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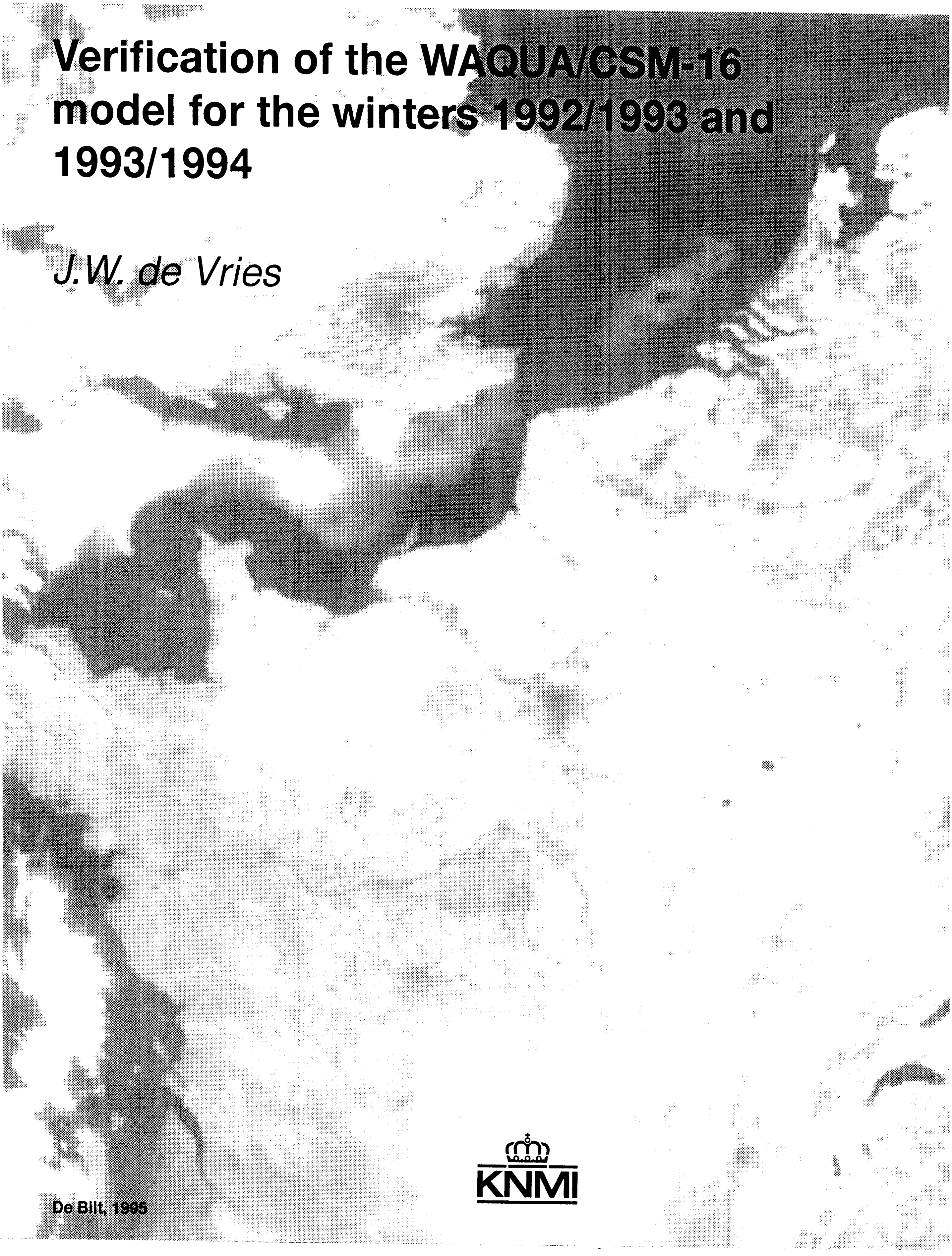

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J.W. de Vries

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Postbus 201
3730 AE De Bilt
the Netherlands
Telephone 030-206 911
Telefax 030-210 407

(after 10-10-'95
tel. +31(0)30-22 06 911
fax +31(0)30-22 10 407)

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Verification of the WAQUA/CSM-16 model for the winters 1992/1993 and 1993/1994

Hans de Vries

Contents

Introduction

1

The WAQUA/CSM-16 model [1, 3], developed by the Dutch National Institute for Coastal and Marine Management (RIKZ), Delft Hydraulics, the former Data Processing Division of Rijkswaterstaat and KNMI, is being used for day-to-day sea level forecasts at KNMI's Marine Meteological Service (MMD) since 1990. The model solves the shallow water equations on the Northwest European Continental Shelf on a $\frac{1}{4}^\circ \times \frac{1}{6}^\circ$ (about 16 km × 16 km) grid, using 10-m wind $\vec{u}_{10}$ and mean sea level pressure p_{msl} input from KNMI's limited area model or the UK Met. Office fine mesh model (UKMO). Furthermore a Kalman filter is used for real-time assimilation of sea level observations.

In 1993 the high resolution local area atmospheric model HIRLAM replaced KNMI's old FM-LAM. This report presents the results of sea level forecasts with input from both models. Unfortunately, lack of computer resources at the time when the coupling of the storm surge model to the new HIRLAM was completed prohibited running both atmospheric models in parallel to enable a more direct comparison of their results. Therefore forecasts made with FM-LAM input are taken from the winter 1992 - 1993 (i.e. September 1992 - April 1993) and the HIRLAM data from the winter 1993 - 1994 (September 1993 - April 1994). For the latter period also results with UKMO input are available.

This report gives an overview of the performance of the model in these periods. Quantities used to identify this performance are: the correlation between the model forecasts and the observations, and the bias and standard deviation of the model forecasts with respect to the observations.

The water level observations and harmonic-analysis astronomical tides have been supplied by RIKZ.

Operational forecasts

2

Sea level forecasts are produced by the WAQUA/CSM-16 model several times per day for 36 hours ahead, closely following the available meteorological input. Hence, a forecast on input from HIRLAM is made 4 times per day and a forecast on UKMO input 2 times per day. Time series from these forecasts for various locations along the North Sea coasts are collected for later evaluation.

The model is equipped with a Kalman filter module which allows for assimilation of observed sea levels in the model [4, 5]. As the atmospheric models need 3 - 4 hours for their data assimilation and forecast runs, WAQUA/CSM-16 runs 3 - 4 hours after the start of the forecast, and hence can already assimilate observed sea levels up to that moment.

Data assimilation gives a significant contribution to the high accuracy which is especially required for the management of the storm surge barrier in the Oosterschelde and the one under construction in the Rotterdam Waterway. Unlike in atmospheric modelling, however, it is not a vital part of sea level forecasting. Therefore, model results both with and without data assimilation are available for the meteorologist. This enables an assessment of the effect of data assimilation and provides a backup in the (rare) case that bad observations pass the quality control algorithm (described in [11]) and are assimilated into the model, spoiling the forecasts instead of improving them. Moreover, it appears from the evaluation that after a certain forecast period the forecasts *with* data assimilation are *worse* than the forecasts without data assimilation (see Section 4.2).

Evaluation

3

For meaningful operational use it is important not only to have the model forecasts themselves, but also to know the characteristics of the model results. Of course a meteorologist who uses the model will after some time acquire some experience with its behaviour. Nevertheless, continuous *objective* evaluation of model results is required. In different institutes or communities, the terminology for evaluating or validating models is not unique. Dee [2] e.g. would classify the work which is described in this Report as part of the "functional validation". At KNMI usually the term "verification" is used.

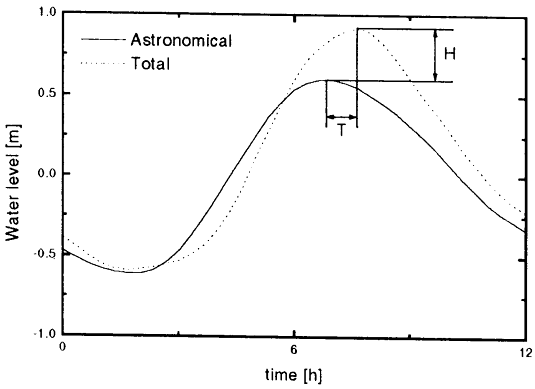

Figure 3.1: Definition of the skew surge and time shift

For the verification, the model skew surges (H) and time shifts (T), defined in Figure 3.1, are compared with observations:

$$\Delta H = H_{\text{mod}} - H_{\text{obs}}$$

$$\Delta T = T_{\text{mod}} - T_{\text{obs}},$$

where the subscript **mod** indicates a model result and the subscript **obs** the corresponding observation.

Averages, standard deviations and root mean square errors of these are calculated. The average (or bias) $\overline{x}$, standard deviation σ_x and root mean square error RMS_x in the quantity x are defined as

$$\overline{x} = \sum_i \frac{x_i}{N},$$

$$\sigma_x^2 = \sum_i \frac{(x_i - \overline{x})^2}{N-1}$$

and

$$\mathrm{RMS}_x^2 = \sum_i \frac{x_i^2}{N},$$

implying that

$$\sigma_x^2 = \frac{N}{N-1}\left(\mathrm{RMS}_x^2 - \overline{x}^2\right).$$

Results

4

A storm surge season yields a wealth of data which can be used for verification — in each location roughly two high and two low tides per day and four forecasts of 36 hours ahead on HIRLAM (or FM-LAM) input and two on input from UKMO.

In the selection of results for presentation the following issues played a role:

1. High and low tides are always presented separately. It appears that the model characteristics for both are too different to justify a combined treatment.
2. The model skew surge plotted versus the observed skew surge shows the scatter of the forecasts around the average and systematic deviations of the forecasts from the observations. Forecast period ranges of 12 hours are taken together.
3. The bias and standard deviation of the skew surge errors as a function of the forecast period show the average error growth in the model. Generally all dependence on the height of the surge itself is lost.
   The biases and standard deviations are calculated over a forecast period interval and assigned to its centre. The length of these intervals has to be chosen with care. If it is too short, the results might show the characteristics of specific events rather than the average characteristics of the model system.

   As an example one could consider a forecast interval of three hours for sea level forecasts on HIRLAM input. The repetition period of 6 hours causes every second interval of 3 hours to contain forecasts for the same group of tides and forecasts for completely different sets of tides in neighbouring intervals. Experience learns that successive forecasts for the same tide do not change dramatically and therefore the results for all odd intervals and all even intervals will be strongly correlated, but the results for neighbouring intervals need not. This is even more so because the main period of the tidal signal (12^h25^m for the M_2 constituent) is close to an integral multiple of the repetition period of the forecasts, which brings different forecasts for successive tides (e.g. part of the same storm surge) close together in the same 3-hour interval. This effect might lead to an oscillating behaviour of the bias or standard deviation, especially when the total number of forecasts is not very large. In data for one month this can be seen clearly and sometimes even in data for as much as eight months. A safe way to avoid this problem is to take the forecast interval for averaging equal to the repetition period of the forecasts, i.e. 6 hours for HIRLAM and 12 hours for UKMO.

4. Statistics of the time shift errors either show the model time step or the fact that the exact moment of the tidal extreme is not a relevant quantity when the sea level is more or less constant during a few hours around the tidal extreme. This is the case along the Dutch coast due to the interference between the tidal wave which propagates through the Southern Bight of the North Sea and the part which directly crosses from the Britisch coast to the German Bight. Therefore, presentation of the time shift data does not give interesting information.

This report will focus on results for Vlissingen, Roompot Buiten, Hoek van Holland, Den Helder, Harlingen, Delfzijl, Wick, Lowestoft and Southend. The first six give a good coverage of the Dutch coast and are the basic locations for the Storm Surge Warning Service SVSD; Lowestoft and Southend are examples for the British coast and Wick, at the Northeast coast of Schotland is very important for the assessment of external surges, both by the meteorologist and the Kalman filter.

Forecasts for Cuxhaven are used by the city of Hamburg for flood protection. Evaluation of these forecasts will be the subject of a separate report.

Periods chosen are September 1992 – April 1993, when FM-LAM was still fully operational and September 1993 – April 1994 when the wind and pressure input was coming from HIRLAM and an alternative version on input from UKMO was available. Both April months are included. The last winter period has been divided into two: During December 1993 it became clear that the observations from Dover which were assimilated into the model, were suffering from a systematic offset of ±70 cm [10]. On average this neutralizes the positive effect of the assimilation of other observations, especially in the Southern North Sea. From January 1994 observations from Dover are no longer assimilated and the Kalman filter can again improve the forecasts.

4.1 Model versus observed skew surges

Contour plots of the model skew surges (H_{waq} without and H_{kal} with Kalman filter) versus the observed skew surges (H_{obs}) are given in Figures 4.1 – 4.5. Results are only given for Hoek van Holland: all stations show essentially the same features, although the location and width of the figure, reflecting the bias and standard deviation, might be different.

Figures 4.1 – 4.5 show on the upper row the forecasts for high (H1) and low (L1) tides for forecast periods t_f between 0 and 12 hours ahead without Kalman filter; the second

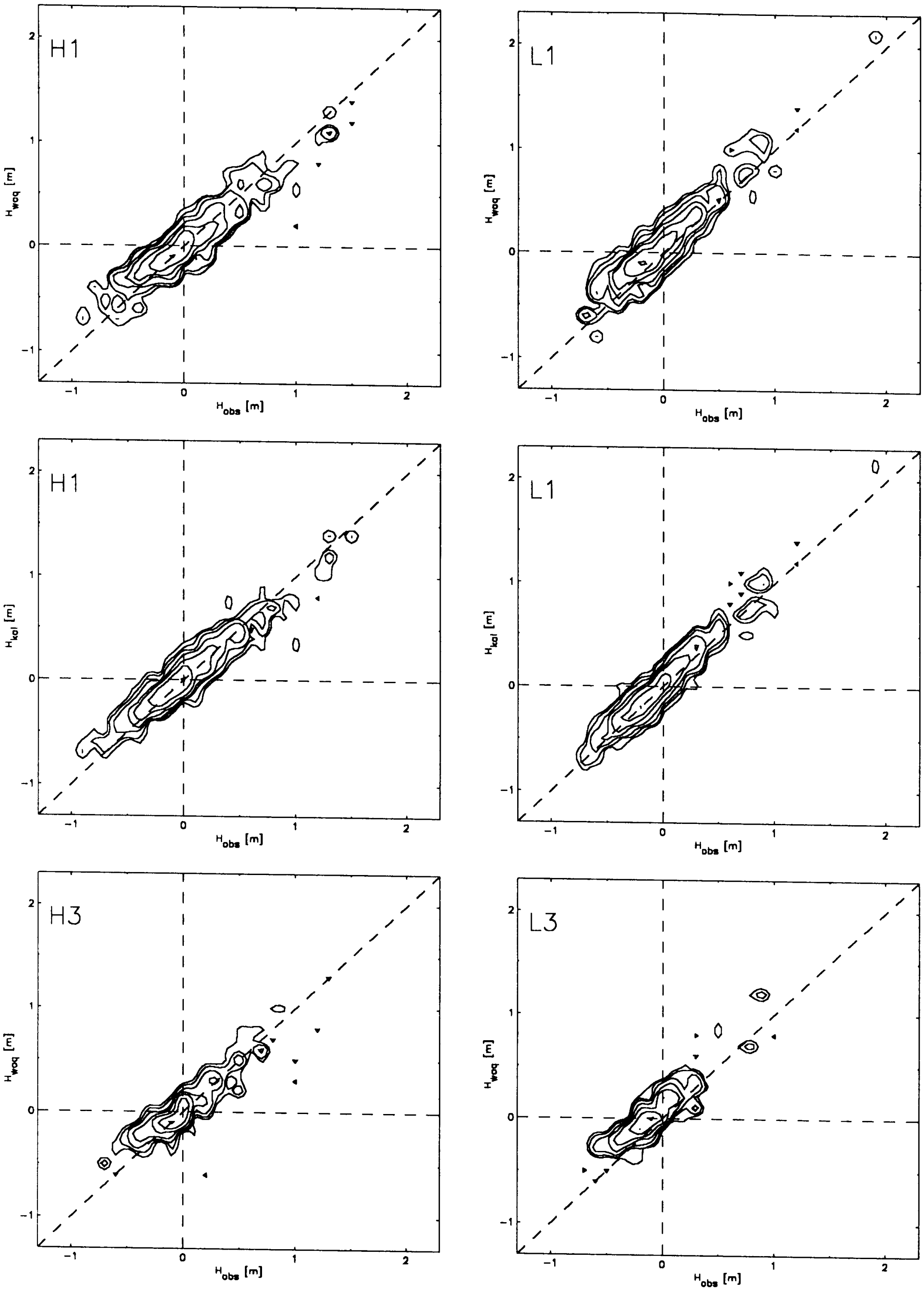

Figure 4.1: Hoek van Holland — FM-LAM Sep 1992 - Apr 1993. For an explanation, see Section 4.1.

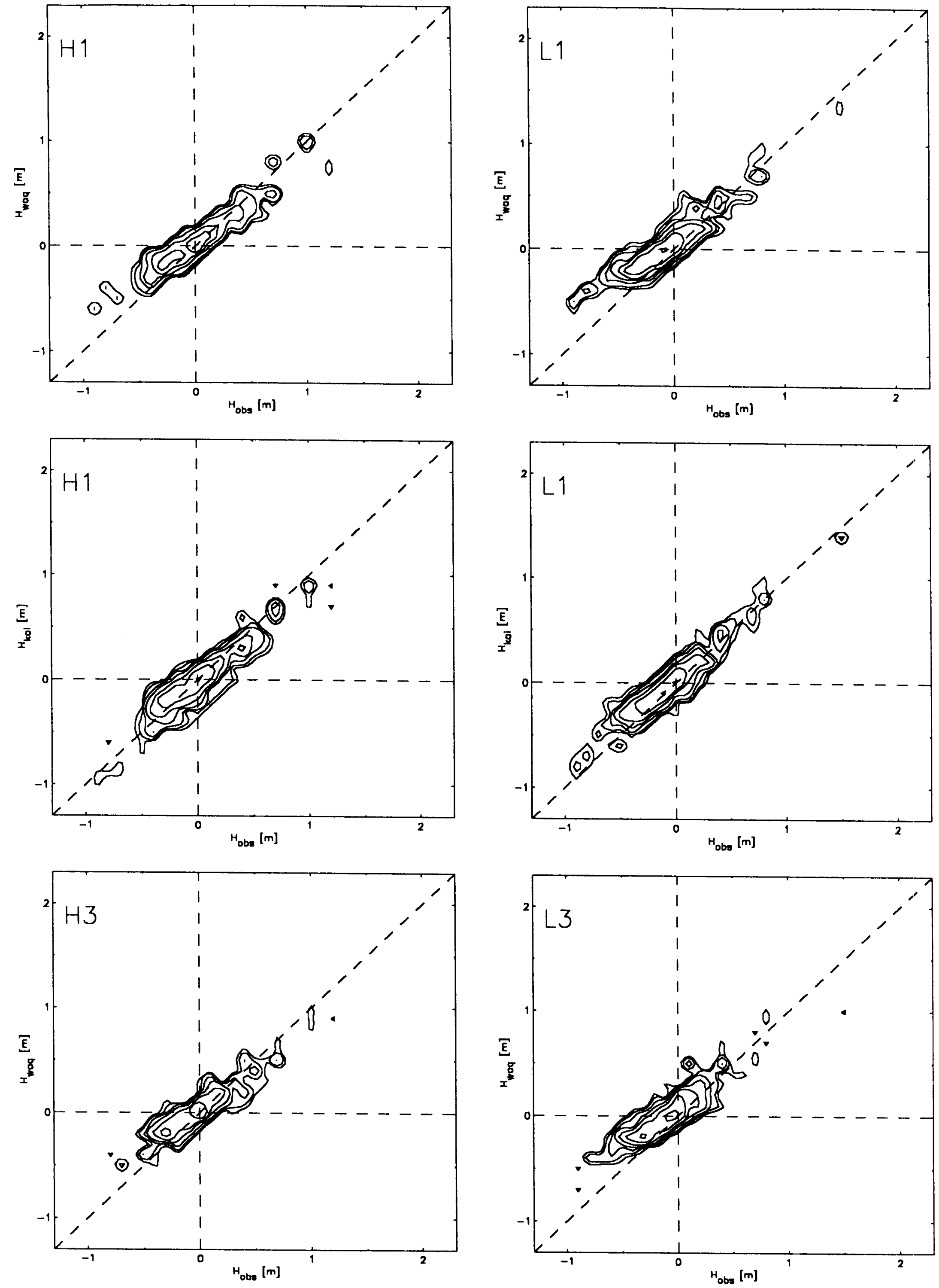

Figure 4.2: Hoek van Holland — HIRLAM Sep 1993 - Dec 1993

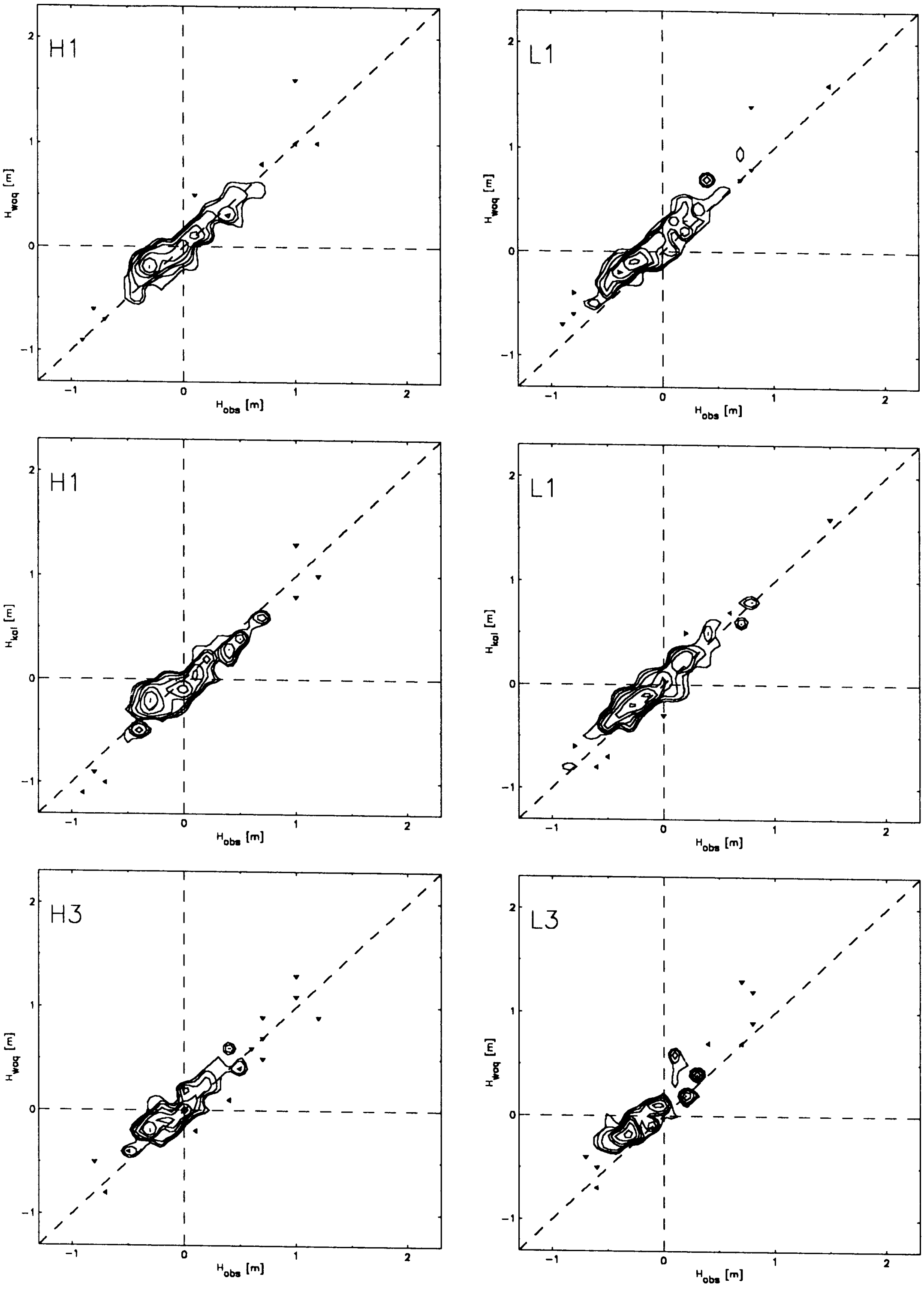

Figure 4.3: Hoek van Holland — UKMO Sep 1993 - Dec 1993

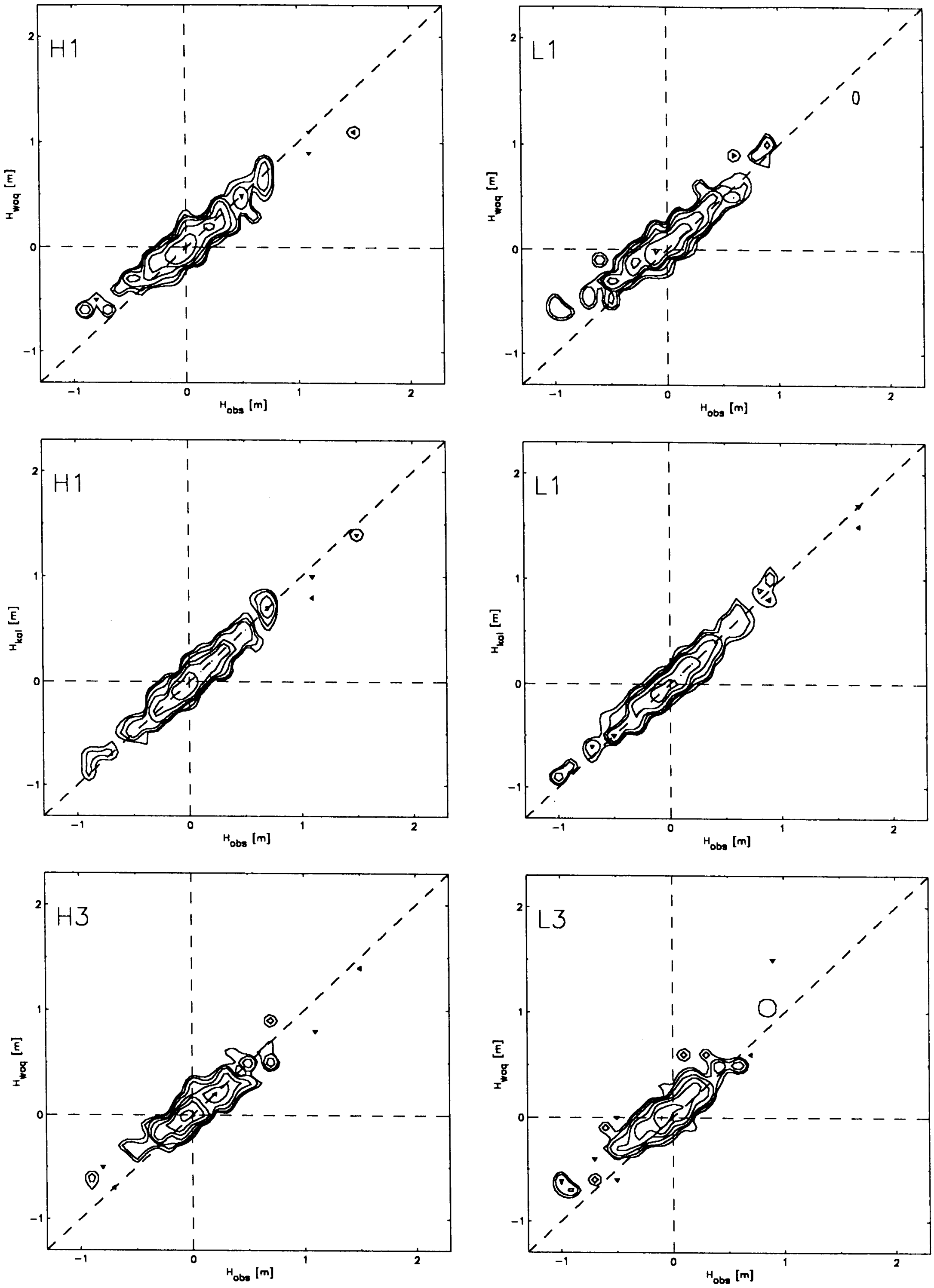

Figure 4.4: Hoek van Holland — HIRLAM Jan 1994 - Apr 1994

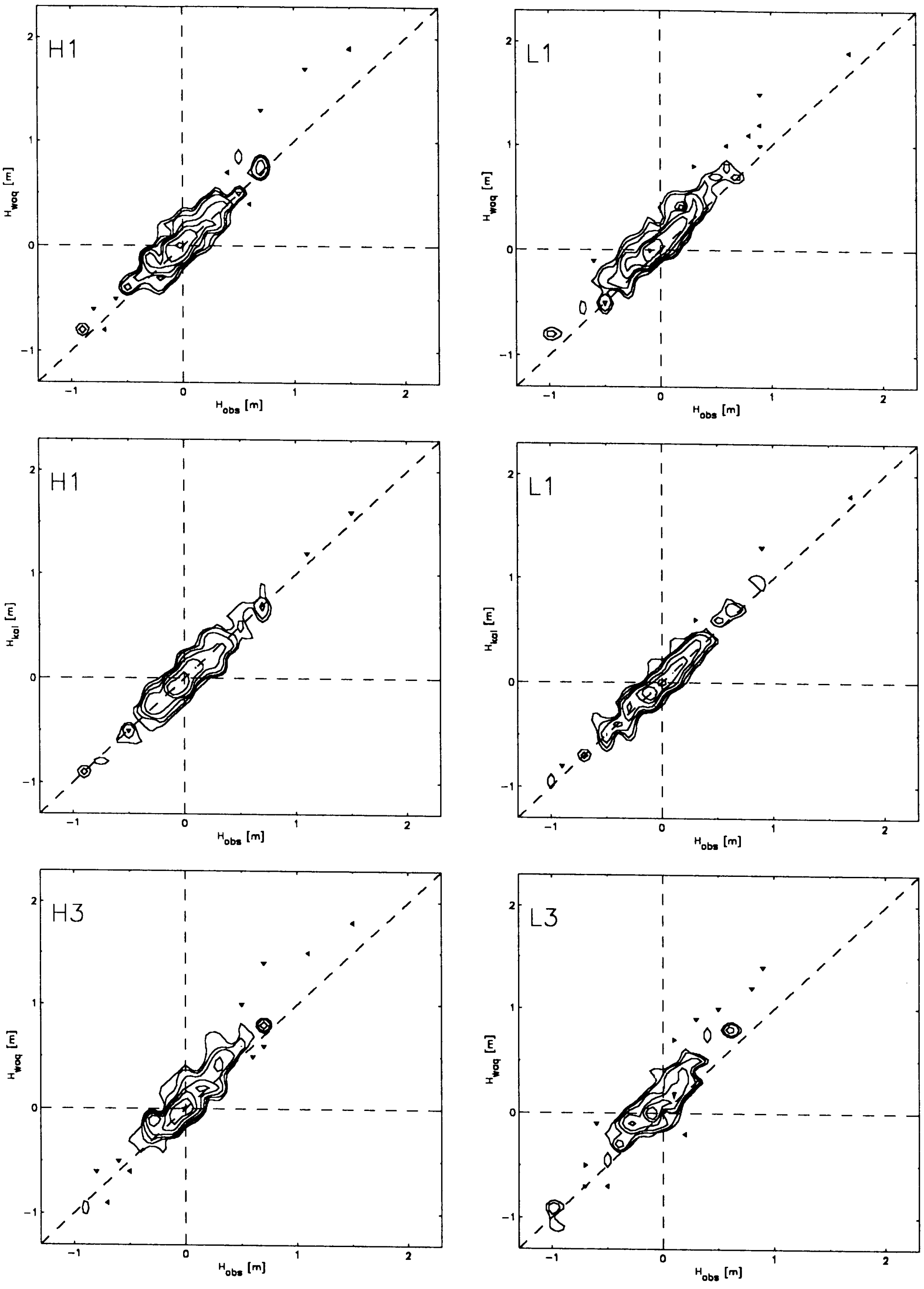

Figure 4.5: Hoek van Holland — UKMO Jan 1994 - Apr 1994

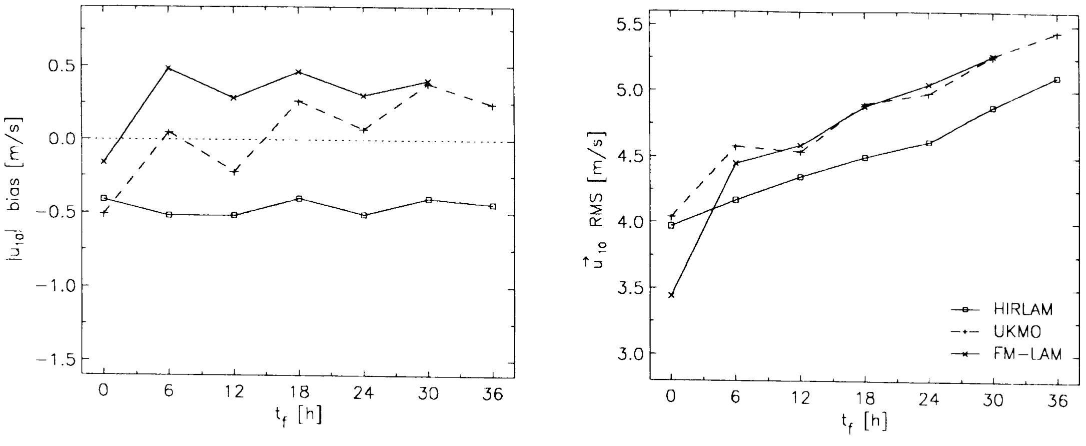

Figure 4.6: $\vec{u}_{10}$ verification in the Northern North Sea for Feb - May 1993

row shows H1 and L1 with Kalman filter. The third row shows forecasts without Kalman filter for $t_f = 24 - 36$ h (H3 and L3).

For each of the plots the domain has been covered with a 10 cm × 10 cm grid. Contour lines are shown of the number of tides in each of these grid cells. The contour intervals start at 0.8, ensuring that every single tide will be represented, and increase logarithmically up to 90% of the maximum value. In the ideal case that $H_{\mathrm{mod}} = H_{\mathrm{obs}}$ the figure would coincide with the dashed diagonal.

The main features, illustrated in the contour plots for Hoek van Holland, but also valid for the other stations, are:

- The figures with Kalman filter follow the diagonal better than those without Kalman filter — except for September - December 1993, when the results were corrupted by the offset in Dover. They are shifted towards the diagonal, narrower and more straight.
  For September - December 1993, the Kalman filter still has effect, and in several cases a significant improvement for more extreme surges has been obtained. On average, however, the offset in Dover hampers a reduction of the standard deviation.

- The shift towards the diagonal and the narrowing of the figure mean that the Kalman filter corrects for the bias and decreases the standard deviation.

- The fact that the figure with Kalman filter is more straight than without indicates that systematic effects as a function of the surge are corrected by the Kalman filter. This is especially so for the systematic underestimation of negative surges along the Dutch coast. As can be seen all figures without Kalman filter tend to bend upwards for $H_{\mathrm{obs}} < 0$, a trend which is removed by the Kalman filter.

- The model generally performs worse for low tides than for high tides. In partic-

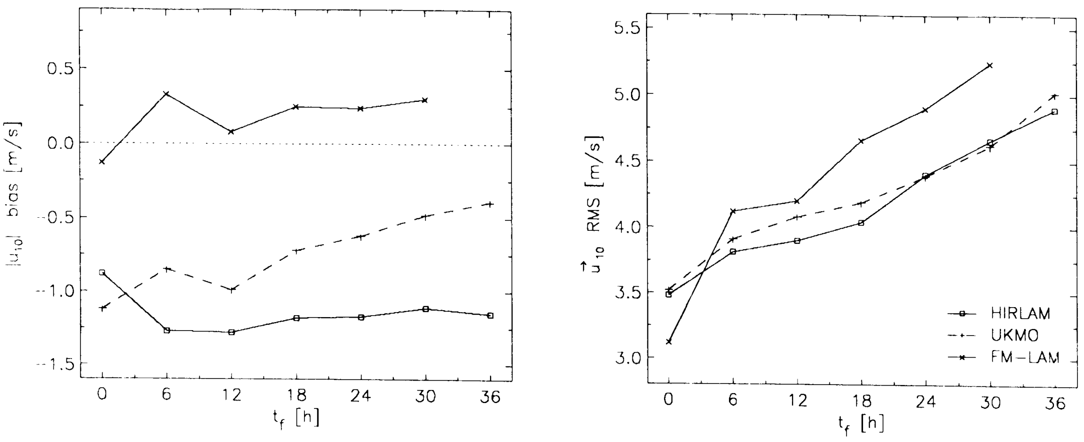

Figure 4.7: $\vec{u}_{10}$ verification in the Southern North Sea for Feb – May 1993

ular, all the figures for low tides seem to be displaced from the main diagonal, indicating a bias. This can be more clearly seen in the plots of bias and standard deviation as a function of the forecast period in Section 4.2.

- The drag relation for the model has been tuned to match with input from FM-LAM. As a result the data are well aligned with the main diagonal in Figure 4.1. As the drag relation has not been tuned to HIRLAM input yet, a different behaviour of e.g. the bias in the wind speed will affect the storm surge results. As an example Figures 4.6 and 4.7 give the bias in $|\vec{u}_{10}|$ and rms vector difference in $\vec{u}_{10}$ for respectively the Northern and Southern parts of the North Sea for HIRLAM, UKMO and FM-LAM. The more negative bias of HIRLAM in both areas can also be identified in Figures 4.2 and 4.4: the tilt of the figures without Kalman filter with respect to the main diagonal signifies a systematic underestimation of the surges.

- Figures 4.2 and 4.4 show more coherent results for HIRLAM than Figures 4.3 and 4.5 for UKMO. Partly this is caused by the 6-hour repetition period for HIRLAM, which gives twice as many forecasts as UKMO and hence smoother figures. However, the single forecasts for larger storm surges and a comparison of the UKMO results with and without Kalman filter show that the scatter in the UKMO forecasts without Kalman filter is indeed bigger than in the HIRLAMforecasts.

  For positive surges, especially above 0.5 m, the forecasts on UKMO input generally tend to overpredict. This observation is not supported by Figures 4.6 and 4.7, which show a bias for UKMO which is smaller than the bias for FM-LAM, which was used for tuning the drag relation. The reason for the overprediction might be the imperfect treatment of land-sea transitions (discussed further in Chapter 5).

4.2 Bias and standard deviation

Also for the bias and standard deviation holds that the results for Hoek van Holland show the most important features which are common to all stations. These are therefore shown for all periods in Figure 4.8. For an assessment of the behaviour of bias and standard deviation which is characteristic for the other stations, the results for high and low tides for the period January – April 1994 are shown for all stations in Figures 4.9 and 4.10. Note that, although the figures show points for every 3 hours, each of these points is an average over 6 (FM-LAM and HIRLAM) or 12 (UKMO) hours (see point 3 on page 7).

Figure 4.8 shows the bias and standard deviation for Hoek van Holland for all periods described earlier on page 8. The bias without Kalman filter is a solid line, the bias with Kalman filter a dashed line, the standard deviation without Kalman filter a solid line with squares and the standard deviation with Kalman filter a dashed line with squares. The top half of the figure shows results for high tides; the lower half the results for low tides. All plots are labeled with the name of the atmospheric model and the first month of the verification period. For January – April 1994 on HIRLAM there are two versions: with hourly wind and pressure input, labeled with an extra *(1)* and with three-hourly wind and pressure input.

Figures 4.9 and 4.10 show similar plots for 8 other stations for the period January – April 1994.

The main features in Figures 4.8 – 4.10 are:

- The observation from Section 4.1 is confirmed that the bias for low tides is higher than for high tides. Standard deviations are comparable for all stations, except for Den Helder and Delfzijl, which reflects the problems in modelling the complex Waddenzee with a 16-km model in which drying and flooding can not occur.

- The Kalman filter considerably improves the standard deviation for t_f up to 12 – 15 hours along the Dutch coast. For Lowestoft and Wick this period is shorter. Forecasts for the Dutch coast benefit from the time it takes the tidal Kelvin wave and its disturbances to travel along the British East coast to the Southern North Sea.

- Also the bias is brought down to only a few centimetres, and at the Dutch coast this is even sustained to $t_f = 18-24$h. After this period, however, the bias makes a (severe) overshoot, making forecasts with Kalman filter worse for $t_f > 18-24$ h than forecasts without Kalman filter.
  An overshoot is also present in the standard deviations for several stations, but is less pronounced there.

- Due to the offset in Dover, the Kalman filter does not improve the forecasts for Hoek van Holland in the period September – December 1993. Results from the

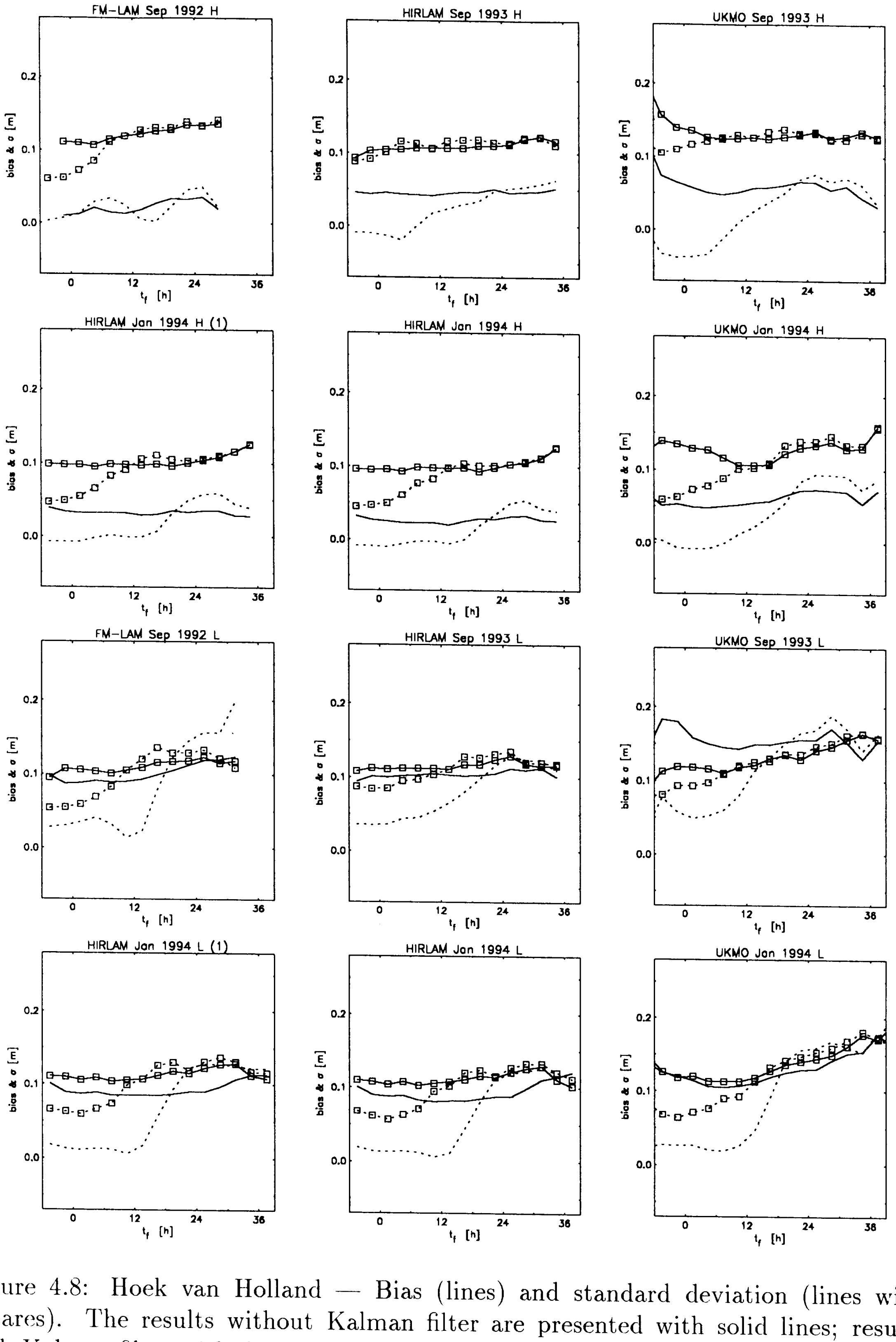
FM-LAM Sep 1992 H
HIRLAM Sep 1993 H
UKMO Sep 1993 H
HIRLAM Jan 1994 H (1)
HIRLAM Jan 1994 H
UKMO Jan 1994 H
FM-LAM Sep 1992 L
HIRLAM Sep 1993 L
UKMO Sep 1993 L
HIRLAM Jan 1994 L (1)
HIRLAM Jan 1994 L
UKMO Jan 1994 L

Figure 4.8: Hoek van Holland — Bias (lines) and standard deviation (lines with squares). The results without Kalman filter are presented with solid lines; results with Kalman filter with dashed lines. For further explanation, see Section 4.2.

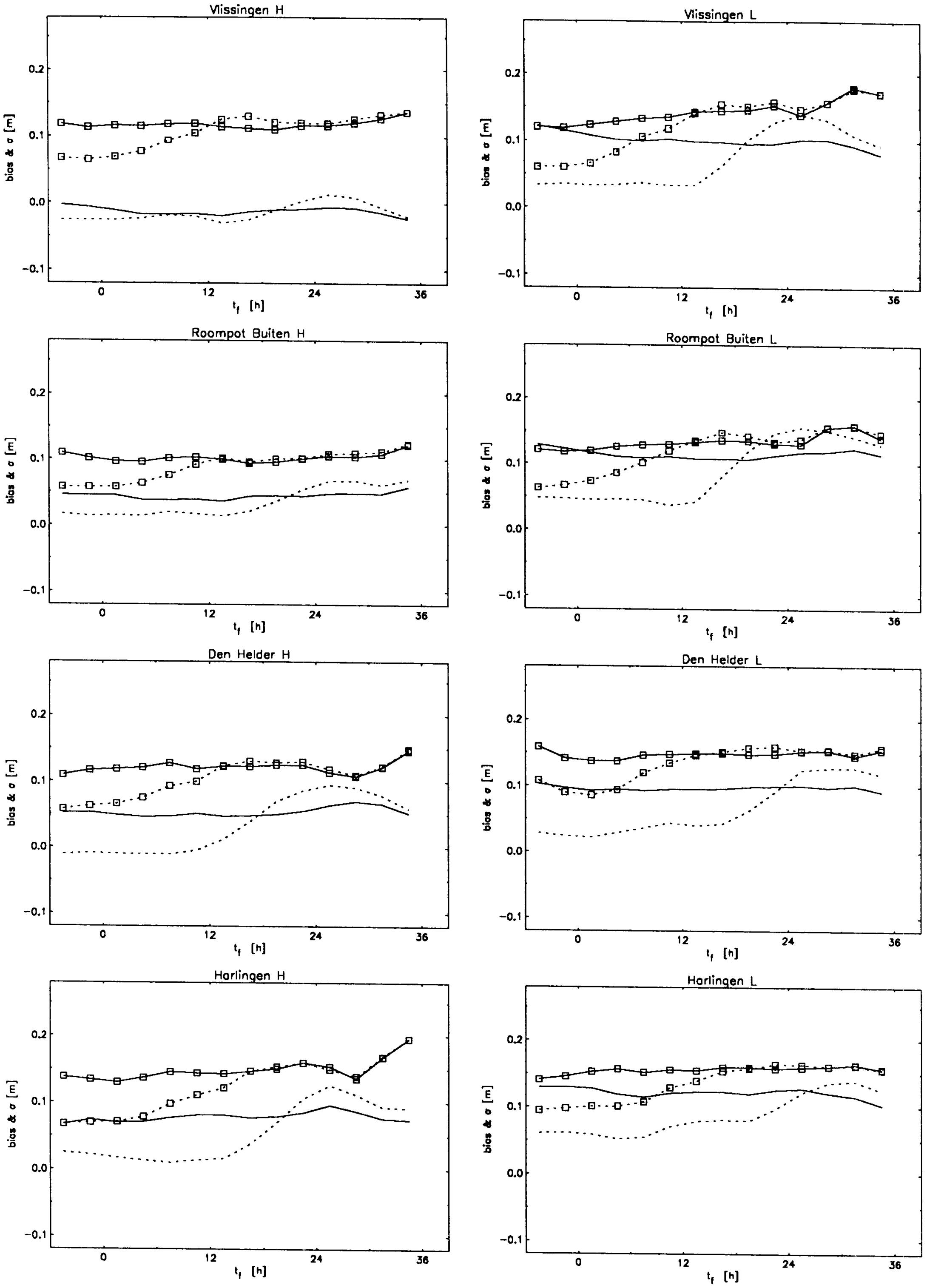

Figure 4.9: Bias and standard deviation for Vlissingen, Roompot Buiten, Den Helder and Harlingen, January - April 1994. See Figure 4.8 and Section 4.2.

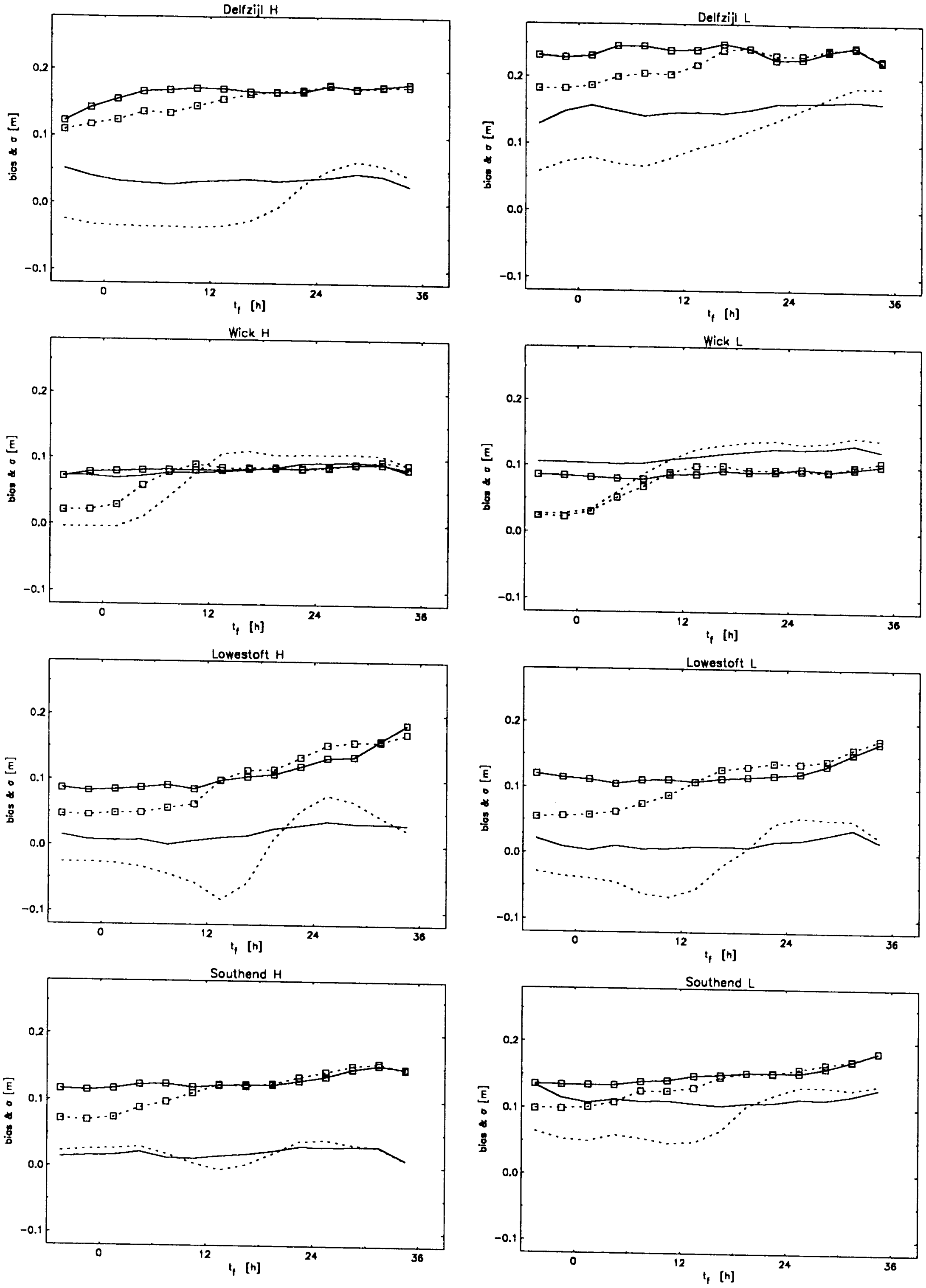

Figure 4.10: Bias and standard deviation for Delfzijl, Wick, Lowestoft and Southend, January – April 1994. See Figure 4.8 and Section 4.2.

more Northerly British stations and Dutch stations in de Waddenzee show that the Kalman filter still improves forecasts there.

- Error growth is generally small in the results of the storm surge forecast model, which integrates its wind and pressure input over space and time and is therefore not very sensitive to error growth in the atmospheric model. Figures 4.6 and 4.7 show that the error growth in HIRLAM is less than in FM-LAM.
- The errors in the hindcasts on UKMO analyses are much bigger than in the forecasts.
- Results for forecasts with hourly and three-hourly wind and pressure input from HIRLAM (Figure 4.8) for January – April 1994 are not exactly equal, but no significant change in the forecast skill can be observed.

4.3 Tabulated statistical results

Tables 4.1 – 4.3 give statistical results for the sea level forecasts with $t_f = 0 - 12$ h on FM-LAM in September 1992 – April 1993 and on HIRLAM and UKMO in January – April 1994. Bias, standard deviation and also RMS error are given for high tides (H) and low tides (L). The tables confirm the conclusions from Sections 4.1 and 4.2, but give a broader overview over the Dutch and British coasts.

Table 4.1: Verification statistics for WAQUA(FM-LAM) in September 1992 - April 1993: $t_f = 0 - 12$ h

Gauge		Without data assimilation				With data assimilation			
		$< \Delta H >$ [m]	σ_H [m]	RMS_H [m]	N	$< \Delta H >$ [m]	σ_H [m]	RMS_H [m]	N
Vlissingen	H	-0.01	0.13	0.13	1111	0.03	0.11	0.11	1025
	L	0.10	0.10	0.14	1111	0.04	0.07	0.08	1015
Roompot buiten	H	0.05	0.11	0.12	1122	0.06	0.09	0.11	1053
	L	0.10	0.10	0.14	1108	0.03	0.08	0.08	1015
Hoek van Holland	H	0.02	0.11	0.11	1106	0.03	0.10	0.10	1021
	L	0.09	0.10	0.14	963	0.03	0.08	0.08	1033
Scheveningen	H	0.04	0.12	0.12	1105	0.03	0.10	0.10	1006
	L	0.11	0.10	0.15	1083	0.07	0.08	0.10	1067
IJmuiden	H	0.03	0.12	0.12	1069	0.02	0.10	0.10	1004
	L	0.09	0.10	0.14	1037	0.04	0.08	0.09	991
Den Helder	H	0.06	0.12	0.13	1017	0.03	0.09	0.09	1016
	L	0.10	0.11	0.14	1117	0.05	0.08	0.09	1064
West Terschelling	H	0.08	0.10	0.13	778	0.06	0.08	0.10	763
	L	0.26	0.11	0.28	850	0.21	0.08	0.22	810
Harlingen	H	0.11	0.13	0.17	1072	0.08	0.09	0.12	986
	L	0.18	0.12	0.21	1166	0.12	0.10	0.16	1062
Huibertgat	H	0.07	0.10	0.13	1105	0.04	0.08	0.09	1016
	L	0.16	0.12	0.19	1117	0.09	0.10	0.13	1018
Delfzijl	H	0.06	0.13	0.15	1107	0.02	0.11	0.11	1018
	L	0.15	0.16	0.22	1119	0.09	0.14	0.16	1023
Wick	H	0.05	0.07	0.09	627	0.08	0.15	0.17	591
	L	0.10	0.09	0.13	650	0.01	0.15	0.15	605
Lowestoft	H	-0.03	0.10	0.11	1014	-0.06	0.08	0.10	919
	L	-0.03	0.10	0.10	1013	-0.05	0.08	0.09	913
Dover	H	0.00	0.11	0.11	800	-0.03	0.08	0.09	726
	L	0.03	0.10	0.11	804	0.01	0.07	0.07	708
Cadzand	H	-0.01	0.13	0.13	567	0.00	0.11	0.11	1069
	L	0.08	0.10	0.13	560	0.04	0.08	0.09	1051
Euro platform	H	0.00	0.10	0.10	1140	0.01	0.08	0.08	1047
	L	0.06	0.09	0.11	1133	0.00	0.07	0.07	1039
Texel Noordzee	H	0.09	0.12	0.15	442	0.03	0.10	0.11	912
	L	0.12	0.12	0.17	491	0.09	0.11	0.14	951

Table 4.2: Verification statistics for WAQUA(HIRLAM) in January – April 1994: $t_f = 0 - 12$ h

Gauge		Without data assimilation				With data assimilation			
		$<\Delta H>$ [m]	σ_H [m]	RMS_H [m]	N	$<\Delta H>$ [m]	σ_H [m]	RMS_H [m]	N
Vlissingen	H	-0.01	0.12	0.12	546	-0.02	0.09	0.09	546
	L	0.11	0.13	0.17	558	0.03	0.09	0.10	556
Roompot buiten	H	0.04	0.10	0.11	572	0.02	0.07	0.07	572
	L	0.11	0.12	0.17	576	0.04	0.09	0.10	571
Hoek van Holland	H	0.02	0.10	0.10	555	-0.01	0.07	0.07	555
	L	0.09	0.11	0.14	551	0.01	0.07	0.07	544
Scheveningen	H	0.03	0.10	0.11	484	0.00	0.08	0.08	482
	L	0.12	0.11	0.16	493	0.06	0.08	0.10	491
IJmuiden	H	0.03	0.11	0.12	540	-0.02	0.07	0.08	539
	L	0.09	0.11	0.14	521	0.03	0.08	0.08	518
Den Helder	H	0.05	0.12	0.13	535	-0.01	0.08	0.08	531
	L	0.09	0.14	0.17	579	0.03	0.11	0.11	579
West Terschelling	H	0.09	0.10	0.13	545	0.03	0.06	0.07	545
	L	0.26	0.12	0.28	547	0.18	0.08	0.19	544
Harlingen	H	0.07	0.14	0.16	529	0.01	0.09	0.09	525
	L	0.12	0.15	0.19	583	0.06	0.11	0.12	580
Huibertgat	H	0.03	0.12	0.12	557	-0.03	0.08	0.09	557
	L	0.10	0.14	0.18	574	0.02	0.10	0.10	573
Delfzijl	H	0.03	0.16	0.17	548	-0.03	0.14	0.14	546
	L	0.15	0.24	0.28	558	0.07	0.20	0.21	556
Wick	H	0.08	0.08	0.11	235	0.03	0.07	0.08	235
	L	0.11	0.08	0.13	218	0.07	0.07	0.09	218
North Shields	H	0.03	0.09	0.10	392	-0.03	0.09	0.09	392
	L	0.07	0.10	0.12	383	0.00	0.09	0.09	383
Lowestoft	H	0.01	0.09	0.09	206	-0.04	0.05	0.07	204
	L	0.01	0.11	0.11	210	-0.05	0.07	0.08	209
Southend	H	0.02	0.12	0.12	528	0.02	0.09	0.10	527
	L	0.11	0.14	0.18	510	0.05	0.11	0.12	510
Dover	H	0.11	0.23	0.25	475	0.06	0.23	0.24	475
	L	0.13	0.25	0.28	508	0.08	0.24	0.26	507
Newhaven	H	-0.02	0.11	0.11	482	-0.04	0.10	0.11	482
	L	-0.33	0.09	0.34	521	-0.33	0.08	0.34	520
Cadzand	H	0.01	0.10	0.11	569	-0.01	0.08	0.08	569
	L	0.09	0.13	0.16	554	0.03	0.10	0.10	552
Euro platform	H	0.04	0.09	0.10	559	0.01	0.07	0.07	558
	L	0.07	0.10	0.12	551	0.00	0.07	0.07	550
Goeree	H	0.04	0.09	0.10	445	0.02	0.07	0.07	445
	L	0.12	0.11	0.16	428	0.05	0.08	0.09	425
Meetpost Noordwijk	H	0.05	0.10	0.11	543	0.00	0.07	0.07	543
	L	0.11	0.11	0.15	525	0.05	0.08	0.09	521
Texel Noordzee	H	0.07	0.10	0.12	444	0.00	0.09	0.09	442
	L	0.11	0.11	0.16	461	0.05	0.08	0.10	458

Table 4.3: Verification statistics for WAQUA(UKMO) January – April 1994: $t_f = 0-12\text{h}$

Gauge		Without data assimilation				With data assimilation			
		$<\Delta H>$ [m]	σ_H [m]	RMS_H [m]	N	$<\Delta H>$ [m]	σ_H [m]	RMS_H [m]	N
Vlissingen	H	0.00	0.14	0.14	222	-0.03	0.10	0.11	222
	L	0.14	0.12	0.18	226	0.05	0.09	0.10	226
Roompot buiten	H	0.06	0.12	0.13	226	0.01	0.08	0.08	226
	L	0.15	0.11	0.18	227	0.06	0.09	0.10	227
Hoek van Holland	H	0.05	0.12	0.13	226	-0.01	0.08	0.08	226
	L	0.11	0.11	0.16	225	0.02	0.08	0.09	225
Scheveningen	H	0.06	0.14	0.15	202	0.00	0.10	0.10	202
	L	0.16	0.12	0.20	200	0.08	0.09	0.11	200
IJmuiden	H	0.04	0.13	0.14	215	-0.02	0.09	0.09	215
	L	0.12	0.12	0.17	213	0.05	0.09	0.10	213
Den Helder	H	0.08	0.10	0.13	222	0.00	0.08	0.08	222
	L	0.14	0.14	0.20	223	0.05	0.11	0.12	223
West Terschelling	H	0.11	0.11	0.15	201	0.04	0.07	0.08	201
	L	0.30	0.14	0.33	207	0.19	0.08	0.21	207
Harlingen	H	0.13	0.13	0.18	220	0.05	0.09	0.10	220
	L	0.20	0.18	0.27	224	0.10	0.12	0.16	224
Huibertgat	H	0.04	0.11	0.11	225	-0.04	0.08	0.09	225
	L	0.14	0.15	0.20	227	0.03	0.11	0.11	227
Delfzijl	H	0.05	0.13	0.14	225	-0.04	0.11	0.12	225
	L	0.19	0.18	0.26	224	0.08	0.16	0.18	224
Wick	H	0.08	0.08	0.11	95	0.06	0.10	0.12	95
	L	0.11	0.09	0.14	92	0.09	0.08	0.12	92
North Shields	H	0.02	0.10	0.10	154	-0.04	0.10	0.11	154
	L	0.06	0.10	0.12	149	0.01	0.10	0.10	149
Lowestoft	H	-0.01	0.10	0.10	80	-0.07	0.07	0.10	80
	L	-0.02	0.11	0.11	88	-0.09	0.07	0.11	88
Southend	H	-0.04	0.17	0.17	206	-0.04	0.11	0.12	206
	L	0.05	0.14	0.15	205	-0.01	0.13	0.13	205
Dover	H	0.10	0.22	0.24	189	0.04	0.21	0.22	189
	L	0.11	0.23	0.25	198	0.06	0.23	0.23	198
Newhaven	H	-0.03	0.10	0.10	194	-0.06	0.09	0.11	194
	L	-0.33	0.08	0.34	208	-0.34	0.07	0.35	208
Cadzand	H	0.01	0.13	0.13	223	-0.02	0.09	0.10	223
	L	0.12	0.11	0.16	223	0.04	0.09	0.10	223
Euro platform	H	0.06	0.12	0.13	226	0.01	0.07	0.07	226
	L	0.10	0.11	0.15	225	0.01	0.08	0.08	225
Goeree	H	0.05	0.10	0.11	182	0.01	0.08	0.08	182
	L	0.14	0.10	0.17	185	0.06	0.08	0.10	185
Meetpost Noordwijk	H	0.06	0.13	0.14	219	0.00	0.09	0.09	219
	L	0.14	0.11	0.18	214	0.06	0.08	0.10	214
Texel Noordzee	H	0.11	0.14	0.18	197	0.02	0.12	0.12	197
	L	0.17	0.16	0.23	193	0.07	0.10	0.13	193

Conclusions

5

1. The WAQUA/CSM-16 model produces sea level forecasts with a standard deviation of less than 15 cm along big parts of the Dutch and British coasts. The Kalman filter brings this even down for $t_f < 12$ h to less than 10 cm.

2. The bias of the forecasts differs for high and low tides: for high tides it is generally below 5 cm, but for low tides 10 – 15 cm is common. Also here the Kalman filter gives a considerable improvement for $t_f < 18 - 24$ h.

3. The Waddenzee is not very well represented by the model, which does not allow for drying or flooding and has a resolution of only 16 km. Therefore, in stations in or near the Waddenzee (Den Helder, Texel Noordzee, Harlingen, Delfzijl, West Terschelling and Huibertgat) results are worse, with standard deviations and biases up to 25 cm.

4. For $t_f > 18$ h the Kalman filter deteriorates the forecast instead of improving it. Possible explanations are the treatment of the open boundaries and an implementation error: The Kalman filter does not allow to change the flow through the open model boundaries. This means that external surges which are detected e.g. through the observations from Wick have to be generated by changing the meteorology elsewhere in the model domain. This unphysical correction might later lead to an unphysical surge in the North Sea. The implementation error has been detected in a detailed test of the filter behaviour [8].

5. After the introduction of HIRLAM the sea level forecasts exhibit a systematic underestimation of the surges. From October 1994 the wind in the Southern part of the North Sea is increased by 10% as a provisional correction. Preliminary results show that the underestimation in this area has disappeared. However, a more elaborate recalibration of the wind-drag is required.

6. The model results with input from UKMO are not as good as the results on HIRLAM. This does not necessarily reflect the quality of the atmospheric model.

A proper calibration of the drag relation for $\vec{u}_{10}$ from UKMO has never been performed. Moreover, UKMO is received at KNMI with a coarser resolution than the model grid. In the interpolation no special care is taken at the land-sea boundaries. In WAQUA/CSM-16 this is solved in the same way as in its predecessor IOS: in the Southern part of the North Sea the winds are increased by 15% [9]. Improvement might also be found in skipping the analyses. This report shows that the sea level 'forecasts' on UKMO analyses are significantly worse that the forecasts for e.g. $t_f = 6$ h, although Figures 4.6 and 4.7 do not show any similar effects.

Proper treatment of the land-sea boundaries, which would require uninterpolated UKMO wind fields and a description of the land-sea mask, and tuning of the model on this input might therefore improve the sea level results. However, the costs of this effort have to be considered in relation with the status of the product: at the moment the sea level forecasts on UKMO are a backup for the forecasts on HIRLAM.

7. In periods when the weather, and therefore the surge, is varying only slowly on a time scale of several days, systematic errors which depend on the height of the surge (as demonstrated in Figures 4.1 – 4.5) might cause an apparent bias in the model which slowly varies with time. This, however, only reflects the systematic shortcomings of the model for certain surge ranges.

   In this kind of situations the best operational practice is to consider the model error of a previous tide for the adjustment of the forecasts.

8. It is difficult to draw conclusions on the behaviour of the model for extreme surges. Figures 4.1 – 4.5 explicitly show the extreme surges and for HIRLAM they are generally consistent with the rest of the figures. However, every (severe) storm is a new challenge for the models and might present a totally new situation. A complicating factor in a statistical assessment of extreme surges is the fact that frequent model improvements prohibit the collection of a data set which is consistent and large enough to perform a meaningful statistical analysis.

9. No significant effect on the bias and standard deviation has been found of hourly instead of three-hourly wind and pressure input. Detailed tests with different methods of handling the meteorological input (e.g. interpolation in time or not; interpolating wind or wind stress; bi-linear interpolation or some other method) in different situations are necessary to decide about the meteo-input interval. For the time being, the operational version of the model uses hourly input and a parallel version three-hourly.

Future

6

RIKZ and KNMI are working on a new version of the storm surge model. The main new features of this version are:

- A finer grid of $\frac{1}{8}^\circ \times \frac{1}{12}^\circ$ (about 8 km × 8 km).
- Drying and flooding (especially important in the Waddenzee) will be possible.
- The Kalman filter will be extended and include the possibility to adjust the open boundaries. Moreover, the implementation error which is suspected to cause problems should be removed.
- The preprocessing of the meteo-input, including the drag relation and various interpolation issues, should be re-investigated and tuned to give optimal sea level forecasts.
- As a future extension assimilating of wind observations in the storm surge model and a different treatment of the wind statistics in the Kalman filter are considered [6, 7].

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