By using an improved bathymetry, to a large extent derived from EMODnet (section 2.4) whereas in the older models NOOS bathymetry was used, the need to adjust bathymetry during the calibration was reduced. Therefore, in DCSM-FM only the bottom roughness is calibrated.

4.1.6 Roughness area distribution

Practically it is not possible to adjust the bottom roughness in each network node since far too many parameters would then have to be estimated in proportion to the available amount of measurement data, which would lead to the problem of identifiability. Therefore, our approach is to specify larger sections as adaptation parameters. These sections are defined as samples with a section number. During the calibration OpenDA-DUD prescribes a uniform adjustment factor to each section, after which these values are interpolated on the network using triangular interpolation. By leaving a distance between the prescribed samples a smooth transition in the resulting bottom roughness is ensured.

For the present calibration, the roughness sections of DCSM-FM 0.5nm were used as a starting point. These were chosen after many experiments with various measurement stations, thresholds and number and location of roughness sections. As the present model has a finer resolution and extends further upstream in the estuaries in the southern North Sea, several roughness sections were adjusted and added in these parts of the model domain. For consistency and efficiency reasons, the roughness values outside the southern North Sea (the part of the model which is the same in both DCSM-FM schematisations) were adopted from DCSM-FM 0.5nm and these areas were therefore not again calibrated. Furthermore, as the total number of roughness sections increased and the run time of the relatively fine DCSM-FM 100m increased compared to the relatively coarse model, excluding these areas outside of the main area of interest helped to keep the calibration procedure feasible in terms of run times. The calibrated roughness values of 24 areas were adopted from the relatively coarse model and thus 42 remaining roughness sections are used during the OpenDA-DUD calibration of DCSM-FM 100m.

Where possible the initial roughness values were taken from the calibrated DCSM-FM 0.5nm model, while in the added sections an initial bottom roughness of 0.028 $s/m^{1/3}$ is prescribed. During the calibration deviations between 0.012 $s/m^{1/3}$ and 0.050 $s/m^{1/3}$ were allowed. On overview of the final roughness sections (samples) is presented in Figure 4.5. In Figure 4.6 and Figure 4.7 the sections in the German Bight and Dutch waters are shown in more detail.

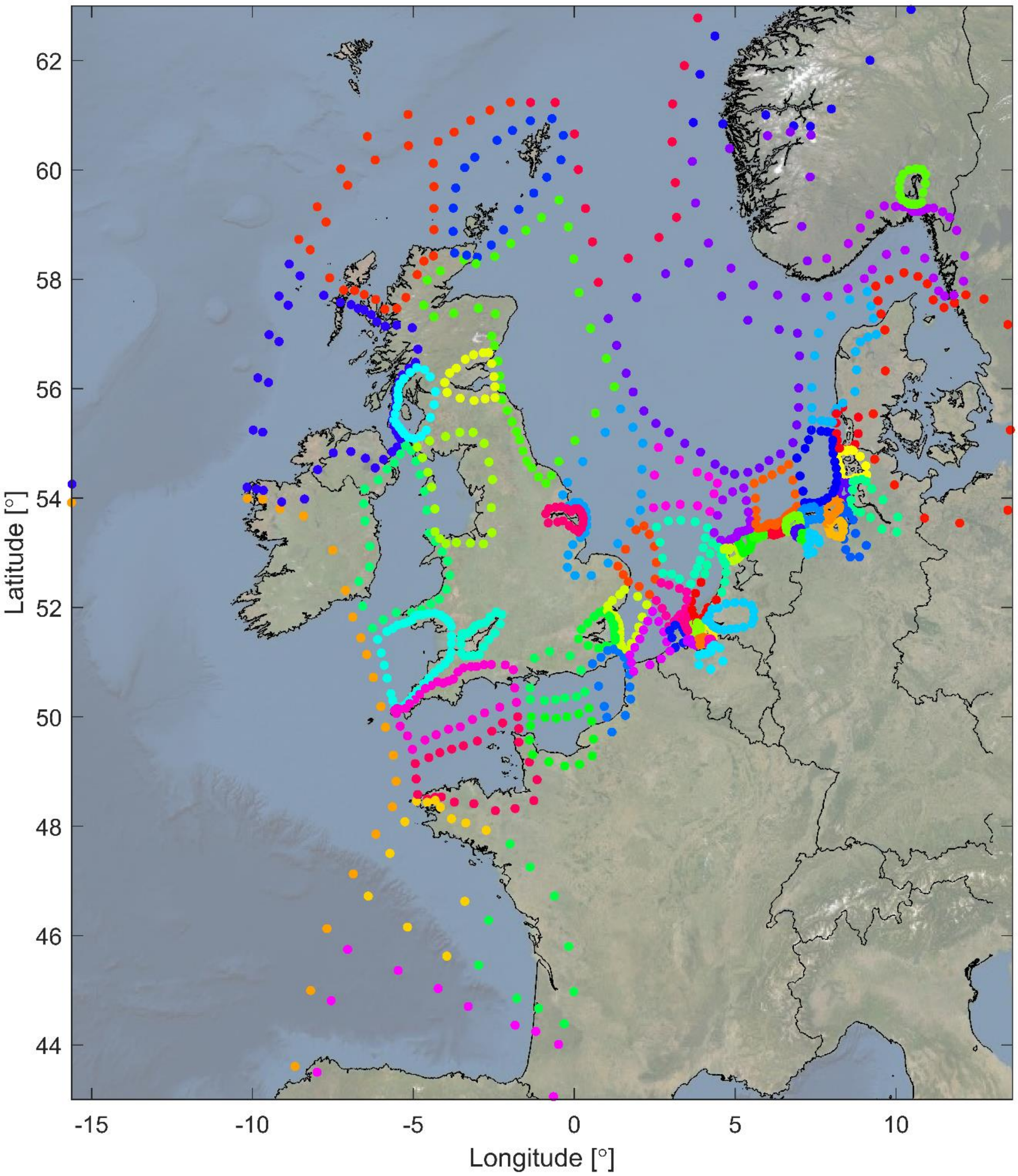

Figure 4.5 *Overview of samples used to define roughness adjustments. Each colour represents a different calibration area.*

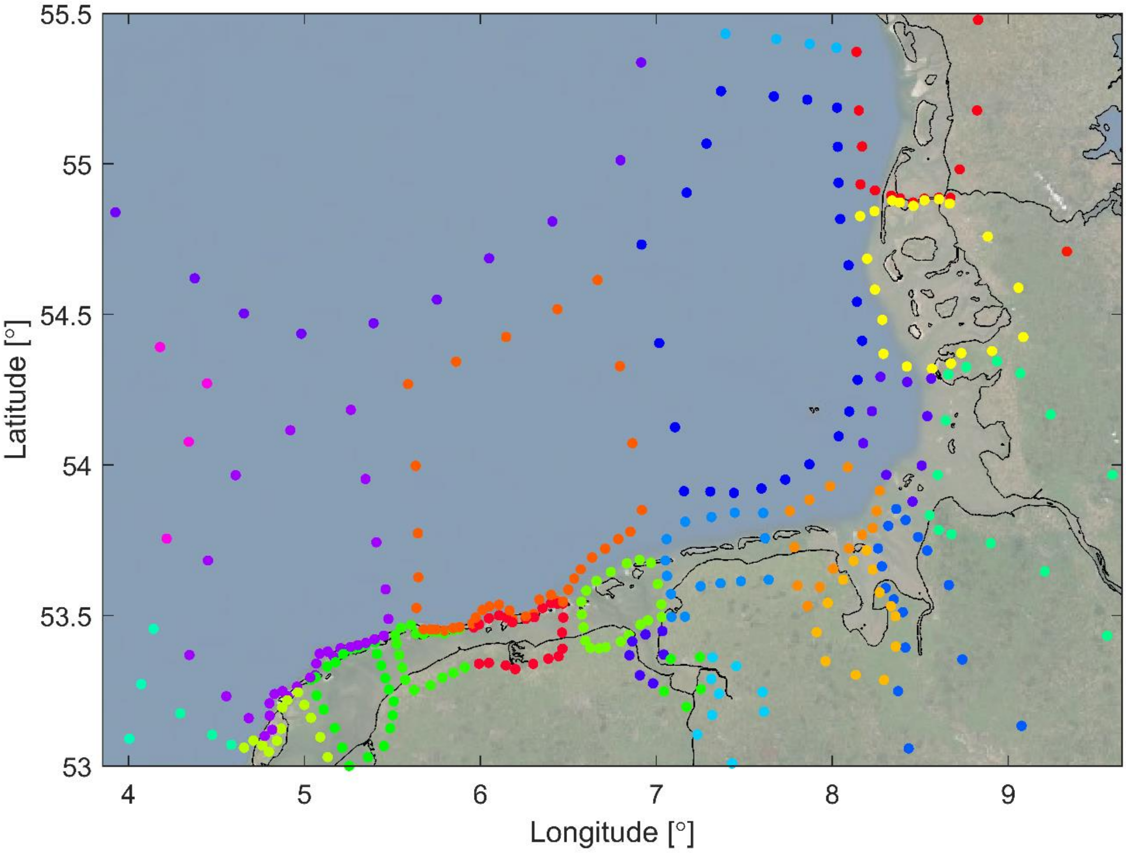

Figure 4.6 Samples used to define roughness adjustments in the German Bight. Each colour represents a different calibration area.

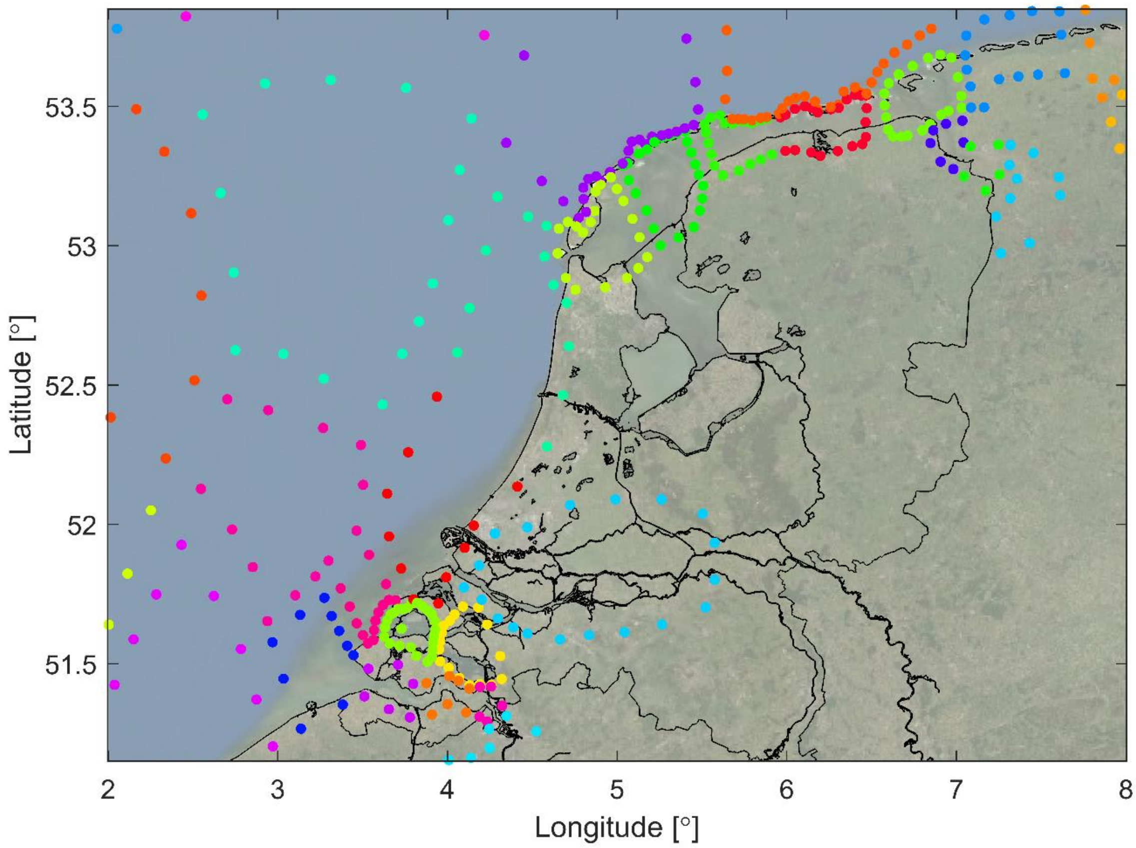

Figure 4.7 Samples used to define roughness adjustments in Dutch waters. Each colour represents a different calibration area.

4.2 Calibration results

The roughness in the model is described by a combination of a uniform default value and a sample set with (calibrated) multiplication factors for different areas. Various calibration experiments have been performed, with increasing computation length and varying number and shape of the roughness areas, to determine these calibrated multiplication factor for each area. The final calibration experiment, using 42 roughness areas and covering the entire year 2017 is described in this section. For this experiment the initial roughness perturbation for all roughness areas was set to 5% of the initial roughness. The calibrated roughness values were constrained between 0.012 s/m$^{1/3}$ and 0.050 s/m$^{1/3}$.

In Figure 4.8, the calibration process and improvement in cost function is visualised. The uncalibrated (unperturbed) run with an initial, uniform roughness value of 0.028 s/m$^{1/3}$, yields a cost function of 8809 (indicated by the yellow dot). The first point on the green line (indicated by the green dot) represents the first guess of the OpenDA-DUD experiment. This already represents an improvement compared to the uncalibrated model (yellow dot) because the initial values were mostly taken from the calibrated DCSM-FM 0.5nm model. The other small dots on the green line represent the cost function for single perturbations of each roughness area. Once this is known for all roughness areas, the problem is linearized and combinations of adjusted roughness fields are assessed in the optimization (indicated by the blue line) to minimize the cost function.

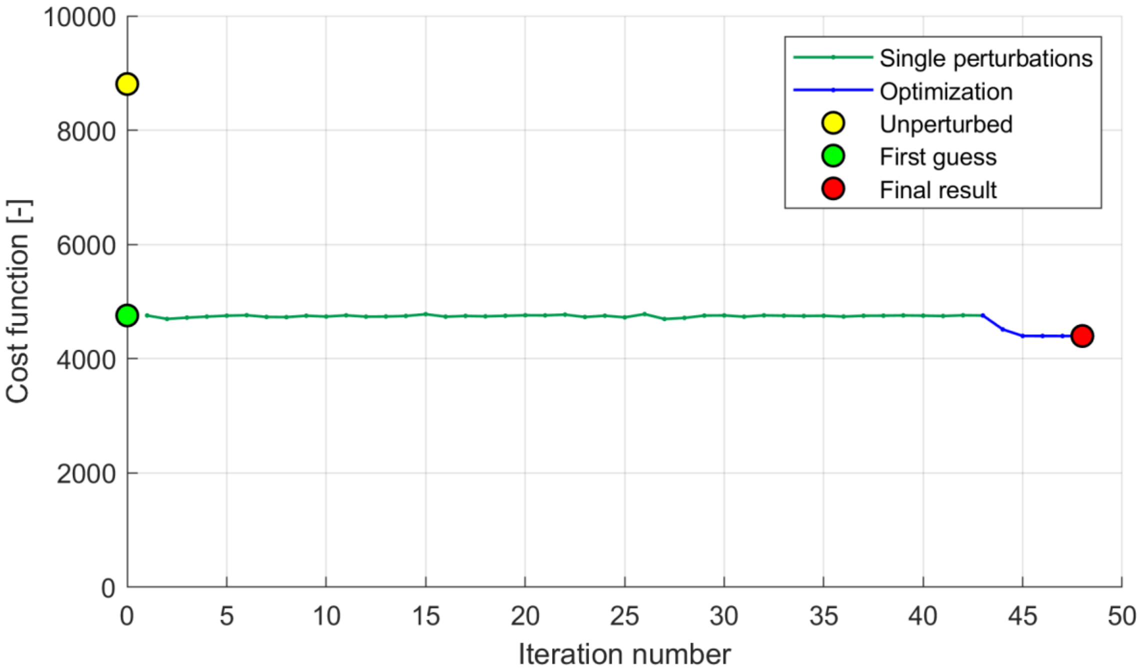

Figure 4.8 Cost function of the OpenDA-dud calibration

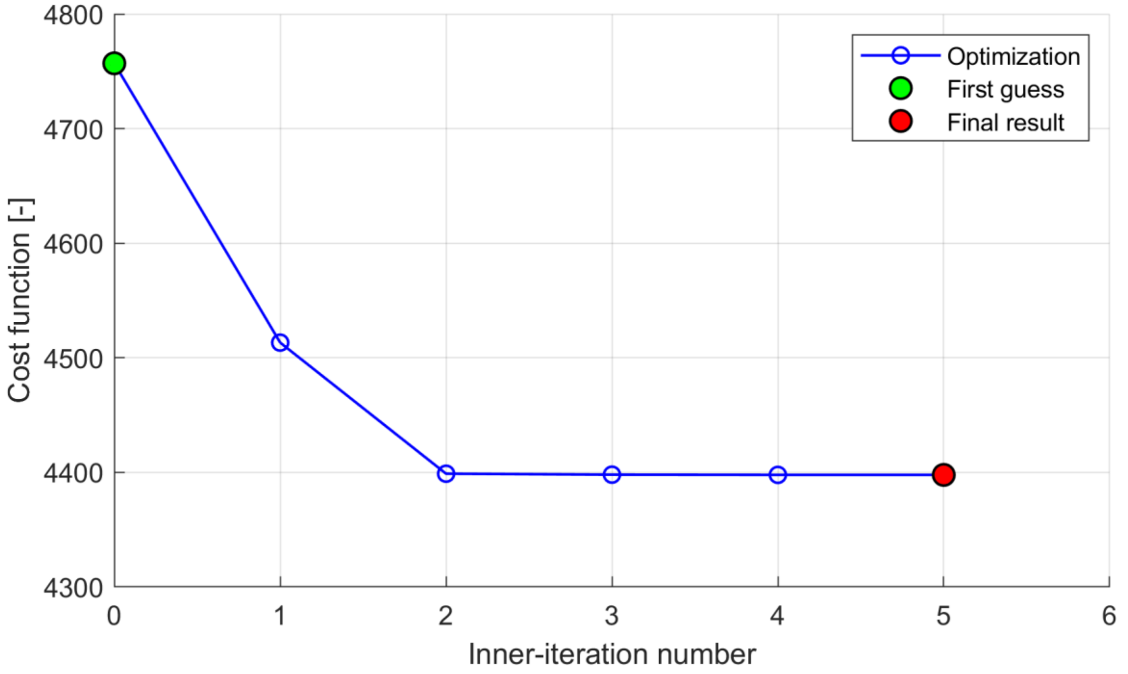

Figure 4.9 Cost function of the OpenDA-dud calibration for the optimization

In Figure 4.9 the iteration part of the optimization is shown in more detail, by leaving out the single perturbations. The green dot represents the first guess of the OpenDA-DUD experiment. This figure illustrates how the cost function reduces substantially during the first four iterations. The iteration with the minimum cost function is picked as the final roughness field, indicated here with a red dot.

During the calibration, the cost function starts at 4757 and reduces to 4398, which is a percentage decrease of about 7.5%. However, note that this final calibration starts with the calibrated roughness sections from DCSM-FM 0.5nm (except for a few added sections). The uncalibrated run with an initial, uniform roughness value of 0.028 s/m$^{1/3}$, yields a cost function is 8809. This implies that due to calibration for the bottom roughness a final improvement of 50% is achieved.

The resulting roughness field can be found in section 2.5.

5 Validation

5.1 Introduction

After reducing uncertainty in the bottom roughness by means of an OpenDA-DUD optimization for the year 2017 (Chapter 4), the model is validated against shelf-wide measurements for the five-year period 2013-2017. This period includes the significant 5-6 December 2013 storm Xaver (the so-called ‘Sinterklaasstorm’ in Dutch). For meteorological forcing HiRLAM v7.2 has been used (cf. section 2.7). The validation results are presented in this chapter.

5.1.1 Quantitative evaluation measures (Goodness-of-Fit parameters)

Time series: total water level, tide and surge

To assess the quality of the computed water levels, the root-mean-square error (RMSE) is computed based on measured and computed total water levels for the entire 2013-2017 validation period. In addition, as it provides further insight in the origins of remaining errors, the tide and surge component are separated from the total water level (see section 5.1.2) and the quality of both tide and surge is assessed separately.

High waters

The validation results will also be assessed on the capacity to accurately hindcast peaks in water level, including the most extreme high waters in the validation period. Minor differences in timing between computed and measured high waters are less critical than a correct representation of the peak water level. Therefore, the vertical difference between each computed and measured high water (approximately twice a day) is computed and based on this, the error statistics can be determined. Measured and modelled high waters are matched if the difference in timing is less than 4 hrs.

The same can be done for the tidal signal derived from measured and modelled water levels, which yields the quality of the tidal high waters. What remains after subtracting these tidal high waters from the total high waters is called the skew surge, i.e. the difference between the peak water level and the astronomical peak. Note that the skew surge is generally lower than the highest ‘normal’ surge in the hours surrounding the high water peak.

In addition, a subdivision is made between three categories of high water events, based on the height of the measured skew surge:

- events with the 99% lowest skew surge heights,
- events with skew surge heights between 99.0% and 99.8%
- the highest 0.2% skew surges

The latter category represents storm conditions yielding the most extreme skew surge conditions observed in the years 2013-2017. If measurements are complete, this category consists of 8 values, while the first two categories then contain 3492 and 28 values, respectively.

For the total high waters, tidal high waters and skew surge, the bias, standard deviation (std) and RMSE is determined for each of these categories.

Low waters

Since there is also an interest in the accuracy with which low waters are represented (e.g. relevant for water authorities draining into the sea by gravity flow), especially during storm surges, the error statistics for low waters are also computed. This is done in a similar manner as for the high waters. This also holds for the subdivision in categories. Note that the skew surge on which the event classification is based is then determined for the low waters.

Mean water level

The water levels computed with DCSM-FM (or any other hydrodynamic model) refer to an equipotential surface of the Earth's gravity field. Gradients in baroclinic pressure (i.e. due to density differences) affect the movement of water and can, consequently, affect the long-term mean water level (Mean Dynamic Topography, or MDT). However, the density in the model is assumed to be constant and uniform. Furthermore, while tide and surge caused by variations in atmospheric pressure are accounted for at the open boundaries, steric effects (i.e., changes in sea level due to thermal expansion and salinity variations) are not. This affects the representation of the mean water level. Therefore, the bias between measured and computed water levels in each station, determined over the entire five-year validation period, will be disregarded in all Goodness-of-Fit criteria used here. This is achieved by correcting the measurements for this bias before these criteria are determined. Consequently, when considering the entire period, the Root-Mean-Square (RMS) of the error signal is equal to the standard deviation thereof. Another advantage of this approach is that it removes the need to convert all measurements to a uniform vertical reference plane that is valid for the entire model domain. Note that since the model does not correctly represent the MDT, a post-processing correction needs to be added when using this model in an operational setting.

5.1.2 Harmonic analysis

The separation of the tide and surge contribution to the total water level is done by means of harmonic analysis using the MATLAB package t_tide (Pawlowicz et al., 2002). After obtaining the tide through harmonic analysis and prediction, the surge (or ‘non-tidal residual’) is obtained by subtracting the predicted tide from the total water level signal.

Since the 18.6-year nodal cycle is assumed to be constant in the harmonic analysis, we restricted the analysis period to one year. This implies that for each year in the 5-year validation period, the harmonic analysis is performed.

Harmonic analysis is only performed when the completeness index of the measurements is larger than 80% and the length of the available measurements within the analysis period is larger than 300 days.

Based on the possibility to separate constituents using a time series of one year, 118 constituents have been selected to be used in the harmonic analysis. Note that the number of constituents used here is much larger than the number of constituents prescribed on the open boundaries of the model (cf. Table 2.1). This is because many more shallow water constituents, such as compound tides and overtides, are generated inside the model domain, especially in shallow areas where non-linear processes become important. At the location of the open boundaries the amplitudes of these additional constituents are generally assumed to be negligible.

Table 5.1 List of harmonic constituents used for harmonic analysis

Component name	Angular frequency (°/h)	Component name	Angular frequency (°/h)
SA	0.0410667	3MS4	56.9523127
SSA	0.0821373	MN4	57.4238338

MSM	0.4715211	ST9	57.5059711
MM	0.5443746	ST40	57.8860712
MSF	1.0158958	M4	57.9682085
MF	1.0980330	ST10	58.0503457
ALP1	12.3827652	SN4	58.4397296
2Q1	12.8542863	KN4	58.5218669
SIG1	12.9271398	MS4	58.9841042
Q1	13.3986609	MK4	59.0662415
RHO1	13.4715145	SL4	59.5284789
O1	13.9430356	S4	60.0000000
TAU1	14.0251729	SK4	60.0821373
BET1	14.4145567	MNO5	71.3668694
NO1	14.4966940	2MO5	71.9112441
CHI1	14.5695475	MNK5	72.4649025
PI1	14.9178647	2MP5	72.9271398
P1	14.9589314	2MK5	73.0092771
S1	15.0000020	MSK5	74.0251729
K1	15.0410686	2SK5	75.0410686
PSI1	15.0821353	ST11	85.4013260
PHI1	15.1232059	2NM6	85.8635634
THE1	15.5125897	ST12	85.9457007
J1	15.5854433	2MN6	86.4079380
SO1	16.0569644	ST13	86.4900753
OO1	16.1391017	ST41	86.8701754
UPS1	16.6834763	M6	86.9523127
2NS2	26.8794591	MSN6	87.4238338
ST37	26.9523127	MKN6	87.5059711
OQ2	27.3509802	2MS6	87.9682085
EPS2	27.4238338	2MK6	88.0503458
ST2	27.5059711	NSK6	88.5218669
2N2	27.8953549	2SM6	88.9841042
MU2	27.9682085	MSK6	89.0662415
N2	28.4397296	ST16	101.9112441
NU2	28.5125831	3MK7	101.9933814
OP2	28.9019670	ST18	114.8476676
H1	28.9430376	3MN8	115.3920423
M2	28.9841043	ST19	115.4741796
H2	29.0251709	M8	115.9364170
MKS2	29.0662415	ST20	116.4079381
LDA2	29.4556253	ST21	116.4900753
L2	29.5284789	3MS8	116.9523127
T2	29.9589333	3MK8	117.0344500
S2	30.0000000	ST22	117.5059711
R2	30.0410667	ST23	117.9682085
K2	30.0821373	ST24	118.0503458
MSN2	30.5443747	ST26	130.4331109
ETA2	30.6265119	4MK9	130.9774856

2SM2	31.0158958	ST27	131.9933813
SKM2	31.0980330	ST28	144.3761465
NO3	42.3827652	M10	144.9205212
MO3	42.9271398	ST29	145.3920423
M3	43.4761564	ST30	145.9364170
SO3	43.9430356	ST31	146.4900753
MK3	44.0251729	ST32	146.9523127
SK3	45.0410687	M12	173.9046254
ST8	56.4079380	ST34	174.9205212
N4	56.8794591	ST35	175.4741796

5.2 Shelf-wide results

A spatial overview of the RMSE-values of the total water level, tide and surge of all shelf-wide tide gauge stations is given in Figure 5.1 and Figure 5.2 (left- and right-hand side panel), respectively.

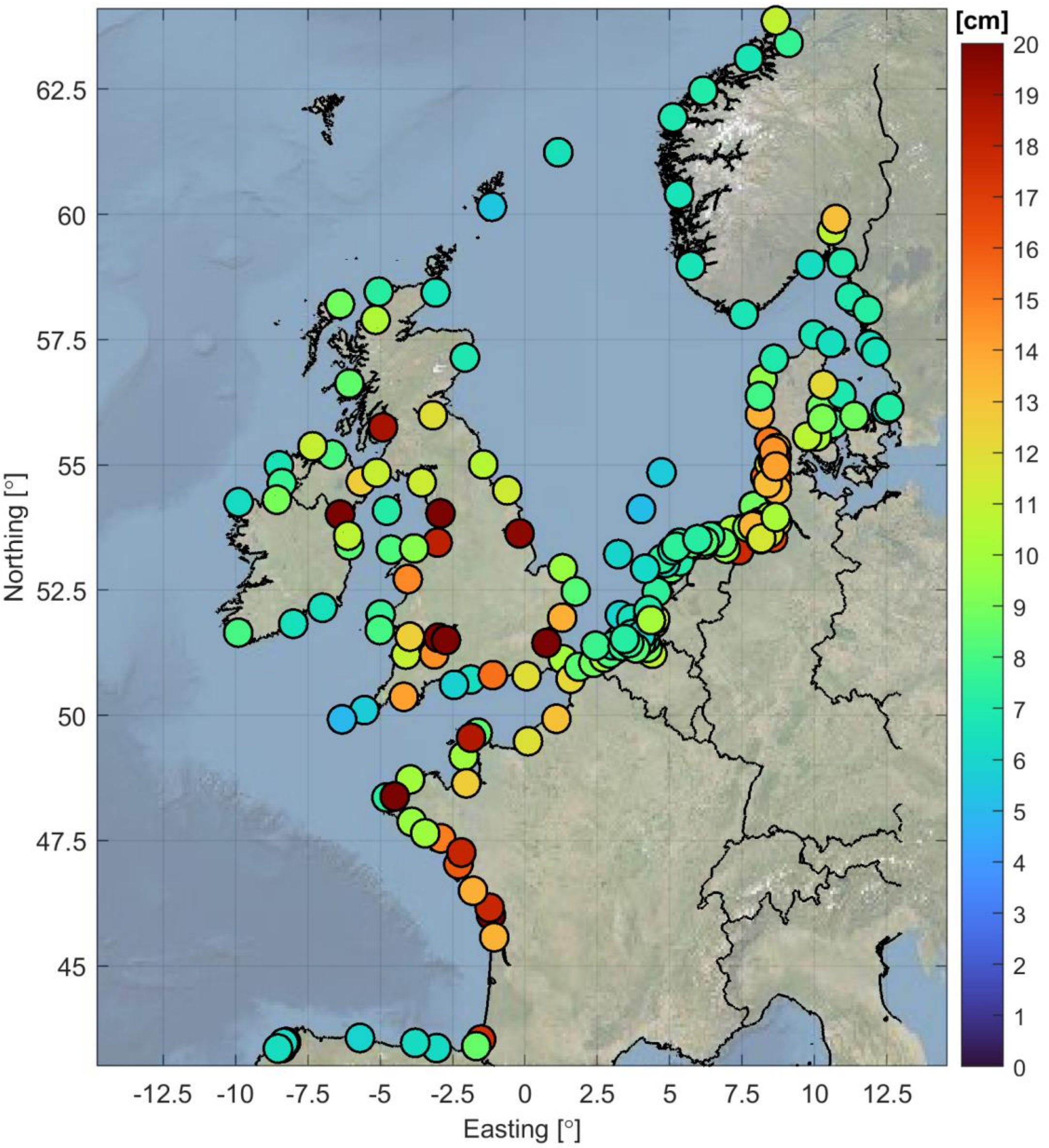

Figure 5.1 Spatial overview of the RMSE-values (cm) of the total water level for the period 2013-2017 of all shelf-wide tide gauge stations

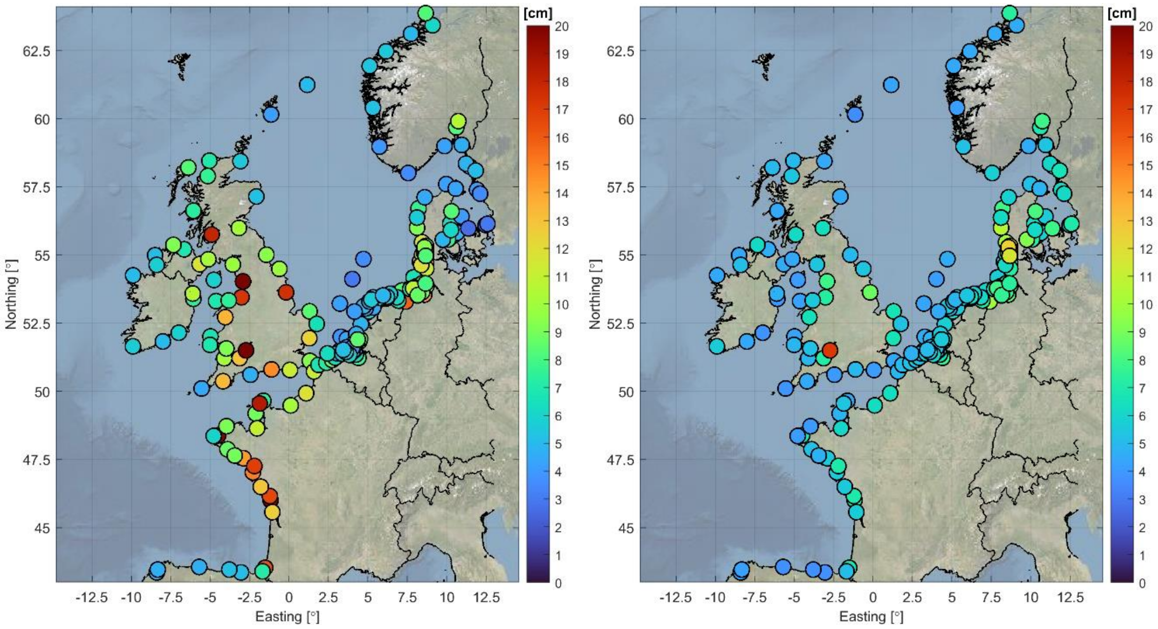

Figure 5.2 Spatial overview of the RMSE-values (cm) of the tide (left panel) and surge (right panel) for the period 2013-2017 of all shelf-wide tide gauge stations

The mean model skill in terms of RMSE for the tide, surge and total water level for all shelf-wide tide gauge stations is summarized in Table 5.2. The error statistics of all individual shelf-wide tide gauge stations (of DCSMv6-ZUNOv6, Delft3D-FM 0.5nm and Delft3D-FM 100m) can be found in Table A.1 in the Appendix.

Table 5.2 Mean statistics (RMSE in cm) of the tide, surge and total water level for the period 2013-2017 of all shelf-wide tide gauge stations

Stations	**RMSE tide (cm)**	**RMSE surge (cm)**	**RMSE water level (cm)**
Shelf-wide	8.3	6.1	10.6

The error statistics of DCSM-FM 100m for three skew surge categories, at all shelf-wide tide gauge stations, can be found in Table A.2 (high water skew surge) and Table A.3 (low water skew surge) in the Appendix.

5.3 Dutch coastal waters

5.3.1 Observation stations

For further analysis of the results, the emphasis will be on a set of 47 Dutch coastal stations with three nearby Belgian and six German stations added. A list of these 56 stations is presented in Table 5.3.

Compared to the set used for validating the DCSM-FM 0.5nm model (Zijl & Groenenboom, 2019), stations further upstream have been added in the Western Scheldt (Bath, Prosperpolder, Liefkenshoek, Kallo, Antwerpen and Hemiksem), the Rhine-Meuse Delta (Maassluis, Vlaardingen, Spijkenisse, Rotterdam, Goidschalxoord) and Wadden Sea (Emden, Pogum, Leerort, Terborg). Another difference compared to the previous set, is that measurements of station Zeebrugge are excluded due to shifts in datum prior to 2017 (the validation period).

To further aid analysis of the model quality, a sub-division is also made in four different sets of stations: 5 offshore stations (more than 10-15 km from coast), 16 stations along the North Sea coast, 12 stations in the Eastern and Western Scheldt (Southwestern Delta), 5 stations in the Rhine-Meuse Delta and 18 stations in the Wadden Sea, including the Ems-Dollard. Within each region, the stations are listed in order of increasing M2 phase lag.

Table 5.3 Names of the tide gauge stations used for quantitative model evaluation in Dutch coastal waters. Some Belgian and German stations nearby have been added, indicated here with BE and DE, respectively. The stations are further subdivided in five groups: Offshore, Coast, South-western delta (SWD), Rhine-Meuse Delta (RMD) and Wadden Sea (incl. Ems-Dollard)

<table>
<tr><th colspan="4">Offshore</th></tr>
<tr><td>1</td><td>EURPFM</td><td>4</td><td>K13APFM</td></tr>
<tr><td>2</td><td>LICHTELGRE</td><td>5</td><td>F16</td></tr>
<tr><td>3</td><td>Q1</td><td></td><td></td></tr>
<tr><th colspan="4">Coast</th></tr>
<tr><td>6</td><td>Wandelaar (BE)</td><td>14</td><td>HOEKVHLD</td></tr>
<tr><td>7</td><td>Bol_Van_Heist (BE)</td><td>15</td><td>SCHEVNGN</td></tr>
<tr><td>8</td><td>Scheur_Wielingen_Bol_van_Knokke (BE)</td><td>16</td><td>IJMDBTHVN</td></tr>
<tr><td>9</td><td>CADZD</td><td>17</td><td>DENHDR</td></tr>
<tr><td>10</td><td>WESTKPLE</td><td>18</td><td>TEXNZE</td></tr>
<tr><td>11</td><td>ROOMPBTN</td><td>19</td><td>TERSLNZE</td></tr>
<tr><td>12</td><td>BROUWHVSGT08</td><td>20</td><td>WIERMGDN</td></tr>
<tr><td>13</td><td>HARVT10</td><td>21</td><td>HUIBGT</td></tr>
<tr><th colspan="4">Southwestern Delta</th></tr>
<tr><td>22</td><td>VLISSGN</td><td>28</td><td>KALLO</td></tr>
<tr><td>23</td><td>TERNZN</td><td>29</td><td>Antwerpen_tij_Zeeschelde</td></tr>
<tr><td>24</td><td>HANSWT</td><td>30</td><td>ROOMPBNN</td></tr>
<tr><td>25</td><td>BATH</td><td>31</td><td>STAVNSE</td></tr>
<tr><td>26</td><td>Prosperpolder_tij_Zeeschelde</td><td>32</td><td>BERGSDSWT</td></tr>
<tr><td>27</td><td>LIEFKENSHOEK</td><td>33</td><td>KRAMMSZWT</td></tr>
<tr><th colspan="4">Rhine-Meuse Delta</th></tr>
<tr><td>34</td><td>MAASSS</td><td>37</td><td>ROTTDM</td></tr>
<tr><td>35</td><td>VLAARDGN</td><td>38</td><td>GOIDSOD</td></tr>
<tr><td>36</td><td>SPIJKNSE</td><td></td><td></td></tr>
<tr><th colspan="4">Wadden Sea</th></tr>
<tr><td>39</td><td>OUDSD</td><td>48</td><td>BORKUM_Sudstrand (DE)</td></tr>
<tr><td>40</td><td>DENOVBTN</td><td>49</td><td>BorkumFischerbalje (DE)</td></tr>
<tr><td>41</td><td>VLIELHVN</td><td>50</td><td>EMSHORN (DE)</td></tr>
<tr><td>42</td><td>WESTTSLG</td><td>51</td><td>EEMSHVN</td></tr>
<tr><td>43</td><td>KORNWDZBTN</td><td>52</td><td>DUKEGAT</td></tr>
<tr><td>44</td><td>HARLGN</td><td>53</td><td>DELFZL</td></tr>
<tr><td>45</td><td>NES</td><td>54</td><td>KNOCK (DE)</td></tr>
<tr><td>46</td><td>LAUWOG</td><td>55</td><td>EMDEN_Neue_Seeschl (DE)</td></tr>
<tr><td>47</td><td>SCHIERMNOG</td><td>56</td><td>POGUM (DE)</td></tr>
</table>

5.3.2 Total water levels, tide and surge

5.3.2.1 DCSM-FM 100m

A spatial overview of the RMSE-values of the total water level, tide and surge of the Dutch coastal stations is presented in Figure 5.3 and Figure 5.4 (left- and right-hand side panel), respectively. Generally, the total water level RMSE is 6-8 cm in North Sea waters. In these stations, the tide and surge RMSE is generally 4-6 cm. The quality deteriorates somewhat in the Dutch estuaries and Wadden Sea, in particular the RMM area, the Ems-Dollard and the Scheldt river. In these areas the model resolution is relatively low compared to the variability in geometry and bathymetry. The result is a poorer representation of the tide, while some impact is also noticeable in the surge quality, presumably due to a worsening representation of the non-linear tide-surge interaction.

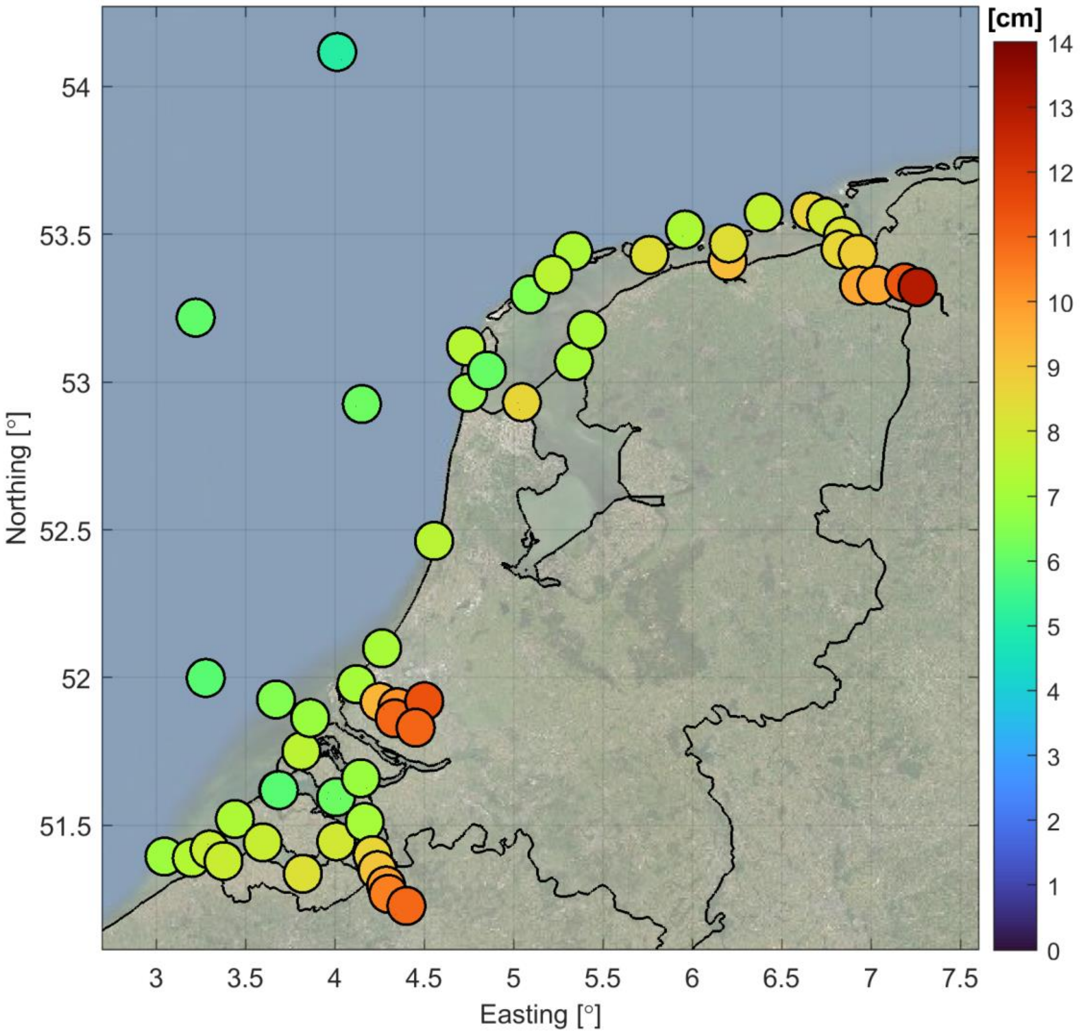

Figure 5.3 Spatial overview of the RMSE-values (cm) of the total water level for the period 2013-2017 of the Dutch coastal stations

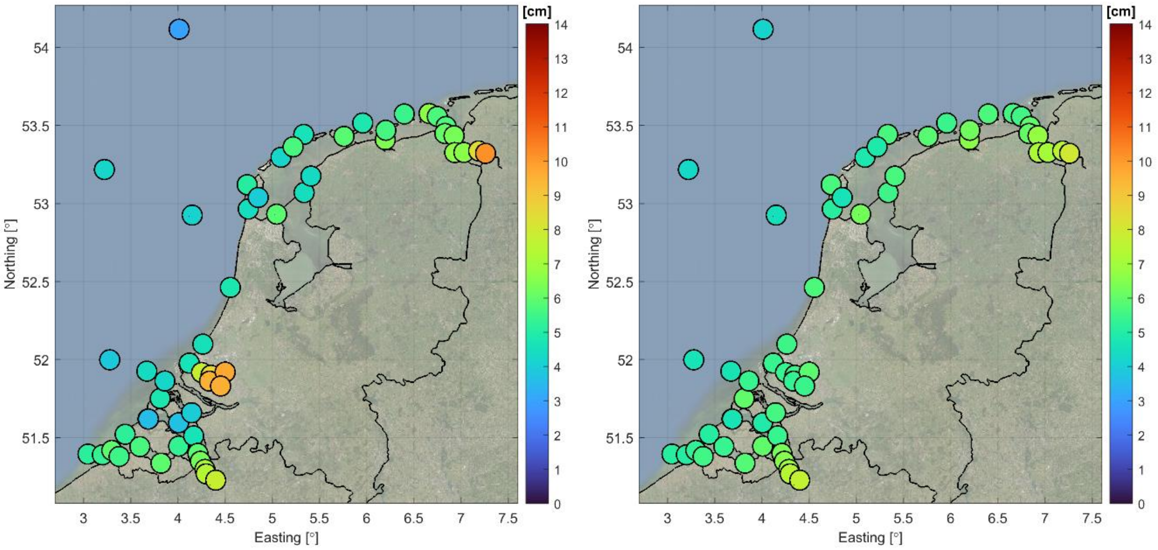

Figure 5.4 Spatial overview of the RMSE-values (cm) of the tide (left panel) and surge (right panel) for the period 2013-2017 of the Dutch coastal stations

5.3.2.2 Comparison against DCSMv6 and DCSMv6-ZUNOv4 (fifth-generation models)

Table 5.4 shows the RMSE of tide, surge and total water level in Dutch coastal stations, for the sixth-generation model DCSM-FM 100m, in comparison to the fifth-generation models DCSMv6 and DCSMv6-ZUNOv4. A spatial overview of the absolute and percentage difference in RMSE (DCSM-FM 100m minus DCSMv6-ZUNOv4), for both total water level, tide and surge, is illustrated in Figure 5.5 to Figure 5.7.

These results show that on average the tide representation is similar compared to DCSMv6-ZUNOv4. This is despite the exclusion of bathymetry as a calibration parameter in the development of DCSM-FM. However, there are some regions where a deterioration is present, notably off and in the downstream part of the Western Scheldt and in the RMM area. The poor tide representation in the RMM area is probably caused by the use of rectangular cells (not boundary fitted) in an area with a course grid compared to the relevant spatial scales of the bathymetry and geometry. While in DCSMv6-ZUNOv4 the grid was also relatively coarse, unlike DCSM-FM 100m it was aligned with the main channel and the bathymetry was adjusted during the calibration to correct for remaining errors in the tidal propagation. The origin of the poorer tide representation in and around the Western Scheldt is unknown. Note that in 5 of the 6 main locations (Dutch: ‘hoofdlocaties’), the tide representation of DCSM-FM is better than DCSMv6-ZUNOv4. The only exception is Vlissingen, where the RMSE of the tide is 5.7 cm against 4.8 for DCSMv6-ZUNOv4. It should however be noted that the quality of the tide representation in DCSMv6-ZUNOv4 has deteriorated since the year for which it has been calibrated (2007).

The quality of the surge in DCSM-FM 100m has improved slightly (by 0.2 cm in all regions) compared to DCSMv6-ZUNOv4. In 5 of the 6 main locations (Dutch: ‘hoofdlocaties’), the quality of the surge of DCSM-FM is better than DCSMv6-ZUNOv4. The only exception is Hoek van Holland, where the RMSE of the surge is 5.4 cm against 5.3 for DCSMv6-ZUNOv4.

Table 5.4 Statistics (RMSE in cm) of tide, surge and total water level of the fifth-generation models (DCSMv6 and DCSMv6-ZUNOv4) and the sixth-generation model (DCSM-FM 100m) for the Dutch coastal stations. The main locations (Dutch: 'hoofdlocaties') are shown in bold. The mean value per region is determined based on the overlapping stations that are present in the different models.

Station	**RMSE tide (cm)**			**RMSE surge (cm)**			**RMSE water level (cm)**		
	DCSMv6	DCSMv6-ZUNOv4	DCSM-FM 100m	DCSMv6	DCSMv6-ZUNOv4	DCSM-FM 100m	DCSMv6	DCSMv6-ZUNOv4	DCSM-FM 100m
Wandelaar	4.9	4.4	5.2	5.4	5.3	5.1	7.0	6.6	6.9
Bol_Van_Heist	4.3	4.7	5.3	5.5	5.3	5.1	7.0	7.1	7.4
Scheur_Wielingen_Bo.	4.4	5.3	5.9	5.6	5.5	5.3	7.1	7.6	7.8
CADZD	4.3	4.4	5.5	5.9	5.7	5.6	7.3	7.3	7.8
WESTKPLE	3.8	4.4	5.2	5.3	5.2	5.1	6.6	6.8	7.3
EURPFM	4.8	4.0	3.9	4.9	4.7	4.6	6.8	6.1	5.9
VLISSGN	**5.2**	**4.8**	**5.7**	**5.9**	**5.5**	**5.4**	**7.9**	**7.3**	**7.8**
ROOMPBTN	**3.9**	**4.4**	**3.6**	**5.4**	**5.2**	**4.9**	**6.6**	**6.8**	**6.1**
LICHTELGRE	4.1	4.9	4.4	4.9	4.8	4.7	6.4	6.8	6.5
BROUWHVSGT08	4.6	5.0	4.8	6.2	6.1	6.0	7.6	7.8	7.5
TERNZN	7.9	5.6	5.9	6.5	6.0	5.8	10.3	8.2	8.3
HARVT10	4.3	4.4	4.2	5.5	5.4	5.4	7.0	7.0	6.8
ROOMPBNN	7.2	4.3	3.6	5.1	4.9	4.7	8.8	6.4	5.9
HANSWT	14.2	6.1	5.3	7.8	6.2	6.0	16.2	8.6	8.0
HOEKVHLD	**4.8**	**5.0**	**4.6**	**5.8**	**5.3**	**5.4**	**7.5**	**7.3**	**7.1**
STAVNSE	5.8	3.9	3.7	5.5	5.2	5.0	7.9	6.4	6.2
BERGSDSWT	7.1	4.6	4.6	6.0	5.5	5.4	9.2	7.1	7.1
KRAMMSZWT		4.3	4.0		6.4	5.6		7.7	6.9
BATH	27.0	5.7	5.9	12.3	6.4	6.3	29.6	8.6	8.6
Prosperpolder_tij_Zee.			6.3			6.5			9.0
LIEFKENSHOEK		6.9	7.1		7.0	6.9		9.8	9.9
SCHEVNGN	5.0	5.2	4.6	5.7	5.6	5.5	7.6	7.6	7.1
KALLO		6.8	7.4		7.4	7.4		10.1	10.5
MAASSS		5.3	7.8		5.4	5.4		7.6	9.4
Antwerpen_tij_Zeesch.		7.7	7.8		7.9	7.7		11.1	10.9
VLAARDGN		5.7	8.5		5.4	5.5		7.9	10.1
SPIJKNSE		6.3	9.5		5.2	5.3		8.2	10.9
ROTTDM		5.9	9.7		5.7	5.9		8.2	11.4
GOIDSOD		6.6	9.5		5.8	5.5		8.7	11.0
IJMDBTHVN	5.9	6.3	4.8	6.0	5.9	5.7	8.4	8.7	7.5
Q1	4.7	4.2	4.2	4.6	4.6	4.5	6.6	6.2	6.1
DENHDR	**5.1**	**4.6**	**4.5**	**5.3**	**5.2**	**5.1**	**7.4**	**6.9**	**6.8**
TEXNZE	5.1	4.9	5.0	5.7	5.7	5.6	7.6	7.4	7.4
K13APFM	3.4	3.4	4.2	4.5	4.4	4.3	5.6	5.5	6.0
F16	2.8	2.9	3.0	4.1	4.4	4.1	5.0	5.2	5.1
OUDSD	4.3	4.8	4.0	4.9	4.7	4.6	6.5	6.7	6.1
DENOVBTN	6.0	6.5	5.9	6.8	6.8	6.3	9.1	9.4	8.6
TERSLNZE	4.3	4.1	4.6	5.8	5.8	5.7	7.2	7.0	7.3
VLIELHVN	5.8	4.7	4.2	5.1	5.0	4.9	7.7	6.9	6.5
WESTTSLG	4.5	3.6	5.7	5.5	5.0	4.9	7.1	6.1	7.5

KORNWDZBTN	4.3	3.7	4.5	6.3	5.7	5.5	7.6	6.8	7.1
WIERMGDN	4.8	4.1	4.9	5.7	5.7	5.5	7.4	6.9	7.2
HUIBGT	5.4	4.9	5.4	6.1	6.1	5.7	7.9	7.5	7.6
HARLGN	**8.0**	**4.5**	**4.3**	**7.8**	**5.8**	**5.7**	**11.2**	**7.3**	**7.1**
NES	8.8	5.9	5.9	7.7	6.0	5.9	11.7	8.4	8.3
LAUWOG	9.4	6.5	6.4	7.5	6.8	6.6	12.0	9.4	9.2
SCHIERMNOG	10.3	7.2	5.6	7.9	6.9	6.2	13.0	10.0	8.3
BORKUM_Sudstrand		4.4	6.6		5.8	5.6		7.2	8.6
BorkumFischerbalje		4.7	5.7		5.8	5.5		7.4	7.9
EMSHORN		5.6	5.7		6.2	6.0		8.4	8.2
EEMSHVN	6.3	6.8	6.1	6.8	6.3	6.0	9.3	9.3	8.6
DUKEGAT		8.2	6.3		7.1	6.7		10.5	8.8
DELFZL	**15.4**	**6.8**	**6.6**	**11.1**	**7.5**	**7.2**	**19.0**	**10.1**	**9.8**
KNOCK		7.1	6.6		7.3	7.0		10.2	9.7
EMDEN_Neue_Seesc.			8.4			7.5			11.2
POGUM		51.5	10.1		12.1	8.0		52.9	12.9
Average (total)	6.5	6.1	5.7	6.2	5.9	5.7	9.0	8.6	8.1
Average (offshore)	4.0	3.9	3.9	4.6	4.6	4.4	6.1	6.0	5.9
Average (coast)	4.7	4.8	4.9	5.7	5.6	5.4	7.3	7.3	7.2
Average (SWD)	10.6	5.0	5.0	7.0	5.7	5.5	12.9	7.5	7.4
Average (WS)	7.6	5.5	5.4	7.0	6.0	5.8	10.4	8.2	7.9
Average (RMM)									

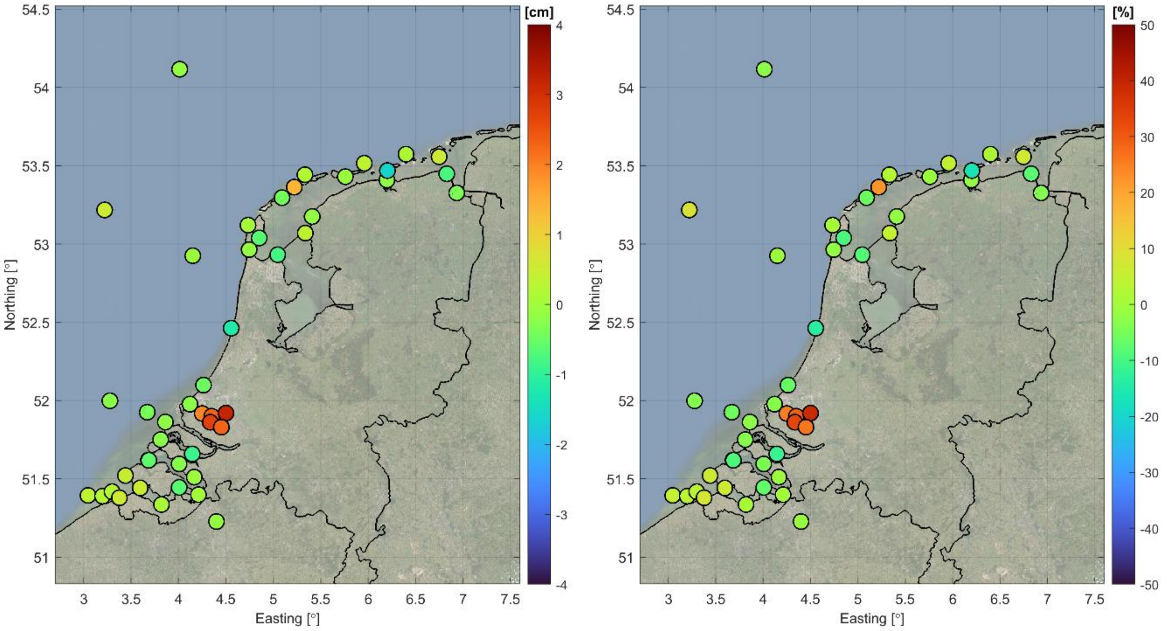

Figure 5.5 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4) in RMSE of the ***total water level*** *for the period 2013-2017 of the Dutch coastal stations. Left: difference (cm); right: relative difference (%).*

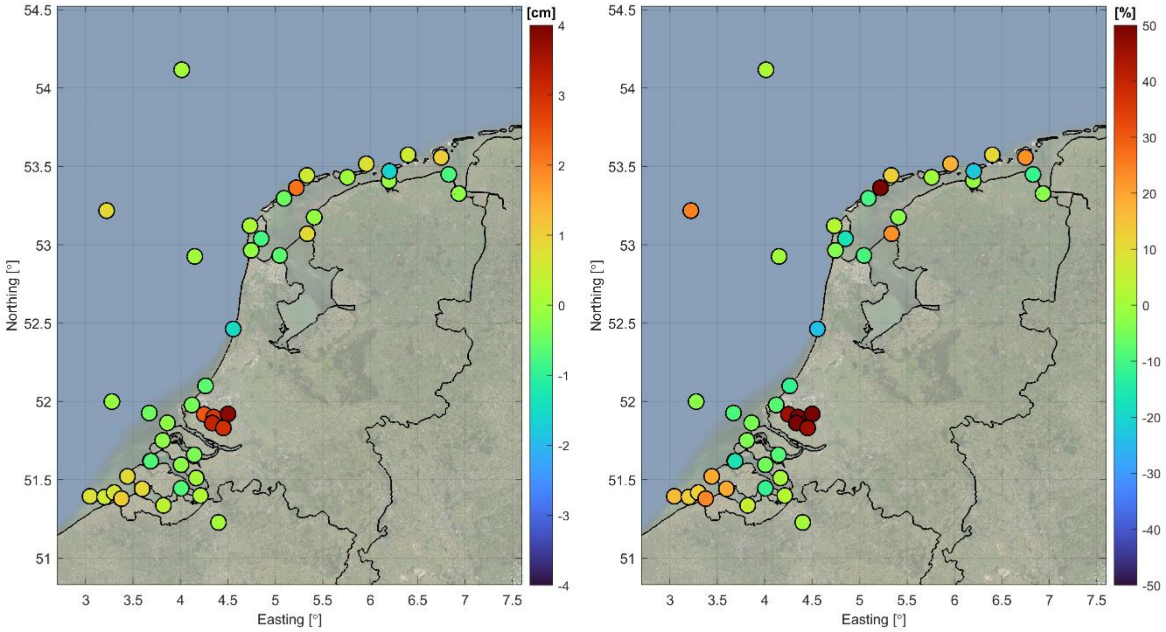

Figure 5.6 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4) in RMSE of the ***tide*** *for the period 2013-2017 of the Dutch coastal stations. Left: difference (cm); right: relative difference (%).*

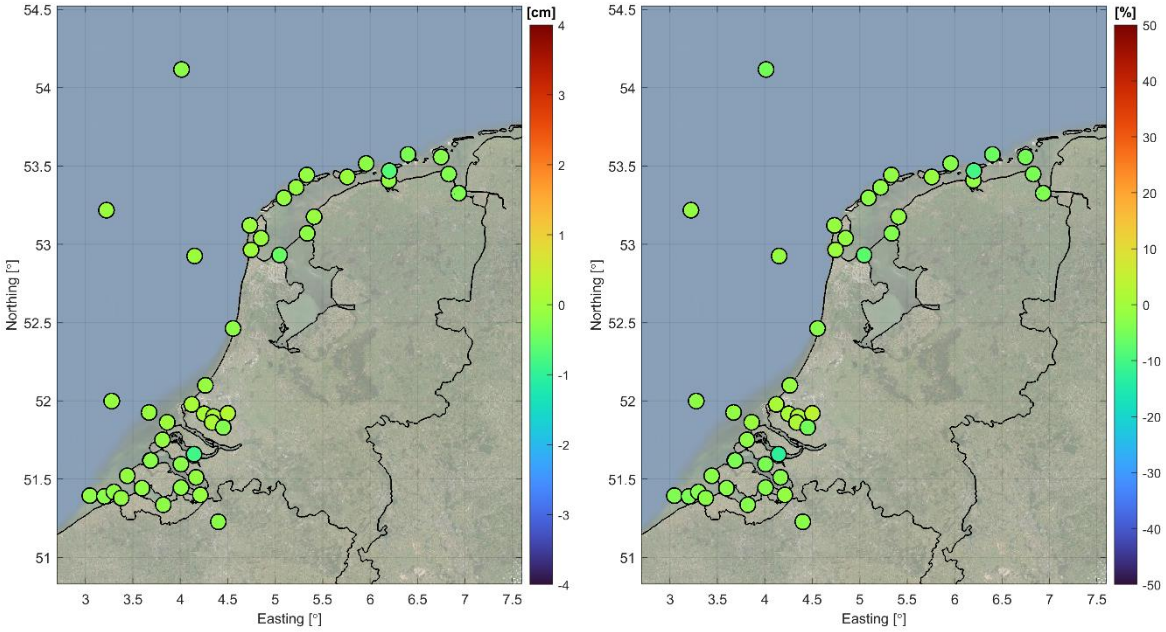

Figure 5.7 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4) in RMSE of the ***surge*** *for the period 2013-2017 of the Dutch coastal stations. Left: difference (cm); right: relative difference (%).*

5.3.2.3 Comparison against DCSM-FM 0.5nm (sixth-generation model)

Table 5.5 shows the RMSE of tide, surge and total water level in Dutch coastal stations, for the sixth-generation model DCSM-FM 100m, in comparison to the sixth-generation model DCSM-FM 0.5nm. A spatial overview of the absolute and percentage difference in RMSE (DCSM-FM 0.5nm minus DCSM-FM 100m), for both total water level, tide and surge, is illustrated in Figure 5.8 to Figure 5.10.

These results show major improvements in tide in the upstream parts of the Eastern and Western Scheldt and in the Wadden Sea, including the Ems-Dollard. These are exactly the areas where DCSM-FM 0.5nm performed poorly due to the coarseness of the network. In the offshore and coastal stations there is a limited improvement in the surge quality (by 0.1 cm). The improvement is larger in the Wadden Sea (from 5.9 cm to 5.4 cm) and Southwestern Delta (from 6.6 cm to 5.9 cm), presumably due to a better representation of the local bathymetry on the higher resolution network and due to improved tide-surge interaction.

Table 5.5 Statistics (RMSE in cm) of tide, surge and total water level of the sixth-generation models (DCSM-FM 0.5nm and DCSM-FM 100m) for the Dutch coastal stations. The main locations (Dutch: 'hoofdlocaties') are shown in bold. The mean value per region is determined based on the overlapping stations that are present in the different models.

Station	**RMSE tide (cm)**		**RMSE surge (cm)**		**RMSE water level (cm)**	
	DCSM-FM 0.5nm	DCSM-FM 100m	DCSM-FM 0.5nm	DCSM-FM 100m	DCSM-FM 0.5nm	DCSM-FM 100m
Wandelaar		5.2		5.1		6.9
Bol_Van_Heist	5.5	5.3	5.2	5.1	7.5	7.4
Scheur_Wielingen_Bo.	5.7	5.9	5.4	5.3	7.7	7.8
CADZD	5.8	5.5	5.7	5.6	8.1	7.8
WESTKPLE	6.3	5.2	5.1	5.1	8.1	7.3
EURPFM	3.7	3.9	4.7	4.6	5.8	5.9
VLISSGN	6.3	5.7	5.6	5.4	8.4	7.8
ROOMPBTN	3.8	3.6	5.0	4.9	6.3	6.1
LICHTELGRE	4.7	4.4	4.7	4.7	6.7	6.5
BROUWHVSGT08	6.1	4.8	6.1	6.0	8.5	7.5
TERNZN	6.7	5.9	6.2	5.8	9.1	8.3
HARVT10	4.3	4.2	5.4	5.4	6.9	6.8
ROOMPBNN	4.4	3.6	4.9	4.7	6.6	5.9
HANSWT	18.9	5.3	7.1	6.0	20.2	8.0
HOEKVHLD	4.4	4.6	5.8	5.4	7.3	7.1
STAVNSE	5.5	3.7	5.4	5.0	7.7	6.2
BERGSDSWT	11.0	4.6	6.2	5.4	12.6	7.1
KRAMMSZWT	8.1	4.0	6.3	5.6	10.2	6.9
BATH		5.9		6.3		8.6
Prosperpolder_tij_Zee.		6.3		6.5		9.0
LIEFKENSHOEK		7.1		6.9		9.9
SCHEVNGN	4.5	4.6	5.6	5.5	7.1	7.1
KALLO		7.4		7.4		10.5
MAASSS		7.8		5.4		9.4
Antwerpen_tij_Zeesch.		7.8		7.7		10.9
VLAARDGN		8.5		5.5		10.1
SPIJKNSE		9.5		5.3		10.9
ROTTDM		9.7		5.9		11.4
GOIDSOD		9.5		5.5		11.0
IJMDBTHVN	5.4	4.8	5.8	5.7	7.9	7.5
Q1	4.2	4.2	4.6	4.5	6.3	6.1
DENHDR	4.2	4.5	5.1	5.1	6.6	6.8

TEXNZE	5.0	5.0	5.6	5.6	7.4	7.4
K13APFM	4.3	4.2	4.4	4.3	6.1	6.0
F16	3.0	3.0	4.1	4.1	5.0	5.1
OUDSD	4.6	4.0	4.7	4.6	6.6	6.1
DENOVBTN	7.4	5.9	6.9	6.3	10.1	8.6
TERSLNZE	4.4	4.6	5.6	5.7	7.1	7.3
VLIELHVN	3.8	4.2	5.0	4.9	6.3	6.5
WESTTSLG	4.8	5.7	5.0	4.9	7.0	7.5
KORNWDZBTN	4.6	4.5	5.7	5.5	7.3	7.1
WIERMGDN	4.8	4.9	5.5	5.5	7.2	7.2
HUIBGT	5.2	5.4	5.7	5.7	7.5	7.6
HARLGN	8.7	4.3	6.8	5.7	11.0	7.1
NES	15.4	5.9	7.6	5.9	17.2	8.3
LAUWOG	14.2	6.4	7.5	6.6	16.0	9.2
SCHIERMNOG	24.2	5.6	9.9	6.2	26.1	8.3
BORKUM_Sudstrand	7.3	6.6	5.7	5.6	9.2	8.6
BorkumFischerbalje	6.7	5.7	5.7	5.5	8.8	7.9
EMSHORN	7.6	5.7	6.1	6.0	9.7	8.2
EEMSHVN	7.2	6.1	6.2	6.0	9.5	8.6
DUKEGAT	8.0	6.3	7.0	6.7	10.1	8.8
DELFZL	10.8	6.6	7.9	7.2	13.4	9.8
KNOCK	11.0	6.6	7.7	7.0	13.4	9.7
EMDEN_Neue_Seesc.		8.4		7.5		11.2
POGUM		10.1		8.0		12.9
Average (total)	7.0	5.7	5.9	5.7	9.2	8.1
Average (offshore)	4.0	3.9	4.5	4.4	6.0	5.9
Average (coast)	5.0	4.9	5.5	5.4	7.4	7.3
Average (SWD)	8.7	4.7	5.9	5.4	10.7	7.2
Average (WS)	9.1	5.6	6.6	5.9	11.4	8.1
Average (RMM)						

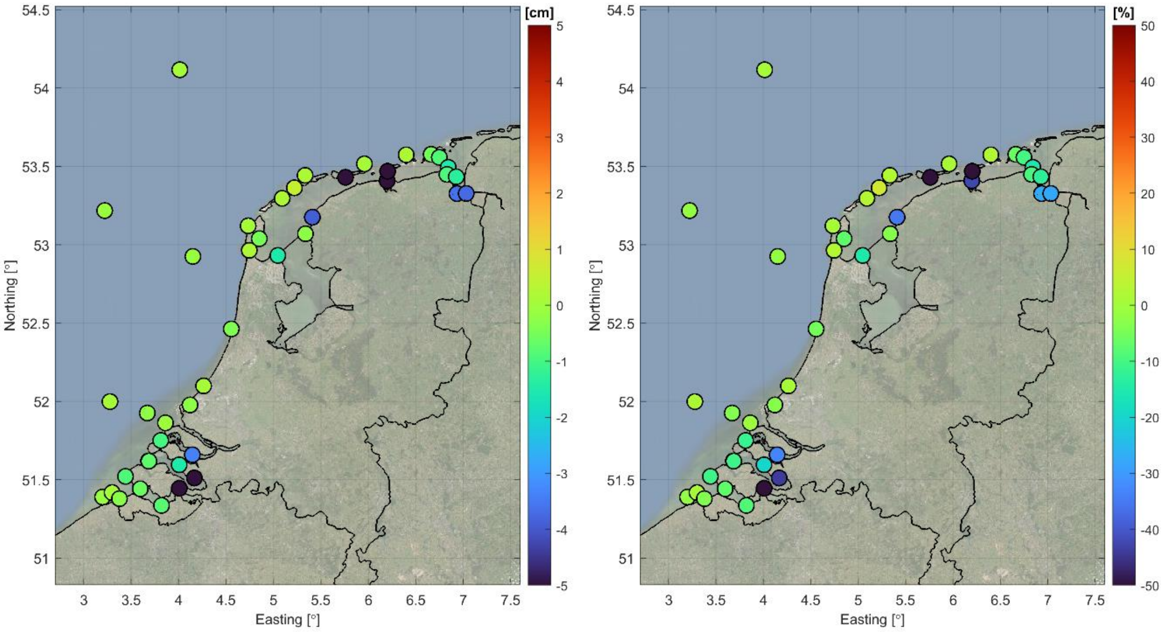

Figure 5.8 Spatial overview of the difference (DCSM-FM 100m minus DCSM-FM 0.5nm) in RMSE of the **total water level** for the period 2013-2017 of the Dutch coastal stations. Left: difference (cm); right: relative difference (%).

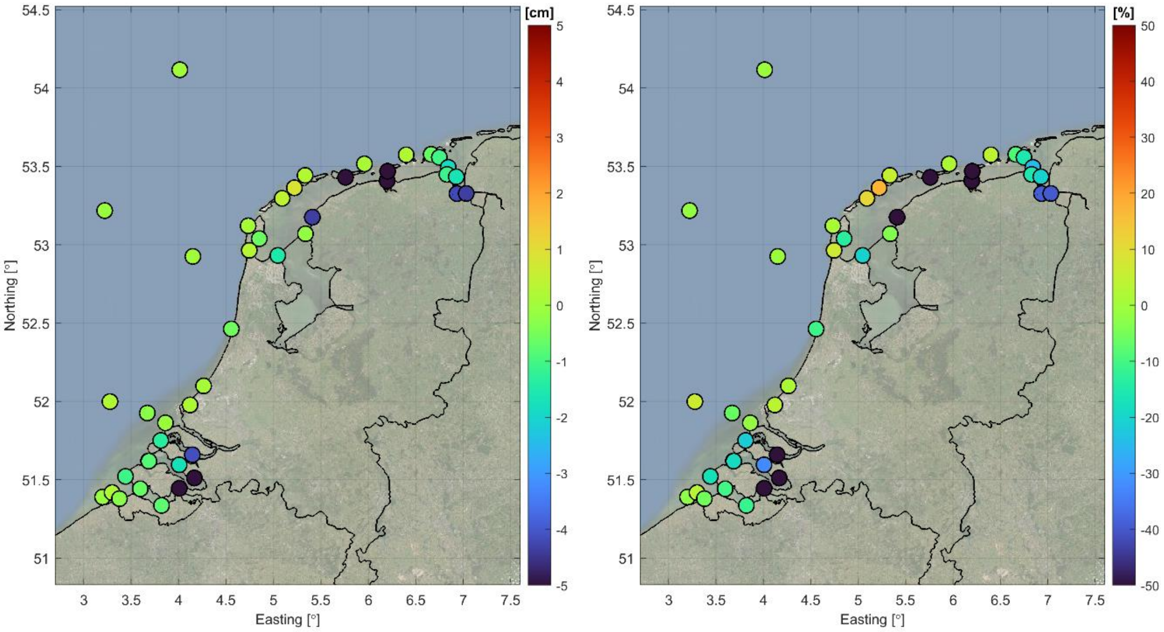

Figure 5.9 Spatial overview of the difference (DCSM-FM 100m minus DCSM-FM 0.5nm) in RMSE of the **tide** for the period 2013-2017 of the Dutch coastal stations. Left: difference (cm); right: relative difference (%).

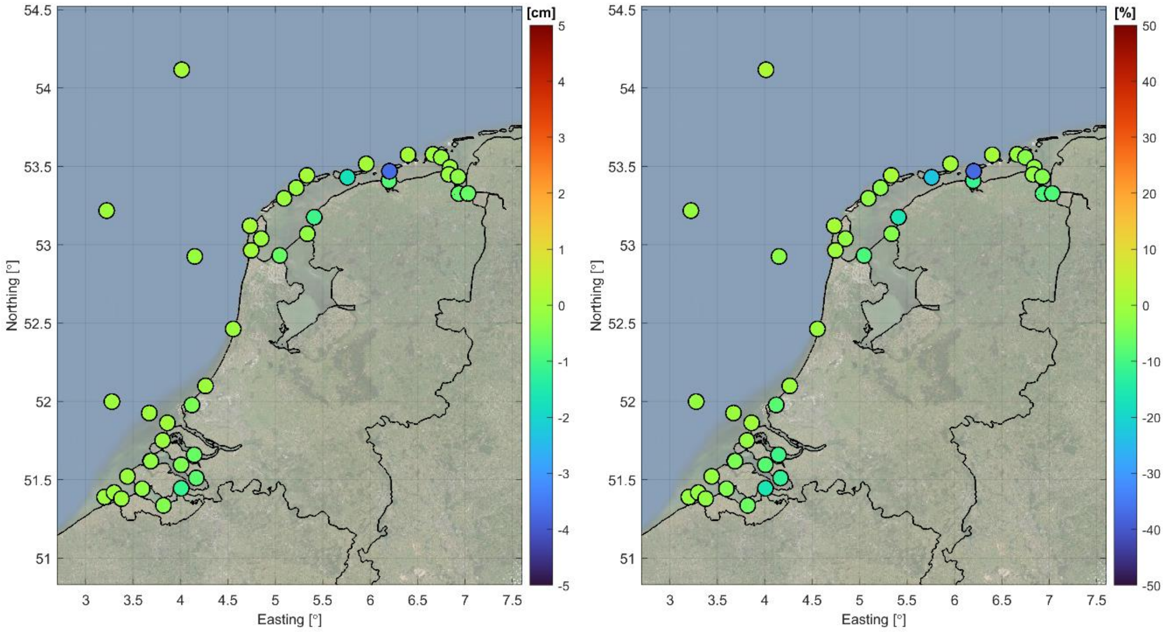

Figure 5.10 Spatial overview of the difference (DCSM-FM 100m minus DCSM-FM 0.5nm) in RMSE of the ***surge*** *for the period 2013-2017 of the Dutch coastal stations. Left: difference (cm); right: relative difference (%).*

5.3.3 Tide (frequency domain)

5.3.3.1 Amplitude and phase error of the M2-component

Figure 5.11 illustrates the amplitude and phase error of the M2-component, respectively. These results show that generally, in stations not hampered by a poor model resolution, the amplitude error is less than 4 cm, while the phase error is less than 2°.

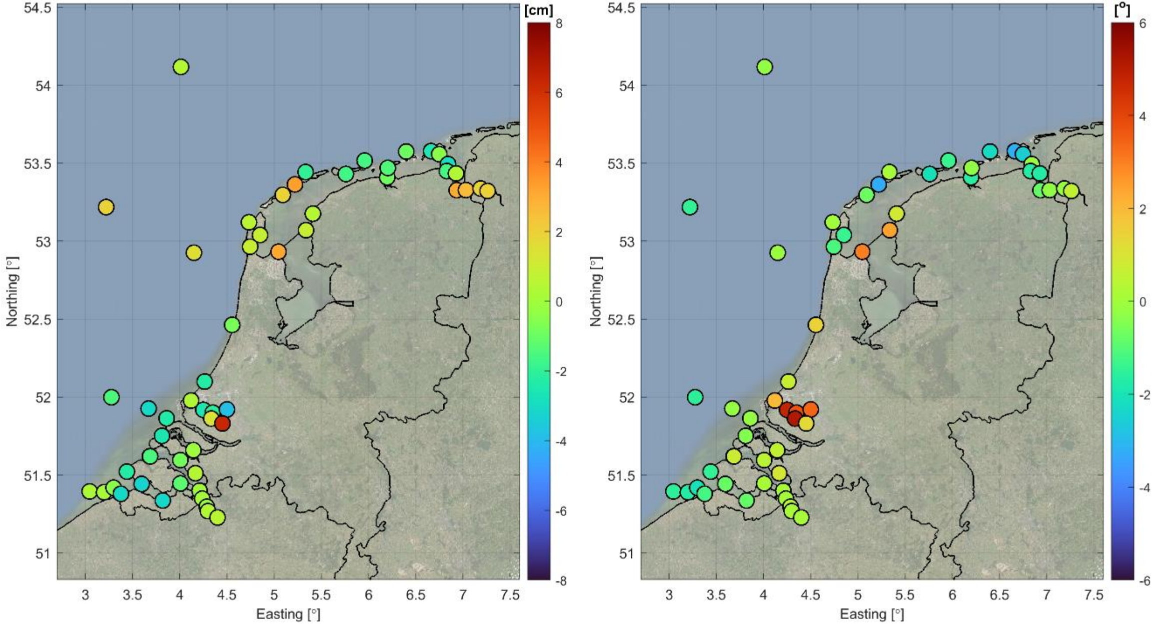

Figure 5.11 Spatial overview of the amplitude error (cm; left) and phase error (°) of the M2-component

5.3.3.2 *Contribution of harmonic components to tidal error*

In Table 5.6 to Table 5.11 an overview is given of the errors in the 10 harmonic constituents with the largest contribution to the tidal error in each of the 6 main locations. These results show that even though M2 is the largest constituent in these stations, it only has the largest contribution to the tidal error in two of the six stations considered here (Vlissingen en Hoek van Holland).

In tide gauge stations Roompot Buiten, Den Helder, and Delfzijl H1 is the harmonic constituent with the largest contribution to the tidal error, while in the other three stations this constituent has the second largest contribution. H1 has an angular frequency that differs one cycle per year from the M2 frequency and together with H2 represents an annual modulation of the M2 tide. Only a minor part of this modulation is gravitational in nature. While the origin is poorly understood, it is at least partially related to the seasonal nature of dissipation due to storms as well as seasonal temperature stratification in the central North Sea. The latter contribution cannot be represented with a 2D barotropic model such as DCSM-FM.

Table 5.6 Overview of the 10 tidal components that have the largest contribution (in terms of vector difference) to the tidal error for station Vlissingen

Vlissingen									
Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)	Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)
M2	171.6	-3.3	-0.8	4.0	N2	28.3	-1.3	-0.3	1.3
H1	3.6	-2.7	-45.2	3.0	SSA	2.9	-0.6	22.4	1.2
M4	12.7	-2.4	3.3	2.5	3MS8	4.4	-1.0	-8.6	1.1
S2	46.4	-1.6	0.0	1.6	NO1	1.1	-0.4	60.5	1.0
MS4	8.4	-1.4	-1.0	1.4	K1	7.1	0.3	-6.7	0.9

Table 5.7 Overview of the 10 tidal components that have the largest contribution (in terms of vector difference) to the tidal error for station Roompot Buiten

Roompot Buiten									
Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)	Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)
H1	2.2	-1.4	-45.2	1.7	NO1	1.1	-0.4	62.4	1.0
M2	133.0	-0.2	-0.7	1.6	K1	7.4	0.3	-7.2	1.0
SSA	3.2	-0.7	23.5	1.3	SA	8.3	-1.0	1.3	1.0
M6	6.7	0.3	-9.1	1.1	S1	0.7	0.9	4.9	0.9
M4	12.3	-0.7	4.0	1.1	SIG1	0.3	0.7	-41.5	0.8

Table 5.8 Overview of the 10 tidal components that have the largest contribution (in terms of vector difference) to the tidal error for station Hoek van Holland

Hoek van Holland									
Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)	Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)
M2	76.5	0.4	2.0	2.7	SA	8.6	-0.7	-7.1	1.3
H1	1.6	-0.9	-79.1	1.6	M4	17.9	0.8	2.9	1.2
S2	18.1	0.3	4.7	1.5	SSA	3.6	-0.7	16.5	1.2
M6	4.5	-0.9	13.2	1.3	H2	0.8	0.0	87.5	1.1
K1	8.0	0.8	-6.6	1.3	N2	11.3	-0.6	4.3	1.0

Table 5.9 Overview of the 10 tidal components that have the largest contribution (in terms of vector difference) to the tidal error for station Den Helder

Den Helder									
Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)	Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)
H1	2.4	-1.8	-71.5	2.3	2MS6	5.5	1.0	-8.9	1.4
M4	10.3	0.2	8.9	1.6	SSA	4.7	-0.6	16.0	1.3
M2	62.6	0.9	-1.2	1.6	H2	0.8	-0.2	148.9	1.2
SA	10.8	-1.5	-1.6	1.5	K1	7.7	0.8	-6.1	1.1
S2	17.5	0.9	-3.8	1.5	M6	5.8	0.2	-9.5	1.0

Table 5.10 Overview of the 10 tidal components that have the largest contribution (in terms of vector difference) to the tidal error for station Harlingen

Harlingen									
Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)	Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)
M4	10.7	0.1	12.6	2.4	NO1	1.2	-0.6	66.0	1.1
H1	2.5	-2.0	4.6	2.0	MS4	5.9	0.2	9.5	1.0
SSA	5.9	-0.3	13.2	1.4	MN4	3.4	0.1	16.7	1.0
M2	80.8	0.5	0.9	1.3	2MS6	3.7	-1.0	-0.6	1.0
M6	4.2	-1.2	5.7	1.3	MU2	11.0	-0.3	5.0	1.0

Table 5.11 Overview of the 10 tidal components that have the largest contribution (in terms of vector difference) to the tidal error for station Delfzijl

Delfzijl									
Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)	Comp.	Obs. ampl. (cm)	Ampl. error (cm)	Phase error (º)	VD (cm)
H1	6.1	-4.2	-47.8	5.0	H2	0.8	0.2	-134.4	1.7
M2	131.7	2.9	-0.8	3.5	NO1	1.4	-0.6	68.0	1.3
M4	18.1	-1.4	5.2	2.1	M6	6.9	-0.1	-10.6	1.3
MS4	10.7	-1.5	6.0	1.8	SSA	6.2	-0.3	10.3	1.1
2MS6	6.5	-1.3	-11.3	1.7	MN4	5.9	-0.5	8.0	0.9

5.3.4 Skew surge (high waters)

The error statistics for three skew surge categories, at the Dutch coastal stations, can be found in Table 5.12. A spatial overview of the RMSE of the high water skew surge (<99.0%, i.e., calm conditions) in the Dutch coastal stations is presented in Figure 5.12. This shows a skew surge error of around 5-6 cm in North Sea waters and most parts of the Wadden Sea and Dutch estuaries. The value of 6.0 cm is only exceeded in Rotterdam, the Belgian part of the Scheldt river (from Prosperpolder onward) and the Ems-Dollard (upstream from Dukegat). The largest error (8.3 cm) is found in Antwerp. The high water skew surge is less sensitive to the quality with which the tide is represented (compared to the surge), which yields a more uniform model quality.

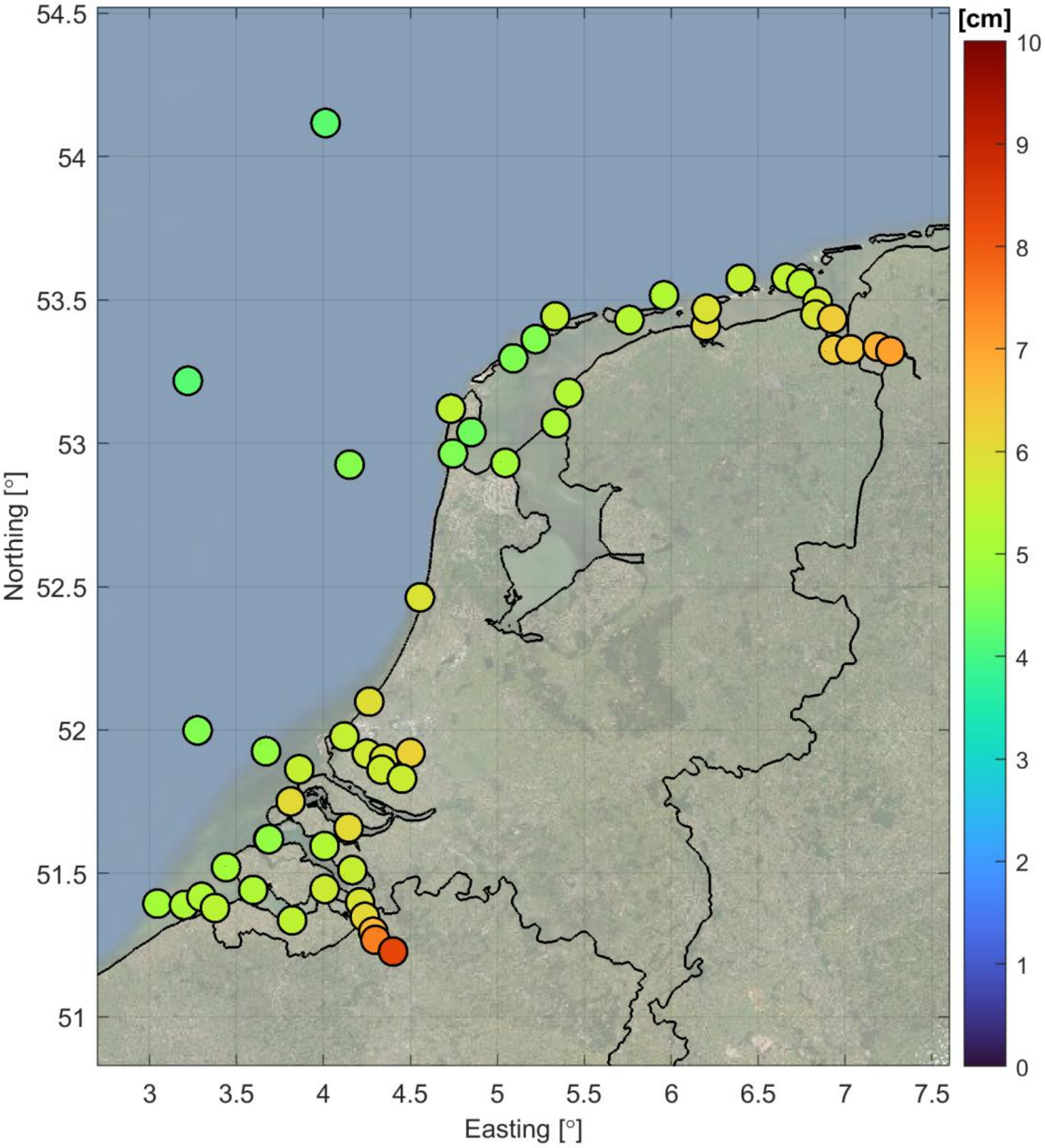

Figure 5.12 Spatial overview of the RMSE (cm) of the skew surge height for high waters (<99.0% skew surges)

In Figure 5.13, the bias and RMSE of the most extreme (>99.8%) skew surge events are presented. This shows an excellent quality in southern waters, with RMSE values less than 10-15 cm. One notable exception in that region is Brouwershavense Gat, which exhibits a bias of

-15.1 cm and consequently has an RMSE of 20.9 cm. This is presumably caused by the presence of seiches during storms, which are not represented in the model.

Stations in the north, especially inside the Wadden Sea show larger skew surge errors. This is mostly due to a large systematic underestimation of the skew surge during storms. The bias is generally largest in the eastern part of the Wadden Sea and the Ems-Dollard in particular. There, the bias can reach 30-40 cm.

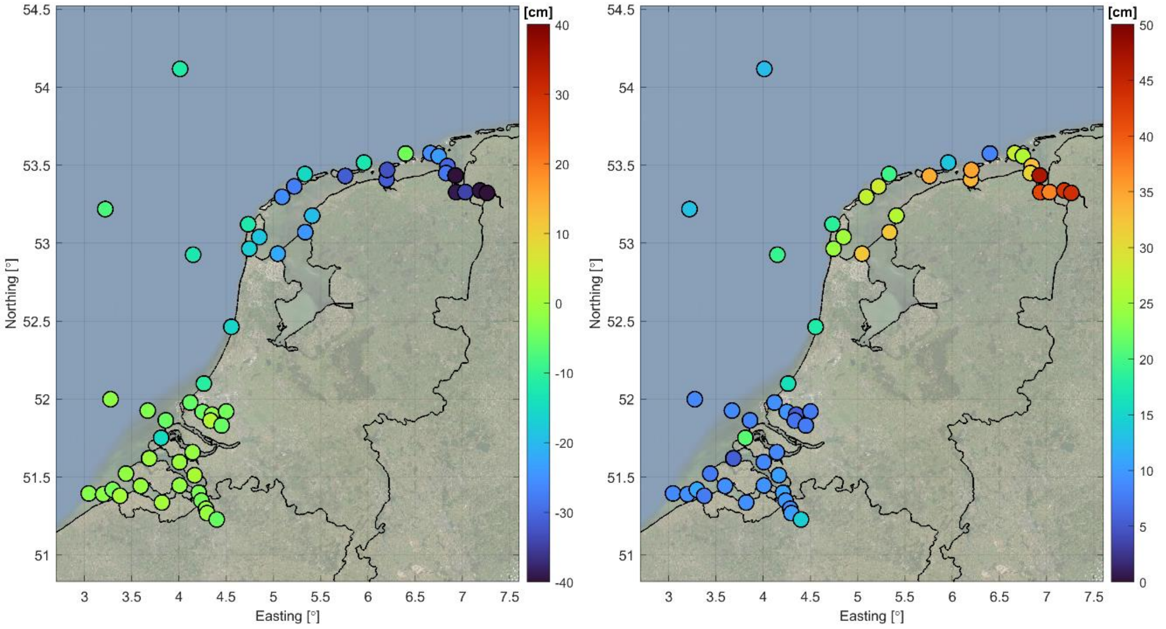

Figure 5.13 Spatial overview of the bias in cm (left panel) and RMSE in cm (right panel) of the skew surge height for high waters (>99.8% skew surges)

Table 5.12 Overview of the model skill to represent tidal high waters (all events) and skew surge heights (high waters) for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal high water		**Skew surge (high water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Total	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar	0.1	2.7	-0.3	5.0	0.6	8.1	-2.8	8.5	8.9
Bol_Van_Heist	0.6	2.7	-1.0	5.2	0.0	7.6	-2.2	9.0	9.3
Scheur_Wielingen_.	-0.6	2.7	-0.1	5.2	-0.6	9.3	-4.0	10.3	11.0
CADZD	-4.8	5.8	0.1	5.4	0.6	8.1	0.2	7.7	7.7
WESTKPLE	-4.4	5.4	0.3	5.0	2.5	7.3	-1.9	7.6	7.8
EURPFM	-2.9	3.9	0.3	4.6	0.8	7.2	-1.9	8.4	8.6
VLISSGN	-6.7	7.9	0.1	5.2	1.7	8.3	-1.0	9.2	9.3
ROOMPBTN	-2.1	3.5	-0.5	4.9	-1.6	9.7	-8.2	8.3	11.7
LICHTELGRE	-6.3	7.3	-0.5	4.8	0.2	8.0	-3.1	8.4	8.9
BROUWHVSGT08	-6.6	7.7	-1.3	6.0	-5.9	14.5	-15.1	14.5	20.9
TERNZN	-6.2	7.9	0.1	5.4	0.9	10.2	0.2	9.3	9.3
HARVT10	-4.7	5.7	-1.1	5.5	-0.7	11.0	-5.3	6.3	8.2
ROOMPBNN	-3.2	4.0	-0.5	4.8	3.2	9.6	-0.4	5.6	5.6
HANSWT	-1.0	5.5	1.0	5.7	2.9	9.8	-1.8	9.4	9.6
HOEKVHLD	1.3	3.9	-0.1	5.5	-1.7	11.5	-5.5	7.4	9.2
STAVNSE	-1.2	3.0	-0.1	5.2	6.0	11.4	-0.6	8.7	8.7
BERGSDSWT	1.2	3.6	0.5	5.5	8.5	12.6	1.0	10.4	10.4
KRAMMSZWT	-0.1	3.1	-0.6	6.0	2.9	10.9	-1.5	8.6	8.7
BATH	1.1	6.5	1.1	5.8	2.8	11.1	-3.4	10.1	10.7
Prosperpolder_tij_Z.	1.2	6.5	1.6	6.1	3.0	12.0	-3.9	9.1	9.9
LIEFKENSHOEK	2.9	7.1	2.8	6.7	0.1	11.2	-1.3	8.9	9.0
SCHEVNGN	-2.4	4.4	-1.3	6.0	-3.0	10.4	-10.8	12.2	16.3
KALLO	5.9	8.9	3.7	7.5	0.5	11.5	-1.1	10.2	10.3
MAASSS	-6.3	8.5	-0.1	5.7	2.4	8.5	-4.9	8.3	9.6
Antwerpen_tij_Zees.	6.5	8.9	4.7	8.3	1.7	11.0	-5.2	13.5	14.4
VLAARDGN	-9.4	12.0	-1.8	5.8	2.4	9.8	-2.3	5.0	5.5
SPIJKNSE	-2.2	6.6	-0.5	5.6	2.9	8.7	1.9	6.9	7.1
ROTTDM	-14.5	17.0	-2.2	6.2	-0.2	9.8	-4.1	6.5	7.7
GOIDSOD	4.4	7.7	0.3	5.6	1.1	7.9	-5.1	5.8	7.7
IJMDBTHVN	0.2	3.6	-1.5	5.9	-4.2	12.7	-15.8	7.9	17.7
Q1	0.8	3.4	-0.7	4.7	-1.0	9.8	-12.4	14.7	19.2
DENHDR	1.0	3.0	-0.6	4.6	-4.6	8.8	-17.0	17.6	24.5
TEXNZE	2.6	4.9	-1.1	5.4	-5.7	13.8	-12.2	13.8	18.4
K13APFM	-0.5	3.3	-0.1	4.2	0.7	6.3	-7.7	10.6	13.1
F16	0.6	2.8	-0.3	4.2	-0.5	5.4	-11.7	4.4	12.5
OUDSD	0.3	2.8	-0.4	4.4	-3.3	7.9	-18.2	17.1	24.9
DENOVBTN	2.7	4.0	-0.7	5.0	-6.7	10.4	-22.2	23.1	32.0
TERSLNZE	0.1	3.0	-0.9	5.5	-5.0	11.7	-15.1	12.5	19.6
VLIELHVN	1.9	3.4	-0.2	4.6	-4.5	9.9	-25.6	9.1	27.2
WESTTSLG	2.7	3.9	-0.3	4.6	-4.5	10.1	-27.4	7.7	28.4

KORNWDZBTN	2.9	4.3	-0.7	5.1	-5.7	11.2	-24.1	21.0	32.0
WIERMGDN	-2.0	3.8	-0.4	5.3	3.8	10.1	-12.7	4.8	13.6
HUIBGT	-1.9	4.2	-0.7	5.5	7.3	11.5	-4.2	7.3	8.4
HARLGN	3.5	4.8	-0.4	5.3	-5.3	12.1	-19.6	17.6	26.4
NES	1.7	3.7	0.2	5.3	-11.6	16.3	-31.5	13.4	34.2
LAUWOG	1.3	4.5	-0.1	6.0	-8.0	14.2	-31.1	12.8	33.7
SCHIERMNOG	1.6	3.8	0.0	5.9	-7.9	13.9	-32.6	12.4	34.9
BORKUM_Sudstran.	-2.1	4.3	-0.3	5.4	-1.3	9.9	-25.4	11.5	27.9
BorkumFischerbalje	0.8	3.4	-0.1	5.4	0.6	9.3	-23.6	11.3	26.2
EMSHORN	-0.2	3.7	-0.1	5.7	-3.6	11.8	-30.1	12.7	32.7
EEMSHVN	1.0	3.9	-0.4	5.8	-3.5	11.7	-28.4	11.9	30.8
DUKEGAT	2.3	5.0	-0.4	6.4	-2.7	16.1	-43.9	15.6	46.6
DELFZL	4.8	6.5	0.5	6.4	-4.8	13.4	-39.0	14.2	41.5
KNOCK	5.0	6.6	0.4	6.4	-2.3	13.2	-34.1	14.7	37.2
EMDEN_Neue_See.	6.9	8.6	0.0	6.8	-0.9	15.3	-39.5	17.2	43.1
POGUM	7.6	9.6	-0.3	7.1	-1.5	16.5	-41.0	15.4	43.8
Average (total)	-0.3	5.3	-0.1	5.6	-0.9	10.7	-13.2	10.8	18.4
Average (offshore)	-1.7	4.1	-0.3	4.5	0.0	7.4	-7.4	9.3	12.5
Average (coast)	-1.5	4.2	-0.7	5.4	-1.1	10.4	-8.3	9.7	13.3
Average (SWD)	0.0	6.1	1.2	6.0	2.9	10.8	-1.6	9.4	9.7
Average (WS)	2.5	4.8	-0.2	5.6	-4.3	12.4	-29.8	14.4	33.5
Average (RMM)	-5.6	10.4	-0.9	5.8	1.7	9.0	-2.9	6.5	7.5

Comparison against DCSMv6 and DCSMv6-ZUNOv4 (fifth-generation models) and DCSM-FM 0.5nm (sixth-generation model)

The error statistics (at the Dutch coastal stations) for the fifth- and sixth-generation models can be found in the Appendix (DCSMv6: Table A.4; DCSMv6-ZUNOv4: Table A.5; DCSM-FM 0.5nm; Table A.6). These results are summarised in Table 5.13, where the station-averaged error statistics for each region are compared for all four-, fifth- and sixth-generation models. In this table, the model skill is determined solely taking into account stations that are present in all four models.

The results show that for the lowest 99% skew surges, the skew surge error of DCSM-FM 100m is lower than for the other three models, in all regions. For the highest class of skew surge events, the quality is similar for all four models, with some minor regional differences. In three of the four regions DCSM-FM 100m is slightly better than the other models, while in the Wadden Sea it is lightly worse. The quality of the tidal high waters is better than DCSM-FM 0.5nm in all regions, except for the Wadden Sea, where it is marginally worse (4.2 cm vs. 4.1 cm). Compared to DCSMv6-ZUNOv4, the tidal high waters have the same quality on average, with the offshore and Southwestern Delta stations performing a bit worse, and the coastal and Wadden Sea stations slightly better.

Table 5.13 Comparison of the station-averaged model skill to represent tidal high waters (all events) and skew surge heights (high waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations.

	Tidal high water		**Skew surge (high water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Total	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	std (cm)	RMSE (cm)
DCSMv6	2.8	5.5	-0.2	5.7	1.5	11.5	-10.7	12.3	17.8
DCSMv6-ZUNOv4	2.5	4.4	-0.3	5.4	-0.9	10.8	-13.5	12.1	19.0
DCSM-FM 0.5nm	-0.8	4.8	-0.4	5.5	-0.5	10.5	-11.9	11.4	18.0
DCSM-FM 100m	-0.7	4.4	-0.4	5.2	-1.7	10.5	-12.7	11.0	18.0
Offshore									
DCSMv6	0.9	3.4	-0.2	4.8	0.2	7.7	-8.2	9.6	13.5
DCSMv6-ZUNOv4	0.8	3.0	-0.2	4.6	0.1	7.5	-9.0	9.4	13.5
DCSM-FM 0.5nm	-1.9	4.3	-0.3	4.6	-0.4	7.4	-7.7	9.8	13.0
DCSM-FM 100m	-1.7	4.1	-0.3	4.5	0.0	7.4	-7.4	9.3	12.5
Coast									
DCSMv6	1.6	3.9	-0.8	5.6	0.2	11.1	-8.8	11.1	14.8
DCSMv6-ZUNOv4	2.9	4.5	-0.6	5.5	-1.2	11.2	-10.6	11.2	15.9
DCSM-FM 0.5nm	-2.2	4.8	-1.0	5.6	-1.2	10.7	-9.3	10.1	14.3
DCSM-FM 100m	-1.6	4.3	-0.7	5.4	-1.2	10.5	-8.7	9.8	13.6
South-western Delta									
DCSMv6	3.3	9.6	0.4	6.4	8.1	13.2	2.7	9.6	10.2
DCSMv6-ZUNOv4	2.0	4.4	0.0	5.4	2.7	10.1	-2.9	10.1	10.6
DCSM-FM 0.5nm	2.7	6.4	0.2	5.9	6.7	11.8	2.7	8.8	9.6
DCSM-FM 100m	-2.8	5.3	0.2	5.3	3.9	10.3	-0.4	8.8	8.8
Wadden Sea									
DCSMv6	5.0	6.4	0.1	6.0	0.2	12.9	-21.5	16.7	27.8
DCSMv6-ZUNOv4	3.2	4.8	-0.1	5.6	-2.8	12.2	-25.3	15.8	30.2
DCSM-FM 0.5nm	-0.4	4.1	-0.1	5.6	-3.7	11.0	-25.2	15.3	30.0
DCSM-FM 100m	2.2	4.2	-0.2	5.3	-6.0	11.9	-27.2	14.6	31.5

5.3.5 Skew surge (low waters)

The error statistics for three low water skew surge categories, at the Dutch coastal stations, can be found in Table 5.14. A spatial overview of the RMSE of the low water skew surge (<99.0%, i.e., calm conditions) in the Dutch coastal stations is presented in Figure 5.14. This shows a skew surge error of around 5-6 cm in North Sea waters and most parts of the Wadden Sea and Dutch estuaries. Values of 6.5 cm and higher only occur at station Den Oever buiten (8.7 cm) cm and in the Ems-Dollard (Dukegat and further upstream). The relatively high error in Den Oever buiten might be caused by discharges through the sluices during low water.

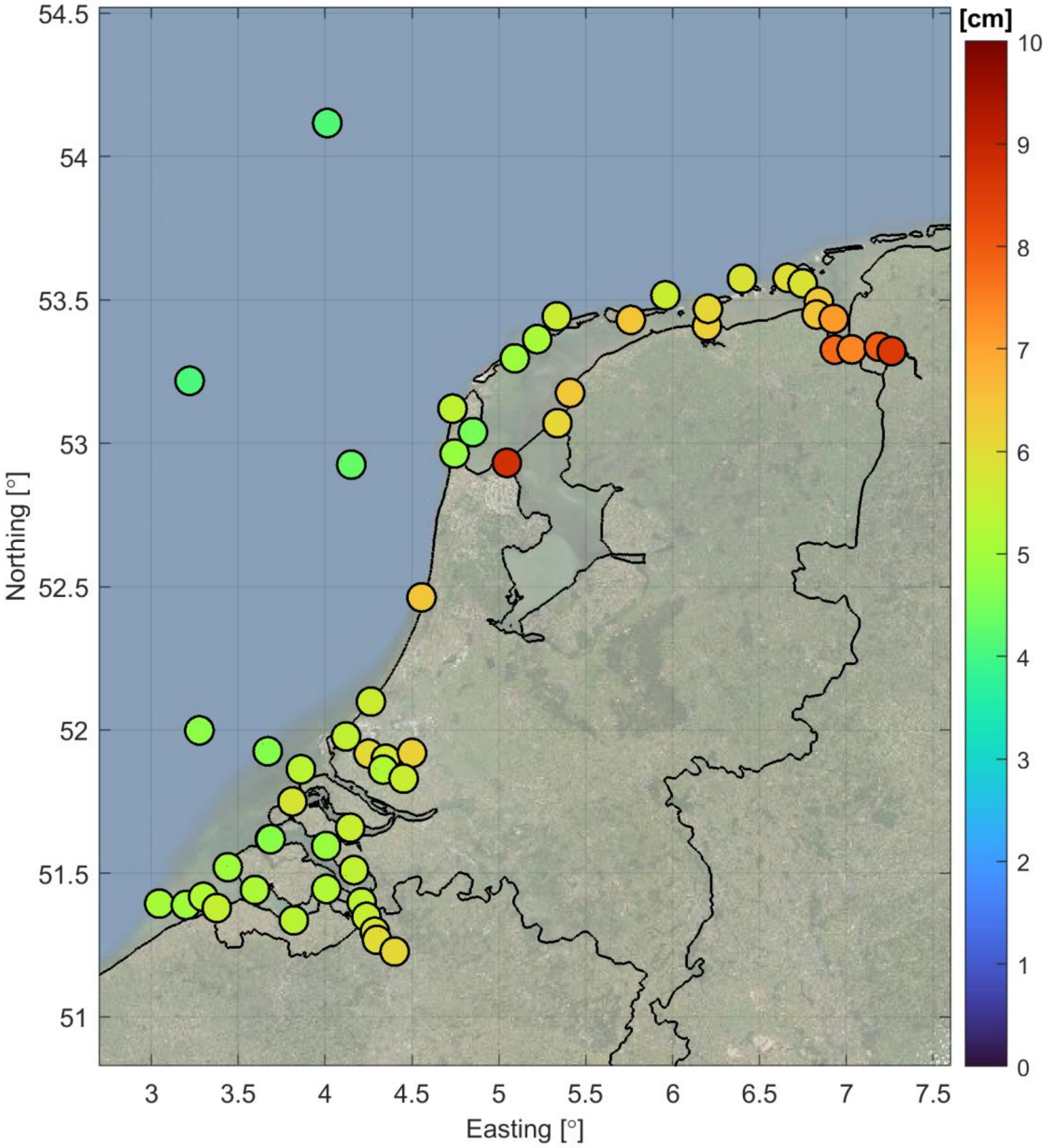

Figure 5.14 Spatial overview of the RMSE (cm) of the skew surge height for low waters (<99.0% skew surges)

In Figure 5.15, the bias and RMSE of the low water skew surge during the most extreme (>99.8%) skew surge events are presented. In southern waters this shows a larger systematic underestimation of low waters than for high waters during the same category of events. The underestimation increases in upstream direction inside the Western Scheldt, with a bias of -18.9 cm at Antwerp. In northern waters, the systematic error (bias) is less severe than for the high water skew surge, in particular in the Ems-Dollard where the bias is 10-15 cm, compared to 30-40 cm for the high water skew surge. The highest bias in the low water skew surge can be found in Nes, with a value of -28.1 cm.

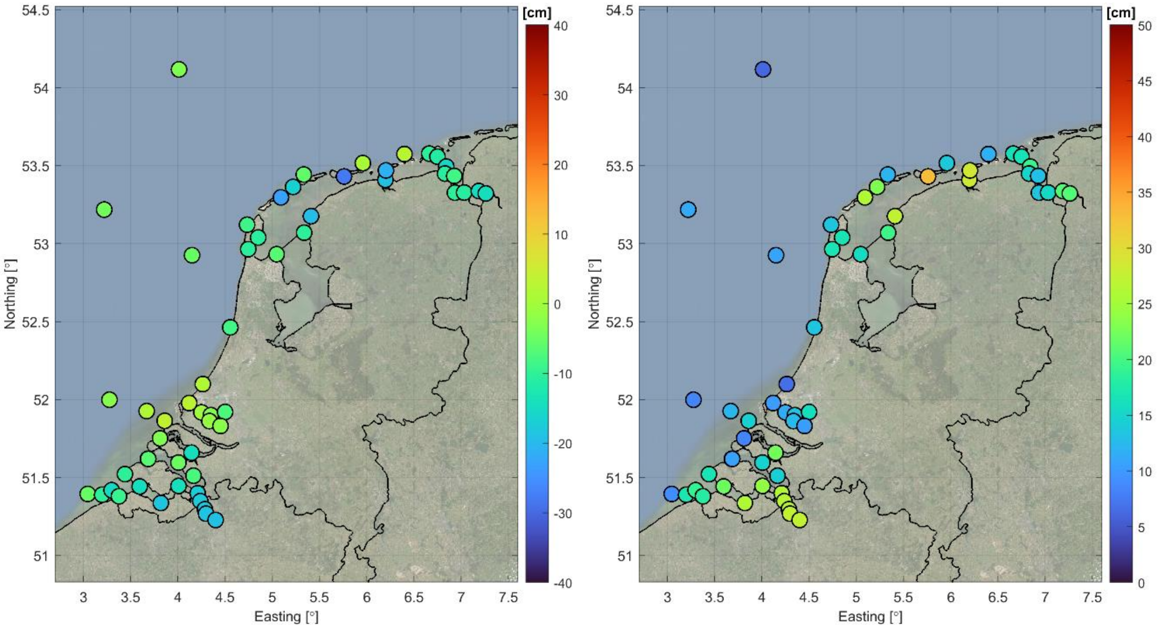

Figure 5.15 Spatial overview of the bias in cm (left panel) and RMSE in cm (right panel) of the skew surge height for low waters (>99.8% skew surges)

Table 5.14 Overview of the model skill to represent tidal low waters (all events) and skew surge heights (low waters) for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal low water		**Skew surge (low water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Total	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar	-2.9	4.9	0.2	5.1	-2.2	10.8	-5.3	7.4	9.1
Bol_Van_Heist	-2.3	4.4	0.1	5.0	-0.5	10.2	-10.3	13.7	17.1
Scheur_Wielingen_.	-2.0	4.2	-0.2	5.2	-0.3	11.1	-15.0	11.6	19.0
CADZD	-0.6	4.0	-0.2	5.5	1.0	10.2	-9.2	15.4	18.0
WESTKPLE	0.4	3.9	0.0	5.0	1.6	9.3	-10.3	13.5	17.0
EURPFM	0.8	4.1	0.7	4.7	3.9	8.1	-2.8	8.0	8.5
VLISSGN	-0.5	4.3	-0.2	5.2	0.1	9.0	-14.4	16.5	21.9
ROOMPBTN	-0.9	3.7	0.2	4.8	0.2	10.4	-9.0	12.5	15.4
LICHTELGRE	2.2	4.4	0.2	4.7	2.2	8.0	1.5	12.1	12.2
BROUWHVSGT08	1.5	4.8	0.1	5.8	1.6	10.2	-3.3	7.7	8.3
TERNZN	-0.2	4.5	-0.3	5.4	-0.6	9.6	-18.3	18.5	26.0
HARVT10	2.3	4.7	0.3	5.4	5.2	9.6	3.7	14.0	14.5
ROOMPBNN	0.4	3.4	-0.3	4.7	0.3	9.2	-6.3	8.7	10.7
HANSWT	-1.6	4.9	-0.6	5.2	-3.1	12.9	-14.3	19.1	23.9
HOEKVHLD	0.1	4.0	0.1	5.5	5.5	10.6	2.9	9.8	10.2
STAVNSE	1.4	3.9	0.3	4.9	-2.3	9.6	-4.8	13.9	14.7
BERGSDSWT	2.8	5.4	0.6	5.4	-3.1	12.8	-7.6	12.2	14.4
KRAMMSZWT	1.2	4.0	1.6	5.6	-1.3	9.9	-14.5	17.1	22.4
BATH	-3.9	6.3	-1.0	5.4	-3.2	12.0	-17.4	19.6	26.2
Prosperpolder_tij_Z.	-4.6	6.7	-0.8	5.6	-3.4	12.7	-17.8	19.5	26.4

LIEFKENSHOEK	-4.9	6.8	-1.1	5.8	-4.6	13.1	-17.9	19.6	26.5
SCHEVNGN	4.3	6.1	1.1	5.6	4.4	9.4	1.9	6.6	6.8
KALLO	-6.2	8.0	-0.9	6.0	-3.7	13.1	-18.7	20.2	27.5
MAASSS	3.3	6.0	1.3	6.0	4.7	9.5	-0.3	11.5	11.5
Antwerpen_tij_Zees.	-7.4	8.9	-1.1	6.1	-5.1	14.2	-18.9	19.9	27.5
VLAARDGN	2.6	4.9	0.8	5.7	0.6	8.8	-3.3	12.9	13.3
SPIJKNSE	-0.1	3.7	0.7	5.2	2.7	9.1	-1.3	12.6	12.6
ROTTDM	3.4	5.5	0.3	6.2	-0.5	10.0	-7.2	14.2	15.9
GOIDSOD	-3.6	5.8	-0.7	5.6	1.4	9.1	-2.3	9.9	10.2
IJMDBTHVN	2.2	6.0	1.7	6.4	3.3	7.9	-8.2	10.5	13.4
Q1	-2.7	4.3	0.3	4.3	2.2	7.3	-5.3	9.6	10.9
DENHDR	-3.7	5.3	0.5	4.9	-1.3	8.7	-10.4	13.3	16.9
TEXNZE	-1.7	3.9	1.3	5.4	4.3	8.1	-8.7	10.4	13.6
K13APFM	0.1	3.0	0.3	4.1	0.0	4.8	-4.3	10.5	11.3
F16	-1.0	3.1	0.4	4.1	0.9	5.9	-3.2	5.2	6.1
OUDSD	-3.1	4.8	0.3	4.5	-2.4	8.3	-10.5	13.0	16.7
DENOVBTN	-6.1	8.0	-0.7	8.7	3.3	10.4	-6.5	14.4	15.8
TERSLNZE	2.6	4.5	0.8	5.6	4.9	10.7	-5.9	10.5	12.1
VLIELHVN	-3.8	5.2	0.5	4.9	-4.4	11.3	-23.0	12.4	26.2
WESTTSLG	-5.0	6.4	0.4	5.1	-3.3	11.3	-16.7	15.7	22.9
KORNWDZBTN	-1.3	3.4	-0.5	6.1	1.8	10.8	-10.0	17.0	19.7
WIERMGDN	2.6	5.0	0.3	5.6	4.5	10.7	0.7	13.7	13.8
HUIBGT	2.8	5.6	0.3	5.8	5.1	9.9	2.5	11.5	11.8
HARLGN	3.0	4.5	0.2	6.4	-4.4	10.7	-19.7	18.9	27.3
NES	3.6	6.3	0.6	6.4	-15.5	18.3	-28.1	17.1	32.9
LAUWOG	2.3	6.2	0.6	6.3	-11.8	16.8	-18.9	21.1	28.3
SCHIERMNOG	3.1	5.9	0.6	6.1	-12.2	17.1	-21.1	19.3	28.6
BORKUM_Sudstran.	5.2	7.8	0.4	5.9	-7.4	13.0	-10.4	12.5	16.3
BorkumFischerbalje	1.9	5.7	0.0	5.9	-4.2	11.5	-11.4	11.8	16.4
EMSHORN	3.6	6.3	0.2	6.4	-7.1	12.2	-15.7	11.5	19.4
EEMSHVN	1.5	5.6	0.4	6.4	-3.5	11.6	-10.7	10.6	15.1
DUKEGAT	0.0	5.2	0.6	7.1	-2.4	10.5	-8.2	10.1	13.0
DELFZL	-1.0	5.6	1.2	7.8	-5.9	14.5	-10.1	9.2	13.7
KNOCK	-0.9	5.7	0.4	7.4	-7.1	14.8	-10.8	11.0	15.4
EMDEN_Neue_See.	2.3	7.5	1.4	7.9	-9.5	17.4	-14.9	14.4	20.7
POGUM	4.0	8.5	1.5	8.5	-11.0	18.3	-14.5	14.8	20.8
Average (total)	-0.1	5.3	0.3	5.7	-1.5	11.0	-9.7	13.4	17.3
Average (offshore)	-0.1	3.8	0.4	4.4	1.8	6.8	-2.8	9.1	9.8
Average (coast)	0.3	4.7	0.4	5.4	2.3	9.9	-5.3	11.4	13.6
Average (SWD)	-2.0	5.6	-0.3	5.4	-2.5	11.5	-14.2	17.1	22.3
Average (WS)	0.5	6.0	0.4	6.6	-5.9	13.3	-14.5	14.2	20.5
Average (RMM)	1.1	5.2	0.5	5.7	1.8	9.3	-2.9	12.2	12.7

Comparison against DCSMv6 and DCSMv6-ZUNOv4 (fifth-generation models) and DCSM-FM 0.5nm (sixth-generation model)

The error statistics (at the Dutch coastal stations) for the fifth- and sixth-generation models can be found in the Appendix (DCSMv6: Table A.7; DCSMv6-ZUNOv4: Table A.8; DCSM-FM 0.5nm: Table A.9). These results are summarised in Table 5.15, where the station-averaged error statistics are compared against those of the fifth- and sixth-generation models. The results show that for the lowest 99% skew surges, the low water skew surge error of DCSM-FM 100m is lower than for the other three models, in all regions. For the highest class of skew surge events, the quality is slightly better than DCSM-FM 0.5nm, in particular in the Wadden Sea stations, but slightly worse than DCSMv6-ZUNOv4. The tidal low waters generally have a somewhat better quality than the other three models, in particular in the Southwestern Delta and Wadden Sea stations.

Table 5.15 Comparison of the station-averaged model skill to represent tidal low waters (all events) and skew surge heights (low waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations.

	Tidal low water		**Skew surge (low water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Total	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	std (cm)	RMSE (cm)
DCSMv6	0.5	6.0	0.2	5.9	-2.1	12.2	-10.3	12.8	17.8
DCSMv6-ZUNOv4	-3.2	5.3	0.3	5.7	0.4	10.9	-7.5	12.3	15.7
DCSM-FM 0.5nm	2.9	7.0	0.2	5.8	-3.4	12.1	-12.5	13.3	19.5
DCSM-FM 100m	0.1	4.8	0.3	5.5	-0.5	10.4	-9.0	12.9	16.6
Offshore									
DCSMv6	-2.3	4.1	0.4	4.5	2.0	7.4	-3.5	8.9	9.7
DCSMv6-ZUNOv4	-1.4	3.8	0.4	4.5	1.8	7.2	-3.9	8.6	9.5
DCSM-FM 0.5nm	0.4	3.7	0.4	4.4	1.2	6.7	-3.3	9.4	10.2
DCSM-FM 100m	-0.1	3.8	0.4	4.4	1.8	6.8	-2.8	9.1	9.8
Coast									
DCSMv6	-1.5	4.7	0.3	5.6	2.1	10.6	-4.7	11.4	14.2
DCSMv6-ZUNOv4	-3.0	5.2	0.5	5.6	2.5	10.7	-4.6	11.3	14.2
DCSM-FM 0.5nm	0.9	4.8	0.4	5.5	1.8	9.6	-6.1	11.7	14.3
DCSM-FM 100m	0.5	4.7	0.4	5.4	2.6	9.8	-5.3	11.6	13.9
South-western Delta									
DCSMv6	1.5	6.0	0.1	5.5	-1.2	11.7	-13.4	12.4	18.8
DCSMv6-ZUNOv4	-3.8	5.6	-0.1	5.4	0.4	11.4	-9.6	13.0	16.9
DCSM-FM 0.5nm	-0.8	5.9	0.0	5.2	-4.2	11.4	-15.2	14.3	21.0
DCSM-FM 100m	0.4	4.4	-0.1	5.1	-1.5	10.5	-10.9	14.8	18.6
Wadden Sea									
DCSMv6	3.8	8.6	0.1	7.2	-10.3	16.8	-19.2	16.8	25.9
DCSMv6-ZUNOv4	-4.0	6.1	0.2	6.5	-3.1	12.6	-12.0	15.0	20.0
DCSM-FM 0.5nm	8.7	12.2	0.1	7.1	-12.3	18.2	-24.0	16.7	29.8
DCSM-FM 100m	-0.6	5.6	0.3	6.3	-5.3	12.8	-15.9	15.3	22.5

6 Conclusions and recommendations

6.1 Conclusions

Upon request of Rijkswaterstaat (RWS) Deltares has developed a sixth-generation hydrodynamic model of the Northwest European Shelf: the Dutch Continental Shelf Model – Flexible Mesh (DCSM-FM). This model is the latest in a line of DCSM models developed by RWS and Deltares and a successor to the fifth-generation WAQUA model DCSMv6-ZUNOv4. Specifically, this model covers the North Sea and adjacent shallow seas and estuaries in the Netherlands, such as the Wadden Sea, the Ems-Dollard estuary, the Western Scheldt and the Eastern Scheldt.

The development of the present model is part of a more comprehensive project in which sixth-generation models are developed for all waters managed and maintained by RWS. An important difference with the previous fifth-generation models is the use of the D-HYDRO Suite, the new software framework for modelling free surface flows, which was first released in 2015 and allows for the use of unstructured grids.

Since the proposed applications on the North Sea pose a wide range and sometimes mutually exclusive demands on a model, two horizontal schematizations were proposed: a relatively coarse two-dimensional model (DCSM-FM 0.5nm; Zijl & Groenenboom, 2019) and a relatively fine schematization (DCSM-FM 100m; described in the present report) with further refinement in most Dutch coastal waters. DCSM-FM 0.5nm is primarily aimed at ensemble forecasting, but also forms a sound basis for a subsequent 3D model development, including temperature and salinity as state parameters. DCSM-FM 100m is primarily aimed at deterministic water level forecasting at HMC and WMCN-kust.

The bottom roughness in DCSM-FM was calibrated using the open-source data assimilation toolbox OpenDA. This was done against 211 shelf-wide tide-gauge measurements, covering the entire calendar year 2017. Compared to the uncalibrated version of the model, this has led to a 50% reduction in the cost function. Before being used, the measurements were extensively checked on quality.

DCSM-FM 100m was validated against measurements for the period 2013-2017 and compared against the fifth-generation models DCSMv6 and DCSMv6-ZUNOv4 as well as the sixth-generation model DCSM-FM 0.5nm. An analysis of total water levels as well as the contribution of tide and surge in Dutch waters showed that:

- Generally, the total water level RMSE is 6-8 cm in North Sea waters. In these stations, the tide and surge RMSE is generally 4-6 cm. The quality deteriorates somewhat in the Dutch estuaries and Wadden Sea, in particular the RMM area, the Ems-Dollard and the Scheldt river. In these areas the model resolution is relatively low compared to the variability in geometry and bathymetry.
- These results show that on average the tide representation is similar compared to DCSMv6-ZUNOv4. This is despite the exclusion of bathymetry as a calibration parameter in the development of DCSM-FM.
- The quality of the surge in DCSM-FM 100m has generally improved slightly in all regions compared to DCSMv6-ZUNOv4.
- Compared to the coarser DCSM-FM 0.5m, DCSM-FM 100m shows major improvements in tide in the upstream parts of the Eastern and Western Scheldt and in the Wadden Sea, including the Ems-Dollard.

The model is also assessed with respect of its capacity to represent the high water skew surge, i.e., the difference between a total high water and the associated astronomical high water, ignoring small differences in timing. This is done for three categories of events, subdivided based on the height of the measured skew surge. With respect to the skew surge the following can be concluded:

- The RMSE of the high water skew surge (<99.0%, i.e., calm conditions) in the Dutch coastal stations is around 5-6 cm in North Sea waters and most parts of the Wadden Sea and Dutch estuaries.
- The most extreme (>99.8%) skew surge events shows an excellent quality in southern waters, with RMSE values less than 10-15 cm. Errors are much larger inside the (eastern) Wadden Sea, mostly due to a large systematic underestimation of the skew surge during storms. In the Ems-Dollard the bias can reach 30-40 cm during these events.
- With respect to the lowest 99% high water skew surges, DCSM-FM has on average a slightly better quality compared to the fifth-generation models DCSMv6 and DCSMv6-ZUNOv4 and the sixth-generation model DCSM-FM 0.5nm. For the highest class of skew surge events, the quality is similar for all four models.

Since there is also an interest in the accuracy with which low waters are represented (e.g. relevant for water authorities draining into the sea by gravity flow), especially during storm surges, the error statistics for low waters are also computed. With respect to the low water skew surge, the following can be concluded:

- In North Sea waters as well as the Wadden Sea and Dutch estuaries a low water skew surge RMSE of around 5-6 cm is found. Values of 6.5 cm and higher only occur at station Den Oever buiten and in the Ems-Dollard (Dukegat and further upstream).
- The low water skew surge in southern waters during the most extreme (>99.8%) skew surge events shows a larger systematic underestimation than for high waters during the same category of events. The underestimation increases in upstream direction inside the Western Scheldt. In northern Dutch waters, the systematic error (bias) is less severe than for the high water skew surge, in particular in the Ems-Dollard where the bias is 10-15 cm, compared to 30-40 cm for the high water skew surge.
- For the highest class of skew surge events (>99.8%), the quality is slightly better than DCSM-FM 0.5nm, in particular in the Wadden Sea stations, but slightly worse than DCSMv6-ZUNOv4.
- During the lowest 99% skew surges, the low water skew surge error of DCSM-FM 100m is lower in all regions than for the fifth-generation models DCSMv6 and DCSMv6-ZUNOv4 and the sixth-generation model DCSM-FM 0.5nm.
- The tidal low waters generally have a somewhat better quality than the other three models, in particular in the Southwestern Delta and Wadden Sea stations.

6.2 Recommendations

6.2.1 Bathymetry

Outside Dutch coastal waters, the model bathymetry is based on the EMODnet October 2016 version. In the meantime, the more recent September 2018 version has become available and a 2020 version will become available at the end of that year. Since significant bathymetry errors are known to exist in the October 2016 EMODnet bathymetry dataset, it is recommended to update the model bathymetry with the most recent version.

Furthermore, the quality of the tide representation of DCSM-FM 100m is similar compared to the fifth-generation model DCSMv6-ZUNOv4. Since this is based on the validation for the years 2013-2017 it should be noted that the quality of the tide representation in the fifth-generation model has deteriorated since the year for which it has been calibrated (2007). A better result for DCSM-FM 100m might therefore have been expected. A reason why this is not the case could be the exclusion of bathymetry as a calibration parameter. It is therefore recommended to investigate whether adjusting the bathymetry within reasonable bounds would be beneficial to the quality of the tide.

6.2.2 Boundary conditions

The tidal boundary conditions are based on the FES2012 global tide model. It is recommended to upgrade this to the most recent available version FES2014.

6.2.3 Annual M2 modulation

In tide gauge stations Roompot Buiten, Den Helder, and Delfzijl H1 is the harmonic constituent with the largest contribution to the tidal error, while in Vlissingen, Hoek van Holland and Harlingen this constituent has the second largest contribution. H1 has an angular frequency that differs one cycle per year from the M2 frequency and, together with H2, represents an annual modulation of the M2 tide. Only a minor part of this modulation is gravitational in nature. While the origin is poorly understood, it is presumably mainly related to the seasonal nature of dissipation due to storms as well as seasonal temperature stratification in the central North Sea. The latter contribution cannot be represented with a 2D barotropic model such as DCSM-FM. It is therefore recommended to investigate whether a better tide quality can be achieved by using a 3D baroclinic version of DCSM-FM.

6.2.4 Meteorological forcing

The present calibration and validation were performed using HiRLAM v7.2 meteorological forcing, even though HiRLAM v7.2 will be replaced by Harmonie form the 2020/2021 storm season onwards. It is therefore recommended to further validate DCSM-FM using Harmonie meteorological forcing. Care should be taken with the way the wind fording is applied. Currently, the use of stress (which is used to force the fifth-generation models with Harmonie) prevents the application of the Relative Wind Effect, with which this model is calibrated.

6.2.5 Forecast accuracy

The validation in the present report is based on hindcast computations. Since the model will be used for forecasting applications, it is recommended to also assess the forecast quality as a function of the lead time.

6.2.6 Mean Dynamic Topography

The water levels computed with DCSM-FM (or any other hydrodynamic model) refer to an equipotential surface of the Earth's gravity field. Gradients in baroclinic pressure (i.e. due to density differences) affect the movement of water and can, consequently, affect the long-term mean water level (or Mean Dynamic Topography). Salinity and temperature are not included in DCSM-FM as state parameters, since in a 2D model this would not produce a realistic solution. Consequently, the density is assumed to be constant and uniform. Furthermore, at the open boundaries, steric effects (i.e., changes in sea level due to thermal expansion and salinity

variations) are not taken into account. This affects the representation of the Mean Dynamic Topography (MDT). Therefore, the bias between measured and computed water levels in each station, determined over the entire five-year validation period, is disregarded in all Goodness-of-Fit criteria used here.
One approach to properly compute the MDT is to use a 3D model with salinity and temperature as state parameters. While this is feasible and useful for many applications, for some this would result in an unacceptably high computational burden. An alternative approach would then be to add the depth-averaged horizontal baroclinic pressure gradients obtained from an external solution to the 2D model equations (Slobbe et al., 2013). It is recommended to consider both the first and second solution.

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A Model validation

A.1 Shelf-wide results

A.1.1 Tide, surge and total water level

Table A.1 Statistics (RMSE-values in cm) of tide, surge and total water level of the fifth-generation model (DCSMv6-ZUNOv4) and the sixth-generation models (DCSM-FM 0.5nm and DCSM-FM 100m) for all shelf-wide tide gauge stations.

Station	**RMSE tide (cm)**			**RMSE surge (cm)**			**RMSE water level (cm)**		
	DCSMv6-ZUNOv4	DCSM-FM 0.5 nm	DCSM-FM 100m	DCSMv6-ZUNOv4	DCSM-FM 0.5 nm	DCSM-FM 100m	DCSMv6-ZUNOv4	DCSM-FM 0.5 nm	DCSM-FM 100m
BAKE_A		9.2	9.0		7.9	7.9		10.2	10.0
BAKE_Z		8.0	7.7		7.2	7.2		10.5	10.3
BHV_ALTER_LT		30.5	14.2		9.9	8.5		32.0	16.5
BORKUM_Sudstrand	4.4	7.3	6.6	5.8	5.7	5.6	7.2	9.2	8.6
BorkumFischerbalje	4.7	6.7	5.7	5.8	5.7	5.5	7.4	8.8	7.9
CUXHAVEN_STEUBH		8.6	9.2		7.7	7.5		11.5	11.9
DAGEBULL		14.6	14.0		8.5	7.7		16.9	16.0
DUKEGAT	8.2	8.0	6.3	7.1	7.0	6.7	10.5	10.1	8.8
DWARSGAT		12.4	9.3		7.6	7.5		14.5	11.9
EMDEN_Neue_Seesc.			8.4			7.5			11.2
EMSHORN	5.6	7.6	5.7	6.2	6.1	6.0	8.4	9.7	8.2
HELGOLAND_BINNE.		7.7	6.6		5.5	5.4		9.4	8.5
HELGOLAND_SUDH		8.2	6.7		5.8	5.7		10.1	8.9
HOOKSIELPLATE		7.6	7.3		6.9	6.8		10.3	10.0
HORNUM		16.8	14.4		5.6	5.4		17.7	15.4
KNOCK	7.1	11.0	6.6	7.3	7.7	7.0	10.2	13.4	9.7
LANGEOOG		7.7	7.2		7.0	6.9		9.6	9.0
LEUCHTTURM_ALT.		7.2	6.8		6.2	6.2		9.5	9.2
LIST		11.3	10.4		5.9	5.6		12.7	11.9
MELLUMPLATE		7.4	7.1		6.8	6.8		10.1	9.8
MITTELGRUND		9.8	9.8		8.0	7.9		11.3	11.1
NORDERNEX_RIFFG		7.3	8.2		6.0	5.9		9.4	10.1
PELLWORM_Anleger		12.4	11.3		7.4	7.2		14.4	13.4
POGUM	51.5		10.1	12.1		8.0	52.9		12.9
TERBORG			15.7			9.9			17.7
ROBBENSUDSTEER.		14.9	8.9		8.1	7.6		16.9	11.7
SCHARHORN		7.3	7.3		7.0	7.0		9.9	9.9
SCHILLIG		6.7	6.7		6.5	6.5		9.3	9.3
SPIEKEROOG		7.4	6.7		6.5	6.4		9.8	9.1
WANGEROOGE_NO.		7.8	7.9		6.5	6.4		10.4	10.4
WANGEROOGE_OST		6.0	6.8		6.5	6.5		8.7	9.3
WANGEROOGE_WE.		9.6	10.9		7.0	7.9		11.8	13.4
WHV_ALTER_VORH.		9.4	8.4		7.8	7.8		12.2	11.5

WHV_NEUER_VORH.		8.5	8.7		7.6	7.6		11.5	11.6
WITTDUN		15.2	11.9		6.3	6.1		16.3	13.2
ZEHNERLOCH		8.1	8.0		7.5	7.4		10.3	10.2
ABDN	5.7	4.8	5.3	4.7	4.6	4.5	7.5	6.6	6.9
BANGR	6.6	12.2	11.7	4.4	4.6	4.6	7.9	13.1	12.6
BARMH	10.8	13.5	13.5	7.8	6.6	6.5	13.0	14.8	14.8
BOURNMH							5.1	6.3	6.4
CROMR	6.4	8.0	8.4	6.7	6.7	6.6	8.3	9.4	9.7
DEVPT	7.7	13.4	13.2	4.1	4.5	4.5	8.7	14.2	14.1
DOVR	6.1	8.9	9.3	4.5	4.4	4.4	7.7	9.7	10.0
FISHGD	11.1	6.8	6.7	4.6	4.4	4.4	11.7	7.7	7.6
HARWH	5.6	13.6	12.4	6.7	6.9	6.6	8.1	14.9	13.7
HEYSHM	11.8	28.7	29.3	7.2	7.8	7.9	13.1	29.6	30.2
HINKLPT	10.0	13.0	12.9	7.3	7.2	7.2	12.4	14.7	14.6
HOLHD	5.7	6.8	6.9	4.7	4.3	4.3	7.3	8.1	8.1
ILFCBE	7.6	10.0	10.0	5.1	4.9	4.9	9.2	11.0	11.0
IMMHM	14.3	16.2	17.4	9.4	8.7	8.8	17.5	18.5	19.6
KINLBVE	6.6	7.3	7.0	5.2	5.0	4.9	7.2	7.7	7.3
LEITH	7.0	10.3	10.1	6.7	6.4	6.4	9.7	12.1	11.9
LERWK	5.7	4.3	4.1	4.7	3.7	3.6	7.3	5.6	5.5
LIVPL	9.3	17.4	17.3	6.9	7.1	7.2	10.9	18.3	18.2
LLANDNO	8.5	7.6	7.5	5.6	5.5	5.5	10.0	9.4	9.3
LOWST	4.1	5.1	6.5	5.5	5.3	5.3	6.7	7.2	8.3
MILFHVN	8.9	7.1	7.0	7.0	4.9	4.9	10.9	8.1	8.0
MILLPT	9.4	18.5	17.9	5.7	6.2	6.2	10.9	19.4	18.9
MUMBS	9.7	9.3	9.2	5.4	5.2	5.2	10.7	12.7	12.6
NEWHVN	4.9	11.2	11.2	4.2	4.2	4.1	6.5	12.0	11.9
NEWLN	5.4	4.4	4.4	3.9	3.8	3.8	6.6	5.7	5.7
NEWPT							20.7	29.0	27.6
NORTHSS	4.9	8.6	9.5	5.2	5.0	5.0	7.0	9.9	10.6
PORTERIN	6.3	5.9	5.8	4.3	4.1	4.1	7.6	7.2	7.1
Portbury		59.2	58.2		17.0	17.1		62.1	61.2
PORTPTK	7.6	10.6	10.1	4.3	4.4	4.4	8.7	11.5	11.0
PORTRH	8.1	7.2	6.9	4.6	4.6	4.6	9.1	8.3	8.1
PORTSMH	6.0	18.6	14.6	4.7	5.1	5.0	7.7	19.1	15.3
SHEERNS							10.9	18.2	23.5
StHelierJersey	8.3	8.6	9.0	4.9	4.8	4.8	9.4	9.5	9.9
STMARYS							5.0	5.0	5.0
STORNWY	8.7	8.3	8.3	5.2	5.0	5.0	9.4	8.8	8.9
TOBMRY	8.3	7.0	7.3	4.5	4.5	4.5	9.4	8.3	8.6
ULLPL	8.2	7.7	7.6	5.7	5.4	5.5	10.9	10.4	10.3
WEYMH	6.8	4.7	4.7	4.1	4.0	4.0	7.9	5.8	5.8
WHITBY	5.4	8.9	9.8	5.6	5.5	5.4	8.2	10.6	11.3
WICK	5.7	5.3	5.5	4.7	4.5	4.5	6.9	6.5	6.6
WORKTN	6.7	9.8	9.8	5.4	5.4	5.4	8.6	11.2	11.2
Aalesund		5.4	5.5		4.5	4.5		7.0	7.0
Aranmore		5.3	5.1		4.4	4.4		6.8	6.7

Ballum		14.8	16.3		14.2	14.3		19.8	21.1
Ballycotton		5.2	5.1		4.4	4.4		6.6	6.5
Ballyglass	5.4	5.0	5.0	4.7	4.4	4.4	6.7	6.3	6.3
Bergen		5.1	5.2		4.1	4.2		6.5	6.6
BoulogneSurMer	6.9	11.0	11.2	5.3	4.9	4.9	8.6	12.0	12.2
Brest	22.0	20.4	19.7	4.8	6.7	6.6	22.6	21.2	20.5
Calais	5.1	9.9	6.7	5.2	5.3	5.1	7.2	11.2	8.4
Castletownbere		5.7	5.7		5.7	5.7		8.0	8.0
Cherbourg	6.0	7.2	7.4	4.3	4.4	4.4	7.3	8.4	8.5
Dielette		17.8	18.4		5.3	5.3		18.0	18.5
Dieppe		11.5	11.8		6.3	6.4		12.8	13.0
Dundalk							57.9	36.9	36.6
Dunkerque	5.1	7.8	7.2	5.3	5.2	5.2	7.3	9.4	8.8
Dunmore		6.0	5.8		3.8	3.8		6.6	6.5
Esbjerg	12.3	12.2	11.7	8.6	10.1	9.9	14.9	15.7	15.2
Havneby	6.7	23.2	23.1	7.4	10.2	9.5	8.5	24.9	24.5
Heimsjoe		6.8	6.1		4.6	4.6		8.2	7.6
Helgeroa	4.1	4.2	4.3	4.7	4.6	4.6	6.2	6.2	6.3
Hirtshals	4.1	4.2	4.2	5.2	5.1	5.2	6.6	6.6	6.7
Howth		7.4	7.4		4.0	4.0		8.4	8.4
HvideSandeKyst		9.2	9.2		10.4	10.5		13.5	13.5
Killybegs	96.9	5.8	5.7	15.0	5.1	5.1	98.0	7.7	7.7
Kristiansund		5.0	4.9		4.5	4.5		6.7	6.7
LeConquet	7.7	6.2	6.0	4.2	4.1	4.1	8.7	7.4	7.2
LeHavre	6.8	10.1	10.0	6.3	6.3	6.3	9.3	11.9	11.8
MalinHead		9.5	9.1		6.2	6.2		11.3	11.0
Maloy		5.3	5.4		4.4	4.4		6.9	6.9
Mausund		8.5	8.3		7.2	7.3		11.1	10.9
Oscarsborg	5.9	8.2	8.3	6.3	6.8	6.9	8.6	10.7	10.8
Oslo		10.2	10.5		7.7	7.8		12.8	13.1
Ribe		8.4	8.2		11.5	11.6		13.7	13.6
Roscoff	7.0	8.5	9.1	4.1	4.0	4.0	8.1	9.4	9.9
SaintMalo	10.9	10.5	11.1	6.5	6.0	6.0	12.7	12.1	12.6
SkerriesHarbour		10.3	10.6		4.7	4.7		10.5	10.7
Sligo							11.0	9.0	9.0
Stavanger		4.0	4.0		5.3	5.3		6.6	6.6
ThyboronKyst		7.6	7.6		7.9	7.9		9.5	9.5
TorsmindeKyst		5.6	5.6		6.1	6.2		7.8	7.9
Tregde	3.3	3.5	3.6	5.4	5.7	5.7	6.3	6.7	6.7
Viker	4.4	4.6	4.6	5.3	5.3	5.3	6.9	7.0	7.0
VLAKTVDRN		5.6	6.0		5.9	5.9		7.9	8.1
Aarhus		6.3	6.3		6.2	6.2		8.7	8.8
Ballen		4.8	4.8		5.9	5.8		8.0	8.0
BayonneBoucau		16.4	16.2		6.9	6.9		17.7	17.5
Bilbao		5.2	5.1		3.7	3.7		6.3	6.2
Bogense		7.6	7.6		7.3	7.3		10.1	10.0
BrestNus30								23.8	23.0

Brons		31.1	30.0		21.3	21.5		37.0	36.3
Concarneau		8.6	8.6		5.2	5.2		9.7	9.7
Coruna		4.7	4.7		4.1	4.1		6.3	6.2
Ferrol2								6.8	6.7
Ferrol		4.7	4.7		4.2	4.3		6.3	6.3
Fredericia		4.8	4.8		9.3	9.2		10.7	10.7
Frederikshavn	4.7	4.2	4.3	4.9	4.8	4.8	6.7	6.3	6.4
Gijon		4.7	4.7		3.7	3.7		5.9	5.9
Grena		4.0	4.1		5.5	5.6		6.9	6.9
Hanstholm	5.0	4.5	4.5	7.7	5.9	5.8	8.9	7.1	7.0
Herbaudiere		14.4	15.0		5.5	5.5		15.4	16.0
Hornbaek	3.1	3.0	3.1	5.5	5.3	5.3	6.4	6.3	6.3
Hov		6.1	6.1		6.1	6.1		9.1	9.1
Langosteira								6.4	6.3
IleDAix		19.2	19.7		7.3	7.3		20.3	20.8
Kristineberg1		4.9	4.9		5.2	5.3		7.0	7.0
LaRochelle		16.0	16.6		7.0	7.0		17.2	17.9
LeCrouesty		13.9	14.3		5.4	5.5		14.7	15.0
LesSablesDOlonne		12.4	12.8		5.5	5.5		13.2	13.7
Mando		8.5	9.4		12.3	12.6		13.6	14.4
Onsala		4.1	4.1		6.2	6.2		6.4	6.4
PortBloc		12.6	12.6		5.6	5.6		13.5	13.5
PortTudy		8.9	9.0		4.8	4.8		9.8	9.9
Ringhals	3.6	3.5	3.6	6.5	6.1	6.1	6.8	6.6	6.6
SaintNazaire		16.3	16.8		6.9	7.0		17.4	17.9
Santander		5.2	5.2		3.7	3.7		6.3	6.3
SjaellandsOdde		2.7	2.7		7.8	7.8		8.9	8.9
Smogen	4.7	4.8	4.8	6.1	6.0	6.0	6.9	6.9	7.0
Socoa		7.1	7.1		5.1	5.1		8.6	8.6
Stenungsund	5.9	5.1	5.1	7.1	6.6	6.6	7.8	7.2	7.2
Udbyhoej		8.2	8.3		8.0	8.1		11.9	12.0
Vidaa		8.5	8.2		11.5	11.6		14.2	14.1
Viken	3.3	3.0	3.0	7.4	7.0	7.0	7.6	7.2	7.2
A2	4.1	5.2	5.1	5.3	5.1	5.1	6.7	7.3	7.2
Appelzak	4.0	5.6	5.4	5.4	5.3	5.2	6.9	8.0	7.7
Blankenberge		6.7	6.3		5.6	5.6		8.5	8.2
Bol_Van_Heist	4.7	5.5	5.3	5.3	5.2	5.1	7.1	7.5	7.4
Nieuwpoort		8.5	8.6		5.5	5.5		10.1	10.2
Oostende	4.9	6.8	6.3	5.4	5.2	5.2	7.3	8.6	8.2
Scheur_Wielingen_Bo.	5.3	5.7	5.9	5.5	5.4	5.3	7.6	7.7	7.8
Wandelaar	4.4		5.2	5.3		5.1	6.6		6.9
Westhinder	4.0	6.6	6.3	4.9	4.9	4.7	6.2	8.1	7.8
LIEFKENSHOEK	6.9		7.1	7.0		6.9	9.8		9.9
KALLO	6.8		7.4	7.4		7.4	10.1		10.5
Antwerpen_tij_Zeesch.	7.7		7.8	7.9		7.7	11.1		10.9
BATH	5.7		5.9	6.4		6.3	8.6		8.6
Prosperpolder_tij_Zee.			6.3			6.5			9.0

BERGSDSWT	4.6	11.0	4.6	5.5	6.2	5.4	7.1	12.6	7.1
BROUWHVSGT08	5.0	6.1	4.8	6.1	6.1	6.0	7.8	8.5	7.5
CADZD	4.4	5.8	5.5	5.7	5.7	5.6	7.3	8.1	7.8
DELFZL	6.8	10.8	6.6	7.5	7.9	7.2	10.1	13.4	9.8
DENHDR	4.6	4.2	4.5	5.2	5.1	5.1	6.9	6.6	6.8
DENOVBTN	6.5	7.4	5.9	6.8	6.9	6.3	9.4	10.1	8.6
EEMSHVN	6.8	7.2	6.1	6.3	6.2	6.0	9.3	9.5	8.6
EURPFM	4.0	3.7	3.9	4.7	4.7	4.6	6.1	5.8	5.9
GOIDSOD	6.6		9.5	5.8		5.5	8.7		11.0
HANSWT	6.1	18.9	5.3	6.2	7.1	6.0	8.6	20.2	8.0
HARLGN	4.5	8.7	4.3	5.8	6.8	5.7	7.3	11.0	7.1
HARVT10	4.4	4.3	4.2	5.4	5.4	5.4	7.0	6.9	6.8
HOEKVHLD	5.0	4.4	4.6	5.3	5.8	5.4	7.3	7.3	7.1
HOLWD	15.4	31.0	22.7	12.1	14.6	12.8	19.6	34.3	26.0
HUIBGT	4.9	5.2	5.4	6.1	5.7	5.7	7.5	7.5	7.6
IJMDBTHVN	6.3	5.4	4.8	5.9	5.8	5.7	8.7	7.9	7.5
KORNWDZBTN	3.7	4.6	4.5	5.7	5.7	5.5	6.8	7.3	7.1
KRAMMSZWT	4.3	8.1	4.0	6.4	6.3	5.6	7.7	10.2	6.9
LAUWOG	6.5	14.2	6.4	6.8	7.5	6.6	9.4	16.0	9.2
LICHTELGRE	4.9	4.7	4.4	4.8	4.7	4.7	6.8	6.7	6.5
MAASSS	5.3		7.8	5.4		5.4	7.6		9.4
NES	5.9	15.4	5.9	6.0	7.6	5.9	8.4	17.2	8.3
OUDSD	4.8	4.6	4.0	4.7	4.7	4.6	6.7	6.6	6.1
ROOMPBNN	4.3	4.4	3.6	4.9	4.9	4.7	6.4	6.6	5.9
ROOMPBTN	4.4	3.8	3.6	5.2	5.0	4.9	6.8	6.3	6.1
ROTTDM	5.9		9.7	5.7		5.9	8.2		11.4
SCHEVNGN	5.2	4.5	4.6	5.6	5.6	5.5	7.6	7.1	7.1
SCHIERMNOG	7.2	24.2	5.6	6.9	9.9	6.2	10.0	26.1	8.3
SPIJKNSE	6.3		9.5	5.2		5.3	8.2		10.9
STAVNSE	3.9	5.5	3.7	5.2	5.4	5.0	6.4	7.7	6.2
TERNZN	5.6	6.7	5.9	6.0	6.2	5.8	8.2	9.1	8.3
TERSLNZE	4.1	4.4	4.6	5.8	5.6	5.7	7.0	7.1	7.3
TEXNZE	4.9	5.0	5.0	5.7	5.6	5.6	7.4	7.4	7.4
VLAARDGN	5.7		8.5	5.4		5.5	7.9		10.1
VLIELHVN	4.7	3.8	4.2	5.0	5.0	4.9	6.9	6.3	6.5
VLISSGN	4.8	6.3	5.7	5.5	5.6	5.4	7.3	8.4	7.8
WESTKPLE	4.4	6.3	5.2	5.2	5.1	5.1	6.8	8.1	7.3
WESTTSLG	3.6	4.8	5.7	5.0	5.0	4.9	6.1	7.0	7.5
WIERMGDN	4.1	4.8	4.9	5.7	5.5	5.5	6.9	7.2	7.2
F16	2.9	3.0	3.0	4.4	4.1	4.1	5.2	5.0	5.1
F3PFM	3.4	3.6	3.6	4.5	4.5	4.6	5.4	5.5	5.6
K13APFM	3.4	4.3	4.2	4.4	4.4	4.3	5.5	6.1	6.0
NORTHCMRT	4.0	5.0	5.0	4.3	4.4	4.4	5.7	6.5	6.5
Q1	4.2	4.2	4.2	4.6	4.6	4.5	6.2	6.3	6.1

A.1.2 High waters

Table A.2 Overview of the DCSM-FM 100m model skill to represent tidal high waters (all events) and skew surge heights (high waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for all shelf-wide tide gauge stations.

	Tidal high water		**Skew surge (high water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
BAKE_A	-6.2	9.2	0.5	7.8	2.9	13.7	2.6	11.8	12.1
BAKE_Z	-5.4	7.3	1.4	6.7	9.3	14.9	-6.8	10.2	12.3
BHV_ALTER_LT	11.1	12.9	-0.2	8.7	5.9	16.9	-13.0	15.4	20.2
BORKUM_Sudstran.	-2.1	4.3	-0.3	5.4	-1.3	9.9	-25.4	11.5	27.9
BorkumFischerbalje	0.8	3.4	-0.1	5.4	0.6	9.3	-23.6	11.3	26.2
CUXHAVEN_STEU.	-2.0	6.5	-0.2	8.5	11.1	19.2	-3.9	11.0	11.7
DAGEBULL	-12.9	13.5	0.3	6.4	5.8	15.4	-3.3	13.0	13.4
DUKEGAT	2.3	5.0	-0.4	6.4	-2.7	16.1	-43.9	15.6	46.6
DWARSGAT	-6.4	7.9	0.4	7.2	2.6	14.2	-13.3	10.0	16.6
EMDEN_Neue_See.	6.9	8.6	0.0	6.8	-0.9	15.3	-39.5	17.2	43.1
EMSHORN	-0.2	3.7	-0.1	5.7	-3.6	11.8	-30.1	12.7	32.7
HELGOLAND_BIN.	-4.6	5.8	-0.4	5.6	4.7	11.1	-6.5	9.1	11.2
HELGOLAND_SUD.	-2.7	4.4	-1.4	5.7	1.2	12.5	-13.4	7.0	15.1
HOOKSIELPLATE	-5.6	7.2	-0.5	7.0	4.3	13.5	-13.5	12.1	18.2
HORNUM	-4.7	5.6	0.3	5.7	1.2	11.1	-13.8	9.3	16.7
KNOCK	5.0	6.6	0.4	6.4	-2.3	13.2	-34.1	14.7	37.2
LANGEOOG	-4.5	6.4	-0.5	7.1	-4.9	12.6	-36.3	12.2	38.3
LEUCHTTURM_AL.	-7.1	8.2	-0.2	6.5	4.4	13.8	-2.3	10.8	11.1
LIST	-14.7	15.1	-0.1	6.5	3.8	10.9	-5.2	15.2	16.0
MELLUMPLATE	-6.2	7.5	0.0	6.8	4.2	14.0	-12.0	8.6	14.7
MITTELGRUND	-3.3	7.6	0.1	8.2	1.8	13.2	-2.7	9.3	9.7
NORDERNEX_RIF.	-4.3	5.8	-0.1	6.0	-3.9	12.4	-31.6	14.1	34.6
PELLWORM_Anleg.	-14.1	14.8	-0.5	7.0	10.8	16.7	5.2	11.4	12.6
POGUM	7.6	9.6	-0.3	7.1	-1.5	16.5	-41.0	15.4	43.8
TERBORG	3.0	7.5	-0.4	8.2	-3.9	17.3	-11.1	9.0	14.3
ROBBENSUDSTEE.	3.8	6.4	0.1	7.6	3.1	14.7	-13.0	13.9	19.0
SCHARHORN	-5.3	7.5	-0.3	7.2	4.7	15.4	-4.1	9.4	10.2
SCHILLIG	-6.3	7.8	0.0	6.6	5.5	13.6	-12.3	10.6	16.2
SPIEKEROOG	-4.2	5.6	1.7	7.0	-1.5	12.7	-31.7	9.7	33.1
WANGEROOGE_N.	-8.3	9.3	-1.4	7.0	1.6	12.1	-0.9	8.5	8.6
WANGEROOGE_O.	-8.1	9.2	-0.2	6.7	-3.1	13.6	-21.2	9.1	23.1
WANGEROOGE_W.	-10.9	11.8	0.7	6.9	-5.4	15.7	-28.3	10.9	30.3
WHV_ALTER_VOR.	-4.6	7.4	-0.7	8.0	5.6	17.5	-13.3	16.5	21.2
WHV_NEUER_VO.	-5.2	7.7	-0.7	7.8	2.6	15.5	-16.7	15.1	22.5
WITTDUN	-8.7	9.3	0.1	5.6	3.5	14.1	-4.9	10.6	11.6
ZEHNERLOCH	-3.5	6.9	-0.8	7.8	4.6	12.3	8.2	18.4	20.1
ABDN	-3.3	5.1	0.1	4.4	-4.3	7.2	-11.5	8.9	14.5

BANGR	1.0	5.5	0.5	4.5	-0.6	7.9	-2.4	3.7	4.4
BARMH	-13.7	14.7	-0.8	5.8	-7.7	11.6	-2.2	2.0	3.0
CROMR	7.5	9.2	1.1	6.4	5.1	6.4	2.4	10.2	10.4
DEVPT	-3.8	5.1	0.7	4.0	-2.8	6.6	0.8	6.0	6.0
DOVR	6.4	7.5	0.2	4.4	3.6	4.6	4.7	1.9	5.1
FISHGD	-8.9	10.2	-1.3	4.3	-2.0	3.8	-4.3	4.4	6.1
HARWH	-10.1	11.9	0.2	8.4	-3.3	9.9	10.8	7.0	12.8
HEYSHM	40.6	42.9	2.1	7.6	-3.3	10.6	-1.1	6.0	6.1
HINKLPT	10.1	12.5	0.1	6.2	0.7	10.8	-2.1	10.4	10.6
HOLHD	-1.0	5.4	0.0	4.1	-1.0	4.3	3.8	4.3	5.7
ILFCBE	-5.0	6.8	0.4	4.5	1.1	7.1	-3.5	7.2	8.0
IMMHM	4.0	7.3	6.4	9.3	5.0	15.3	-15.3	4.4	15.9
KINLBVE	2.7	6.9	-0.7	4.5	-1.2	7.0	4.4	4.9	6.6
LEITH	-8.2	9.8	0.3	6.2	-5.2	10.5	-7.6	11.3	13.6
LERWK	0.2	3.1	-0.4	3.5	-1.5	5.1	-5.0	7.1	8.7
LIVPL	-3.4	8.0	-1.7	6.1	-2.4	8.5	-8.3	20.3	21.9
LLANDNO	5.5	8.3	2.1	5.6	4.5	8.1	3.6	7.2	8.1
LOWST	0.8	3.5	-0.2	5.3	3.3	9.3	-3.9	17.6	18.1
MILFHVN	-10.2	11.3	1.0	4.9	-2.0	7.8	-7.2	4.7	8.6
MILLPT	-15.9	19.2	-0.1	6.3	2.0	12.5	0.3	10.3	10.3
MUMBS	-1.6	4.6	0.3	4.5	0.0	9.8	-7.5	2.5	7.9
NEWHVN	1.8	3.8	-0.1	4.2	-2.1	6.3	0.5	12.0	12.0
NEWLN	-2.1	3.8	-0.5	3.8	-1.2	5.4	-4.3	4.8	6.5
NORTHSS	-5.9	7.8	-0.3	5.1	-4.7	9.6	-4.7	10.6	11.6
PORTERIN	3.3	6.0	-0.2	4.2	0.9	6.5	0.7	4.8	4.8
Portbury	20.8	25.3	4.0	10.3	0.5	13.1	-4.8	11.4	12.4
PORTPTK	-4.5	6.8	0.7	4.3	-0.2	7.4	-7.9	4.2	8.9
PORTRH	-0.4	6.6	0.0	4.6	3.8	7.6	0.7	4.2	4.2
PORTSMH	4.5	6.0	-0.6	4.7	-4.4	7.5	0.4	8.1	8.1
StHelierJersey	-2.5	5.4	0.2	4.7	0.1	7.6	3.6	9.1	9.8
STORNWY	2.6	7.5	-1.2	4.8	-1.0	6.8	-2.0	3.9	4.4
TOBMRY	-1.8	5.6	0.1	4.3	1.9	7.9	2.0	8.6	8.8
ULLPL	5.6	9.3	0.5	4.9	-1.1	10.9	3.2	10.5	11.0
WEYMH	-3.1	4.1	-0.8	3.5	-6.0	7.7	6.1	1.3	6.3
WHITBY	-5.7	7.7	1.8	5.2	-5.4	10.0	-9.1	11.7	14.8
WICK	-0.1	4.1	-1.4	4.5	-5.0	7.0	-12.9	8.6	15.5
WORKTN	-4.6	8.8	-0.1	5.6	6.5	13.1	13.2	10.3	16.7
Aalesund	2.7	5.8	-0.1	4.4	-0.1	6.6	-0.7	4.4	4.5
Aranmore	2.8	6.3	0.1	4.3	-2.0	8.0	0.1	3.3	3.3
Ballum	9.6	11.0	0.3	7.6	2.8	16.2	-2.2	24.4	24.5
Ballycotton	0.3	4.4	-0.5	4.5	-4.7	7.0	-5.9	4.1	7.2
Ballyglass	1.0	4.3	0.0	4.3	-0.8	6.3	1.1	4.6	4.8
Bergen	-3.8	5.0	0.1	4.3	1.9	6.3	2.1	3.6	4.2
BoulogneSurMer	2.5	4.5	-0.9	4.6	0.8	6.1	2.5	12.7	13.0
Brest	7.2	9.7	1.1	5.4	4.7	10.2	0.6	3.9	4.0
Calais	-1.0	3.8	-0.6	4.8	-2.1	6.2	-3.4	5.7	6.6
Castletownbere	2.1	4.8	0.4	5.6	-1.7	6.3	-0.2	5.8	5.8

Cherbourg	-7.4	8.7	-0.9	4.1	-9.1	10.1	-13.0	3.8	13.6
Dielette	-23.7	25.4	0.2	4.5	-2.2	4.6	-10.6	4.8	11.6
Dieppe	3.2	6.2	0.1	5.3	-2.5	8.1	0.0	6.6	6.6
Dunkerque	-0.6	3.5	-0.7	4.9	-1.2	7.2	-6.0	5.4	8.1
Dunmore	-3.1	4.5	1.1	3.8	-0.5	3.7	4.6	0.3	4.6
Esbjerg	-5.5	7.7	0.1	9.3	2.3	13.7	-1.1	20.7	20.7
Havneby	-13.2	14.6	0.1	8.2	3.2	11.6	-0.4	19.8	19.8
Heimsjoe	-0.8	5.3	0.1	4.5	-4.3	7.6	-3.9	4.0	5.6
Helgeroa	3.2	4.4	-0.5	4.7	-3.5	7.3	-3.7	2.9	4.7
Hirtshals	2.7	4.1	-2.4	5.8	-3.4	9.1	-6.5	10.6	12.4
Howth	6.6	8.8	-0.1	4.0	1.1	5.6	-3.5	5.7	6.7
HvideSandeKyst	4.5	8.5	-2.7	10.1	-28.2	30.9	-24.9	6.6	25.8
Killybegs	3.7	6.6	0.2	4.9	-2.8	9.6	0.4	4.1	4.1
Kristiansund	0.9	4.9	0.0	4.5	0.1	6.5	0.2	3.4	3.4
LeConquet	-0.1	4.6	-0.5	3.9	-5.6	9.3	-2.1	5.4	5.8
LeHavre	7.0	8.7	-0.2	6.7	-28.0	32.0	-56.2	33.6	65.4
MalinHead	2.0	6.5	0.1	6.2	-0.7	6.5	0.2	4.4	4.4
Maloy	0.9	4.3	-0.4	4.3	-1.8	6.8	-3.3	7.7	8.4
Mausund	-3.0	8.1	0.3	6.9	-17.2	18.7	-29.0	7.0	29.8
Oscarsborg	5.9	7.6	0.5	6.8	-6.4	10.3	3.5	5.8	6.8
Oslo	9.1	10.9	1.0	7.6	-3.8	10.3	1.7	7.4	7.6
Ribe	2.7	5.6	1.2	9.0	-7.4	14.5	-27.3	21.9	35.0
Roscoff	-5.7	7.2	-0.3	3.8	-2.3	6.3	-2.2	6.0	6.4
SaintMalo	7.2	8.8	0.3	5.5	-5.4	9.5	-3.5	12.5	13.0
SkerriesHarbour	8.0	10.2	-1.0	4.6	5.7	6.9	-2.5	2.5	3.6
Stavanger	-3.1	4.4	-0.3	5.3	-2.1	6.1	4.7	4.3	6.4
ThyboronKyst	1.3	5.9	-1.8	7.9	-5.7	11.1	-11.7	11.8	16.7
TorsmindeKyst	3.2	4.3	-1.3	6.2	-6.0	9.8	-8.0	10.1	12.8
Tregde	1.9	3.6	-0.6	5.7	-2.7	9.5	-2.5	4.7	5.4
Viker	3.1	4.5	-0.3	5.4	-4.7	8.1	-2.4	5.4	5.9
VLAKTVDRN	-3.0	4.8	-0.1	5.5	5.8	7.6	4.0	4.8	6.2
Aarhus	4.2	5.3	-0.9	6.1	-10.7	15.1	-9.8	5.4	11.2
Ballen	2.4	3.5	-0.8	5.5	-10.1	13.1	-24.9	9.9	26.8
BayonneBoucau	12.5	14.5	-0.6	6.0	-17.0	18.2	-24.5	9.1	26.1
Bilbao	3.9	6.0	0.0	3.6	-6.3	7.6	-3.2	3.3	4.5
Bogense	1.5	3.8	1.3	7.0	-9.2	13.2	-14.7	3.3	15.1
Brons	34.8	35.4	2.4	10.7	-6.2	18.2	-20.5	23.7	31.4
Concarneau	3.6	7.1	-1.7	4.9	-8.0	10.7	-4.1	10.1	10.9
Coruna	1.9	5.1	0.1	4.0	-5.5	6.4	-2.7	3.0	4.0
Ferrol	1.5	4.9	0.1	4.2	-6.7	7.4	-4.6	3.6	5.9
Fredericia	1.6	3.1	-2.2	9.0	4.5	15.1	-12.6	0.6	12.7
Frederikshavn	3.4	4.4	-0.9	4.7	-7.6	10.6	-10.6	5.5	12.0
Gijon	2.1	4.8	0.1	3.5	-3.4	4.9	-1.4	3.4	3.7
Grena	2.8	4.0	-1.9	6.0	-13.2	13.9	-12.3	2.3	12.5
Hanstholm	2.5	3.9	-2.7	6.2	-0.5	6.8	-11.8	9.0	14.8
Herbaudiere	9.8	14.9	-0.8	5.3	-9.5	13.6	-9.6	6.6	11.7
Hornbaek	2.2	3.1	-3.1	5.9	-8.8	12.4	-3.9	5.1	6.4

Hov	3.2	4.9	-2.2	6.3	-13.1	15.4	-18.5	8.3	20.3
IleDAix	20.3	25.2	0.0	7.0	-5.0	13.7	-13.4	5.2	14.4
Kristineberg1	3.4	4.8	-0.5	5.4	-5.6	9.1	-0.7	1.6	1.7
LaRochelle	18.5	22.8	-0.4	6.8	-6.8	12.7	-12.7	6.6	14.3
LeCrouesty	7.6	11.8	-0.7	5.0	-4.8	10.2	-2.8	11.3	11.7
LesSablesDOlonne	11.8	14.9	-2.7	5.5	-10.5	13.7	-5.6	9.5	11.0
Mando	2.7	6.6	1.5	10.1	1.5	15.4	-3.5	31.8	31.9
Onsala	0.7	3.3	-0.3	6.2	-1.8	8.5	4.8	2.9	5.6
PortBloc	6.3	10.8	-0.4	5.0	-7.5	11.2	-9.7	3.9	10.5
PortTudy	5.0	8.2	-0.6	4.5	-6.5	9.4	-3.5	7.8	8.6
Ringhals	1.9	3.3	-1.7	6.0	1.7	8.3	-4.2	3.5	5.5
SaintNazaire	2.5	14.0	-0.3	6.4	-1.1	16.2	-5.8	6.5	8.7
Santander	1.9	4.7	0.1	3.6	-4.2	5.4	-3.6	4.4	5.7
SjaellandsOdde	1.7	2.6	-7.0	8.6	-17.5	19.8	-10.6	10.2	14.7
Socoa	3.7	5.7	-0.6	3.9	-8.8	9.7	-4.3	4.7	6.4
Stenungsund	3.3	4.5	-0.3	6.3	-3.6	4.3	-0.4	0.0	0.4
Udbyhoej	5.4	6.4	-3.9	7.5	-13.6	19.2	-6.9	1.0	7.0
Vidaa	-5.7	7.3	-0.3	8.0	0.1	13.5	-12.1	18.7	22.2
Viken	1.8	2.9	-1.9	7.0	6.9	9.5	-0.5	1.4	1.5
A2	0.1	2.9	-0.7	5.0	1.8	9.1	-0.6	9.3	9.3
Appelzak	-4.0	4.6	0.0	5.0	-4.3	12.5	-8.2	3.6	9.0
Blankenberge	-1.7	4.0	-0.8	4.9	-6.6	18.8	-7.9	4.6	9.1
Bol_Van_Heist	0.6	2.7	-1.0	5.2	0.0	7.6	-2.2	9.0	9.3
Nieuwpoort	0.1	3.7	0.2	5.3	-1.6	6.9	-1.8	6.2	6.5
Oostende	1.7	3.4	-0.4	5.2	-0.9	8.4	-1.3	9.2	9.3
Scheur_Wielingen_.	-0.6	2.7	-0.1	5.2	-0.6	9.3	-4.0	10.3	11.0
Wandelaar	0.1	2.7	-0.3	5.0	0.6	8.1	-2.8	8.5	8.9
Westhinder	-0.1	2.8	-0.3	4.8	0.6	5.9	2.4	5.6	6.1
LIEFKENSHOEK	2.9	7.1	2.8	6.7	0.1	11.2	-1.3	8.9	9.0
KALLO	5.9	8.9	3.7	7.5	0.5	11.5	-1.1	10.2	10.3
Antwerpen_tij_Zees.	6.5	8.9	4.7	8.3	1.7	11.0	-5.2	13.5	14.4
BATH	1.1	6.5	1.1	5.8	2.8	11.1	-3.4	10.1	10.7
Prosperpolder_tij_Z.	1.2	6.5	1.6	6.1	3.0	12.0	-3.9	9.1	9.9
BERGSDSWT	1.2	3.6	0.5	5.5	8.5	12.6	1.0	10.4	10.4
BROUWHVSGT08	-6.6	7.7	-1.3	6.0	-5.9	14.5	-15.1	14.5	20.9
CADZD	-4.8	5.8	0.1	5.4	0.6	8.1	0.2	7.7	7.7
DELFZL	4.8	6.5	0.5	6.4	-4.8	13.4	-39.0	14.2	41.5
DENHDR	1.0	3.0	-0.6	4.6	-4.6	8.8	-17.0	17.6	24.5
DENOVBTN	2.7	4.0	-0.7	5.0	-6.7	10.4	-22.2	23.1	32.0
EEMSHVN	1.0	3.9	-0.4	5.8	-3.5	11.7	-28.4	11.9	30.8
EURPFM	-2.9	3.9	0.3	4.6	0.8	7.2	-1.9	8.4	8.6
GOIDSOD	4.4	7.7	0.3	5.6	1.1	7.9	-5.1	5.8	7.7
HANSWT	-1.0	5.5	1.0	5.7	2.9	9.8	-1.8	9.4	9.6
HARLGN	3.5	4.8	-0.4	5.3	-5.3	12.1	-19.6	17.6	26.4
HARVT10	-4.7	5.7	-1.1	5.5	-0.7	11.0	-5.3	6.3	8.2
HOEKVHLD	1.3	3.9	-0.1	5.5	-1.7	11.5	-5.5	7.4	9.2
HOLWD	-0.6	4.8	-0.2	7.4	-11.2	18.3	-35.4	16.1	38.9

HUIBGT	-1.9	4.2	-0.7	5.5	7.3	11.5	-4.2	7.3	8.4
IJMDBTHVN	0.2	3.6	-1.5	5.9	-4.2	12.7	-15.8	7.9	17.7
KORNWDZBTN	2.9	4.3	-0.7	5.1	-5.7	11.2	-24.1	21.0	32.0
KRAMMSZWT	-0.1	3.1	-0.6	6.0	2.9	10.9	-1.5	8.6	8.7
LAUWOG	1.3	4.5	-0.1	6.0	-8.0	14.2	-31.1	12.8	33.7
LICHTELGRE	-6.3	7.3	-0.5	4.8	0.2	8.0	-3.1	8.4	8.9
MAASSS	-6.3	8.5	-0.1	5.7	2.4	8.5	-4.9	8.3	9.6
NES	1.7	3.7	0.2	5.3	-11.6	16.3	-31.5	13.4	34.2
OUDSD	0.3	2.8	-0.4	4.4	-3.3	7.9	-18.2	17.1	24.9
ROOMPBNN	-3.2	4.0	-0.5	4.8	3.2	9.6	-0.4	5.6	5.6
ROOMPBTN	-2.1	3.5	-0.5	4.9	-1.6	9.7	-8.2	8.3	11.7
ROTTDM	-14.5	17.0	-2.2	6.2	-0.2	9.8	-4.1	6.5	7.7
SCHEVNGN	-2.4	4.4	-1.3	6.0	-3.0	10.4	-10.8	12.2	16.3
SCHIERMNOG	1.6	3.8	0.0	5.9	-7.9	13.9	-32.6	12.4	34.9
SPIJKNSE	-2.2	6.6	-0.5	5.6	2.9	8.7	1.9	6.9	7.1
STAVNSE	-1.2	3.0	-0.1	5.2	6.0	11.4	-0.6	8.7	8.7
TERNZN	-6.2	7.9	0.1	5.4	0.9	10.2	0.2	9.3	9.3
TERSLNZE	0.1	3.0	-0.9	5.5	-5.0	11.7	-15.1	12.5	19.6
TEXNZE	2.6	4.9	-1.1	5.4	-5.7	13.8	-12.2	13.8	18.4
VLAARDGN	-9.4	12.0	-1.8	5.8	2.4	9.8	-2.3	5.0	5.5
VLIELHVN	1.9	3.4	-0.2	4.6	-4.5	9.9	-25.6	9.1	27.2
VLISSGN	-6.7	7.9	0.1	5.2	1.7	8.3	-1.0	9.2	9.3
WESTKPLE	-4.4	5.4	0.3	5.0	2.5	7.3	-1.9	7.6	7.8
WESTTSLG	2.7	3.9	-0.3	4.6	-4.5	10.1	-27.4	7.7	28.4
WIERMGDN	-2.0	3.8	-0.4	5.3	3.8	10.1	-12.7	4.8	13.6
F16	0.6	2.8	-0.3	4.2	-0.5	5.4	-11.7	4.4	12.5
F3PFM	1.2	3.6	-0.4	4.6	-2.8	6.5	-10.1	6.2	11.8
K13APFM	-0.5	3.3	-0.1	4.2	0.7	6.3	-7.7	10.6	13.1
NORTHCMRT	-1.9	4.0	0.0	4.4	-1.9	5.3	-2.4	7.4	7.8
Q1	0.8	3.4	-0.7	4.7	-1.0	9.8	-12.4	14.7	19.2

A.1.3 Low waters

Table A.3 Overview of the DCSM-FM 100m model skill to represent tidal low waters (all events) and skew surge heights (low waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for all shelf-wide tide gauge stations.

	Tidal low water		**Skew surge (low water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
BAKE_A	3.7	7.6	1.7	8.0	12.2	18.2	3.0	8.3	8.8
BAKE_Z	4.7	8.1	2.0	7.7	9.0	15.5	4.4	17.7	18.2
BHV_ALTER_LT	11.6	13.3	1.4	8.3	-6.4	14.9	-30.3	25.3	39.4
BORKUM_Sudstran.	5.2	7.8	0.4	5.9	-7.4	13.0	-10.4	12.5	16.3
BorkumFischerbalje	1.9	5.7	0.0	5.9	-4.2	11.5	-11.4	11.8	16.4

CUXHAVEN_STEU.	-11.3	12.7	0.0	6.9	-1.4	14.8	-17.2	16.1	23.5
DAGEBULL	25.8	27.0	2.5	11.0	-22.5	25.4	-31.1	16.7	35.3
DUKEGAT	0.0	5.2	0.6	7.1	-2.4	10.5	-8.2	10.1	13.0
DWARSGAT	8.1	10.5	0.9	7.6	-7.9	14.5	-17.5	10.2	20.3
EMDEN_Neue_See.	2.3	7.5	1.4	7.9	-9.5	17.4	-14.9	14.4	20.7
EMSHORN	3.6	6.3	0.2	6.4	-7.1	12.2	-15.7	11.5	19.4
HELGOLAND_BIN.	3.8	6.1	0.6	5.7	0.0	10.8	-8.6	8.9	12.4
HELGOLAND_SUD.	2.3	5.1	0.1	5.8	6.6	10.8	-4.2	9.2	10.1
HOOKSIELPLATE	7.6	10.0	0.6	7.4	-6.0	14.9	-24.8	16.5	29.8
HORNUM	1.0	3.9	0.3	5.9	2.1	12.0	-6.7	8.4	10.7
KNOCK	-0.9	5.7	0.4	7.4	-7.1	14.8	-10.8	11.0	15.4
LANGEOOG	2.9	6.2	-0.2	6.5	-13.1	17.7	-26.4	8.4	27.7
LEUCHTTURM_AL.	5.3	8.0	0.3	6.4	-0.1	11.3	-10.1	10.0	14.2
LIST	13.4	14.3	0.4	6.1	-10.1	14.4	-13.1	15.0	19.9
MELLUMPLATE	7.3	9.7	0.5	7.1	-3.5	11.9	-16.7	12.1	20.7
MITTELGRUND	-6.6	9.4	-0.1	7.9	0.2	15.4	-16.6	17.7	24.3
NORDERNEX_RIF.	4.1	6.7	0.5	5.9	-10.7	15.1	-20.0	9.3	22.1
PELLWORM_Anleg.	18.4	19.8	1.1	7.7	-14.5	20.3	-20.5	12.8	24.2
POGUM	4.0	8.5	1.5	8.5	-11.0	18.3	-14.5	14.8	20.8
TERBORG	9.4	13.3	-1.7	10.6	-12.0	19.0	-6.8	4.9	8.4
ROBBENSUDSTEE.	10.3	12.1	1.1	8.1	-4.9	12.9	-22.2	17.8	28.5
SCHARHORN	2.5	6.4	-0.1	7.1	1.2	11.0	-13.5	14.5	19.8
SCHILLIG	7.1	9.4	0.4	7.0	-4.6	13.6	-22.5	15.0	27.0
SPIEKEROOG	3.2	6.7	0.7	6.2	-12.6	15.8	-31.6	10.4	33.3
WANGEROOGE_N.	5.4	7.8	0.1	6.6	5.2	11.2	-6.0	9.6	11.3
WANGEROOGE_O.	5.1	7.9	0.6	6.5	-11.6	15.8	-32.6	12.5	34.9
WANGEROOGE_W.	14.2	16.9	0.8	11.7	-18.9	22.6	-35.1	10.7	36.7
WHV_ALTER_VOR.	9.3	11.3	0.9	8.2	-5.5	15.6	-25.3	18.8	31.5
WHV_NEUER_VO.	8.7	10.9	1.0	8.2	-5.6	14.7	-25.5	18.0	31.3
WITTDUN	12.0	13.2	0.2	6.9	-10.8	16.2	-14.8	11.4	18.7
ZEHNERLOCH	-6.6	9.1	-0.7	7.4	3.8	14.4	-15.1	15.3	21.5
ABDN	1.0	4.9	1.1	4.6	-0.7	6.3	-5.9	8.1	10.0
BANGR	-3.1	5.4	1.2	4.5	1.1	7.3	2.5	5.9	6.4
BARMH	6.9	8.8	0.8	5.6	-0.6	5.8	-2.8	2.8	3.9
CROMR	1.5	5.8	1.6	6.5	2.9	8.0	1.9	3.7	4.1
DEVPT	7.5	10.8	-1.6	4.7	-4.6	7.9	-1.5	7.2	7.3
DOVR	-6.7	7.6	0.3	4.0	-0.3	2.0	-2.9	5.9	6.6
FISHGD	5.4	7.4	-0.7	4.3	-1.1	6.6	4.3	6.6	7.9
HARWH	3.9	6.6	0.1	6.2	-3.0	11.2	-4.5	8.2	9.4
HEYSHM	-5.2	9.0	-0.3	6.1	4.0	15.0	-2.3	10.0	10.3
HINKLPT	-6.2	12.9	2.1	7.3	-4.5	12.4	-12.0	11.1	16.3
HOLHD	0.8	4.4	0.6	4.1	2.6	7.4	1.2	5.1	5.3
ILFCBE	0.6	6.7	0.4	4.8	3.1	9.4	-5.8	4.5	7.4
IMMHM	16.4	19.9	4.3	7.8	-4.2	6.8	-2.7	2.3	3.5
KINLBVE	3.7	6.2	0.2	4.8	2.9	6.4	9.7	6.1	11.4
LEITH	1.3	7.6	-0.3	6.1	-5.7	9.4	-11.4	11.9	16.5
LERWK	0.0	3.2	0.8	3.8	0.7	4.7	-3.1	4.4	5.4

LIVPL	2.5	10.5	-2.9	7.8	-8.9	17.8	5.5	11.6	12.8
LLANDNO	-7.9	9.7	0.6	5.1	3.4	7.6	0.0	8.1	8.1
LOWST	-0.8	3.6	0.5	5.0	4.5	8.3	0.2	7.1	7.1
MILFHVN	5.8	7.8	0.4	4.7	-1.8	6.0	-4.3	8.4	9.4
MILLPT	-4.3	7.5	-0.2	6.1	3.4	7.2	0.1	8.0	8.0
MUMBS	-1.7	5.6	0.5	4.7	-5.8	10.9	-3.9	4.7	6.1
NEWHVN	-2.2	4.4	0.6	3.9	2.4	8.1	-3.9	9.7	10.5
NEWLN	0.4	3.6	0.6	3.8	2.1	5.3	1.6	4.0	4.3
NORTHSS	5.1	8.4	0.1	4.8	-6.7	10.7	-7.8	8.3	11.4
PORTERIN	-3.1	5.1	0.3	3.9	0.6	5.4	1.3	6.4	6.5
Portbury	67.2	77.9	6.4	16.6	-28.2	34.2	-33.5	25.0	41.8
PORTPTK	2.0	4.9	0.8	4.3	-1.0	5.9	-6.5	7.2	9.7
PORTRH	-2.0	5.7	0.4	4.6	2.5	6.7	1.6	3.5	3.9
PORTSMH	1.9	10.0	-1.8	5.1	-6.2	14.7	-4.2	4.3	6.0
StHelierJersey	6.5	10.0	0.1	4.7	-1.5	8.8	-0.1	4.2	4.2
STORNWY	7.5	10.6	-0.2	4.8	-1.2	5.4	-3.2	6.7	7.4
TOBMRY	5.2	8.4	-0.1	4.5	-1.7	6.5	1.0	5.6	5.7
ULLPL	2.7	7.1	1.6	5.2	4.5	6.6	-0.9	8.8	8.9
WEYMH	3.4	5.3	0.5	3.8	2.2	3.2	4.6	6.1	7.6
WHITBY	4.7	7.8	2.6	5.7	-4.4	8.3	-11.5	10.6	15.6
WICK	2.1	5.9	-0.4	4.4	-3.2	5.7	-8.5	4.7	9.7
WORKTN	1.8	5.0	0.1	5.0	4.0	10.6	2.1	12.7	12.9
Aalesund	-2.7	5.8	0.1	4.5	-0.6	6.1	2.5	7.9	8.3
Aranmore	-2.0	4.4	0.0	4.3	-1.5	4.8	-4.7	5.9	7.6
Ballum	-28.2	30.4	-2.7	21.2	46.1	49.1	36.5	16.7	40.1
Ballycotton	-0.5	4.8	-0.7	4.3	-2.8	5.7	0.2	2.1	2.1
Ballyglass	-1.6	5.0	-0.1	4.4	-0.2	4.5	-5.1	4.2	6.6
Bergen	0.8	3.7	-0.3	4.0	-0.2	4.6	-5.4	2.9	6.1
BoulogneSurMer	2.5	5.5	0.7	4.4	1.2	7.2	2.0	7.6	7.9
Brest	-1.5	6.2	-0.2	5.3	-2.5	9.4	2.6	2.9	3.9
Calais	4.4	6.8	1.9	5.0	-1.5	6.6	-7.3	3.1	7.9
Castletownbere	-2.3	5.1	0.1	5.6	-1.8	6.6	-0.3	6.3	6.3
Cherbourg	10.1	12.3	2.4	4.9	-0.6	6.6	-0.4	4.8	4.8
Dielette	25.2	27.2	1.2	5.4	-10.0	12.1	-10.4	2.7	10.8
Dieppe	-0.3	5.2	1.3	5.5	1.5	5.9	-2.9	4.5	5.3
Dunkerque	2.3	5.4	1.0	5.3	-5.4	11.1	-3.7	7.3	8.2
Esbjerg	18.8	20.3	0.2	10.3	-16.8	20.4	-13.3	10.0	16.6
Havneby	29.5	31.0	0.5	9.5	-17.6	20.5	-25.0	13.8	28.6
Heimsjoe	-1.4	5.7	0.3	4.5	-2.6	6.2	-2.9	5.4	6.2
Helgeroa	-2.9	4.1	0.4	4.4	-0.1	3.7	2.9	3.4	4.4
Hirtshals	-2.6	4.0	2.3	5.6	4.3	9.5	6.2	9.2	11.0
Howth	-7.8	9.4	-0.1	3.7	2.8	7.9	-2.6	5.8	6.3
HvideSandeKyst	-2.6	8.5	2.4	10.7	-5.4	16.9	0.2	12.4	12.4
Killybegs	-3.0	5.7	-0.2	5.0	-2.3	7.3	-5.2	7.7	9.3
Kristiansund	-1.6	5.3	0.1	4.5	1.8	7.1	5.5	9.0	10.5
LeConquet	2.1	5.0	0.7	4.5	0.5	7.0	4.4	5.8	7.3
LeHavre	1.9	5.8	2.2	5.5	-2.0	6.9	1.1	11.4	11.5

MalinHead	-1.8	5.4	0.0	5.8	-2.5	6.0	2.8	8.6	9.0
Maloy	-1.5	4.8	0.5	4.4	-0.4	5.2	2.0	6.6	6.9
Mausund	0.4	8.0	0.6	6.9	-15.2	16.9	-20.3	9.9	22.6
Oscarsborg	-3.8	5.8	-0.3	6.4	-7.7	9.6	-8.9	5.7	10.6
Oslo	-7.1	9.2	-0.7	7.4	-9.1	11.9	-12.8	4.3	13.5
Ribe	6.4	9.0	-1.0	12.8	-6.6	15.5	-2.8	20.3	20.5
Roscoff	8.1	10.0	-0.2	4.2	-2.0	6.3	0.2	4.8	4.8
SaintMalo	4.5	9.8	0.4	5.5	-2.7	6.2	-5.3	10.6	11.8
SkerriesHarbour	-7.9	10.2	-0.7	4.2	11.2	13.3	14.9	13.1	19.9
Stavanger	-1.0	3.6	0.4	5.2	-2.4	7.1	0.3	4.4	4.4
ThyboronKyst	-1.6	7.2	1.2	8.3	3.8	10.5	-1.6	1.7	2.4
TorsmindeKyst	-4.8	5.9	1.2	6.7	9.6	11.9	4.6	7.7	9.0
Tregde	-2.0	3.4	0.5	5.7	0.9	6.8	0.3	11.4	11.4
Viker	-2.8	4.3	0.2	5.1	-2.9	5.7	-0.2	4.9	4.9
VLAKTVDRN	-3.3	5.3	0.0	5.8	2.3	11.2	4.3	13.5	14.2
Aarhus	-3.9	5.7	0.7	6.1	0.3	7.6	2.7	3.2	4.1
Ballen	-2.5	3.5	0.9	5.6	-2.4	6.8	0.3	1.2	1.2
BayonneBoucau	-18.7	24.7	0.4	7.5	-13.7	15.2	-13.4	9.0	16.1
Bilbao	-1.1	4.1	0.0	3.7	-4.6	6.6	-4.3	4.9	6.5
Bogense	-0.4	4.0	2.4	7.3	-3.4	9.3	-10.3	7.3	12.7
Brons	-47.3	48.7	-4.0	23.6	63.1	64.8	61.4	18.5	64.1
Concarneau	-2.2	6.4	2.4	5.6	2.1	7.4	-0.2	6.7	6.7
Coruna	-0.7	4.4	0.0	4.2	-6.0	6.8	-3.3	5.1	6.0
Ferrol	-0.4	4.4	0.0	4.2	-6.0	6.6	-3.2	3.3	4.6
Fredericia	-0.4	3.2	-1.9	8.8	-12.0	18.1	2.7	1.4	3.1
Frederikshavn	-2.6	3.9	0.8	4.8	-1.4	5.9	-6.1	9.2	11.0
Gijon	0.2	4.3	0.0	3.9	-3.6	4.7	-1.8	2.3	2.9
Grena	-3.1	4.5	0.4	5.2	-7.1	7.8	-2.6	3.4	4.3
Hanstholm	-2.7	4.6	2.3	6.5	9.1	10.9	16.6	11.7	20.3
Herbaudiere	-4.5	12.1	1.3	5.5	0.9	6.3	-2.9	9.7	10.1
Hornbaek	-2.1	3.5	0.4	4.9	0.0	7.4	-0.5	8.6	8.7
Hov	-3.3	4.5	-0.6	5.7	-5.8	9.2	2.4	5.4	5.9
IleDAix	-4.5	18.1	0.1	7.1	-4.4	10.1	-2.9	18.0	18.2
Kristineberg1	-3.0	4.1	0.7	5.1	-0.7	7.0	1.7	4.4	4.7
LaRochelle	-3.1	16.4	0.5	6.9	-4.0	9.4	-2.1	8.7	8.9
LeCrouesty	-2.4	10.4	1.0	5.7	-0.4	7.8	1.8	11.5	11.6
LesSablesDOlonne	-1.9	9.5	0.7	5.3	-2.6	7.8	-6.6	9.3	11.4
Mando	0.0	8.1	-4.0	16.8	3.3	13.4	12.4	11.4	16.8
Onsala	-1.2	2.4	-1.1	5.8	0.1	5.8	-8.5	2.1	8.8
PortBloc	-8.6	11.2	0.0	5.7	-8.9	11.4	-9.3	5.1	10.6
PortTudy	-2.3	6.9	0.6	4.7	-0.4	5.3	1.3	8.2	8.3
Ringhals	-1.7	3.3	-0.7	6.1	2.9	6.6	5.8	5.9	8.3
SaintNazaire	-2.0	13.2	-1.0	6.8	-2.7	10.0	-5.9	15.7	16.8
Santander	0.8	4.4	0.0	3.6	-2.8	5.5	-7.6	10.7	13.1
SjaellandsOdde	-1.7	2.8	-4.7	6.9	-4.9	8.2	-4.8	4.1	6.3
Socoa	0.7	6.2	1.2	6.7	-11.1	14.1	-21.0	13.8	25.2
Stenungsund	-3.0	5.9	0.0	6.2	-1.2	1.8	0.3	5.7	5.7

Udbyhoej	-3.0	3.9	-3.8	8.0	-10.7	12.6	-16.4	0.1	16.4
Vidaa	-7.0	11.4	-3.0	19.5	18.0	22.5	13.8	13.9	19.6
Viken	-1.6	3.3	-0.4	6.6	4.7	8.9	12.6	3.3	13.1
A2	-1.4	3.8	0.1	5.0	-0.1	10.7	-9.2	12.3	15.4
Appelzak	0.4	3.7	0.3	5.2	-2.6	7.3	-10.9	1.3	10.9
Blankenberge	-2.2	4.3	1.3	5.2	4.6	11.6	-12.1	14.7	19.1
Bol_Van_Heist	-2.3	4.4	0.1	5.0	-0.5	10.2	-10.3	13.7	17.1
Nieuwpoort	-3.0	5.0	0.3	5.1	-5.4	12.3	-2.4	7.3	7.7
Oostende	-2.6	4.3	0.7	4.9	0.6	10.7	-8.9	10.3	13.6
Scheur_Wielingen_.	-2.0	4.2	-0.2	5.2	-0.3	11.1	-15.0	11.6	19.0
Wandelaar	-2.9	4.9	0.2	5.1	-2.2	10.8	-5.3	7.4	9.1
Westhinder	0.8	4.3	0.0	4.6	-2.0	8.8	-3.7	7.1	8.0
LIEFKENSHOEK	-4.9	6.8	-1.1	5.8	-4.6	13.1	-17.9	19.6	26.5
KALLO	-6.2	8.0	-0.9	6.0	-3.7	13.1	-18.7	20.2	27.5
Antwerpen_tij_Zees.	-7.4	8.9	-1.1	6.1	-5.1	14.2	-18.9	19.9	27.5
BATH	-3.9	6.3	-1.0	5.4	-3.2	12.0	-17.4	19.6	26.2
Prosperpolder_tij_Z.	-4.6	6.7	-0.8	5.6	-3.4	12.7	-17.8	19.5	26.4
BERGSDSWT	2.8	5.4	0.6	5.4	-3.1	12.8	-7.6	12.2	14.4
BROUWHVSGT08	1.5	4.8	0.1	5.8	1.6	10.2	-3.3	7.7	8.3
CADZD	-0.6	4.0	-0.2	5.5	1.0	10.2	-9.2	15.4	18.0
DELFZL	-1.0	5.6	1.2	7.8	-5.9	14.5	-10.1	9.2	13.7
DENHDR	-3.7	5.3	0.5	4.9	-1.3	8.7	-10.4	13.3	16.9
DENOVBTN	-6.1	8.0	-0.7	8.7	3.3	10.4	-6.5	14.4	15.8
EEMSHVN	1.5	5.6	0.4	6.4	-3.5	11.6	-10.7	10.6	15.1
EURPFM	0.8	4.1	0.7	4.7	3.9	8.1	-2.8	8.0	8.5
GOIDSOD	-3.6	5.8	-0.7	5.6	1.4	9.1	-2.3	9.9	10.2
HANSWT	-1.6	4.9	-0.6	5.2	-3.1	12.9	-14.3	19.1	23.9
HARLGN	3.0	4.5	0.2	6.4	-4.4	10.7	-19.7	18.9	27.3
HARVT10	2.3	4.7	0.3	5.4	5.2	9.6	3.7	14.0	14.5
HOEKVHLD	0.1	4.0	0.1	5.5	5.5	10.6	2.9	9.8	10.2
HOLWD	40.2	44.1	3.8	18.0	-52.6	55.9	-57.1	22.9	61.5
HUIBGT	2.8	5.6	0.3	5.8	5.1	9.9	2.5	11.5	11.8
IJMDBTHVN	2.2	6.0	1.7	6.4	3.3	7.9	-8.2	10.5	13.4
KORNWDZBTN	-1.3	3.4	-0.5	6.1	1.8	10.8	-10.0	17.0	19.7
KRAMMSZWT	1.2	4.0	1.6	5.6	-1.3	9.9	-14.5	17.1	22.4
LAUWOG	2.3	6.2	0.6	6.3	-11.8	16.8	-18.9	21.1	28.3
LICHTELGRE	2.2	4.4	0.2	4.7	2.2	8.0	1.5	12.1	12.2
MAASSS	3.3	6.0	1.3	6.0	4.7	9.5	-0.3	11.5	11.5
NES	3.6	6.3	0.6	6.4	-15.5	18.3	-28.1	17.1	32.9
OUDSD	-3.1	4.8	0.3	4.5	-2.4	8.3	-10.5	13.0	16.7
ROOMPBNN	0.4	3.4	-0.3	4.7	0.3	9.2	-6.3	8.7	10.7
ROOMPBTN	-0.9	3.7	0.2	4.8	0.2	10.4	-9.0	12.5	15.4
ROTTDM	3.4	5.5	0.3	6.2	-0.5	10.0	-7.2	14.2	15.9
SCHEVNGN	4.3	6.1	1.1	5.6	4.4	9.4	1.9	6.6	6.8
SCHIERMNOG	3.1	5.9	0.6	6.1	-12.2	17.1	-21.1	19.3	28.6
SPIJKNSE	-0.1	3.7	0.7	5.2	2.7	9.1	-1.3	12.6	12.6
STAVNSE	1.4	3.9	0.3	4.9	-2.3	9.6	-4.8	13.9	14.7

TERNZN	-0.2	4.5	-0.3	5.4	-0.6	9.6	-18.3	18.5	26.0
TERSLNZE	2.6	4.5	0.8	5.6	4.9	10.7	-5.9	10.5	12.1
TEXNZE	-1.7	3.9	1.3	5.4	4.3	8.1	-8.7	10.4	13.6
VLAARDGN	2.6	4.9	0.8	5.7	0.6	8.8	-3.3	12.9	13.3
VLIELHVN	-3.8	5.2	0.5	4.9	-4.4	11.3	-23.0	12.4	26.2
VLISSGN	-0.5	4.3	-0.2	5.2	0.1	9.0	-14.4	16.5	21.9
WESTKPLE	0.4	3.9	0.0	5.0	1.6	9.3	-10.3	13.5	17.0
WESTTSLG	-5.0	6.4	0.4	5.1	-3.3	11.3	-16.7	15.7	22.9
WIERMGDN	2.6	5.0	0.3	5.6	4.5	10.7	0.7	13.7	13.8
F16	-1.0	3.1	0.4	4.1	0.9	5.9	-3.2	5.2	6.1
F3PFM	0.6	3.5	0.3	4.5	-0.7	5.7	-3.9	6.7	7.7
K13APFM	0.1	3.0	0.3	4.1	0.0	4.8	-4.3	10.5	11.3
NORTHCMRT	0.4	3.7	0.2	4.4	-0.9	3.6	-3.5	5.8	6.8
Q1	-2.7	4.3	0.3	4.3	2.2	7.3	-5.3	9.6	10.9

A.2 Dutch coastal waters

A.2.1 High waters

A.2.1.1 DCSMv6

Table A.4 Overview of the DCSMv6 model skill to represent skew surge heights (high waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal high water		**Skew surge (high water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar	2.5	3.8	-0.9	5.4	0.8	8.0	-2.8	8.5	8.9
Bol_Van_Heist	2.7	3.7	-1.6	5.6	0.4	7.9	-2.3	9.8	10.0
Scheur_Wielingen_.	1.9	3.5	-0.5	5.5	1.0	9.8	-3.9	10.8	11.5
CADZD	1.2	3.1	0.0	5.6	2.6	8.4	1.5	9.3	9.4
WESTKPLE	-2.2	4.0	0.4	5.3	3.6	7.8	-1.4	8.5	8.6
EURPFM	3.2	3.9	0.3	4.9	0.9	6.7	-2.7	11.5	11.8
VLISSGN	-0.1	3.7	-0.1	5.6	5.0	10.0	1.6	9.9	10.1
ROOMPBTN	1.3	2.8	-0.4	5.1	-1.7	9.3	-10.0	12.4	15.9
LICHTELGRE	-0.7	3.1	-0.1	5.1	-0.3	7.1	-4.3	10.9	11.7
BROUWHVSGT08	-1.4	3.9	-0.1	6.2	-5.3	13.3	-15.0	17.0	22.6
TERNZN	-2.8	7.4	0.0	6.3	9.1	14.4	6.1	8.9	10.8
HARVT10	0.6	2.8	-0.8	5.7	-0.1	10.3	-6.9	8.1	10.6
ROOMPBNN	1.9	3.4	-1.6	5.5	1.0	10.4	-0.3	7.2	7.2
HANSWT	18.4	19.3	1.5	8.0	15.2	18.5	6.2	10.8	12.5
HOEKVHLD	1.2	3.9	-2.4	6.1	-1.4	12.7	-9.6	8.3	12.6
STAVNSE	-10.1	10.6	-0.3	6.0	8.5	12.4	0.7	8.1	8.1
BERGSDSWT	12.3	13.0	3.1	6.7	10.1	13.4	1.8	12.7	12.9
KRAMMSZWT									
BATH	35.6	37.1	8.4	12.0	19.3	23.3	11.0	12.3	16.5
Prosperpolder_tij_Z.									
LIEFKENSHOEK									
SCHEVNGN	2.4	4.1	-1.2	5.9	-3.2	11.1	-12.6	13.9	18.8
KALLO									
MAASSS									
Antwerpen_tij_Zees.									
VLAARDGN									
SPIJKNSE									
ROTTDM									
GOIDSOD									
IJMDBTHVN	5.9	6.6	-1.5	6.1	-3.2	14.2	-17.7	10.1	20.4
Q1	2.6	4.6	-0.9	5.3	-0.9	11.3	-12.3	13.2	18.1
DENHDR	2.1	3.4	-0.3	4.7	-2.2	8.8	-14.1	16.4	21.6
TEXNZE	1.8	4.2	-1.2	5.5	-4.2	13.7	-12.3	13.3	18.1
K13APFM	-0.4	3.1	-0.1	4.4	1.7	7.2	-9.3	8.7	12.8

F16	-0.2	2.4	-0.4	4.2	-0.4	6.1	-12.4	3.5	12.9
OUDSD	2.4	3.5	-0.1	4.8	1.3	8.0	-12.0	15.7	19.8
DENOVBTN	3.3	4.4	-0.4	5.3	-4.1	10.6	-17.8	20.8	27.4
TERSLNZE	2.3	3.9	-0.8	5.5	-0.9	12.4	-11.7	11.8	16.6
VLIELHVN	3.1	4.3	0.1	5.0	1.2	10.1	-17.7	10.1	20.4
WESTTSLG	5.1	5.9	0.6	5.3	-2.0	11.4	-22.4	10.0	24.6
KORNWDZBTN	3.9	5.3	-0.3	5.5	-0.2	11.1	-17.9	20.8	27.5
WIERMGDN	1.9	3.7	-0.6	5.5	7.4	12.4	-11.6	7.0	13.6
HUIBGT	2.2	4.5	-0.6	5.9	10.4	14.3	-4.8	10.8	11.9
HARLGN	4.0	5.6	0.0	5.8	-1.2	12.4	-15.0	20.8	25.7
NES	5.2	6.6	0.2	5.9	-4.9	13.9	-25.2	13.9	28.8
LAUWOG	2.5	5.4	0.3	6.3	-6.8	14.4	-39.4	18.2	43.4
SCHIERMNOG	4.0	5.5	0.5	6.2	-3.1	13.5	-34.0	16.5	37.8
BORKUM_Sudstran.									
BorkumFischerbalje									
EMSHORN									
EEMSHVN	4.9	6.5	-0.4	7.2	10.9	17.0	-12.4	14.6	19.2
DUKEGAT									
DELFZL	16.6	17.5	1.0	8.3	11.5	20.1	-22.9	22.0	31.7
KNOCK									
EMDEN_Neue_See.									
POGUM									
Average (total)	3.6	6.3	0.0	5.9	1.9	11.7	-9.9	12.2	17.5
Average (offshore)	0.9	3.4	-0.2	4.8	0.2	7.7	-8.2	9.6	13.5
Average (coast)	1.6	3.9	-0.8	5.6	0.2	10.9	-8.4	11.0	14.4
Average (SWD)	7.9	13.5	1.6	7.2	9.7	14.6	3.9	10.0	11.1
Average (WS)	5.0	6.4	0.1	6.0	0.2	12.9	-21.5	16.7	27.8
Average (RMM)									

A.2.1.2 DCSMv6-ZUNOv4

Table A.5 Overview of the DCSMv6-ZUNOv4 model skill to represent skew surge heights (high waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal high water		**Skew surge (high water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar	1.6	3.3	-0.9	5.2	0.0	7.9	-5.3	9.0	10.4
Bol_Van_Heist	3.5	4.4	-1.6	5.5	-0.7	8.2	-4.3	10.2	11.1
Scheur_Wielingen_.	3.2	4.5	-0.6	5.4	0.0	9.5	-5.9	10.9	12.5
CADZD	0.6	3.7	-0.3	5.5	0.8	8.3	-1.0	9.1	9.2
WESTKPLE	1.0	3.5	-0.2	5.1	1.4	7.6	-3.8	9.2	10.0
EURPFM	1.7	2.8	0.3	4.7	0.7	6.1	-4.9	11.5	12.5
VLISSGN	1.6	4.0	-0.3	5.3	1.5	8.7	-3.4	10.9	11.4
ROOMPBTN	3.3	4.0	0.3	5.1	-2.5	9.4	-10.8	13.7	17.4

LICHTELGRE	1.9	3.3	0.0	4.9	-1.2	7.3	-7.6	11.0	13.4
BROUWHVSGT08	2.1	3.8	0.1	6.1	-6.9	14.3	-17.3	17.2	24.4
TERNZN	3.5	5.5	-0.2	5.6	0.2	10.0	-2.8	11.7	12.1
HARVT10	2.6	3.7	-0.1	5.6	-1.7	10.3	-9.6	8.0	12.5
ROOMPBNN	-1.5	2.7	-0.4	4.8	0.8	9.4	-3.4	5.1	6.1
HANSWT	6.2	7.8	0.8	5.7	1.5	10.3	-5.8	11.9	13.2
HOEKVHLD	1.3	4.2	-1.2	5.6	-3.7	11.9	-10.7	9.0	13.9
STAVNSE	1.1	2.8	0.1	5.3	5.5	10.6	-1.5	9.5	9.6
BERGSDSWT	0.9	3.3	0.2	5.5	6.6	11.4	-0.5	11.4	11.4
KRAMMSZWT	3.4	4.6	2.0	8.1	3.1	11.3	-3.5	7.9	8.7
BATH	4.0	7.3	0.7	5.9	2.7	12.2	-6.0	11.8	13.2
Prosperpolder_tij_Z.									
LIEFKENSHOEK	5.9	8.5	1.7	6.4	0.5	12.0	-6.4	10.3	12.1
SCHEVNGN	4.3	5.3	-1.0	5.8	-4.3	11.8	-14.5	14.1	20.2
KALLO	6.7	9.2	2.2	6.9	0.6	12.5	-7.1	11.7	13.6
MAASSS	2.7	4.4	-0.4	5.2	-0.4	8.0	-10.8	9.5	14.4
Antwerpen_tij_Zees.	8.7	10.5	4.2	8.1	1.8	11.4	-10.7	14.6	18.1
VLAARDGN	1.5	4.4	-1.2	5.4	-0.7	9.0	-5.7	7.9	9.8
SPIJKNSE	2.9	4.9	-0.7	5.2	-1.3	7.8	-5.1	6.9	8.5
ROTTDM	1.2	4.3	-0.9	5.6	-3.5	10.4	-7.5	9.2	11.9
GOIDSOD	4.0	5.3	0.3	5.7	-2.4	8.1	-9.5	6.4	11.5
IJMDBTHVN	8.3	8.9	-0.8	5.9	-4.6	15.0	-19.3	10.2	21.8
Q1	1.3	3.3	-0.8	4.8	-1.3	10.6	-11.8	12.6	17.3
DENHDR	2.6	3.6	-0.5	4.6	-4.9	9.5	-17.0	15.4	22.9
TEXNZE	2.7	5.0	-1.4	5.5	-4.6	14.3	-13.0	12.8	18.2
K13APFM	-1.3	3.3	-0.2	4.2	1.7	7.2	-9.6	8.5	12.8
F16	0.6	2.5	-0.3	4.4	0.7	6.5	-11.0	3.5	11.6
OUDSD	0.7	2.7	-0.2	4.5	-2.5	8.9	-17.8	15.8	23.8
DENOVBTN	2.6	3.8	-0.4	5.2	-4.6	10.1	-18.5	20.7	27.8
TERSLNZE	2.4	4.2	-0.8	5.5	-1.8	12.4	-13.1	11.5	17.5
VLIELHVN	2.6	3.9	-0.1	4.8	-2.5	11.2	-25.9	9.7	27.6
WESTTSLG	0.3	2.5	-0.1	4.7	-3.1	11.2	-27.0	8.2	28.2
KORNWDZBTN	2.4	3.8	-0.4	5.2	-3.9	11.7	-22.5	19.7	29.9
WIERMGDN	2.4	4.1	-0.5	5.3	5.2	11.4	-13.9	6.4	15.3
HUIBGT	2.8	4.7	-0.7	5.8	9.6	13.7	-4.2	10.1	10.9
HARLGN	2.4	3.7	-0.3	5.4	-4.5	13.0	-19.2	18.9	26.9
NES	5.6	6.7	-0.3	5.5	-10.5	16.8	-31.3	14.0	34.3
LAUWOG	3.5	5.8	-0.4	6.4	-2.6	12.9	-29.0	16.9	33.6
SCHIERMNOG	4.1	5.5	-0.5	6.5	-0.9	13.5	-28.0	14.8	31.7
BORKUM_Sudstran.	2.5	4.5	-0.2	5.8	1.7	10.4	-22.6	13.2	26.2
BorkumFischerbalje	4.6	5.7	0.1	5.8	4.6	11.1	-18.8	12.7	22.7
EMSHORN	5.9	7.0	-0.1	6.2	1.9	11.7	-26.2	14.2	29.8
EEMSHVN	5.9	7.1	-0.2	6.4	2.0	11.5	-23.8	14.2	27.7
DUKEGAT	7.9	9.2	-0.5	7.1	2.6	15.7	-40.3	17.5	44.0
DELFZL	5.4	7.0	1.3	7.1	2.9	13.4	-35.4	20.8	41.1
KNOCK	6.3	7.7	0.6	7.0	5.3	14.6	-27.3	20.2	34.0
EMDEN_Neue_See.									

POGUM	-10.5	12.2	0.9	8.6	12.2	21.2	-34.7	28.4	44.8
Average (total)	2.8	5.1	-0.1	5.7	-0.1	11.0	-13.8	12.2	19.2
Average (offshore)	0.8	3.0	-0.2	4.6	0.1	7.5	-9.0	9.4	13.5
Average (coast)	2.8	4.4	-0.6	5.5	-1.2	11.0	-10.2	11.1	15.5
Average (SWD)	3.7	6.0	1.0	6.1	2.3	10.9	-4.6	10.6	11.8
Average (WS)	3.1	5.8	0.0	6.0	-0.1	12.9	-26.4	16.5	31.4
Average (RMM)	2.5	4.7	-0.6	5.4	-1.7	8.6	-7.7	8.0	11.2

A.2.1.3 DCSM-FM 0.5nm

Table A.6 Overview of the DCSM-FM 0.5nm model skill to represent skew surge heights (high waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal high water		**Skew surge (high water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar									
Bol_Van_Heist	-0.5	2.7	-1.0	5.3	0.3	7.5	-2.6	9.2	9.6
Scheur_Wielingen_.	-2.6	3.8	-0.2	5.3	0.1	9.3	-3.7	10.4	11.1
CADZD	-5.6	6.5	0.0	5.5	1.5	8.2	0.4	7.9	7.9
WESTKPLE	-7.0	7.9	0.5	5.1	3.0	7.2	-2.0	7.7	8.0
EURPFM	-2.9	4.0	0.1	4.7	0.4	7.1	-2.4	8.8	9.2
VLISSGN	-4.6	6.0	0.1	5.6	2.7	8.5	-0.4	10.1	10.1
ROOMPBTN	-1.7	3.3	-0.5	5.0	-0.6	9.7	-8.2	8.9	12.1
LICHTELGRE	-6.8	7.7	-0.5	4.9	0.0	7.8	-3.7	8.8	9.6
BROUWHVSGT08	-9.6	10.6	-1.4	6.2	-5.3	13.8	-15.4	14.6	21.2
TERNZN	0.4	4.7	1.0	6.0	1.9	10.1	3.6	10.4	11.0
HARVT10	-4.8	5.8	-0.9	5.6	-0.7	10.7	-6.3	6.5	9.0
ROOMPBNN	0.9	2.6	-0.8	5.2	5.2	10.0	1.2	5.9	6.0
HANSWT	1.8	5.9	0.0	6.7	9.8	14.4	8.7	8.3	12.1
HOEKVHLD	-0.2	3.9	-3.9	7.1	-2.6	13.2	-9.7	7.4	12.2
STAVNSE	6.3	6.9	0.1	5.8	8.1	12.3	0.6	8.4	8.4
BERGSDSWT	11.6	12.3	0.9	6.0	12.6	15.6	2.6	9.5	9.9
KRAMMSZWT	9.8	10.8	-0.9	7.5	2.8	11.8	1.4	11.7	11.8
BATH									
Prosperpolder_tij_Z.									
LIEFKENSHOEK									
SCHEVNGN	-1.5	3.9	-1.6	6.2	-3.8	10.5	-12.1	12.8	17.6
KALLO									
MAASSS									
Antwerpen_tij_Zees.									
VLAARDGN									
SPIJKNSE									
ROTTDM									
GOIDSOD									

IJMDBTHVN	1.4	4.1	-1.5	6.1	-4.6	12.9	-16.7	8.5	18.8
Q1	0.9	3.7	-0.6	5.1	-1.8	10.1	-12.7	15.5	20.1
DENHDR	0.6	3.3	-0.7	4.8	-5.7	9.0	-18.4	17.8	25.6
TEXNZE	2.6	4.7	-1.2	5.4	-5.9	13.9	-12.7	13.5	18.5
K13APFM	-1.1	3.6	-0.1	4.3	0.3	6.6	-7.9	10.6	13.2
F16	0.5	2.7	-0.4	4.2	-0.6	5.3	-11.8	5.2	12.9
OUDSD	0.8	3.0	-0.3	4.5	-2.6	7.2	-17.7	17.7	25.0
DENOVBTN	3.4	4.5	-0.8	5.2	-5.3	9.6	-20.8	22.5	30.6
TERSLNZE	0.2	3.0	-1.0	5.5	-5.1	11.9	-15.9	12.5	20.2
VLIELHVN	0.8	2.9	-0.2	4.6	-3.4	9.0	-24.0	9.0	25.6
WESTTSLG	-1.4	3.1	-0.3	4.7	-2.2	9.0	-24.1	7.6	25.3
KORNWDZBTN	2.1	3.9	-0.5	5.3	-4.0	10.3	-22.9	21.1	31.2
WIERMGDN	-1.5	3.5	-0.4	5.3	4.2	10.2	-12.7	5.5	13.8
HUIBGT	-2.3	4.4	-0.7	5.7	8.0	11.9	-4.1	7.7	8.7
HARLGN	0.3	3.6	0.1	5.7	-3.2	11.4	-18.1	18.4	25.8
NES	-2.9	4.6	0.5	5.7	-7.1	13.6	-26.8	13.9	30.2
LAUWOG	-2.6	5.1	0.6	6.5	-5.5	13.0	-30.8	14.8	34.1
SCHIERMNOG	-4.4	5.9	0.8	6.5	-4.5	12.7	-28.8	13.1	31.6
BORKUM_Sudstran.	-2.9	4.8	-0.2	5.6	-0.3	9.5	-24.6	11.7	27.2
BorkumFischerbalje	-0.4	3.4	-0.1	5.6	3.3	9.8	-18.8	11.1	21.8
EMSHORN	0.2	3.8	0.0	5.7	-3.2	11.7	-29.0	13.8	32.1
EEMSHVN	0.3	4.0	-0.3	5.9	-3.2	11.7	-27.1	13.1	30.1
DUKEGAT	1.5	4.9	-0.3	6.4	-2.6	16.4	-42.7	15.8	45.6
DELFZL	-0.9	4.6	-0.6	6.7	0.6	13.5	-36.5	17.5	40.4
KNOCK	-0.7	4.4	0.3	6.7	3.1	13.6	-29.3	17.2	34.0
EMDEN_Neue_See.									
POGUM									
Average (total)	-0.5	4.9	-0.4	5.6	-0.4	10.7	-13.6	11.7	19.5
Average (offshore)	-1.9	4.3	-0.3	4.6	-0.4	7.4	-7.7	9.8	13.0
Average (coast)	-2.2	4.8	-1.0	5.6	-1.2	10.7	-9.3	10.1	14.3
Average (SWD)	3.7	7.0	0.1	6.1	6.2	11.8	2.5	9.2	9.9
Average (WS)	-0.4	4.2	-0.1	5.7	-2.5	11.4	-26.4	14.9	30.7
Average (RMM)									

A.2.2 Low waters

A.2.2.1 DCSMv6

Table A.7 Overview of the DCSMv6 model skill to represent skew surge heights (low waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal low water		**Skew surge (low water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar	-4.6	6.4	0.3	5.4	-2.4	11.4	-6.6	7.1	9.7

Bol_Van_Heist	-2.4	4.9	0.1	5.4	-0.7	11.4	-11.7	13.5	17.9
Scheur_Wielingen_.	-1.7	4.5	-0.3	5.6	0.7	12.3	-16.0	11.3	19.6
CADZD	-2.4	4.8	-0.3	6.0	2.1	11.6	-9.1	13.7	16.5
WESTKPLE	1.9	4.6	0.0	5.2	0.8	9.7	-12.3	11.0	16.5
EURPFM	-3.7	5.5	0.8	5.0	4.4	8.9	-3.3	8.3	9.0
VLISSGN	0.8	4.6	0.2	5.5	0.1	10.3	-16.1	14.0	21.3
ROOMPBTN	-0.7	3.9	0.3	5.2	-2.3	12.2	-12.0	11.3	16.4
LICHTELGRE	-2.1	4.4	0.3	4.9	0.3	8.2	-1.4	9.5	9.5
BROUWHVSGT08	-1.2	4.9	-0.7	6.2	-2.2	12.4	-7.7	8.1	11.2
TERNZN	4.7	6.7	0.3	5.8	-1.1	10.7	-22.1	16.0	27.2
HARVT10	-2.1	4.5	0.3	5.4	2.8	9.1	3.0	13.2	13.5
ROOMPBNN	-4.9	6.0	0.4	5.0	1.3	10.1	-7.6	5.8	9.6
HANSWT	8.0	9.6	-0.8	5.7	-4.7	14.6	-24.8	16.1	29.6
HOEKVHLD	-2.5	4.8	0.5	5.8	3.7	10.0	3.7	11.4	12.0
STAVNSE	2.6	4.4	0.1	5.4	-3.1	10.9	-7.2	10.8	12.9
BERGSDSWT	-2.3	4.5	0.2	5.4	0.2	13.5	-2.9	11.8	12.1
KRAMMSZWT									
BATH	21.9	23.3	-2.2	7.5	-9.3	19.4	-34.8	18.5	39.4
Prosperpolder_tij_Z.									
LIEFKENSHOEK									
SCHEVNGN	-1.8	4.5	0.8	5.5	3.6	9.6	4.8	7.9	9.3
KALLO									
MAASSS									
Antwerpen_tij_Zees.									
VLAARDGN									
SPIJKNSE									
ROTTDM									
GOIDSOD									
IJMDBTHVN	-1.6	4.7	1.5	5.9	2.2	9.6	-1.9	11.1	11.3
Q1	-3.5	4.6	0.4	4.4	2.9	7.4	-4.2	10.3	11.1
DENHDR	-4.2	5.5	0.5	5.0	-2.4	8.4	-11.8	12.1	16.9
TEXNZE	-3.0	4.6	1.3	5.4	4.8	8.6	-8.6	9.7	12.9
K13APFM	-1.2	3.0	0.2	4.2	0.9	5.9	-6.0	10.7	12.3
F16	-1.0	2.9	0.4	4.2	1.4	6.6	-2.8	5.9	6.5
OUDSD	-2.7	4.4	0.3	4.8	-3.7	8.2	-13.5	11.2	17.5
DENOVBTN	-1.5	4.9	-0.7	8.6	0.6	9.7	-9.7	17.2	19.7
TERSLNZE	-1.7	4.1	0.6	5.8	7.6	11.9	-2.4	10.8	11.0
VLIELHVN	-7.4	8.3	0.4	5.2	-5.6	11.5	-19.6	12.2	23.1
WESTTSLG	-0.4	4.2	0.2	6.0	-10.9	16.3	-26.0	16.0	30.5
KORNWDZBTN	1.2	3.4	-0.3	6.8	1.5	11.4	-10.9	17.3	20.4
WIERMGDN	0.2	4.5	0.4	5.8	5.5	11.4	5.4	14.2	15.2
HUIBGT	0.8	5.0	0.0	6.1	5.7	11.0	5.7	10.9	12.3
HARLGN	13.4	14.3	-0.2	9.0	-11.4	17.0	-27.3	20.0	33.8
NES	6.9	10.7	-1.1	8.5	-20.7	25.0	-30.5	21.9	37.6
LAUWOG	10.0	11.9	0.1	6.8	-18.8	23.1	-27.3	21.7	34.9
SCHIERMNOG	9.1	10.7	-0.6	6.8	-17.3	21.7	-21.9	18.3	28.5
BORKUM_Sudstran.									

BorkumFischerbalje									
EMSHORN									
EEMSHVN	0.2	6.1	0.8	7.4	-7.8	14.8	-6.9	13.8	15.5
DUKEGAT									
DELFZL	13.3	16.0	1.7	9.5	-19.0	25.6	-17.9	15.6	23.7
KNOCK									
EMDEN_Neue_See.									
POGUM									
Average (total)	0.9	6.4	0.2	5.9	-2.3	12.4	-10.8	12.8	18.2
Average (offshore)	-2.3	4.1	0.4	4.5	2.0	7.4	-3.5	8.9	9.7
Average (coast)	-1.7	4.8	0.3	5.6	1.8	10.7	-4.8	11.1	13.9
Average (SWD)	4.4	8.5	-0.2	5.8	-2.4	12.8	-16.5	13.3	21.7
Average (WS)	3.8	8.6	0.1	7.2	-10.3	16.8	-19.2	16.8	25.9
Average (RMM)									

A.2.2.2 DCSMv6-ZUNOv4

Table A.8 Overview of the DCSMv6-ZUNOv4 model skill to represent skew surge heights (low waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal low water		**Skew surge (low water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar	-2.7	5.3	0.2	5.3	-3.5	11.8	-7.0	6.5	9.6
Bol_Van_Heist	-2.7	5.1	0.0	5.3	-1.7	11.9	-12.2	13.0	17.8
Scheur_Wielingen_.	-3.5	5.4	-0.2	5.5	-0.1	12.6	-15.6	10.8	19.0
CADZD	-3.6	5.4	-0.2	5.9	0.8	11.3	-9.7	13.9	16.9
WESTKPLE	-1.7	4.5	0.1	5.2	1.4	9.9	-11.9	10.9	16.1
EURPFM	-0.9	4.4	0.7	4.9	4.0	8.7	-4.6	7.6	8.9
VLISSGN	-3.8	5.8	-0.2	5.5	-0.1	10.3	-15.4	14.5	21.1
ROOMPBTN	-3.5	5.2	0.2	5.2	-1.1	11.7	-10.3	10.9	15.0
LICHTELGRE	-1.2	4.5	0.3	4.8	-0.7	7.6	-3.7	9.6	10.2
BROUWHVSGT08	-1.5	5.3	-0.3	6.0	-2.2	12.0	-8.4	8.4	11.8
TERNZN	-4.9	6.6	-0.2	5.8	-0.2	10.7	-17.9	16.5	24.4
HARVT10	-1.7	4.7	0.4	5.4	2.3	8.7	0.8	12.9	12.9
ROOMPBNN	-2.8	4.4	0.1	4.9	1.4	9.9	-6.7	5.8	8.9
HANSWT	-4.6	6.4	-0.2	5.5	-2.0	13.2	-15.1	17.6	23.2
HOEKVHLD	-4.4	6.2	1.4	6.0	4.4	9.4	3.3	11.8	12.2
STAVNSE	-2.2	4.3	0.2	5.2	0.7	10.6	-2.5	11.7	12.0
BERGSDSWT	-4.8	6.1	-0.1	5.3	2.4	13.8	-0.2	12.1	12.1
KRAMMSZWT	-2.3	4.6	0.6	5.6	2.2	11.4	-11.5	13.3	17.5
BATH	-4.3	6.4	-0.8	5.7	-1.1	12.9	-16.3	17.8	24.2
Prosperpolder_tij_Z.									
LIEFKENSHOEK	-5.3	7.0	-0.8	6.2	-1.8	13.2	-15.9	18.3	24.2
SCHEVNGN	-4.2	5.8	1.0	5.6	5.0	10.0	6.0	8.1	10.1

KALLO	-4.5	6.7	-1.0	6.4	-1.8	13.3	-17.7	19.0	25.9
MAASSS	-3.5	6.2	1.8	6.4	6.2	9.6	4.6	12.8	13.6
Antwerpen_tij_Zees.	-6.5	8.1	-0.1	6.5	-2.8	14.4	-16.0	19.8	25.4
VLAARDGN	-3.6	6.1	1.3	6.2	3.9	8.4	1.9	12.0	12.2
SPIJKNSE	-5.2	6.9	1.5	6.0	5.6	9.1	1.9	11.2	11.4
ROTTDM	-3.1	6.3	1.6	6.8	2.6	8.1	-4.0	13.1	13.7
GOIDSOD	-4.8	6.7	1.1	6.2	4.4	7.3	3.8	7.4	8.3
IJMDBTHVN	-3.7	5.6	1.4	5.8	3.0	9.7	-1.9	10.7	10.8
Q1	-2.3	3.9	0.4	4.4	2.2	7.2	-4.8	10.4	11.4
DENHDR	-4.4	5.5	0.7	4.9	-1.4	8.9	-10.8	12.7	16.7
TEXNZE	-2.4	4.2	1.6	5.5	4.4	8.3	-8.9	9.9	13.4
K13APFM	-0.6	2.8	0.2	4.1	1.4	5.6	-5.2	10.0	11.3
F16	-1.8	3.2	0.4	4.3	2.4	6.7	-1.2	5.3	5.4
OUDSD	-4.4	5.5	0.4	4.7	-1.5	7.7	-10.6	11.9	15.9
DENOVBTN	-7.5	9.0	-0.4	9.2	5.6	11.4	-1.6	15.5	15.5
TERSLNZE	-3.0	5.0	0.6	5.7	7.5	12.1	-3.4	10.0	10.6
VLIELHVN	-5.8	6.9	0.3	5.0	-4.2	12.1	-21.5	12.9	25.0
WESTTSLG	-1.6	4.0	0.3	5.3	-6.7	13.8	-21.5	15.6	26.6
KORNWDZBTN	-3.0	4.3	-0.6	6.5	4.4	11.6	-7.5	15.9	17.5
WIERMGDN	-2.3	4.7	0.3	5.9	7.4	11.9	5.4	14.2	15.2
HUIBGT	-1.7	4.8	0.4	6.2	7.8	12.3	8.3	10.9	13.7
HARLGN	0.9	2.8	-0.5	6.0	-1.6	11.1	-18.0	16.4	24.4
NES	-2.8	5.3	0.1	6.1	-11.0	15.3	-23.2	16.7	28.5
LAUWOG	-5.8	7.9	0.0	6.5	-5.1	13.9	-7.4	22.2	23.4
SCHIERMNOG	-2.1	5.4	0.1	6.3	-7.3	14.7	-9.3	20.1	22.1
BORKUM_Sudstran.	0.5	5.2	0.4	6.2	-6.3	13.4	-7.5	12.5	14.6
BorkumFischerbalje	-3.7	5.9	-0.2	6.2	-3.0	11.7	-8.3	11.4	14.1
EMSHORN	-2.1	5.2	0.5	6.7	-7.0	13.2	-13.0	12.1	17.7
EEMSHVN	-6.2	8.0	1.0	6.9	-2.7	12.4	-6.9	10.1	12.2
DUKEGAT	-7.3	8.8	1.1	7.7	-0.7	11.9	-2.2	10.3	10.6
DELFZL	-5.7	7.8	1.3	8.5	-3.4	14.5	-4.6	8.0	9.2
KNOCK	-6.2	8.2	0.2	8.1	-4.5	14.7	-5.4	10.4	11.7
EMDEN_Neue_See.									
POGUM	51.8	54.8	-0.6	12.5	-44.0	46.8	-52.0	24.6	57.5
Average (total)	-2.4	6.6	0.3	6.0	-0.7	11.8	-8.2	12.7	16.6
Average (offshore)	-1.4	3.8	0.4	4.5	1.8	7.2	-3.9	8.6	9.5
Average (coast)	-2.9	5.2	0.5	5.6	2.1	10.8	-4.8	11.0	13.9
Average (SWD)	-4.2	6.0	-0.2	5.7	-0.3	12.2	-12.3	15.1	19.9
Average (WS)	-0.6	9.1	0.2	7.0	-5.8	14.7	-13.0	14.5	20.4
Average (RMM)	-4.1	6.4	1.5	6.3	4.6	8.5	1.6	11.3	11.8

A.2.2.3 DCSM-FM 0.5nm

Table A.9 Overview of the DCSM-FM 0.5nm model skill to represent skew surge heights (low waters), for three different event classes, in terms of bias (cm) and the RMSE (cm) for Dutch coastal stations

	Tidal low water		**Skew surge (low water)**						
	all		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
Station	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	bias (cm)	RMSE (cm)	Bias (cm)	Std (cm)	RMSE (cm)
Wandelaar									
Bol_Van_Heist	-2.8	4.8	0.0	5.1	-1.2	10.1	-11.1	13.9	17.8
Scheur_Wielingen_.	-1.8	4.2	-0.5	5.3	-1.3	10.8	-16.5	11.4	20.1
CADZD	-1.6	4.4	-0.6	5.6	-0.1	9.8	-10.5	15.2	18.4
WESTKPLE	1.5	4.1	-0.1	4.9	0.6	8.6	-11.1	12.7	16.9
EURPFM	0.8	4.1	0.6	4.8	3.4	7.9	-3.8	8.4	9.2
VLISSGN	-3.6	5.7	-0.2	5.3	-1.2	8.6	-16.8	15.1	22.6
ROOMPBTN	0.6	3.7	0.2	4.8	-0.7	10.3	-10.4	12.4	16.1
LICHTELGRE	3.0	4.8	0.2	4.7	1.0	7.5	0.1	12.2	12.2
BROUWHVSGT08	6.6	8.2	-0.3	5.9	-2.1	9.9	-8.8	7.7	11.7
TERNZN	-7.0	8.4	0.0	5.5	-2.4	9.7	-22.3	16.9	28.0
HARVT10	2.5	4.8	0.3	5.4	4.3	9.2	2.2	14.1	14.3
ROOMPBNN	3.0	4.6	-0.3	4.8	-2.8	9.7	-9.9	9.3	13.6
HANSWT	-2.8	5.9	-1.0	5.4	-7.9	15.5	-22.2	18.1	28.7
HOEKVHLD	0.5	4.1	0.8	5.8	4.3	9.9	4.8	9.6	10.7
STAVNSE	1.6	4.2	0.6	5.1	-5.2	10.8	-8.4	14.1	16.4
BERGSDSWT	4.0	6.3	1.1	5.3	-5.9	14.1	-11.5	12.2	16.8
KRAMMSZWT	-0.7	4.2	0.9	5.4	-3.1	11.0	-17.4	16.0	23.7
BATH									
Prosperpolder_tij_Z.									
LIEFKENSHOEK									
SCHEVNGN	2.9	5.0	1.1	5.6	4.0	9.4	1.5	7.0	7.1
KALLO									
MAASSS									
Antwerpen_tij_Zees.									
VLAARDGN									
SPIJKNSE									
ROTTDM									
GOIDSOD									
IJMDBTHVN	1.1	5.8	1.8	6.4	3.3	9.0	-5.6	11.3	12.6
Q1	-1.7	3.8	0.4	4.4	1.6	7.2	-5.6	10.2	11.7
DENHDR	-2.4	4.4	0.6	4.9	-1.5	8.8	-11.1	13.1	17.2
TEXNZE	-1.3	3.7	1.3	5.4	3.9	8.0	-9.7	10.2	14.1
K13APFM	0.5	3.0	0.4	4.1	-0.4	4.8	-4.3	10.9	11.7
F16	-0.2	2.9	0.3	4.0	0.6	5.8	-3.1	5.3	6.1
OUDSD	-1.6	3.9	0.3	4.5	-3.2	8.6	-11.6	13.0	17.4
DENOVBTN	-4.7	6.9	-0.4	8.7	3.9	11.2	-7.0	15.0	16.6
TERSLNZE	2.0	4.0	0.7	5.6	5.0	10.7	-6.1	10.7	12.3

VLIELHVN	0.2	3.7	0.4	5.3	-8.4	13.6	-27.8	12.7	30.6
WESTTSLG	-1.1	4.0	0.4	5.5	-7.7	13.8	-22.3	17.8	28.5
KORNWDZBTN	1.1	3.4	0.1	6.3	1.4	11.1	-11.3	17.8	21.1
WIERMGDN	2.2	4.8	0.1	5.7	4.5	10.8	0.7	14.0	14.0
HUIBGT	4.1	6.4	0.1	5.9	4.1	9.3	0.9	11.7	11.7
HARLGN	14.0	14.8	-0.1	8.1	-12.0	15.8	-28.6	20.8	35.4
NES	21.0	23.1	-0.2	8.9	-28.4	30.5	-44.1	20.1	48.4
LAUWOG	14.9	16.6	-0.1	6.4	-20.7	23.5	-30.7	21.8	37.7
SCHIERMNOG	27.2	29.2	-1.6	10.0	-34.5	36.9	-41.8	21.3	46.9
BORKUM_Sudstran.	8.6	10.6	0.4	6.2	-10.7	15.0	-14.3	13.3	19.5
BorkumFischerbalje	5.5	7.9	0.1	6.0	-7.9	12.9	-12.0	12.4	17.2
EMSHORN	10.5	12.1	0.6	6.7	-14.2	17.3	-22.0	12.6	25.4
EEMSHVN	8.1	10.2	1.1	6.7	-10.6	15.2	-16.9	11.4	20.3
DUKEGAT	10.3	12.1	1.1	7.4	-11.1	15.1	-15.7	11.3	19.3
DELFZL	16.5	18.2	1.6	8.1	-15.0	19.5	-21.8	11.7	24.7
KNOCK	13.0	14.8	0.7	7.7	-15.3	19.6	-22.3	13.0	25.8
EMDEN_Neue_See.									
POGUM									
Average (total)	3.6	7.5	0.3	5.9	-4.4	12.5	-13.2	13.2	19.8
Average (offshore)	0.4	3.7	0.4	4.4	1.2	6.7	-3.3	9.4	10.2
Average (coast)	0.9	4.8	0.4	5.5	1.8	9.6	-6.1	11.7	14.3
Average (SWD)	-0.8	5.6	0.2	5.3	-4.1	11.3	-15.5	14.5	21.4
Average (WS)	9.0	12.0	0.3	7.0	-12.1	17.5	-21.9	15.4	27.2
Average (RMM)									