Deltares

Validation of DCSM-FM (2020-2023)

HARMONIE and D-HYDRO migration

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Summary

This report assesses the impact on water level accuracy resulting from two key model transitions: the migration from the HARMONIE40 to the HARMONIE43 meteorological model, and the intended shift from the fifth-generation WAQUA model (DCSMv6-ZUNOv4) to the sixth-generation D-HYDRO DCSM-FM 100m model. The analysis considers the effects of the HARMONIE migration on both the two-dimensional operational DCSM-FM 100m setup and the three-dimensional 3D DCSM-FM model, with specific focus on atmospheric exchange processes.

To evaluate these transitions, multi-year hydrodynamic hindcast computations were conducted and validated against tide gauge data from Dutch coastal waters. This analysis encompasses a wide range of weather and hydrodynamic conditions, including storm Pia in December 2023 (for ECMWF and HARMONIE40). The results from HARMONIE were compared to those using ECMWF meteorological forcing.

Findings indicate that ECMWF provides the best overall results for DCSM-FM 100m, achieving the lowest average surge error, with an RMSE of 5.6 cm, followed closely by HA40 (5.9 cm) and HA43 (6.0 cm). Although HA43 exhibits slightly higher average errors than HA40, it performs better at specific inland stations in the Western and Eastern Scheldt, Wadden Sea, and Ems-Dollard estuary. For skew surge under calm conditions, ECMWF also records the lowest errors, with an RMSE of 5.2 cm compared to 5.6 cm for both HA40 and HA43. During extreme conditions, where skew surge underestimation contributes significantly to high water errors, HA40 displays the lowest negative bias, followed by HA43, and finally ECMWF.

Overall, DCSM-FM 100m consistently outperforms its predecessor, DCSMv6-ZUNOv4, in tide, surge, and total water level predictions, as well as skew surge estimates under both calm and storm conditions. Based on these findings, it is recommended that DCSM-FM 100m replace DCSMv6-ZUNOv4 as the primary operational tide-surge model at HMC and WMCN.

The report concludes with several targeted recommendations for improvements to further enhance forecast quality.

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1 Introduction

1.1 Background

This report focuses on several key developments in meteorological and hydrodynamic modelling supporting the storm surge forecasting at the Water Management Centre Netherlands (WMCN). First, we discuss the consequences for tide-surge forecasting quality due to the upcoming migration to a new version of the HARMONIE meteorological model (HA43), which is expected to enhance meteorological forecasts through improved resolution and a larger computational domain. Additionally, the report covers the integration of HA43 for 3D modeling with the 3D DCSM-FM model, which involves exchange of heat with the atmoshere. Another topic is the transition to the sixth generation of hydrodynamic models, DCSM-FM, which will replace the current WAQUA models for both deterministic and probabilistic forecasting. Lastly, we examine the performance of these models during the recent storm Pia, with a specific focus on discrepancies between forecasted and observed water levels, and whether these differences align with hindcast simulations.

1.2 Migration HA40 to HA43

The Royal Netherlands Meteorological Institute (KNMI) plans to migrate to a new version of the HARMONIE model (HA43) in 2024. While the current version, HA40, runs on KNMI's supercomputer in De Bilt, HA43 will be operated on a new supercomputer located in Iceland. This migration is part of a collaborative effort within the UWC West consortium, which includes Denmark, Iceland, and Ireland. As a result, the computational domain of HA43 will be larger than that of HA40.

Currently, the domain of HA40 is smaller than that of the DCSM, meaning that meteorological fields for forcing the hydrodynamic model need to be supplemented with data from other sources. For this, the ECMWF IFS/HRES model is used, which also provides the boundary conditions for HARMONIE. With the larger domain of HA43, covering the full DCSM-FM domain, this addition is no longer required.

In addition to the expanded domain, HA43 will feature several improvements. For instance, the horizontal grid resolution will be increased: HA43 will have a grid size of 1.8 km, compared to 2.5 km in HA40. The vertical resolution will also be enhanced, from 65 model layers (with the lowest layer at 12 m) in HA40 to 90 layers (with the lowest at 5 m) in HA43. Furthermore, significant updates to the model's physics have been made.

1.3 Migration WAQUA to D-HYDRO

In addition to migrating to a new version of the HARMONIE model, WMCN also plans to transition to a new generation of hydrodynamic models for the upcoming 2024/2025 storm season. The current fifth-generation WAQUA models, DCSMv6 and DCSMv6-ZUNOv4, will be phased out and replaced by the sixth-generation D-HYDRO models. These include DCSM-FM 100m (DCSMv7) for deterministic forecasts, and the coarser DCSM-FM 0.5nm (DCSMv7c) model for probabilistic forecasts based on the ECMWF Ensemble Prediction System (EPS).

The sixth-generation models are already running in pre-operational mode at WMCN and HMC. However, before making the final decision to fully transition, RWS-VWM requires a quantitative justification. This justification will involve comparing the quality of computed water levels between the two generations of models.

1.4 Validation storm Pia

There is also specific interest in the performance of the models during the recent storm Pia in December 2023. During this storm, the model-informed forecasts were sometimes substantially higher than observed water level extremes, in particular for Delfzijl. The question is whether this discrepancy aligns with the results of a hindcast simulation.

1.5 Guide to reader

This report provides a comprehensive analysis of the consequences for water level quality of the migration from the HA40 to HA43 meteorological model, as well as from the fifth-generation WAQUA hydrodynamic models to the sixth-generation D-HYDRO models. It begins with background information on these transitions (Chapter 1), followed by detailed descriptions of the models and methodologies used (Chapter 2). The report then compares meteorological forcing (Chapter 3) and validates model performance using both two-dimensional and three-dimensional approaches (Chapters 4 and 5). In Chapter 6 the impact of migrating from the fifth-generation WAQUA model to the sixth-generation D-HDYRO model is assessed. Special attention is given to the validation of storm Pia (Chapter 7), which provides a practical case study for assessing model accuracy. The report concludes with key findings and recommendations (Chapter 8).

2 Models, measurements and method

2.1 Hydrodynamic models

2.1.1 Fifth-generation WAQUA model: DCSMv6-ZUNOv4

The fifth-generation model selected for this study is the North Sea model DCSMv6-ZUNOv4 (waqua-dcsmv6_zunov4-j17-v1). This is the same version used in a previous hindcast comparison with the sixth-generation D-HYDRO model (Zijl et al., 2023), as well as in a forecast analysis (Zijl et al., 2021). It is also the version currently in operational use. The model covers the Northwest European Continental Shelf, including the entire North Sea, adjacent coastal seas (such as the Wadden Sea), and estuaries (the Eastern and Western Scheldt).

The model consists of two interconnected domains that function as a single model using a technique known as domain decomposition. The outer domain, DCSMv6, includes the deep ocean, the Irish Sea, and the northern part of the North Sea. The inner domain, ZUNOv4, covers the English Channel, as well as the central and southern parts of the North Sea. Along the Dutch coast, and in the estuaries and the Wadden Sea, the grid resolution is particularly refined.

Figure 2.1 provides an overview of the bathymetry and the two model domains. The model settings are consistent with those used in operational scenarios and in the 2019 hindcast analysis (Zijl et al., 2019). A detailed description of the model can be found in Zijl et al. (2013) and Zijl (2013).

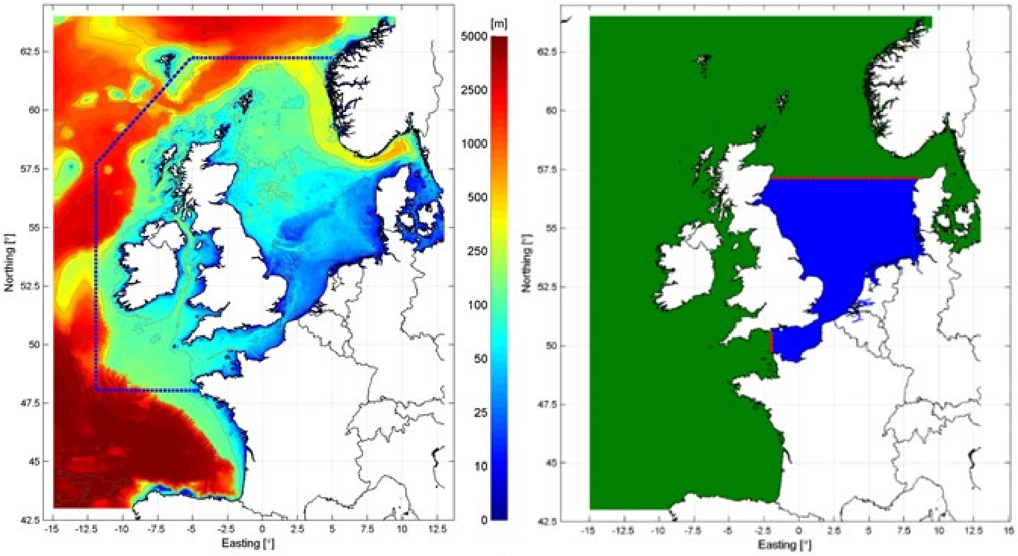

Figure 2.1 DCSMv6-ZUNOv4 model bathymetry (left) and model sub-domains (right) of DCSMv6 (green) and ZUNOv4 (blue).

2.1.2 Sixth-generation D-HYDRO model: DCSM-FM 100m

The sixth-generation model selected for this study is the 2022 release of the Dutch Continental Shelf Model – Flexible Mesh with 100m coastal resolution (DCSM-FM 100m. This model is also referred to as referred to as *dflowfm2d-noordzee_100m-j22_6-v1a*.

DCSM-FM 100m covers the northwest European continental shelf between 15°W to 13°E and 43°N to 64°N (Figure 2.2) and has a spatially varying grid size. 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 bathymetric and geometric information is obtained from Baseline-NL, which is an ArcGIS database used for hydrodynamic model development at Rijkswaterstaat. For areas outside the Rijkswaterstaat management area, bathymetry has originally been derived from a gridded bathymetric dataset (December 2020 version) from the European Marine Observation and Data Network (EMODnet). The resulting bathymetry and model extent are presented in Figure 2.2. The bottom roughness in 3D DCSM-FM has been used as a calibration parameter to improve tide propagation. A spatially varying Manning roughness coefficient is determined using data-assimilation techniques by running the model in 2D mode using more than 200 tide gauge stations covering the full model domain.

At the lateral boundaries total water levels are prescribed, consisting of tide and surge. The tidal levels are derived by harmonic expansion using the amplitude and phase of 39 harmonic constituents, based on a blend of three different global sources, namely FES2014 (Lyard et al., 2021), GTSMv4.1 (Muis et al., 2016) and EOT20 (Hart-Davis et al., 2021). In the D-HYDRO software the specified amplitudes and phases are converted into timeseries covering the required period by means of harmonic prediction. Surge levels at the open boundaries are approximated with a so-called inverse barometer correction, which depends on the local time-varying air pressure.

A detailed description of this model can be found in Zijl et al. (2023). Compared to the standard release of DCSM-FM 100m, a periodic surface forcing has been added to account for the contribution of baroclinic processes to the (semi-)annual variation of the sea surface height (Zijlker & Zijl, 2023). This development has yet to be implemented in the operational system (RWsOS Noordzee), but is unlikely to influence conclusions on the relative performance of HA40 and HA43.

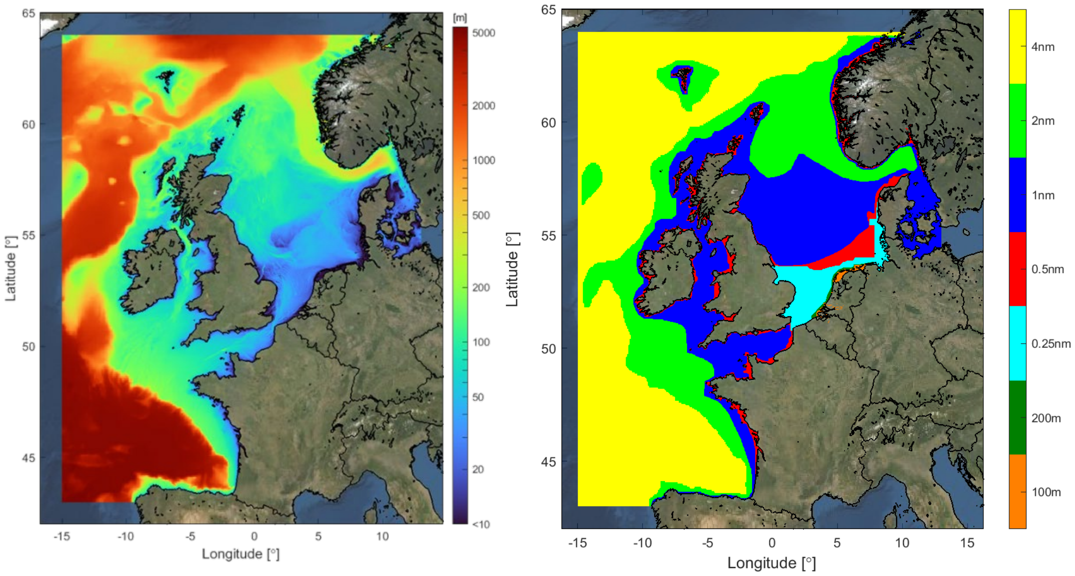

Figure 2.2 DCSM-FM 100m model domain and bathymetry (left) and horizontal network resolution (right).

2.2 Meteorological models

2.2.1 HARMONIE

HARMONIE-AROME (HIRLAM ALADIN Research on Mesoscale Operational NWP in Europe) has been the operational Numerical Weather Prediction (NWP) model used by KNMI since 2012. It is a limited-area model, specifically designed for high-resolution weather forecasting, and was developed through a collaboration between several European countries. The model is part of the shared efforts under the HIRLAM (High-Resolution Limited Area Model) and ALADIN (Aire Limitée Adaptation dynamique Développement InterNational) consortia. For a detailed description of HARMONIE-AROME, refer to Bengtsson et al. (2017).

The horizontal resolution of HARMONIE has improved significantly over time. In the current HARMONIE-AROME cycle 43 (HA43), the horizontal grid resolution has been increased from 2.5 km (as in HA40) to 1.8 km. However, for the purposes of this study, the meteorological reforecast data provided by KNMI for HA43 were interpolated onto a rectangular grid with a resolution of 2.5 km—consistent with the (non-native) grid used to provide the HA40 data on.

The HARMONIE40 data for this study cover the period from 2020 to 2023. Note that some parameters used to derive air-sea heat fluxes in 3D DCSM-FM cover a shorter period. The HA40 data were obtained from Rijkswaterstaat's MATROOS operational database, while the HA43 meteorological forcing data, spanning from October 2020 to September 2023, were made available directly by KNMI.

2.2.2 ECMWF IFS/HRES

The ECMWF IFS/HRES (Integrated Forecasting System/High-Resolution) is a global meteorological model developed by the European Centre for Medium-Range Weather Forecasts (ECMWF). It delivers high-resolution weather forecasts with a horizontal grid spacing of approximately 9 km on a global scale. The IFS/HRES model is widely used for operational forecasting, known for its accuracy and comprehensive data assimilation system, which integrates a wide range of global observations to enhance forecast reliability.

For this study, hourly ECMWF IFS/HRES data were provided by KNMI for the years 2020–2023. These datasets are derived from six-hourly forecasts, including the boundary condition (BC) run.

2.2.3 Meteorological forcing parameters

Table 2.1 lists the meteorological variables used from ECMWF, HARMONIE40 and HARMONIE43 to force DCSM-FM 100m and 3D DCSM-FM. For the depth-averaged (2D) runs, only air pressure and horizontal momentum exchange with the atmosphere is taken into account. For the 3D simulations, additional forcing variables are used to model heat exchange with the atmosphere, radiation fluxes, precipitation and evaporation. As precipitation and evaporation were not available for all sources, these forcing variables were taken from the ERA5 reanalysis dataset in all cases. The impact of evaporation and precipitation on water levels is expected to be negligible.

Table 2.1 Overview of forcing parameters used for ECMWF, HARMONIE40 and HARMONIE43 runs

ECMWF variable name	HARMONIE40 variable	HARMONIE43 parameter (long name)
Air pressure		
Pressure at mean sea level	Air_pressure_at_fixed_height	Pres (Pressure)
Horizontal momentum exchange with atmosphere		
U-component of neutral wind velocity at 10m	Windstress_u	uflux (Momentum flux, u-component)
V-component of neutral wind velocity at 10m	Windstress_v	vflux (Momentum flux, v-component)
Charnock parameter	-	-
Temperature		
Dewpoint temperature at 2m	Dewpoint_temperature	Td (Dewpoint temperature)
Air temperature at 2m	air_temperature	T (Temperature)
Radiation		
Surface net solar radiation	net_upward_shortwave_flux_in_air	swavr (Short wave radiation flux)
Surface thermal radiation downwards	net_upward_longwave_flux_in_air	lwavr (Long wave radiation flux)
Precipitation and evaporation		
ERA5 precipitation used	**ERA5 precipitation used**	**ERA5 precipitation used**
ERA5 precipitation used	**ERA5 evaporation rate used**	**ERA5 evaporation rate used**

2.3 Validation approach

2.3.1 Hindcast vs. reforecast

During the migration from Hirlam to HARMONIE, a validation study was conducted using the operational WAQUA models available at that time (Zijl et al., 2021). In many cases, especially when changes that require assessment relate to the hydrodynamic model, a hindcast study is sufficient for determining model quality. However, uncertainty in meteorological forecasts increases with longer forecast horizons, which is why a reforecast study was justified when migrating to a completely new meteorological model.

To streamline the workload for this migration, it is proposed that no hydrodynamic reforecast be conducted in this study, limiting the scope to hindcast simulations. This approach is justified because the earlier transition from Hirlam to HARMONIE was more significant compared to the planned migration from HA40 to HA43. Furthermore, the shift from the fifth to the sixth generation of models is not expected to affect the relative increase in uncertainty as a function of forecast horizon.

2.4 Observation stations

For the quantitative analysis of the results, the focus will be on the Dutch coast. In addition to 37 Dutch stations, three stations along the Belgian North Sea coast and six German stations in the Ems-Dollard region have also been included. A list of these 46 stations is provided in

Table 4.3. Compared to the validation of the 2022 release of DCSM-FM 100m (Zijl et al., 2023), five stations in the Rhine-Meuse Delta (Maassluis, Vlaardingen, Spijkenisse, Rotterdam, and Goidschalxoord), as well as four Belgian stations in the Western Scheldt (Prosperpolder, Liefkenshoek, Kallo, and Antwerp), were excluded. The offshore location F16 was also omitted.

Tide gauge observations for this study were sourced from various platforms. Data for Dutch stations were obtained from the Rijkswaterstaat Data Distribution Layer (DDL), while observations for German stations were provided by the Federal Institute of Hydrology (BAFG). Data for Belgian stations were retrieved via the API of Meetnet Vlaamse Banken (MVB).

Table 2.2 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 four groups: Offshore, Coast, Southwestern Delta (SWD) and Wadden Sea (incl. Ems-Dollard)

	Offshore		
1	EURPFM	3	Q1
2	LICHTELGRE	4	K13APFM
	Coast		
5	Wandelaar (BE)	13	HOEKVHLD
6	Bol_Van_Heist (BE)	14	SCHEVNGN
7	Scheur_Wielingen_Bol_van_Knokke (BE)	15	IJMDBTHVN
8	CADZD	16	DENHDR
9	WESTKPLE	17	TEXNZE
10	ROOMPBTN	18	TERSLNZE
11	BROUWHVSGT08	19	WIERMGDN
12	HARVT10	20	HUIBGT
	Southwestern Delta		
	VLISSGN	25	ROOMPBNN
22	TERNZN	26	STAVNSE
23	HANSWT	27	BERGSDSWT
24	BATH	28	KRAMMSZWT
	Wadden Sea		
29	OUDSD	38	BORKUM_Sudstrand (DE)
30	DENOVBTN	39	BorkumFischerbalje (DE)
31	VLIELHVN	40	EMSHORN (DE)
32	WESTTSLG	41	EEMSHVN
33	KORNWDZBTN	42	DUKEGAT
34	HARLGN	43	DELFZL
35	NES	44	KNOCK (DE)
36	LAUWOG	45	EMDEN_Neue_Seeschl (DE)
37	SCHIERMNOG	46	POGUM (DE)

2.5 Quantitative evaluation measures

The validation methods are in line with the development report of DCSM-FM 100m (Zijl, et al. 2022). This report focuses on the quantitative evaluation of the full time series, including a subdivision in tide and surge as well as errors in skew surges under various conditions.

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 three- or four-year validation period. In addition, as it provides further insight into the origins of remaining errors, the tide and surge components are separated from the total water level and the quality of both tide and surge is assessed separately.

High waters
The validation results are also 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

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

In all statistics used here, the bias over the full validation period has first been removed from the error signal. This is slightly different from the operational implementation, where the bias is removed in the so-called static bias correction based on an historical period, but it’s unlikely to influence conclusions on the relative performance of HA40 and HA43.

3 Comparison of meteorological forcing

3.1 Introduction

Before using the collected meteorological data for model forcing, a brief analysis has been performed. The results thereof are presented in this chapter. In section 3.2, times series at offshore location Platform K13a are compared, whereas in section 3.3, spatial fields of mean wind stress are compared.

3.2 Time series at Platform K13a

3.2.1 Wind speed

Wind speed measurements at offshore location platform K13a have been obtained from RWS Matroos for the years 2020-2023. Because of some missing data and availability of HA43 data, the period considered has been restricted to October 2020 to March 2023. The original measurement height was 73.8 m, but the values in Matroos have already been converted to 10 m height by dividing with a so-called Benschop factor of 1.23. In the present study, the measurements have first been converted back to measurement height (by multiplying with the Benschop factor), after which they were converted again to 10 m height using Charnock relation to account for the wind- and wave-dependent sea surface roughenss and a Monin-Obukhov approach to account for atmospheric stability. The formulations used are based on ECMWF (2023). Besides the wind speed magnitude, this boundary layer model requires the time-varying input parameters air temperature, dew point temperature, air pressure, sea surface temperature and Charnock parameter, which were obtained from the ECMWF IFS/HRES data.

In Figure 3.1 scatter plots comparing the 10 m wind speed magnitude to measuremed values are presented. This is done for ECMWF IFS/HRES, HA40 and HA43. These results show a good fit for all models with an RMSE of 1.2 m/s. Under high wind speed conditions (>15 m/s), ECMWF IFS/HRES slightly underestimating the wind speed, whereas HA40 and HA43 show a slight overestimation.

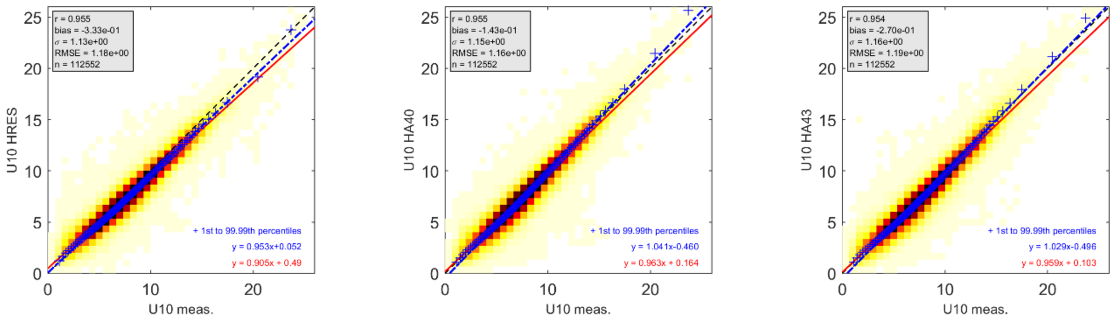

Figure 3.1 Scatter plots of measured and modelled wind speed magnitude at 10 m height at measurement location platform K13a, for ECMWF IFS/HRES (left), HA40 (middle) and HA43 (right), for the period October 2020 to March 2023. The red line represents a linear fit of all data points; the blue line represents a linear fit of the percentiles (blue crosses).

3.2.2 Wind stress

While a comparison of wind speeds is useful, it is ultimately the wind stress that generates storm surges (together with gradients in air pressure). Event though the wind speed is an important component in determining the wind stress, it is also useful to compare the wind stress between the various meteorological products. For both HA40 and HA43 the wind stress is provided. For ECMWF IFS/HRES, the wind stress was computed based on the neutral wind speed, the time-varying air density (computed from air pressure, air temperature and dew point temperature) and the wind drag coefficient derived with a Charnock formulation, using the ECMWF time-varying Charnock parameter. For converting the measured wind speed magnitudes to stress, the same approach as described above to convert from measurement height to 10 m was used. Note that as the aim here is to compare meteorological products in a relative sense, the exact method to derive 'measured' wind stress is less important than its consistent use for all comparions.

In Figure 3.2 scatter plots comparing the wind stress magnitude to 'measuremed' values are presented. This is again done for ECMWF IFS/HRES, HA40 and HA43. These results show a an underestimation for all models. However, the underestimation is much less severe in ECMWF IFS/HRES compared to HA40 and HA43, and is slightly less severe in HA43 compared to HA40.

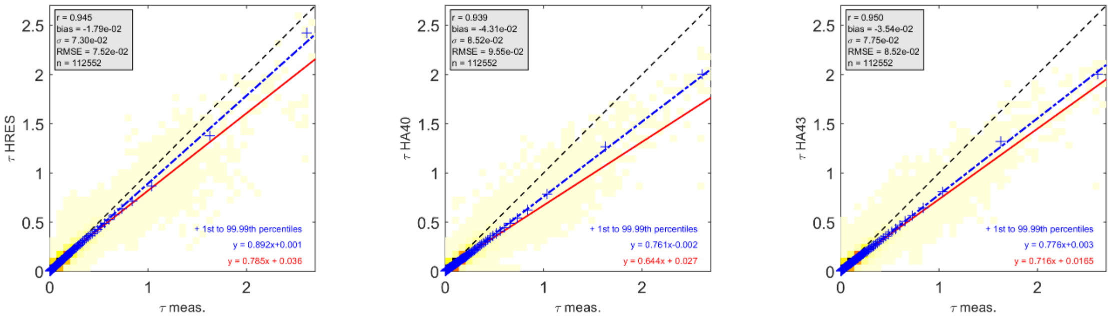

Figure 3.2 Scatter plots of measured and modelled wind stress magnitude at measurement location platform K13a, for ECMWF IFS/HRES (left), HA40 (middle) and HA43 (right), for the period October 2020 to March 2023. The red line represents a linear fit of all data points; the blue line represents a linear fit of the percentiles (blue crosses).

3.2.3 Wind drag coefficient

Since the differences in wind stress between meteorological products are much larger than the differences in wind speed, the origin of the differing wind speed should lie in the wind drag coefficients used (the differences in air density are expected to be much smaller). By dividing the wind stress with the air density and the square of the wind speed magnitude, the neutral wind drag coefficient can be computed. The word neutral implies that effects of atmospheric stability on the wind stress are incorporated in the wind drag coefficient. These effects can also be taken into account in the wind speed, yielding the neutral wind speed. However, this requires information on the neutral wind speed from HARMONIE, which is not available.

In Figure 3.3 scatter plots showing the neutral drag coefficient as a function of wind speed are presented for ECMWF IFS/HRES and HA40. On the right, the ratio between the drag coefficients of both models is presented. These results show that for wind speeds higher than around 5 m/s, the wind drag coefficient in HA40 is much lower than in ECMWF IFS/HRES.

The results also show much more variation in the ECWMF IFS/HRES neutral wind drag coefficients. For lower wind speeds, it is expected that the effect of atmospheric stability is the main contributor. In that respect it is notable that stable conditions, with a low neutral drag coefficient, are much less pronounced in HA40. For higher wind speeds, the impact of atmospheric stability becomes smaller and the main contributor is expected to be the variability in wave conditions, which affect the sea surface roughness. The ECMWF meteorological model derives its Charnock coefficient from the WAM wave model, whereas no such wave model is coupled to HA40 and HA43.

Similar scatter plots are presented for ECMWF IFS/HRES and HA43 in Figure 3.4 and for HA40 and HA43 in Figure 3.5. These show that wind drag coefficients in HA43 are on average 10-20% higher than in HA40, but still significantly lower compared to ECMWF IFS/HRES for wind speeds higher than around 5 m/s. Moreover, it is notable that the effects of a stably strafified atmosphere are more pronounced in HA43 compared to HA40, yielding a wind drag distribution that is more comparable to ECMWF IFS/HRES under low wind conditions.

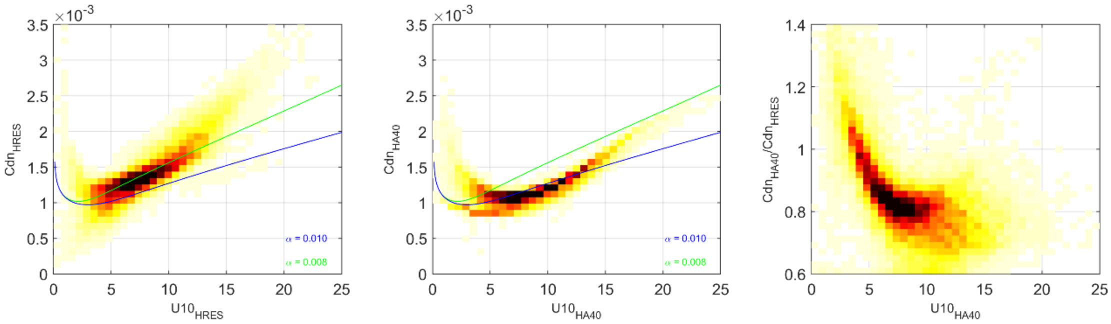

*Figure 3.3 Scatter plots of neutral wind drag coefficients at platform K13a as a function of wind speed, for **ECMWF IFS/HRES** (left) and **HA40** (middle), for the period October 2020 to March 2023. To the right, the ratio between HA40 and ECMWF IFS/HRES is shown. The blue and green line indicate the wind drag coefficient based on a Charnock formulation with a Charnock parameter of 0.01 and 0.025, respectively.*

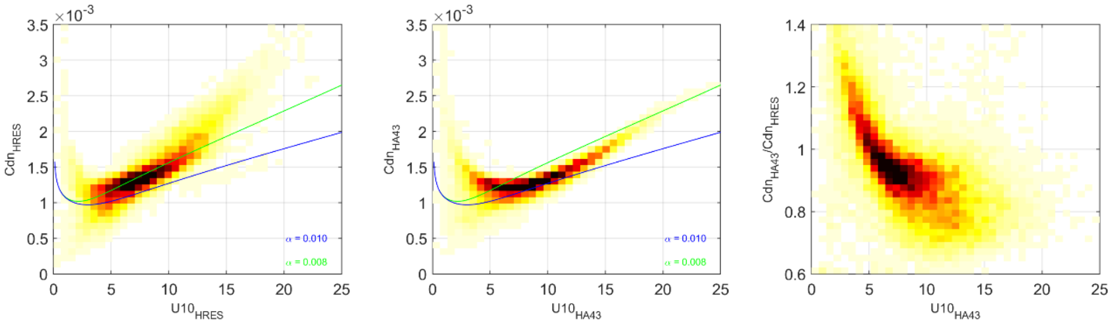

*Figure 3.4 Scatter plots of neutral wind drag coefficients at platform K13a as a function of wind speed, for **ECMWF IFS/HRES** (left) and **HA43** (middle), for the period October 2020 to March 2023. To the right, the ratio between HA43 and ECMWF IFS/HRES is shown. The blue and green line indicate the wind drag coefficient based on a Charnock formulation with a Charnock parameter of 0.01 and 0.025, respectively.*

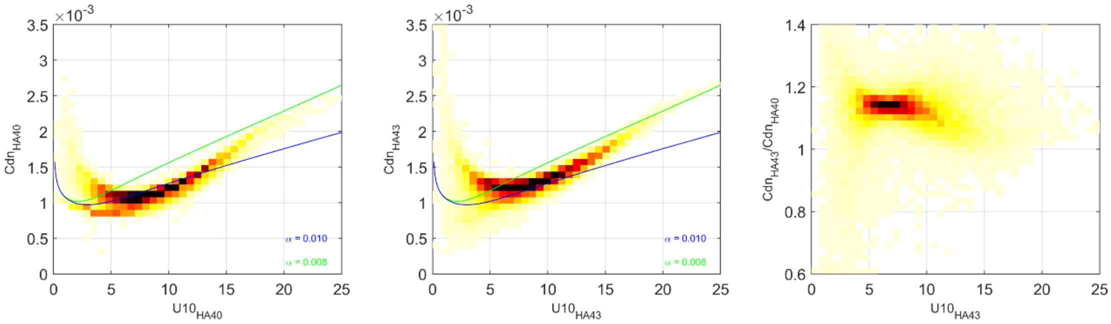

*Figure 3.5 Scatter plots of neutral wind drag coefficients at platform K13a as a function of wind speed, for **HA40** (left) and **HA43** (middle), for the period October 2020 to March 2023. To the right, the ratio between HA43 and HA40 is shown. The blue and green line indicate the wind drag coefficient based on a Charnock formulation with a Charnock parameter of 0.01 and 0.025, respectively.*

3.3 Mean wind stress magnitude

The results in the previous section focus solely on the measured and modeled meteorological conditions at platform K13a. In addition to these localized findings, it is valuable to briefly examine spatial patterns and the differences between the meteorological models. To do this, the mean wind stress over a 3-year period (October 2020 – September 2023), during which all three meteorological models are available, has been analyzed. For both versions of HARMONIE, wind stress data is directly available. The method used to derive wind stress from the ECMWF model follows the approach outlined in Section 3.2.2, consistent with the wind stress calculations in DCSM-FM, when applying time- and space-varying air density and using neutral wind as a forcing parameter.

Figure 3.6 to Figure 3.8 present the wind stress results for ECMWF IFS/HRES, HA40, and HA43. Figure 3.6 shows the entire DCSM-FM domain, Figure 3.7 zooms in on Dutch coastal waters, and Figure 3.8 focuses on the Dutch Wadden Sea, the Ems-Dollard, and Lake IJssel.

The results in Figure 3.6 reveal a distinct and sharp north-south transition crossing the west of Ireland. This marks the extent of the HA40 domain, which is smaller than the DCSM-FM domain. To compensate for this, ECMWF IFS/HRES data was used to supplement the HA40 data before it was employed to force the operational models and stored in the Matroos operational database, from which this data was retrieved. Despite HA40 using boundary conditions derived from ECMWF IFS/HRES, there is still a noticeable transition because wind stress is not a state variable transferred between models and the method for deriving wind stress from state variables differs between these models. The outer regions of the ECMWF IFS/HRES plot are similar to those of the HA40 plot, but not identical. Although both models are based on the same meteorological data, differences likely arise due to the different methods used to calculate wind stress.

HA40 shows a lower mean wind stress over the North Sea compared to ECMWF IFS/HRES. In HA43, the wind stress increases slightly, as also observed in the K13a time series (section 3.2.2). However, the mean wind stress in this region remains lower than that in ECMWF IFS/HRES. While HA43 produces higher mean wind stress in the North Sea and Wadden Sea compared to HA40, this does not extend to the outer oceanic areas. In these regions, HA43 produces lower wind stress than HA40, which, in fact, relied on ECMWF data for those areas.

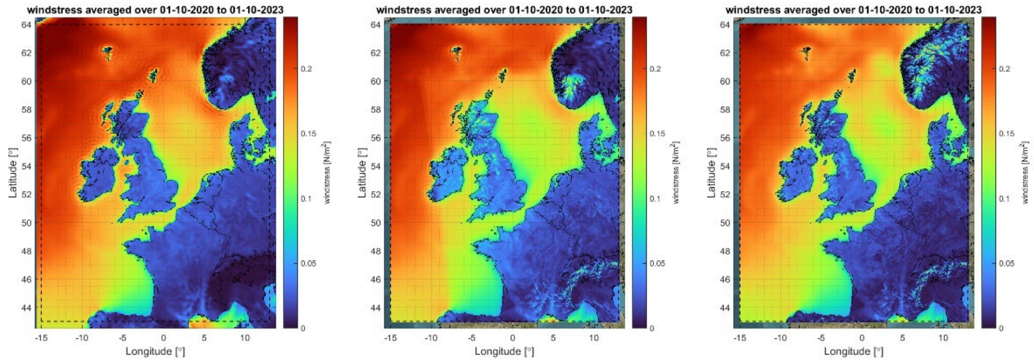

Figure 3.6 Contour plot of mean wind stress (N/m^2) in the period October 2020 to September 2023, for ECMWF IFS/HRES (left), HA40 (middle) and HA43 (right), for the entire DCSM-FM modain. The dashed black line indicates the extent of the DCSM-FM domain.

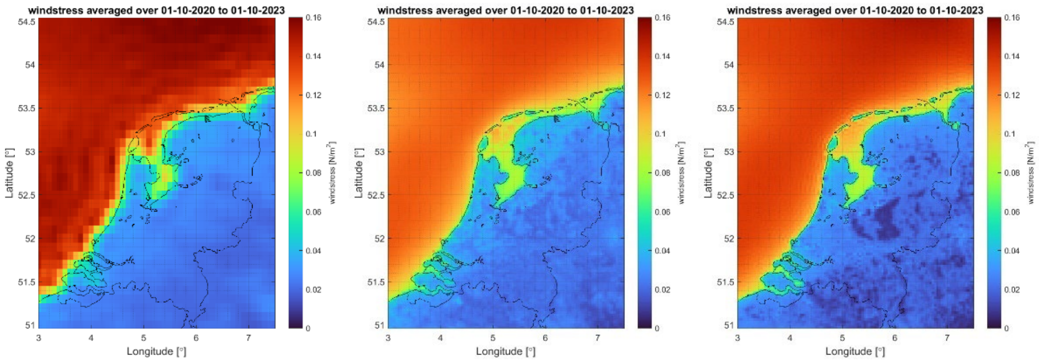

Figure 3.7 Contour plot of mean wind stress (N/m^2) in the period October 2020 to September 2023, for ECMWF IFS/HRES (left), HA40 (middle) and HA43 (right), for Dutch coastal waters.

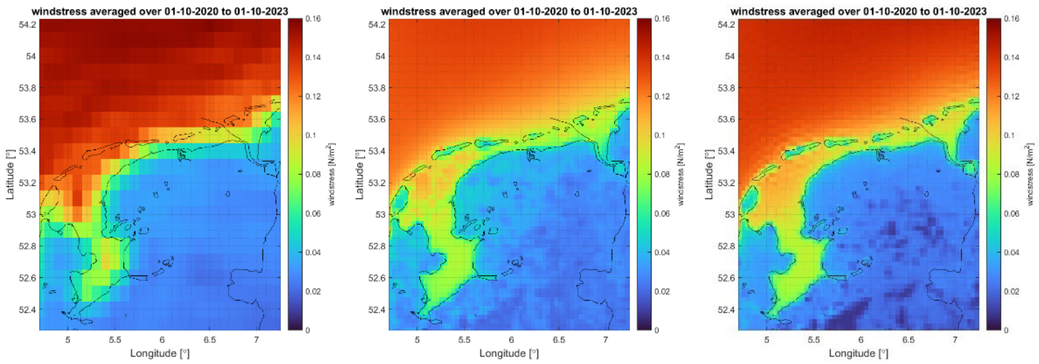

Figure 3.8 Contour plot of mean wind stress (N/m^2) in the period October 2020 to September 2023, for ECMWF IFS/HRES (left), HA40 (middle) and HA43 (right), for the Dutch Wadden Sea, Ems-Dollard and Lake IJssel.

4 Validation results HARMONIE43 (2D)

This chapter presents the validation results of the comparison that was done for the following meteorological forcings for DCSM-FM 100m:

- ECMWF-IFS
- HARMONIE40 (HA40)
- HARMONIE43 (HA43)

To account for the air-sea momentum flux, the ECMWF run was forced with neutral wind and the wave-age-depenent Charnock parameter, while the HARMONIE runs were forced with wind stress directly.

The validation period used for this comparison is October 6th, 2020 until October 1^{st,} 2023 because of the availability constraint of HA43. The computations started at least 5 days earlier to allow for model spin-up, starting from stagnant conditions (i.e., a cold start).

The moveable surge barriers in the model (Eastern Scheldt, Maeslant, Hartel surge barrier and the Ems Sperrwerk) are operated based on the historical gate heights. For the Dutch barriers, time series of the gate heigths have been provided by Rijkswaterstaat. The gate heights of the Ems Sperrwerk have been inferred from tide gauge measurements at Leerort, the first station upstream from this barrier.

4.1 Tide, surge and total water levels

Table 4.1 shows the RMSE of the tide, surge and total water level in Dutch coastal stations for the different available meteorological forcings. As expected, the tidal error is very similar between the different runs: 4.9 cm averaged over all stations for ECMWF, HA40 and HA43. The minor differences in tidal quality can be explained by the impact of meteorological forcing on the radiational tides such as the annual constituent Sa, the sem-annual constituent Ssa and the daily constituent S1.

ECMWF results in the best representation of surge, followed by HA40 and HA43. Surge error averaged over all stations is 5.6 cm for ECMWF, 5.9 cm for HA40 and 6.0 cm for HA43. In the different areas (offshore, coastal, Southwestern Delta and the Wadden Sea) the same order is observed. As a result of the differences in surge error, the total water level is best represented by the ECMWF run (ECMWF: 7.4 cm, HA40: 7.7 cm and HA43: 7.8 cm).

Figure 4.1, Figure 4.2, and Figure 4.3 give a spatial overview of the differences between the HA40 and HA43 run for total water level, tide and surge. This spatial comparison confirms that the total water level with HA43 is (on average) represented worse than with HA40 but spatial differences exist. Deterioration is mainly seen along the Dutch coast and in the northern part of the Wadden Sea. Further inland in the Western Scheldt, Eastern Scheldt, along the Afsluitdijk and in the Ems-Dollard estuary (past Delfzijl) the quality of the surge and total water level signal error is more equal.

Table 4.1 RMSE in cm of tide, surge and total water level of the sixth-generation model (DCSM-FM 100m) for the Dutch coastal stations, both based on ECMWF-IFS, HARMONIE40 and HARMONIE43 meteo forcing. The validation period used is 2020-10-06 until 2023-10-01. The main locations (Dutch: 'hoofdlocaties') are shown in bold.

Station	RMSE tide [cm]			RMSE surge [cm]			RMSE water level [cm]		
	ECMWF	HA40	HA43	ECMWF	HA40	HA43	ECMWF	HA40	HA43
Wandelaar	4,7	4,3	4,4	5,0	5,3	5,4	6,5	6,6	6,6
Bol_Van_Heist	4,1	4,0	4,0	5,0	5,3	5,3	6,5	6,7	6,7
Scheur_Wielingen_Bol_van_Knokke	4,5	4,5	4,5	4,8	5,2	5,4	6,6	6,8	6,9
CADZD	4,7	4,4	4,5	5,5	5,6	5,7	7,2	7,1	7,2
WESTKPLE	4,1	3,8	3,8	4,8	5,1	5,1	6,3	6,4	6,4
EURPFM	3,0	3,0	3,1	4,3	4,5	4,6	5,2	5,4	5,5
VLISSGN	**4,8**	**4,5**	**4,6**	**5,2**	**5,5**	**5,5**	**7,1**	**7,1**	**7,1**
ROOMPBTN	**3,3**	**3,6**	**3,6**	**4,9**	**5,3**	**5,3**	**5,9**	**6,4**	**6,4**
LICHTELGRE	3,7	3,5	3,5	4,5	4,8	4,9	5,7	5,9	5,9
BROUWHVSGT08	3,9	3,8	3,9	5,5	5,8	5,9	6,7	6,9	7,1
TERNZN	5,0	4,9	4,9	5,8	6,1	6,1	7,7	7,8	7,8
HARVT10	3,6	3,5	3,5	5,1	5,4	5,3	6,2	6,5	6,4
ROOMPBNN	3,8	3,9	4,0	4,7	5,0	5,0	6,1	6,4	6,4
HANSWT	5,3	5,5	5,5	6,1	6,2	6,2	8,0	8,3	8,3
HOEKVHLD	**3,8**	**4,0**	**4,0**	**5,1**	**5,4**	**5,5**	**6,4**	**6,7**	**6,8**
STAVNSE	3,8	3,9	4,0	5,2	5,4	5,4	6,4	6,7	6,7
BERGSDSWT	6,0	6,1	6,2	6,6	6,8	6,8	8,9	9,2	9,2
KRAMMSZWT	4,3	4,4	4,5	5,5	5,7	5,7	7,0	7,2	7,3
BATH	5,9	6,3	6,3	6,6	6,7	6,7	8,9	9,2	9,2
SCHEVNGN	3,7	3,7	3,7	5,3	5,6	5,7	6,5	6,7	6,8
IJMDBTHVN	3,8	3,9	3,8	5,5	5,9	5,9	6,7	7,0	7,0
Q1	4,0	3,9	3,9	4,5	4,7	4,9	5,4	5,6	5,8
DENHDR	**3,5**	**3,6**	**3,6**	**4,9**	**5,3**	**5,3**	**6,0**	**6,4**	**6,4**
TEXNZE	5,1	5,2	5,2	5,3	5,6	5,6	7,4	7,6	7,7
K13APFM	3,2	3,2	3,3	4,3	4,4	4,6	5,2	5,3	5,4
OUDSD	4,1	4,3	4,3	4,7	5,0	5,1	6,2	6,6	6,7
DENOVBTN	6,5	6,8	6,8	6,3	6,4	6,4	9,0	9,3	9,3
TERSLNZE	4,2	4,0	4,0	5,3	5,4	5,6	6,8	6,7	6,9
VLIELHVN	5,0	5,3	5,3	4,8	5,2	5,3	6,9	7,4	7,5
WESTTSLG	7,7	8,0	8,0	4,9	5,3	5,5	9,1	9,6	9,7
KORNWDZBTN	4,0	4,3	4,3	5,5	6,0	5,9	6,8	7,4	7,3
WIERMGDN	4,2	4,1	4,1	5,0	5,1	5,4	6,6	6,6	6,7
HUIBGT	4,4	4,4	4,3	5,2	5,4	5,5	6,8	7,0	7,0
HARLGN	**5,5**	**5,6**	**5,6**	**5,9**	**6,4**	**6,4**	**8,1**	**8,5**	**8,5**
NES	5,4	5,5	5,5	6,2	6,9	7,1	8,2	8,8	9,0

Station	RMSE tide [cm]			RMSE surge [cm]			RMSE water level [cm]		
	ECMWF	HA40	HA43	ECMWF	HA40	HA43	ECMWF	HA40	HA43
LAUWOG	5,8	5,7	5,7	6,3	6,7	7,0	8,6	8,8	9,0
SCHIERMNOG	6,2	6,2	6,2	8,6	9,0	9,1	10,6	10,9	11,0
BORKUM_Sudstrand	5,4	5,2	5,2	5,5	5,9	6,2	7,7	7,9	8,1
BorkumFischerbalje	4,9	5,0	5,0	5,3	5,7	6,0	7,2	7,6	7,8
EMSHORN	5,3	5,1	5,1	5,8	6,3	6,5	7,9	8,2	8,3
EEMSHVN	5,7	5,7	5,7	6,2	6,6	6,7	8,4	8,7	8,8
DUKEGAT	5,1	5,2	5,2	5,9	6,3	6,4	7,8	8,2	8,2
DELFZL	**5,8**	**6,3**	**6,2**	**7,1**	**7,5**	**7,6**	**9,2**	**9,9**	**9,8**
KNOCK	6,1	6,2	6,2	7,0	7,4	7,5	9,4	9,7	9,7
EMDEN_Neue_Seeschl	8,2	8,5	8,4	7,3	7,7	7,7	11,0	11,5	11,4
POGUM	9,9	10,3	10,2	8,0	8,4	8,3	12,7	13,3	13,2
Average (total)	**4,9**	**4,9**	**4,9**	**5,6**	**5,9**	**6,0**	**7,4**	**7,7**	**7,8**
Average (offshore)	**3,5**	**3,4**	**3,4**	**4,4**	**4,6**	**4,7**	**5,4**	**5,5**	**5,7**
Average (coast)	**4,1**	**4,0**	**4,1**	**5,2**	**5,4**	**5,5**	**6,6**	**6,8**	**6,8**
Average (SWD)	**4,9**	**5,0**	**5,0**	**5,7**	**5,9**	**5,9**	**7,5**	**7,7**	**7,8**
Average (WS)	**5,9**	**6,1**	**6,0**	**6,2**	**6,6**	**6,7**	**8,6**	**9,0**	**9,1**

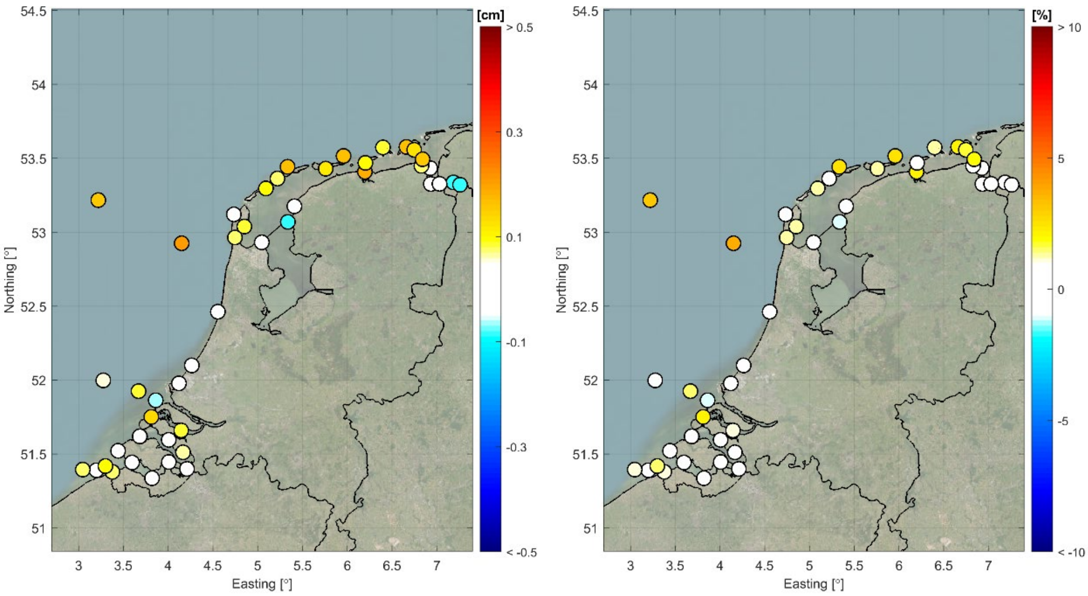

Figure 4.1 Spatial overview of the difference (HA43 minus HA40 for DCSM-FM 100m) in RMSE of the ***total water level*** *for the period October 2020 – October 2023 of the Dutch coastal stations. Left: difference [cm]; right: relative difference (%).*

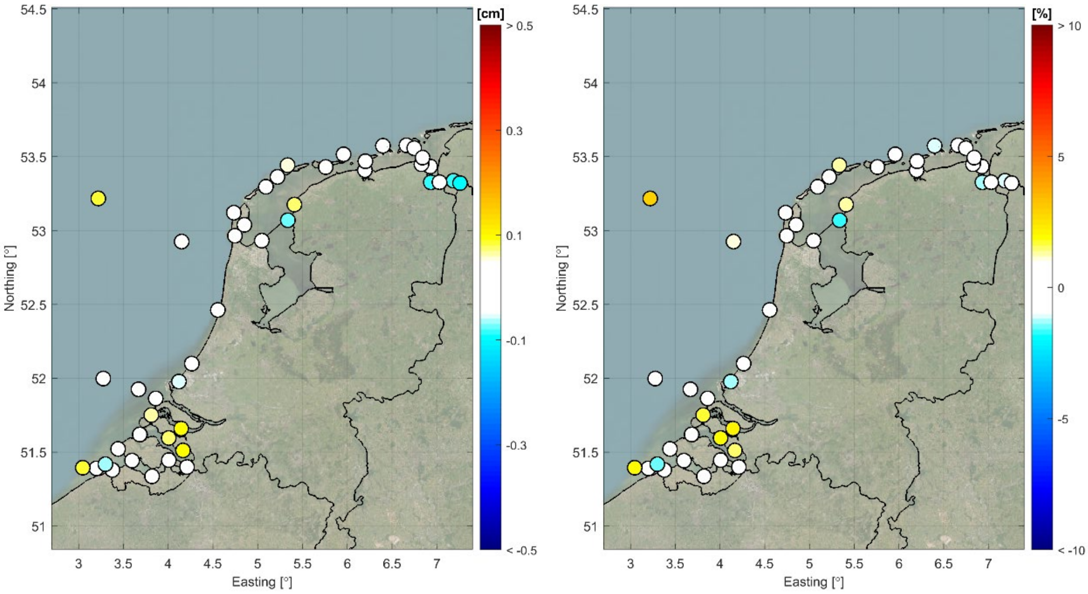

*Figure 4.2 Spatial overview of the difference (HA43 minus HA40 for DCSM-FM 100m)) in RMSE of the **tide** for the period October 2020 – October 2023 of the Dutch coastal stations. Left: difference [cm]; right: relative difference (%).*

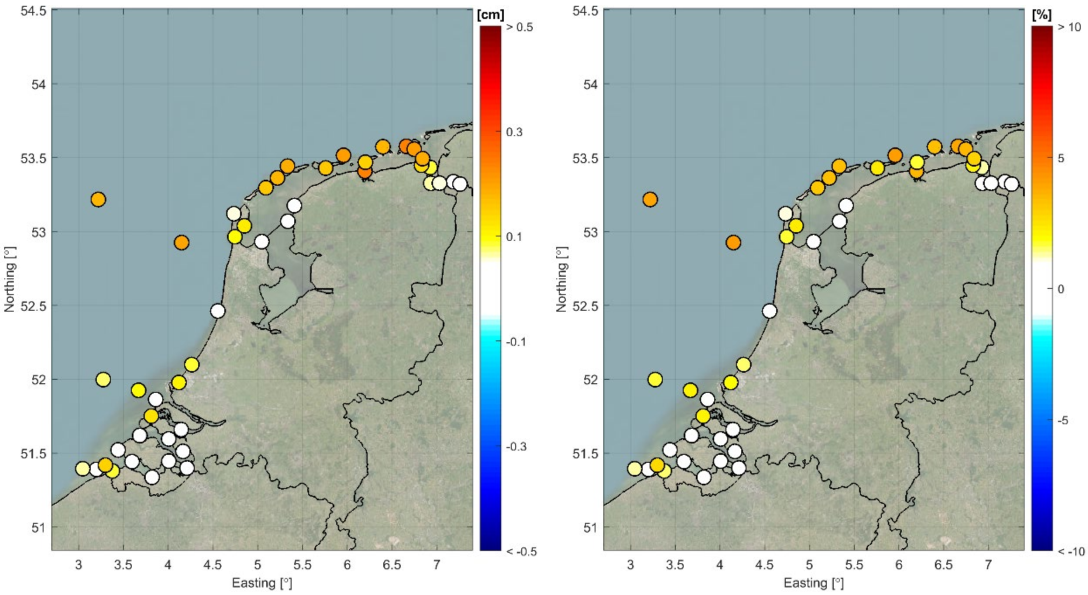

*Figure 4.3 Spatial overview of the difference (HA43 minus HA40 for DCSM-FM 100m)) in RMSE of the **surge** for the period October 2020 – October 2023 of the Dutch coastal stations. Left: difference [cm]; right: relative difference (%).*

4.2 Skew surge (high waters)

The error statistics for high waters in three different skew surge categories, in different areas in the Netherlands can be found in Table 4.2. Under relatively calm conditions, the lowest 99% storm surges, the skew surge error is the smallest for EMWF forcing in all different areas considered: RMSE of the skew surge is 5.2 cm for ECMWF and 5.6 cm for both HA40 and HA43.

Under more extreme conditions (99.0%-99.8% skew surges), averaged over all stations ECMWF also performs best. However, this better performance is mainly seen in the offshore and coastal stations. HA40 performs best in the Southwestern Delta and the Wadden Sea. This is likely due to the much higher spatial resolution of HA40, compared to ECMWF. Unfortunately, HA43 performance is the worst of the three forcings in all areas under these conditions. The difference is the smallest in the Southwestern Delta.

Under the most extreme conditions (>99.8% skew surges), HA40 performs best in all considered areas. Differences between the different forcings mainly follow from bias differences. Averaged over all stations, the extreme skew surge RMSE is on average better in HA40 (16.0 cm) compared to ECMWF (21.8 cm), but deteriorates in HA43 (18.8 cm) compared to HA40. For the offshore stations, ECMWF is the second-best forcing. In the Southwestern Delta and the Wadden Sea, HA43 is the second-best forcing as the skew surge is significantly underestimated using ECMWF forcing. This is likely due to the limited resolution of ECMWF compared to the geometry of the estuaries.

Figure 4.4 shows the spatials differences between HA40 and HA43 for skew surge error under calm conditions: the <99.0% skew surges. The results indicate that under these conditions, HA40 leads to better results for offshore stations and coastal stations. An explanation for this could be the blending with ECMWF that is performed for HA40 (section 3.3). Contrarily, HA43 leads to better results in the Ems-Dollard, close to the main coastline in the Wadden Sea and within the Southwestern Delta.

Figure 4.5 shows the spatial differences between HA40 and HA43 for skew surge RMSE and bias of the <99.8% skew surges. From this figure, it is clear that HA43 underestimated these skew surges more than HA40 does, except for stations in the Eastern- and Western Scheldt and around the entrance of the Ems-Dollard.

Table 4.2 Skew surge errors in the period October 2020 – September 2023, averaged over different areas (Table 2.2) based on different meteorological forcings: ECMWF IFS, HARMONIE40 and HARMONIE43. Results for all stations are presented in Appendix A.

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Total									
ECMWF	-0.2	7.0	-0.4	5.2	-9.6	12.3	-20.1	7.6	21.8
HARMONIE40	0.8	7.4	-0.4	5.6	-9.9	12.6	-12.4	7.9	16.0
HARMONIE43	0.7	7.3	-0.4	5.6	-12.2	15.0	-16.1	8.4	18.8
Offshore									
ECMWF	-1.6	5.7	-0.5	4.5	-5.2	6.8	-9.9	4.6	11.6
HARMONIE40	-1.1	5.7	-0.5	4.6	-6.9	9.4	-5.9	7.5	9.9
HARMONIE43	-1.1	5.8	-0.4	4.7	-9.1	11.0	-11.9	7.9	14.4
Coast									
ECMWF	-1.7	6.6	-0.7	5.0	-7.0	10.8	-14.9	6.4	16.6
HARMONIE40	-0.7	6.7	-0.8	5.3	-8.9	12.3	-11.0	9.0	15.4
HARMONIE43	-0.7	6.7	-0.7	5.3	-10.8	13.6	-14.9	8.4	17.7
Southwestern Delta									

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
ECMWF	0.3	7.0	0.0	5.1	-5.9	10.0	-10.6	6.2	12.3
HARMONIE40	1.5	7.3	0.0	5.3	-6.2	9.0	-1.9	8.6	9.3
HARMONIE43	1.4	7.2	0.0	5.2	-7.5	10.4	-5.6	8.4	10.5
Wadden Sea									
ECMWF	1.2	7.6	-0.4	5.6	-14.6	16.0	-31.2	10.0	32.8
HARMONIE40	2.2	8.4	-0.3	6.4	-13.1	15.2	-19.6	6.6	20.8
HARMONIE43	2.1	8.2	-0.3	6.1	-16.3	19.0	-22.7	8.6	24.4

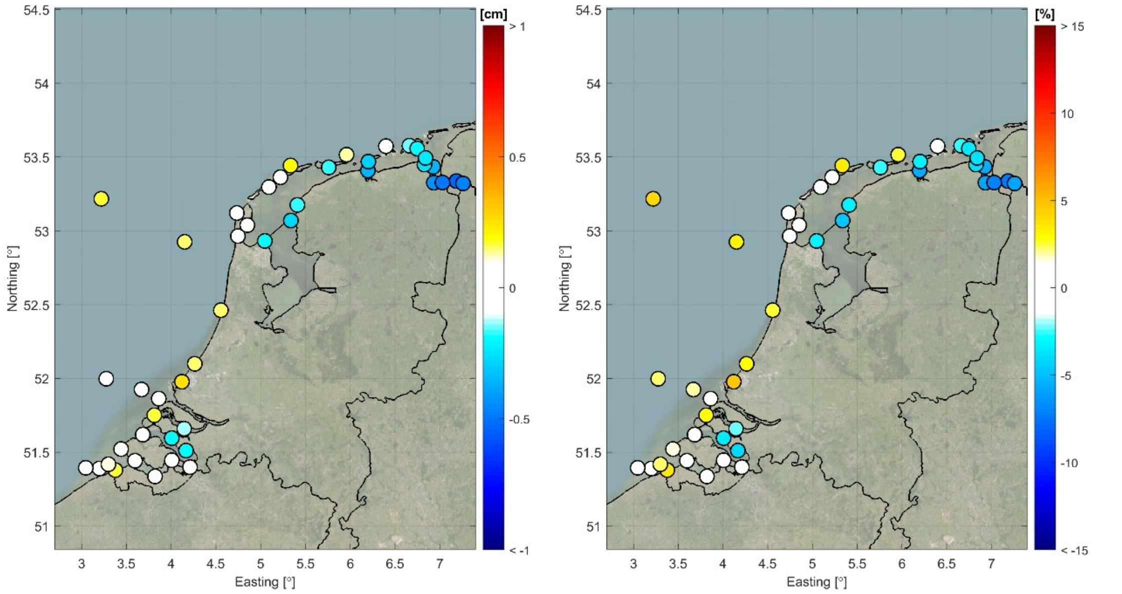

Figure 4.4 Spatial overview of the difference (HA43 minus HA40 for DCSM-FM 100m) in skew surge for the skew surges < 99.0% for the period October 2020 – October 2023 of the Dutch coastal stations. Left: difference in RMSE [cm]; right: difference in RMSE [%].

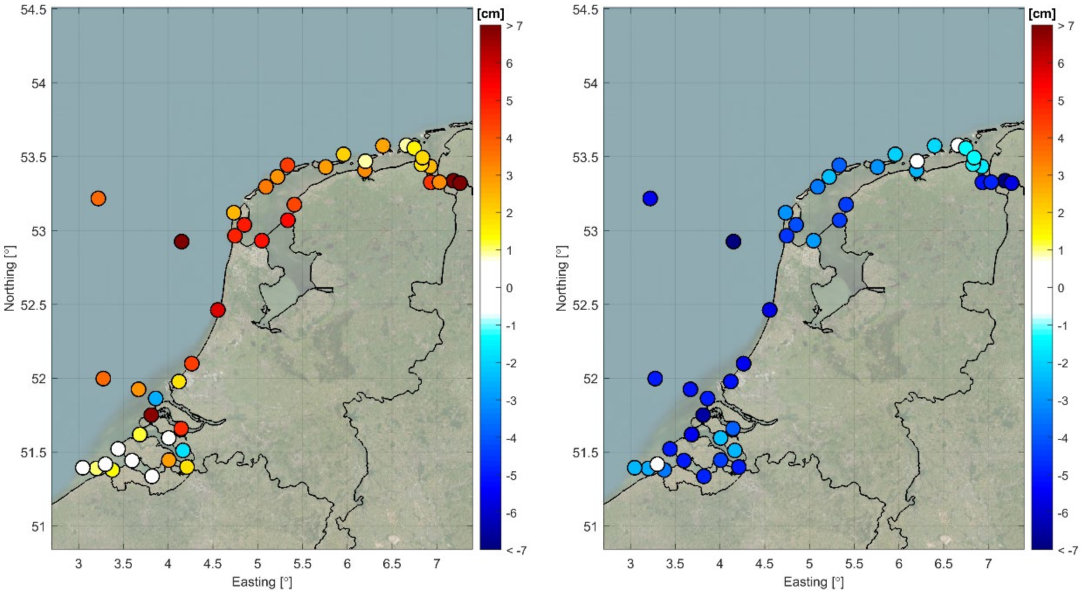

Figure 4.5 Spatial overview of the difference (HA43 minus HA40 for DCSM-FM 100m) in skew surge for the skew surges > 99.8% for the period October 2020 – October 2023 of the Dutch coastal stations. Left: difference in RMSE [cm]; right: difference in bias [cm].

5 Validation results HARMONIE (3D)

5.1 Introduction

This chapter presents the validation results for the 3D DCSM-FM model, comparing performance under the following meteorological forcings:

- ECMWF IFS/HRES
- HARMONIE40
- HARMONIE43

In its original configuration, 3D DCSM-FM is forced with ERA5 reanalysis data, where the air-sea momentum flux is calculated based on the neutral wind speed at 10 meters above sea level. For consistency with the Atmospheric Boundary Layer (ABL) in ERA5, a Charnock formulation is applied, using a time- and space-varying Charnock coefficient. This method can also be used when applying ECMWF IFS/HRES forcing. However, since HARMONIE uses a different ABL approach, and neither the neutral wind speed nor the Charnock coefficient are available, various alternatives for prescribing the relevant forcing were considered:

- **Using the wind speed from HARMONIE** and assuming a uniform and constant Charnock coefficient along with neutral atmospheric conditions for the wind stress conversion (in D-HYDRO). This approach results in a discrepancy between the air-side stress computed by HARMONIE and the water-side stress used by 3D DCSM-FM.
- **Deriving the neutral (stress-equivalent) wind speed** based on the HARMONIE wind stress, using the same Charnock coefficient and air density as applied in D-HYDRO. This ensures consistency with the wind stress computed by HARMONIE. However, the drawback is that the derived wind speed may be inconsistent with HARMONIE, potentially affecting turbulent heat fluxes, which also depend on wind speed.
- **Inferring either the wind drag coefficient or the Charnock coefficient** from both the HARMONIE wind speed and stress and applying the time- and space-varying value with the original wind speed. This would ensure consistency in both wind and stress, though differences in turbulent heat fluxes may still arise due to different formulations in D-HYDRO compared to HARMONIE. Currently, time- and space-varying wind drag coefficients cannot be prescribed in D-HYDRO. Attempts to derive the Charnock coefficient were unsuccessful, as the Cd coefficient is insensitive to Charnock values under low wind speed conditions (see Figure 3.3). Accounting for atmospheric stability effects under low wind conditions would require substantial adjustments to the wind drag coefficient, which was unfeasible with Charnock modifications.

For both HA40 and HA43, the first method was used, with a constant Charnock coefficient of 0.01. This value was chosen to represent the HA40 drag coefficient for winds between 10 and 15 m/s (see Figure 3.3). Additionally, two sensitivity tests were conducted using HA43 forcing. The first test applied an increased Charnock coefficient of 0.025, the same as used by Groenenboom & Zijl (2022). In the second test, method 2 was applied, deriving the stress-equivalent wind speed.

The validation period for this comparison covered the entire year of 2022, with the second half of 2021 used for spin-up. Spin-up started from stagnant conditions with salinity and temperature fields based on results from the global CMEMS model. While this spin-up period is relatively short compared to residence times in the southern North Sea, its impact on water level and temperature predictions is expected to be limited. The movable Eastern Scheldt barrier was kept open throughout the simulation. Due to data limitations, precipitation and evaporation rates were based on ERA5 in all scenarios.

The validation focuses on various aspects of water levels (Section 5.2 and 5.3) and water temperature (Section 5.4), as these are the parameters most affected by changes in meteorological forcing.

5.2 Tide, surge and total water levels

Table 5.1 presents the Root Mean Square Error (RMSE) for tide, surge, and total water levels at stations along the Dutch coast, comparing the performance of ECMWF, HA40, and HA43 meteorological forcing. For both HA40 and HA43, the modeled wind speeds were used in combination with a Charnock coefficient of 0.01.

On average, there is no difference in tidal quality between HA40 and HA43 (both with an RMSE of 6.8 cm), while ECMWF performs slightly better (with an RMSE of 6.4 cm). This relative performance is consistent across all sub-areas. Closer examination reveals that the improved tidal accuracy in ECMWF is mainly due to better representation of the semi-annual and annual tidal constituents (Sa and Ssa), as well as the primary semi-diurnal constituent, M2. The impact on these tides is likely driven by the Relative Wind Effect, which accounts for the influence of surface currents on air-sea momentum exchange (wind stress).

Notably, the errors for the NO1 tidal constituent are very high across all three setups, with a vector difference of 19-20 cm, though this is not fully reflected in the RMSE values. The large vector difference is likely due to a slight mismatch in tidal frequency between the observed constituent, boundary forcing and modeled tide, as well as assumptions in the harmonic analysis used here.

The Wadden Sea shows large errors, mainly due to inaccuracies in the modeling of drying and flooding. These errors are unavoidable because of the model grid's coarseness relative to the complex local bathymetry in this region.

For surge and total water levels, the RMSE increases progressively from ECMWF (5.3 cm for surge, 8.3 cm for total water level) to HA40 (6.1 cm and 9.2 cm, respectively), and further to HA43 (6.7 cm and 9.6 cm).

Table 5.1 Statistics (RMSE in cm) of tide, surge and total water level for the year 2022, for Dutch coastal stations, based on of 3D DCSM-FM with ECMWF IFS/HRES, HARMONIE40 and HARMONIE43 meteorological forcing.

Station	RMSE tide [cm]			RMSE surge [cm]			RMSE water level [cm]		
	ECMWF	HA40	HA43	ECMWF	HA40	HA43	ECMWF	HA40	HA43
Wandelaar	3,6	4,0	4,0	4,0	4,8	5,3	5,4	6,3	6,6
Bol_Van_Heist	4,6	5,0	5,0	4,0	4,8	5,2	6,1	6,9	7,3
Scheur_Wielingen_Bol_van_Knokke	4,7	5,1	5,1	4,4	5,1	5,6	6,1	7,0	7,4
CADZD	5,0	5,4	5,5	5,0	5,1	5,5	7,0	7,4	7,7
WESTKPLE	4,1	4,4	4,4	4,1	4,6	5,1	5,7	6,3	6,7
EURPFM	4,5	4,8	4,8	3,7	4,5	4,9	5,8	6,5	6,9
VLISSGN	5,5	5,9	5,9	4,5	5,1	5,5	7,1	7,8	8,1
ROOMPBTN	5,7	6,2	6,2	4,4	5,1	5,6	7,2	8,0	8,4

Station	RMSE tide [cm]			RMSE surge [cm]			RMSE water level [cm]		
	ECMWF	HA40	HA43	ECMWF	HA40	HA43	ECMWF	HA40	HA43
LICHTELGRE	3,5	3,9	4,0	4,1	4,9	5,3	5,4	6,3	6,7
BROUWHVSGT08	4,8	5,3	5,4	5,4	6,4	7,0	7,2	8,3	8,8
TERNZN	7,5	8,0	8,1	5,2	5,8	6,2	9,1	9,9	10,2
HARVT10	3,8	4,1	4,2	4,6	5,1	5,5	5,9	6,5	6,8
ROOMPBNN	6,3	6,6	6,6	4,2	4,8	5,2	7,5	8,2	8,4
HANSWT	16,9	17,4	17,5	6,2	6,6	7,0	18,0	18,6	18,9
HOEKVHLD	5,5	5,8	5,8	5,4	5,5	5,9	7,7	8,0	8,3
STAVNSE	9,1	9,5	9,5	4,6	5,1	5,4	10,2	10,8	11,0
BERGSDSWT	14,9	15,4	15,5	5,4	5,6	5,9	15,8	16,4	16,6
KRAMMSZWT	12,2	12,7	12,8	5,6	6,0	6,4	13,5	14,0	14,3
SCHEVNGN	3,8	4,2	4,2	5,0	5,6	6,0	6,3	6,9	7,3
IJMDBTHVN	4,0	4,3	4,3	5,2	5,6	6,0	6,5	7,1	7,4
Q1	4,6	4,9	4,9	4,2	5,0	5,5	5,3	6,3	6,7
DENHDR	3,4	3,8	3,8	4,3	5,6	6,1	5,5	6,7	7,2
TEXNZE	5,6	5,9	5,8	5,0	5,5	6,0	7,5	8,1	8,3
K13APFM	4,1	4,7	4,7	4,3	5,1	5,6	4,4	5,5	6,0
OUDSD	3,7	4,1	4,1	4,2	5,5	6,1	5,6	6,8	7,4
DENOVBTN	4,8	5,2	5,3	6,3	7,1	7,6	7,9	8,8	9,3
TERSLNZE	3,3	3,7	3,7	4,8	5,3	5,8	5,8	6,5	6,9
VLIELHVN	12,7	12,8	12,9	6,8	8,1	8,6	14,4	15,1	15,5
WESTTSLG	4,8	5,3	5,4	4,8	6,0	6,6	6,8	8,0	8,5
KORNWDZBTN	4,3	4,7	4,6	5,1	6,2	6,8	6,6	7,7	8,2
WIERMGDN	3,9	4,4	4,4	4,6	5,1	5,8	6,0	6,8	7,3
HUIBGT	3,7	4,1	4,1	4,6	5,3	6,0	5,9	6,7	7,2
HARLGN	5,3	5,5	5,4	6,1	6,9	7,5	8,1	8,8	9,2
NES	9,9	10,1	10,1	7,4	9,2	9,8	12,4	13,6	14,0
LAUWOG	5,3	5,8	5,7	6,6	8,2	9,1	8,5	10,1	10,7
SCHIERMNOG	16,2	16,5	16,5	10,2	11,6	12,2	19,2	20,2	20,5
BORKUM_Sudstrand	5,4	5,8	5,8	5,1	6,8	7,6	7,4	8,9	9,5
BorkumFischerbalje	6,9	7,4	7,3	5,0	6,4	7,2	8,5	9,8	10,3
EMSHORN	5,5	6,0	6,0	5,7	7,4	8,2	7,9	9,5	10,2
EEMSHVN	7,4	7,7	7,7	5,8	7,2	8,0	9,4	10,5	11,1
DUKEGAT	6,1	6,6	6,5	6,0	7,1	7,8	8,6	9,7	10,2
DELFZL	8,5	8,9	8,8	7,5	8,4	9,0	11,4	12,2	12,6
KNOCK	8,7	8,9	8,9	7,4	8,6	9,2	11,4	12,4	12,8
Average (total)	6,4	6,8	6,8	5,3	6,1	6,7	8,3	9,2	9,6
Average (offshore)	4,2	4,6	4,6	4,1	4,9	5,3	5,2	6,2	6,6
Average (coast)	4,3	4,7	4,7	4,7	5,3	5,8	6,4	7,1	7,5
Average (SWD)	10,3	10,8	10,8	5,1	5,6	5,9	11,6	12,2	12,5
Average (WS)	7,2	7,6	7,6	6,3	7,5	8,2	9,6	10,8	11,2

Table 5.2 presents the Root Mean Square Error (RMSE) for tide, surge, and total water levels at Dutch coastal stations, comparing different implementations of HARMONIE43 meteorological forcing. These implementations include the use of modeled wind speeds combined with a Charnock coefficient of 0.01 and 0.025, as well as the use of stress-equivalent wind. The first implementation (with Charnock 0.01) was also presented in Table 5.1.

The results indicate that increasing the Charnock coefficient has a positive effect on tidal accuracy, with a similar but slightly lesser effect when using stress-equivalent wind. With an increased Charnock value of 0.025, the average tidal accuracy marginally surpasses that achieved with ECMWF forcing (RMSE 6.3 cm vs. 6.4 cm for ECMWF).

For surge, the improvements are even more pronounced when using the alternative implementations. A Charnock value of 0.025 again delivers the best results, with an average RMSE of 5.3 cm, matching the performance with ECMWF forcing.

This improvement in both tide and surge accuracy is also reflected in the total water level results. A Charnock value of 0.025 consistently produces the lowest overall error across all sub-areas examined.

Since the use of stress-equivalent wind should theoretically generate the same wind stress as in the two-dimensional computations (except for the relative wind effect), these findings suggest that operational tide-surge forecasting with HA43 could be further improved compared to the current implementation in RWsOS Noordzee, either by using the HARMONIE wind speed with carefully chosen Charnock coefficient, or by fine-tuning the wind stress—such as applying a multiplication factor.

Table 5.2 Statistics (RMSE in cm) of tide, surge and total water level for the year 2022, for Dutch coastal stations, based on of 3D DCSM-FM with different implementations of HARMONIE43 meteorological forcing.

Station	RMSE tide [cm]			RMSE surge [cm]			RMSE water level [cm]		
	HA43 C=0.01	HA43 C=0.025	HA43 stress	HA43 C=0.01	HA43 C=0.025	HA43 stress	HA43 C=0.01	HA43 C=0.025	HA43 stress
Wandelaar	4,0	3,5	3,7	5,3	4,0	4,3	6,6	5,3	5,7
Bol_Van_Heist	5,0	4,5	4,7	5,2	4,0	4,2	7,3	6,0	6,4
Scheur_Wielingen_Bol_van_Knokke	5,1	4,6	4,8	5,6	4,4	4,6	7,4	6,0	6,4
CADZD	5,5	4,9	5,2	5,5	4,9	4,8	7,7	6,9	7,0
WESTKPLE	4,4	4,0	4,2	5,1	4,0	4,1	6,7	5,6	5,8
EURPFM	4,8	4,4	4,6	4,9	3,6	3,9	6,9	5,7	6,0
VLISSGN	5,9	5,4	5,6	5,5	4,5	4,6	8,1	7,0	7,2
ROOMPBTN	6,2	5,6	5,9	5,6	4,4	4,5	8,4	7,1	7,4
LICHTELGRE	4,0	3,4	3,6	5,3	4,1	4,3	6,7	5,3	5,7
BROUWHVSGT08	5,4	4,7	5,0	7,0	5,3	5,8	8,8	7,1	7,6
TERNZN	8,1	7,3	7,7	6,2	5,2	5,3	10,2	8,9	9,3
HARVT10	4,2	3,8	3,9	5,5	4,6	4,6	6,8	5,8	6,0
ROOMPBNN	6,6	6,2	6,4	5,2	4,1	4,3	8,4	7,4	7,7
HANSWT	17,5	16,8	17,2	7,0	6,1	6,2	18,9	17,9	18,3
HOEKVHLD	5,8	5,4	5,5	5,9	5,3	5,2	8,3	7,6	7,6

Station	RMSE tide [cm]			RMSE surge [cm]			RMSE water level [cm]		
	HA43 C=0.01	HA43 C=0.025	HA43 stress	HA43 C=0.01	HA43 C=0.025	HA43 stress	HA43 C=0.01	HA43 C=0.025	HA43 stress
STAVNSE	9,5	8,9	9,3	5,4	4,6	4,6	11,0	10,1	10,4
BERGSDSWT	15,5	14,8	15,2	5,9	5,4	5,3	16,6	15,7	16,1
KRAMMSZWT	12,8	12,1	12,5	6,4	5,6	5,6	14,3	13,3	13,7
SCHEVNGN	4,2	3,7	3,9	6,0	5,0	5,1	7,3	6,2	6,4
IJMDBTHVN	4,3	3,9	4,1	6,0	5,1	5,2	7,4	6,4	6,6
Q1	4,9	4,2	4,5	5,5	4,2	4,5	6,7	5,2	5,6
DENHDR	3,8	3,3	3,5	6,1	4,4	4,8	7,2	5,5	5,9
TEXNZE	5,8	5,5	5,6	6,0	5,1	5,1	8,3	7,4	7,5
K13APFM	4,7	4,2	4,4	5,6	4,3	4,6	6,0	4,3	4,8
OUDSD	4,1	3,5	3,7	6,1	4,2	4,6	7,4	5,5	5,9
DENOVBTN	5,3	4,5	4,8	7,6	6,2	6,4	9,3	7,6	8,0
TERSLNZE	3,7	3,3	3,3	5,8	4,8	4,8	6,9	5,8	5,9
VLIELHVN	12,9	12,7	12,8	8,6	6,9	7,3	15,5	14,5	14,8
WESTTSLG	5,4	4,6	5,0	6,6	4,9	5,2	8,5	6,8	7,2
KORNWDZBTN	4,6	3,9	4,2	6,8	5,1	5,2	8,2	6,4	6,7
WIERMGDN	4,4	3,8	4,0	5,8	4,7	4,7	7,3	6,0	6,2
HUIBGT	4,1	3,8	3,8	6,0	4,7	4,7	7,2	6,0	6,1
HARLGN	5,4	5,3	5,2	7,5	6,0	6,0	9,2	8,0	8,0
NES	10,1	9,8	9,9	9,8	7,5	8,2	14,0	12,3	12,9
LAUWOG	5,7	5,1	5,3	9,1	6,6	7,4	10,7	8,4	9,1
SCHIERMNOG	16,5	16,1	16,3	12,2	10,2	10,9	20,5	19,1	19,6
BORKUM_Sudstrand	5,8	5,4	5,4	7,6	5,2	5,8	9,5	7,5	7,9
BorkumFischerbalje	7,3	6,8	7,0	7,2	5,0	5,4	10,3	8,4	8,8
EMSHORN	6,0	5,5	5,6	8,2	5,6	6,3	10,2	7,8	8,4
EEMSHVN	7,7	7,4	7,5	8,0	5,8	6,2	11,1	9,4	9,7
DUKEGAT	6,5	6,0	6,1	7,8	5,9	6,1	10,2	8,4	8,7
DELFZL	8,8	8,4	8,5	9,0	7,2	7,5	12,6	11,0	11,3
KNOCK	8,9	8,6	8,6	9,2	7,1	7,6	12,8	11,2	11,5
Average (total)	6,8	6,3	6,5	6,7	5,3	5,5	9,6	8,2	8,5
Average (offshore)	4,6	4,1	4,3	5,3	4,1	4,3	6,6	5,1	5,5
Average (coast)	4,7	4,3	4,4	5,8	4,7	4,8	7,5	6,3	6,5
Average (SWD)	10,8	10,2	10,5	5,9	5,1	5,1	12,5	11,5	11,8
Average (WS)	7,6	7,1	7,2	8,2	6,2	6,6	11,2	9,5	9,9

5.3 Skew surge (high waters)

Table 5.3 presents the error statistics for high water skew surge across three different skew surge categories and various regions. Under relatively calm conditions, corresponding to the lowest 99% of storm surges, ECMWF forcing produces the smallest skew surge error across all regions when considering the initial three runs. The average skew surge RMSE is 4.8 cm for ECMWF, 5.5 cm for HA40, and 5.9 cm for HA43. However, when including the adjusted

HA43 experiments, HA43 with a Charnock coefficient of 0.025 matches the overall quality of ECMWF, outperforming it slightly in the Southwestern Delta. HA43 with stress-equivalent wind shows a slight decline in accuracy but still performs better than both the HA40 and HA43 base runs.

Under extreme conditions (skew surges exceeding the 99.8th percentile), ECMWF again outperforms the other models when considering the first three runs. The RMSE increases from 17.6 cm for ECMWF to 28.1 cm for HA40 and 32.6 cm for HA43. The gap between ECMWF and both HA40 and HA43 is largest for offshore and coastal regions. When including the adjusted HA43 experiments, the HA43 run with a Charnock coefficient of 0.025 delivers the best results, marginally outperforming ECMWF. The HA43 run with stress-equivalent wind is close behind. However, regional variations exist: ECMWF still performs best in offshore, coastal, and Southwestern Delta stations, while in the Wadden Sea, both adjusted HA43 runs significantly outperform ECMWF, with RMSE values of 20-21 cm compared to ECMWF's 29.8 cm.

Table 5.3 Skew surge errors statistics for the year 2022, averaged over different areas, with ECMWF IFS/HRES, HA40 and HA43 meteorological forcing, including alternative implementations of HA43 meteorological forcing.

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Total									
ECMWF	2,8	7,7	-0,5	4,8	-8,3	10,9	-16,3	4,5	17,6
HARMONIE40 C=0.010	3,3	8,9	-0,5	5,5	-17,4	18,8	-27,5	3,7	28,1
HARMONIE43 C=0.010	3,3	9,2	-0,5	5,9	-19,5	21,1	-32,0	4,9	32,6
HARMONIE43 C=0.025	2,6	7,5	-0,5	4,8	-6,7	12,1	-10,2	5,1	14,7
HARMONIE43 stress	3,1	8,0	-0,5	5,0	-10,1	13,4	-12,4	4,2	15,1
Offshore									
ECMWF	1,3	5,7	-0,5	4,2	-3,5	6,3	-5,9	0,9	6,0
HARMONIE40 C=0.010	1,5	6,6	-0,6	4,8	-11,1	13,0	-21,6	5,6	22,6
HARMONIE43 C=0.010	1,5	7,0	-0,6	5,2	-11,8	13,6	-27,2	5,6	28,0
HARMONIE43 C=0.025	1,1	5,6	-0,5	4,2	-2,4	8,0	-7,9	4,4	9,8
HARMONIE43 stress	1,4	5,9	-0,6	4,5	-5,1	8,8	-10,0	3,2	11,1
Coast									
ECMWF	1,1	6,2	-1,0	4,5	-5,5	8,7	-11,8	3,7	12,8
HARMONIE40 C=0.010	1,7	7,2	-1,0	5,1	-14,6	16,5	-23,7	3,2	24,1
HARMONIE43 C=0.010	1,7	7,6	-1,0	5,4	-16,5	18,2	-28,7	4,4	29,3
HARMONIE43 C=0.025	1,0	6,1	-1,0	4,5	-4,8	10,2	-9,3	5,1	13,4
HARMONIE43 stress	1,5	6,5	-1,0	4,7	-8,0	11,4	-11,4	4,3	13,8
Southwestern Delta									
ECMWF	10,9	12,9	-0,1	5,0	-1,7	5,9	-4,5	3,1	7,4
HARMONIE40 C=0.010	11,5	13,5	-0,1	5,0	-8,2	9,5	-10,4	3,3	11,7
HARMONIE43 C=0.010	11,4	13,5	-0,1	5,2	-8,7	10,8	-14,7	2,5	15,0

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
HARMONIE43 C=0.025	10,7	12,6	-0,2	4,8	3,2	8,9	4,2	2,8	9,8
HARMONIE43 stress	11,2	12,9	-0,2	4,7	-1,3	7,8	0,4	2,8	7,5
Wadden Sea									
ECMWF	1,3	7,5	-0,2	5,1	-15,2	16,5	-28,4	6,8	29,8
HARMONIE40 C=0.010	1,8	9,2	-0,1	6,3	-25,7	26,7	-40,4	3,8	40,6
HARMONIE43 C=0.010	1,7	9,6	-0,1	6,8	-29,3	30,4	-44,2	6,4	44,8
HARMONIE43 C=0.025	1,2	7,2	-0,1	5,1	-14,0	16,3	-17,9	6,4	19,4
HARMONIE43 stress	1,6	7,9	-0,2	5,6	-17,3	18,9	-19,7	5,0	20,7

5.4 Sea surface temperature

Table 5.4 and Table 5.5 present the error statistics for the modeled sea surface temperature at selected stations, using different meteorological forcing: ECMWF IFS/HRES, HA40, and HA43, along with alternative implementations of HA43. For comparison, results using ERA5 meteorological forcing are also included, as this is the default meteorological forcing for the 3D DCSM-FM model.

The results show that, despite both ERA5 and ECMWF IFS/HRES being ECMWF products with similar atmospheric boundary layer implementations, the higher-resolution ECMWF IFS/HRES model performs worse at all stations. When using HA40 forcing, the model quality improves, surpassing ERA5 at all stations except Lichteiland Goeree. The difference between HA40 and HA43 is relatively minor, with the largest RMSE difference being 0.07°C at Europlatform (better in HA40) and the other differences much smaller.

As expected, the impact of increasing the Charnock coefficient to 0.025 is minimal, since this parameter only affects the momentum flux and (in the current D-HYDRO implementation) does not influence the Stanton and Dalton bulk transfer coefficients used for sensible and latent heat flux calculations. Switching to HA43 with stress-equivalent wind leads to a slight increase in RMSE of around 0.1°C at most stations, except for Lichteiland Goeree, where the quality marginally improves.

Figure 5.1 to Figure 5.6 show time series and scatter plots of observed versus modeled sea surface temperature at Europlatform. These highlight that the largest discrepancies occur during the summer months, which is also when the differences between the various meteorological forcing setups are most pronounced.

Table 5.4 *Bias, standard deviation and RMSE of sea surface temperature in 2022, for stations Platform Q1 and Europlatform, with ECMWF IFS/HRES, HA40 and HA43 meteorological forcing, including alternative implementations of HA43 meteorological forcing.*

	Platform Q1			Europlatform		
Meteorological forcing	**bias [°C]**	**std [°C]**	**RMSE [°C]**	**bias [°C]**	**std [°C]**	**RMSE [°C]**
ERA5	-0.40	0.21	0.46	-0.50	0.24	0.55
ECMWF	-0.60	0.23	0.64	-0.66	0.34	0.74
HARMONIE40 C=0.010	-0.23	0.28	0.36	-0.35	0.23	0.41
HARMONIE43 C=0.010	-0.24	0.25	0.35	-0.39	0.28	0.48
HARMONIE43 C=0.025	-0.22	0.25	0.33	-0.35	0.32	0.47
HARMONIE43 stress	-0.35	0.27	0.44	-0.50	0.30	0.58

Table 5.5 *Bias, standard deviation and RMSE of sea surface temperature in 2022, for stations Lichteiland Goeree and Nes, with ECMWF IFS/HRES, HA40 and HA43 meteorological forcing, including alternative implementations of HA43 meteorological forcing.*

	Lichteiland Goeree			Nes		
Meteorological forcing	**bias [°C]**	**std [°C]**	**RMSE [°C]**	**bias [°C]**	**std [°C]**	**RMSE [°C]**
ERA5	-0.01	0.39	0.39	-0.68	0.54	0.87
ECMWF	-0.18	0.49	0.52	-0.77	0.51	0.92
HARMONIE40 C=0.010	0.12	0.45	0.46	-0.43	0.48	0.64
HARMONIE43 C=0.010	0.08	0.47	0.48	-0.47	0.44	0.64
HARMONIE43 C=0.025	0.11	0.51	0.52	-0.47	0.44	0.64
HARMONIE43 stress	-0.04	0.49	0.49	-0.57	0.46	0.73

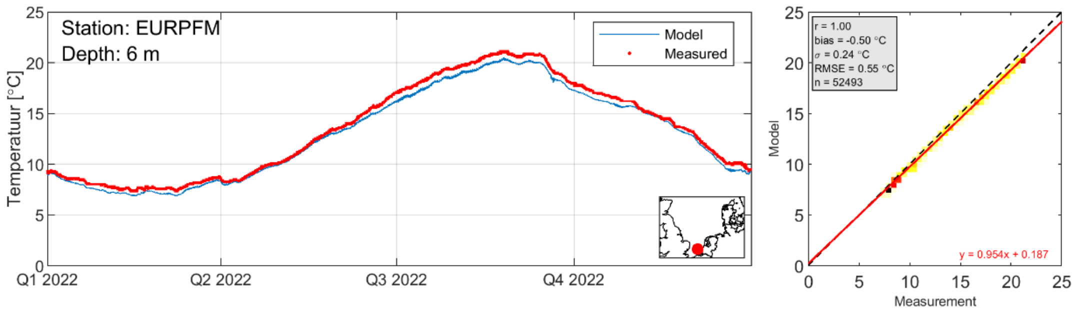

Figure 5.1 *Timeseries and scatterplot of measured and modelled (**ERA5** meteo) sea surface temperature in station Europlatform*

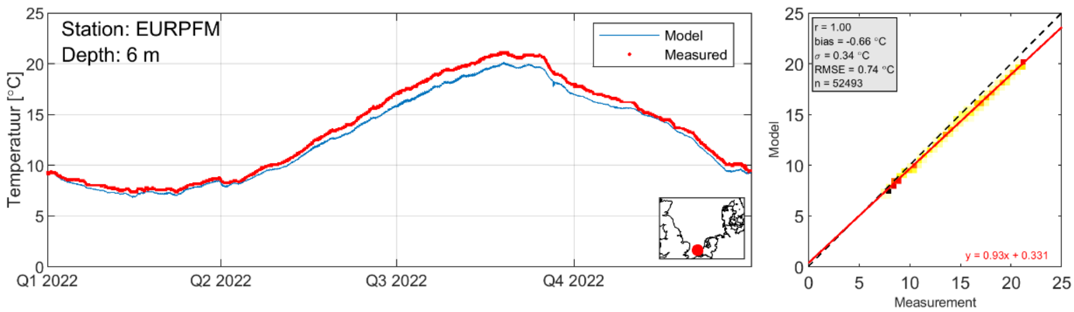

Figure 5.2 *Timeseries and scatterplot of measured and modelled (**ECMWF meteo**) sea surface temperature in station Europlatform.*

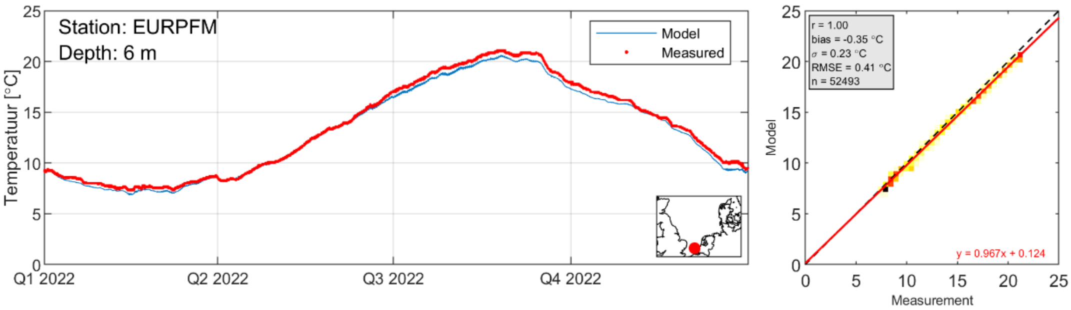

Figure 5.3 *Timeseries and scatterplot of measured and modelled (**HA40 meteo**) sea surface temperature in station Europlatform.*

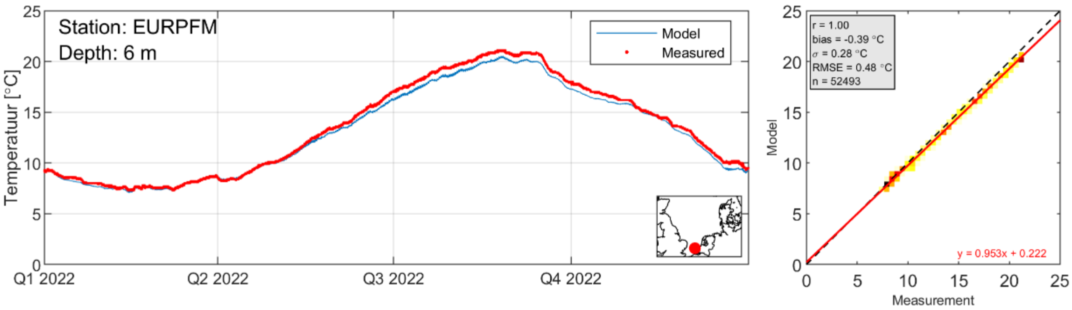

Figure 5.4 *Timeseries and scatterplot of measured and modelled (**HA43 meteo; Charnock coefficient 0.010**) sea surface temperature in station Europlatform.*

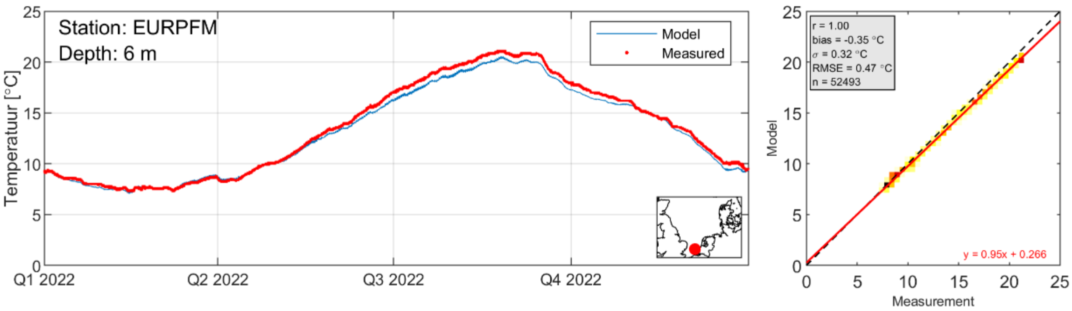

Figure 5.5 *Timeseries and scatterplot of measured and modelled (**HA43 meteo; Charnock coefficient 0.025**) sea surface temperature in station Europlatform.*

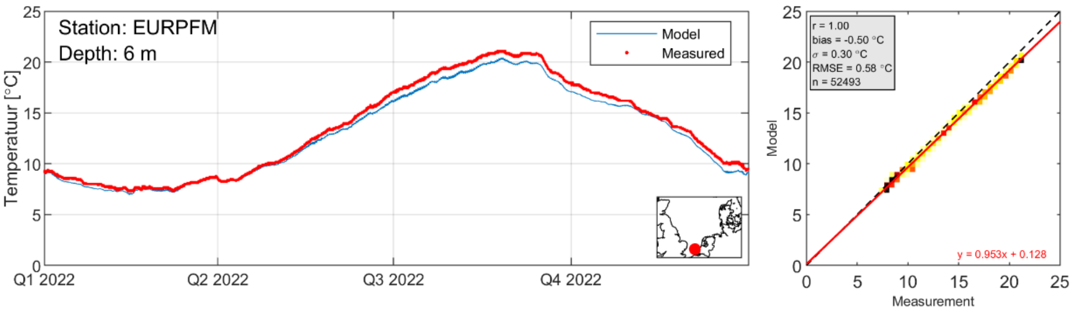

Figure 5.6 *Timeseries and scatterplot of measured and modelled (**HA43 meteo; stress-equivalent wind**) sea surface temperature in station Europlatform.*

6 Results comparison D-HYDRO vs WAQUA

This chapter presents the validation results of the comparison that was done between the sixth-generation D-HYDRO model DCSM-FM 100m and its fifth-generation WAQUA precursor DCSMv6-ZUNOv4.

The validation period used for this comparison is from January 1st, 2020 until January 1st, 2024. The applied meteorological forcing is ECMWF IFS/HRES. The moveable surge barriers in the model (Eastern Scheldt, Maeslant, Hartel surge barrier and the Ems Sperrwerk) are simulated in an open position, which is also the case in the operational system. For calculations of the error statistics, periods during which storm surge barriers have closed in reality are discarded for stations in the Eastern Scheldt (i.e., the stations in the validation set most affected by the closure).

6.1 Tide, surge and total water levels

Table 6.1 shows the RMSE of the tide, surge and total water level in Dutch coast stations for DCSMv6-ZUNOv4 and DCSM-FM 100m.

The results show that the quality of tides is on average better in DCSM-FM 100m (RMSE: 6.8 cm vs 5.3 cm). This conclusion is in line with earlier validation for the years 2013-2017 (Zijl, et al. 2022). The spatial difference plot of tide RMSE in Figure 6.2 reveals that this improvement is seen in most stations, with only a few exceptions.

The quality of the surge signal is on average also slightly better in DCSM-FM 100m (RMSE 5.8 vs 5.6 cm). The largest absolute improvement is seen in the Ems-Dollard (Emden and Pogum). The resolution of DCSMv6-ZUNOv4 is too coarse to accurately represent the Ems-Dollard past Delfzijl. Along the Dutch coast, the improvements of RMSE are smaller: about 0.2 cm (Figure 6.3)

Due to the better representation of tide and surge, the total water level is represented significantly better in DCSM-FM 100m (RMSE 9.1 cm vs 7.7 cm), as can be seen in Figure 6.1.

Of the 46 stations considered, only 6 show a deterioration in total water level quality. The stations with the largest absolute deterioration are West Terschelling (6.7 cm to 9.1 cm), Bergsediepsluis (7.2 cm to 8.9 cm), Harlingen (7.5 cm to 8.3 cm) and Borkum Sudstrand (7.1 cm to 7.8 cm). The simulation results in Bergsediepsluis West are affected by drying cells in DCSM-FM 100m. If necessary, this can be solved in a future release of the model by adjusting the bathymetry locally. In the validation report of the 2022 release of DCSM-FM 100m (Zijl et al., 2022) it was noted that compared to the first release of DCSM-FM 100m the quality of the tide in West Terschelling deteriorated significantly. It was speculated that excluding this station from the calibration might yield better results in surrounding stations including Terschelling Noordzee and possibly also Harlingen. Based on the present results, the recommendation to test whether this would improve the model still stands.

Table 6.1 RMSE in cm of tide, surge and total water level of the fifth-generation model DCSMv6-ZUNOv4 and the sixth-generation model (DCSM-FM 100m) for the Dutch coastal stations, both based on ECMWF meteo forcing. The validation period used is 2020-01-01 until 2024-01-01. The main locations (Dutch: 'hoofdlocaties') are shown in bold.

Station	**RMSE tide [cm]**		**RMSE surge [cm]**		**RMSE water level [cm]**	
	DCSMv6-ZUNOv4	**DCSM-FM 100m**	**DCSMv6-ZUNOv4**	**DCSM-FM 100m**	**DCSMv6-ZUNOv4**	**DCSM-FM 100m**
Wandelaar	4,6	4,6	4,8	4,6	6,8	6,6
Bol_Van_Heist	5,1	4,4	5,2	5,0	7,2	6,7
Scheur_Wielingen_Bol_van_Knokke	5,2	5,1	5,0	4,8	7,2	6,9
CADZD	5,1	5,2	5,6	5,5	7,6	7,5
WESTKPLE	5,0	4,5	5,0	4,8	7,0	6,5
EURPFM	4,5	3,4	4,4	4,3	6,2	5,4
VLISSGN	**5,4**	**5,2**	**5,4**	**5,2**	**7,6**	**7,4**
ROOMPBTN	**4,9**	**3,7**	**5,2**	**4,9**	**7,2**	**6,1**
LICHTELGRE	5,3	4,3	4,7	4,6	6,9	6,0
BROUWHVSGT08	5,4	4,3	5,6	5,3	7,7	6,9
TERNZN	6,2	5,5	6,1	5,9	8,7	8,0
HARVT10	4,7	4,1	5,4	5,1	7,1	6,5
ROOMPBNN	4,7	4,2	4,8	4,6	6,7	6,2
HANSWT	6,8	5,8	6,2	6,1	9,2	8,4
HOEKVHLD	**5,3**	**4,1**	**5,1**	**5,1**	**7,3**	**6,6**
STAVNSE	4,3	4,1	5,2	5,0	6,7	6,5
BERGSDSWT	4,7	6,2	5,4	6,4	7,2	8,9
KRAMMSZWT	4,4	4,6	5,6	5,4	7,1	7,1
BATH	6,7	6,3	7,0	7,0	9,7	9,4
SCHEVNGN	5,4	4,2	5,5	5,3	7,7	6,8
IJMDBTHVN	6,2	4,2	5,8	5,5	8,4	6,9
Q1	4,9	4,2	4,5	4,3	6,2	5,6
DENHDR	**4,8**	**3,9**	**5,0**	**4,9**	**6,9**	**6,3**
TEXNZE	5,4	5,4	5,4	5,3	7,6	7,5
K13APFM	3,9	3,6	4,5	4,3	5,8	5,3
OUDSD	5,5	4,4	4,8	4,6	7,3	6,4
DENOVBTN	7,6	7,0	6,8	6,4	10,2	9,5
TERSLNZE	4,1	4,4	5,3	5,3	6,7	6,9
VLIELHVN	4,6	5,1	4,8	4,8	6,7	7,0
WESTTSLG	4,7	7,7	4,8	4,9	6,7	9,1
KORNWDZBTN	4,7	4,4	5,6	5,5	7,3	7,1
WIERMGDN	4,2	4,5	5,1	5,0	6,6	6,7
HUIBGT	4,7	4,6	5,4	5,2	7,1	7,0
HARLGN	**5,0**	**5,8**	**5,6**	**6,0**	**7,5**	**8,3**

Station	RMSE tide [cm]		RMSE surge [cm]		RMSE water level [cm]	
	DCSMv6-ZUNOv4	DCSM-FM 100m	DCSMv6-ZUNOv4	DCSM-FM 100m	DCSMv6-ZUNOv4	DCSM-FM 100m
NES	7,0	5,6	6,2	6,2	9,3	8,4
LAUWOG	6,0	5,9	6,3	6,4	8,7	8,7
SCHIERMNOG	9,6	7,0	7,9	7,7	12,4	10,4
BORKUM_Sudstrand	4,6	5,5	5,4	5,5	7,1	7,8
BorkumFischerbalje	5,1	5,1	5,3	5,3	7,4	7,3
EMSHORN	5,8	5,7	5,8	5,9	8,2	8,2
EEMSHVN	7,4	6,0	6,1	6,1	9,6	8,6
DUKEGAT	9,1	7,3	6,8	6,7	9,8	8,1
DELFZL	**7,0**	**6,2**	**7,3**	**7,3**	**10,1**	**9,6**
KNOCK	7,0	6,8	7,2	7,2	10,0	9,9
EMDEN_Neue_Seeschl	20,3	8,9	8,8	7,7	22,1	11,7
POGUM	51,6	10,7	12,7	8,8	53,1	13,8
Average (total)	**6,8**	**5,3**	**5,8**	**5,6**	**9,1**	**7,7**
Average (offshore)	**4,6**	**3,9**	**4,5**	**4,4**	**6,3**	**5,6**
Average (coast)	**5,0**	**4,5**	**5,3**	**5,1**	**7,3**	**6,8**
Average (SWD)	**5,4**	**5,2**	**5,7**	**5,7**	**7,9**	**7,7**
Average (WS)	**9,6**	**6,4**	**6,6**	**6,3**	**11,9**	**8,9**

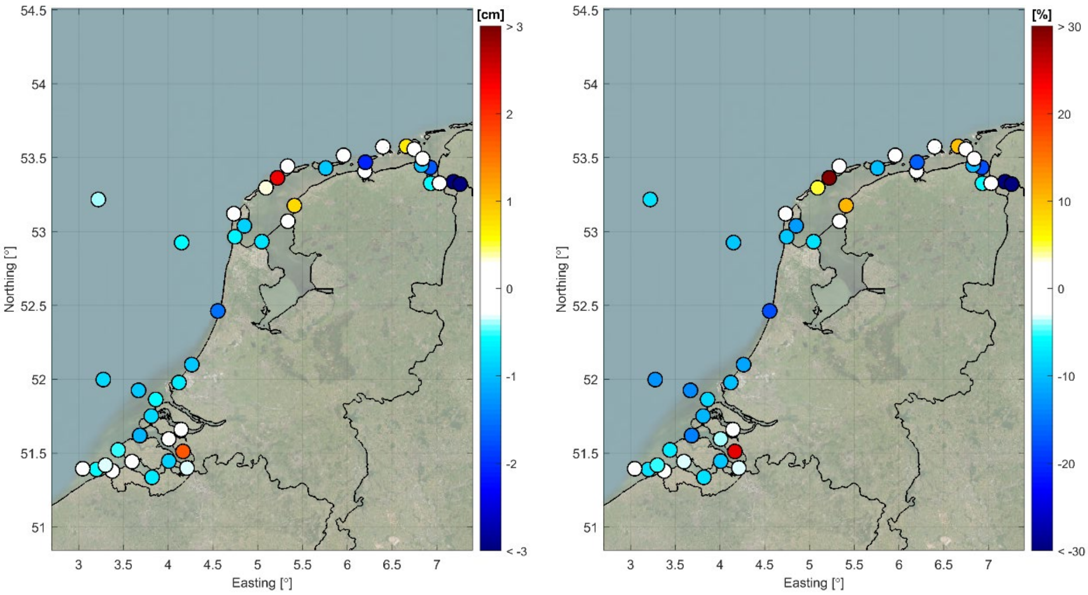

*Figure 6.1 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4 with ECMWF) in RMSE of the **total water level** for the period 2020-2023 of the Dutch coastal stations. Left: difference [cm]; right: relative difference (%).*

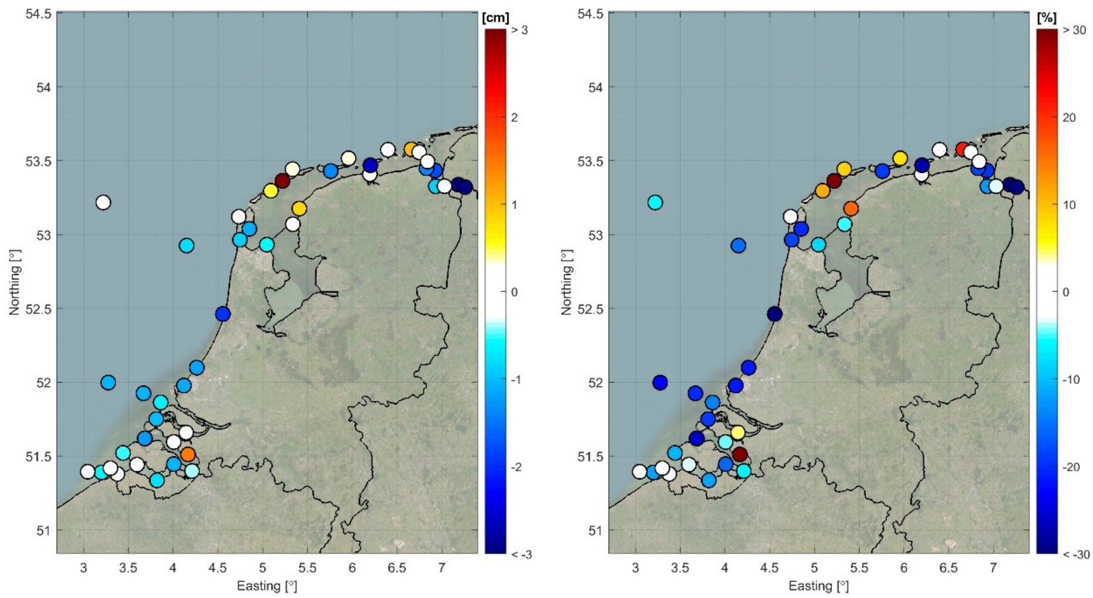

Figure 6.2 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4 with ECMWF) in RMSE of the ***tide*** *for the period 2020-2023 of the Dutch coastal stations. Left: difference [cm]; right: relative difference (%).*

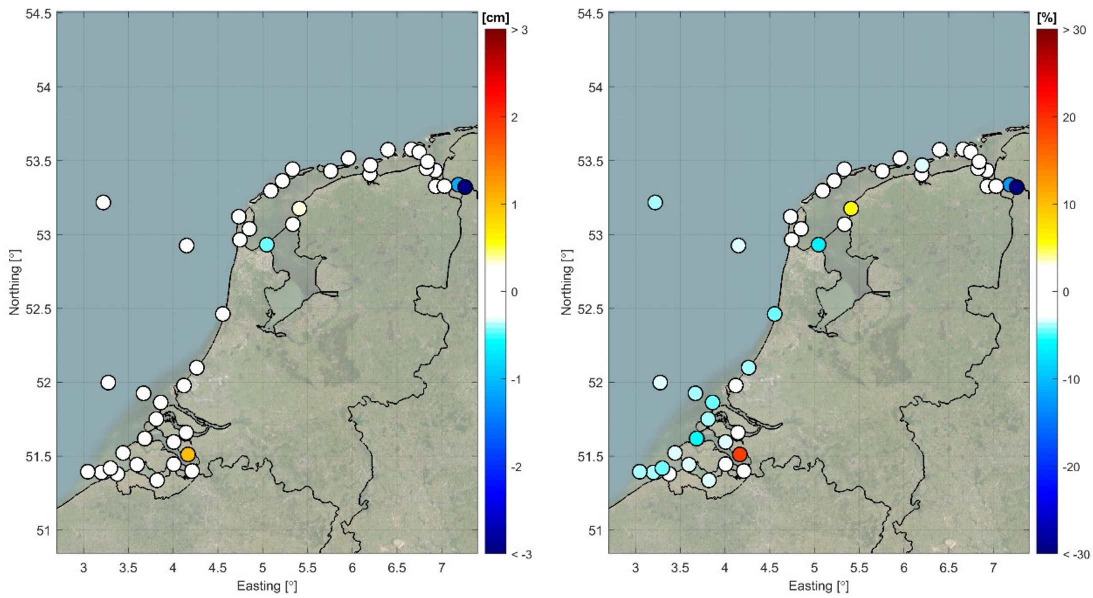

Figure 6.3 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4 with ECMWF) in RMSE of the ***surge*** *for the period 2020-2023 of the Dutch coastal stations. Left: difference [cm]; right: relative difference (%).*

6.2 Skew surge

The error statistics for high waters in three different skew surge categories, in different areas in the Netherlands can be found in Table 6.2. The results indicate that the skew surge error under relatively calm conditions (<99.0% storm surge) is slightly smaller for DCSM-FM 100m in all areas considered. The largest improvement is observed in the Southwestern Delta.

Figure 6.4 shows the spatial differences in skew surge RMSE between DCSM-FM 100m and DCSMv6-ZUNOv4. It confirms that the most significant improvements are seen in the

Southwestern Delta and the Ems-Dollard. The only station that sees a slight (0.3 cm) deterioration of skew surge error under calm conditions is Hoek van Holland. An explanation for this could be the better representation of the Rhine-Meuse delta in DCSMv6-ZUNOv4.

For the most extreme storms (>99.8% storm surges), the average skew surge error is very similar between both models (RMSE DCSMv6-ZUNOv4: 18.8 cm, DCSM-FM 100m 18.1). However, Figure 6.5 reveals spatial differences: skew surge errors are lower in DCSM-FM 100m in the Southwestern Delta, along the Dutch coast and in the Wadden Sea. Contrarily, in the Ems-Dollard, skew surge errors are higher in DCSM-FM 100m due to a systematic underestimation (bias) of the most extreme events.

Table 6.2 High water errors in the period 2020-2023 averaged over different areas (Table 1.1) based on DCSMv6-ZUNOv4 and DCSM-FM 100m, with open storm surge barriers and ECMWF forcing.

	Total HW error		**Skew surge (high water)**						
	All HWs		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
	bias [cm]	**RMSE [cm]**	**bias [cm]**	**RMSE [cm]**	**bias [cm]**	**RMSE [cm]**	**bias [cm]**	**std [cm]**	**RMSE [cm]**
Total									
DCSMv6-ZUNOv4	2,2	7,2	-0,2	5,3	-9,2	12,2	-16,3	8,6	18,8
DCSM-FM 100m	-0,5	7,0	-0,4	5,1	-9,8	12,4	-15,2	8,7	18,1
Offshore									
DCSMv6-ZUNOv4	0,8	5,7	-0,3	4,5	-5,6	7,9	-10,5	6,5	12,5
DCSM-FM 100m	-1,8	5,9	-0,4	4,4	-5,0	7,0	-8,4	5,8	10,3
Coast									
DCSMv6-ZUNOv4	2,0	6,7	-0,6	5,1	-7,2	11,1	-13,7	8,7	16,9
DCSM-FM 100m	-2,0	6,8	-0,6	5,0	-7,4	10,9	-11,7	8,3	15,2
Southwestern Delta									
DCSMv6-ZUNOv4	3,0	7,8	0,5	5,4	-7,6	10,6	-11,5	7,0	13,6
DCSM-FM 100m	0,0	7,1	0,1	5,1	-7,2	10,1	-9,1	8,4	12,5
Wadden Sea									
DCSMv6-ZUNOv4	2,4	7,8	-0,1	5,6	-13,8	15,9	-24,3	10,0	26,5
DCSM-FM 100m	1,5	7,6	-0,3	5,5	-15,8	17,4	-25,4	10,1	27,5

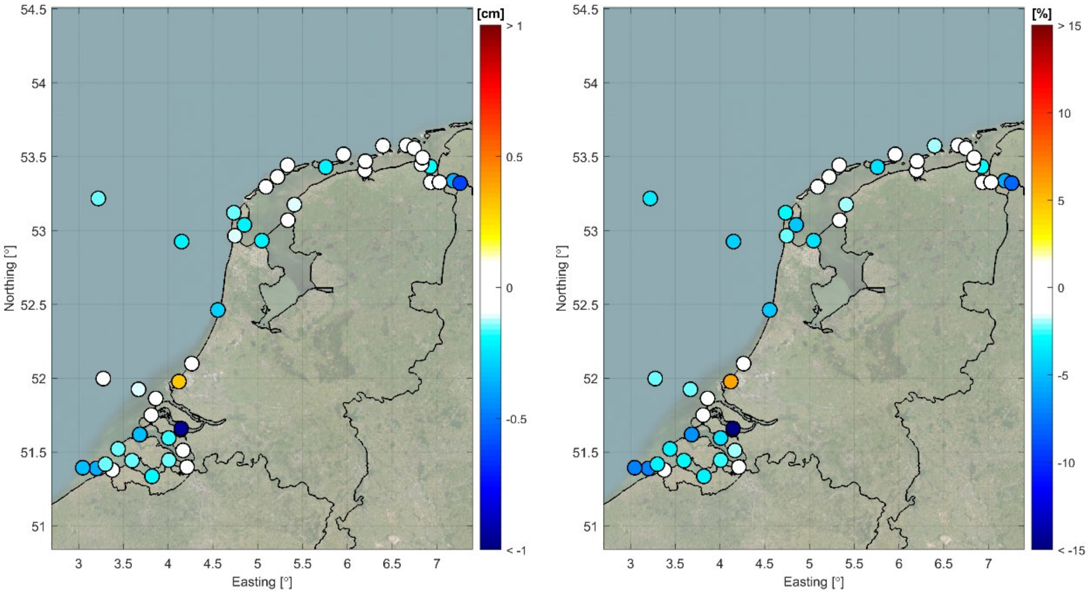

Figure 6.4 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4 with ECMWF) in skew surge for the skew surges <99.0% for the period 2020-2023 of the Dutch coastal stations. Left: difference in RMSE [cm]; right: difference in RMSE [%].

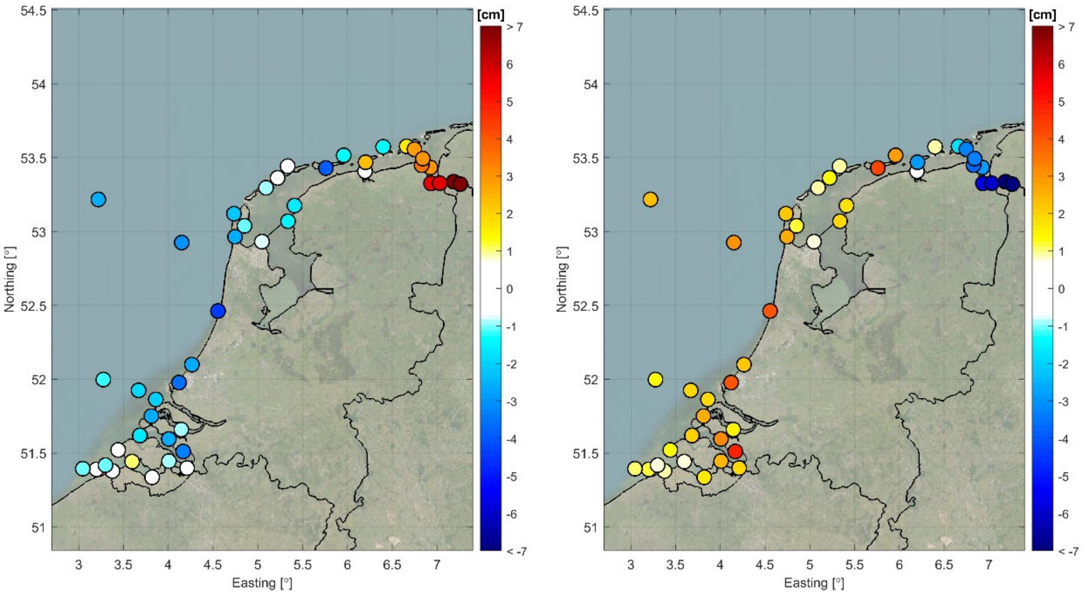

Figure 6.5 Spatial overview of the difference (DCSM-FM 100m minus DCSMv6-ZUNOv4 with ECMWF) in skew surge for the skew surges > 99.8% for the period 2020-2023 of the Dutch coastal stations. Left: difference in RMSE [cm]; right: difference in bias [cm].

7 Validation of storm Pia

Special attention is given to storm Pia[1], the most extreme storm surge event in the validation period 2020-2023. Pia occured December 21st and 22nd, 2023 and resulted in extreme highwaters in all sectors along the Dutch coast. Table 7.1 list relevant high water quantities during the highest high water of storm Pia for the five main locations of WMCN Kust en Benedenrivieren. The model results are based on DCSM-FM 100m with ECMWF IFS/HRES and HARMONIE40 forcing and recorded barrier closures. Note that before determining the error statistics, the bias over the entire validation period is removed from the model results.

The first column lists the measured skew surge. The following columns list the tidal high water error, the skew surge error and the total high water error. The tidal high water error is largest at Vlissingen (up to 0.05 m) and even smaller in other stations (<0.02 m). For coastal stations Vlissingen, Hoek van Holland and Den Helder, the skew surge error does not exceed 0.10 cm. At Harlingen and Delfzijl, the skew surge is underestimated by 0.18 m and 0.29 m using ECMWF IFS/HRES meteorological forcing. With HARMONIE40 forcing, the skew surge underestimation is much less severe, with values of -0.06 m for Harlingen and -0.10 m for Delfzijl.

Detailed information per station is provided in Figure 7.1 until Figure 7.5. The scatterplots of all skew surge errors versus the measured skew surge in the bottom row of figures show storm Pia as red dot(s). These figures indicate how model performance during Pia compares to the rest of the validation period. For all stations, especially Harlingen and Delfzijl, it generally holds that the higher the skew surge, the larger the underestimation that skew surge is in DCSM-FM 100m. This effect is illustrated by the trend lines in the figures. This effect is known and the reason an empirical correction for high waters is used in operational forecasting by WMCN Kust en Benedenrivieren. For all stations, the most extreme high-water during storm Pia is above the trend line, meaning the underestimation of the high water is less than would be expected from an empirical correction for high waters.

Table 7.1 Error statistics during storm: Measured skew surge, skew surge error, skew tide error and high water error. Model run: DCSM-FM 100m, forced by ECMWF IFS/HRES and HARMONIE40 meteo, storm surge barriers closed according to measured time series.

Station	Measured skew surge [m]	Tidal high water error [m]		Skew surge error [m]		High water error [m]	
		ECMWF	HA40	ECMWF	HA40	ECMWF	HA40
VLISSGN	1.33	-0.05	-0.03	0.09	0.01	0.04	0.02
HOEKVHLD	1.77	-0.01	0.00	-0.10	-0.07	-0.11	-0.07
DENHDR	1.53	-0.01	0.00	-0.05	-0.02	-0.06	-0.02
HARLGN	1.86	0.01	0.02	-0.18	-0.06	-0.16	-0.04
DELFZL	2.40	-0.02	-0.00	-0.29	-0.10	-0.31	-0.10

[1] 579-25-sr101_stormvloedrapport_pia_met_bijlagen.pdf (rws.nl)

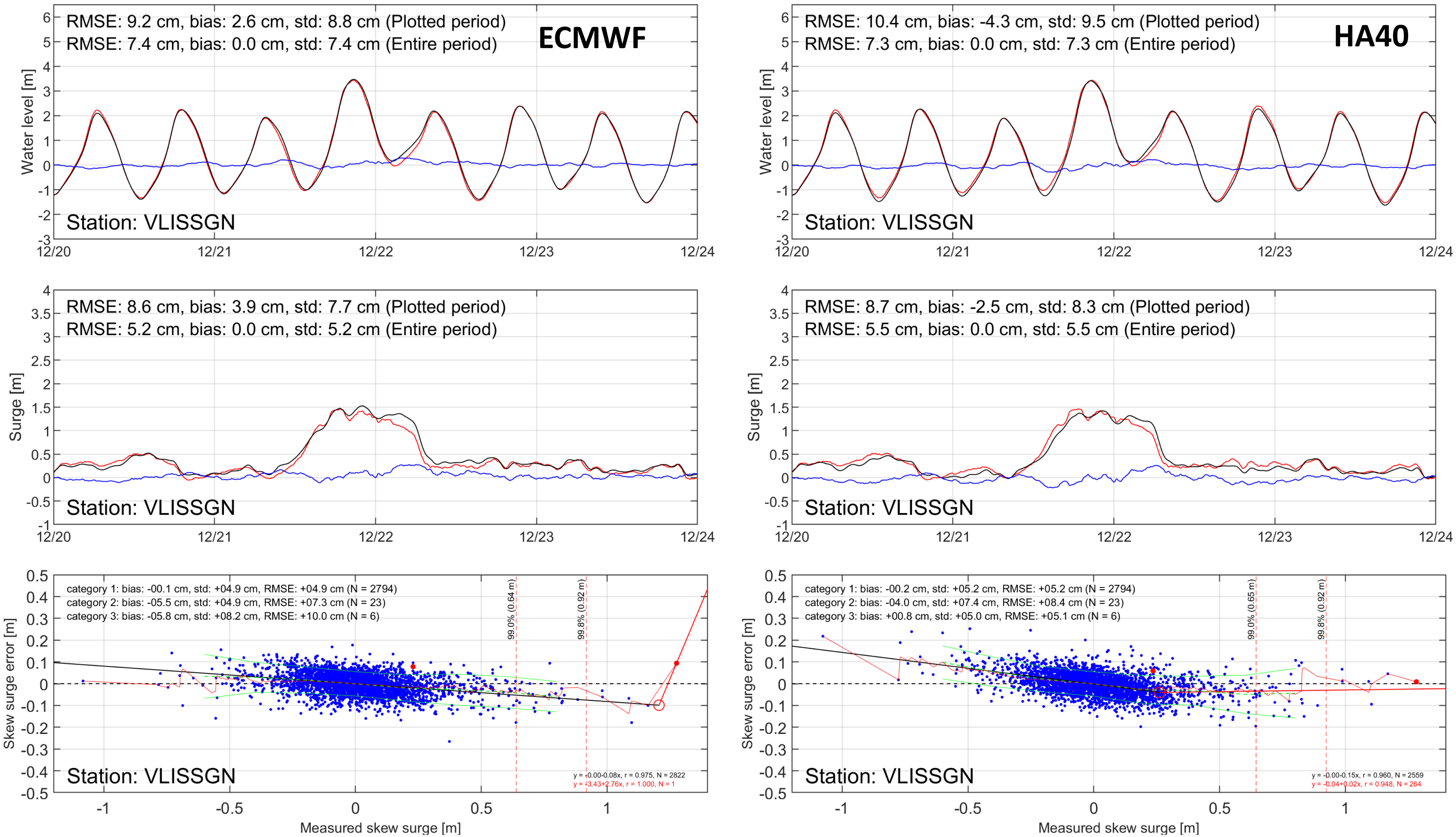

Figure 7.1 ***Top row**: timeseries of waterlevel during storm Pia for station Vlissingen, **middle row**: time series of surge during storm Pia, **bottom row,** scatterplot of all skew surge errors versus measured skew surge. Skew surge event during Pia is markted in red. **Left:** ECMWF meteo, **Right,** HA40 meteo*

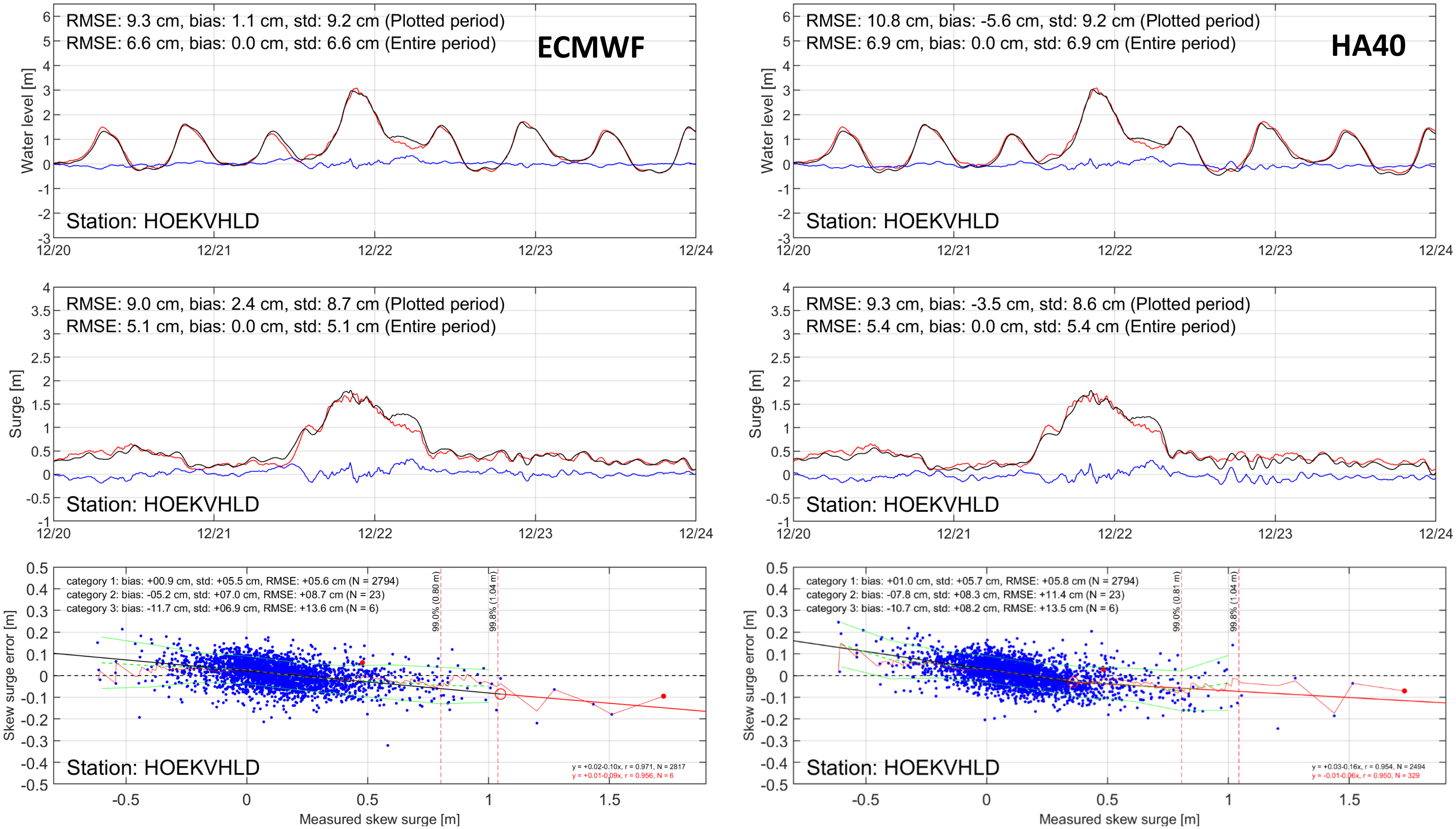

Figure 7.2 ***Top row****: timeseries of waterlevel during storm Pia for station Hoek van Holland,* ***middle row****: time series of surge during storm Pia,* ***bottom row,*** *scatterplot of all skew surge errors versus measured skew surge. Skew surge event during Pia is markted in red.* ***Left:*** *ECMWF meteo,* ***Right,*** *HA40 meteo*

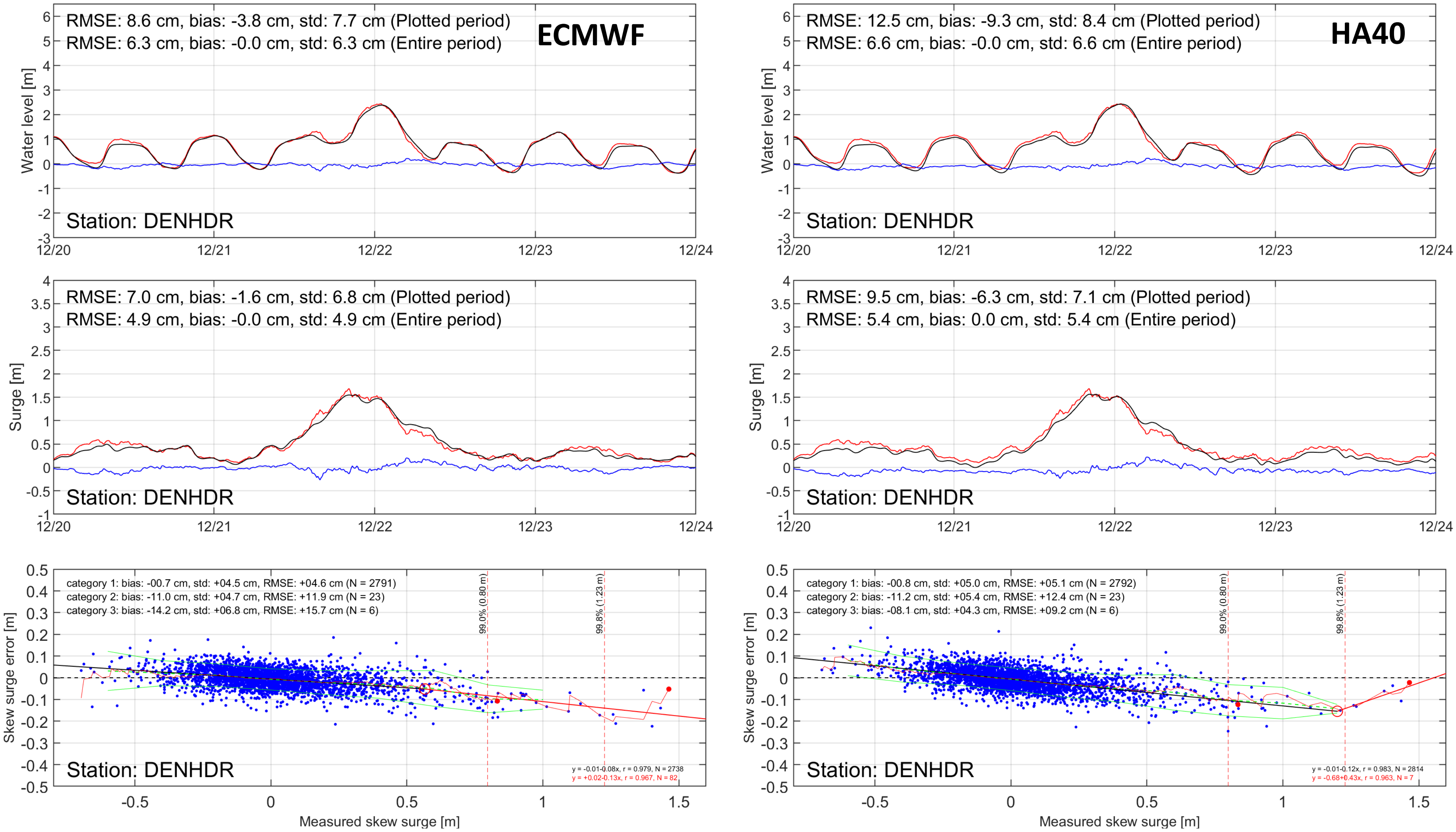

*Figure 7.3 **Top row**: timeseries of waterlevel during storm Pia for station Den Helder, **middle row**: time series of surge during storm Pia, **bottom row,** scatterplot of all skew surge errors versus measured skew surge. Skew surge event during Pia is markted in red. **Left:** ECMWF meteo, **Right,** HA40 meteo*

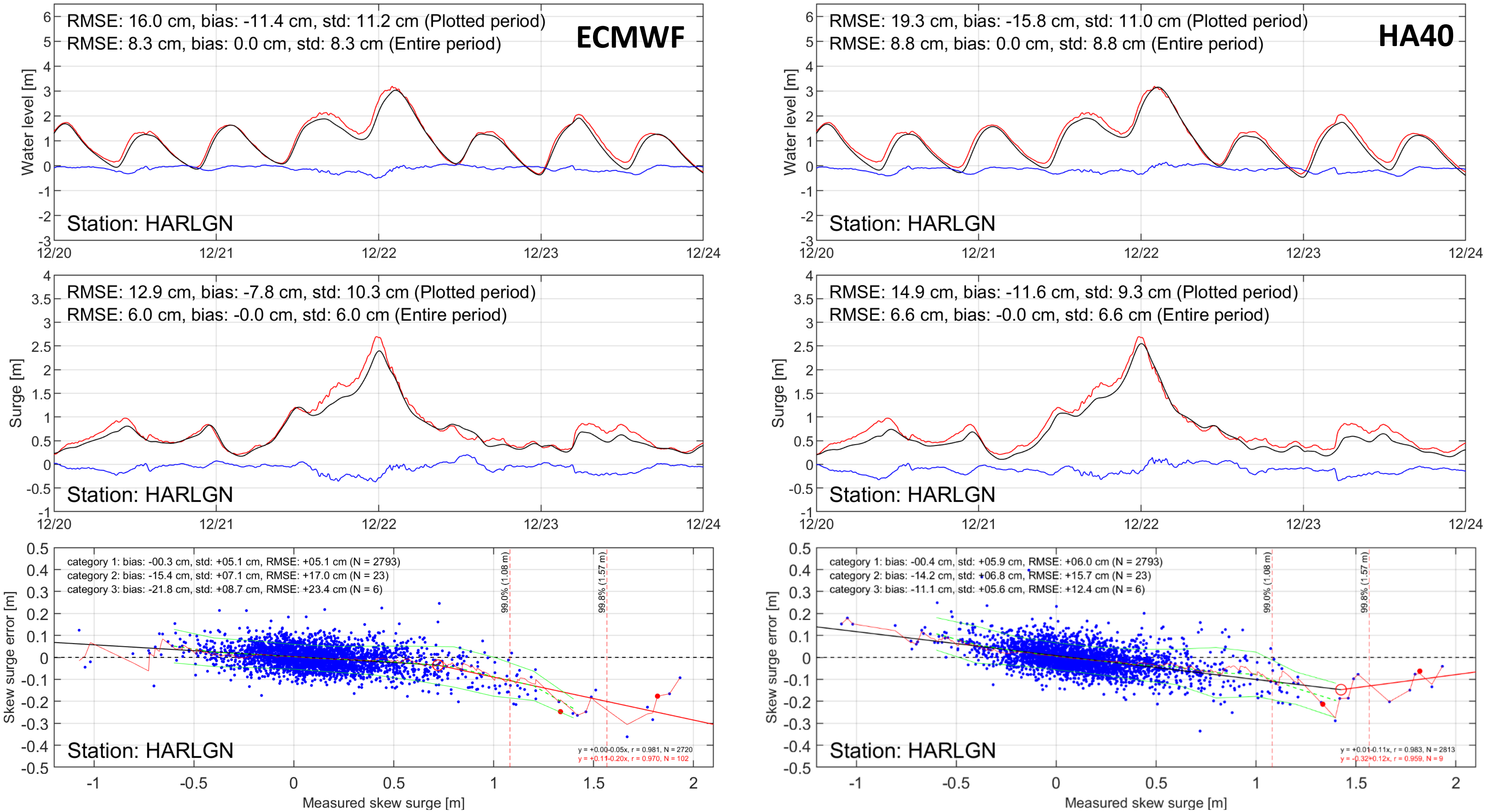

*Figure 7.4 **Top row**: timeseries of waterlevel during storm Pia for station Harlingen, **middle row**: time series of surge during storm Pia, **bottom row,** scatterplot of all skew surge errors versus measured skew surge. Skew surge event during Pia is markted in red. **Left:** ECMWF meteo, **Right,** HA40 meteo*

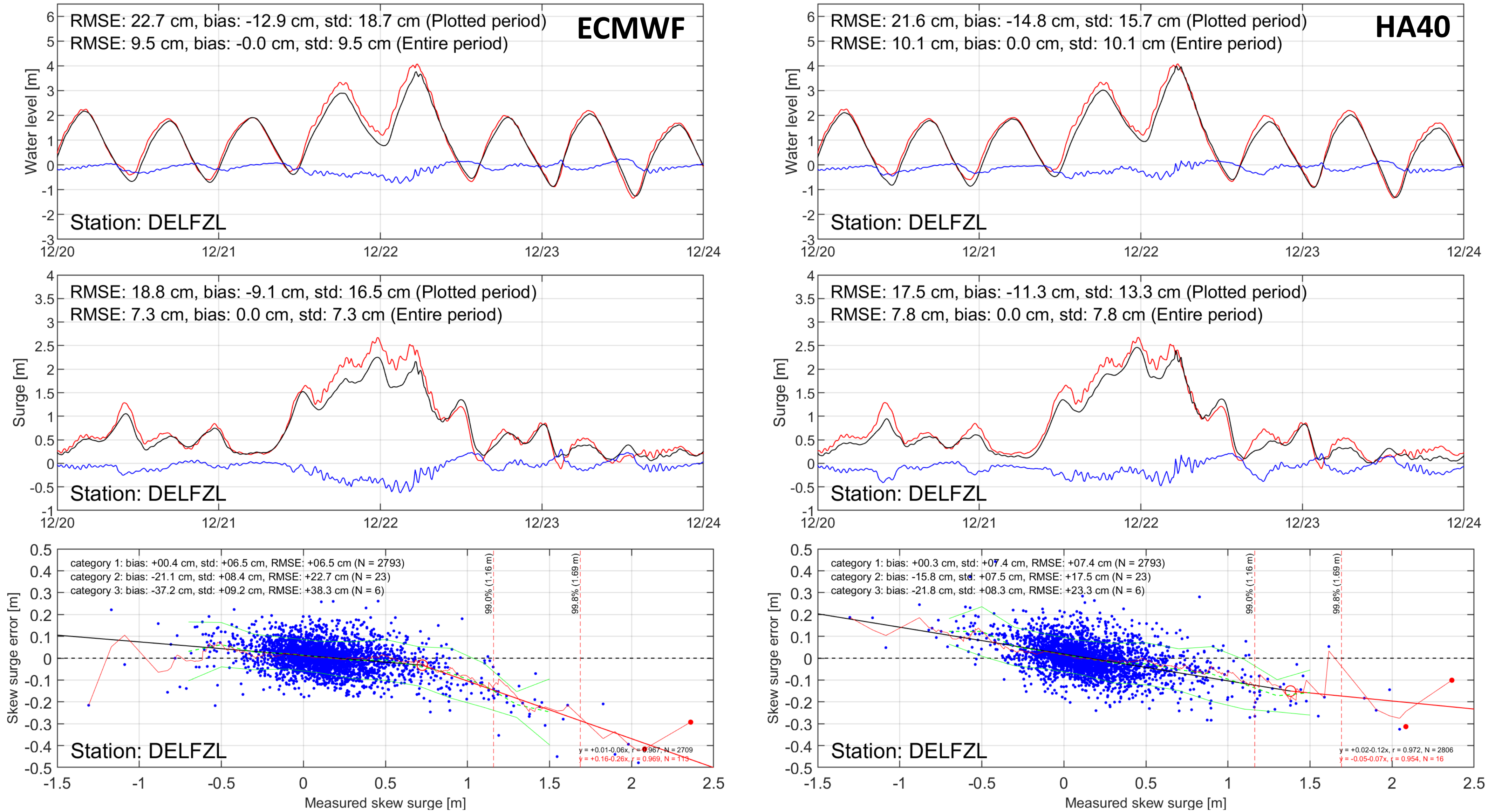

Figure 7.5 ***Top row**: timeseries of waterlevel during storm Pia for station Delfzijl, **middle row**: time series of surge during storm Pia, **bottom row,** scatterplot of all skew surge errors versus measured skew surge. Skew surge event during Pia is markted in red. **Left:** ECMWF meteo, **Right,** HA40 meteo*

8 Conclusions and recommendations

8.1 Conclusions

This report provides a comprehensive analysis of the consequences for water level quality of the migration from the HARMONIE40 to HARMONIE43 meteorological model, as well as from the fifth-generation WAQUA DCSMv6-ZUNOv4 model to the sixth-generation D-HYDRO DCSM-FM 100m model. The impact of the HARMONIE model migration is assessed for both the two-dimensional, operational DCSM-FM 100m model as well as the 3D DCSM-FM model. Finally, attention is given to the performance of the models during the recent storm Pia in December 2023. For all these topics, the conclusions are summarized below.

8.1.1 HARMONIE migration: analysis of ECMWF, HA40 and HA43 forcing data

- Comparison to measurement data at Platform K13a shows that under high wind speed conditions (>15 m/s), ECMWF slightly underestimates the wind speed, whereas HA40 and HA43 show a slight overestimation.
- At the same location, the wind stress is underestimated in all models. However, the underestimation is much less severe in ECMWF compared to HA40 and HA43, and is slightly less severe in HA43 compared to HA40.
- For wind speeds higher than around 5 m/s, the wind drag coefficient in HA40 is much lower than in ECMWF . Wind drag coefficients in HA43 are on average 10-20% higher than in HA40, but still significantly lower compared to ECMWF .
- Looking at the spatial distribution of the mean wind stress, HA40 shows lower values over the North Sea compared to ECMWF. In HA43, the mean wind stress in this region increases slightly compared to HA40, but remains lower than in ECMWF. While HA43 produces higher mean wind stress in the North Sea and Wadden Sea compared to HA40, this does not extend to the outer oceanic areas. In these regions, HA43 produces lower wind stress than HA40, which, in fact, relied on ECMWF data for those areas.

8.1.2 HARMONIE migration: DCSM-FM 100m validation with ECMWF, HA40 and HA43

- Forcing DCSM-FM 100m with ECMWF results in the best representation of surge, followed by HA40 and HA43. Surge error averaged over all stations is 5.6 cm for ECMWF, 5.9 cm for HA40 and 6.0 cm for HA43.
- On average, the surge error is slightly larger with HA43 than with HA40, but spatial differences exist where HA43 outperforms HA40 for the more inland stations in the Western and Eastern Scheldt, Wadden Sea and Ems-Dollard estuary.
- Under relatively calm conditions (<99.0% storm surges), ECMWF leads to the lowest skew surge errors with an RMSE of 5.2 cm, while both HA40 and HA43 have an average RMSE of 5.6 cm.
- Under the most extreme conditions (>99.8% storm surges), underestimation (negative bias) of skew surge is the largest contributing factor to high water errors. This bias is lowest in HA40 meteo, followed by HA43 and then by ECMWF. There are large spatial differences in relative performance: while HA43 performs better in estuaries and the Wadden Sea, ECMWF results in smaller or similar biases offshore and along the coast.

8.1.3 HARMONIE migration: 3D DCSM-FM with ECMWF, HA40 and HA43

- On average, there is no difference in tidal quality between HA40 and HA43 (both with an RMSE of 6.8 cm), while ECMWF performs slightly better (with an RMSE of 6.4 cm).

- For surge and total water levels, the RMSE increases progressively from ECMWF (5.3 cm for surge, 8.3 cm for total water level) to HA40 (6.1 cm and 9.2 cm, respectively), and further to HA43 (6.7 cm and 9.6 cm).
- Under relatively calm conditions, corresponding to the lowest 99% of storm surges, ECMWF forcing produces the smallest skew surge error across all regions. The average skew surge RMSE is 4.8 cm for ECMWF, 5.5 cm for HA40, and 5.9 cm for HA43.
- Under extreme conditions (skew surges exceeding the 99.8th percentile), ECMWF again outperforms the other models. The RMSE increases from 17.6 cm for ECMWF to 28.1 cm for HA40 and 32.6 cm for HA43.
- Increasing the Charnock coefficient from 0.01 to 0.025 has a positive effect on tidal accuracy, with a similar but slightly lesser effect when using stress-equivalent wind. For surge, the improvements are even more pronounced: a Charnock value of 0.025 again delivers the best results, with an average RMSE of 5.3 cm, matching the performance with ECMWF forcing. The latter also holds for the skew surge quality under relatively calm conditions. For the most extreme conditions, the HA43 run with increased Charnock coefficient marginally outperforms ECMWF. However, regional variations exist: ECMWF still performs best in offshore, coastal, and Southwestern Delta stations, while in the Wadden Sea, both adjusted HA43 runs significantly outperform ECMWF. Note that while these experiments were performed with 3D DCSM-FM, these relative differences in model quality are probably unrelated to three-dimensional or baroclinic processes and would have been similar in experiments with the two-dimensional DCSM-FM 100m.
- Despite ERA5 and ECMWF having similar atmospheric boundary layer implementations, the higher-resolution ECMWF IFS/HRES model performs worse with respect to sea surface temperature at four locations. When using HA40 forcing, the model quality improves, surpassing ERA5 at all stations except Lichteiland Goeree. The difference between HA40 and HA43 with respect to quality of sea surface temperature is relatively minor. The impact on temperature of increasing the Charnock coefficient to 0.025 is minimal, while switching to stress-equivalent wind leads to a slight increase in RMSE in most stations.

8.1.4 WAQUA to D-HDYRO migration: DCSMv6-ZUNOv4 vs. DSCM-FM 100m

- The quality of total water levels in Dutch waters is significantly better in DCSM-FM 100m than in DCSMv6-ZUNOv4 (RMSE 9.1 cm vs 7.7 cm), due to both better tide and surge representation. This is in line with findings from earlier validation for the years 2013 to 2017.
- Skew surge errors under calm conditions (<99.0% skew surges) are lower in DCSM-FM 100m in all stations except for Hoek van Holland.
- Under extreme conditions, skew surge error are lowest in DCSM-FM from the Southwestern Delta up to the entry of the Ems-Dollard estuary. Due a larger underestimation of extreme skew surge in DCSM-FM, DCSMv6-ZUNOv4 yields better results in the Ems-Dollard.

8.1.5 Storm Pia validation

- Storm Pia was the most significant skew surge event during the validation period of 2020 to 2023. Due to the unavailability of HA43 forcing data for this event, the validation primarily focused on ECMWF and HA40 meteorological models.
- The tidal error at high water was notably small, not exceeding 5 cm across all five main WMCN locations.

- While the skew surge was generally underestimated during this storm, the extent of the underestimation was less severe than anticipated based on the empirical correction method typically employed in operational setting.
- With ECMWF forcing, the total high water error varied from +4 cm in Vlissingen to -31 cm in Delfzijl. In contrast, HA40 forcing resulted in a narrower range of errors, from +2 cm in Vlissingen to -10 cm in Delfzijl.

8.2 Recommendations

8.2.1 Improved meteorological forcing flexibility in D-HYDRO

The current approach for applying HARMONIE forcing in 2D tide-surge models uses wind stress, but models like 3D DCSM-FM also require wind speed data to calculate sensible and latent heat fluxes. D-HYDRO presently lacks the capability to prescribe both stress and wind speed simultaneously. It is recommended to enable this functionality in D-HYDRO and in addition to allow a time- and space-varying wind drag coefficient. These changes would facilitate research into improved and consistent coupling between meteorological and hydrodynamic models.

8.2.2 Measured and modelled stress-equivalent wind

This study revealed significant differences in wind drag coefficients between various meteorological models, which complicates the interpretation of wind speed forecasts for operational use. Moreover, these wind drag coefficients are not consistent with the assumptions used to convert wind speed measurement to standard height. For instance, while ECMWF shows lower wind speeds than HA40 and HA43 under high wind conditions, its higher drag coefficient results in greater wind stress. Forecasters primarily see wind speeds, so this may not be apparent. It is recommended to develop methods that make modelled and measured wind stress-equivalent wind speeds visible to forecasters, enhancing clarity in model comparisons.

8.2.3 Use of native HA43 grid

The HA43 data used in this study were provided on a rectangular 2.5 km grid, despite HA43's native resolution of 1.8 km on a Lambert grid. To avoid potential data loss from interpolation and take advantage of higher-resolution forcing, it is recommended to apply HA43 on its native grid in the operational tide-surge models. For efficiency of data storage, a coarsened grid may be applied in regions beyond the southern North Sea where high resolution is less critical.

8.2.4 Optimizing wind stress in HA43 and ECMWF

Experiments with 3D DCSM-FM suggest that operational tide-surge forecasting accuracy could be improved by forcing HARMONIE with a carefully adjusted Charnock coefficient or by fine-tuning wind stress, such as by using a multiplication factor. This approach could also benefit ECMWF forcing and is recommended for further exploration to enhance operational forecast accuracy.

8.2.5 Improved summer sea surface temperature and heat-flux parameterizations

Sea surface temperature validation showed the greatest discrepancies during summer, coinciding with the largest variations between different meteorological forcing setups. This may be due to inconsistencies between the heat-flux parameterizations in D-HYDRO and those in the meteorological models. While efforts have improved consistency for momentum fluxes, this has not been extended to heat fluxes. It is recommended to investigate and align these parameterizations to improve water temperature accuracy in 3D models such as 3D DCSM-FM.

8.2.6 Migration to DCSM-FM 100m for operational use

DCSM-FM 100m consistently outperformed its predecessor, DCSMv6-ZUNOv4, in tide, surge, and total water level predictions, as well as in skew surge estimates under both calm and storm conditions. It is therefore recommended that DCSM-FM 100m replace DCSMv6-ZUNOv4 as the primary operational tide-surge model at HMC and WMCN.

8.2.7 Recalibration to improve quality at Harlingen

Although the overall performance of DCSM-FM 100m has improved, some locations, such as West Terschelling and WMCN main location Harlingen, showed a decrease in water level quality. Previous validation suggested excluding West Terschelling from calibration to improve accuracy in nearby stations, including Terschelling Noordzee and Harlingen. Based on current findings, it is recommended to test this approach.

8.2.8 Improved schematization of the Rhine-Meuse Delta (RMM) in DCSM-FM 100m

Skew surge accuracy at Hoek van Holland under calm conditions is slightly reduced in DCSM-FM 100m compared to DCSMv6-ZUNOv4, possibly due to differences in the representation of the Rhine-Meuse Delta in the model schematization. Earlier work on the shape of the high waters in Hoek van Holland has suggested a large sensitivity to the quality and detail with which the local bathymetry and geometry is represented in this area. Given this, it is recommended to refine the RMM schematization in DCSM-FM 100m.

8.2.9 Skew surge underestimation in the Ems-Dollard

DCSMv6-ZUNOv4 remains more accurate than DCSM-FM 100m in predicting extreme skew surges in the Ems-Dollard due to larger systematic underestimation. To address this, it is recommended to investigate and adjust relevant aspects of the model setup to enhance its performance in this region.

8.2.10 Improvement of NO1 tidal accuracy

The validation of 3D DCSM-FM revealed very large vector difference errors in the diurnal NO1 tidal constituent across all model configurations, likely stemming from a subtle frequency mismatch between the observed constituent, the constituent-based boundary forcing and the harmonic analysis during post-processing. It is recommended that further investigation be conducted to better understand the source of this NO1 inaccuracy and to enhance model precision.

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A Appendix A: Skew surge error comparison ECMWF, HA40 and HA43 for DCSM-FM 100m

This appendix shows the detailed statistics underpinning Table 4.2.

Appendix table A.1: Skew surge error, FM100M, ECMWF, 20201001 - 20231001

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	-2,2	6,1	-0,7	4,9	-3,3	10,2	-10,1	3,6	10,8
Bol_Van_Heist	-0,5	5,4	-0,9	4,8	-4,1	6,9	-8,0	9,4	12,4
Scheur_Wielingen_ Bol_van_Knokke	0,1	5,6	0,4	4,6	-4,8	11,1	-16,3	4,3	16,8
CADZD	-3,0	7,0	-0,6	5,3	-3,6	8,9	-12,9	10,9	16,9
WESTKPLE	-2,2	6,0	0,0	4,7	-4,7	8,6	-9,3	4,0	10,1
EURPFM	0,2	5,1	0,1	4,4	-3,9	5,6	-10,9	5,1	12,0
VLISSGN	-3,4	7,2	-0,2	4,9	-3,5	6,9	-10,6	5,3	11,9
ROOMPBTN	0,0	5,7	-0,6	4,8	-9,0	11,8	-16,1	7,1	17,6
LICHTELGRE	-4,4	7,3	-0,5	4,6	-5,8	7,6	-9,9	8,1	12,8
BROUWHVSGT08	-5,1	8,6	-0,8	5,1	-14,2	16,9	-30,3	9,4	31,7
TERNZN	-1,9	7,1	0,1	5,3	-5,8	8,8	-11,3	7,7	13,6
HARVT10	-5,3	8,2	-1,9	5,3	-4,2	7,9	-9,0	11,7	14,8
ROOMPBNN	-3,0	6,0	-0,8	4,6	-7,0	9,1	-8,7	4,7	9,9
HANSWT	3,3	7,9	0,6	5,6	-8,2	14,3	-17,5	9,9	20,0
HOEKVHLD	2,5	6,8	0,7	5,5	-5,1	8,4	-14,0	6,5	15,4
STAVNSE	-0,4	5,7	-0,3	4,9	-4,2	6,4	-6,8	4,1	7,9
BERGSDSWT	1,5	5,7	0,3	4,8	-1,1	7,6	-5,4	4,3	6,9
KRAMMSZWT	-0,1	5,8	-0,5	5,0	-6,8	8,4	-9,0	3,2	9,5
BATH	6,5	10,3	0,9	5,9	-10,8	18,8	-15,7	10,2	18,7
SCHEVNGN	-3,5	7,8	-1,5	5,6	-12,2	14,8	-22,7	6,6	23,7
IJMDBTHVN	-1,8	7,0	-1,5	5,6	-10,0	12,0	-14,9	4,3	15,6
Q1	-1,0	5,3	-1,3	4,6	-7,8	8,4	-16,2	0,6	16,2
DENHDR	-0,2	5,5	-0,8	4,5	-10,2	11,4	-19,3	2,9	19,5
TEXNZE	0,4	7,1	-1,6	5,0	-12,6	13,9	-18,9	11,4	22,1
K13APFM	-1,3	5,0	-0,2	4,2	-3,2	5,7	-2,8	4,6	5,4
OUDSD	1,2	5,6	-0,5	4,4	-9,6	10,4	-20,3	7,0	21,5
DENOVBTN	3,4	7,3	-1,0	5,2	-14,9	15,9	-27,7	10,0	29,4
TERSLNZE	-1,3	6,0	-1,0	5,0	-10,2	13,4	-14,9	2,7	15,1
VLIELHVN	2,6	6,2	-0,4	4,5	-12,1	13,6	-18,2	4,8	18,8
WESTTSLG	3,5	6,8	-0,3	4,7	-12,1	13,9	-22,4	8,5	24,0

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
KORNWDZBTN	2,2	6,8	-0,7	5,0	-13,3	15,1	-28,7	8,3	29,9
WIERMGDN	-2,1	5,9	-0,6	4,7	-4,4	8,8	-11,9	3,2	12,3
HUIBGT	-3,3	6,8	-0,7	5,0	0,3	7,4	-9,8	4,9	11,0
HARLGN	2,4	6,6	-0,4	5,0	-12,6	14,7	-26,4	8,8	27,8
NES	2,1	7,0	-0,1	5,4	-16,0	17,0	-33,4	3,4	33,6
LAUWOG	-2,4	7,6	-0,5	5,7	-16,0	17,8	-35,4	11,2	37,1
SCHIERMNOG	-1,7	10,6	0,1	8,4	-20,1	21,2	-42,3	10,8	43,6
BORKUM_Sudstrand	-3,3	7,2	-0,3	5,1	-11,0	12,0	-28,1	9,8	29,8
BorkumFischerbalje	0,0	6,3	-0,2	4,9	-10,3	11,5	-25,3	10,4	27,4
EMSHORN	-1,7	7,0	-0,3	5,3	-13,8	14,7	-31,8	9,5	33,2
EEMSHVN	-0,6	7,2	-0,8	5,9	-15,8	17,2	-33,1	11,5	35,0
DUKEGAT	0,3	7,2	-0,6	5,6	-12,7	14,3	-32,6	10,5	34,2
DELFZL	3,9	9,5	0,3	6,5	-19,3	20,7	-39,0	11,6	40,6
KNOCK	0,9	8,4	0,1	6,1	-18,5	19,8	-34,2	12,8	36,5
EMDEN_Neue_Seeschl	4,7	9,9	-0,2	6,4	-17,0	18,8	-40,7	14,0	43,0
POGUM	4,5	10,4	-0,7	7,0	-17,2	18,8	-41,5	16,9	44,8
Average (total)	-0,2	7,0	-0,4	5,2	-9,6	12,3	-20,1	7,6	21,8
Average (offshore)	-1,6	5,7	-0,5	4,5	-5,2	6,8	-9,9	4,6	11,6
Average (coast)	-1,7	6,6	-0,7	5,0	-7,0	10,8	-14,9	6,4	16,6
Average (SWD)	0,3	7,0	0,0	5,1	-5,9	10,0	-10,6	6,2	12,3
Average (WS)	1,2	7,6	-0,4	5,6	-14,6	16,0	-31,2	10,0	32,8

Appendix table A.2: Skew surge error, FM100M, HA40, 20201001 - 20231001

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	-0,9	6,0	-0,8	5,1	-4,7	12,5	-5,6	7,9	9,7
Bol_Van_Heist	0,8	5,8	-0,9	5,0	-4,8	9,6	-6,1	7,7	9,9
Scheur_Wielingen_ Bol_van_Knokke	1,6	6,3	0,4	4,9	-7,4	10,4	-22,0	1,9	22,1
CADZD	-1,6	6,4	-0,5	5,1	-5,2	10,1	-8,3	16,3	18,3
WESTKPLE	-0,9	5,9	0,0	4,8	-6,3	9,7	-1,9	9,3	9,5
EURPFM	1,0	5,3	0,2	4,4	-5,5	8,9	-7,5	8,1	11,1
VLISSGN	-1,9	6,8	-0,2	5,0	-5,4	8,0	-1,1	8,2	8,3
ROOMPBTN	1,3	6,0	-0,6	5,0	-9,9	12,5	-7,6	12,7	14,8
LICHTELGRE	-3,4	6,9	-0,5	4,7	-7,9	11,5	-10,3	10,4	14,7
BROUWHVSGT08	-3,9	8,0	-0,7	5,4	-15,7	18,4	-24,7	11,8	27,4
TERNZN	-0,4	7,1	0,1	5,5	-6,2	10,0	0,6	9,4	9,4
HARVT10	-4,3	7,9	-1,9	5,6	-8,5	10,9	-2,5	16,6	16,8
ROOMPBNN	-2,2	6,1	-0,8	4,9	-9,1	11,1	-5,4	6,9	8,8
HANSWT	4,7	8,8	0,6	5,8	-5,1	8,0	-5,7	10,7	12,1
HOEKVHLD	3,6	7,3	0,8	5,5	-9,8	11,9	-7,8	13,4	15,5
STAVNSE	0,5	6,0	-0,2	5,1	-6,4	8,2	-1,0	9,0	9,1
BERGSDSWT	2,7	6,4	0,3	5,0	-3,6	8,1	3,1	9,8	10,3
KRAMMSZWT	0,8	6,1	-0,5	5,2	-9,1	11,4	-4,1	5,1	6,5
BATH	8,1	11,4	0,8	6,1	-4,8	7,5	-1,5	9,6	9,7
SCHEVNGN	-2,6	7,5	-1,5	5,7	-15,4	17,8	-20,8	9,7	22,9
IJMDBTHVN	-0,8	7,2	-1,5	6,0	-11,3	13,6	-16,1	5,1	16,9
Q1	-0,7	5,3	-1,5	4,9	-9,4	10,5	-5,9	5,8	8,3
DENHDR	0,2	5,9	-0,8	5,0	-11,5	12,4	-11,8	4,4	12,6
TEXNZE	0,8	7,4	-1,7	5,3	-13,6	14,8	-16,4	7,2	17,9
K13APFM	-1,2	5,1	-0,1	4,3	-4,8	6,9	0,0	5,7	5,7
OUDSD	1,6	6,0	-0,5	4,8	-10,2	11,1	-9,8	3,4	10,4
DENOVBTN	3,9	8,0	-1,1	6,0	-15,4	16,7	-15,2	4,2	15,7
TERSLNZE	-0,5	6,1	-1,0	5,2	-10,7	13,2	-11,2	5,8	12,6
VLIELHVN	3,2	6,8	-0,4	5,1	-12,2	13,6	-13,2	3,5	13,7
WESTTSLG	4,2	7,5	-0,3	5,3	-12,1	13,9	-15,7	4,7	16,4
KORNWDZBTN	2,8	7,6	-0,8	5,9	-12,8	14,5	-17,6	3,5	18,0
WIERMGDN	-1,3	6,0	-0,6	5,1	-5,9	10,1	-7,6	9,9	12,5
HUIBGT	-2,3	6,9	-0,7	5,4	-1,8	8,2	-5,3	4,9	7,2
HARLGN	3,1	7,5	-0,4	5,8	-12,3	14,6	-14,8	5,6	15,8
NES	3,1	8,0	0,0	6,3	-14,9	16,0	-26,6	6,8	27,5
LAUWOG	-1,4	8,0	-0,5	6,5	-15,0	17,1	-23,6	5,6	24,3

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
SCHIERMNOG	-0,6	11,0	0,2	9,0	-19,2	20,7	-35,9	7,6	36,7
BORKUM_Sudstrand	-2,2	7,5	-0,3	5,8	-10,7	12,8	-19,8	6,8	21,0
BorkumFischerbalje	1,2	7,1	-0,2	5,6	-9,3	11,5	-18,0	6,8	19,3
EMSHORN	-0,5	7,6	-0,3	6,1	-12,1	14,5	-22,3	6,0	23,1
EEMSHVN	0,6	8,0	-0,8	6,6	-13,5	16,6	-23,0	8,0	24,3
DUKEGAT	1,5	8,0	-0,6	6,4	-10,4	13,9	-20,2	7,4	21,5
DELFZL	5,2	10,7	0,4	7,3	-15,3	17,9	-22,1	8,6	23,8
KNOCK	2,2	9,5	0,2	7,0	-14,3	17,3	-18,5	12,0	22,0
EMDEN_Neue_Seeschl	6,1	11,3	-0,2	7,2	-13,9	16,4	-18,4	8,1	20,1
POGUM	6,0	11,7	-0,7	7,9	-12,3	15,3	-18,8	10,2	21,4
Average (total)	0,8	7,4	-0,4	5,6	-9,9	12,6	-12,4	7,9	16,0
Average (offshore)	-1,1	5,7	-0,5	4,6	-6,9	9,4	-5,9	7,5	9,9
Average (coast)	-0,7	6,7	-0,8	5,3	-8,9	12,3	-11,0	9,0	15,4
Average (SWD)	1,5	7,3	0,0	5,3	-6,2	9,0	-1,9	8,6	9,3
Average (WS)	2,2	8,4	-0,3	6,4	-13,1	15,2	-19,6	6,6	20,8

Appendix table A.3: Skew surge error, FM100M, HA43, 20201001 - 20231001

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	-1,0	6,0	-0,7	5,1	-5,6	11,7	-8,1	5,3	9,7
Bol_Van_Heist	0,7	5,6	-0,9	5,0	-5,8	9,4	-8,8	6,6	11,0
Scheur_Wielingen_ Bol_van_Knokke	1,5	6,3	0,5	5,0	-9,2	12,2	-21,8	1,5	21,9
CADZD	-1,7	6,6	-0,5	5,3	-6,4	9,6	-11,8	15,7	19,7
WESTKPLE	-1,0	5,9	0,0	4,9	-7,1	10,4	-6,9	6,8	9,7
EURPFM	1,0	5,4	0,2	4,5	-8,2	10,4	-12,4	7,9	14,7
VLISSGN	-2,0	6,8	-0,2	5,0	-5,7	7,7	-6,1	6,5	8,9
ROOMPBTN	1,2	6,0	-0,5	5,1	-11,8	14,8	-13,1	9,3	16,0
LICHTELGRE	-3,5	7,0	-0,4	4,8	-9,6	12,0	-15,4	8,8	17,7
BROUWHVSGT08	-3,9	8,3	-0,7	5,5	-18,6	21,2	-31,3	13,7	34,2
TERNZN	-0,5	7,0	0,1	5,4	-7,0	10,3	-4,2	8,2	9,2
HARVT10	-4,3	7,8	-1,8	5,5	-10,4	11,8	-7,5	12,0	14,2
ROOMPBNN	-2,3	6,0	-0,7	4,7	-10,7	12,8	-7,5	7,4	10,6
HANSWT	4,6	8,7	0,6	5,7	-6,1	8,7	-10,1	11,1	15,0
HOEKVHLD	3,6	7,5	0,9	5,8	-10,6	12,2	-12,9	11,4	17,2
STAVNSE	0,4	5,7	-0,2	4,9	-8,3	10,2	-3,3	8,2	8,9
BERGSDSWT	2,5	6,1	0,3	4,8	-4,7	9,7	0,6	8,5	8,5
KRAMMSZWT	0,7	6,0	-0,4	5,1	-10,4	14,0	-8,0	7,8	11,1
BATH	8,0	11,3	0,8	6,0	-6,8	10,0	-6,5	9,5	11,5
SCHEVNGN	-2,7	7,7	-1,4	5,9	-17,0	18,8	-26,2	7,6	27,3
IJMDBTHVN	-0,9	7,4	-1,4	6,1	-13,8	15,9	-21,8	6,5	22,7
Q1	-0,7	5,7	-1,3	5,1	-12,5	13,8	-14,0	7,3	15,8
DENHDR	0,1	6,1	-0,7	5,1	-14,6	15,8	-16,3	6,1	17,4
TEXNZE	0,8	7,5	-1,6	5,4	-16,2	17,4	-19,5	6,2	20,4
K13APFM	-1,1	5,2	0,0	4,4	-6,1	7,7	-5,6	7,5	9,3
OUDSD	1,5	6,1	-0,4	4,8	-14,4	15,3	-13,9	6,4	15,3
DENOVBTN	3,8	7,9	-1,0	5,8	-18,9	20,4	-18,0	10,6	20,9
TERSLNZE	-0,5	6,3	-0,8	5,4	-12,2	15,0	-15,0	8,0	17,0
VLIELHVN	3,2	6,9	-0,3	5,1	-14,7	15,9	-16,7	3,9	17,1
WESTTSLG	4,2	7,6	-0,2	5,3	-15,1	17,3	-18,1	7,2	19,5
KORNWDZBTN	2,7	7,4	-0,7	5,6	-15,0	17,0	-22,0	7,3	23,2
WIERMGDN	-1,2	6,1	-0,3	5,2	-8,5	11,4	-9,7	10,9	14,6
HUIBGT	-2,3	6,8	-0,5	5,3	-4,7	10,3	-7,2	6,9	10,0
HARLGN	3,0	7,3	-0,3	5,6	-13,8	16,6	-19,2	6,3	20,2
NES	2,9	7,8	0,0	6,1	-18,6	20,2	-29,6	7,0	30,4
LAUWOG	-1,6	7,7	-0,4	6,1	-18,8	20,9	-26,0	8,5	27,4

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
SCHIERMNOG	-0,8	10,7	0,3	8,7	-24,3	26,0	-35,5	12,2	37,6
BORKUM_Sudstrand	-2,3	7,4	-0,2	5,6	-15,0	17,2	-20,3	8,0	21,8
BorkumFischerbalje	1,1	6,8	-0,1	5,4	-13,4	16,1	-19,4	7,3	20,7
EMSHORN	-0,7	7,4	-0,2	5,9	-15,5	18,7	-23,6	8,1	24,9
EEMSHVN	0,4	7,7	-0,7	6,4	-16,7	20,7	-24,4	9,1	26,0
DUKEGAT	1,3	7,6	-0,5	6,1	-12,9	18,0	-21,8	10,1	24,0
DELFZL	4,9	10,1	0,4	6,9	-17,4	21,6	-27,2	7,7	28,3
KNOCK	1,9	8,8	0,2	6,5	-16,7	21,1	-23,4	9,2	25,1
EMDEN_Neue_Seeschl	5,8	10,7	-0,2	6,7	-17,4	20,5	-25,3	11,0	27,6
POGUM	5,7	11,1	-0,7	7,4	-15,5	19,1	-24,4	15,3	28,8
Average (total)	0,7	7,3	-0,4	5,6	-12,2	15,0	-16,1	8,4	18,8
Average (offshore)	-1,1	5,8	-0,4	4,7	-9,1	11,0	-11,9	7,9	14,4
Average (coast)	-0,7	6,7	-0,7	5,3	-10,8	13,6	-14,9	8,4	17,7
Average (SWD)	1,4	7,2	0,0	5,2	-7,5	10,4	-5,6	8,4	10,5
Average (WS)	2,1	8,2	-0,3	6,1	-16,3	19,0	-22,7	8,6	24,4

B Skew surge error comparison between DCSMv6-ZUNOv4 and DCSM-FM 100m

This appendix shows the detailed statistics underpinning Table 6.2.

Appendix table B.1: Skew surge error, DCSMv6-ZUNOv4, ECMWF, 20200101 – 202401001, open structures

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	0,7	5,7	-0,8	4,7	-5,2	10,7	-9,7	3,8	10,4
Bol_Van_Heist	2,1	6,1	-1,4	5,2	-4,8	8,0	-7,6	8,1	11,1
Scheur_Wielingen _Bol_van_Knokke	2,4	6,2	-0,4	4,7	-6,4	11,1	-10,9	7,6	13,3
CADZD	0,2	6,6	-0,8	5,3	-4,6	11,5	-3,7	9,4	10,1
WESTKPLE	1,1	6,0	-0,3	4,8	-4,2	8,2	-6,4	7,7	10,0
EURPFM	2,2	5,6	0,1	4,4	-4,6	6,3	-9,6	8,7	13,0
VLISSGN	2,4	7,0	-0,2	5,0	-4,9	7,1	-7,0	6,0	9,2
ROOMPBTN	3,6	7,0	0,1	5,1	-9,6	12,9	-20,5	11,0	23,3
LICHTELGRE	2,1	6,0	0,0	4,7	-4,4	7,9	-10,8	7,0	12,8
BROUWHVSGT08	2,5	7,2	0,0	5,2	-12,8	15,1	-28,1	13,2	31,0
TERNZN	4,1	8,3	0,0	5,5	-7,5	9,9	-9,0	8,1	12,1
HARVT10	2,3	6,5	0,1	5,4	-4,9	12,0	-9,0	13,2	16,0
ROOMPBNN	-2,0	5,7	-0,3	4,7	-9,1	10,4	-9,9	6,3	11,8
HANSWT	7,8	11,1	0,7	6,1	-9,1	12,6	-14,8	10,6	18,2
HOEKVHLD	-1,5	7,2	-1,0	5,3	-7,3	10,3	-18,5	8,4	20,3
STAVNSE	0,8	5,7	0,3	4,9	-6,4	7,9	-11,1	4,7	12,1
BERGSDSWT	-0,6	5,8	0,1	4,9	-4,9	8,4	-11,6	4,4	12,4
KRAMMSZWT	4,0	7,3	2,1	5,9	-7,2	8,8	-13,2	5,1	14,2
BATH	7,7	11,6	0,9	6,1	-12,1	19,5	-15,0	11,0	18,6
SCHEVNGN	3,3	7,9	-0,8	5,6	-11,6	14,1	-24,6	8,5	26,1
IJMDBTHVN	6,8	10,0	-0,7	6,0	-10,9	13,9	-21,4	5,7	22,2
Q1	0,2	5,5	-1,2	4,7	-9,4	10,0	-14,7	5,9	15,9
DENHDR	2,2	6,1	-0,6	4,7	-11,6	12,3	-16,6	7,2	18,1
TEXNZE	1,9	7,3	-1,6	5,1	-12,8	14,9	-20,8	8,0	22,3
K13APFM	-1,2	5,6	-0,2	4,4	-4,2	7,4	-7,0	4,5	8,3
OUDSD	0,6	5,8	-0,3	4,6	-10,9	11,8	-17,3	8,0	19,1
DENOVBTN	2,6	7,2	-0,5	5,5	-15,9	17,3	-21,1	10,7	23,7
TERSLNZE	0,8	6,1	-0,9	5,0	-6,8	11,2	-9,8	8,2	12,8

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
VLIELHVN	2,0	6,2	0,0	4,6	-13,3	14,4	-16,1	5,8	17,1
WESTTSLG	0,7	5,9	0,0	4,7	-14,1	15,8	-15,8	9,8	18,6
KORNWDZBTN	2,1	6,9	-0,4	5,1	-16,9	18,4	-23,6	8,2	25,0
WIERMGDN	1,4	5,7	-0,4	4,7	-3,2	5,9	-7,4	10,0	12,5
HUIBGT	1,7	6,0	-0,5	5,1	1,4	6,4	-3,5	9,9	10,5
HARLGN	2,0	6,8	-0,3	5,2	-15,9	17,5	-23,6	8,4	25,0
NES	4,7	8,7	-0,4	5,7	-19,0	20,0	-32,3	9,2	33,6
LAUWOG	1,8	7,3	-0,5	5,8	-14,6	17,0	-29,6	15,3	33,3
SCHIERMNOG	3,2	10,3	-0,5	7,7	-11,9	15,8	-25,6	17,5	31,0
BORKUM_Sudstrand	2,1	6,5	-0,1	5,0	-9,3	12,0	-20,0	10,1	22,4
BorkumFischerbalje	4,0	7,4	0,1	5,0	-8,1	10,7	-17,7	9,3	20,0
EMSHORN	5,1	8,5	-0,1	5,3	-11,6	13,6	-25,8	7,5	26,8
EEMSHVN	5,1	9,0	-0,1	5,8	-12,2	14,9	-24,4	8,8	26,0
DUKEGAT	6,6	10,0	-1,2	6,6	-11,2	13,5	-31,0	7,0	31,7
DELFZL	6,0	10,7	1,4	6,6	-15,9	18,2	-35,6	8,9	36,7
KNOCK	2,9	9,0	0,4	6,2	-15,5	17,7	-31,3	10,7	33,1
EMDEN_Neue_Seeschl	-3,4	9,9	0,2	6,8	-11,0	14,5	-33,9	9,7	35,2
POGUM	-9,5	13,6	1,0	7,6	-12,3	17,5	-37,6	11,8	39,4
Average (total)	2,1	7,4	-0,2	5,4	-9,5	12,5	-17,7	8,7	20,1
Average (offshore)	0,8	5,7	-0,3	4,5	-5,6	7,9	-10,5	6,5	12,5
Average (coast)	2,0	6,7	-0,6	5,1	-7,2	11,1	-13,7	8,7	16,9
Average (SWD)	3,0	7,8	0,5	5,4	-7,6	10,6	-11,5	7,0	13,6
Average (WS)	2,1	8,3	-0,1	5,8	-13,3	15,6	-25,7	9,8	27,6

Appendix table B.2: Skew surge error, FM100M, ECMWF, 20200101 – 202401001, open structures

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	-2,2	5,9	-0,4	4,4	-4,8	10,4	-8,5	3,6	9,3
Bol_Van_Heist	-0,8	5,5	-0,9	4,8	-4,4	7,5	-6,5	8,5	10,7
Scheur_Wielingen_Bol_van_Knokke	-0,5	5,7	0,2	4,6	-6,7	10,9	-10,2	6,7	12,2
CADZD	-3,4	7,3	-0,3	5,2	-5,3	11,4	-2,8	9,9	10,3

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
WESTKPLE	-2,6	6,3	0,1	4,7	-4,6	7,9	-5,1	8,0	9,5
EURPFM	-0,1	5,3	0,3	4,3	-4,1	5,4	-8,3	8,5	11,8
VLISSGN	-3,7	7,5	-0,1	4,9	-5,5	7,3	-6,2	8,2	10,3
ROOMPBTN	-0,4	5,9	-0,5	4,8	-9,8	12,4	-18,5	11,2	21,6
LICHTELGRE	-4,7	7,7	-0,4	4,6	-4,3	7,4	-8,8	6,4	10,9
BROUWHVSGT08	-5,5	9,0	-0,8	5,1	-14,1	16,0	-25,5	12,5	28,4
TERNZN	-2,2	7,4	0,1	5,3	-7,9	9,8	-7,5	10,2	12,7
HARVT10	-5,8	8,7	-1,6	5,3	-4,5	11,0	-7,1	12,0	13,9
ROOMPBNN	-3,3	6,2	-0,6	4,4	-7,1	8,6	-6,7	5,5	8,6
HANSWT	3,0	8,3	0,6	6,0	-9,6	13,0	-12,4	12,1	17,4
HOEKVHLD	1,9	7,1	0,9	5,6	-5,2	8,6	-14,5	8,5	16,8
STAVNSE	-0,8	5,7	-0,2	4,7	-5,1	6,9	-8,0	5,2	9,5
BERGSDSWT	1,0	5,6	0,4	4,8	-2,0	6,8	-6,8	6,2	9,2
KRAMMSZWT	-0,4	5,8	-0,3	5,0	-7,3	8,3	-11,8	6,0	13,2
BATH	6,3	10,4	0,8	6,0	-13,7	20,3	-13,2	13,4	18,8
SCHEVNGN	-3,8	8,2	-1,3	5,6	-11,4	13,8	-22,5	6,6	23,5
IJMDBTHVN	-2,1	7,3	-1,4	5,7	-9,8	12,6	-17,4	3,8	17,8
Q1	-1,2	5,5	-1,2	4,5	-7,6	8,2	-11,7	5,2	12,8
DENHDR	-0,3	5,7	-0,7	4,6	-10,9	11,9	-14,0	6,6	15,5
TEXNZE	0,2	7,2	-1,6	5,0	-13,1	15,8	-18,6	7,5	20,1
K13APFM	-1,3	5,2	-0,1	4,2	-3,8	6,8	-4,7	3,3	5,7
OUDSD	1,1	5,7	-0,4	4,4	-10,6	11,4	-16,1	8,1	18,0
DENOVBTN	3,5	7,5	-0,8	5,3	-16,8	17,9	-20,3	10,5	22,9
TERSLNZE	-1,5	6,0	-1,0	4,9	-8,9	12,1	-8,9	8,8	12,5
VLIELHVN	2,4	6,3	-0,3	4,5	-14,1	14,8	-15,1	5,8	16,2
WESTTSLG	3,3	6,8	-0,2	4,7	-14,7	15,9	-14,5	10,7	18,0
KORNWDZBTN	2,1	6,8	-0,7	5,1	-16,8	18,2	-21,7	8,9	23,5
WIERMGDN	-2,3	6,0	-0,4	4,7	-4,9	6,3	-4,6	10,2	11,2
HUIBGT	-3,4	6,9	-0,6	5,0	-0,2	5,0	-2,6	8,7	9,1
HARLGN	2,4	6,7	-0,3	5,1	-15,4	17,0	-21,8	8,6	23,4
NES	2,0	7,2	0,0	5,5	-17,4	18,4	-28,1	9,8	29,7
LAUWOG	-2,5	7,6	-0,4	5,8	-16,5	18,4	-29,7	14,1	32,9
SCHIERMNOG	-1,7	10,3	-0,3	7,6	-14,4	17,2	-28,5	17,1	33,2
BORKUM_Sudstrand	-3,3	7,3	-0,2	5,0	-12,0	14,3	-21,8	10,2	24,1
BorkumFischerbalje	-0,2	6,4	-0,1	5,0	-11,3	13,6	-21,1	9,1	22,9

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
EMSHORN	-1,8	7,2	-0,1	5,3	-15,1	17,0	-29,0	7,3	29,9
EEMSHVN	-0,9	7,4	-0,5	5,8	-16,2	18,7	-28,2	8,9	29,6
DUKEGAT	0,3	7,4	-1,2	6,4	-14,1	16,5	-33,9	7,7	34,7
DELFZL	3,4	9,5	0,4	6,5	-21,5	23,2	-41,1	9,3	42,2
KNOCK	0,5	8,7	0,3	6,3	-20,6	22,4	-37,2	11,1	38,8
EMDEN_Neue_Seeschl	4,3	10,0	-0,1	6,4	-19,6	21,9	-43,6	10,7	44,9
POGUM	4,3	10,6	-0,6	7,0	-21,8	25,2	-47,0	12,9	48,7
Average (total)	-0,5	7,1	-0,4	5,2	-10,6	13,1	-17,2	8,8	19,9
Average (offshore)	-1,8	5,9	-0,4	4,4	-5,0	7,0	-8,4	5,8	10,3
Average (coast)	-2,0	6,8	-0,6	5,0	-7,4	10,9	-11,7	8,3	15,2
Average (SWD)	0,0	7,1	0,1	5,1	-7,2	10,1	-9,1	8,4	12,5
Average (WS)	1,1	7,7	-0,3	5,6	-16,1	17,9	-27,7	10,0	29,6

C Appendix C: Skew surge error comparison ECMWF, HA40 and HA43 for 3D DCSM-FM 0.5nm

This appendix shows the detailed statistics underpinning Table 4.2.

Appendix table C.1: Skew surge error, 3D FM0.5NM, ECMWF, 20220101 - 20230101

	Total HW error		**Skew surge (high water)**						
	All HWs		**<99.0% skew surges**		**99.0% - 99.8% skew surges**		**>99.8% skew surges**		
	bias [cm]	**RMSE [cm]**	**bias [cm]**	**RMSE [cm]**	**bias [cm]**	**RMSE [cm]**	**bias [cm]**	**std [cm]**	**RMSE [cm]**
Wandelaar	1,5	4,9	-0,6	4,0	-2,8	5,1	-3,1	1,4	3,4
Bol_Van_Heist	3,4	5,6	-1,1	4,0	-2,7	5,5	-5,8	1,6	6,0
Scheur_Wielingen_ Bol_van_Knokke	2,2	5,0	-0,8	4,1	-1,4	4,2	-7,3	0,9	7,3
CADZD	1,0	6,2	-1,5	5,2	-3,3	5,9	2,6	1,7	3,1
WESTKPLE	0,8	5,4	-0,1	4,0	-4,0	5,3	-5,5	1,6	5,7
EURPFM	4,8	6,7	0,0	3,8	-3,9	4,9	-8,8	1,6	8,9
VLISSGN	5,5	8,6	0,5	4,7	-4,6	6,5	-8,8	1,9	9,0
ROOMPBTN	5,9	8,3	-0,8	4,4	-7,5	8,9	-25,0	3,8	25,3
LICHTELGRE	1,1	5,7	-0,4	4,2	-1,4	3,2	-4,6	1,1	4,7
BROUWHVSGT08	-3,5	8,4	-1,8	5,2	-13,2	15,2	-24,0	7,4	25,1
TERNZN	8,8	11,6	0,0	5,0	-4,3	7,5	-11,4	5,3	12,5
HARVT10	1,6	5,7	-1,0	4,4	2,9	5,4	-11,6	4,6	12,5
ROOMPBNN	7,1	8,5	-0,9	4,1	-3,4	4,2	-3,3	0,8	3,4
HANSWT	10,1	12,9	0,4	5,7	-8,2	9,8	-13,9	6,7	15,4
HOEKVHLD	2,4	7,2	-2,3	5,6	-4,6	8,8	-12,0	1,8	12,1
STAVNSE	12,4	13,6	-0,2	4,4	2,4	3,4	2,4	2,8	3,7
BERGSDSWT	17,9	19,0	1,1	4,9	5,7	6,4	4,9	3,7	6,1
KRAMMSZWT	14,4	15,9	-1,9	6,2	0,6	3,5	-1,4	0,7	1,6
SCHEVNGN	1,7	7,1	-1,3	5,0	-14,1	16,4	-18,3	9,4	20,6
IJMDBTHVN	3,6	7,7	-0,7	5,0	-3,3	8,4	-12,4	5,8	13,7
Q1	1,3	5,7	-1,1	4,8	-9,2	10,8	-8,9	0,0	8,9
DENHDR	-1,8	5,4	-0,7	4,1	-10,5	12,0	-17,7	3,9	18,1
TEXNZE	1,5	6,2	-1,6	4,7	-11,1	14,9	-19,6	8,6	21,4
K13APFM	-2,2	4,5	-0,5	4,2	0,4	6,1	-1,3	0,9	1,6
OUDSD	1,1	5,5	-0,2	4,1	-12,2	12,9	-20,4	10,2	22,8
DENOVBTN	1,4	6,1	-0,8	4,5	-18,4	18,9	-27,7	18,0	33,0
TERSLNZE	-0,7	5,1	-1,3	4,4	-9,2	11,8	-10,4	0,9	10,4
VLIELHVN	-4,1	6,3	0,1	4,4	-10,1	10,8	-16,8	2,8	17,0

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
WESTTSLG	1,6	6,0	-0,1	4,4	-10,4	12,5	-23,3	4,2	23,6
KORNWDZBTN	1,9	6,3	-0,6	4,6	-18,5	19,6	-22,7	11,5	25,5
WIERMGDN	-0,3	5,0	-0,5	4,2	-3,4	5,2	-8,5	3,5	9,2
HUIBGT	-1,4	5,7	-0,5	4,5	0,0	6,3	-10,6	2,4	10,8
HARLGN	0,1	6,2	-0,3	5,0	-16,7	18,5	-14,7	11,1	18,4
NES	1,1	7,0	0,2	5,2	-16,1	18,2	-20,6	7,1	21,8
LAUWOG	0,6	7,4	0,0	5,3	-18,1	18,5	-32,6	12,4	34,9
SCHIERMNOG	-1,1	12,6	0,2	6,6	-18,2	20,0	-30,8	11,7	32,9
BORKUM_Sudstran d	0,1	6,6	-0,1	4,8	-11,8	14,4	-31,8	2,8	31,9
BorkumFischerbalje	2,1	6,9	0,0	4,8	-8,5	11,6	-28,5	5,0	28,9
EMSHORN	3,0	7,8	0,3	5,1	-17,8	18,7	-36,1	4,1	36,3
EEMSHVN	4,1	8,1	-0,1	5,4	-17,7	18,4	-37,7	5,0	38,1
DUKEGAT	4,2	8,5	-0,2	5,4	-16,8	17,2	-38,8	1,1	38,8
DELFZL	3,4	9,8	-1,0	6,7	-16,3	18,7	-39,6	1,4	39,6
KNOCK	0,8	8,5	-0,2	6,2	-14,8	15,3	-32,8	0,0	32,8
Average (total)	2,8	7,7	-0,5	4,8	-8,3	10,9	-16,3	4,5	17,6
Average (offshore)	1,3	5,7	-0,5	4,2	-3,5	6,3	-5,9	0,9	6,0
Average (coast)	1,1	6,2	-1,0	4,5	-5,5	8,7	-11,8	3,7	12,8
Average (SWD)	10,9	12,9	-0,1	5,0	-1,7	5,9	-4,5	3,1	7,4
Average (WS)	1,3	7,5	-0,2	5,1	-15,2	16,5	-28,4	6,8	29,8

This appendix shows the detailed statistics underpinning Table 4.2.

Appendix table C.2: Skew surge error, 3D FM0.5NM, HARMONIE40, 20220101 - 20230101

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	2,2	5,7	-0,6	4,4	-8,9	10,7	-10,5	1,7	10,7
Bol_Van_Heist	4,1	6,5	-1,1	4,4	-9,1	10,6	-12,5	4,6	13,3
Scheur_Wielingen_ Bol_van_Knokke	2,9	5,9	-0,8	4,5	-4,8	8,4	-13,5	3,5	13,9
CADZD	1,7	6,6	-1,5	4,9	-11,5	13,3	-3,1	3,8	4,9
WESTKPLE	1,5	6,2	-0,1	4,2	-8,5	9,5	-15,6	0,6	15,6
EURPFM	5,2	7,5	0,0	4,3	-11,4	12,8	-18,4	0,7	18,4
VLISSGN	6,3	9,5	0,5	4,8	-8,1	9,4	-16,5	2,8	16,8
ROOMPBTN	6,6	9,4	-0,8	5,0	-12,3	12,7	-36,0	1,2	36,0
LICHTELGRE	1,7	6,6	-0,4	4,5	-9,9	11,7	-18,7	5,3	19,4

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
BROUWHVSGT08	-2,8	9,2	-1,8	5,8	-18,0	19,3	-37,9	0,9	37,9
TERNZN	9,6	12,3	0,0	5,0	-6,3	8,6	-16,4	4,7	17,1
HARVT10	2,2	6,6	-1,0	4,9	-9,2	13,2	-19,2	3,6	19,6
ROOMPBNN	7,5	9,2	-0,8	4,5	-12,9	13,2	-13,8	1,9	13,9
HANSWT	10,7	13,5	0,3	5,7	-11,2	13,0	-21,5	6,6	22,5
HOEKVHLD	2,9	7,9	-2,3	5,7	-14,7	17,3	-28,6	4,5	29,0
STAVNSE	12,8	14,0	-0,2	4,4	-7,1	7,9	-2,2	1,6	2,7
BERGSDSWT	18,5	19,5	1,1	4,8	-2,1	4,5	2,0	0,9	2,2
KRAMMSZWT	14,8	16,2	-1,9	6,0	-9,9	10,2	-4,4	4,8	6,5
SCHEVNGN	2,1	8,3	-1,3	5,5	-25,7	27,6	-35,4	7,2	36,1
IJMDBTHVN	4,0	8,8	-0,8	5,7	-14,8	16,4	-32,0	5,7	32,5
Q1	1,2	7,1	-1,4	5,7	-17,3	18,0	-26,9	5,0	27,4
DENHDR	-1,9	7,2	-0,7	5,3	-21,1	22,4	-31,1	4,8	31,5
TEXNZE	1,5	7,4	-1,7	5,4	-24,6	24,9	-35,0	0,7	35,0
K13APFM	-2,1	5,4	-0,5	4,6	-5,9	9,5	-22,3	11,5	25,2
OUDSD	1,1	6,9	-0,2	5,1	-22,1	22,9	-31,5	2,8	31,6
DENOVBTN	1,5	7,7	-0,8	5,8	-29,6	30,5	-35,5	0,3	35,5
TERSLNZE	-0,2	6,6	-1,2	5,3	-21,1	22,4	-25,2	0,1	25,2
VLIELHVN	-3,7	7,3	0,2	5,5	-19,2	19,8	-28,0	4,5	28,3
WESTTSLG	1,9	7,4	0,0	5,3	-20,1	21,2	-34,5	4,2	34,7
KORNWDZBTN	2,1	8,0	-0,6	5,9	-28,1	29,1	-37,5	0,7	37,5
WIERMGDN	0,3	6,7	-0,4	5,2	-15,5	18,0	-21,9	6,4	22,8
HUIBGT	-0,6	7,0	-0,4	5,1	-13,9	16,9	-21,2	2,0	21,3
HARLGN	0,4	7,5	-0,3	5,9	-26,1	27,5	-28,4	1,8	28,5
NES	1,8	8,8	0,2	6,5	-24,5	26,0	-43,0	2,9	43,1
LAUWOG	1,3	9,3	0,1	6,6	-29,4	30,7	-42,5	8,8	43,4
SCHIERMNOG	-0,4	14,1	0,2	8,0	-31,0	34,0	-41,1	7,9	41,9
BORKUM_Sudstrand	0,9	8,7	0,0	6,1	-24,3	25,6	-42,4	7,4	43,0
BorkumFischerbalje	3,0	8,7	0,1	5,7	-20,6	21,8	-39,2	8,0	40,0
EMSHORN	3,8	10,0	0,3	6,5	-28,4	28,9	-49,6	1,9	49,6
EEMSHVN	5,0	10,1	-0,1	6,5	-28,5	28,9	-50,8	2,3	50,8
DUKEGAT	5,0	10,5	-0,2	6,3	-27,6	27,9	-51,5	1,4	51,5
DELFZL	4,0	11,7	-0,9	7,7	-26,1	26,9	-50,6	2,8	50,7
KNOCK	1,5	10,4	-0,2	7,2	-25,3	26,3	-39,5	3,5	39,6
Average (total)	3,3	8,9	-0,5	5,5	-17,4	18,8	-27,5	3,7	28,1
Average (offshore)	1,5	6,6	-0,6	4,8	-11,1	13,0	-21,6	5,6	22,6
Average (coast)	1,7	7,2	-1,0	5,1	-14,6	16,5	-23,7	3,2	24,1

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Average (SWD)	11,5	13,5	-0,1	5,0	-8,2	9,5	-10,4	3,3	11,7
Average (WS)	1,8	9,2	-0,1	6,3	-25,7	26,7	-40,4	3,8	40,6

This appendix shows the detailed statistics underpinning Table 4.2.

Appendix table C.3: Skew surge error, 3D FM0.5NM, HARMONIE43, 20220101 - 20230101

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	2,2	6,0	-0,6	4,7	-8,7	10,1	-15,8	4,3	16,4
Bol_Van_Heist	4,1	6,8	-1,0	4,6	-9,1	10,1	-18,2	7,5	19,6
Scheur_Wielingen_ Bol_van_Knokke	3,0	6,2	-0,8	4,8	-7,0	9,6	-19,6	6,7	20,7
CADZD	1,7	6,7	-1,5	5,1	-11,7	13,5	-9,2	7,3	11,8
WESTKPLE	1,5	6,4	-0,1	4,5	-9,5	10,7	-21,3	2,8	21,5
EURPFM	5,2	7,7	0,0	4,7	-12,4	14,1	-22,9	1,7	23,0
VLISSGN	6,3	9,5	0,5	5,0	-8,9	9,4	-21,7	0,9	21,7
ROOMPBTN	6,6	9,6	-0,8	5,3	-14,1	15,0	-43,5	0,8	43,5
LICHTELGRE	1,6	6,8	-0,4	4,9	-9,0	10,3	-23,3	6,0	24,1
BROUWHVSGT08	-2,8	9,5	-1,7	6,3	-19,8	21,8	-44,7	0,9	44,7
TERNZN	9,6	12,3	0,0	5,2	-8,4	9,9	-21,1	1,7	21,2
HARVT10	2,2	6,8	-1,0	5,2	-10,4	13,9	-25,0	5,1	25,5
ROOMPBNN	7,5	9,3	-0,7	4,7	-14,8	15,4	-12,1	3,0	12,4
HANSWT	10,7	13,6	0,4	5,9	-11,5	13,1	-28,6	7,6	29,6
HOEKVHLD	2,9	8,2	-2,3	6,0	-15,6	17,6	-33,9	5,5	34,4
STAVNSE	12,7	13,9	-0,2	4,5	-7,0	9,5	-7,5	0,6	7,5
BERGSDSWT	18,4	19,4	1,1	4,9	-2,3	7,1	-2,9	0,6	2,9
KRAMMSZWT	14,7	16,1	-1,9	6,1	-8,1	11,0	-9,2	2,8	9,6
SCHEVNGN	2,2	8,5	-1,3	5,8	-26,1	27,7	-41,9	4,3	42,1
IJMDBTHVN	4,0	9,1	-0,8	6,2	-17,4	18,5	-37,8	6,7	38,3
Q1	1,1	7,5	-1,4	6,0	-19,5	20,4	-35,4	4,2	35,6
DENHDR	-1,9	7,8	-0,6	5,8	-25,7	27,7	-36,6	3,7	36,8
TEXNZE	1,5	7,9	-1,6	5,8	-27,6	28,3	-38,0	1,5	38,0
K13APFM	-2,1	5,9	-0,5	5,1	-6,4	9,5	-27,3	10,5	29,2
OUDSD	1,0	7,6	-0,1	5,7	-27,0	28,3	-35,1	4,0	35,3
DENOVBTN	1,4	8,3	-0,7	6,3	-33,0	35,0	-35,7	5,4	36,1
TERSLNZE	-0,1	7,1	-1,0	5,9	-24,7	26,9	-27,3	2,3	27,4

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
VLIELHVN	-3,8	8,0	0,2	6,0	-22,9	24,0	-33,8	3,2	33,9
WESTTSLG	1,9	7,9	0,0	5,9	-23,4	25,0	-38,0	5,8	38,4
KORNWDZBTN	2,0	8,6	-0,5	6,3	-32,3	33,7	-44,5	9,6	45,5
WIERMGDN	0,4	7,1	-0,2	5,7	-18,0	20,4	-24,2	4,9	24,7
HUIBGT	-0,5	7,3	-0,3	5,5	-17,7	20,2	-22,4	6,3	23,3
HARLGN	0,3	8,1	-0,3	6,4	-30,7	32,2	-37,1	8,5	38,0
NES	1,5	9,1	0,2	6,9	-26,8	27,6	-49,5	4,4	49,7
LAUWOG	1,2	9,5	0,1	7,0	-31,3	32,7	-42,2	12,4	44,0
SCHIERMNOG	-0,6	14,1	0,2	8,4	-33,5	36,3	-40,8	12,3	42,6
BORKUM_Sudstrand	0,9	9,1	0,1	6,6	-28,2	29,3	-44,8	10,9	46,1
BorkumFischerbalje	3,0	9,0	0,2	6,1	-24,8	25,7	-40,8	11,1	42,3
EMSHORN	3,8	10,4	0,4	7,1	-30,5	31,2	-53,6	2,0	53,6
EEMSHVN	5,0	10,5	0,0	7,1	-30,8	31,3	-54,9	2,4	54,9
DUKEGAT	4,9	10,8	-0,1	6,9	-31,1	31,4	-55,8	1,1	55,8
DELFZL	4,0	11,9	-0,8	8,1	-31,4	31,8	-56,8	2,7	56,9
KNOCK	1,4	10,7	-0,1	7,6	-30,8	31,5	-43,7	5,8	44,1
Average (total)	3,3	9,2	-0,5	5,9	-19,5	21,1	-32,0	4,9	32,6
Average (offshore)	1,5	7,0	-0,6	5,2	-11,8	13,6	-27,2	5,6	28,0
Average (coast)	1,7	7,6	-1,0	5,4	-16,5	18,2	-28,7	4,4	29,3
Average (SWD)	11,4	13,5	-0,1	5,2	-8,7	10,8	-14,7	2,5	15,0
Average (WS)	1,7	9,6	-0,1	6,8	-29,3	30,4	-44,2	6,4	44,8

D Appendix C: Skew surge error comparison HA43 with C=0.01, HA43 with C=0.025 and HA43 stress for 3D DCSM-FM 0.5nm

This appendix shows the detailed statistics underpinning Table 5.4.

Appendix table D.1: Skew surge error, 3D FM0.5NM, HARMONIE43 with C = 0.01, 20220101 - 20230101

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	2,2	6,0	-0,6	4,7	-8,7	10,1	-15,8	4,3	16,4
Bol_Van_Heist	4,1	6,8	-1,0	4,6	-9,1	10,1	-18,2	7,5	19,6
Scheur_Wielingen_ Bol_van_Knokke	3,0	6,2	-0,8	4,8	-7,0	9,6	-19,6	6,7	20,7
CADZD	1,7	6,7	-1,5	5,1	-11,7	13,5	-9,2	7,3	11,8
WESTKPLE	1,5	6,4	-0,1	4,5	-9,5	10,7	-21,3	2,8	21,5
EURPFM	5,2	7,7	0,0	4,7	-12,4	14,1	-22,9	1,7	23,0
VLISSGN	6,3	9,5	0,5	5,0	-8,9	9,4	-21,7	0,9	21,7
ROOMPBTN	6,6	9,6	-0,8	5,3	-14,1	15,0	-43,5	0,8	43,5
LICHTELGRE	1,6	6,8	-0,4	4,9	-9,0	10,3	-23,3	6,0	24,1
BROUWHVSGT08	-2,8	9,5	-1,7	6,3	-19,8	21,8	-44,7	0,9	44,7
TERNZN	9,6	12,3	0,0	5,2	-8,4	9,9	-21,1	1,7	21,2
HARVT10	2,2	6,8	-1,0	5,2	-10,4	13,9	-25,0	5,1	25,5
ROOMPBNN	7,5	9,3	-0,7	4,7	-14,8	15,4	-12,1	3,0	12,4
HANSWT	10,7	13,6	0,4	5,9	-11,5	13,1	-28,6	7,6	29,6
HOEKVHLD	2,9	8,2	-2,3	6,0	-15,6	17,6	-33,9	5,5	34,4
STAVNSE	12,7	13,9	-0,2	4,5	-7,0	9,5	-7,5	0,6	7,5
BERGSDSWT	18,4	19,4	1,1	4,9	-2,3	7,1	-2,9	0,6	2,9
KRAMMSZWT	14,7	16,1	-1,9	6,1	-8,1	11,0	-9,2	2,8	9,6
SCHEVNGN	2,2	8,5	-1,3	5,8	-26,1	27,7	-41,9	4,3	42,1
IJMDBTHVN	4,0	9,1	-0,8	6,2	-17,4	18,5	-37,8	6,7	38,3
Q1	1,1	7,5	-1,4	6,0	-19,5	20,4	-35,4	4,2	35,6
DENHDR	-1,9	7,8	-0,6	5,8	-25,7	27,7	-36,6	3,7	36,8
TEXNZE	1,5	7,9	-1,6	5,8	-27,6	28,3	-38,0	1,5	38,0
K13APFM	-2,1	5,9	-0,5	5,1	-6,4	9,5	-27,3	10,5	29,2
OUDSD	1,0	7,6	-0,1	5,7	-27,0	28,3	-35,1	4,0	35,3
DENOVBTN	1,4	8,3	-0,7	6,3	-33,0	35,0	-35,7	5,4	36,1
TERSLNZE	-0,1	7,1	-1,0	5,9	-24,7	26,9	-27,3	2,3	27,4
VLIELHVN	-3,8	8,0	0,2	6,0	-22,9	24,0	-33,8	3,2	33,9

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
WESTTSLG	1,9	7,9	0,0	5,9	-23,4	25,0	-38,0	5,8	38,4
KORNWDZBTN	2,0	8,6	-0,5	6,3	-32,3	33,7	-44,5	9,6	45,5
WIERMGDN	0,4	7,1	-0,2	5,7	-18,0	20,4	-24,2	4,9	24,7
HUIBGT	-0,5	7,3	-0,3	5,5	-17,7	20,2	-22,4	6,3	23,3
HARLGN	0,3	8,1	-0,3	6,4	-30,7	32,2	-37,1	8,5	38,0
NES	1,5	9,1	0,2	6,9	-26,8	27,6	-49,5	4,4	49,7
LAUWOG	1,2	9,5	0,1	7,0	-31,3	32,7	-42,2	12,4	44,0
SCHIERMNOG	-0,6	14,1	0,2	8,4	-33,5	36,3	-40,8	12,3	42,6
BORKUM_Sudstrand	0,9	9,1	0,1	6,6	-28,2	29,3	-44,8	10,9	46,1
BorkumFischerbalje	3,0	9,0	0,2	6,1	-24,8	25,7	-40,8	11,1	42,3
EMSHORN	3,8	10,4	0,4	7,1	-30,5	31,2	-53,6	2,0	53,6
EEMSHVN	5,0	10,5	0,0	7,1	-30,8	31,3	-54,9	2,4	54,9
DUKEGAT	4,9	10,8	-0,1	6,9	-31,1	31,4	-55,8	1,1	55,8
DELFZL	4,0	11,9	-0,8	8,1	-31,4	31,8	-56,8	2,7	56,9
KNOCK	1,4	10,7	-0,1	7,6	-30,8	31,5	-43,7	5,8	44,1
Average (total)	3,3	9,2	-0,5	5,9	-19,5	21,1	-32,0	4,9	32,6
Average (offshore)	1,5	7,0	-0,6	5,2	-11,8	13,6	-27,2	5,6	28,0
Average (coast)	1,7	7,6	-1,0	5,4	-16,5	18,2	-28,7	4,4	29,3
Average (SWD)	11,4	13,5	-0,1	5,2	-8,7	10,8	-14,7	2,5	15,0
Average (WS)	1,7	9,6	-0,1	6,8	-29,3	30,4	-44,2	6,4	44,8

This appendix shows the detailed statistics underpinning Table 5.4.

Appendix table D.2: Skew surge error, 3D FM0.5NM, HARMONIE43 with C = 0.025, 20220101 - 20230101

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	1,3	4,8	-0,7	3,9	0,6	5,7	0,9	5,9	6,0
Bol_Van_Heist	3,2	5,4	-1,1	3,8	0,4	4,3	-0,9	8,7	8,7
Scheur_Wielingen_Bol_van_Knokke	2,0	4,8	-0,8	3,9	3,5	7,2	-2,2	7,6	7,9
CADZD	0,8	6,3	-1,5	5,2	-2,1	6,7	8,5	7,9	11,6
WESTKPLE	0,6	5,2	-0,1	3,7	1,1	7,1	-5,9	0,7	6,0
EURPFM	4,6	6,5	-0,1	3,7	-3,4	8,0	-2,9	2,8	4,1
VLISSGN	5,3	8,3	0,5	4,5	1,9	6,8	-5,8	0,9	5,9
ROOMPBTN	5,8	8,0	-0,8	4,2	-1,5	6,5	-25,1	3,6	25,3
LICHTELGRE	0,9	5,7	-0,4	4,1	0,6	6,4	-6,0	9,9	11,6

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
BROUWHVSGT08	-3,7	8,4	-1,8	5,2	-7,6	12,7	-26,0	2,7	26,1
TERNZN	8,6	11,1	-0,1	4,7	3,1	8,5	-4,3	2,6	5,0
HARVT10	1,4	5,7	-1,0	4,4	0,6	9,0	-5,1	5,4	7,4
ROOMPBNN	7,0	8,3	-0,9	4,0	-3,2	5,1	7,2	0,0	7,2
HANSWT	9,8	12,4	0,3	5,4	1,1	9,7	-6,8	8,3	10,7
HOEKVHLD	2,2	7,1	-2,3	5,5	-2,9	9,0	-16,3	8,6	18,4
STAVNSE	12,2	13,4	-0,3	4,2	5,5	9,5	12,0	4,0	12,6
BERGSDSWT	17,6	18,7	1,0	4,8	10,1	13,0	16,8	3,9	17,3
KRAMMSZWT	14,2	15,7	-1,9	6,2	4,0	9,6	10,0	0,1	10,0
SCHEVNGN	1,6	7,1	-1,3	5,0	-13,2	16,2	-23,9	1,3	23,9
IJMDBTHVN	3,4	7,7	-0,7	5,1	-6,0	8,1	-17,7	9,2	20,0
Q1	1,2	5,7	-0,9	4,9	-8,5	10,5	-13,8	0,7	13,8
DENHDR	-1,9	5,5	-0,5	4,2	-11,5	15,3	-13,3	0,6	13,3
TEXNZE	1,4	6,2	-1,4	4,8	-14,4	15,8	-15,7	1,1	15,7
K13APFM	-2,1	4,5	-0,5	4,2	1,8	7,0	-8,9	4,3	9,9
OUDSD	0,9	5,3	-0,1	4,1	-12,4	14,9	-10,7	0,6	10,7
DENOVBTN	1,3	5,6	-0,7	4,5	-15,8	19,3	-8,6	3,2	9,2
TERSLNZE	-0,6	5,3	-1,1	4,6	-13,0	17,0	-6,6	2,1	6,9
VLIELHVN	-4,2	6,6	0,1	4,7	-11,1	12,8	-12,6	1,6	12,7
WESTTSLG	1,6	5,9	-0,1	4,6	-10,8	13,9	-15,6	1,2	15,7
KORNWDZBTN	1,7	6,0	-0,5	4,7	-12,4	14,5	-20,3	10,6	22,9
WIERMGDN	-0,2	5,1	-0,3	4,2	-5,3	11,4	-3,3	11,2	11,6
HUIBGT	-1,3	5,8	-0,4	4,4	-5,3	11,1	3,7	4,5	5,8
HARLGN	-0,1	6,2	-0,3	5,5	-12,3	14,3	-12,3	8,3	14,9
NES	1,0	6,8	0,2	5,3	-12,6	14,3	-26,7	8,5	28,1
LAUWOG	0,6	7,1	0,1	5,3	-17,5	19,6	-14,4	11,3	18,3
SCHIERMNOG	-1,2	12,5	0,2	6,8	-20,3	24,4	-14,4	11,6	18,5
BORKUM_Sudstrand	0,0	6,6	0,0	4,8	-15,4	17,0	-17,5	9,6	20,0
BorkumFischerbalje	2,1	6,7	0,1	4,7	-11,6	13,5	-12,8	9,7	16,1
EMSHORN	2,9	7,4	0,3	4,9	-14,3	16,9	-27,6	3,4	27,8
EEMSHVN	4,0	7,8	-0,1	5,2	-14,4	17,1	-28,9	3,1	29,1
DUKEGAT	4,0	8,1	-0,2	5,0	-14,7	17,3	-27,9	6,7	28,7
DELFZL	3,3	9,1	-0,9	6,2	-13,3	15,2	-26,9	9,6	28,6
KNOCK	0,7	8,0	-0,1	5,7	-14,2	16,3	-9,0	3,6	9,7
Average (total)	2,6	7,5	-0,5	4,8	-6,7	12,1	-10,2	5,1	14,7
Average (offshore)	1,1	5,6	-0,5	4,2	-2,4	8,0	-7,9	4,4	9,8
Average (coast)	1,0	6,1	-1,0	4,5	-4,8	10,2	-9,3	5,1	13,4

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Average (SWD)	10,7	12,6	-0,2	4,8	3,2	8,9	4,2	2,8	9,8
Average (WS)	1,2	7,2	-0,1	5,1	-14,0	16,3	-17,9	6,4	19,4

This appendix shows the detailed statistics underpinning Table 5.4.

Appendix table D.3: Skew surge error, 3D FM0.5NM, HARMONIE43 stress, 20220101 - 20230101

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
Wandelaar	1,9	5,1	-0,7	4,0	-2,6	5,6	-2,0	3,4	3,9
Bol_Van_Heist	3,8	5,9	-1,1	3,9	-2,8	5,0	-4,0	6,2	7,4
Scheur_Wielingen_ Bol_van_Knokke	2,6	5,2	-0,9	4,1	0,8	5,8	-5,2	5,3	7,4
CADZD	1,4	6,2	-1,6	4,8	-5,3	8,8	5,3	5,7	7,8
WESTKPLE	1,2	5,5	-0,1	3,8	-2,5	6,7	-7,1	0,0	7,1
EURPFM	4,9	6,9	-0,1	4,0	-6,2	9,3	-5,0	0,0	5,0
VLISSGN	5,9	8,8	0,4	4,4	-1,9	6,0	-6,8	1,8	7,1
ROOMPBTN	6,3	8,6	-0,9	4,5	-5,5	8,0	-26,2	4,7	26,6
LICHTELGRE	1,4	6,0	-0,4	4,3	-2,9	7,0	-9,7	8,4	12,9
BROUWHVSGT08	-3,1	8,6	-1,8	5,6	-11,7	15,5	-26,9	3,9	27,2
TERNZN	9,3	11,6	-0,1	4,7	-1,4	7,5	-5,8	2,9	6,5
HARVT10	1,9	5,9	-1,1	4,6	-2,8	9,7	-7,5	2,6	8,0
ROOMPBNN	7,3	8,7	-0,8	4,1	-7,2	8,1	0,9	0,6	1,1
HANSWT	10,4	12,9	0,4	5,4	-3,6	9,2	-9,5	9,3	13,3
HOEKVHLD	2,6	7,3	-2,4	5,6	-7,6	11,4	-17,1	9,9	19,7
STAVNSE	12,5	13,6	-0,2	4,0	0,3	7,0	7,2	1,5	7,4
BERGSDSWT	18,1	19,0	1,0	4,5	5,0	8,6	11,4	1,2	11,4
KRAMMSZWT	14,5	15,8	-2,0	5,9	-0,5	8,1	5,7	1,9	6,0
SCHEVNGN	2,0	7,5	-1,4	5,2	-17,4	19,9	-24,5	0,3	24,5
IJMDBTHVN	3,8	8,2	-0,8	5,5	-9,5	11,4	-20,1	6,4	21,1
Q1	1,3	6,1	-1,2	5,2	-10,4	11,5	-15,2	0,0	15,2
DENHDR	-1,8	6,1	-0,6	4,8	-14,1	16,2	-16,4	2,1	16,5
TEXNZE	1,6	6,5	-1,6	5,0	-16,8	18,1	-17,6	0,7	17,6
K13APFM	-2,1	4,8	-0,5	4,3	-0,8	7,4	-10,2	4,4	11,1
OUDSD	1,0	5,9	-0,2	4,6	-15,3	16,7	-13,9	2,1	14,0
DENOVBTN	1,4	6,4	-0,8	5,1	-19,3	21,7	-13,1	4,9	13,9
TERSLNZE	-0,2	5,7	-1,1	4,9	-15,1	17,8	-8,7	2,0	9,0

	Total HW error		Skew surge (high water)						
	All HWs		<99.0% skew surges		99.0% - 99.8% skew surges		>99.8% skew surges		
	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	RMSE [cm]	bias [cm]	std [cm]	RMSE [cm]
VLIELHVN	-3,9	6,6	0,1	5,0	-12,9	13,5	-14,5	1,0	14,5
WESTTSLG	1,8	6,3	-0,1	4,8	-12,6	15,2	-17,2	1,9	17,3
KORNWDZBTN	2,0	6,6	-0,6	5,1	-17,5	18,9	-18,5	7,2	19,8
WIERMGDN	0,3	5,5	-0,3	4,6	-7,4	11,2	-5,3	11,2	12,4
HUIBGT	-0,8	5,9	-0,4	4,6	-7,7	11,9	1,2	4,1	4,3
HARLGN	0,3	6,3	-0,3	5,5	-16,6	17,8	-10,3	4,9	11,4
NES	1,4	7,3	0,2	5,8	-15,2	16,2	-25,9	5,8	26,5
LAUWOG	1,0	7,8	0,0	5,9	-20,1	21,3	-17,6	11,2	20,8
SCHIERMNOG	-0,8	12,9	0,2	7,4	-22,1	24,8	-16,9	11,1	20,2
BORKUM_Sudstrand	0,6	7,2	0,0	5,3	-17,8	18,5	-20,8	9,4	22,9
BorkumFischerbalje	2,7	7,3	0,1	5,0	-14,3	15,5	-16,2	9,9	19,0
EMSHORN	3,5	8,4	0,3	5,7	-18,7	20,4	-28,2	0,5	28,2
EEMSHVN	4,7	8,7	-0,1	5,8	-18,7	20,6	-29,2	0,9	29,2
DUKEGAT	4,7	9,0	-0,2	5,7	-19,3	21,1	-28,7	2,2	28,8
DELFZL	3,8	10,1	-0,9	6,9	-18,8	20,3	-28,2	3,9	28,5
KNOCK	1,2	8,9	-0,1	6,5	-17,5	19,6	-16,0	3,8	16,5
Average (total)	3,1	8,0	-0,5	5,0	-10,1	13,4	-12,4	4,2	15,1
Average (offshore)	1,4	5,9	-0,6	4,5	-5,1	8,8	-10,0	3,2	11,1
Average (coast)	1,5	6,5	-1,0	4,7	-8,0	11,4	-11,4	4,3	13,8
Average (SWD)	11,2	12,9	-0,2	4,7	-1,3	7,8	0,4	2,8	7,5
Average (WS)	1,6	7,9	-0,2	5,6	-17,3	18,9	-19,7	5,0	20,7

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