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Operational storm surge forecasting in the Netherlands: developments in the last decade

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The accurate forecasting of storm surges is an important issue in the Netherlands. With the emergence of the first numerical hydrodynamic models for surge forecasting at the beginning of the 1980s, new demands and possibilities were raised. This article describes the main phases of the development and the present operational set-up of the Dutch continental shelf model, which is the main hydrodynamic model for storm surges in the Netherlands. It includes a brief discussion of applied data-assimilation techniques, such as Kalman filtering, the model calibration process and some thoughts on quality assurance in an operational environment. After further describing some select recent investigations, the paper concludes with some remarks on future developments in a European context.

Keywords: storm surge; forecasting; Kalman filtering

1. Introduction

In the Netherlands accurate forecasting of storm surges is very important since large areas of the land lie below sea level. Over past centuries, several severe floods of parts of this land have taken place. The last disaster of this kind was caused by the storm on 1 February 1953. During this storm about 135 000 hectares of land were inundated and 1835 people died. This storm led to the Delta plan, which comprised, for example, heightening the dikes and constructing several new dams and barriers, especially in the southwestern part of the country. In order to establish a sufficient level of safety, statistical methods were applied to compute measures that reduced the expected probability of flooding to once every 10 000 years for the most densely populated areas.

In addition to better defence against flooding by the sea, the warning system was also improved. In the case of severe storms, the dikes can be staffed in time to prevent them from breaching. For this purpose forecasts are made by the Dutch storm surge warning service (SVSD) in close cooperation with the Royal Netherlands Meteorological Institute (KNMI). Accurate forecasts at least 6 h ahead are also needed for proper closure of the movable storm surge barriers in the Eastern Scheldt and the New Waterway.

One contribution of 14 to a Theme 'The Big Flood: North Sea storm surge'.

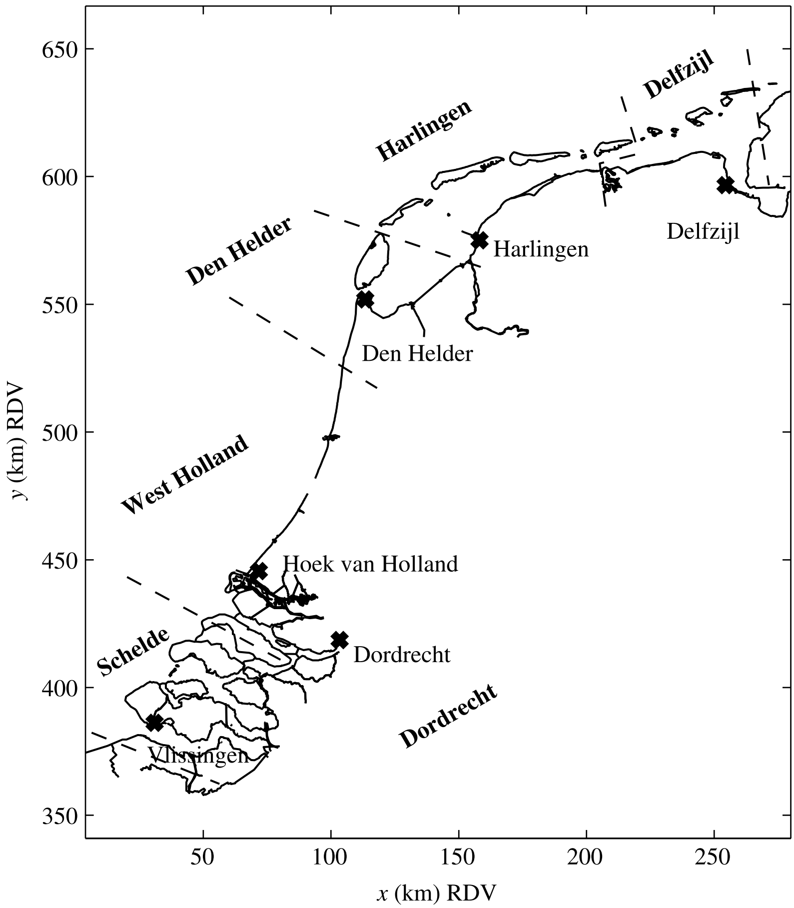

Figure 1. SVSD sections.

Since the mid-1980s, these forecasts are based on a numerical hydrodynamic model called the Dutch continental shelf model (DCSM). This model uses forecasts of the meteorological high-resolution limited area model (HiRLAM) as input. In the early 1990s, a Kalman filter was added to this system to improve the accuracy of the forecasts further by incorporating recent observations of tide gauges.

This article briefly reviews the development of the storm surge model DCSM with a focus on some selected topics from the last decade. These topics mainly concern data assimilation, i.e. model calibration and Kalman filtering, since this field has relatively received a great deal of attention in the Netherlands. Further, some aspects of a systematic validation of the methods and forecasts are reviewed since this is a very important aspect of the development and maintenance of a reliable storm surge forecasting system.

This introduction is followed by a brief description of the operational forecast situation for storm surges in §2. Section 3 overviews the historical development of the DCSM model and §4 discusses issues of forecasting in an operational context. In §5 some select investigations of the last years are presented. The article concludes in §6 with some remarks on future developments in a European context.

Table 1. *Warning and alarm levels used by the SVSD (levels relative to normal Amsterdam level (NAP))*

sector	reference station	pre-warning (cm)	warning (cm)	alarm level (cm)
Schelde	Vlissingen	310	330	370
West Holland	Hook of Holland	200	220	280
Dordrecht	Dordrecht	—	—	250
Den Helder	Den Helder	—	190	260
Harlingen	Harlingen	260	270	330
Delfzijl	Delfzijl	—	300	380

2. Operational forecasting

The operational running of the storm surge model DCSM is performed at KNMI in de Bilt. If the water level in such a forecast exceeds certain thresholds the SVSD is informed. If, after deliberation with the meteorologists from KNMI, the SVSD hydrologist on duty decides that one or more warning levels may be reached, the SVSD office is staffed. For the purpose of issuing warnings, the Dutch coast is divided into several sectors (see figure 1), each with their own thresholds (see table 1). The reason for this division is that the tidal amplitude and time of high water varies significantly along the Dutch coast. Warnings are issued at least 6 h ahead to provide time for the necessary preparations.

In addition to issuing warnings for the protection of dikes and providing information for the general public, the SVSD also cooperates closely with the regional Hydro–Meteo offices in Zeeland and Hook of Holland to decide, for example, if the storm surge barriers in the Eastern Scheldt or the New Waterway should be closed. Also, the DCSM forecasts are used by these Hydro–Meteo offices to provide boundary conditions for their local hydrodynamic models. An example for such a local high-resolution model is the Kustzuid model that covers an area around the Eastern Scheldt and Western Scheldt estuaries. The output of this model is used for ship guidance in the Western Scheldt and, in the future, may also be used to compute the optimal time to start closing the storm surge barrier.

3. Historical development of the DCSM

In the early 1980s, the development of a new nonlinear storm surge model was started. This model, the DCSM was based on the WAQUA software package, which can be used to solve the depth-integrated shallow water equations. The WAQUA system at the Department of Public Works (Rijkswaterstaat) and the TRISULA system (recently renamed to DELFT3D-FLOW) at Delft Hydraulics are based on the work of Leendertse (1970) and Stelling (1984).

The DCSM model covers the area of the northwest European continental shelf to at least the 200 m depth contour (see figure 2), i.e. 12°W to 13°E and 48°N to 62°N. The resolution of the spherical grid is 1/8° by 1/12° (this is approximately 8×8 km). By the standards of 2003, the DCSM is a 'small' model, which can

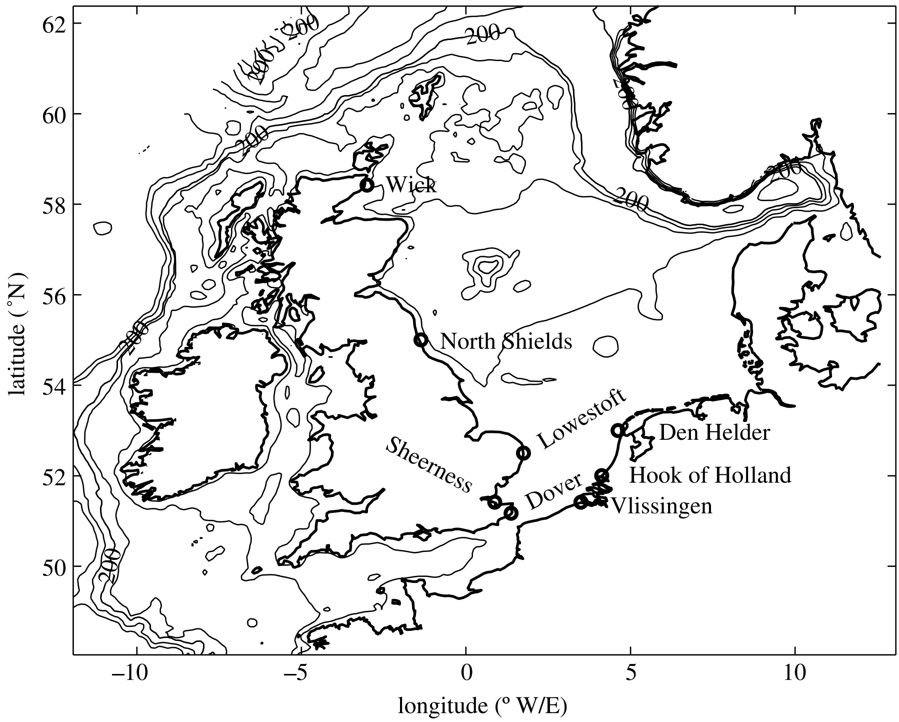

Figure 2. DCSM area with locations used in operational Kalman filter.

compute a forecast 2 days ahead within a minute on a standard personal computer, but in the early 1980s this was a computational challenge, especially in an operational context.

(*a*) *1980–1993*

From the start of the development of the DCSM at the beginning of the 1980s, many people at Rijkswaterstaat, KNMI and Delft Hydraulics have been involved in the development of the model and the software package. Some of these studies were published (Verboom *et al.* 1992; Gerritsen *et al.* 1995), but much of this work was written down in technical reports of the various institutes. Without attempting to give a comprehensive list, the following paragraph shows some examples of the developments during the period 1980–1993.

The bathymetry for the model originates from nautical charts that were digitized. Since there was a considerable uncertainty associated with this bathymetry, for example, the fact that nautical charts tend to list the shallowest depths of a region for safety and the absence of recent hydrographic surveys for parts of the North Sea, much effort was spent calibrating the model. In the first few years, this was done using sensitivity studies and making changes to the bathymetry manually (Verboom *et al.* 1992). Later, automated procedures based on a variational method were developed for this purpose (ten Brummelhuis & Heemink 1990), and replaced most of the manual calibrations.

Earlier versions of the DCSM used a Smith–Banke air–sea drag relation (Gerritsen *et al.* 1995), but after a few seasons it became clear that this was not the best choice; the surges were systematically underestimated. Alternatives were a more complex piecewise linear relation between wind-velocity and drag coefficient and a relation developed by Charnock (1955). In several comparisons (Onvlee 1993; Gerritsen *et al.* 1995), both formulae outperformed the Smith–Banke relation equally. However, the Charnock relation has been chosen for operational use since it contains a better theoretical base.

For operational correction of forecasts with observations, a Kalman filter was developed (Heemink & Kloosterhuis 1990). This filter assimilates the selected water level observations from tide gauges at the British and Dutch coasts. Since the shallow water equations for water much deeper than the vertical tidal range are nearly linear, the Kalman filter can be approximated in a very efficient manner, leading to an additional computational cost of approximately only 10%. This Kalman filter can correct the forecasts up to 12 h ahead if the forecasts deviate from the available water level observations.

(*b*) *1994–2003*

Until 1998, several projects were aimed at further calibration of the storm surge model, DCSM. Most of these used the automated calibration package WAQAD (Mouthaan *et al.* 1994; Verlaan *et al.* 1996). A few local changes were made in the model to compensate for the lack of resolution. These were mainly near narrow channels between islands where a small misrepresentation of the bathymetry may lead to large changes in the flow. It was noted in subsequent calibration exercises that these local modifications removed a compensation effect of the WAQAD calibration for these local errors. The last calibration of the DCSM until now, September 2003, was performed in 1998 during the Datum2 project (Philippart *et al.* 1998), of which the main aim was to assess the potential impact of satellite altimeter sea level observations. Although the impact of the satellite observations proved to be small, with regard to the amount of data and level of accuracy available, it has provided us with some improvements to the calibration of the DCSM. It is now assumed that, with the limited resolution of approximately 8 km and present quality of the bathymetry information, further calibration is not worthwhile.

Parallel to the automated calibration tools, two 'online' data-assimilation methods were developed further. Several algorithms were developed and implemented, including the RRSQRT-Kalman filter (Verlaan 1998) and the ensemble Kalman filter (Evensen 1994). Although these algorithms are much more computationally demanding than the operational steady-state Kalman filter, they allow more complex studies, such as assimilation of satellite altimeter observations (Philippart *et al.* 1998), are much easier to maintain since they do not require a tangent linear model and, if needed, the Kalman gain matrix can be saved for use in a steady-state Kalman filter.

In 2002, the operational meteorological model at KNMI, called HiRLAM, was replaced with a model with a higher resolution. During this update, the grid size was reduced from 55 to 22 km, and the software was upgraded and now includes, for example, a more sophisticated turbulence closure. To assess the impact of this modification on the meteorological forcing to the DCSM, a validation study was carried out. The results of this study are described in §5.

4. Present operational set-up of the DCSM

(*a*) *The automatic production line*

The DCSM model, including the Kalman filter, has been implemented at KNMI for daily operational forecasting (de Vries 1991) where it is part of the automatic production line (APL).

KNMI's APL has been developed to produce regular numerical forecasts with a minimum of human intervention. It is the link between a wealth of observational data and large-scale model results and tailor-made products for customers and forecasts issued by the meteorologists. Observations and model results are gathered in databases where they are available for further use by other models, for presentation to and by meteorologists and for distribution to clients.

(*b*) *Meteorological input*

The heart of the APL is KNMI's limited area atmospheric model, HiRLAM, which currently provides an analysis of the state of the atmosphere and a forecast for up to 48 h ahead four times per day with a resolution of approximately 22 km. HiRLAM takes its boundary conditions—wind, temperature and humidity—from the global model, which runs twice daily at the European Centre for Medium Range Weather Forecasts.

The data from the meteorological model have to be interpolated before they can be used in the storm surge model. In time the data are interpolated linearly. Conversion from the grid of the atmospheric model to the DCSM grid proceeds by a bilinear interpolation in space. However, care has to be taken at land–sea boundaries. The wind over land is usually considerably lower than over sea. Therefore, near the coasts the interpolation has been modified to use only sea points of the atmospheric model for sea points in the storm surge model.

(*c*) *Observations*

Observations of water levels are available from the Rijkswaterstaat networks and from the British Dataring network. These networks collect water levels for the Dutch and British coasts and some platforms in the North Sea.

The storm surge model runs approximately 3 h after the start of the HiRLAM forecast with observations usually already available for the first 2 h of the forecast. Three hours later, a new Kalman filter run is made which uses the same meteorological input but includes more recent observations.

(*d*) *Data quality control*

Before assimilating data into a model it is absolutely necessary to validate the data in some way. The assimilation of only a few erroneous observations does more harm to the forecast than the assimilation of correct observations improves it. A typical example of erroneous observations is given in figure 3. Data can be suddenly corrupted with noise, or possibly due to mechanical problems, the gauge does not change anymore.

Quality control of the observations could make use of the correlations of the observations in the space and time domains. Because of the low observational

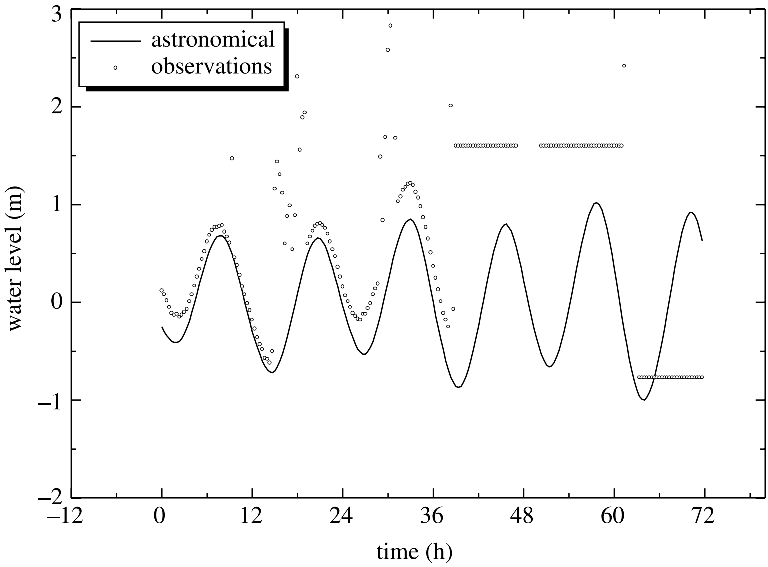

Figure 3. Tidal observations with errors.

density in space and the high density in time, the choice was made for quality control in the time domain. From figure 3 it is clear to the human eye, even without the aid of the astronomical tides, which observations are correct and which are corrupted. However, it appears to be difficult to translate the human pattern recognition process into a computer routine which can serve in a fully automated environment like the APL.

To eliminate scattering observations, restrictions are posed upon the range and, through the first and second derivatives, the continuity and the smoothness of the time-series of total water level, surge and the deviation of the observations from the forecast without data assimilation. Furthermore, some variation is demanded to eliminate hanging gauges.

(*e*) *Human operator*

As already mentioned, the APL has been designed to require a minimum of human interaction. In the case of a storm surge, this strategy changes and human (expert) intervention is explicitly demanded. Statistics of forecast accuracies during storm surge situations show clearly that the experience of the human operator improves the forecast quality compared with the DCSM model, even if data-assimilation techniques are applied. Further, the human expert at the SVSD plays an important role in communicating with local water authorities and the public. The SVSD expert plays a key role in the warning system, even if the executives have the final responsibility to take action.

(*f*) *Quality assurance: reliability and validation*

The software used for operational forecasting with the DCSM is maintained and developed, partly under supervision of Rijkswaterstaat, in two projects, called Simona for the hydrodynamic modelling software and Kalmina for the data-assimilation software. Together, the size of this software has grown to 500 000 lines of source code. This size, and the need for constant further improvement of the numerical model, has made ensuring the reliable operation of DCSM an essential task. In order to reach a sufficient level of reliability, a systematic evaluation at all levels is needed. In this section we will describe several of these tasks in a framework based on the work of Dee (1995).

In this systematic validation framework, the operational forecasts are viewed as an attempt to approximate a part of reality, in this case the water levels at selected locations during storms. This approximation can be split into several steps, each of which can be validated separately.

(i) *Selection of relevant processes:* The first level of approximation concerns the selection of relevant physical processes to include. Hydrostatic pressure forces, stress at the bottom and surface and Coriolis force are considered, whereas the influence of salinity is ignored. Assumptions made in this step can be checked against laboratory experiments and field measurements, though the data collected from the monitoring network is usually not sufficient for this purpose. The choices made are, to a large extent, dependent on the purpose of the model and the area of interest.

(ii) *Mathematical modelling:* The next step is to construct a mathematical model for the selected processes, which in the case of WAQUA takes the form of a set of partial differential equations. The quality of these model parts can be checked against field observations and laboratory experiments. Mathematical models of isolated processes often have a wide range of applicability.

(iii) *Numerical approximation:* For the purpose of operational forecasting, the hydrodynamic models are so complex that no closed form solutions are known and numerical approximation is necessary. For WAQUA, the numerical approximation has been checked by expansion of the truncation errors (Stelling 1984).

(iv) *Implementation into software:* After the numerical solution has been decided, it must be implemented to compute the solution within an acceptable time span. The tests for validating the implementation are repeated often, i.e. at least after each modification of the software and before every release. Another type of validation is performed by comparing model output with field measurements, e.g. from tide gauges. For DCSM a standard statistical comparison has been implemented in the software package BASISANALYSE. Figure 4 shows an example of the output of this package.

(v) *Operational implementation:* When changes in the model are transferred from development at RIKZ to operational production at KNMI, the output is compared for several historical periods to eliminate possible remaining errors in operational embedding. In addition, new versions of the model are implemented in parallel to the operational system, but with the output not provided to the users, for half a year. The decision to switch to the newer version of the model is based on a comparison of the statistics of the new version with the existing operational model over this period. After any such switch, the operational model is then monitored closely. The output is evaluated every few months, after every severe storm and if the hydrologist

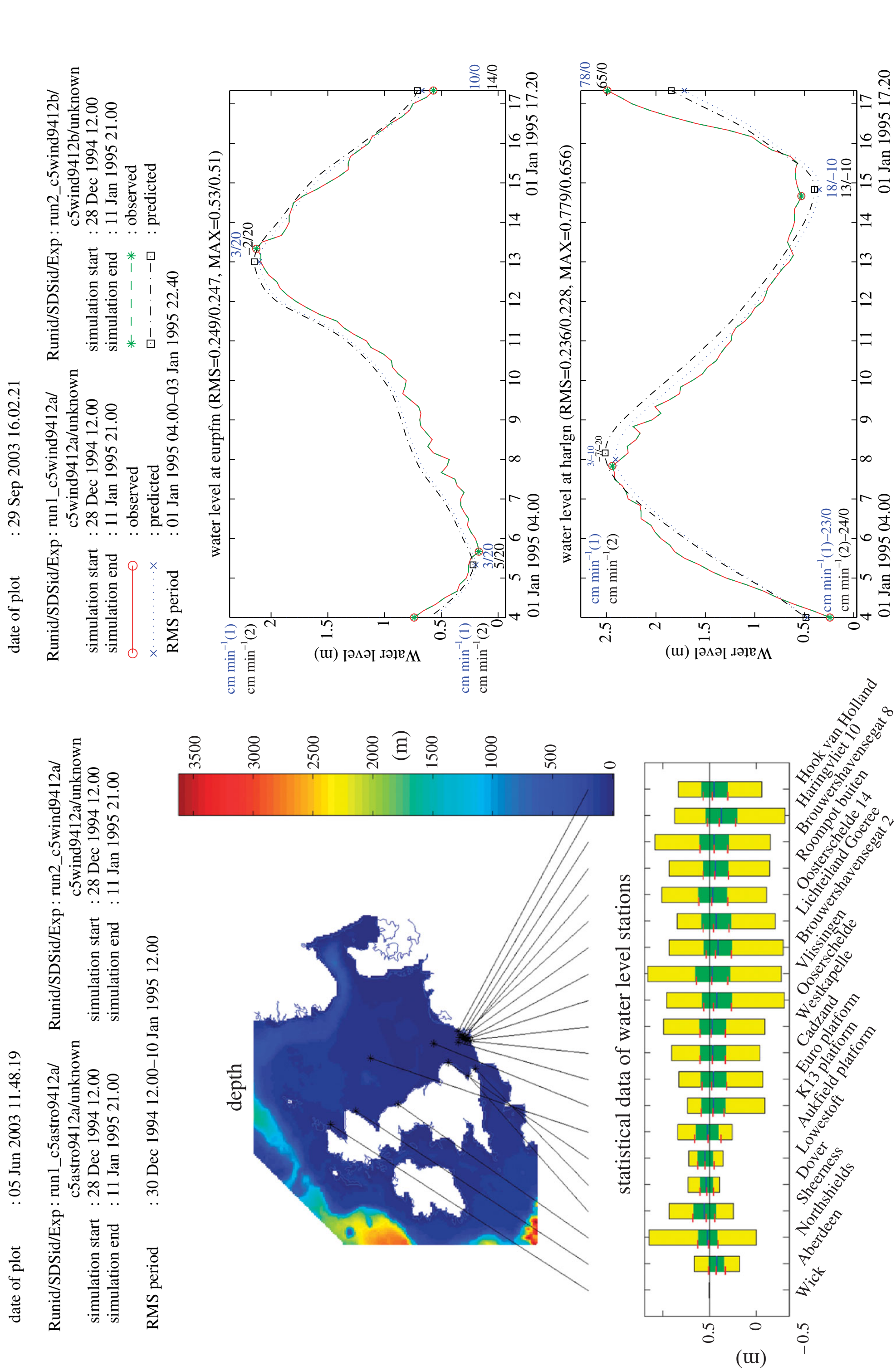

Figure 4. Example of output from the statistical validation tool.

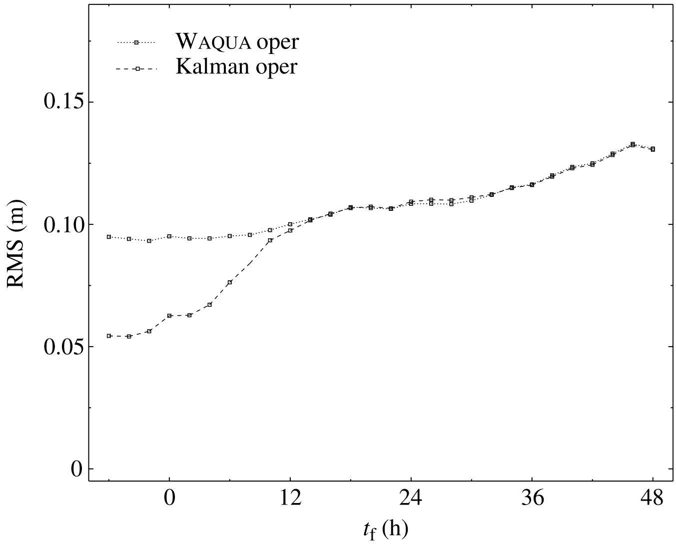

Figure 5. Operational evaluation for location Scheveningen. RMS errors for different forecast ranges with and without Kalman filter.

or meteorologist indicates any flaws. Figure 5 shows an example of operational validation; the root-mean-square (RMS) forecast errors, also referred to as RMSE, with and without Kalman filter for the DCSM are shown.

5. Selected developments

(a) *Change of HiRLAM grid from 55 to 22 km*

As the wind and air pressure fields are the main input components for the hydrodynamical DCSM model, new weather models have a great influence on the final surge forecast quality. Recent developments at KNMI have produced a whole new series of HiRLAM model versions. One main aspect here is the increase of spatial resolution. In March 2002, the former operational HiRLAM-55 km model has been replaced by a 22 km resolution and an 11 km resolution version, both based on the HiRLAM reference version 5.0.6. The increase in resolution from 55 to 22 km and the improvements in a new turbulence scheme led mainly to a significant improvement of the skill in precipitation forecast, but also to an increased accuracy for the surface wind forecast in terms of annual standard deviations (Sheur 2003). A comparison of 55 and 22 km HiRLAM resolutions on DCSM surge forecast quality, based on hindcast studies for several storm situations, showed that the 22 km version could slightly increase the forecast quality in storm situations. Further case studies on storm situations, comparing HiRLAM 22 km and HiRLAM 11 km input for DCSM, showed that the 11 km resolution could not improve the surge forecast quality of the DCSM model. Future evaluations of the operational forecast quality are necessary to confirm these case study results.

(*b*) *Configuration of the Kalman filter*

In 2003, a study was completed which was aimed at an optimized selection of the locations for the Kalman filter for the DCSM. This type of study is known in the literature as an observing system experiment (Atlas 1997).

The present operational configuration has not seen any major changes since the operational start in 1992 (see figure 2). The original selection was based on the assumption that the storm surge dynamics were dominated by the propagation of the tidal Kelvin wave down the British coast together with the direct stress exerted by the wind on the water surface. This led to the selection of several tide gauges along the British and Dutch coasts. At that time, the limited availability of tide gauge data played a role, but many more tide gauge observations have since become available.

In 2001, an inventory revealed more than 100 potential assimilation locations for the DCSM. These tide gauges were assumed to become online in 2003 through the European Union project, SEANET.

Unfortunately, the experiments showed (Verlaan & Zijderveld 2003) that no significant improvement can be realized at present. Figure 6 shows an example of the RMS of the forecast errors up to 6 h ahead for a selection of the locations used for the storm on 4 December, 1999. The other locations used are represented by markers for clarity only. The first bar, from left to right, shows the RMSE for the model without filter, the second for the operational Kalman filter and the others are for various alternative configurations. Although additional observations do improve the analysis and forecasts of storm surges, the improvements are mainly within a 200-km radius of the assimilated location. Since the present operation configuration contains comparatively numerous locations in the southern North Sea, this explains the insignificant improvements. Possibly the accuracy can be improved by adding data from offshore tide gauges. Unfortunately, all observations from offshore tide gauges were to some extent corrupted by measurement errors for the selected year, 1999. Also, no offshore locations were available to us near the north of the Netherlands, where the impact is expected to be largest.

6. Outlook 2004

In the coming years, new developments will be characterized by the demand to further increase forecast quality, and the efficiency and reliability of the whole surge forecast system.

In the North Sea region, different institutions are running operational ocean models. Recently, these institutes have joined forces in 'the north west shelf operational oceanographic system'. One of the first results of this cooperation is an exchange system for the operational storm surge forecasts. The exchange of forecasts can be of great value to both operational forecasters and users since access to forecasts from a variety of models can be used for a better assessment of the actual situation and can also serve as a back-up.

However, an update of the Kalman filter configuration for the DCSM (Verlaan & Zijderveld 2003) is only of practical use if the online data reliability and quality can be ensured. This task is a great challenge for all national institutes involved in surge forecasting for the North Sea area. The SEANET project provided a base for

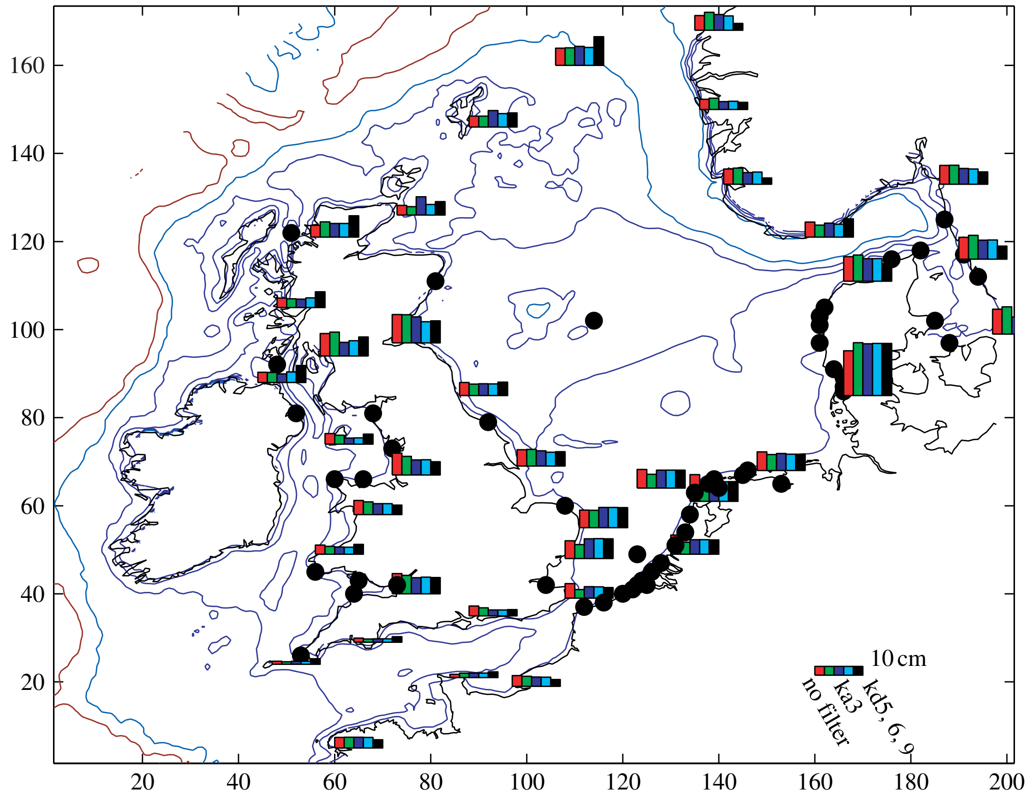

Figure 6. Impact of various Kalman filter configurations on RMSE: RMSE for forecasts from 00.00 to 06.00 on 11 November 1999. DCSM version 5 without a filter and with ka3, kd5, kd6 and kd9 filters.

the exchange of observations, but to realize the aim of a reliable real-time exchange of observations, more effort and commitment from all partners will be necessary.

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