Effect of Ems sperrwerk on surge level in Eems-Dollard estuary

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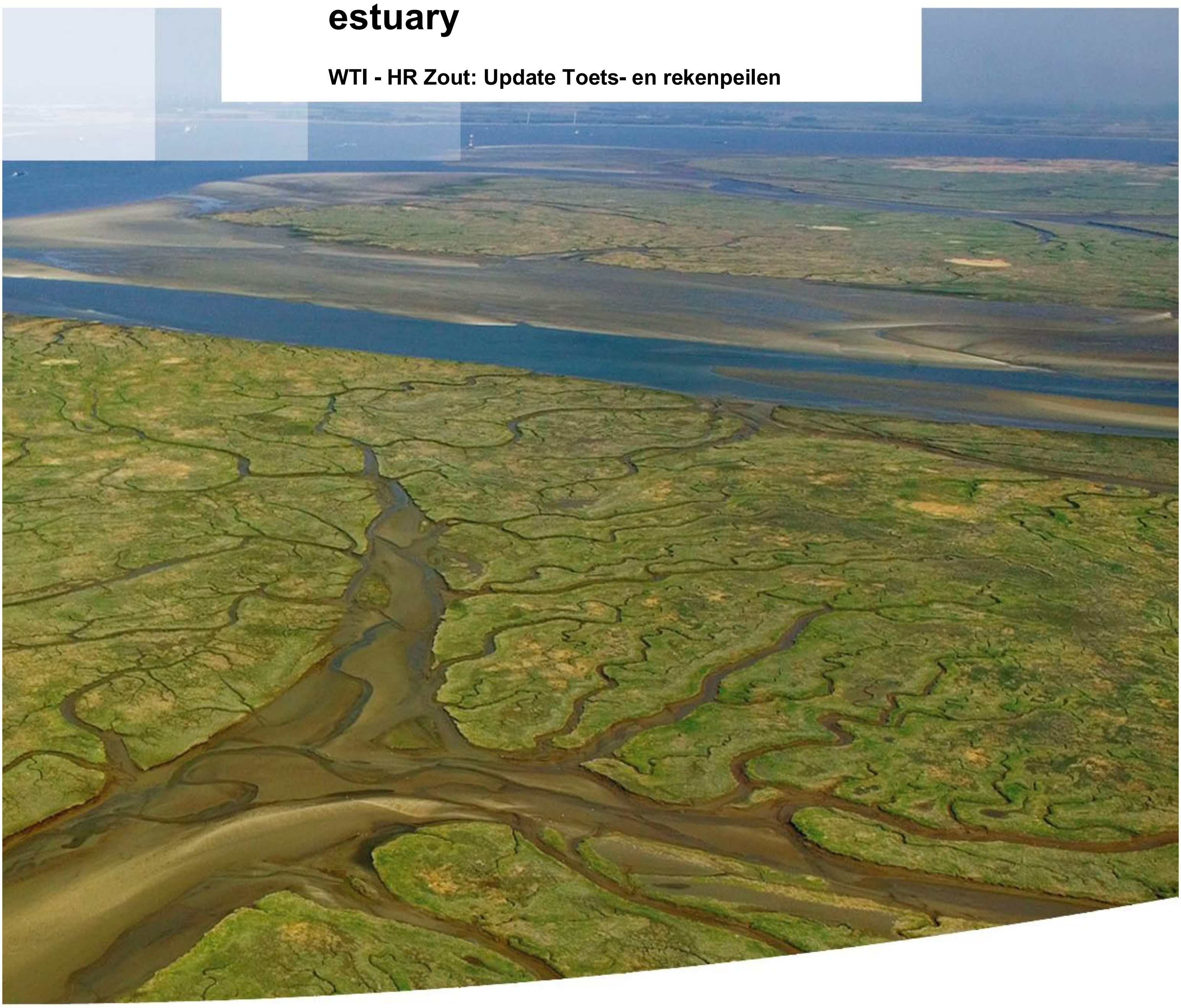

Deltares

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WTI - HR Zout: Update Toets- en rekenpeilen

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1202341-002

Deltares

Title
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Client	Project	Reference	Pages
RWS - Waterdienst	1202341-002	1202341-002-HYE-0034	59

Keywords
Storm surge; Surge barrier; Ems Sperrwerk; Ems river; Eems Dollard; Eemshaven; Delfzijl; Nieuw Statenzijl

Summary
In the context of the WTI program, this report aimed at quantifying the effect of closing the Ems surge barrier ("Ems Sperrwerk") during storms on peak storm water levels in the Eems-Dollard estuary in the northern part of the Netherlands, and near Delzijl in particular. Until now the effect of this barrier (which became effective in 2002) has not been taken into account in the determination of the hydraulic boundary conditions.

A recent study of BAW (2007) indicated that this effect was to increase peak water levels at Delfzijl by 0.15 or 0.20 m during the "Allerheiligen" storm of Nov. 1, 2006 (depending on how the barrier was closed), whereas a previous study at RIKZ (2007) indicated this difference to be only 0.08 m. Here we investigate this discrepancy, by performing a detailed hindcast of this storm.

In the process we have improved the Kuststrook-fijn model used in operational forecast. The new model schematization yields Δ=13.8±0.7 cm at Delfzijl, which is consistent with the results of BAW (2007) for a "closing" barrier. At Nieuwe Statenzijl, the new model schematization yields Δ=19.4±1.4 cm. Other storms which led to the closing of the barrier were selected and intensified to surpass design levels, in increasing steps. This allowed a study of closed-open differences for varying storm types and intensities.

The results of the present study have been applied by Dillingh and Rego (2010), who determined hydraulic boundary conditions along the entire Dutch coast, including the Eems-Dollard estuary.

References
Projectplan WTI – HRZout 2010 (1202341-002-HYE)

Version	Date	Author	Initials	Review	Initials	Approval	Initials
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6	08-07-2010	João de Lima Rego Douwe Dillingh		John de Ronde		Marcel van Gent	
8	09-11-2010	João de Lima Rego Douwe Dillingh		John de Ronde		Marcel van Gent	

State
final

Contents

1 Introduction

1.1 Background

In the framework of the “Wettelijk Toetsinstrumentarium” program (WTI), the Hydraulic Boundary Conditions at the water defences along the Dutch coast are calculated to test the safety and sufficiency of these defences. The Water Act of 2009 demands that every six years the water defences be tested so as to give insight into the actual safety of the primary water defences and to provide a basis for initiating reinforcements if necessary.

Part of the WTI program (“legal set of tools for assessment of the water defences” in a rough translation; see also Groeneweg, 2010) are the hydraulic boundary condition for the tidal waters. Besides the adaptation of the design levels, derived for the situation in 1985, to sea level rise and tidal changes, one has to consider the effect of anthropogenic interventions such as the building of storm surge barriers. The Ems surge barrier (“Ems Sperrwerk”) in the River Ems, which flows out into the Eems Dollard estuary in Germany, is such a barrier and became effective in 2002. The recent study of BAW (2007) indicated that this difference was 0.15 or 0.20 m during the “Allerheiligenvloed” of 1 Nov. 2006 (with a closed and closing barrier, respectively), whereas a previous study at RIKZ (2007) indicated this difference to be only 0.08 m. Until now the effect of this barrier has not been taken into account in the hydraulic boundary conditions.

1.2 Aim

This project aimed at analyzing and quantifying the effect of closing the Ems surge barrier during storms on peak water levels in the Eems Dollard estuary, in the northern part of the Netherlands, and near Delfzijl in particular. In the process we have improved the Kuststrook-fijn model used in operational forecast.

1.3 Approach

The current investigation consisted of the following steps:

- Improving the current model used for surge forecasting along the Dutch coast, the “Kuststrook-fijn.”
- Improving the earlier schematization of the “Allerheiligenvloed” storm (of 1 Nov. 2006) by including better data and by considering the differences to the German report.
- Determining which other storm events led to the closing of the barrier (put to operation in 2002) and use the improved Ems model to represent those as well.
- Taking those 4 recent storms and intensifying them to surpass dyke design levels, in increasing steps, and examine closed-open differences for varying storm types and intensities.
- Developing relationships of closed-open differences as function of types and intensity of storms (and expectedly different from location to location).

The findings of this report (quantification of the closed-open differences along the northern Dutch coast) will allow the updating of hydraulic boundary conditions, very important in other studies.

2 Hindcast of the "Allerheiligenvloed" (storm of Nov. 1st 2006)

The "All Saints storm" ("Allerheiligenvloed" to the Rijkswaterstaat) produced one of the highest highwaters of recent years along the Ems estuary. On November 1st, 2006, water levels reached 5.49 m NAP at the Ems Sperrwerk and at Delfzijl the highwater mark reached 4.83 m NAP.

Because it was such an intense storm, because of the available data for validation, and because of the discrepancy among earlier studies as to what the surge would have been without the closing of the Ems surge barrier (see section 2.2), this event proved to be a good case-study for this investigation.

In Chapter 3 we extend our analysis to other storms and in Chapter 4 we determine a general "correction" to account for the effect of closing the Ems surge barrier ("Ems Sperrwerk") during storms. This correction varies from location to location (i.e. Eemshaven, Delfzijl, Nieuwe Statenzijl). The range of storms to which it should be applied was also determined.

2.1 Model setup

The hydrodynamics in the Ems estuary were determined by applying a section of the Kuststrook-Fijn model covering this estuary (Figure 2.1; henceforth "KSF-Ems"). The KSF-Ems grid has a size of 199×255 ($M_{max} \times N_{max}$) and was run in the depth-averaged (2-D) mode with a time step of 1 minute. The output consists of water level and current fields.

The input to each hindcast simulation with the KSF-Ems model consists of time-varying but spatially uniform wind (MATROOS, 2010), and an open boundary condition with tide and surge level. This was also obtained from MATROOS still in 2007, as this database stores maps of forecast results only for up to one year. They are produced by a cascade of models: the Dutch Continental Shelf Model ("DCSM"), the Zuidelijke Noordzee ("ZUNO"), and the Kuststrook-fijn (KSF), which are run using time varying and spatially varying wind. The *starting* model setup was obtained from an earlier study by M. Verlaan, in the context of RIKZ, 2007) (see next section).

Figure 2.2 shows the entire grid of the Kuststrook-Fijn model version 4 (henceforth "KSF4"), which covers the entire nearshore of The Netherlands (and parts of Belgium to the South and of Germany to the North) extending 50-70 km offshore. The inset shows the extent of the KSF-Ems grid (a sub-section of KSF4). These two models had a time step of 1 minute.

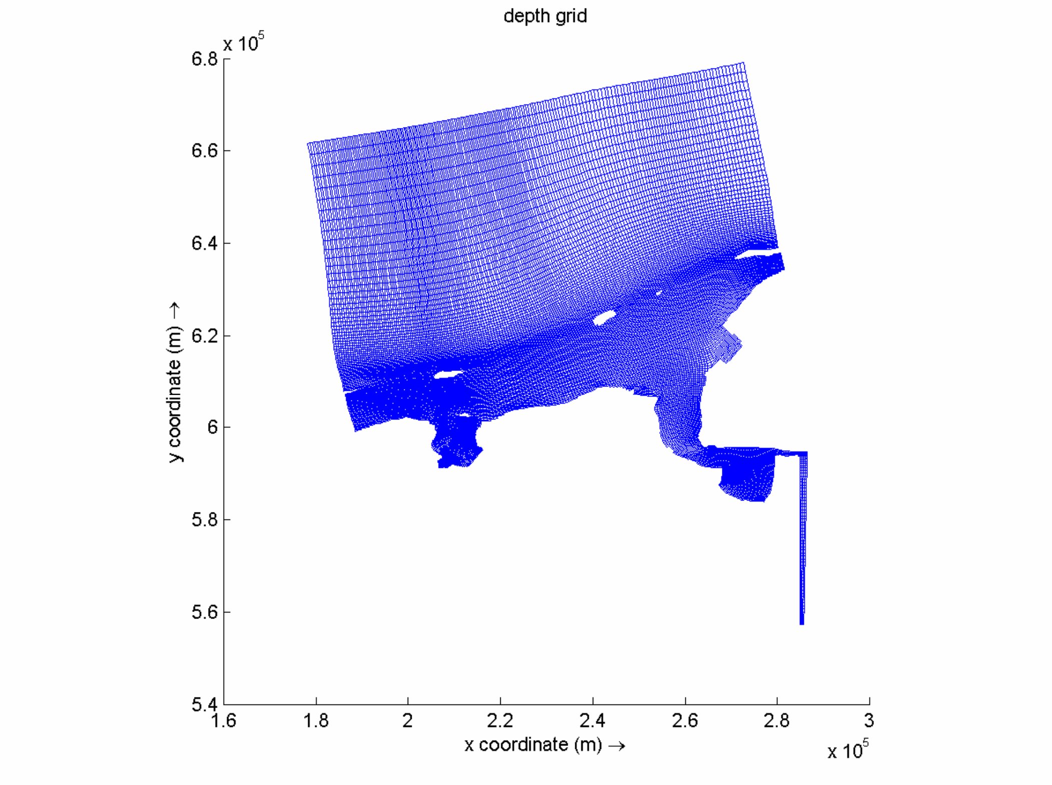

Figure 2.1 *Grid of the Ems estuary model (M_{max} =199, N_{max}=255).*

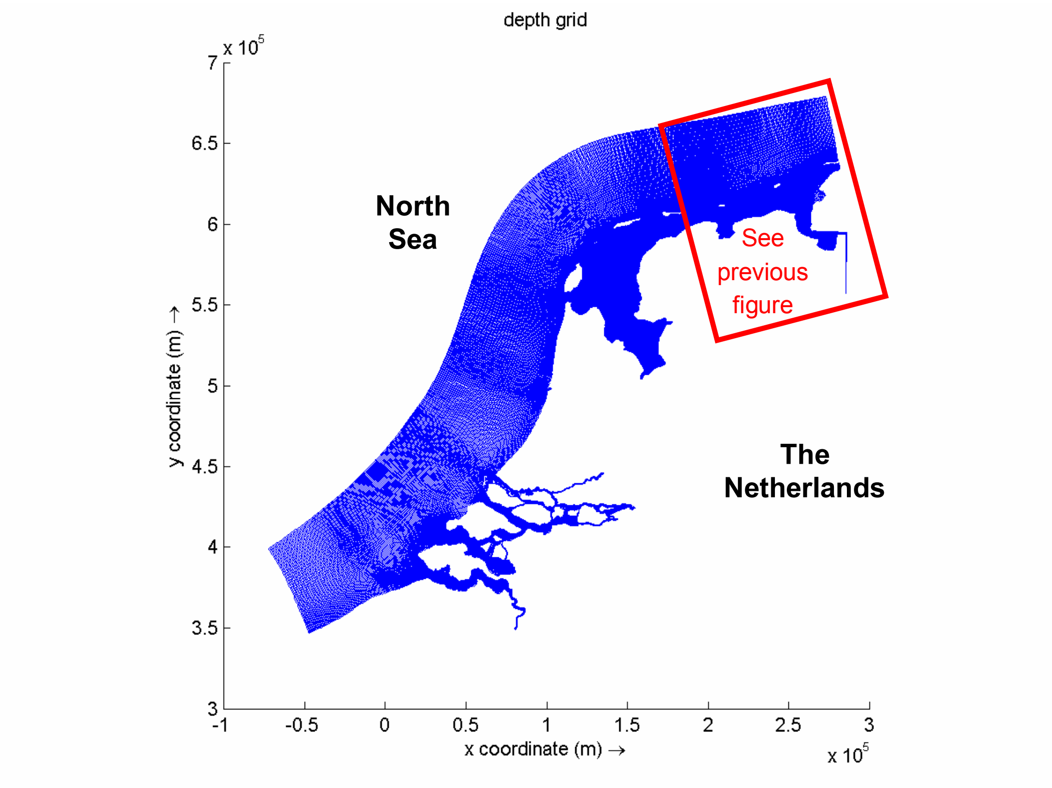

Figure 2.2 *The Kuststrook-fijn model grid (M_{max}= 942, N_{max} = 402).*

The updated version of KSF4 was set up and validated using the most recent available bathymetric data. A description of this model and the results of the validation simulations are given in Spee and Vatvani (2009).

The River Ems discharge was not included in these simulations. Typically it enters the Kuststrook-fijn model as an average discharge of 80 m^3/s. This is an insignificant amount compared to the surge-induced flows through the barrier (see Figure 3.5 - Figure 3.8), and we did not have access to the actual discharge records during these storms – hence River Ems discharges were not included.

2.2 Improvements to the earlier models

The BAW (2007) study applied two models to study the “Allerheiligenvloed” storm surge event: UnTRIM2D with about 214 thousand cells (sides of 3-1000 m) and TRIM-2D with about 6.448 million cells (sides of 15 m). The combined results (from both models), rounded to 5 cm increments, are listed on Table 2.1, for different locations.

Table 2.1 Summary of BAW (2007) results (p. 47). Differences between highwater of closed – open barrier simulations (shown in cm).

	Closing at +3.5 NN	Barrier always closed
Near the Ems barrier	30-50	30-35
Near Pogum	20-30	20-30
In mid-Dollard	20-35	25-30
At Emden (tide gauge)	25	30
At Delfzijl (tide gauge)	15	20

An earlier study (M. Verlaan, *unpublished*, in the context of RIKZ, 2007) concluded that this difference was about 8 cm at Delfzijl. That study modeled the same storm, using the Kuststrook-fijn model with a permanently closed barrier (i.e. placing a “thin dam” at the barrier location). A similar recent investigation, using KSF4 for other storms, in the context of Rego and Dillingh (2010), yielded a comparable conclusion: having a closed Ems barrier river produced higher peak water levels at Delfzijl of about 4-6 cm, depending on the storm (*unpublished results*).

Focusing on the barrier effect at Delfzijl, the values obtained from BAW’s (2007) recent detailed study (15, 20 cm) are thus considerably different than those simplified studies using the Kuststrook-fijn model (8, 4-6 cm). Examining this discrepancy is the main goal of this chapter: i.e. to identify and quantify the contribution of each improvement to the Kuststrook-fijn model.

But the study of BAW (2007) is also not “perfect”, as it did not include the Delfzijl breakwater properly (i.e. overtopping was not allowed), and it is not comprehensive, as it only simulated the effect of one storm.

Table 2.2 Summary of seven improvements to the earlier KSF-Ems model and comparison to the similar BAW (2007) modelling study.

	M. Verlaan (*unpublished*) for RIKZ (2007)	**BAW (2007)**
Grid schematization of River Ems	very coarse	detailed
Depth schematization of River Ems	very simple	detailed
Delfzijl breakwater	not included	included, but as thin dam
Thin dam at Termunterzijl	exagerated length	--
Shallows in northern Dollard	missing	included
“Closing” vs. “closed” barrier	only “closed”	“closed” & “closing”
Location of Delfzijl tide gauge	slightly incorrect	?
Amount of model cells (×10^6)	0.051	6.5

2.2.1 Grid schematization of the River Ems

An obvious weakness in the KSF4 (and KSF-Ems) schematization is that the River Ems is poorly represented. This is not an issue under most circumstances – especially when forecasting storm events, as in these situations the Ems barrier is closed. The Kuststrook-fijn is used for operational surge forecasting and investing many grid cells in this section of the river would be computationally wasteful.

The staff at BAW kindly provided to us a Delft3D model of the Ems Estuary from the North Sea to the weir of Herbrum (henceforth “BAWd3d”) with very detailed bathymetry along the River Ems (email to M. Verlaan on 2 Mar 2010, from Mr. J. Jürges with Bundesanstalt für Wasserbau, Dienststelle Hamburg). We used this to improve our KSF4 model. The BAWd3d model had dimensions M_{max}= 586, N_{max}= 113 and is shown on Figure 2.3.

Figure 2.4 contains the very detailed, very fine grid from BAWd3d against the Kuststrook-fijn’s. Comparing only the River Ems part of each model: KSF4 has a size of 62x17 cells, whereas BAWd3d model is 377x104. The latter is thus 37.2 times larger than the former.

Such detail is not needed (or wanted) in an operational model, but if one is to compare closed-barrier to open-barrier results, one needs to capture the main hydrodynamics of the open-barrier situation as well. BAWd3d was used to improve the River Ems part of KSF4.

With a much coarser horizontal representation, the Kuststrook-fijn model should still be able to capture the “real” elevation-to-volume relation, if one considers the River Ems behind the barrier as a reservoir. Figure 2.5 compares the hypsometry curves of the 3 schematizations: the detailed BAWd3d, the KSF4 (Kuststrook-fijn version 4), and the KSFst (KSF4 with “stretched” River Ems and artificial depths).

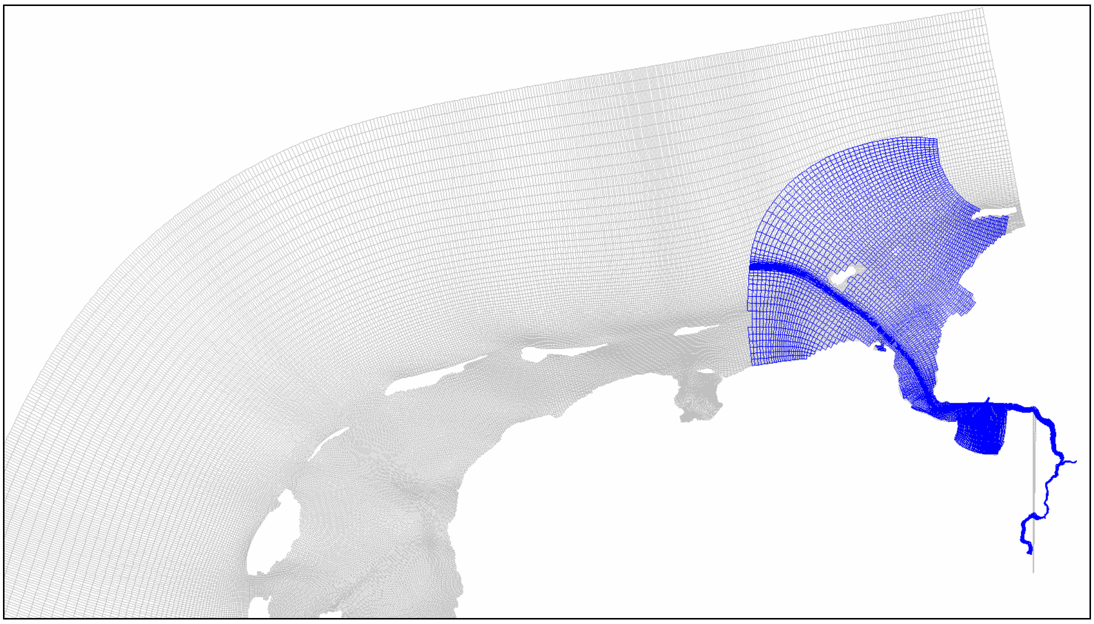

Figure 2.3 *The BAWd3d model grid overlayed on the eastern part of the Kuststrook-fijn's.*

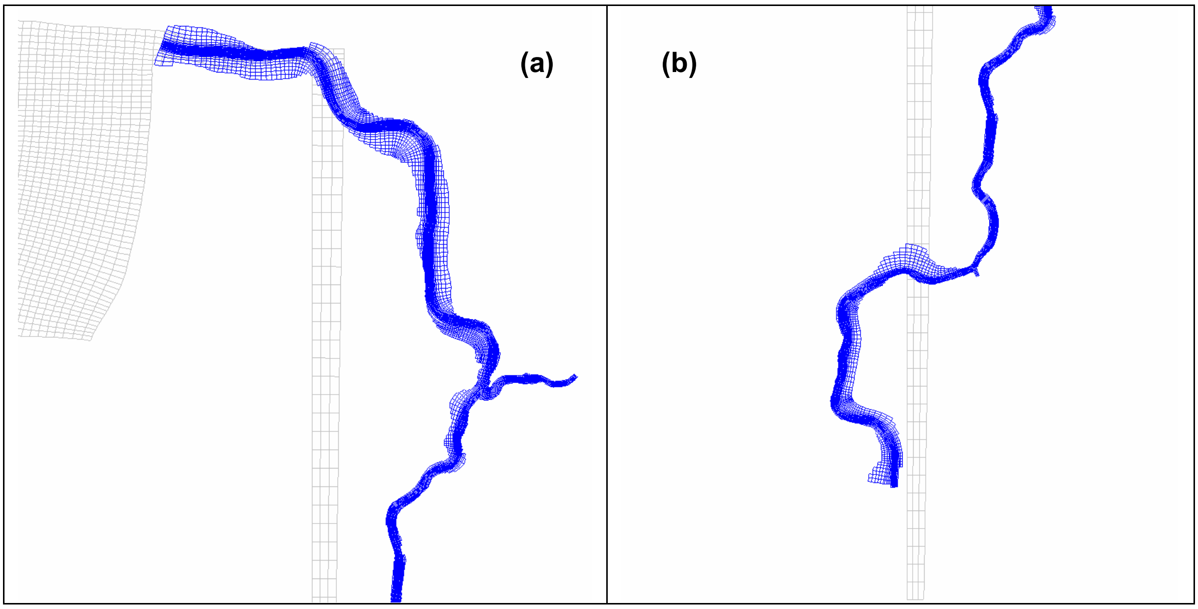

Figure 2.4 *The BAWd3d model grid overlayed on the eastern part of the original Kuststrook-fijn grid: a) northern/downstream section, b) southern/upstream section. Only the River Ems part of BAWd3d is shown here, for clarity.*

The original KSF4 grid and depth schematization is a coarse approximation of the River Ems. Its length represents only a rough distance to the "next" barrier upstream, and its width the approximate width of the main channel. Central cells (Figure 2.4) were assigned representative depths (from 5 m downstream to 4 m upstream, below NAP). The lateral cells were all set to 2 m below NAP.

These shortcomings led to the great mismatch of Figure 2.5. At Mean Sea Level (~NAP), both blue and red curves yield a similar wet area: ~16 ×10^6 m^2. But the blue line – representing the original KSF4 grid – does not extend any further. It entirely misses the floodplain at about 2 m above NAP. In fact, for a water level 5 m above MSL (the Allerheiligen storm registered a highwater 4.49 m above NAP at the Ems Barrier), the “real” river will flood an area of about 36 ×10^6 m^2 (Figure 2.5). This is a large difference that, when incorporated in the Kuststrook-fijn model, is expected to improve results considerably (for the hypothetical open barrier situation). Figure 2.6 shows the bathymetry in the focus area, including the flood-prone banks along the River Ems, at about 2 m above NAP.

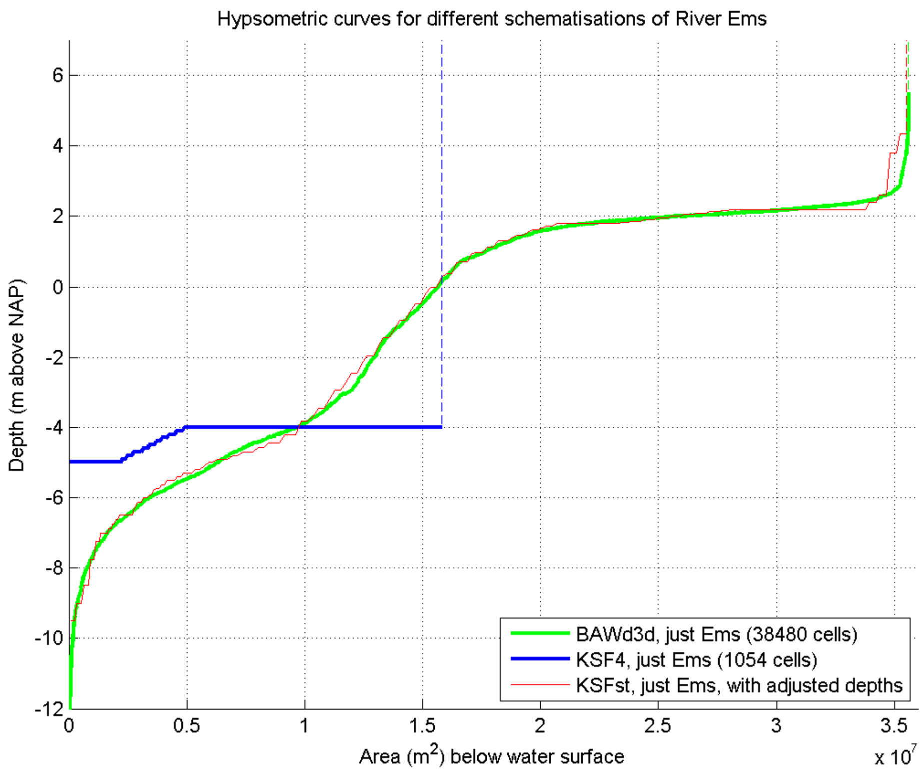

Figure 2.5 *Curves showing how the original Kuststrook-fijn model (blue line) compares to the hypsometry of the BAWd3d detailed model (green line). Red line show the hypsometry obtained with the stretched grid, KSFst (and adjusted model depths).*

The first step was to change the KSF4 grid until it reached the same wet area as BAWd3d for a water level of 5.5 m above NAP. Figure 2.7 illustrates the “stretching” of the KSF-Ems (very simplified) grid representing the River Ems, creating the KSFst grid. More complex changes to our grid were deliberately avoided (such as adjusting to the bending of the river or adding more grid cells), as our goal was to correctly represent open barrier conditions using a model as close to the one operationally used for these forecasts (KSF4).

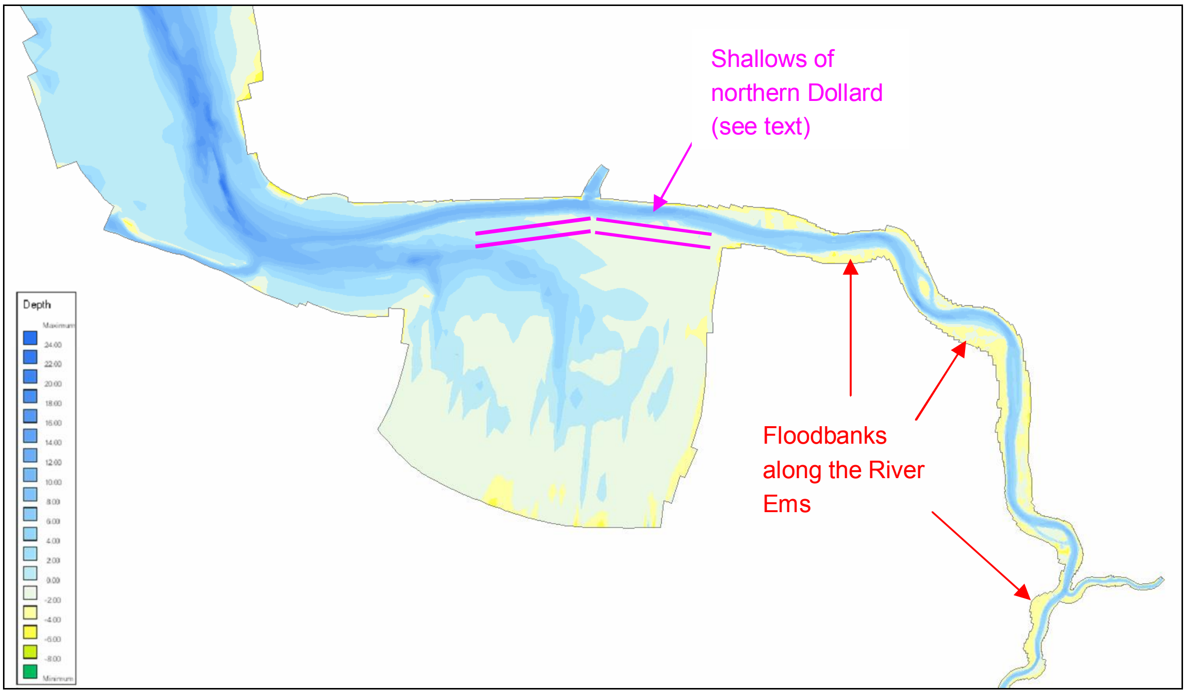

Figure 2.6 Bathymetry of the Delfzijl region, of the Dollard and of lower River Ems (shown here in the detailed BAWd3d schematization).

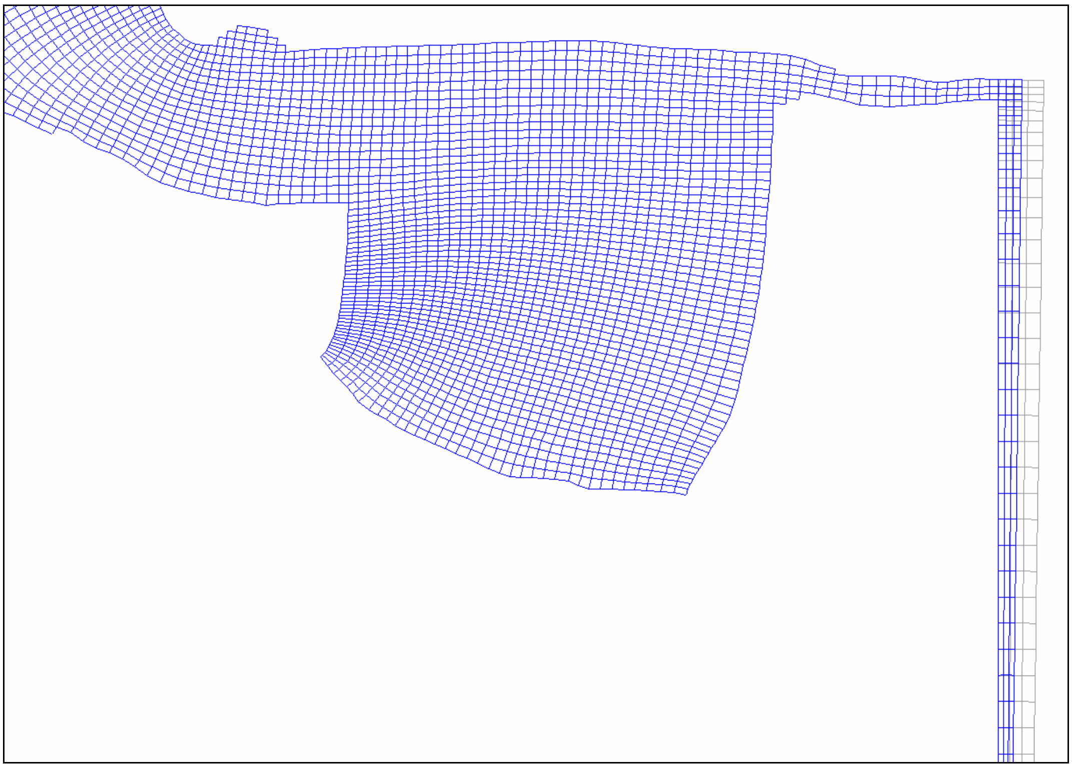

Figure 2.7 The original Kuststrook-fijn grid (blue) overlayed on the “KSFst” grid (grey).

2.2.2 Depth schematization of the River Ems

The next step was to change the depth information in the "stretched" KSF4, insuring that its hypsometry follows the more detailed curve of BAWd3d closely for all intermediate depths/areas (and not just at the MSL and +5.5 m levels). Starting with an educated guess and proceeding with trial and error iterations, a depth scheme was determined which is a good match with the "real" hypsometry (red curve in Figure 2.5), thus creating the bathymetry for the "KSFst" model.

This is still a very simple depth scheme, as the grid resolution was not improved. In the KSFst bathymetry, depth decreases monotonically from the barrier to the upstream end (not linearly; see Figure 2.5) but there is no cross-channel variation. In this sense, the new scheme is less realistic than previously. The goal was to better represent the effect of closing the Ems barrier on its seaward side.

2.2.3 Delfzijl breakwater

The original KSF-Ems model did not include the breakwater along Delfzijl harbor. The BAW (2007) model did include this breakwater, but as a "thin dam" of infinite height. Because the breakwater at Delfzijl is known to overtop during stronger storms, having a very high wall in the model will add error to the water level calculations behind the breakwater. This was the main weakness in their application.

The improved KSFst model included both versions, a very high breakwater (9 m above NAP all along) and a realistic, overtoppable breakwater (heights between 3.6 and 6 m above NAP). Simulating both cases allowed for partial estimates of these effects.

To obtain representative elevations to correctly model the breakwater, data was used from Groningen Seaports (2008) and from AHN (2010). It was noticed that elevations decreased sharply halfway along this structure, and we investigated this change during the May 28th visit to Delfzijl. Table 2.3 lists the geographical information of this decrease in elevation, which we found to be realistic.

Table 2.3 Relevant GPS data obtained on the visit to Delfzijl (May 28, 2010). Geographic data is referenced to WGS 84; projected data is referenced to Amersfoort / RD New.

	Delfzijl gauge	**Breakwater (high)**	**Breakwater (low)**
Latitude (º)	53.32657	53.32412	53.32393
Longitude (º)	6.93334	6.95404	6.95497
X (m)	258013.8	259399.1	259461.1
Y (m)	594453.9	594211.8	594191.7

A large difference in height was confirmed over a distance of only 65 m. About 2/3 of the length of the breakwater (near the harbor entrance) is considerably lower than the “upper” part. The former is 4.3-4.5 m above NAP, whereas the latter is 6.0 m above NAP. This is an important difference, as highwater during storm Allerheiligen was 4.83 m above NAP, meaning that overtopping occurred where the breakwater is lower. Table 2.4 shows how the spatial and vertical data available was used to include the Delfzijl breakwater in the KSFst model (see also Figure 2.19 and Figure 2.20). Figure 2.8 explains the terminology used.

Table 2.4 Information on the model cell-faces that form the breakwater in KSFst. Peak measured water level at Delfzijl was 4.83 m NAP during “Allerheiligenvloed”, resulting in overtopping on 14 of these 19 cell-faces.

M index	N index	direction	crest elevation (m NAP)	overtopping section id
71	166	N	6.0	upper breakwater
71	167	N	6.0	
71	168	N	6.0	
71	169	N	6.0	
71	170	N	6.0	
71	171	N	4.5	jump
71	172	N	4.5	
71	172	M	4.4	
70	173	N	4.4	lower stretch
70	174	N	4.3	
70	175	N	4.3	
70	176	N	4.3	
70	177	N	4.3	
70	178	N	4.3	
70	179	N	4.5	head of breakwater
70	179	M	4.5	
69	180	N	4.5	
71	181	M	3.6	eastern breakwater
70	181	M	3.6	

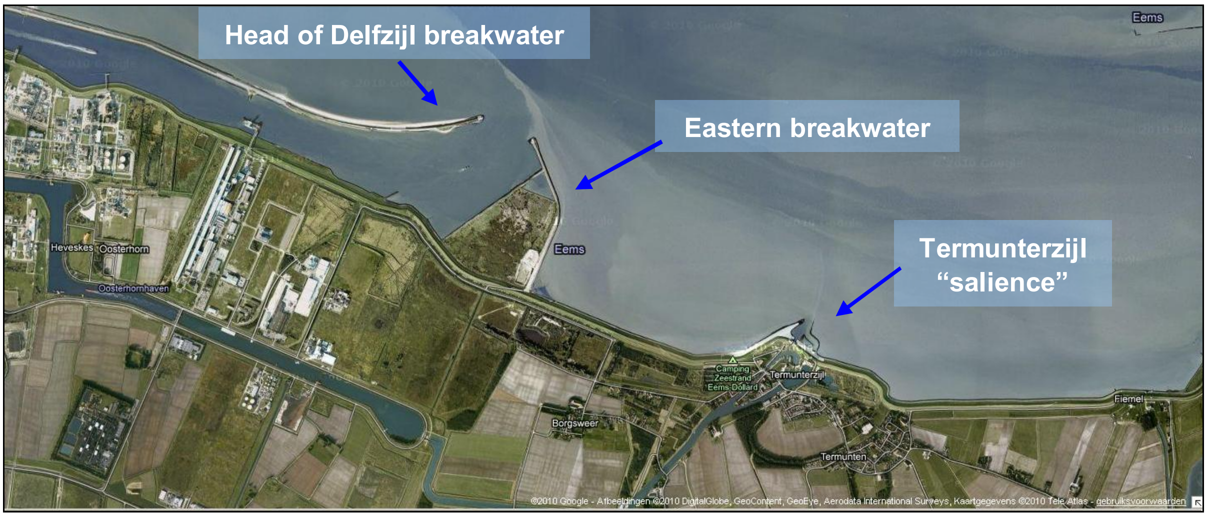

Figure 2.8 Satellite image of region east of Delfzijl (source: Google Maps).

2.2.4 Exaggerated thin dam at Termunterzijl

Another flaw detected in the original KSF4 model was a thin dam of exaggerated length, at Termunterzijl (Figure 2.8), orthogonal to the coastline (see also Rego and Dillingh, 2010). Because it is located between the eastern breakwater and the Ems Dollard, its effect on water levels at Delfzijl may be relevant. In the KSFst model this thin dam is adjusted to 490 m instead of 960 m in length.

2.2.5 Shallows in northern Dollard

The existence of a strip of shallower bottom in the northern part of the Dollard, which “bounds” the main channel leading to the Ems Barrier (see Figure 2.6), was called to our attention during the May 28th visit to Delfzijl. These shallows are dry during low tide. Upon inspection, they were not represented in the KSF4 bathymetry.

The detailed bathymetry from BAWd3d was used to include the shallows in the KSFst schematization. The nodes in rows (M, N) = (58:59, 197:201), (M, N) = (57:58, 202:206), (M, N) = (56:57, 207:227), and (M, N) = (57:58, 228:233) had depths changed to 0.4 m above NAP if their original depth was below that level. Of these 78 nodes, 44 had their depths changed (most had depth of 0-3 below NAP, originally).

2.2.6 “Closing” vs. “closed” surge barrier

Representing the partial closing of the barrier was not accounted for, at all, in the previous study by M. Verlaan (*unpublished*) or in the sensitivity tests in the context of Rego and Dilligh (2010). The barrier was closed from the start of the simulation. But according to BAW (2007) results, a “closing” versus a “closed” scenario results in extra 5 cm difference in the Dollard and at Delfzijl (Table 2.1) and so this is another aspect in which previous studies using KSF4 should be improved.

Operational guidelines for the Ems barrier were obtained from Mr R. Backer (with the Aufgabenbereichsleiter "Sperrwerke", NLWKN-Betriebsstelle Aurich) in an email to M. Verlaan on 18 Feb 2010. The Ems Barrier is to close at NN (Normal Null) +3,5 meters and opens at equal water level on both sides. This is a manual control and there is an on-scene-commander with staff who decides about closing or not closing (which take 35 minutes).

This was incorporated in our simulations by examining water level output, at the barrier, from the open-barrier case and then creating time series of the opening and closing (when levels were increasing from 3.5 m and decreasing from 3.5 m, respectively). The opening and closing duration is represented in our experiments. We also tested the effect of closing the barrier in a slower way (i.e. taking 70 minutes to open or close) to investigate if this affects the surge “reflection” towards Delfzijl (see Table 2.6).

2.2.7 Location of Delfzijl tide gauge

As a last correction, the location of the Delfzijl tide gauge in KSFst was also moved, two cells away from the breakwater entrance. This was based on our GPS measurements (Table 2.3). The original KSF4 had ‘DELFZL’ at (M= 72, N= 169), while its correct location should be at (M= 72, N= 167). This had only a small effect on water levels studied.

2.3 Wind forcing for the Allerheiligen storm

The storm which peaked on November 1st, 2006 caused very high maximum water levels along the Ems estuary, and flooded many high areas in northern Netherlands not protected by the dykes. At Delfzijl, the highwater mark reached 4.83 m NAP. This event was named “Allerheiligenflut” (“All Saints storm”) by the German weather service and “Allerheiligenvloed” by the Rijkswaterstaat.

Time-varying but spatially uniform winds were imposed as forcing of the KSFst model. To simulate this storm, observed wind data and modeled wind results were obtained from MATROOS (2010). The observed wind data at Huibertgat is recorded every 10 minutes, but there is a major gap during the “Allerheiligenvloed” between 02h20 and 06h30 GMT of Nov. 1st 2006 – precisely during peak storm. The “observed wind” simulations described next are thus not entirely measured, but use HIRLAM results for the most important 4 hours of the event.

HIRLAM wind results (also accessed through MATROOS (2010)) are produced by the Dutch Weather Service, KNMI, and have outputs every 3 h at several grid points. For this study, HIRLAM results at the grid point nearest to Huibertgat were used. There are no gaps in this record. Wind records were shifted from GMT to CET (Greenwhich Median Time to Central European Time). Time series of wind speed and direction are plotted and discussed in Section 3.1 (see Figure 3.1, Figure 3.2).

2.4 Set of hindcast simulations

The rather large set of experiments tested is summarized in Table 2.5. The first simulations were designed to decide which atmospheric forcing was more appropriate: the “observed” (see above) or the HIRLAM winds. An early realisation was that winds (both HIRLAM and observed) had to be “strengthened” by about 10% in order to have a close match between observed and modeled water levels at Eemshaven and Delfzijl. Simulated total water levels (tide + surge) were a good match to observations at Huibertgat, which indicates that external surge was indeed well captured in all models without any wind corrections. The nature of the Allerheiligen storm, with local-scale features near the entrance of the Ems estuary and Delfzijl (as seen in “buienradar” images) makes it very difficult to capture the local surge component using 3h winds on a coarse meteorological grid. Therefore, tests were run with winds at 100 and 110% wind speed intensity (runs 1-4; Table 2.5).

With runs 1 through 4 we concluded that “observed” winds did not produce better water level curves than HIRLAM winds at the important locations of Eemshaven, Delfzijl and Nieuw Statenzijl. The 10% increase in wind speeds was also shown to produce better results, and the wind field from run 2 was used throughout the rest of this study.

Table 2.5 Summary of simulations performed for the Allerheiligen storm of Nov. 1st, 2006.

Scen.	run	description	barrier
	01	KSF4 model with HIRLAM wind (100%)	closed
	02	KSF4 model with HIRLAM wind (110%)	closed
	03	KSF4 model with Obs+HIRLAM wind (100%)	closed
	04	KSF4 model with Obs+HIRLAM wind (110%)	closed
All runs below were done in triplicate: with HIRLAM wind strengthened by 8, 10 and 12%			
A1	05	KSF4 (original) model	closed
	06	KSF4 (original) model	open
A2	07	KSF4 (original) model + Delfzijl breakwater up to 9m height	open
	08	KSF4 (original) model + Delfzijl breakwater up to 9m height	closed
B1	09	KSFst model	open
	10	KSFst model	closed
B2	11	KSFst model + Delfzijl breakwater up to 9m height	open
	12	KSFst model + Delfzijl breakwater up to 9m height	closed
B3	13	As above BUT Delfzijl breakwater overtoppable (at 4.3-6m)	open
	14	As above BUT Delfzijl breakwater overtoppable (at 4.3-6m)	closed
B4	15	As above, with shorter thin dam at Termunterzijl	open
	16	As above, with shorter thin dam at Termunterzijl	closed
B5	17	As above, with better shallows in northern Dollard	open
	18	As above, with better shallows in northern Dollard	closed
B6	19	As above, but Ems barrier closing during simulation	closing (35 min)
C	20	As above, but Ems barrier closing slower	closing (70 min)

To have a very close match between observations and simulations, 112% winds should be used with the original KSF4 model (run 05 in Table 2.5), but with the “final” KSFst (run 19 in Table 2.5) 109% winds should be used. A “perfect fit” between observed and modeled water level curves was not the objective, but comparable peak surges were desirable. So it was decided to run each scenario in triplicate, using winds increased by a 8%, 10% and 12%, thereby providing a measure of the spread, or sensitivity to the (uncertain) wind forcing.

After having established this methodology, the list of improvements described above were tested separately, in order to measure the impact of each one. This is summarized in Table 2.5 and is also described next. Each “scenario” consists of 2 runs, e.g. scenario ‘B3’ comprises runs 13 and 14 with open and closed barrier, respectively.

Scenario 'A1' consists of re-running the earlier simulations by M. Verlaan (*unpublished*), which yielded closed barrier - open barrier differences of about 8 cm, at Delfzijl. Scenario 'A2' has the added Delfzijl breakwater, to provide an estimate of the effect of including this feature, but still in the existing over-simplified way (not overtoppable).

Scenario 'B1' uses the KSFst grid/bottom, in which the open barrier situation is much better represented (but without any breakwater at Delfzijl). Scenario 'B2' has the previous improvement and the added Delfzijl breakwater, but over-simplified way. Scenario 'B3' has the previous improvement and real breakwater elevations (Table 2.4) – thus correctly allows overtoping. Scenario 'B4' has the previous improvements and a shorter thin dam at Termunterzijl. Scenario 'B5' has the previous improvements and includes the shallows in the northern Dollard correctly represented.

Scenario 'B6' has the previous improvements and the added detail of a "closing" barrier (using the simeseries of Table 2.6) as opposed to a "closed" barrier during the entire simulation. This is the "final" KSFst model, in which all flaws that we were aware of were corrected. An extra scenario, 'C', was simulated, in which the Ems barrier closes at a slower pace (also in Table 2.6), to test if this affects the surge "reflection" towards Delfzijl.

2.5 The closing of the Ems surge barrier

To capture the effect of the partial closing of the Ems Sperrwerk, this structure was entered in the model as a barrier with time-dependent elevations. In KSFst the barrier consists of two cell faces, which start at -7 m above NAP (fully opened) and begin rising when water levels (at the barrier) reach 3.5 m above NAP. The barrier takes 35 minutes to be fully closed, at +7 m above NAP (Table 2.6).

Table 2.6 *Operating of the Ems barrier, in the model, for the Allerheiligen storm. The times refer to the 7th day of the simulation (i.e. November 1st, 2006). These were determined by inspection of the open barrier simulations, and using their operational rules: close if water level at 3.5 NAP and rising, open if water level at 3.5 NAP and lowering.*

	Actual speed (scenario B6)		**Slower closing (scenario C)**	
	Start	Finish	Start	Finish
Closing	03:45	04:20	03:45	04:55
Opening	07:48	08:23	07:48	08:58

Figure 2.9 shows cumulative discharges through the Ems Barrier, in time, for different simulations. Run 6 (open barrier, original KSF4 model) presents a very low cumulative discharge, as compared to the "upgraded" models with an open barrier, namely runs 9 and 17. For these two, the River Ems has become a much larger reservoir and much more water is allowed to flow through the barrier. The small difference between run 9 and 17 is explained because the other upgrades were more focused on the Delfzijl area.

Discharge curves for runs 19 and 20 are also interesting, and show how the closing of the barrier leaves a greater water volume downstream of the barrier, thus leading to overall higher water levels in the Dollard and at Delfzijl. The curve of run 20 “flattens” at a higher level because it itakes longer to close.

Figure 2.10 and Figure 2.11 show the hydrodynamic conditions near the Ems barrier, just before and just after its closing. After the barrier is closed, a large elevation difference quickly forms between both sides, of about 2 m.

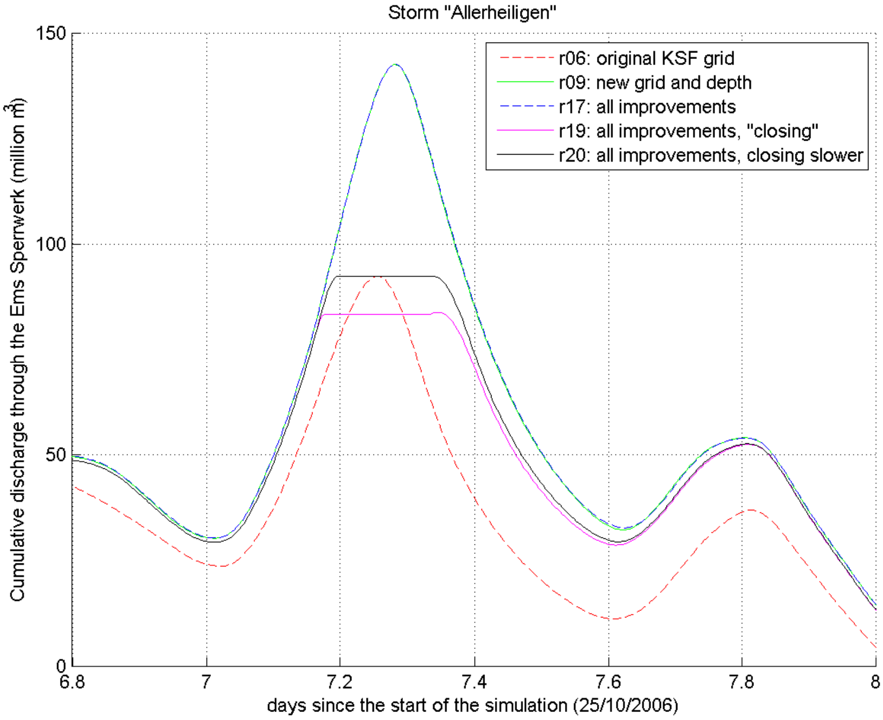

Figure 2.9 *Time series of modeled cumulative discharge through the gates of the Ems barrier. The curves from runs 9 and 17 are virtually overlapping.*

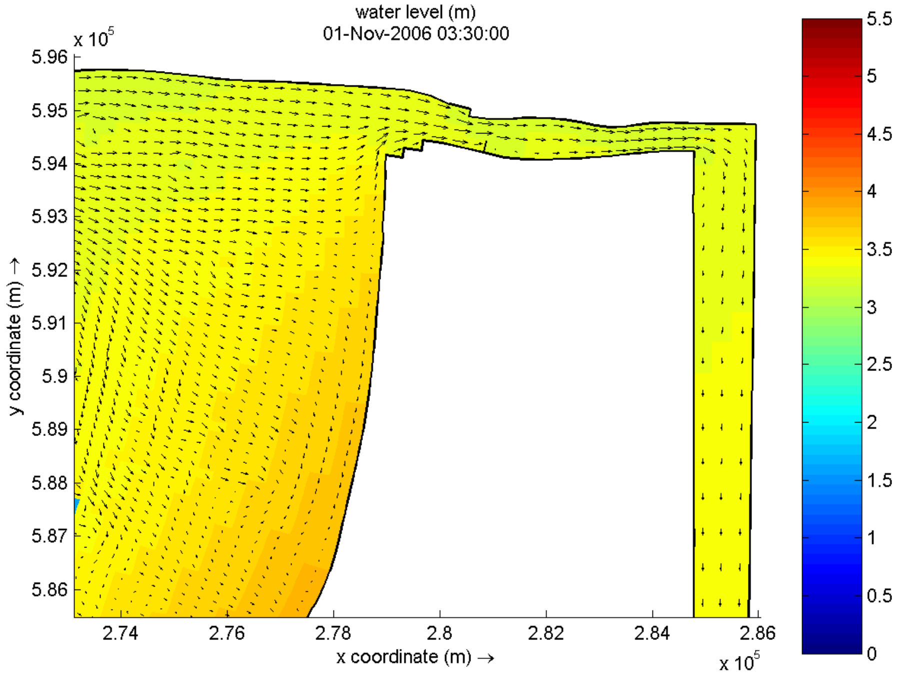

Figure 2.10 *Model results from run 19 (Table 2.5) just before the closing of the Ems barrier: water levels above NAP and depth-averaged velocities.*

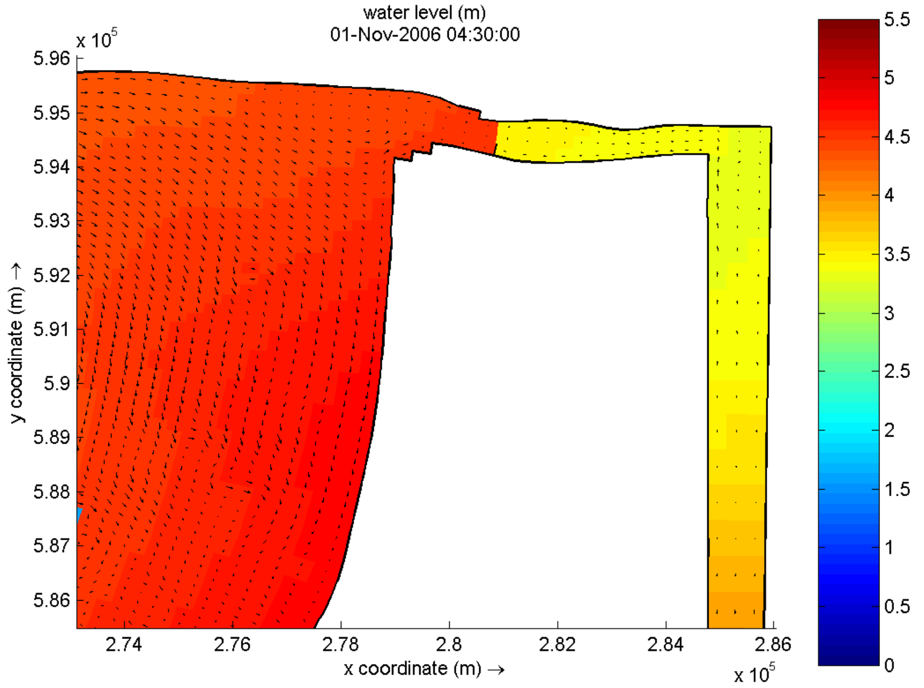

Figure 2.11 *Same as Figure 2.10, but just after the barrier finished closing.*

2.6 Water level validation and model sensitivity to wind forcing

Comparisons were made against observed water levels (MATROOS, 2010). Figure 2.12 and Figure 2.13 show a good match with observations in the outermost locations; simulated levels describe a “band” around observed levels; at Eemshaven there is oscillation not fully captured by the models. Figure 2.14 zooms in on water levels at Eemshaven.

As will be highlighted below (Table 2.7, Table 2.11, Figure 2.24), the closed barrier – open barrier highwater differences at Eemshaven suddenly decrease from about 4.5 cm to nearly zero, comparing scenario ‘B5’ to ‘B6’ (closing barrier to closed barrier scenario). This ~4.5 cm difference still exists for the ‘B6’ scenario, but about half an hour after peak water levels. Thus, at Eemshaven one can see oscillations in water levels of about 10 cm, and a minor shift in time (caused by the closing factor) has this strong effect in peak to peak differences.

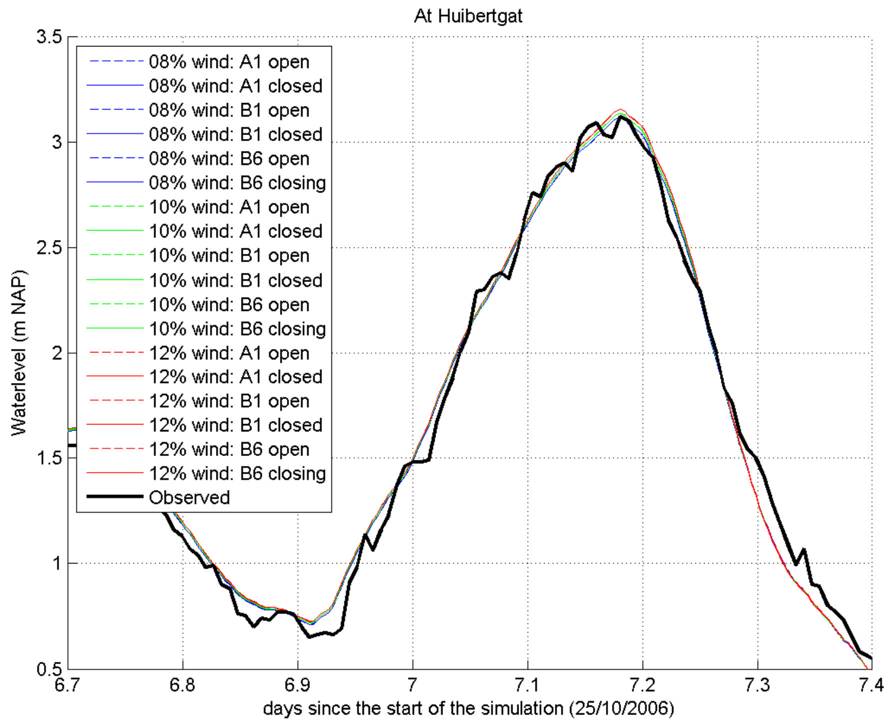

Figure 2.12 *Time series of water levels at Huibertgat. Curves of simulations r05 & r06 (A1 closed & open), r09 & r10 (B1 open & closed), r17 & r19 (B6 open & closing). Dashed lines indicate open cases; blue, green and red indicate 8, 10 and 12% wind increase. Observed curve is black.*

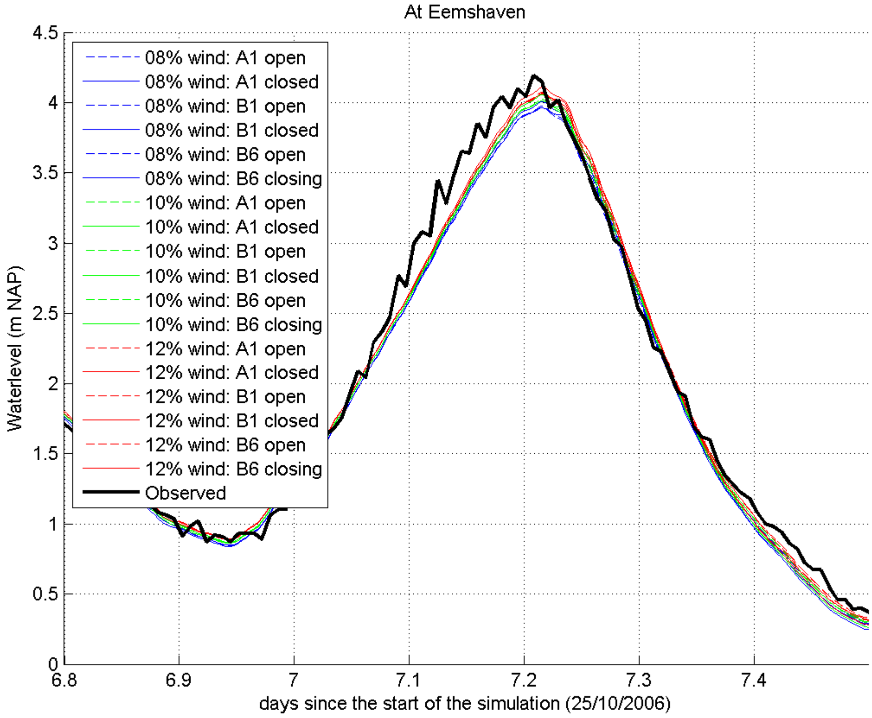

Figure 2.13 Same as Figure 2.12, but at Eemshaven.

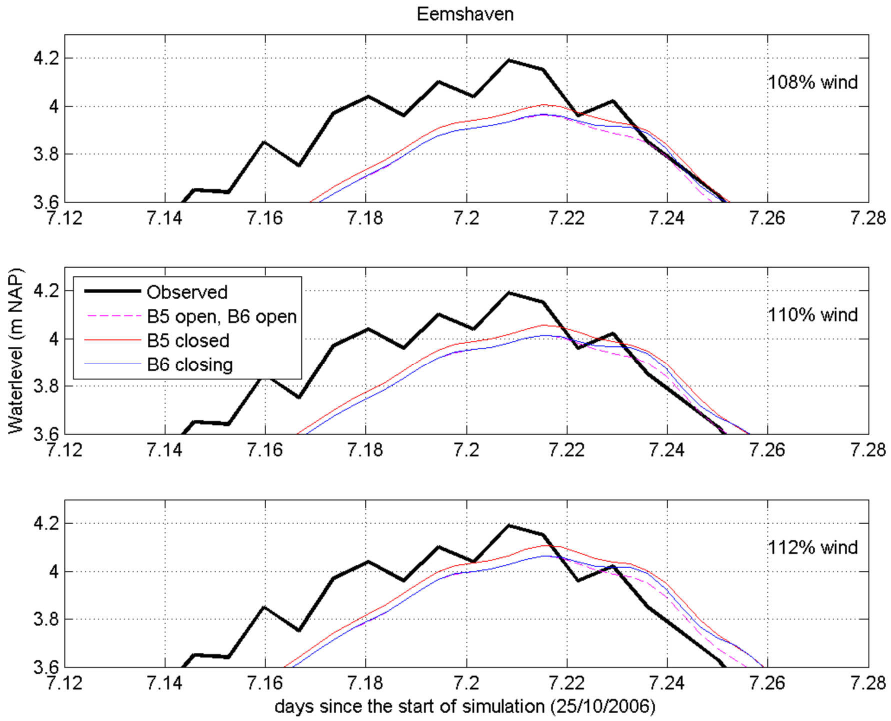

Figure 2.14 Zoom in on water levels near peak high water, at Eemshaven. Top, center and bottom subplots (separated here for clarity) show water level curves for winds 8, 10 and 12% stronger.

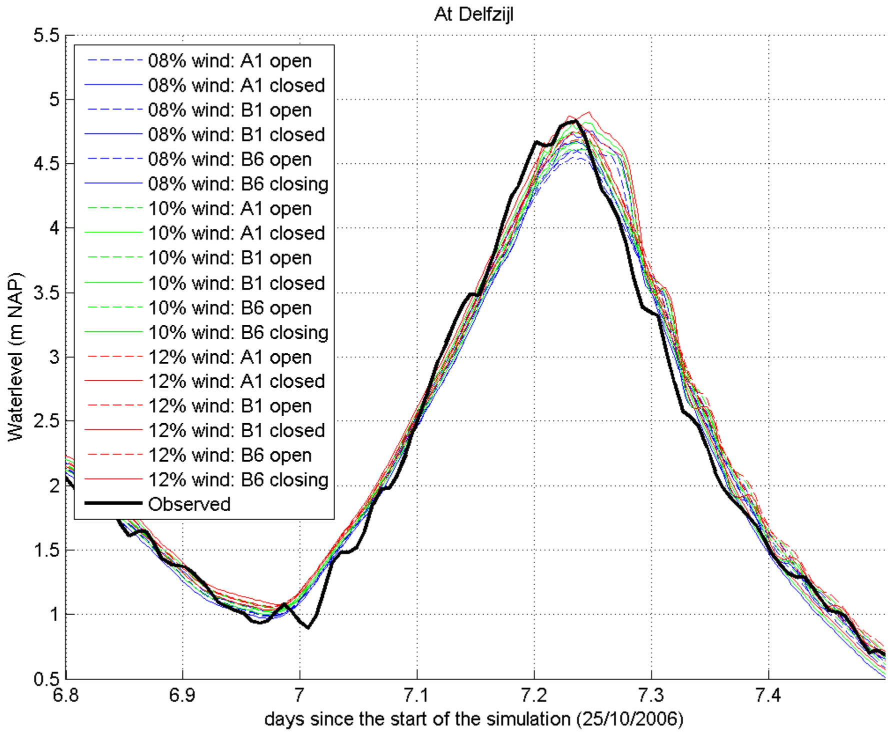

Figure 2.15 Same as Figure 2.12, but at Delfzijl.

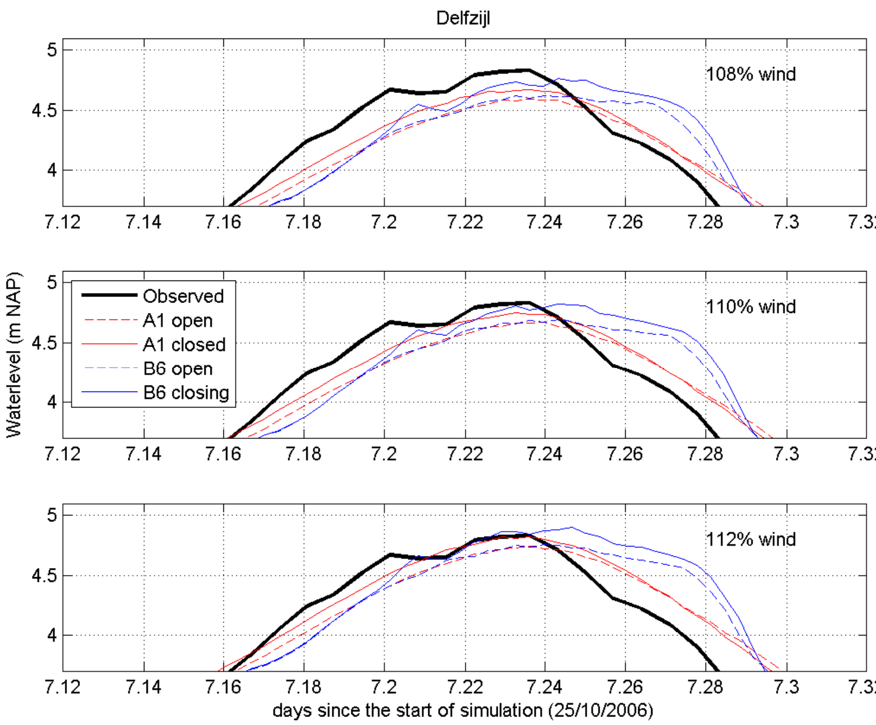

Figure 2.16 Same as Figure 2.14, but at Delfzijl.

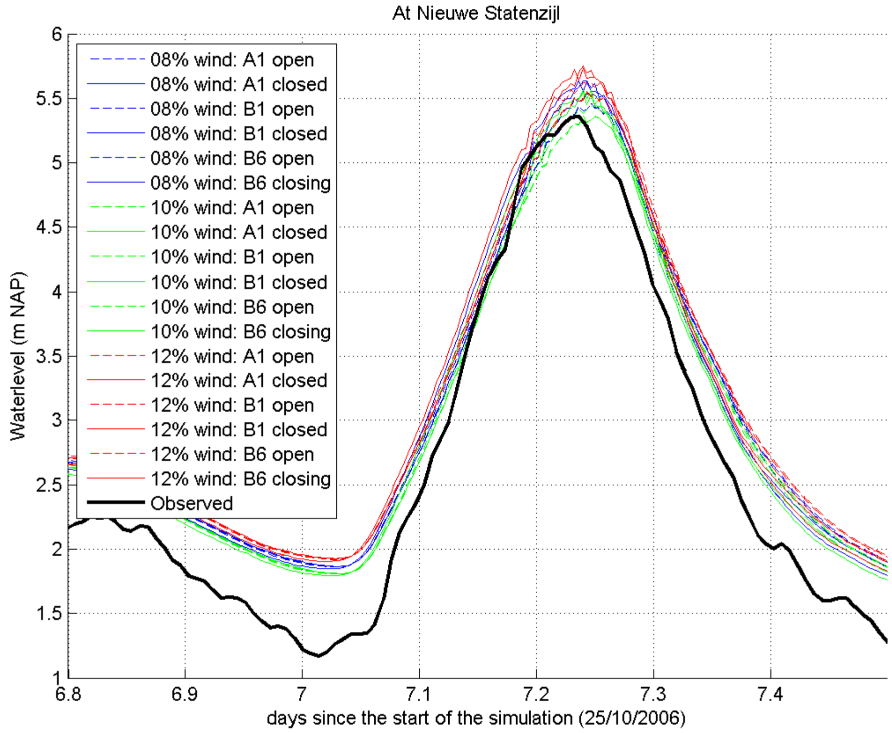

Figure 2.17 Same as Figure 2.12, but at Nieuw Statenzijl.

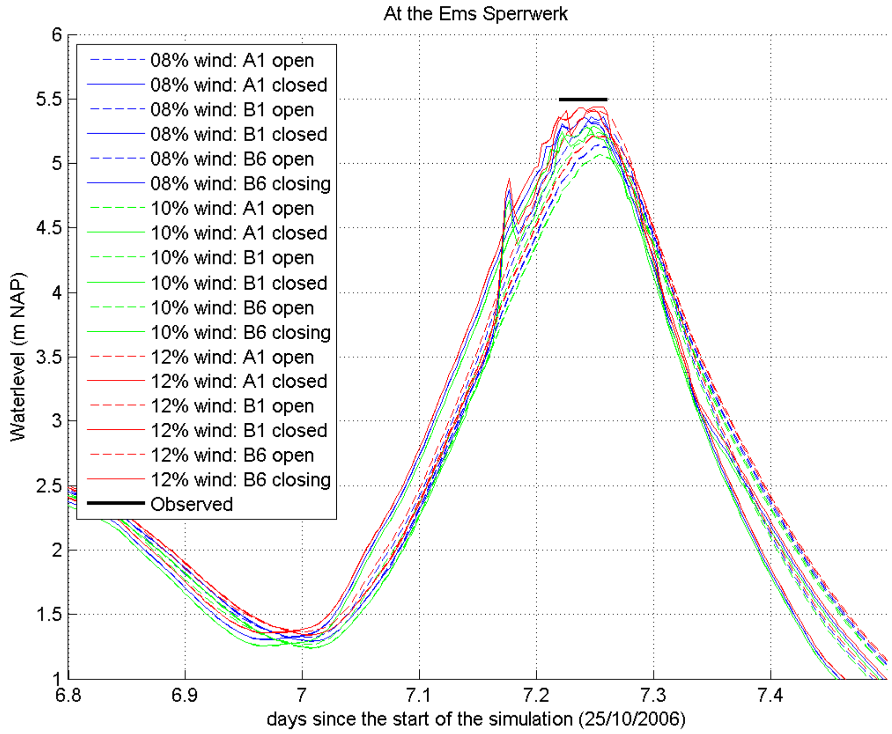

Figure 2.18 Same as Figure 2.12, but at the barrier (only the maximum level was recorded).

Figure 2.15 and Figure 2.16 focus on Delfzijl. There is a good match against measurements, but with a 15-min lag. The observed single oscillation near peak highwater is present in the model output with the “closing” barrier. Figure 2.17 shows Nieuw Statenzijl, where the model tends to overestimate peak water levels. At the Ems Barrier (Figure 2.18), modeled results are a close match to highest levels. Interestingly, an oscillation appears for “closing” conditions (consistent with that seen on Figure 2.16).

2.7 Dynamics around Delfzijl and breakwater overtopping

Before quantifying the differences in peak water levels caused by the closing of the barrier, a brief analysis of the dynamics around Delfzijl is presented. Figure 2.19 and Figure 2.20 show snapshots of model output for “real” conditions (run 19; see Table 2.5), before and during peak surge, respectively. Depth-averaged current velocity vectors are superimposed on maps of water levels, covering the Delfzijl breakwater region.

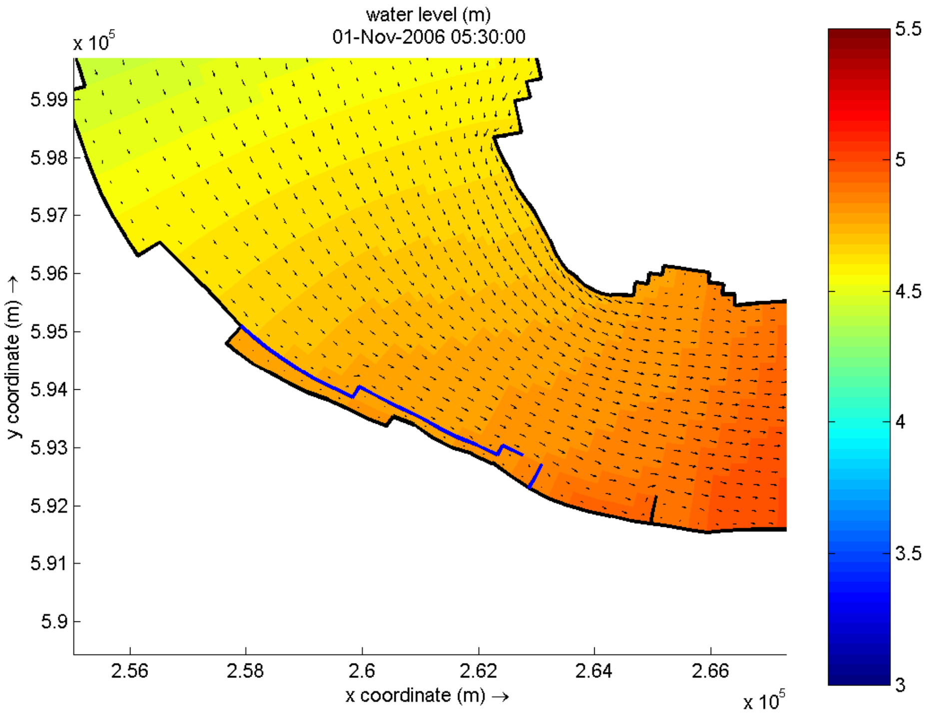

Figure 2.19 Model results (NAP water levels and depth-averaged velocities) about 0.5h before peak surge at Delfzijl (from run 19).

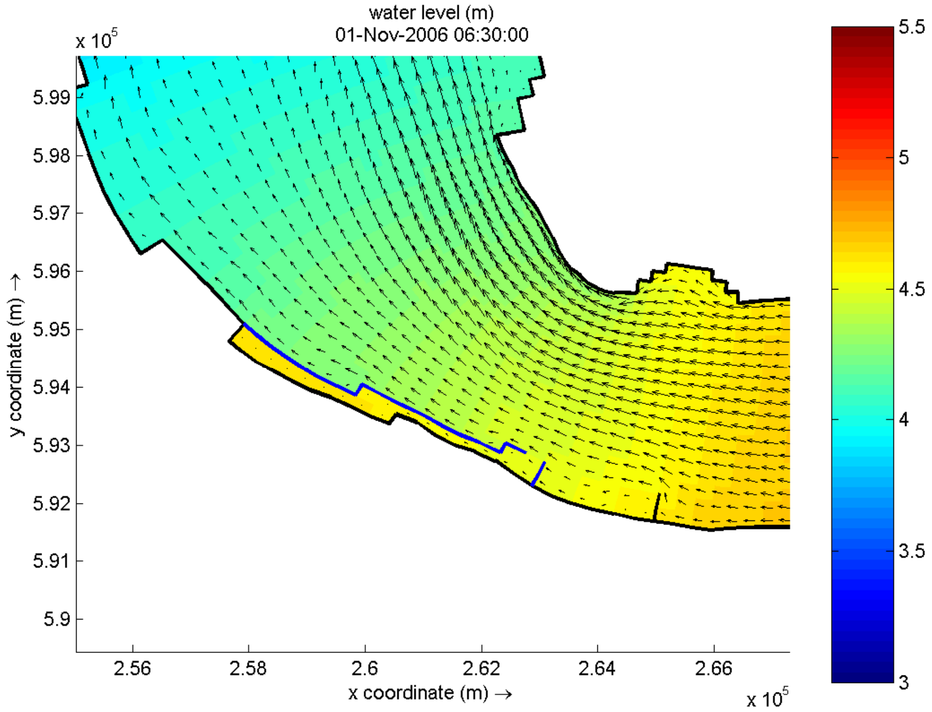

Figure 2.20 *Same as Figure 2.19, but about 0.5h after peak surge.*

Figure 2.19 and Figure 2.20 illustrate the contrasting pre- and post-peak surge dynamics around the Delfzijl breakwater. As expected, the water level gradient is positive towards the barrier in both cases (i.e. water levels increase as one moves upstream). There is little cross-channel variation, and this gradient is almost a one-dimensional feature along the main channel. Thus, while the breakwater “shields” the inner Delfzijl harbor from the stronger currents, it does not protect it from the higher water levels: water levels “behind” the breakwater near Delfzijl are similar to those (higher) water levels at the entrance of the breakwater.

The water level gradient is positive towards the barrier before and after peak surge, but while the depth-averaged flow is upstream before peak surge, it is downstream after the surge. For this reason, the overtopping flows are quite complex. Figure 2.21 contains time series of these quantities, over different sections of the breakwater (defined in Table 2.4). It is shown that most of the overtopping was actually flowing seaward from the harbor, i.e. compared to a wall of infinite height, an overtoppable weir allows for an easier flushing-out of the storm water inside the harbor. This may not always be the case, e.g. in Figure 2.22 (illustrating Allerheiligenvloed simulations with stronger winds; see Chapter 3) the positive and negative curves are more balanced, and yield an almost null net transport (over all the breakwater sections).

Figure 2.21 shows that before peak levels there is significant “negative” overtopping flow *out* of the harbor over the eastern breakwater (pink curve). Here the overtopping flow reverses after peak levels, turning *into* the harbor. For about 1h30 after peak water levels (as measured at the Delfzijl tide gauge) this inflow was partially balanced by the *outflow* in the overtopped lower section of the breakwater (black line in Figure 2.21).

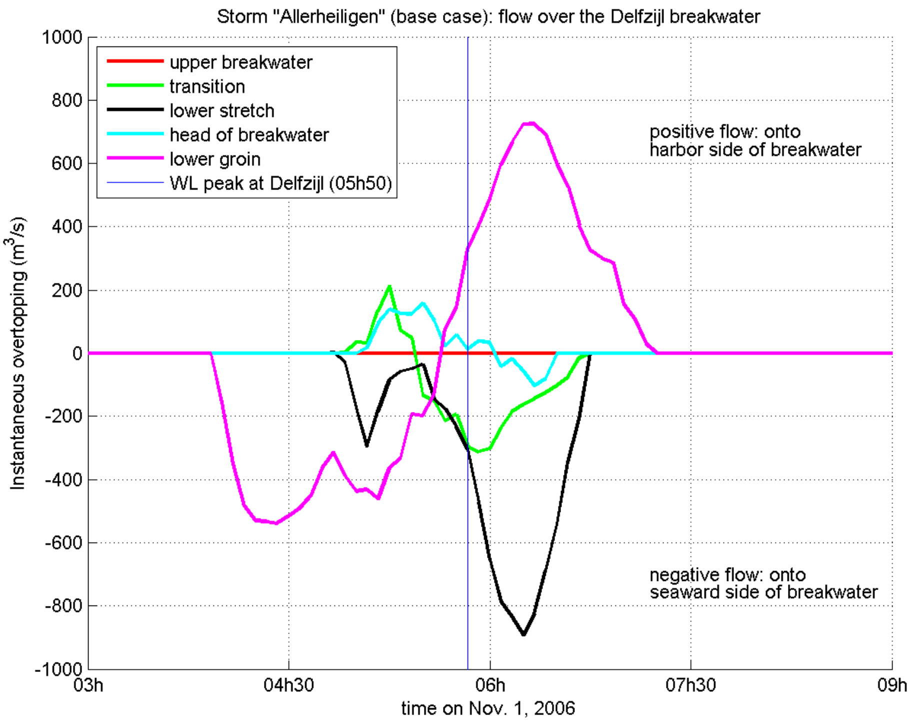

Figure 2.21 *Time series of overtopping discharges, over different sections of the Delfzijl breakwater (defined in Table 2.4). Using results from run #19. Timing of peak water level at Delfzijl tide gauge also shown (vertical blue line).*

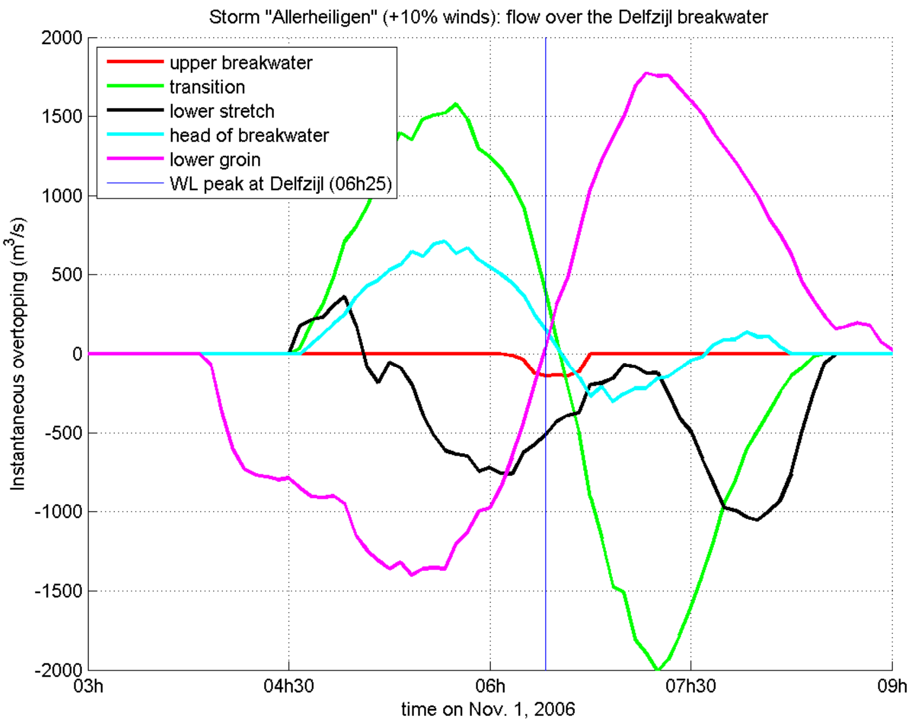

Figure 2.22 *Same as Figure 2.21, but using winds 10% stronger (see Chapter 3).*

Figure 2.23 shows in detail the time-varying dynamics near the eastern breakwater, (a) before it is overtopped, (b) when water is flowing over it, seaward, and (c) when water is flowing over it, into the harbor. The flow through the breakwater entrance (not shown) is still the largest component, into and out of the harbor (peaking at about +1200 and -1200 m^3/s, respectively).

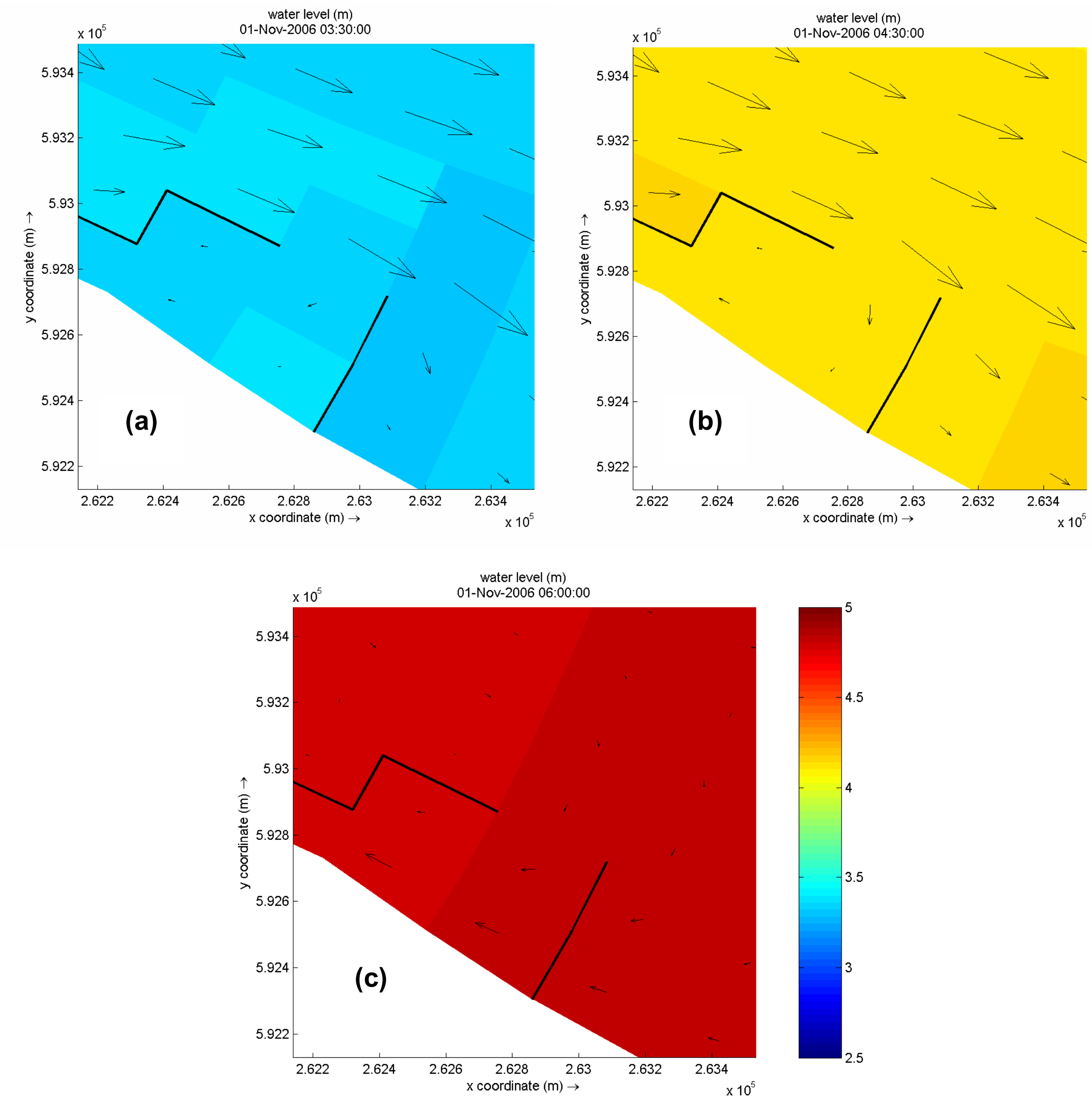

Figure 2.23 Depth-averaged current velocities and water levels (color scale is the same for the 3 snapshots) near the head of Delfzijl breakwater. (a) 2h30 before peak surge, (b) 1h30 before peak surge, (c) at the time of peak surge.

2.8 Effect of the Ems Sperrwerk on peak water levels along Dutch dykes

Table 2.7 through Table 2.10 include results from Figure 2.12 through Figure 2.18. These values were also used to create Figure 2.24, which compares differences in peak highwater for all scenarios visually, including an indication of the uncertainty caused by the wind representation. Table 2.11 further summarizes these results, with the wind uncertainty as a confidence margin. (i.e. it shows the mean value and takes the higher and lower values as “error”).

The ∆ tends to decrease with increasing wind speeds, but there is not a clear pattern: in Scenario B6 (the real situation, after all model improvements) the weaker winds actually produce the smaller ∆’s (by very small amounts). Considering all scenarios, the ∆ sensitivity to wind perturbation ranges between 0.3 and 1.1 cm at Delfzijl, and between 0.1 and 1.3 cm at Nieuwe Statenzijl. Again, in BAW (2007) the differences are reported in increments of 5 cm.

Table 2.7 Differences in peak highwater (∆) for each scenario, at Eemshaven. These differences were computed using winds increased by a 8%, 10% and 12%.This gives a measure of the spread, or sensitivity to the (uncertain) wind forcing. The peak highwater levels are included, for the open barrier (“opn_br”) and closed/closing barrier (“cls_br”) cases. All are shown in meters.

	wind 8% stronger			wind 10% stronger			wind 12% stronger		
	∆	**cls_br**	**opn_br**	**∆**	**cls_br**	**opn_br**	**∆**	**cls_br**	**opn_br**
'A1'	0.033	4.007	3.974	0.035	4.057	4.022	0.034	4.108	4.075
'A2'	0.033	4.006	3.973	0.034	4.056	4.022	0.034	4.109	4.075
‘B1'	0.041	4.007	3.966	0.044	4.057	4.013	0.043	4.108	4.065
'B2'	0.042	4.006	3.964	0.043	4.056	4.013	0.044	4.109	4.065
'B3'	0.041	4.005	3.964	0.043	4.056	4.013	0.044	4.109	4.065
'B4'	0.042	4.005	3.964	0.043	4.056	4.012	0.044	4.109	4.064
'B5'	0.041	4.004	3.963	0.043	4.055	4.012	0.044	4.108	4.064
'B6'	0.001	3.965	3.963	0.001	4.013	4.012	0.002	4.065	4.064
'C'	0.001	3.964	3.963	0.001	4.013	4.012	0.001	4.065	4.064

Table 2.8 Same as Table 2.7, but at Delfzijl.

	wind 8% stronger			wind 10% stronger			wind 12% stronger		
	∆	**cls_br**	**opn_br**	**∆**	**cls_br**	**opn_br**	**∆**	**cls_br**	**opn_br**
'A1'	0.080	4.673	4.593	0.078	4.749	4.671	0.074	4.819	4.745
'A2'	0.092	4.863	4.771	0.080	4.932	4.852	0.097	5.021	4.924
‘B1'	0.122	4.673	4.550	0.137	4.749	4.612	0.123	4.819	4.696
'B2'	0.148	4.863	4.716	0.147	4.932	4.784	0.161	5.022	4.860
'B3'	0.149	4.770	4.621	0.137	4.831	4.694	0.128	4.893	4.765
'B4'	0.147	4.773	4.626	0.145	4.842	4.697	0.139	4.907	4.768
'B5'	0.153	4.771	4.619	0.148	4.838	4.690	0.138	4.897	4.759
'B6'	0.143	4.761	4.619	0.131	4.820	4.690	0.145	4.904	4.759
'C'	0.130	4.749	4.619	0.136	4.826	4.690	0.123	4.883	4.759

Table 2.9 Same as Table 2.7, but at Nieuw Statenzijl.

	wind 8% stronger			wind 10% stronger			wind 12% stronger		
	Δ	**cls_br**	**opn_br**	Δ	**cls_br**	**opn_br**	Δ	**cls_br**	**opn_br**
'A1'	0.100	5.546	5.446	0.102	5.635	5.533	0.106	5.728	5.623
'A2'	0.102	5.547	5.445	0.101	5.638	5.537	0.107	5.730	5.623
‘B1'	0.187	5.546	5.360	0.173	5.635	5.462	0.176	5.728	5.552
'B2'	0.184	5.547	5.363	0.181	5.638	5.457	0.178	5.730	5.552
'B3'	0.181	5.545	5.364	0.181	5.636	5.455	0.178	5.728	5.551
'B4'	0.176	5.546	5.370	0.169	5.637	5.469	0.171	5.732	5.561
'B5'	0.185	5.545	5.360	0.182	5.637	5.455	0.183	5.727	5.543
'B6'	0.204	5.564	5.360	0.180	5.635	5.455	0.207	5.750	5.543
'C'	0.170	5.530	5.360	0.173	5.627	5.455	0.176	5.720	5.543

Table 2.10 Same as Table 2.7, but at the Ems Barrier.

	wind 8% stronger			wind 10% stronger			wind 12% stronger		
	Δ	**cls_br**	**opn_br**	Δ	**cls_br**	**opn_br**	Δ	**cls_br**	**opn_br**
'A1'	0.042	5.279	5.237	0.033	5.355	5.322	0.018	5.429	5.411
'A2'	0.039	5.277	5.238	0.030	5.352	5.322	0.016	5.430	5.414
‘B1'	0.212	5.281	5.069	0.214	5.358	5.144	0.212	5.431	5.219
'B2'	0.215	5.279	5.065	0.214	5.354	5.139	0.217	5.432	5.215
'B3'	0.214	5.279	5.065	0.214	5.354	5.140	0.217	5.433	5.216
'B4'	0.212	5.278	5.067	0.208	5.355	5.148	0.209	5.433	5.223
'B5'	0.213	5.280	5.067	0.216	5.355	5.139	0.222	5.435	5.213
'B6'	0.223	5.289	5.067	0.226	5.365	5.139	0.222	5.435	5.213
'C'	0.258	5.324	5.067	0.244	5.383	5.139	0.239	5.453	5.213

Table 2.11 Summary of peak water level differences (closed barrier – open barrier), at the 4 stations: Eemshaven (“Em”), Delfzijl (“Dz”), Nieuw Statenzijl (“NS”), and Ems Barrier (“Br”). Ensemble values are shown in cm for all 9 scenarios, A1 through C (including hindcasts results for the 3 winds tested; base case, +2% and -2% speed).

	A1 *KSF-Ems*	**A2** *+thin dam breakwater*	**B1** *KSF_st*	**B2** *+breakwater as thin dam*	**B3** *+breakwater as weir*	**B4** *+short dam Termunterz*	**B5** *+Dollard shallows*	**B6** *+closing Ems barrier*	**C** *+closing slower*
Em	3.39 ±0.12	3.35 ±0.06	4.24 ±0.15	4.25 ±0.10	4.26 ±0.12	4.29 ±0.13	4.23 ±0.15	0.15 ±0.01	0.11 ±0.01
Dz	7.70 ±0.28	8.83 ±0.82	12.99 ±0.75	15.45 ±0.70	13.84 ±1.07	14.29 ±0.41	14.51 ±0.74	13.78 ±0.71	12.98 ±0.66
NS	10.28 ±0.29	10.41 ±0.30	17.98 ±0.68	18.11 ±0.33	17.93 ±0.16	17.25 ±0.36	18.35 ±0.14	19.36 ±1.34	17.31 ±0.33
Br	2.98 ±1.19	2.75 ±1.13	21.30 ±0.06	21.57 ±0.12	21.56 ±0.15	20.97 ±0.19	21.73 ±0.43	22.42 ±0.21	24.85 ±0.93

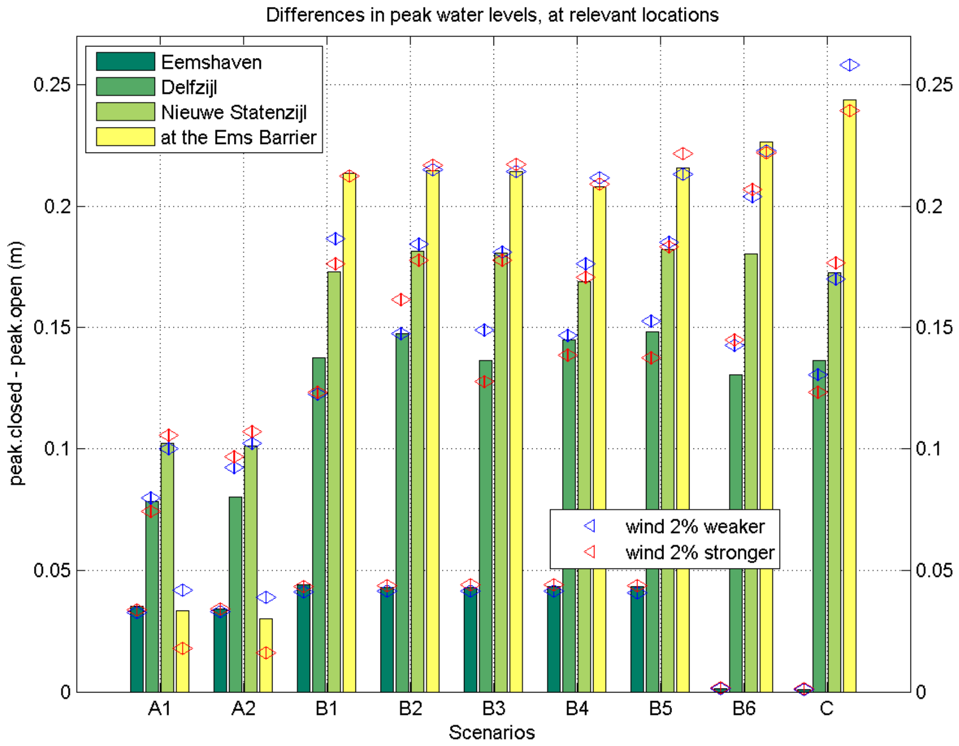

Figure 2.24 *Differences in peak highwater for each scenario. The bars show these differences using a 10% stronger wind; the triangles show the same but using 8% and 12% stronger winds (blue and red, respectively). At each location, for each scenario, the bar and the 2 triangles indicate the spread, or sensitivity to the (uncertain) wind forcing.*

Overall, the new model schematization yields Δ=13.8±0.7 cm at Delfzijl ('B6',Table 2.11), while using the old model one obtains Δ=7.7±0.3 cm ('A1',Table 2.11). At Nieuw Statenzijl, the new model schematization yields Δ=19.4±1.3 cm, whereas using the old model leads to Δ=10.3±0.3 cm. At the Ems Barrier the improvement is even greater, as with the new model schematization Δ=22.4±0.2 cm, while using the old model results in just Δ=3.0±1.2 cm.

Based on Table 2.11, we may also quantify the impact of each one of the improvements listed in Section 2.2 of this report.

The single most important change was the improvement of the model grid and depth "behind" the Ems surge barrier: with a better hypsometry curve for the River Ems the barrier effect at Delfzijl increased by 5.3 cm, a 70% increase ('A1' to 'B1', Table 2.11). With a larger storage capacity behind the barrier, the predictions of the model with an open barrier were lower by 5-6 cm at Delfzijl (Table 2.8), and lower by 7-8 cm at Nieuwe Statezijl (Table 2.9).

Adding a realistic breakwater around Delfzijl harbor, the barrier effect increases by about 0.85 cm ('B1' to 'B3', Table 2.11). This increase is overestimated at 2.5 cm with a "thin dam" breakwater ('B1' to 'B2').

The effect of the shortened thin dam at Termunterzijl and of the Dollard shallows is smaller; these two combined contribute to a larger Δ, by about 0.67 cm.

Closing the barrier, incrementally, during the simulations, decreases the barrier effect at Delfzijl by about 0.63 cm (‘B5’ to ‘B6’, Table 2.11). A much greater impact is seen on the ∆ at Eemshaven; here the closed barrier – open barrier highwater differences decrease from 4.2 cm to 0.15 cm (‘B5’ to ‘B6’). This difference of about 4 cm still occurs for the ‘B6’ scenario, but about half an hour after peak water levels (Figure 2.14). A minor shift in time (caused by the closing factor) has this marked effect in peak to peak differences. The slower closing barrier decreases the barrier effect by 0.8 cm at Delfzijl (‘B6’ to ‘C’); at Nieuw Statenzijl it decreases the barrier effect by 2 cm. At the Ems Barrier a slower barrier actually increases ∆, by about 2.4 cm. The tests in which the Ems barrier was made to close slower allow less water to remain in the Dollard, but create a higher peak at the barrier.

Overall, the ∆ at the Ems Barrier increased from 3 to 22 cm (‘A1’ to ‘B6’), but it did not reach the 30-50 cm reported in BAW (2007). This discrepancy was not unexpected, as the Kuststrook-fijn model (used as the basis for our modelling tests) was not designed for accurate predictions in that area. Indeed, in the KSFst schematization the river Ems is only 3 cells wide (grid the resolution of ~200m), while the BAW (2007) study has a much more detailed representation of the main channel, of the surrounding floodplain and of the barrier (Figure 2.25).

These values should be viewed as an indication of the range of differences to be expected. The uncertainty caused by the approximated wind is estimated by showing the sensitivity of results within a reasonable range of wind speed intensities (base case and ±2% intensity, applied to HIRLAM results in a spatially uniform way), but this does not include other sources of uncertainty. Indeed, in BAW (2007) the differences are reported in increments of 5 cm.

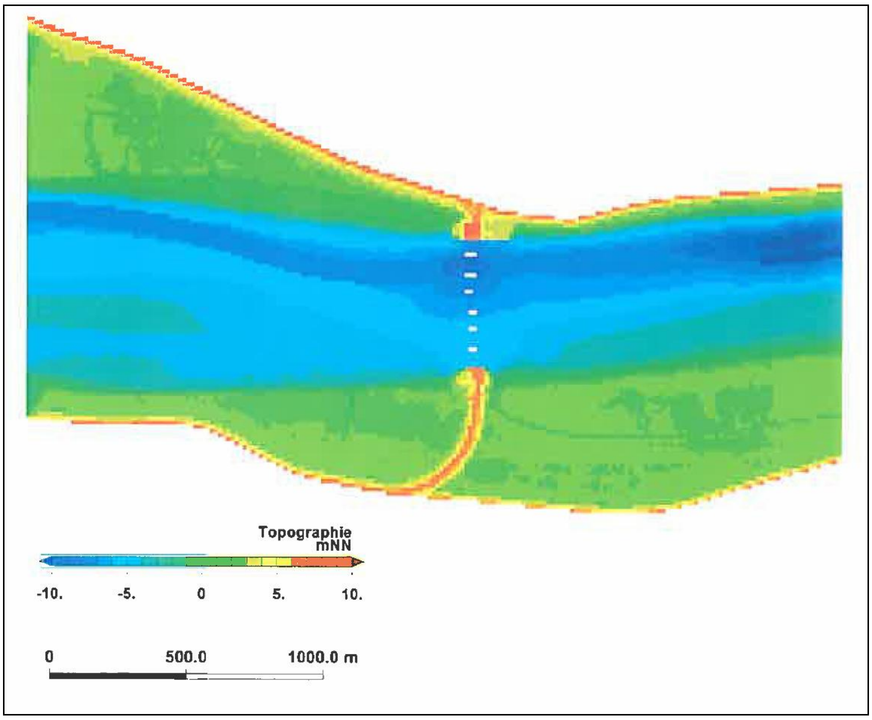

Figure 2.25 Bathymetry of the Ems Sperwerk region, as used in the detailed BAW (2007) model. Adapted from Figure 5 of that report.

3 Modelling more events and testing strengthened storms

The question is what the level at Delfzijl would have been, were the barrier not closed. The purpose of this exercise is to obtain a homogenous time series on extreme storm highwaters. In an earlier research (Roscoe, 2009) data of Delfzijl has been used until March 15, 2007, disregarding the effect of the Ems barrier. Having a model that captures the effect of the Sperrwerk properly, it is also possible to make a good estimation of the Delfzijl water level if there were no Sperrwerk.

We want to know the effect of the Sperrwerk on storm water levels close to the dyke design levels, listed in Table 3.1 for important locations in this region. So we “strengthen” past storms in order to reach those magnitudes. Also, intermediate simulations are of interest, since we want to derive frequency curves for tide gauges under closed Sperrwerk situations, given those frequency curves in the absence of the Sperrwerk. We do that by increasing the recorded wind speeds.

Table 3.1 Dyke design levels in the region of interest (frequency of exceedance of 1/4000 y).

Location	**(above NAP)**
Eemshaven	5.45 m
Delfzijl	5.99 m
Nieuw Statenzijl	6.73 m

3.1 Other storms during which the Sperwerk was closed

Since its construction near Gandersum, there have been 4 storms during which the Ems surge barrier was closed, until March 2007. A list is shown in,Table 3.2 as provided by the German services at the barrier. Since there was no name listed for the event of 17/12/2005, it is here refferred to as the “No Name” storm. The “peak wind direction” for each storm was determined for the purpose of this study, based on Figure 3.1 and Figure 3.2. For each storm, these were determined as the average direction during the period of stronger winds. This is a simplified classification, but one that helps in the analysis of results in the following sections.

It should be noted that changes in atmospheric forcing (even if “mere” intensity increases) may have considerable impact in overall peak levels, due to nonlinear interaction of tide and surge (e.g., Horsburgh and Wilson, 2007; Wolf, 2009; Rego and Li, 2010). The same methodology was taken as in Chapter 2, i.e. HIRLAM wind results were used at 3h intervals, spatially uniform (taken at Huibertgat).

Table 3.2 *Dates on which the Ems barrier was closed (up to March 15, 2007). Heights measured directly on the seaside of the barrier, in meters above Normal Null (2cm below NAP). Source: Mr. Reinhard Backer, Aufgabenbereichsleiter "Sperrwerke" (email of 31/05/2010). * Peak wind directions were determined from Figure 3.1 and Figure 3.2).*

Storm name (Germany)	**Date of peak surge**	**Max. level (m NN)**	**Peak wind direction ***
“NoName”	17/12/2005	3.88	From NW
Allerheiligenvloed	01/11/2006	5.51	From NW
Volkholdvloed	12/01/2007	4.37	From SW
Mariusvloed	19/01/2007	3.80	From W

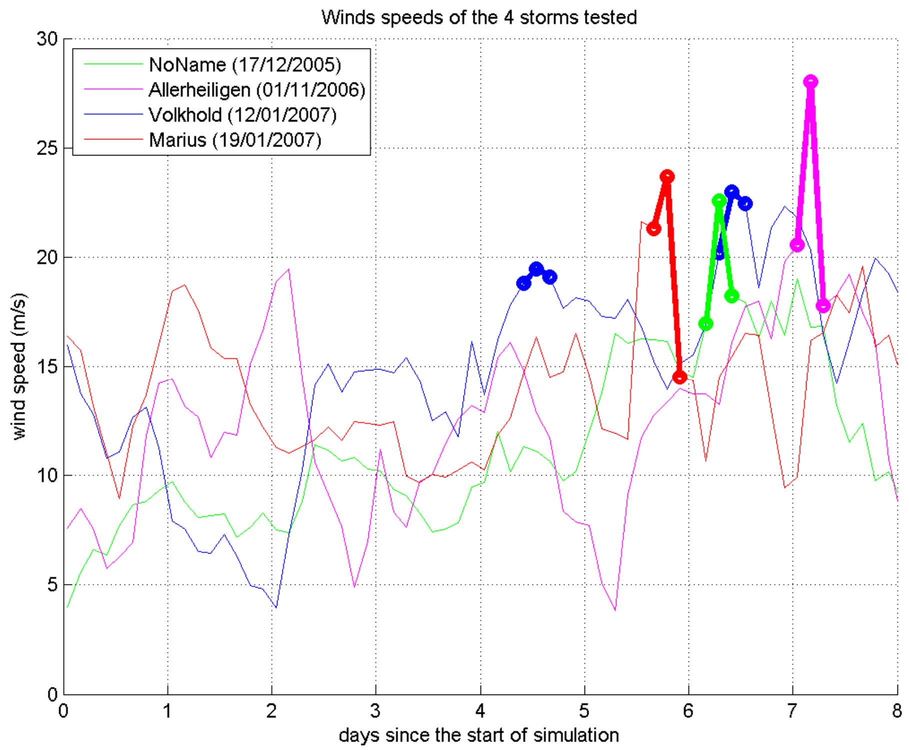

Figure 3.1 *Time series of wind speeds for the 4 storms simulated. Thicker lines highlight the 6h around peak wind speeds, for each storm. Source: KNMI’s HIRLAM wind, obtained from MATROOS (2010).*

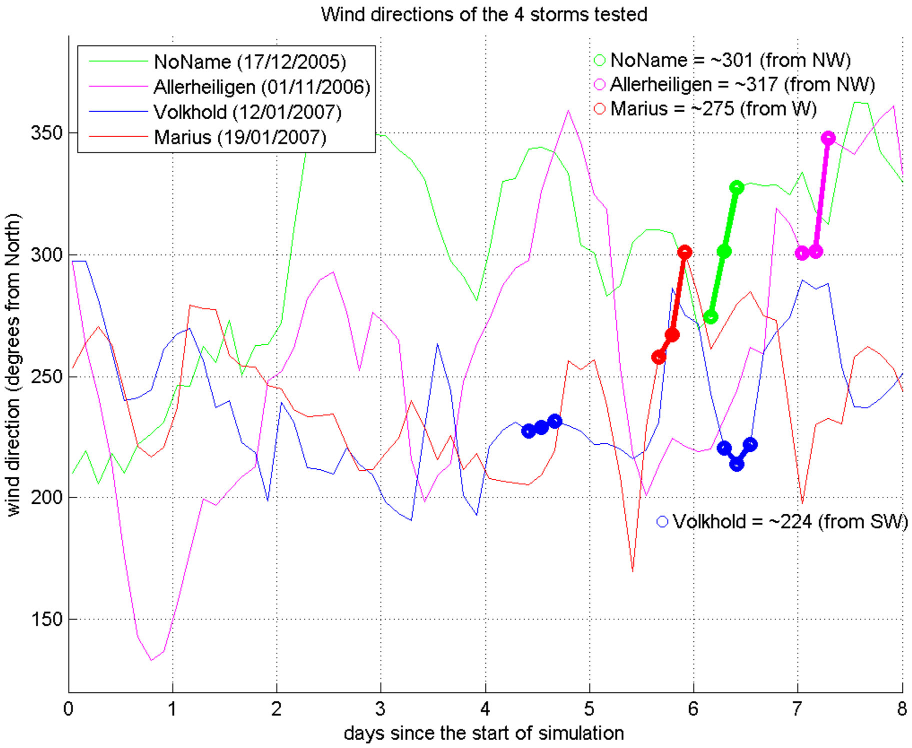

Figure 3.2 *Same as Figure 3.1, but showing wind directions. Thicker lines highlight the 6h around peak wind speeds, for each storm*

3.2 Modelling setup

In this chapter a different methodology was used, as compared to the hindcast of Chapter 2. Because in MATROOS the forecasts of the "cascade" of North Sea models are only stored for one year (and we need to simulate storms of 2005, 2006, 2007; Table 3.2), here we used the Dutch Continental Shelf Model version 5 (henceforth DCSM5) to force the Zuidelijke Noordzee version 3 (ZUNO3) to force the KSF4 to force the KSFst model, developed in Chapter 2.

Figure 3.3 shows the ZUNO3 grid, covering the southern North Sea from the end of the English Channel (near Southampton) to the northern tip of Denmark; time step in ZUNO3 was of 2.5 minutes. Figure 3.4 shows the DCSM5 grid, covering most of the North Sea from the entrance to the Baltic on the east to the Faroe Islands on the northwest and to the northernmost Biscay Bay on the south; these simulations had a time step of 10 minutes. All models simulated 8 days, with the peak storm occurring on the last day.

Time-varying but spatially uniform winds, obtained from MATROOS (2010), were used to force all four models. As recommended by the sensitivity test described in Section 2.4, HIRLAM results produced by KNMI at the grid point nearest to Huibertgat were used.

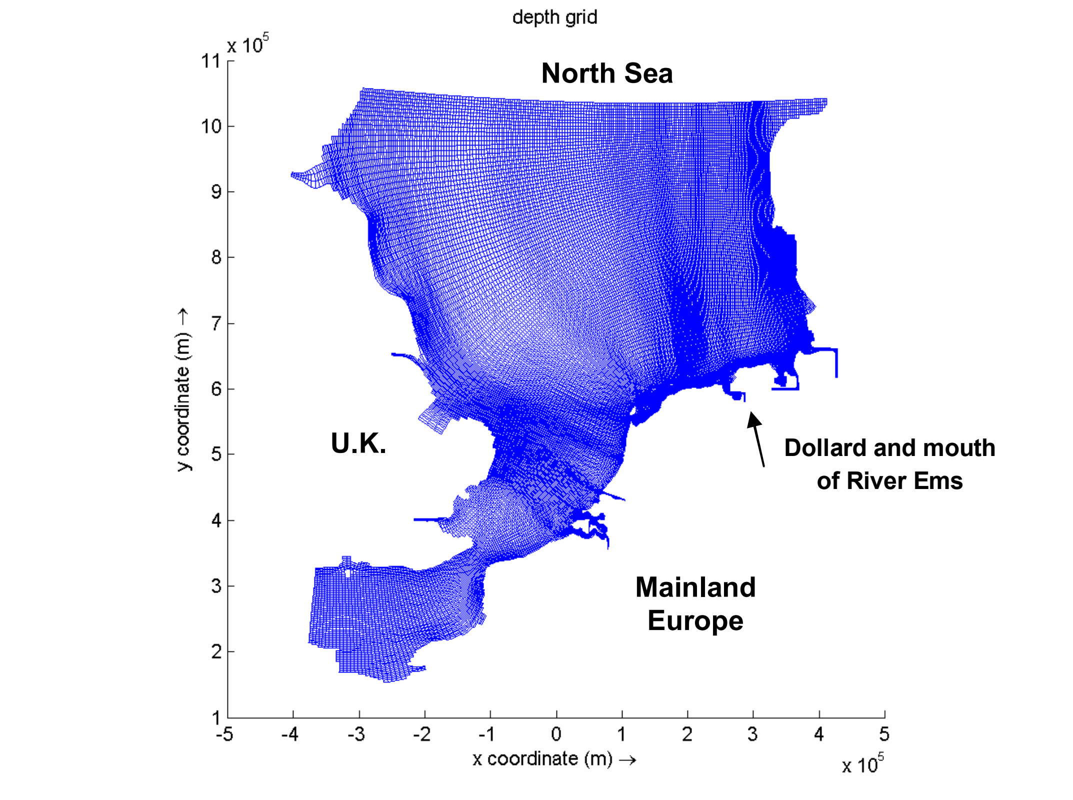

Figure 3.3 *ZUNO model grid (M_{max} = 486, N_{max} = 170).*

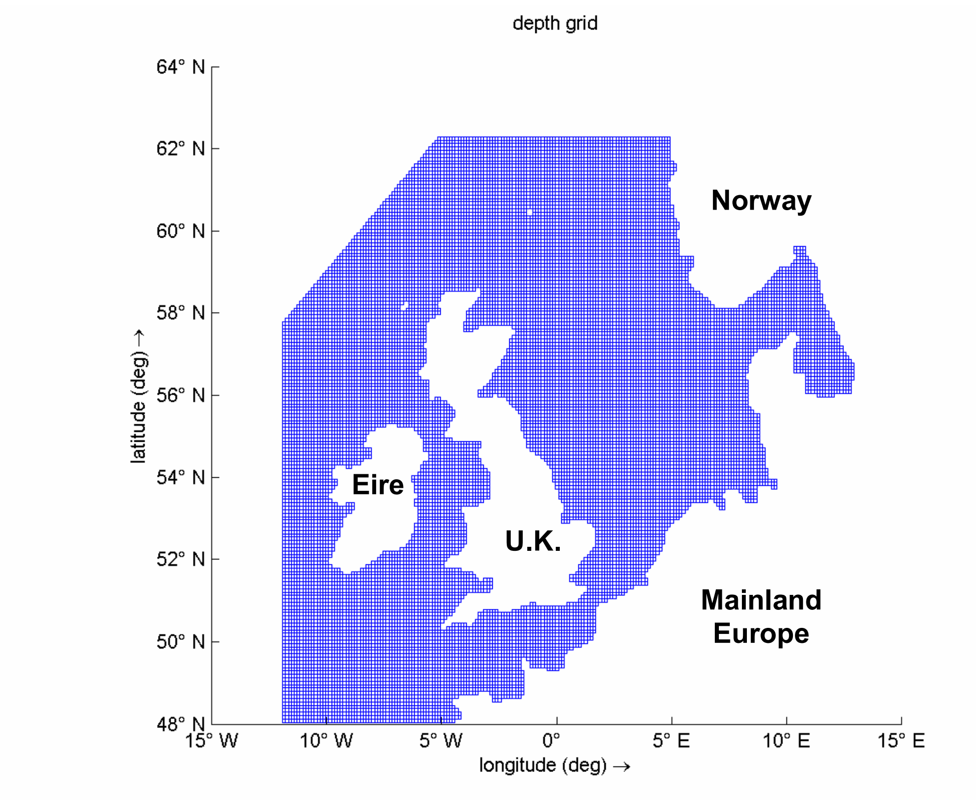

Figure 3.4 *Dutch Continental Shelf Model grid (Mmax= 201, Nmax= 173).*

Using spatially uniform wind fields over the large domains of the DCSM and ZUNO models is an oversimplification, but it is shown in Section 3.3 that the KSFst captures the peak water levels well. The low waters are not as well represented, but they were not the goal of this study. Furthermore, it is the objective of this chapter to compare *differences* in peak water levels (open vs. closing barrier scenarios) under synthetic storms with increasing wind speeds, and not to represent a specific storm as accurately as possible.

Upon confirming that all cascades were representing the desired conditions, i.e. that the DCSM5, the ZUNO3, the KSF4 and the KSFst (Figure 3.9, Figure 3.10, Figure 3.16, Figure 3.17, Figure 3.23, Figure 3.24) converged to the observed water levels around highwater, the chosen storms were strengthened to surpass dyke design levels. Storm "Volkhold", like the "Allerheiligen", also needed a 10% increase in wind speeds to produce water levels that matched observations (these also had to produce water levels at the Barrier above 3.5 m NN). For these two storms, the "base case" is forced by HIRLAM wind speeds of 110%. For storms "Marius" and "NoName", the base case uses HIRLAM wind speeds directly.

The intensity increments were selected such that the "stronger" storm is above the local design levels, but not unrealistically higher. Having base simulations with water levels similar to observed time series (which implies that the closing scheme approximated reality);
Figure 3.6 - Figure 3.7 show time series of discharge through the Ems barrier.

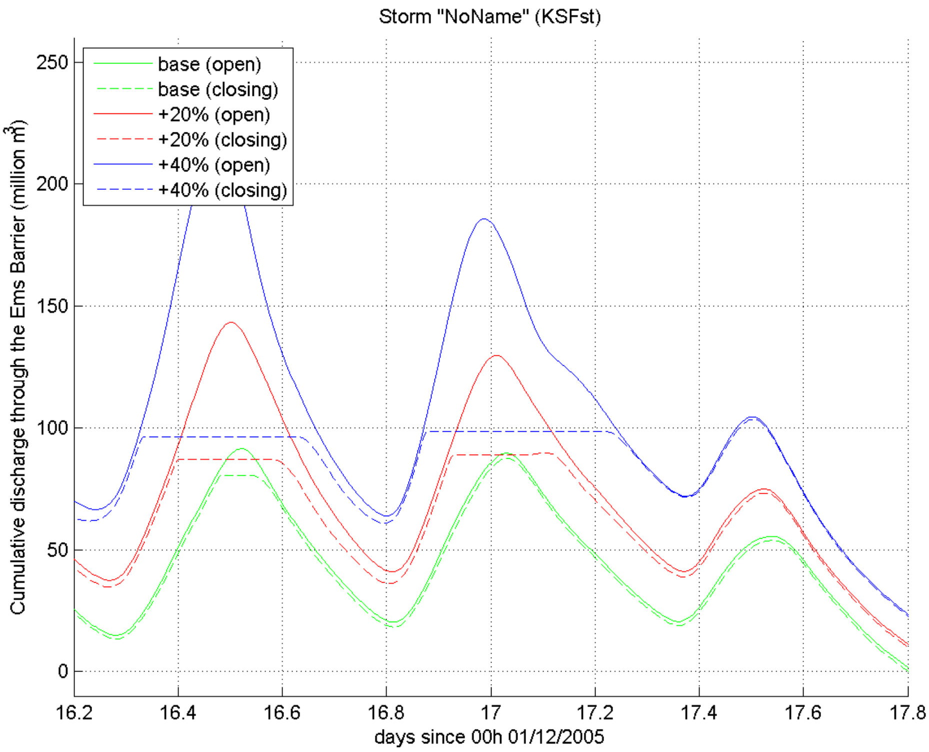

Figure 3.5 *Time series of modeled cumulative discharge through the gates of the Ems barrier. Storm "NoName" with 100%, 120% and 140% wind intensity. Gates close when water level reaches 3.5 m NN (increasing), and opens when water level is below 3.5 m NN (decreasing).*

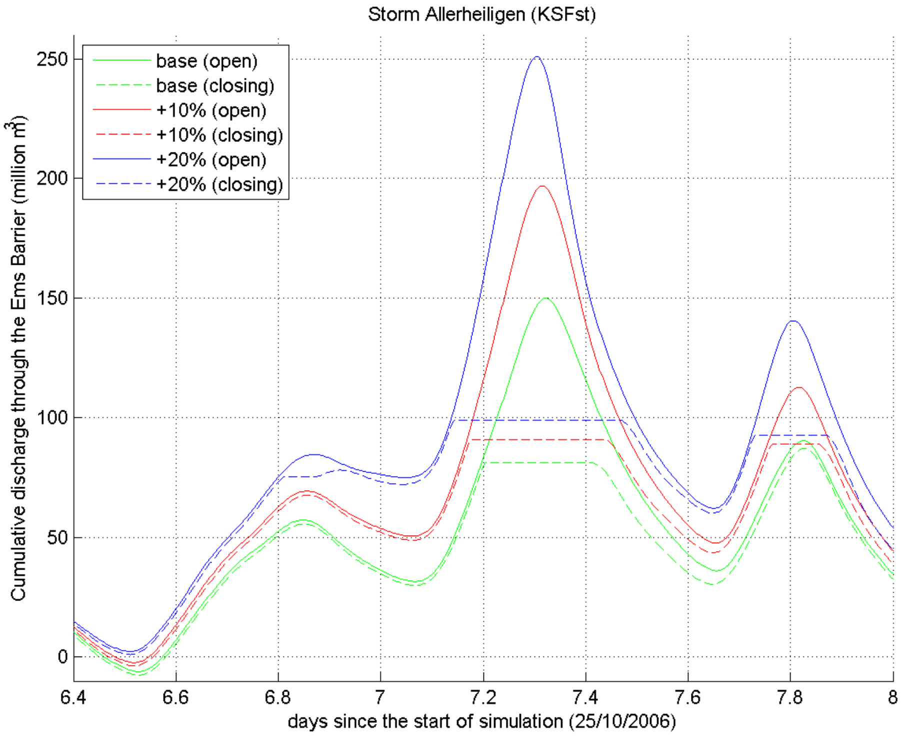

Figure 3.6 *Same as Figure 3.5, but Storm Allerheiligen with 100%, 110% and 120% winds.*

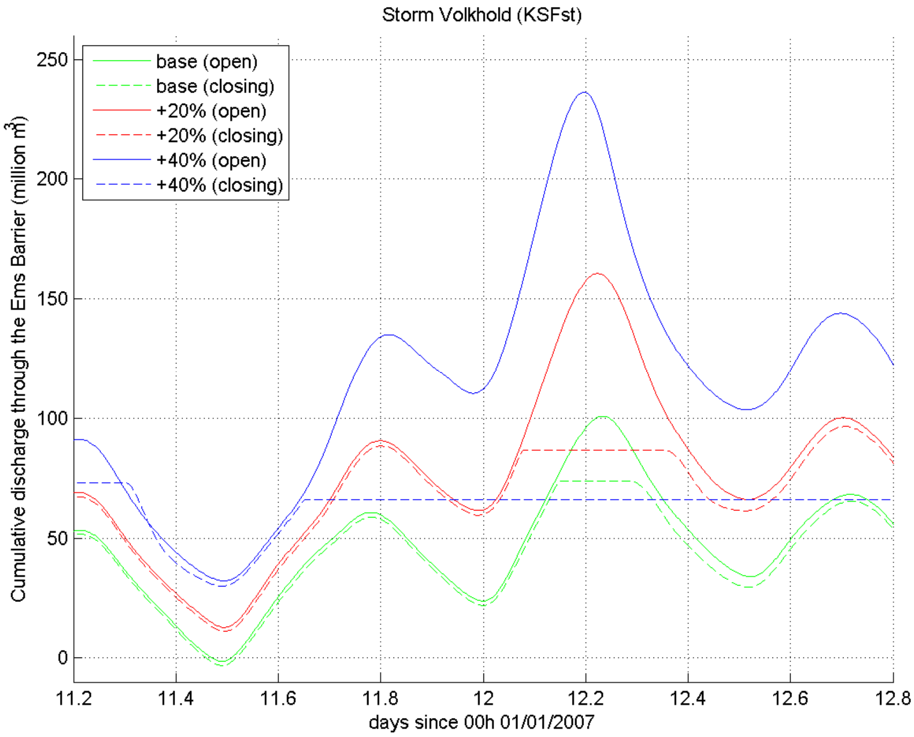

Figure 3.7 *Same as Figure 3.5, but for storm Volkhold.*

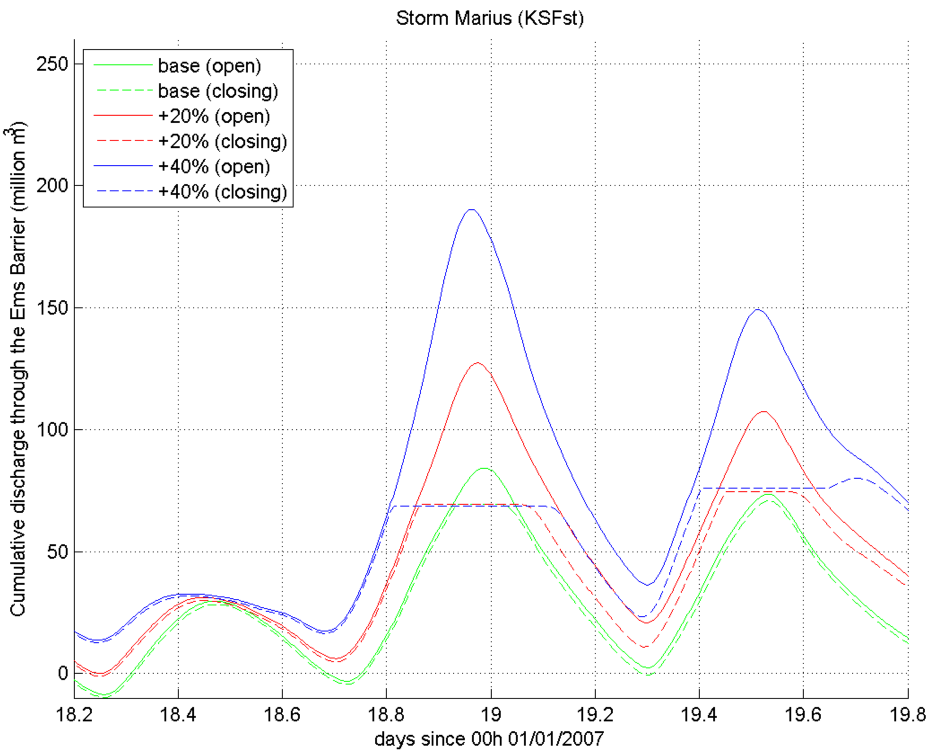

Figure 3.8 *Same as Figure 3.5, but for storm Marius.*

3.3 Water level validation and model sensitivity to wind speed strengthening

Figure 3.9 - Figure 3.15 show results for storm “NoName”; the first two include observed levels and the results from DCSM, ZUNO, KSF4 and KSFst at Huibertgat and at Delfzijl; the following five show results with increasing wind speeds at the five focus locations (Huibertgat, Eemshaven, Delfzijl, Nieuw Statenzijl, and at the Ems Barrier). Figure 3.16 - Figure 3.22 show the same kind of results, only for storm Marius. Figure 3.23 - Figure 3.29 also show the same kind of results, but for storm Volkhold. Figure 3.30 - Figure 3.34 represent storm Allerheiligen, and show results with increasing wind speeds at the five focus locations.

These plots illustrate how the “closing” (incrementally, during the simulation) of the Ems surge barrier, which takes place when local water levels surpass the +3.5 m NAP, generates a sharp, short-scale, peak at the barrier (Figure 3.15, Figure 3.22, Figure 3.29, Figure 3.34).

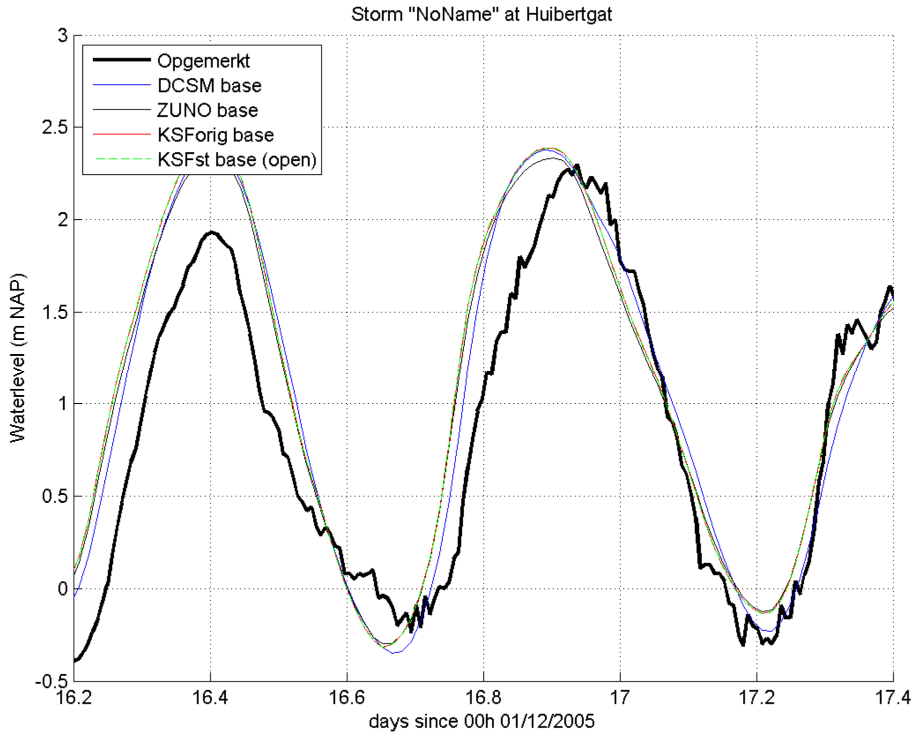

Figure 3.9 *Cascade of modeled water levels for "NoName", at Huibertgat.*

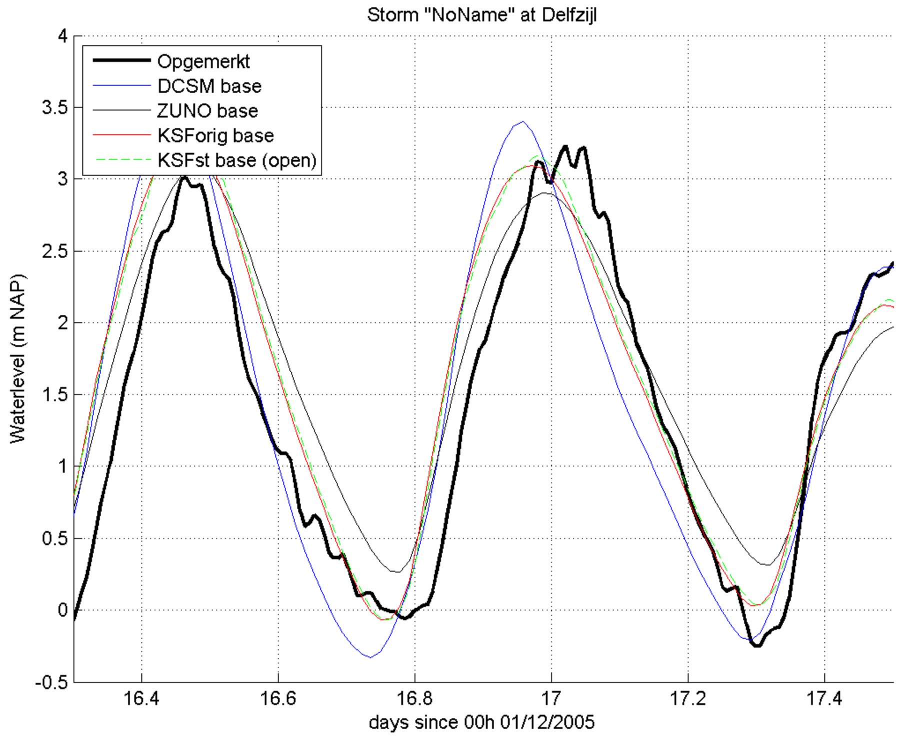

Figure 3.10 *Same as Figure 3.9, but at Delfzijl. Notice change in vertical scale.*

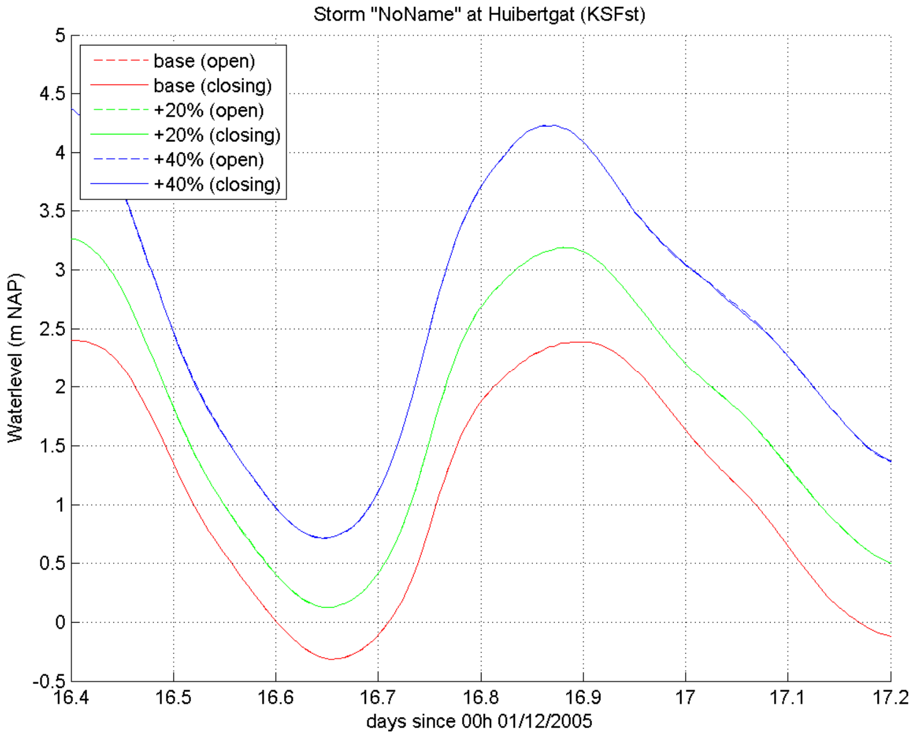

Figure 3.11 *Water levels at Huibertgat for open and closing barrier conditions, modeled with the “stretched” Kuststrook-fijn model (KSFst). Storm NoName with 100%, 120% & 140% wind intensity.*

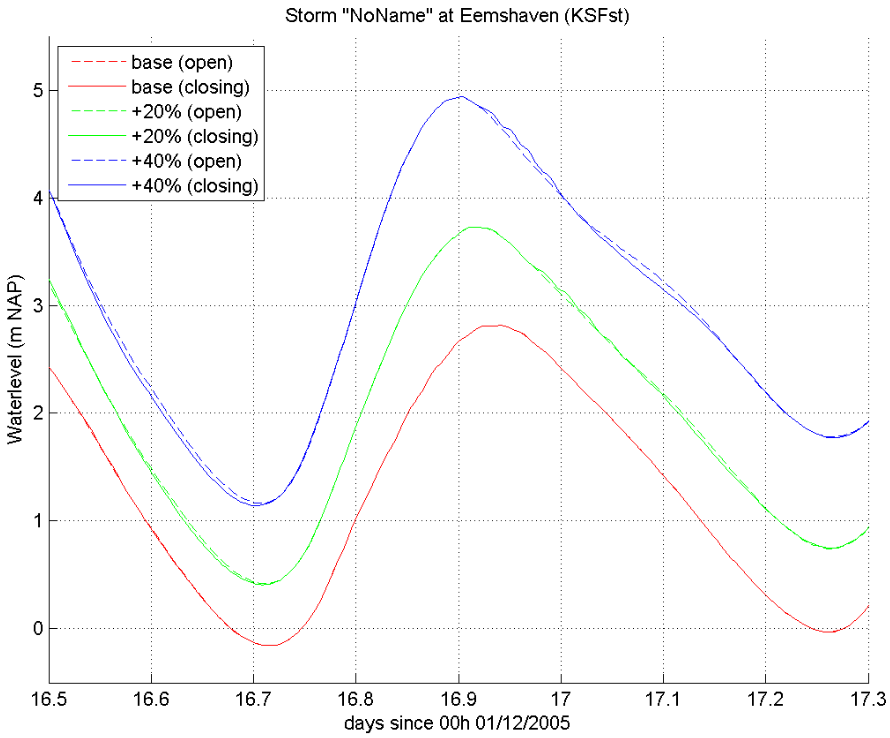

Figure 3.12 *Same as Figure 3.11, but at Eemshaven. Notice change in vertical scale.*

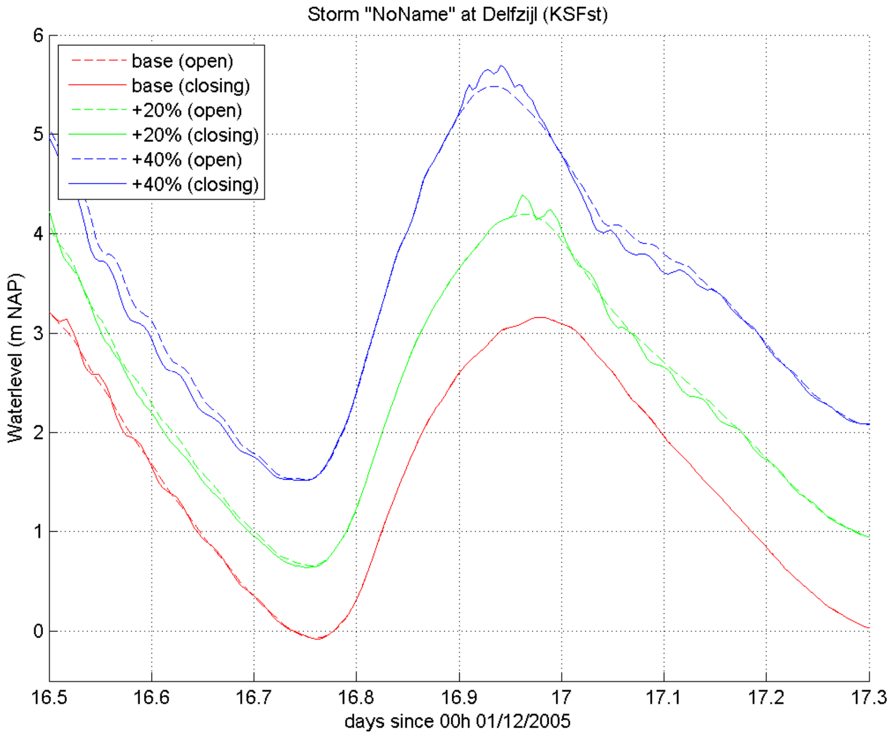

Figure 3.13 Same as Figure 3.11, but at Delfzijl. Notice change in vertical scale.

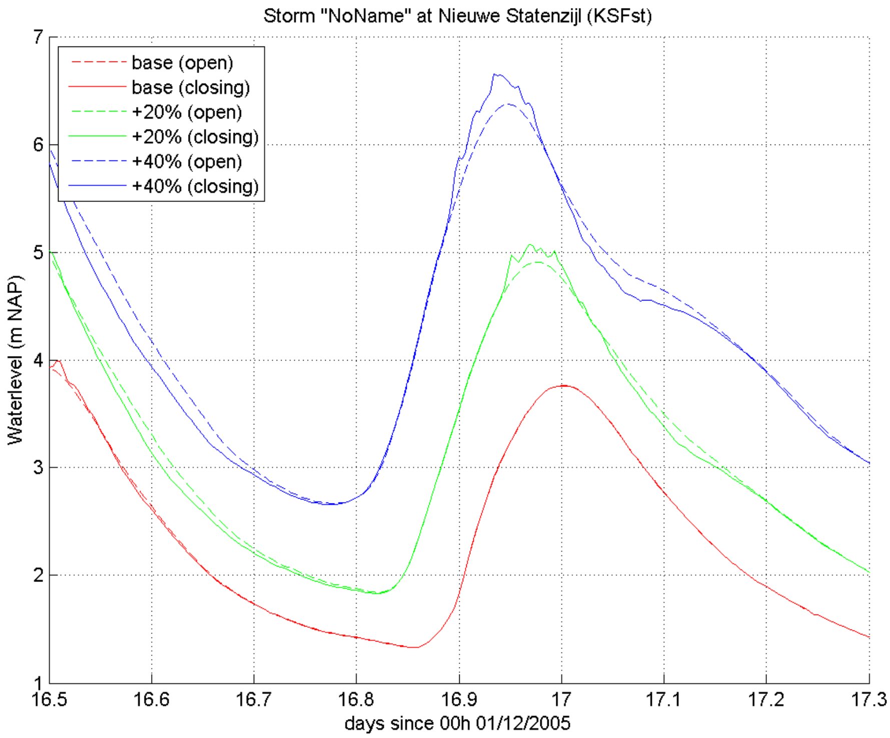

Figure 3.14 Same as Figure 3.11, but at Nieuw Statenzijl. Notice change in vertical scale.

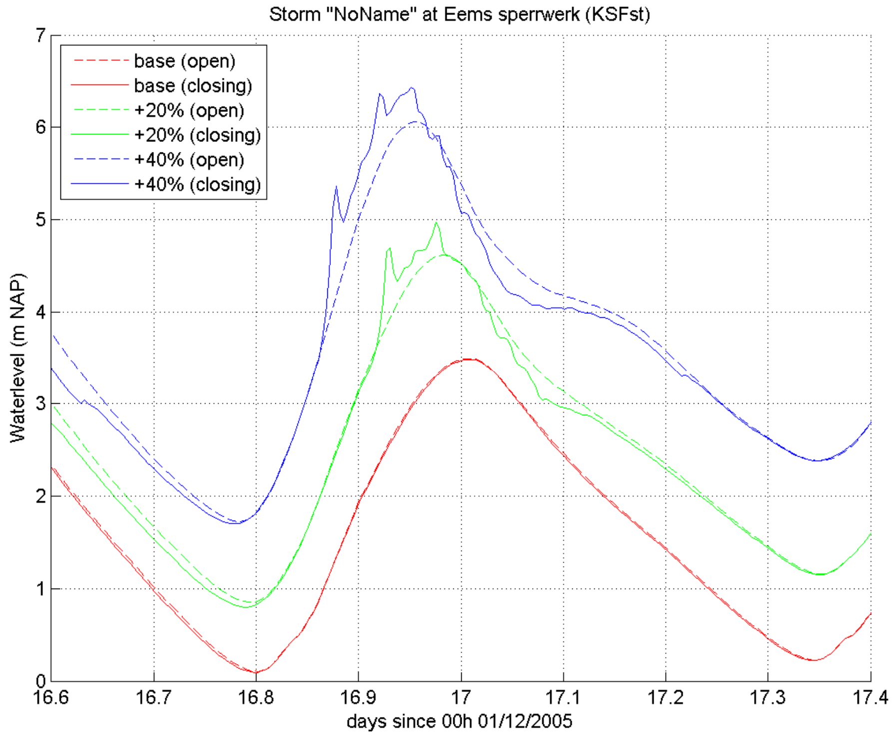

Figure 3.15 *Same as Figure 3.11, but at the Ems Barrier. Notice change in vertical scale.*

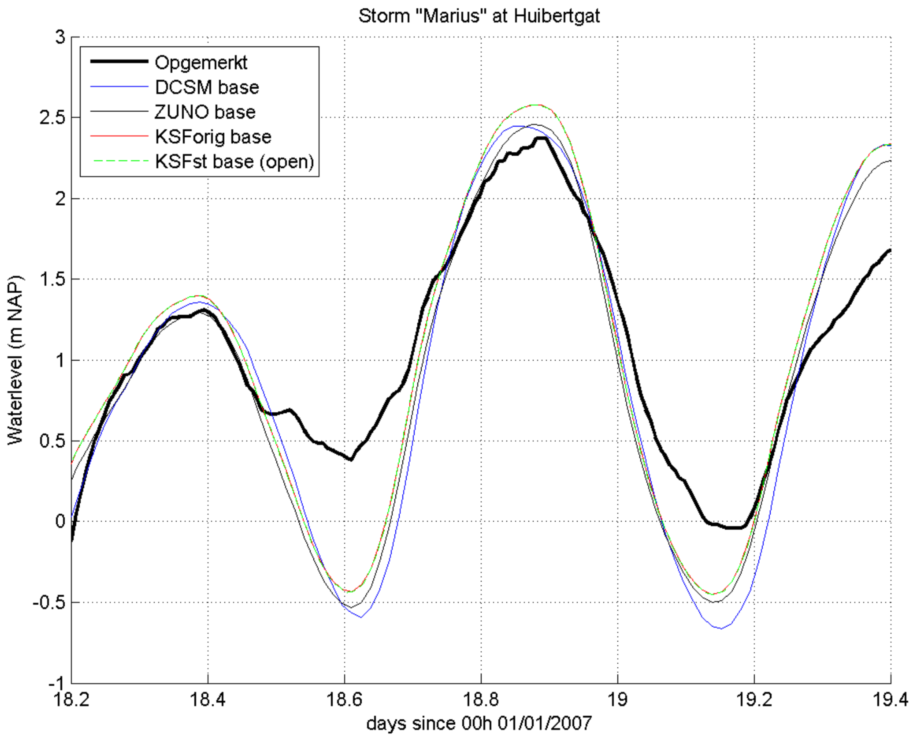

Figure 3.16 *Cascade of modeled water levels for “Marius”, at Huibertgat.*

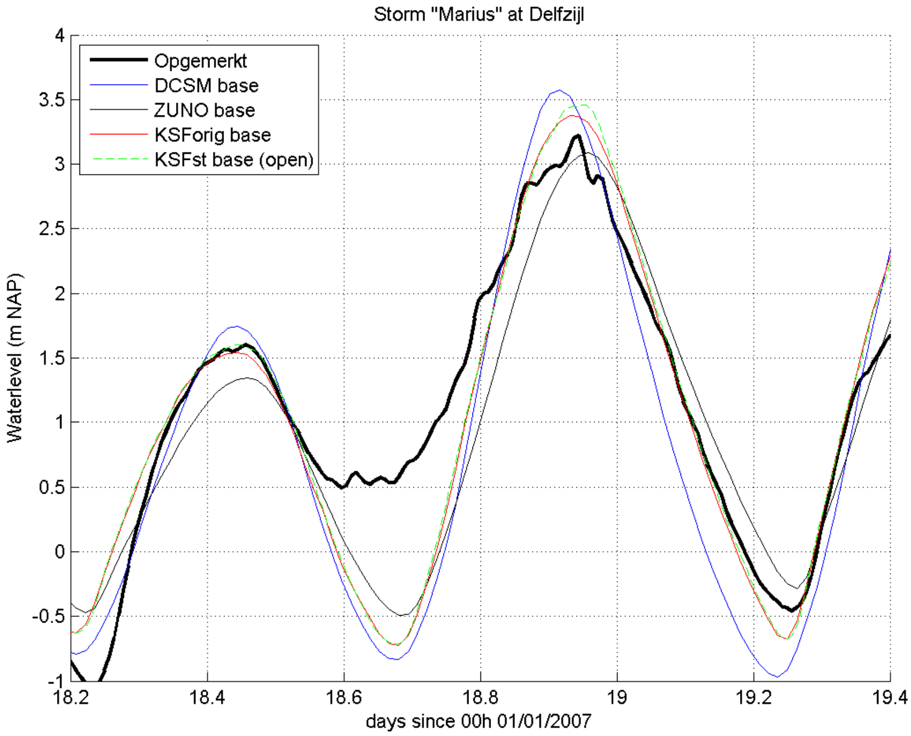

Figure 3.17 *Same as Figure 3.16, but at Delfzijl. Notice change in vertical scale.*

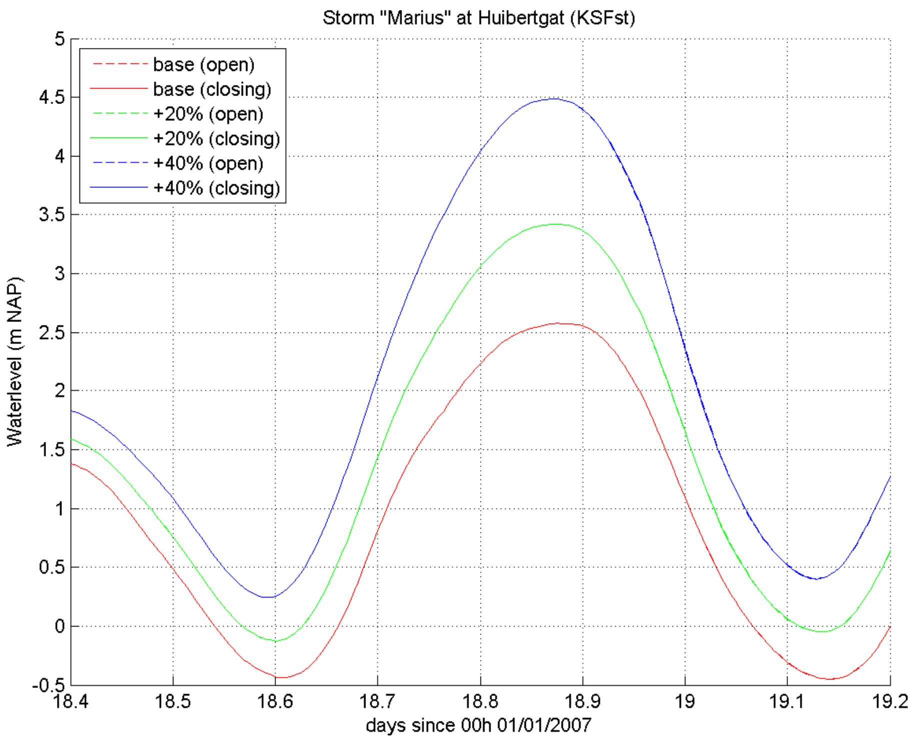

Figure 3.18 *Water levels at Huibertgat for open and closing barrier conditions, modeled with the “stretched” Kuststrook-fijn model (KSFst). Storm Marius with 100%, 120% and 140% wind intensity.*

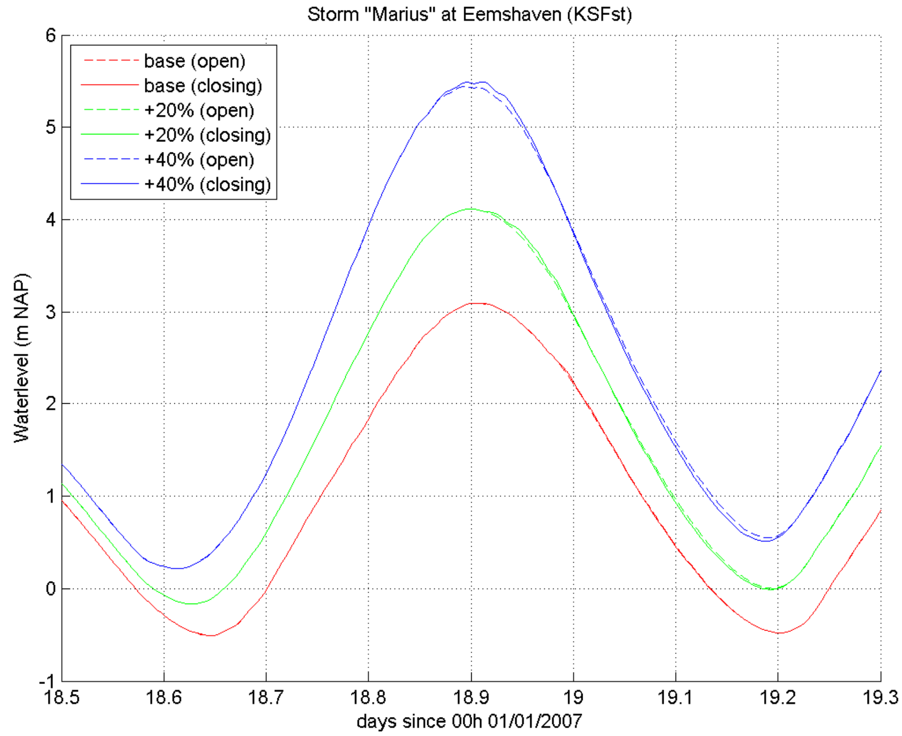

Figure 3.19 Same as Figure 3.18, but at Eemshaven. Notice change in vertical scale.

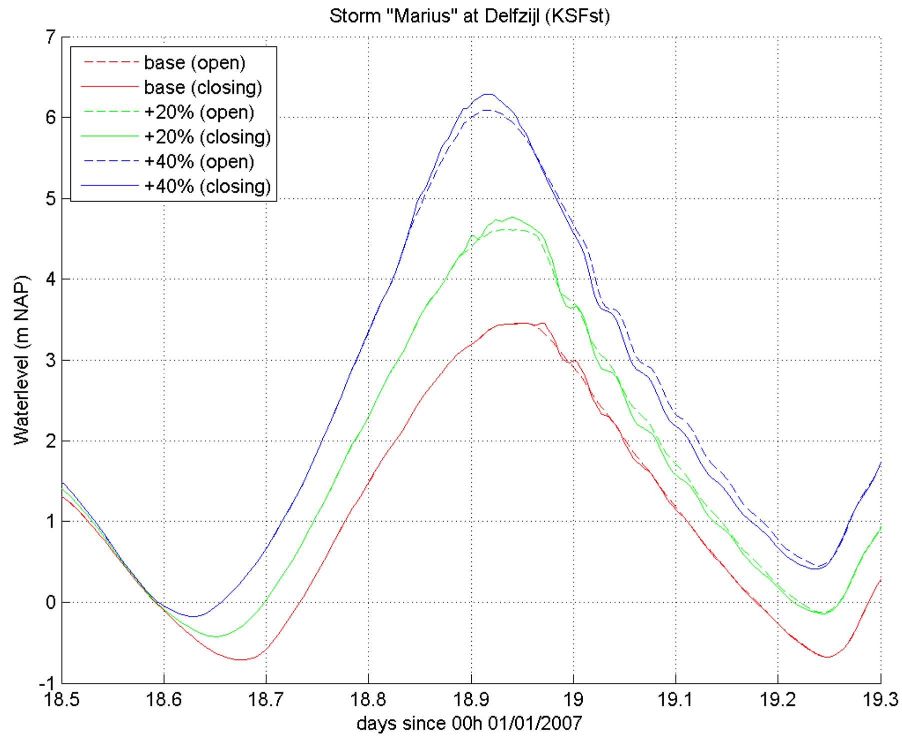

Figure 3.20 Same as Figure 3.18, but at Delfzijl. Notice change in vertical scale.

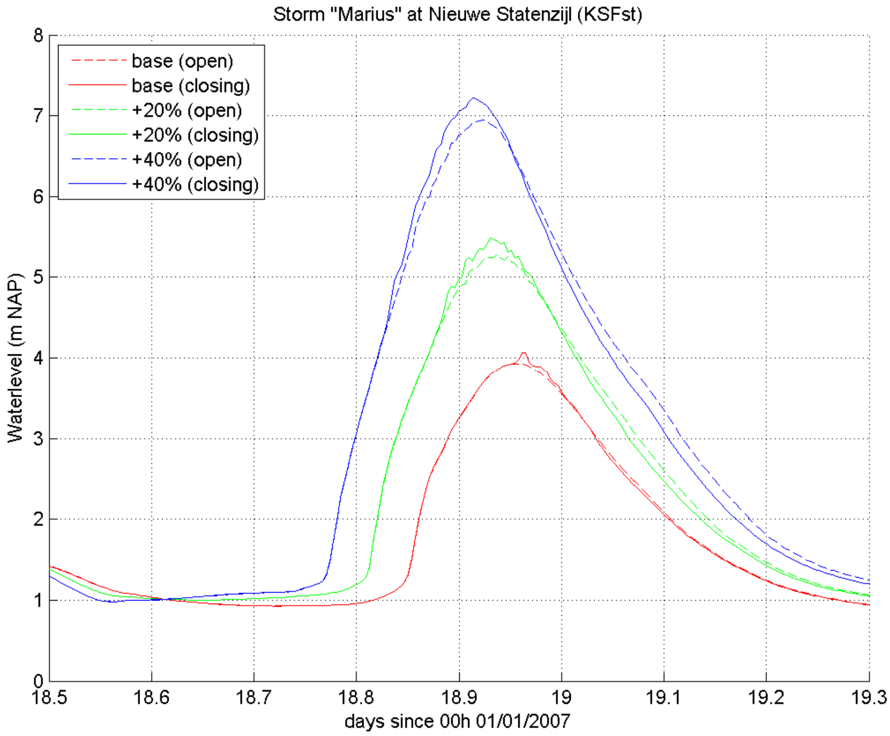

Figure 3.21 *Same as Figure 3.18, but at Nieuw Statenzijl. Notice change in vertical scale.*

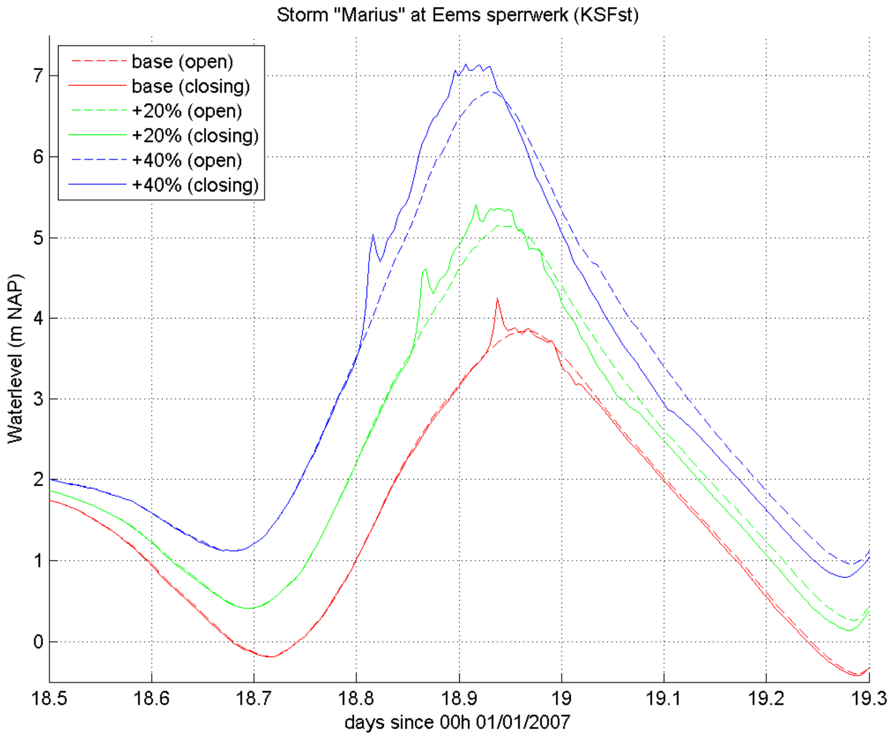

Figure 3.22 *Same as Figure 3.18, but at the Ems Barrier. Notice change in vertical scale.*

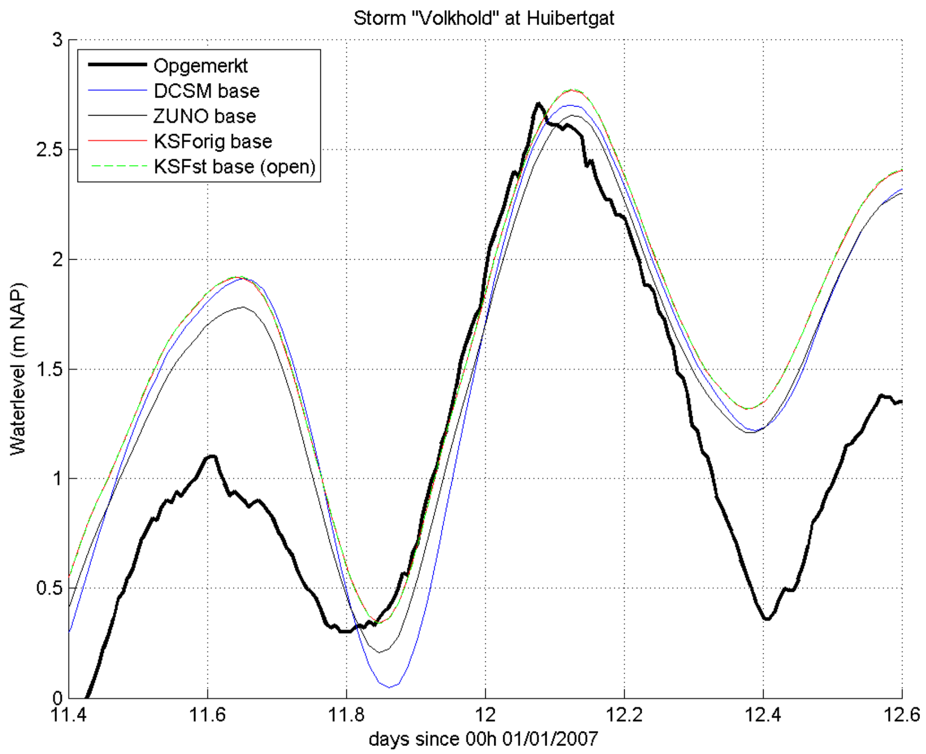

Figure 3.23 Cascade of modeled water levels for Volkhold, at Huibertgat.

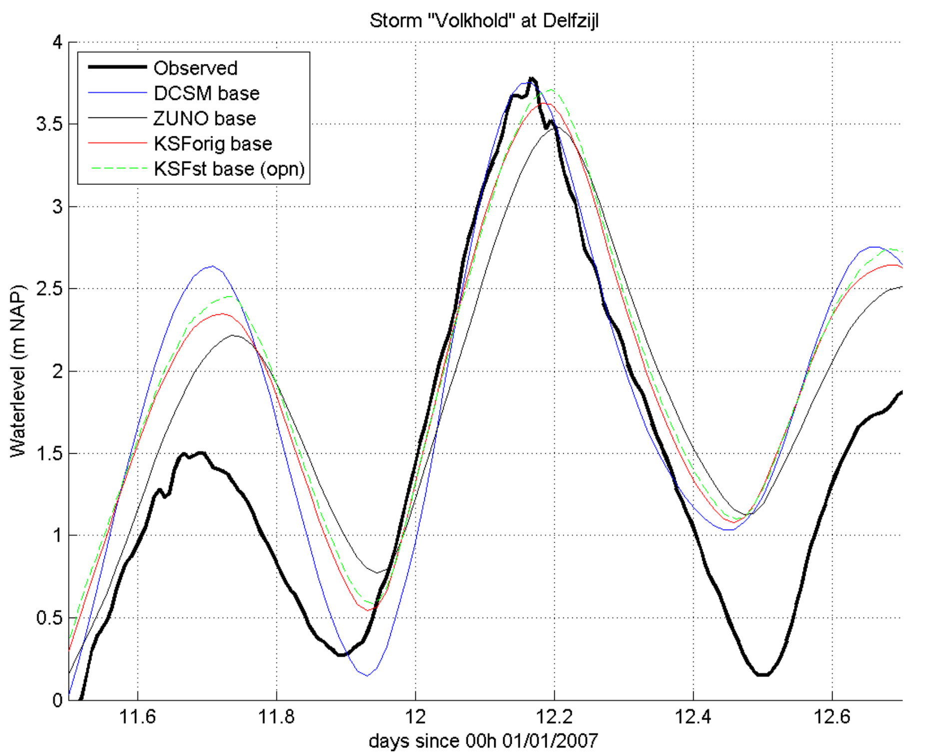

Figure 3.24 Same as Figure 3.23, but at Delfzijl. Notice change in vertical scale.

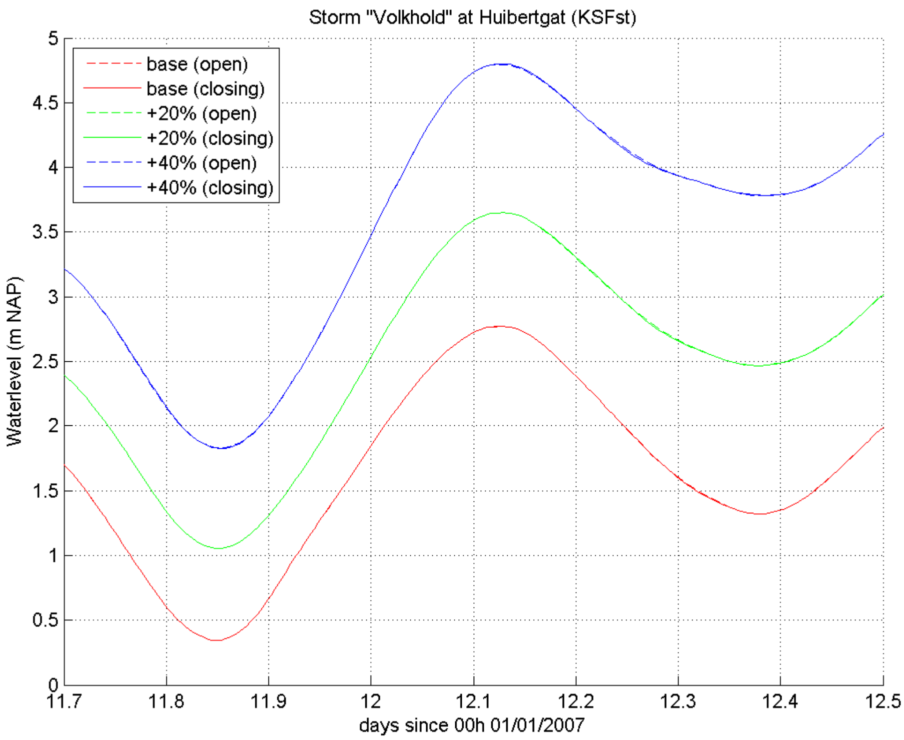

Figure 3.25 *Water levels at Huibertgat for open and closing barrier conditions, modeled with the "stretched" Kuststrook-fijn model (KSFst). Storm Volkhold with 100%, 120% & 140% wind intensity.*

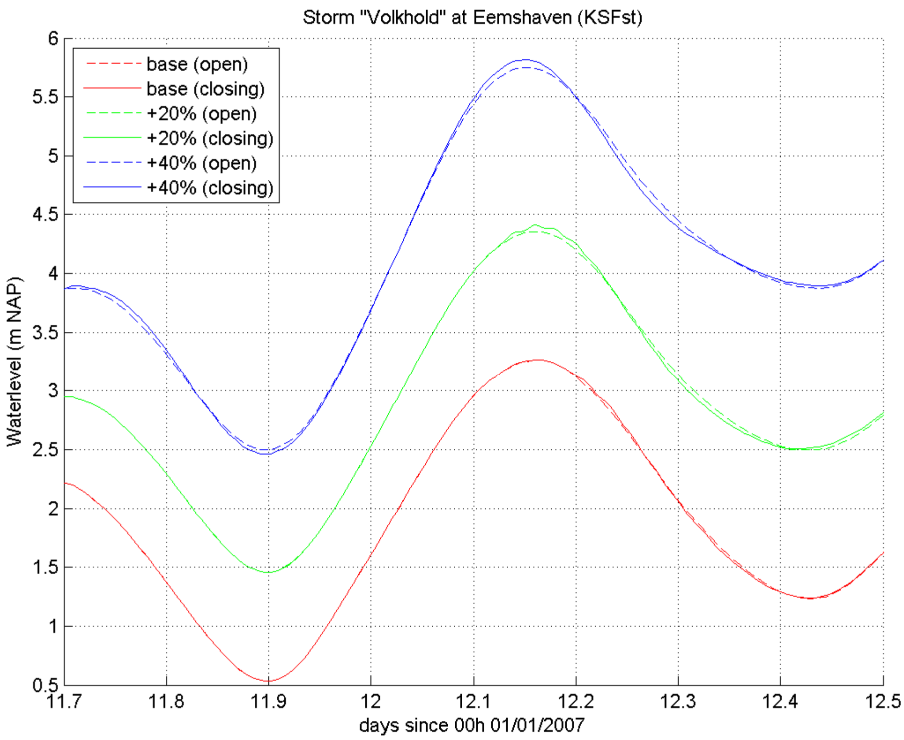

Figure 3.26 *Same as Figure 3.25, but at Eemshaven. Notice change in vertical scale.*

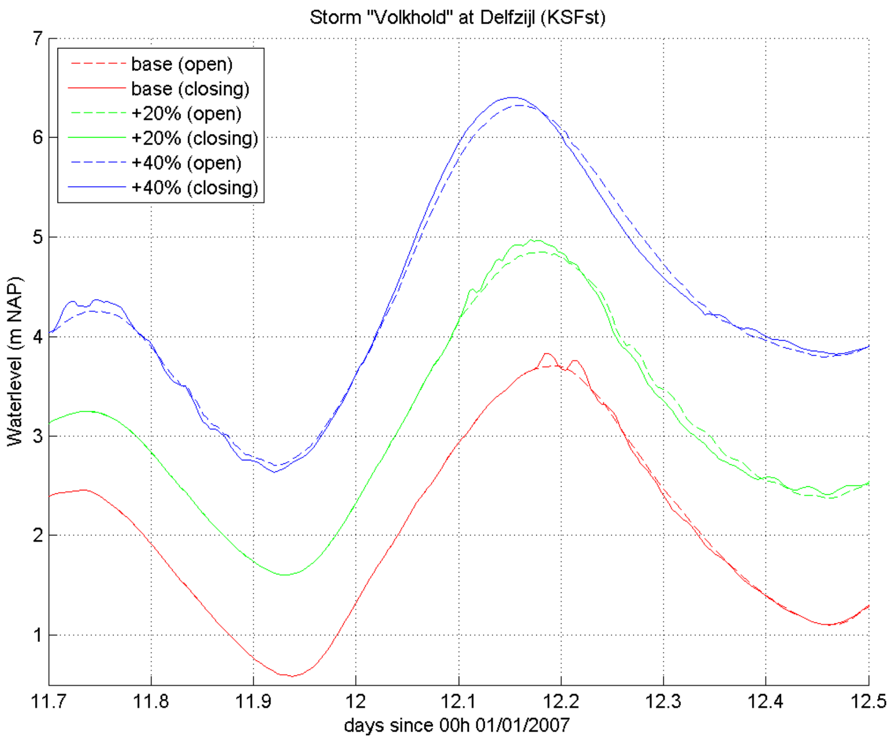

Figure 3.27 *Same as Figure 3.25, but at Delfzijl. Notice change in vertical scale.*

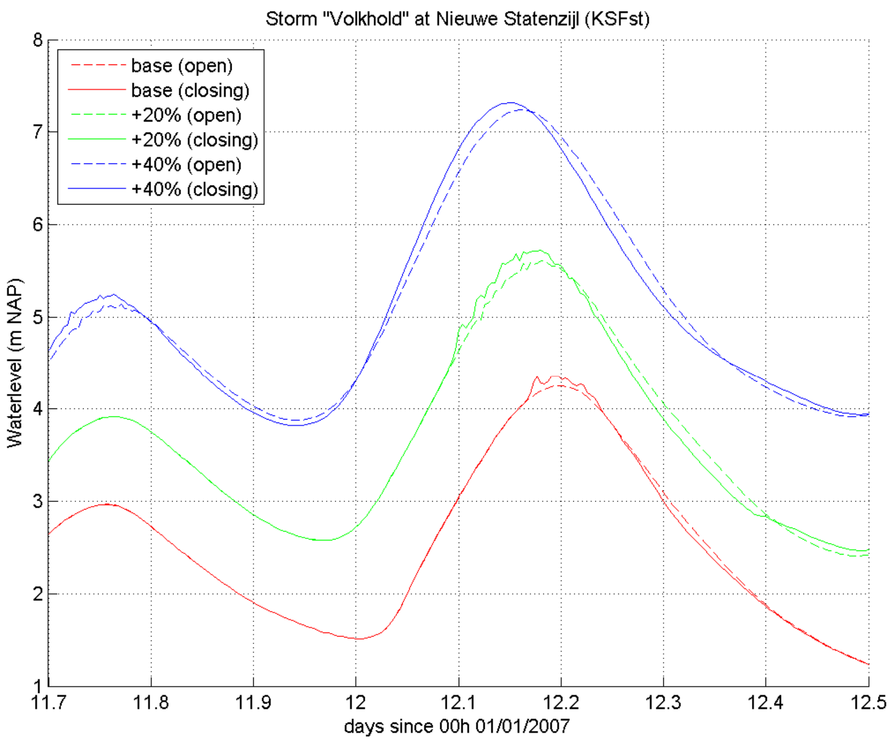

Figure 3.28 *Same as Figure 3.25, but at Nieuw Statenzijl. Notice change in vertical scale.*

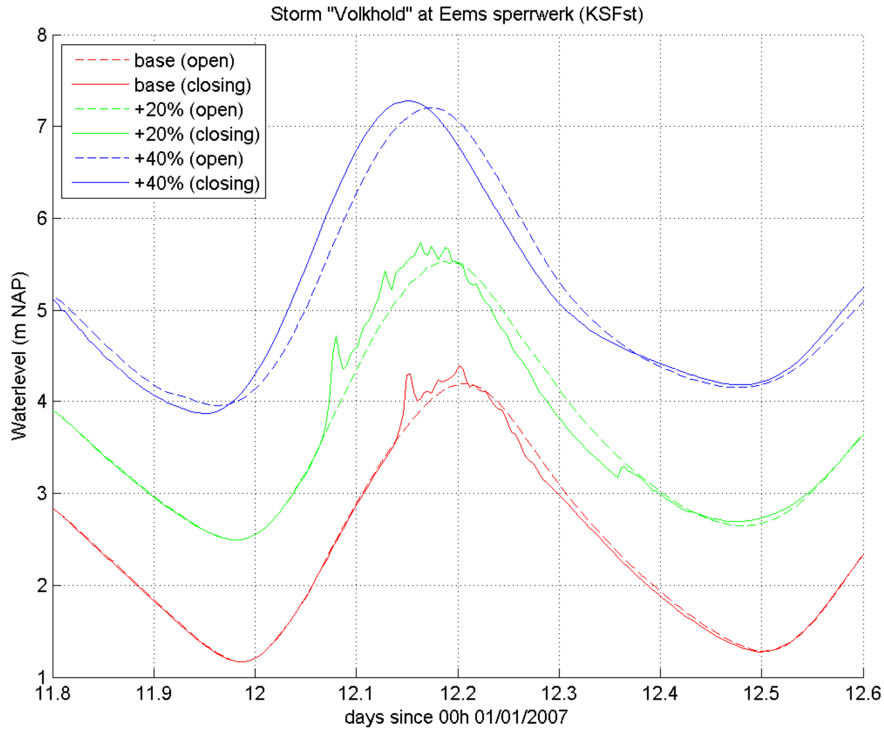

Figure 3.29 *Same as Figure 3.25, but at the Ems Barrier. Notice change in vertical scale.*

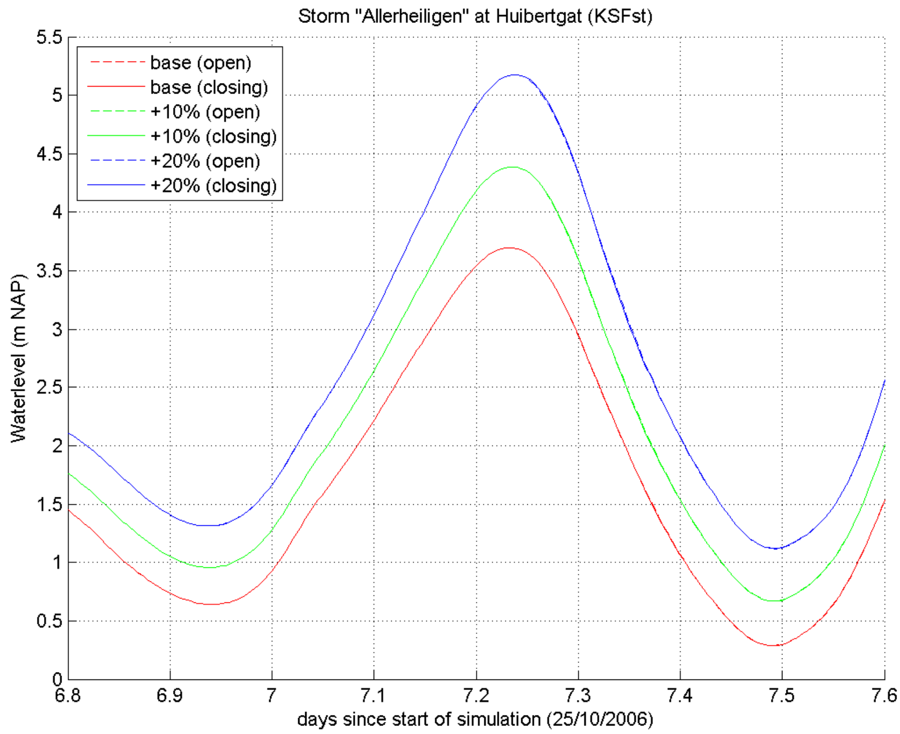

Figure 3.30 *Water levels at Huibertgat for open and closing barrier, modeled with the "stretched" Kuststrook-fijn model (KSFst). Storm Allerheiligen with 100%, 110% & 120% wind intensity. Figure 2.12 shows observed levels.*

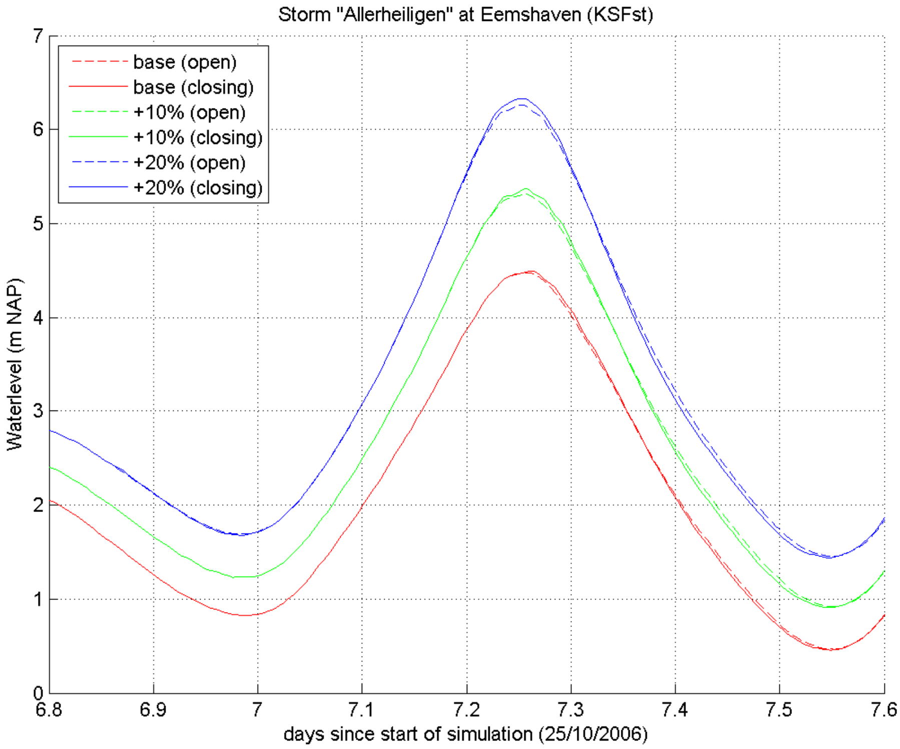

Figure 3.31 *Same as Figure 3.30, but at Eemshaven. Figure 2.13 shows observed levels.*

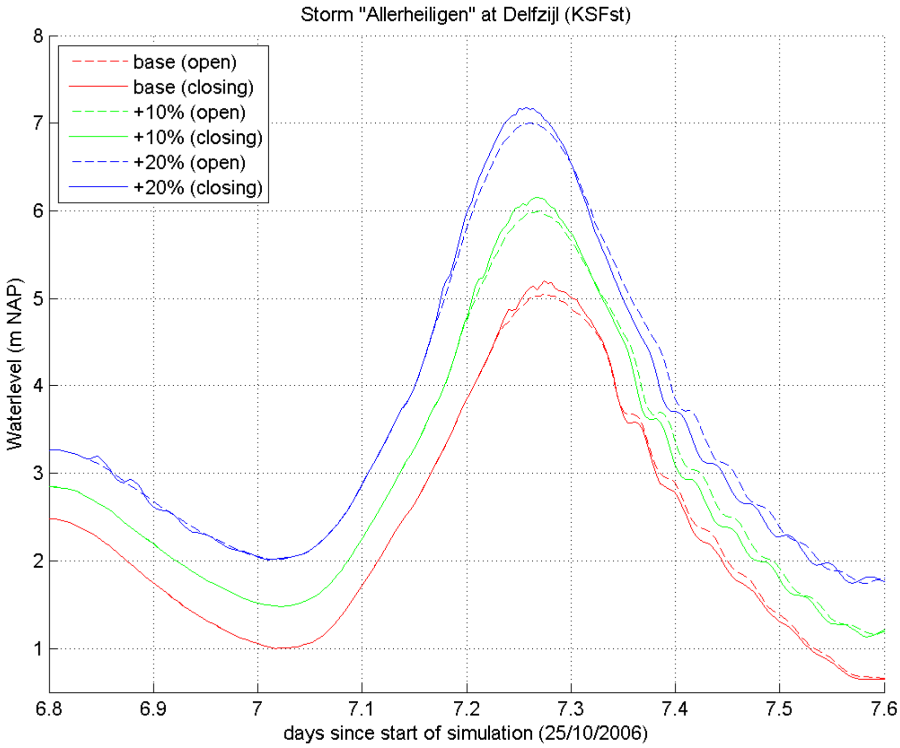

Figure 3.32 *Same as Figure 3.30, but at Delfzijl. Figure 2.15 shows match with observed levels.*

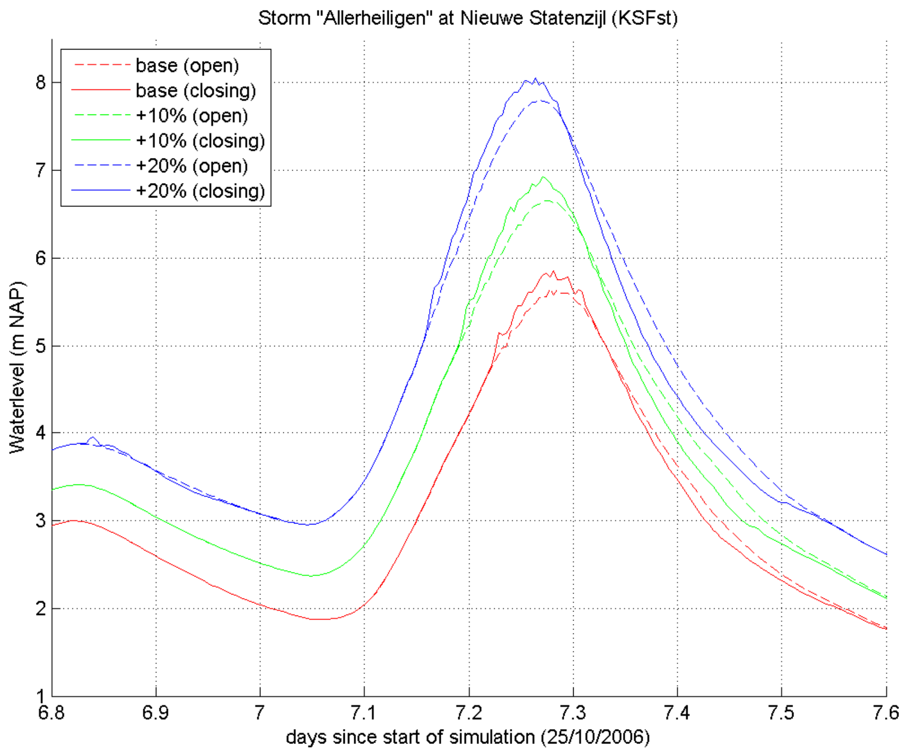

Figure 3.33 Same as Figure 3.30, but at Nieuw Statenzijl. Figure 2.17 shows observed levels.

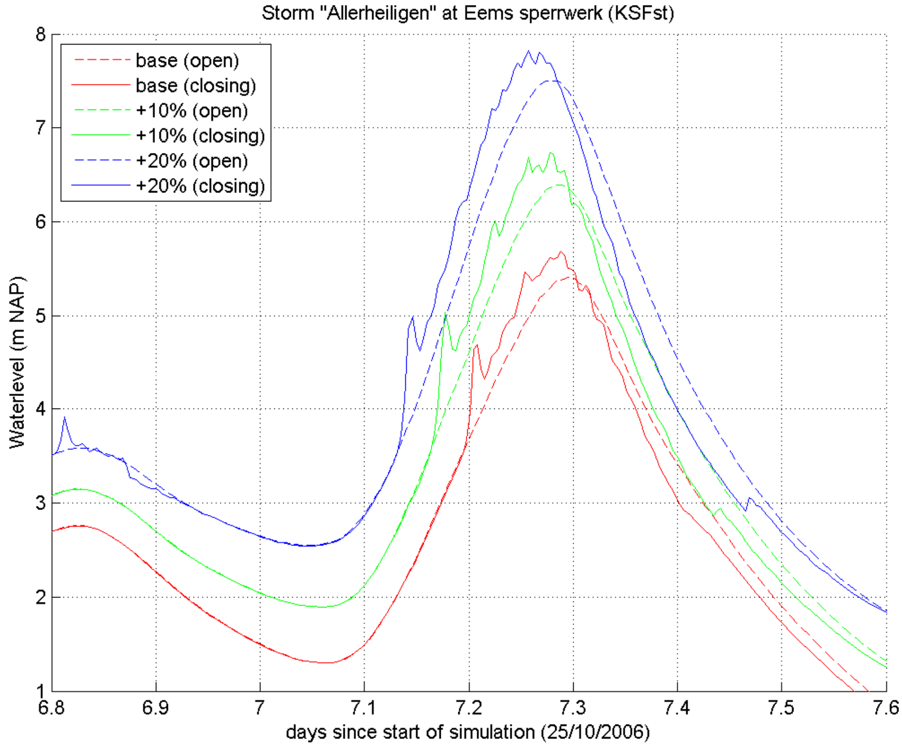

Figure 3.34 Same as Figure 3.30, but at the Ems Barrier. Notice change in vertical scale.

3.4 Effect of the Ems Sperrwerk on peak water levels along Dutch dykes

Results from Section 3.3 are summarized in **Error! Reference source not found.** through Table 3.6, focusing on changes of Δ (i.e., the difference between peak water levels under closed and open barrier). Results for each storm are shown on a separate Table, and each location is analyzed separately. Highwater values that exceed the dyke design level at each location are highlighted in bold (the storm strengthening increments were chosen to surpass design levels, but by a realistic amount).

*Table 3.3 Same as **Error! Reference source not found.**, but for Storm "NoName."*

	Huibertgat			Eemshaven			Delfzijl			Nieuw Statenzijl			Ems Sperrwerk		
	HWop	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*
base	2.387	2.387	0.000	2.817	2.817	0.001	3.342	3.343	0.001	3.760	3.758	-0.002	3.495	3.485	-0.010
+20%	3.192	3.191	-0.001	3.731	3.731	-0.001	4.576	4.718	0.142	4.907	5.072	0.165	4.613	4.967	0.354
+40%	4.230	4.229	0.000	4.936	4.936	-0.001	**6.165**	**6.355**	0.190	6.371	6.648	0.278	6.056	6.435	0.380

*Table 3.4 Same as **Error! Reference source not found.**, but for Storm "Marius."*

	Huibertgat			Eemshaven			Delfzijl			Nieuw Statenzijl			Ems Sperrwerk		
	HWop	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*
base	2.577	2.577	0.000	3.090	3.091	0.001	3.457	3.463	0.006	3.926	4.071	0.145	3.843	4.251	0.408
+20%	3.422	3.422	0.000	4.114	4.115	0.001	4.620	4.769	0.149	5.291	5.486	0.194	5.144	5.411	0.267
+40%	4.487	4.487	0.000	**5.439**	**5.491**	0.052	**6.091**	**6.289**	0.198	**6.949**	**7.216**	0.266	6.805	7.140	0.335

Table 3.5 Summary of HighWater values for Storm "Volkhold" simulations: Results for open and closed Ems surge barrier, as well as the difference (Δ) of these two. Highwater values which exceed the local design levels are highlighted as bold. All values are in meters.

	Huibertgat			Eemshaven			Delfzijl			Nieuw Statenzijl			Ems Sperrwerk		
	HWop	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*
base	2.772	2.772	0.000	3.266	3.267	0.000	3.706	3.832	0.126	4.250	4.359	0.108	4.191	4.394	0.203
+20%	3.650	3.650	0.000	4.356	4.410	0.053	4.853	4.970	0.116	5.607	5.724	0.117	5.529	5.741	0.212
+40%	4.795	4.801	0.006	**5.751**	**5.816**	0.066	**6.322**	**6.405**	0.083	**7.241**	**7.316**	0.076	7.204	7.278	0.074

*Table 3.6 Same as **Error! Reference source not found.** but for Storm "Allerheiligen." Because this was the strongest storm, wind speed increments were smaller (only 10 and 20% increases).*

	Huibertgat			Eemshaven			Delfzijl			Nieuw Statenzijl			Ems Sperrwerk		
	HWop	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*	*HWop*	*HWcl*	*Δ*
base	3.696	3.696	0.000	4.474	4.495	0.020	5.055	5.198	0.142	5.653	5.850	0.197	5.409	5.680	0.271
+10%	4.385	4.385	0.000	5.311	5.372	0.061	**6.003**	**6.151**	0.149	6.658	**6.927**	0.269	6.392	6.731	0.339
+20%	5.173	5.176	0.003	**6.263**	**6.328**	0.066	**7.004**	**7.171**	0.168	**7.798**	**8.052**	0.254	7.503	7.823	0.320

These can be further summarized and viewed in Figure 3.35. This figure shows that different storms yield different values for Δ, indicating that this is not an easily established value. At

Delfzijl, if one excludes smaller peak water levels (<3.5 m), then $0.14 < \Delta < 0.20$. At Nieuw Statenzijl, excluding smaller peak water levels (<4.5 m) yields $0.17 < \Delta < 0.28$. These *ranges* are consistent with expectations from BAW (2007).

Storm Volkhold deviates from the trend in that stronger winds actually produce smaller Δ values. This is because Volkhold had southwesterly winds during peak storm intensity, whereas the other 3 storms had the more common NW (or westerly) peak direction (

Table 3.2). Given the geometry of the estuary, downstream of Delfzijl, the typical storm with NW winds is aligned with the estuary and creates a local surge (that adds on to the external, incoming component). The atypical storm, Volkhold in this example, will thus be less sensitive to local effects. This is a simplified analysis as no storm is constant (wind directions change fast; see Figure 3.2).

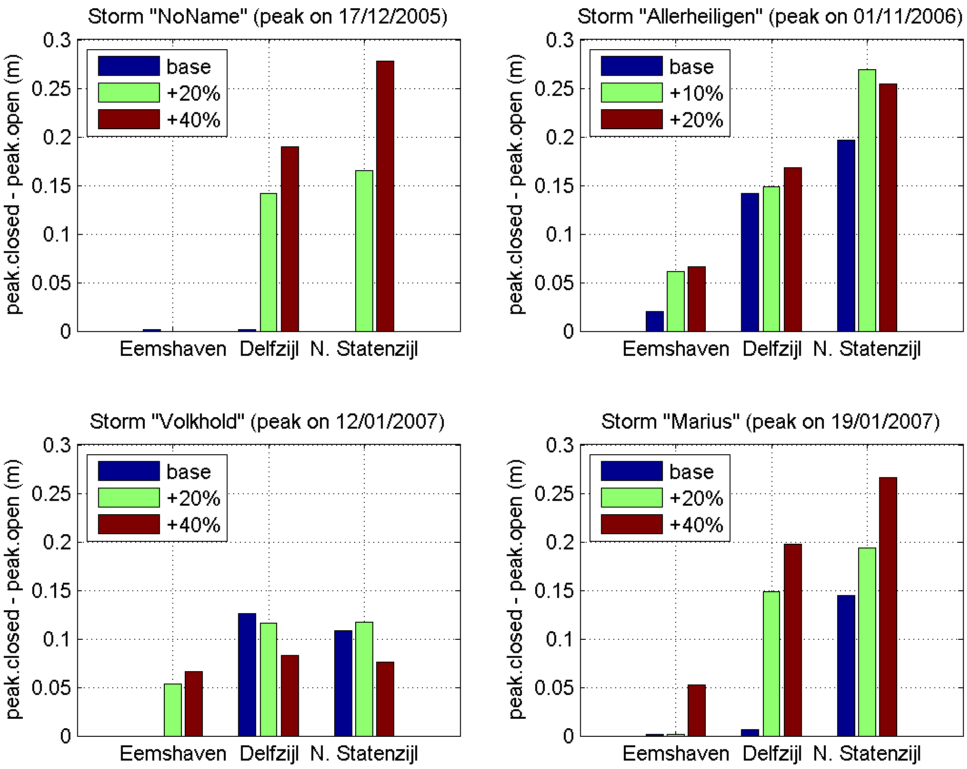

Figure 3.35 Barplot summarizing the increase in peak still water levels caused by the closing of the Ems surge barrier at different locations: Eemshaven, Delfzijl and Nieuw Statenzijl. Each subplot represents one of the 4 storms tested here.

4 Extreme water levels analysis

The relation between Δ (i.e., the difference between peak water levels under closed and open barrier) as a function of "storm intensity" (related to frequency of exceedance) may be of interest, but this varies greatly from location to location. Figure 4.1 offers such a plot, along with linear fits for each location. This is based on the results from Tables 7-10. Figure 4.2 is similar, but excludes data from storm Volkhold (an atypical storm).

4.1 Correcting peak water levels for the effect of the Ems Sperrwerk

Figure 4.1 and Figure 4.2 show plots of Δ against peak highwater with open barrier (with and without data points from Storm Volkhold, respectively). The linear fit equations for the 3 important locations studied here are also shown.

Table 4.1 contains the *R-squared* values of the linear fits and the fit equations for the 3 important locations studied here, with and without data points from Storm Volkhold. Removing such data points considerably improves the correlation coefficients: from 0.47 to 0.74 at Delfzijl, and from 0.37 to 0.73 at Nieuw Statenzijl.

The equation for Eemshaven (slope of 0.021) differs greatly from those at Delfzijl and Nieuw Statenzijl (slopes of 0.050 and 0.056, respectively), indicating that the effect of the barrier is similar in and around the Ems Dollard but that it decreases rapidly towards Huibertgat.

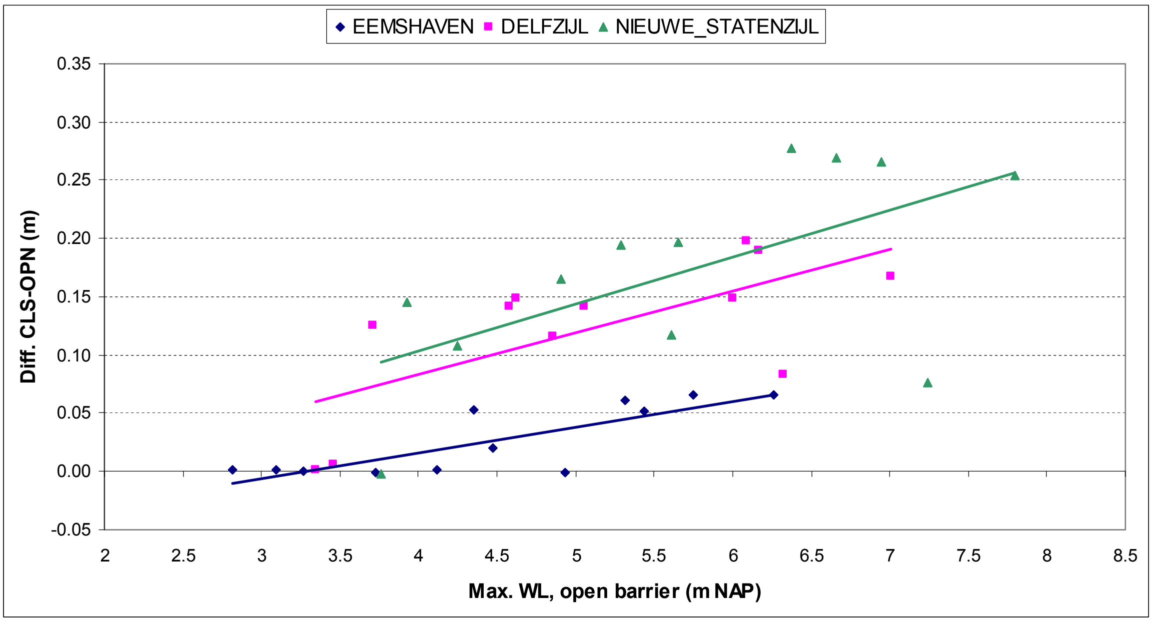

Figure 4.1 *Differences (Peak highwater with closed barrier - Peak highwater with open barrier) as a function of Peak highwater with open barrier. Data from* ***Error! Reference source not found.*** *through Table 3.6. Linear fits shown.*

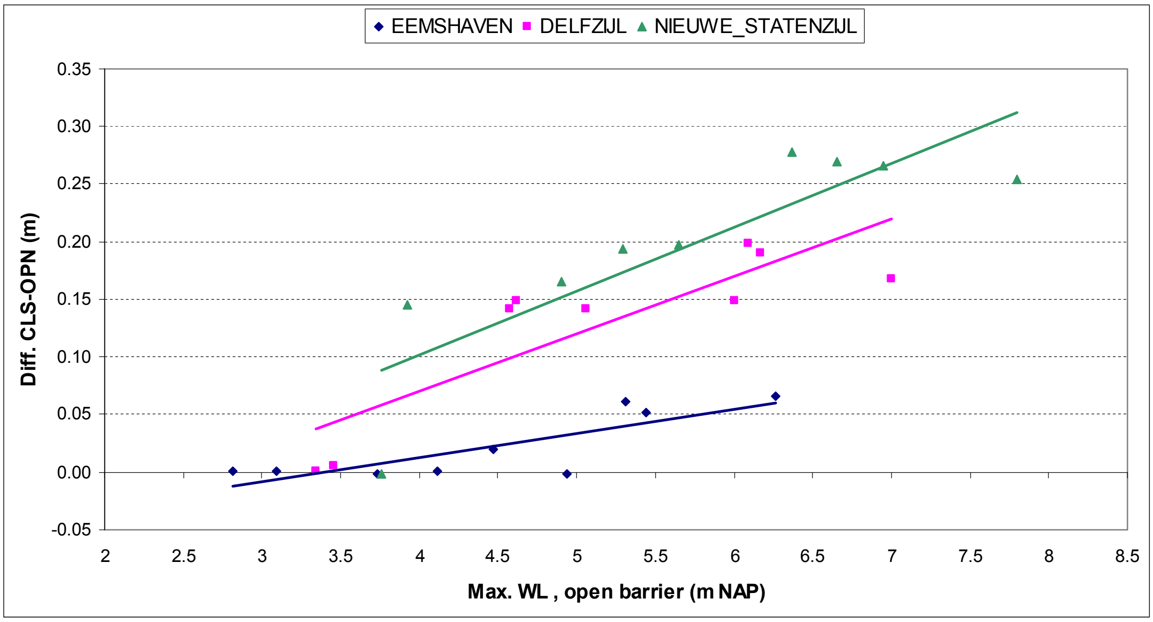

Figure 4.2 *Same as Figure 4.1, but excluding data points of storm Volkhold.*

Table 4.1 *Linear trends summarized (at the three locations of interest).*

	All 4 storms (n=12)		**Excluding Volkhold (n=9)**	
	Linear fit	R^2	Linear fit	R^2
Eemshaven	y = 0.022x - 0.072	0.667	y = 0.021x - 0.072	0.680
Delfzijl	y = 0.036x - 0.061	0.474	y = 0.050x - 0.128	0.741
Nieuwe Statenzijl	y = 0.040x - 0.057	0.372	y = 0.056x - 0.120	0.733

4.2 Determining the range over which these corrections are applicable

In this section we determine at which point (historical) highwater values recorded at tide gauges should be “corrected” for the Ems surge barrier effect. The barrier is known to close for *local* water levels surpassing +3.5 m NN, and a relation is needed between this threshold at the barrier and in other locations (Figure 4.3 - Figure 4.5).

Using the relations derived in Figure 4.3, Figure 4.4 and Figure 4.5 one may compute the peak water level, at each location, above which this “barrier correction” should be applied (i.e. setting x to 3.5). At Delfzijl, this peak value is 3.28 m NAP using the relation with all storms, and 3.32 m NAP using the relation without storm Volkhold.

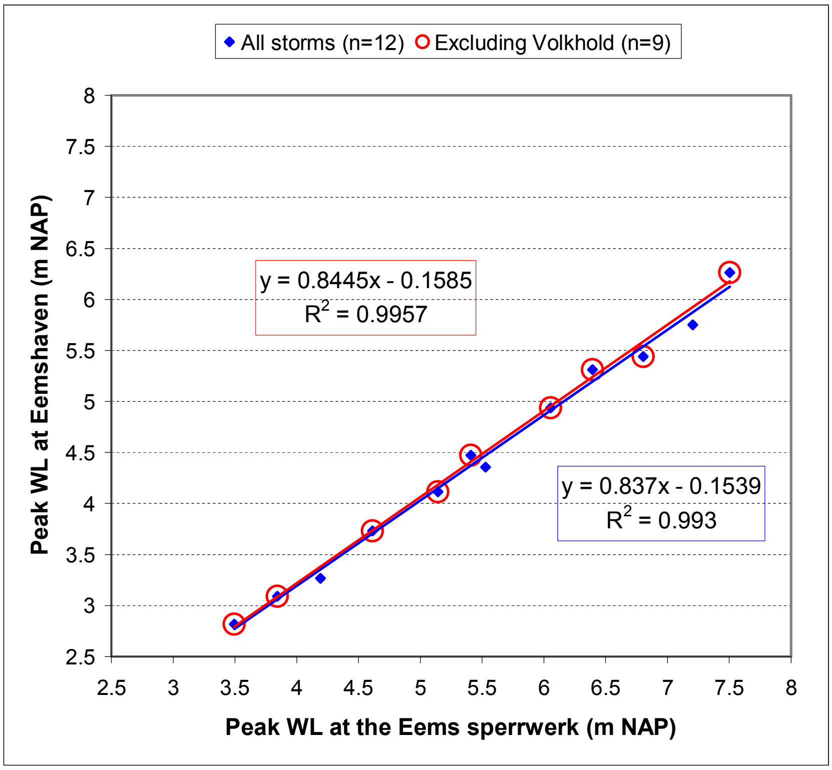

Figure 4.3 *Predicting the peak level at Eemshaven above which the Ems Barrier closes.*

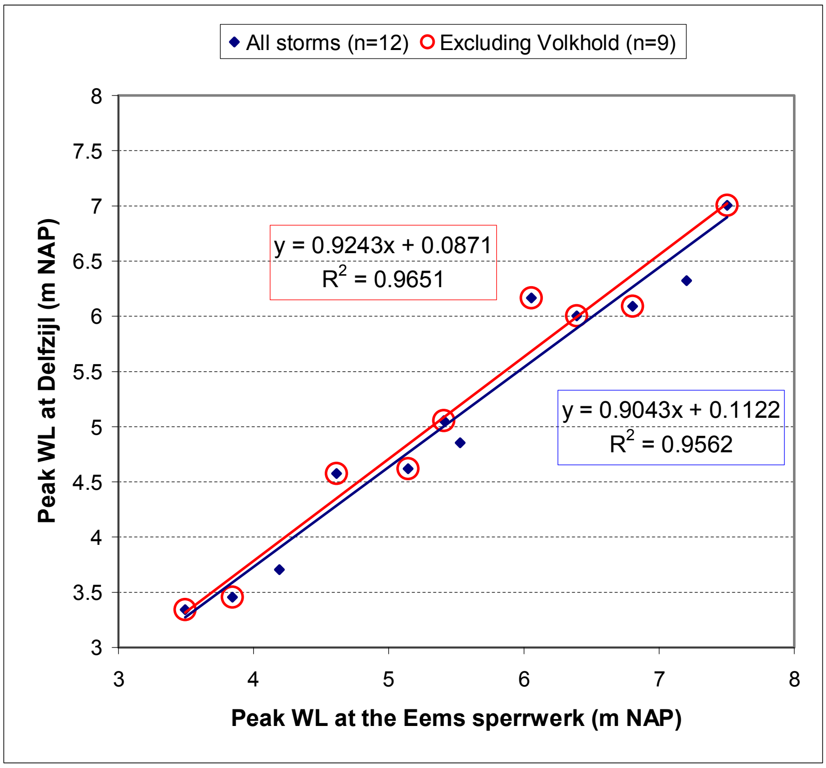

Figure 4.4 *Predicting the peak level at Delfzijl above which the Ems Barrier closes.*

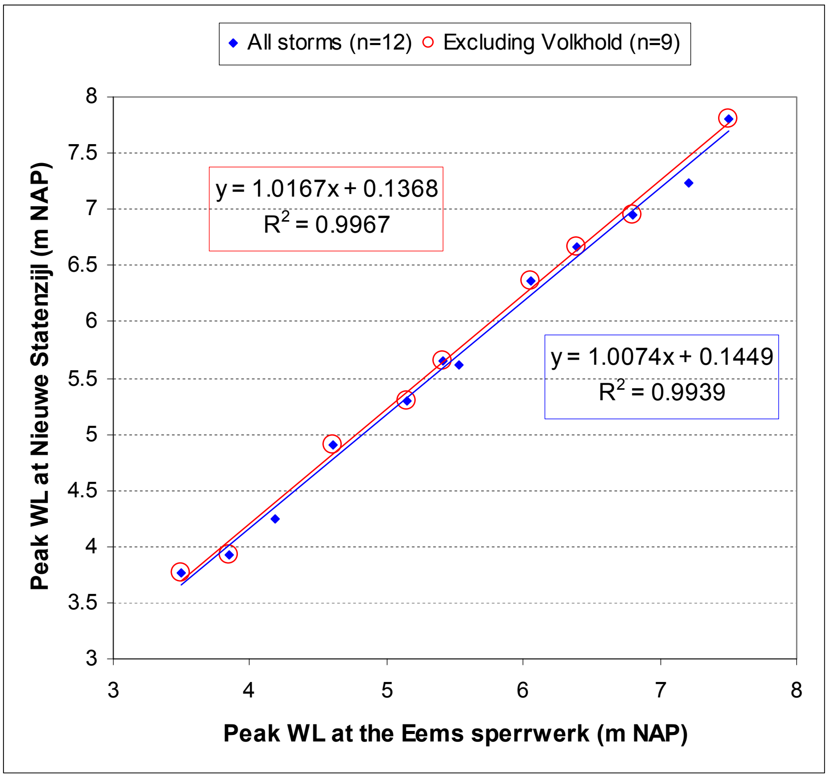

Figure 4.5 Predicting the peak level at Nieuw Statenzijl above which the Ems Barrier closes.

Table 4.2 The threshold peak water level, above which the "barrier correction" should be applied (at the 3 tide gauges studied). Determined using linear fits of Figure 4.3 - Figure 4.5. All shown in meters above NAP.

Relation	**Eemshaven**	**Delfzijl**	**Nieuw Statenzijl**
All storms (n=12)	2.78	3.28	3.67
Excl. Volkhold (n=9)	2.80	3.32	3.70

5 Conclusions

This report aimed at analyzing and quantifying the effect of closing the Ems surge barrier during storms on peak storm water levels near Delfzijl, in the northern Netherlands. The recent study of BAW (2007) indicated that this difference was 0.15 or 0.20 m at Delfzijl during the Allerheiligenvloed (depending on how the barrier was closed in their simulations), whereas a previous study at Deltares (M. Verlaan, *unpublished*) indicated this difference to be only 0.08 m.

In this study we investigated this discrepancy, by performing a detailed hindcast of the "Allerheiligen" storm of Nov. 1, 2006, and in the process we have improved the Kuststrook-fijn model used in operational forecast in the region.

Table 2.11 summarizes the effect, at different locations, of each of the model improvements on the difference between open-barrier and closed-barrier conditions. The new model schematization yields Δ=13.8±0.7 cm at Delfzijl (whereas using the old model, one obtains Δ=7.7±0.3 cm). This is consistent with the results of BAW (2007), i.e. Δ=15 cm for a "closing" barrier (during the simulation). It should be noted that accuracies of tenths of a centimeter are misleading; the BAW (2007) study rounds their Δ values to 5 cm intervals.

At Nieuw Statenzijl, the new model schematization yields Δ=19.4±1.4 cm, whereas using the old model leads to Δ=10.3±0.3 cm. The uncertainty caused by the approximated wind is estimated by showing the sensitivity of results within a reasonable range of wind speed intensities, base case ±2% (see also Figure 2.24).

Other storms which led to the closing of the barrier (put to operation in 2002) were chosen, and intensified to surpass design levels, in increasing steps. This allowed a study of closed-open differences for varying storm types and intensities. Figure 3.35 shows that different storms yield different values for Δ, suggesting this is not an easily established value. At Delfzijl, $0.14 < \Delta < 0.20$. At Nieuw Statenzijl, $0.17 < \Delta < 0.28$. These *ranges* are consistent with expectations from earlier studies.

The relation between Δ as a function of "storm intensity" (related to frequency of exceedance) varies greatly from location to location. Table 4.1 lists the *R-squared* values and the linear fit equations for the 3 important locations studied here, with and without data points from Storm Volkhold (an atypical storm). One may thus compute the threshold peak water level, at Delfzijl, above which this "barrier correction" should be applied (Table 4.2). This peak value is 3.32 m NAP using the relation without storm Volkhold.

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