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The implementation of the WAQUA/CSM-16 model for real time storm surge forecasting

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Hans de Vries

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Chapter 1

Introduction

A meteorlogist, who has to make regular weather and sea state forecasts, will be able to do his job better and faster when he has access to the results of advanced numerical models. With the growing power of computers and networks, the models in an operational environment can gain in usefulness, while becoming increasingly complex. Furthermore, advanced presentation methods facilitate the interpretation of the model results and help the meteorologist to get a better view of the present and future state of the atmosphere and the sea. At the Royal Netherlands Meteorological Institute (KNMI) a system of models, commonly referred to as the Automatic Production Line (APL), has been designed to produce regular numerical forecasts without the need for human intervention. Recently it has been implemented on a CONVEX minisuper computer.

The heart of the APL is a limited area atmospheric circulation model (LAM) [13]. The original intention was that LAM should produce a forecast for 30 hours every 3 hours. At present, however, a 30 hour forecast is made every 6 hours and in between only a data-assimilation run is made. To produce a more detailed update for a limited time span the circulation model VIMOLA runs every hour. The boundary conditions – wind, temperature and humidity – for LAM are supplied by the global circulation model of the European Centre for Medium range Weather Forecasts (ECMWF). The VIMOLA model works on a sub grid of the LAM grid and hence obtains its boundary conditions from the LAM model. Both models incorporate observations of wind and pressure in the analysis of the state of the atmosphere, which serves as an starting condition for the forecast.

As a backup for LAM, the results of the Fine Mesh model of the UK Met. Office in Bracknell can be used. This model produces an analysis every six hours and a 36 hour forecast two times a day.

Further branches on the APL tree are a wave-forecasting model for the North Sea (NEDWAM), a model for the propagation of air contamination (LVO), and a model for the prediction of the water levels in the North Sea (WAQUA), which will be the subject of this report. To transform the output of the circulation models to a wind stress on the sea surface, required by the NEDWAM and WAQUA models, an intermediate module (DVM) has been developed, which performs a detailed analysis of the

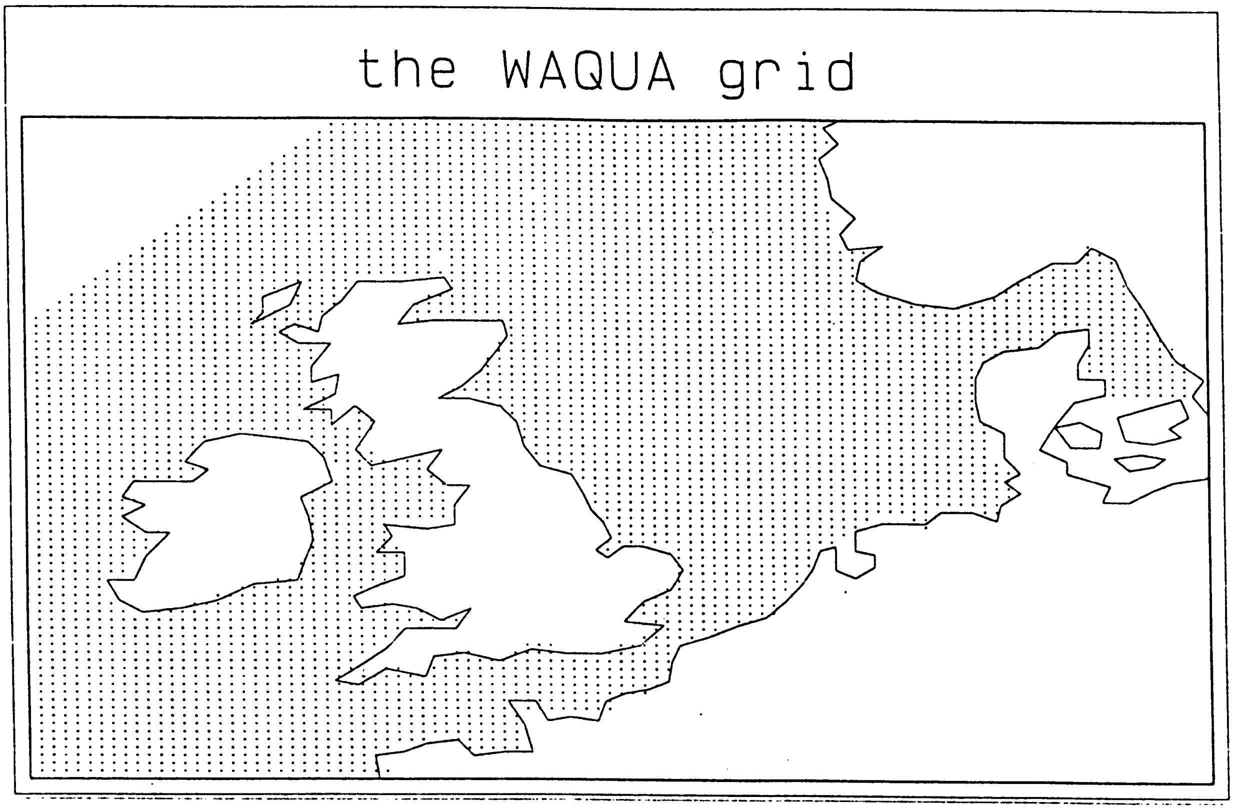

Figure 1.1: The WAQUA model grid

boundary layer between the sea and the lower atmosphere.
For the prediction of water levels in the North Sea the CSM-16 model of the WAQUA system was chosen as the successor of the present IOS model. In the OPWA project, a cooperation of the Tidal Waters Division and the Data Processing Division of Rijkswaterstaat and KNMI, the model was implemented for operational use at KNMI. The WAQUA system was developed by the RAND corporation (USA) and Rijkswaterstaat for two-dimensional hydrodynamic and water-quality simulations of well-mixed estuaries and coastal seas. It solves the well-known shallow water equations, 1.1, 1.2 and 1.3, in which viscosity is neglected.

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(h+\zeta)u + \frac{\partial}{\partial y}(h+\zeta)v = 0 \tag{1.1}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \zeta}{\partial x} = fv - \frac{1}{\rho_w}\frac{\partial p}{\partial x} - \mu\frac{u\sqrt{u^2+v^2}}{h+\zeta} + \frac{\tau_x}{h+\zeta} \tag{1.2}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \zeta}{\partial y} = -fu - \frac{1}{\rho_w}\frac{\partial p}{\partial y} - \mu\frac{v\sqrt{u^2+v^2}}{h+\zeta} + \frac{\tau_y}{h+\zeta} \tag{1.3}$$

with:

t: Time
x, y: Spatial coordinates
ζ: Water level elevation

u, v: x, resp. y components of the current
h: Undisturbed water depth
g: Acceleration of gravity
f: Coriolis parameter
μ: Bottom friction coefficient
$\tau_{x,y}$: x, resp. y components of the wind stress
ρ_w: Density of the water
p: Atmospheric pressure at sea level

The bottom friction coefficient is calculated as $\mu = \rho_w \, g \, C^{-2}$. The Chézy coefficient is generally given by

$$C = \begin{cases} 62 & \text{for } h \leq 42\,m \\ h + 20 & \text{for } 42 \leq h \leq 66\,m \\ 86 & \text{for } h \geq 66\,m \end{cases}$$

Tuning of the model has, however, led to some changes in this scheme.

The wind stress $\vec{\tau}$ is calculated from the 10 m wind $\vec{U}$ according to the relation established by Smith and Banke [10]: $\vec{\tau} = \rho_a \, C_D \, |\vec{U}| \, \vec{U}$, where ρ_a is the density of the air, for which a constant value of $1.205\,kg/m^3$ is taken. The wind-drag coefficient C_D is given by them as $C_D = \alpha + \beta \, |\vec{U}|$, with the constants $\alpha = 0.63$ and $\beta = 0.066$.

Eq. 1.1 is the continuity equation, which assures that the total water mass is conserved. Eqs. 1.2 and 1.3 are the x and y components of the depth averaged equation of motion, the Navier-Stokes equation (see e.g. [2]). In the CSM-16 model the equations are solved in spherical coordinates, which gives them a more complicated appearance, but of course does not add any extra physics.

The equations are solved with a so called Alternating Direction Implicit method (see [11]) on a staggered C-grid with depths at the centres of the grid-boxes. The advective scheme is generally central, but upwind where coasts or other boundaries are encountered. For details the reader is referred to [15] and [12]. The Data Processing Division of Rijkswaterstaat supplied a special version of the WAQUA package, adapted for use on a vector machine [12] and equipped with a Kalman Filter for data assimilation [4].

The CSM-16 model was set up and calibrated by the Tidal Waters Division of Rijkswaterstaat in cooperation with Delft Hydraulics. It covers the whole Northwest-European continental shelf from 12° W to 13° E and 48° N to 62° N (see Fig. 1.1). The distance of the grid points is $\frac{1}{4}^{\circ}$ in the WE direction and $\frac{1}{6}^{\circ}$ in the SN direction, corresponding to 18.6 – 12.9 km and 18.6 km resp. [15,6]. The open boundaries are located in deep (more than 200 m) water beyond the edge of the continental shelf. On the open boundaries the water level is prescribed through the ten tidal constituents M2, S2, N2, K2, O1, K1, Q1, P1, μ2 and L2.

Throughout the rest of this report the CSM-16 model will be referred to as the WAQUA model, although the WAQUA system has a much wider range of applications than the CSM-16 model alone.

Verification of the model and the implementation of the Kalman Filter will be the subject of following reports.

Chapter 2

An outline of the WAQUA model within the APL

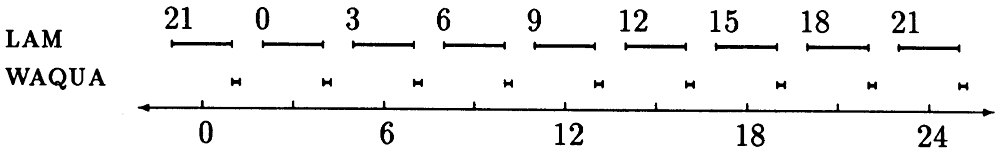

Figure 2.1: The dayly operational run scheme for LAM and WAQUA

In the APL, the simulation of the water movement in the North Sea is performed twice. In the first simulation only the astronomical tides are calculated without the use of wind and pressure input. In the other simulation the water levels and currents due to both the astronomical tides and the wind and pressure effect are calculated. For an accurate determination of the water levels at stations along the (Dutch) coast, the elevations and time differences between the run with wind and the tidal run are added to the tidal information supplied by Rijkswaterstaat, based on an harmonic analysis of historic time series (see appendix G). In this way errors in the calculation of the astronomical tides by WAQUA can be eliminated.

In principle the WAQUA model can handle the drying and flooding of very shallow parts of the sea. For the efficiency of the vectorization, however, this feature had to be removed from the CSM-16 model. For the whole of the continental shelf this introduces only negligible errors, but for the Waddenzee the effect might be significant. Therefore, the forecasts for stations on the coast of Friesland are deduced from stations just outside the Waddenzee. Time series of the elevations at the high and low tides have been analysed to establish a statistical relation between the stations inside and outside the Waddenzee [9]. At present the elevations in West Terschelling and Huibertgat are multiplied by a factor which is linear in the wind stress to obtain the elevation in resp. Harlingen and Delfzijl.

The run with wind and pressure input from the atmospheric circulation model is performed every three hours, following a LAM forecast. The dayly operational run scheme

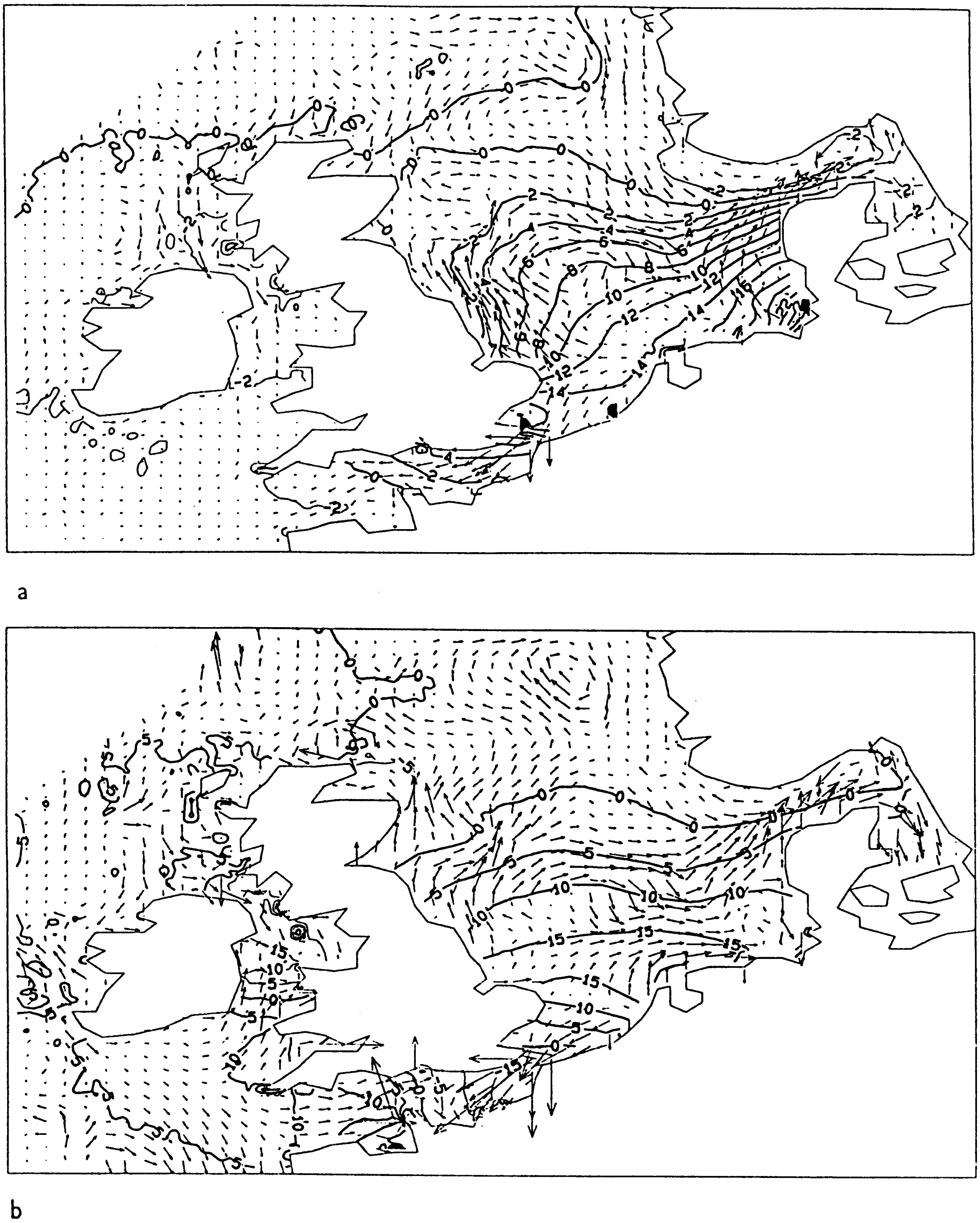

Figure 2.2: Maps from WAQUA for 14 Feb 1989 9 h GMT
Contour labels are heights in dm.
a: Surge and surge currents
b: Total water levels and currents

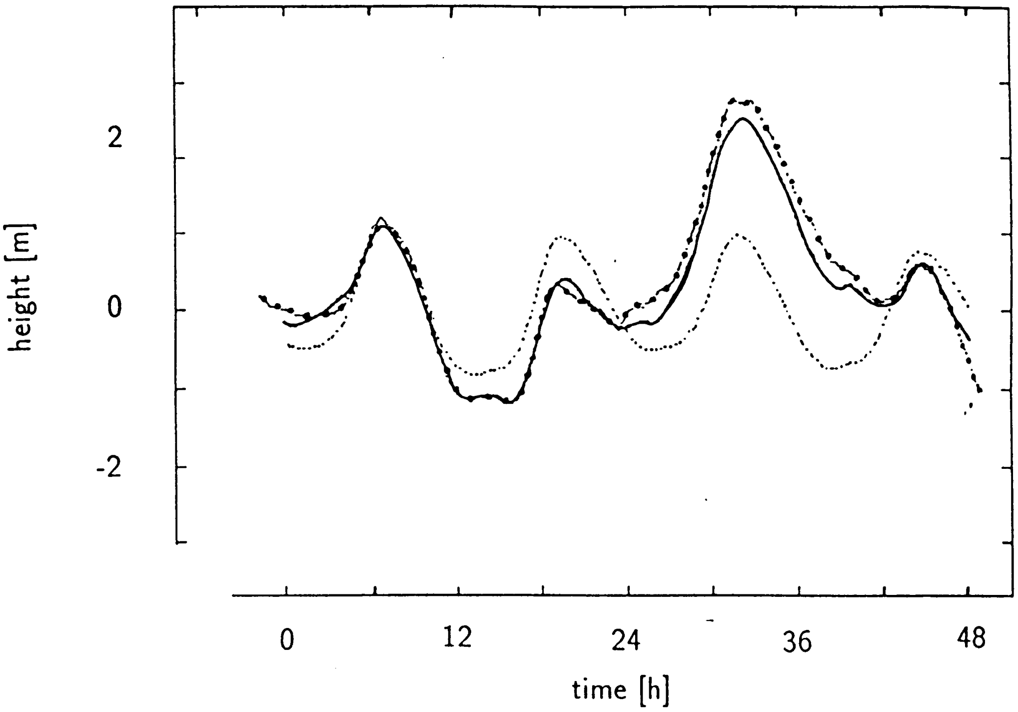

Figure 2.3: Time series for Hoek van Holland, starting on 13 Feb 1989 0 h GMT. Shown are the astronomical tide (dashed line), the model with wind (solid curve) and observations (dot-dashed curve).

is given in fig. 2.1. The wind and pressure input for WAQUA is linearly interpolated in time between 3-hourly LAM fields. Every WAQUA run starts with an analysis from the beginning of the previous forecast until the start of the current forecast with the new analysed wind and pressure field.

The results of the WAQUA forecast are combined with those of the tidal runs to produce maps with elevations and currents for every three hours (see appendix B) and time series for a number of selected stations along the Dutch coast (appendix C). The time step in these series is 20 minutes. Examples of a map and a time series are given in figs. 2.2 and 2.3. Apart from this information, which is coded in GRIB or TSF/BUFR code [17,3], a table is produced which contains data concerning the high and low tides in a few selected stations along the Dutch coast. This table contains the time and height for the astronomical tide calculated from the harmonic analysis, the elevations and time differences of these tides calculated by the model, an uncertainty interval for the high and low tides, eventually the actually measured elevations and the wind-stress values (appendix D). This table is also used for verification purposes.

Uncertainty intervals for the heights of the high and low tides are calculated more or less separately from the actual WAQUA model. The method, described by Van Lindert [7], is based on the sector model of the North Sea, which has been reviewed and refined by Timmerman [14].

Chapter 3

Modular description of the WAQUA system

The WAQUA system is depicted in fig. 3.1. It consists of a number of interconnected modules that perform well defined tasks. Each of the modules is meant to be started by an APL supervisor process, that keeps track of the status of every module and makes sure that all dependencies are observed. (See, however, sect. 3.1.)
The modules generally consist of a shell script that calls FORTRAN programs or other shell scripts. For each FORTRAN program the UNIX utility **make** checks whether the executable code still matches the source code, and, if not, recompiles and links the program.
The most complex part of the WAQUA system is the wind and pressure dependent surge run. This branch can be started as soon as the results of the atmospheric model are available. Every run is identified by a time stamp, *dtg*, which is built up from year, month, day and hour of the start time of the forecast, the analysis *time* in LAM terminology. (In WAQUA terminology the analysis *period* is the time span from the *dtg* of the previous run to the *dtg* of the current run, see sect. 2.) The *dtg* is used in the identification of the results (see appendix A).
The INIT module checks all variable input to the model and determines the time span for which the simulation has to be performed. The METEO module then interpolates the meteorological input to the WAQUA grid and performs conversions of the fields which are required by the model. Just before the simulation starts the KALOBS module gathers the water level data if assimilation is requested (see sect. 3.7). The actual simulation is then performed in the SIM2D11 module. Intermediate result-files are picked up by the POSTPROC module, which combines the results of the forecast with the tidal run and produces databases with fields and time series, and a table with high and low tides, both for operational use and verification.
Parallel to the METEO and SIM2D11 modules the sector model input, used by the POSTPROC module for the calculation of uncertainty intervals, can be prepared. The necessary interpolation of meteorologic information and update of the database is performed by the VAK-PREPROC module. This has to be finished when the POSTPROC module starts. The data from the VAK-PREPROC module are also used by the wave

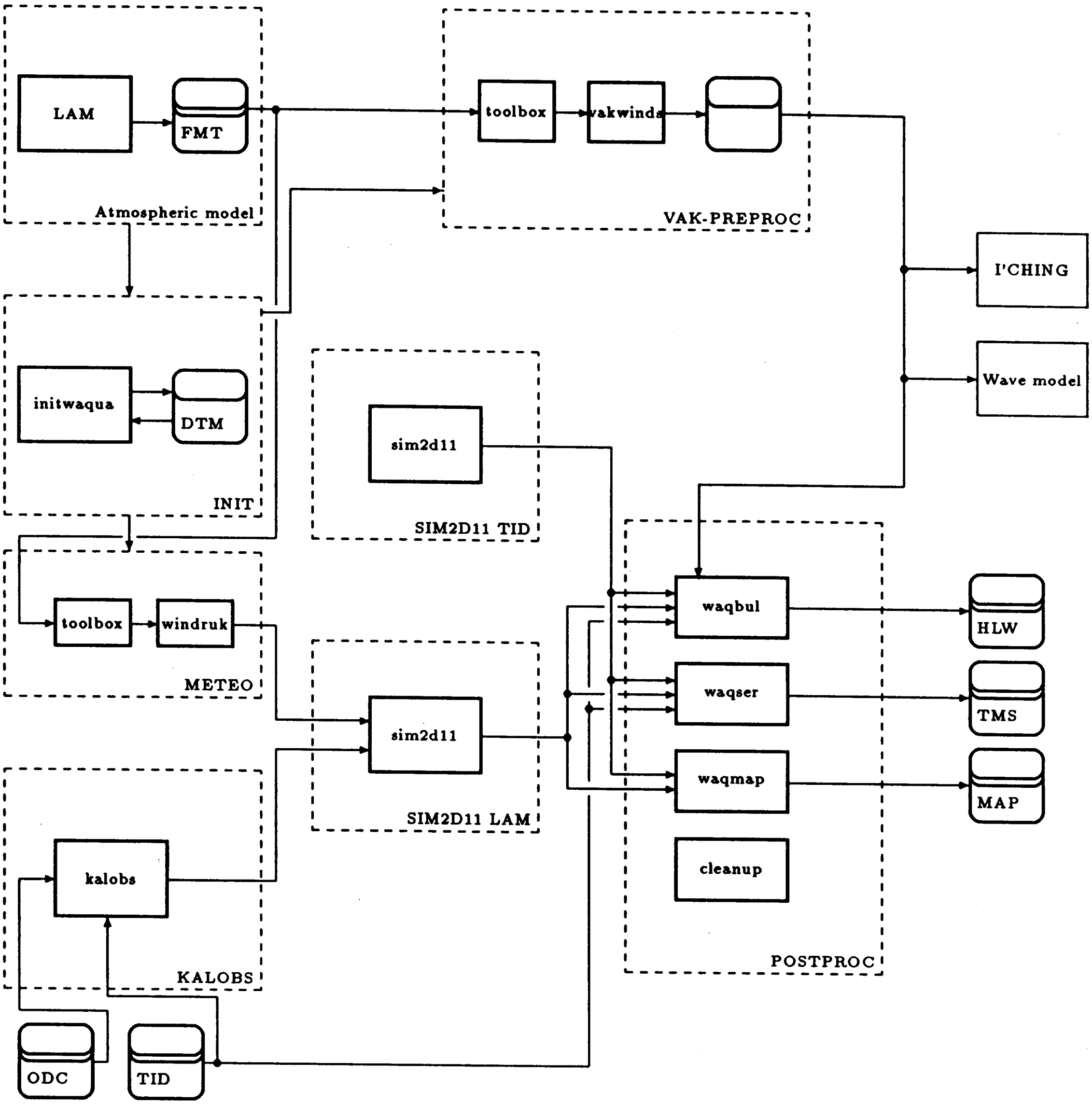

Figure 3.1: The WAQUA system

model for the same purpose and furthermore they are suitable for the I'CHING system, in which they could be used as input for an interactive version of the sector model. With this a meteorologist can improve his understanding of the state of the sea by studying the effect of variations in this input.
The tidal branch, which is independent of input from other sources, can be activated at any moment, but when KALOBS or POSTPROC is started enough results have to be available to span the time range of the surge run. Currently a tidal run of 24 hours is done each day at a fixed moment. The INIT module, however, also checks whether the data are available before allowing a forecast (see sect. 3.3).

3.1 The Supervisor

The supervision of the WAQUA system was originally intended to be part of a general APL supervisor, adapted from the ECMWF. This supervisor could, however, not be installed on the CONVEX machines and a different way of controlling the APL modules had to be found. For the WAQUA system the solution was found in a process which is started at fixed times, currently twice per hour. If this process detects the presence of new results from LAM or Bracknell, a job is queued which starts all appropriate modules in turn, or exits when one of them resulted in an error. If no new meteorological input data are found the process simply exits. Once a day a similar process queues a job which calculates the astronomical tide one day further ahead.
Surge runs are only performed when the date and time for the run lies less than 24 h back. Moreover, for runs that are more than 6 h back only the analysis is performed. In the operational situation a forecast would not be useful anymore, because a next forecast should be already available then.

3.2 Control of the WAQUA system

The main means for communication and synchronization within the WAQUA system is the DTM file, which contains the date and time (*dtg*) for the model run and also the analysis and forecast periods. Furthermore, there are switches for data assimilation, restart conditions, the identification of the circulation model and some items that are of minor importance in the operational environment. The DTM file is described in appendix E.
The items of the DTM file are set and checked by the program initwaqua, which is part of the INIT module. When the post-processing has been successfully completed, the analysis period (*ianal* in appendix E) is set to 0 to mark the last update with analyzed wind and pressure fields, which is at the *dtg* of the last completed run. The next run will then perform an analysis from this moment to the *dtg* of that run and start a forecast beyond that point. This procedure ensures that a new WAQUA run will

always start where the last successful run left off, whatever goes wrong in the mean time, like crashed or skipped WAQUA runs or computer break downs.

3.3 The INIT module

As already mentioned above, the **INIT** module checks the items in the DTM file and sets values for the current WAQUA run by means of the program **initwaqua**. The origin of the meteorologic information is passed as a parameter by the supervisor as well as the new *dtg*. All items in the DTM file that are not related to the simulation period are checked and, if necessary, corrected. The analysis period is calculated as the difference between the old and the new *dtg*s increased by the old analysis period, which is only nonzero when the last WAQUA run failed. This procedure might lead to very long analysis periods. The program **initwaqua**, however, limits the total length of the simulation period. Currently the absolute limit is 51 hours, imposed by the array space in the post-processing programs, but also the availability of the meteo input is used in determining the length of the simulation. The forecast is always set to cover all of the available wind and pressure fields. The analysis period is then determined taking into account the previous analysis, the availability of input and the total length of the run.

When the simulation period has been established, the presence of appropriate tidal-run data is checked. If necessary, these data are generated by a simulation without wind and pressure input.

Special care is taken of the restart data for the run. Under normal conditions the operational version of the simulation program writes a restart field to disk every three hours. Restart data are taken from the most recent surge run. This could also be a run with meteo input from the backup model. If no such data exist, e.g. because the analysis period was truncated, restart data from the tidal branch are taken. If necessary a simulation without meteorological input is performed to produce the restart field for the required moment, allowing for a spin up of at least 48 hours. Starting from a tidal field saves a full 48 hour spin up of the model with wind and pressure input and also prevents a possible surge of panic when the meteorologist compares the results of a surge run starting from a flat sea surface with a fully developed tidal field. The results of a surge run starting from a tidal field are not immediately reliable, but after 12 hours one might expect something which is at least comparable with the sector model.

In case of a rerun **initwaqua** will detect that the *dtg* of the triggering LAM run is older than the *dtg* of the last performed WAQUA run. In this case the analysis period is fixed to zero and the procedure as described above is followed. Furthermore, the database for the sector model (see sect. 3.5), that will probably not contain useful data, is removed. An attempt is made to restore an old version of this database.

3.4 The METEO module

The wind and pressure data for a surge run are made available to the SIM2D11 module by the METEO module. By means of general utilities from the APL toolbox the databases provided by LAM, DVM, Bracknell or any other source are read and the fields are interpolated to the WAQUA grid. The separate program mkasi then converts the interpolated fields to GRIB code and writes them to an ASIMOF database. Because the WAQUA grid is finer than the LAM grid, the interpolated fields need a higher accuracy than the original fields, which is the reason for using mkasi and not the standard ASIMOF output mode of the interpolation program.

For the analysis period the analyzed fields are gathered from WAQUA databases from previous foreacast or analysis runs.

A final conversion of the wind and pressure input is made by windruk. The simulation program expects pressure and wind-stress values on a staggered grid. The stresses can be provided by the boundary-layer model, but as long as this is not operational or gives similar results to LAM (see [1]), or when the Bracknell fields are used, windruk deduces them from the winds at an altitude of 10 m, using a quadratic drag-law. Apart from this, windruk produces a file with wind stresses at the selected water level stations for a correction of high and low tides, especially in the Waddenzee area, which is performed in POSTPROC.

3.5 The VAK-PREPROC module

The sector models that are used to calculate the uncertainties in the results of the WAQUA and NEDWAM models require input that is organized in a fundamentally different way than the other APL models. In stead of fields on a regular grid only field values for a limited number of locations at the North Sea are needed. As a consequence, the database standard for the APL, ASIMOF, can not be used. Another complication is that the sector models need input as far as 12 hours back from the start of a simulation. To avoid the gathering of these data from many scattered old databases, the choice was made to put all input for the sector models into one rotating database. From this database the old fields that are no longer needed are removed and analyzed or forecasted fields are added.

The module VAK-PREPROC first interpolates the LAM winds at 10 m above the sea level and the pressure to the required locations on the North Sea. After that it starts the program vakwinds, which updates the rotating database.

The data are used in the POSTPROC module to calculate the effect of varying the wind speed and direction on the surge according to Van Lindert [7]. The variation still has to be tuned in order to get a meaningful uncertainty interval for the water levels.

3.6 The KALOBS module

The WAQUA system provides the possibilty to assimilate real-time data into the model by means of a Kalman Filter. Observed water levels (cf. appendix F) are collected from the databases of the 'Monitoring Systeem Waterhoogten' (MSW) and the 'Meetnet Noordzee' (MNZ) of Rijkswaterstaat by a stand-alone PC at KNMI. These data are routed through the operational A6 computer to the Non-Standard-Bulletin-Database on the CONVEX.

When the model runs with data-assimilation the available data are processed by **kalobs** just before the actual simulation is started. The program **kalobs** performs a very elementary check on the data and produces input suited for **sim2d11**. Moreover, as the intention of the Kalman filter is to improve the forecast of the storm surge and not of the astronomical tide, the 'real' astronomical tide in the data is replaced by WAQUA's simulation. The harmonic-analysis values of the tide (cf. appendix G) are subtracted from the measurements and the residuals are added to WAQUA's tidal data to create observations whose tidal part behaves just like the astronomical tide in the WAQUA model. In this way the Kalman filter will only correct for errors in the meteorological forcing and the elevations produced by the model can be added to the harmonic analysis of the astronomical tide. Due to the data-cutoff time of LAM and the time it takes to run that model, a WAQUA run is usually not started sooner than 3 h after the *dtg*. This means that during the first part of the forecast observations are already available and can be assimilated into the model.

3.7 The SIM2D11 module

An actual simulation is performed in the **SIM2D11** module by the program **sim2d11**. The input consists of the DTM file, described in sect. 3.2 and the description of the model, which includes the grid, the land contours and the bottom of the sea, together with various other data and switches to guide the simulation. For a surge run also the space varying wind-stress and pressure fields, supplied by the **METEO** module, and the available data as processed by the **KALOBS** module are required. The simulation process produces water levels for stations along the North Sea coast for every 20 minutes and maps of the model area for every three hours. A printer file which lists the fixed input to the program is immediately removed when the simulation finishes. Run-time error messages, warnings and comments on the program flow are redirected to a log file.

The tidal branch, which has to provide the **POSTPROC** module with the water levels due to the astronomical tides can be run independent of the LAM model. It is started once a day to perform a new simulation of 24 hours. It maintains its own DTM file, which is updated after every successful simulation to set the conditions for the next run. Before a surge run the program **initwaqua** checks if there are enough tidal data available and initiates a new 24 hour simulation if necessary.

3.8 The POSTPROC module

The results of the simulation are processed by the POSTPROC module. The program **vultab** reads the files that are produced by **sim2d11** and produces for operational use databases with resp. maps and time sequences and a table with several data on the high and low tides (see appendices B, C and D). In fig. 3.1 these three tasks are indicated by resp **waqmap**, **waqser** and **waqbul**. It is intended to make separate programs for each of the tasks, but at present they are still combined in **vultab**.

When **vultab** completes successfully, the DTM file is updated by setting the analysis period to zero as described in sect. 3.2. Also the switch that indicates a restart run is set to true: when a WAQUA run completes restart fields are automatically available for the next one.

Cleaning up is also a task of the POSTPROC module, however, not before and only if **vultab** has completed successfully. The intermediate files for and from **sim2d11** are removed as well as obsolete wind and pressure databases, restart files, tidal run results and log files that are older than a few days.

Chapter 4

First results

Semi-operational tests with the storm surge model, described in the previous sections have started in January 1989. In this stage the LAM model produced its 30 h forecasts every 12 h, and also three-hourly analyses with observed atmospheric data during the rest of the day. In November of that year the forecast frequency was doubled and full runs were made every 6 h. The VIMOLA model was not yet operational. Neither was the boundary layer module and therefore the storm surge model and also the wave model were driven by the wind at an altitude of 10 m above sea level, produced by the LAM model.

From February on, observations of the water levels along the Dutch coast were available and a comparison with the model could be made. An extensive verification of the testing period will be performed soon. As an example some results for the months February, March, October, November and December 1989 are given in tables 4.1 to 4.5. Due to the low forecast-frequency (2 times each day in stead of 8 times when the APL is fully operational) and occasional failures, the statistics are still rather poor and no differentiation has been made between high storm surges and occasions with relatively little meteorological effect on the water levels. The tables give the averages of the quantities $H_{mod} - H_{obs}$ and $T_{mod} - T_{obs}$, the differences between calculated and observed heights and times of the high and low tides, and also the standard deviations in one case, calculated as $\sigma_x^2 = \sum_i \frac{(x_i-\bar{x})^2}{N-1}$, where N is the total number of cases.

The model results for the stations just outside the Waddenzee, West Terschelling and Huibertgat, are used to deduce an improved forecast for resp. Harlingen and Delfzijl (cf. sect. 2). The values given in tables 4.1 to 4.5 for the outer stations compare these corrected water level forecasts with the observations at the inner stations. From the standard deviations in the examples given here one could conclude that for Delfzijl this approach yields slightly better forecasts, but that the forecasts for Harlingen deteriorate. A more sophisticated relation between the water levels at the inner and outer stations might be necessary to improve the method.

Table 4.1: Forecasts between 0 and 12 h for February 1989

Station	high tides					low tides				
	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N
	[m]	[m]	[h]	[h]		[m]	[m]	[h]	[h]	
Vlissingen	-0.01	0.21	0.08	0.20	34	-0.01	0.16	-0.19	0.36	35
Oosterschelde	0.02	0.18	0.25	0.29	34	-0.05	0.17	0.40	0.92	33
Hoek van Holland	-0.04	0.16	-0.08	1.30	34	0.00	0.15	-0.16	1.88	27
Den Helder	-0.03	0.17	-0.06	1.53	34	-0.04	0.15	0.16	0.45	31
West Terschelling	0.05	0.21	0.05	0.67	24	-0.02	0.16	0.12	0.38	30
Huibertgat	-0.03	0.20	0.00	0.48	22	0.00	0.24	-0.13	0.32	34
Harlingen	0.02	0.20	-0.07	0.45	31	0.04	0.13	-0.05	0.30	33
Delfzijl	0.04	0.23	-0.16	0.37	34	-0.06	0.27	-0.19	0.24	35

Table 4.2: Forecasts between 0 and 12 h for March 1989

Station	high tides					low tides				
	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N
	[m]	[m]	[h]	[h]		[m]	[m]	[h]	[h]	
Vlissingen	-0.02	0.13	0.02	0.23	39	0.02	0.10	0.00	0.27	40
Oosterschelde	0.05	0.12	0.28	0.39	40	-0.06	0.18	0.12	0.75	44
Hoek van Holland	-0.04	0.11	-0.05	0.31	39	-0.03	0.10	0.68	1.70	41
Den Helder	-0.02	0.12	0.16	1.71	35	-0.03	0.15	0.05	0.42	29
West Terschelling	0.01	0.13	0.05	0.48	35	-0.02	0.18	0.13	0.32	34
Huibertgat	0.00	0.13	-0.07	0.38	34	0.00	0.18	0.05	0.38	33
Harlingen	-0.01	0.13	0.03	0.37	42	0.02	0.15	0.12	0.27	39
Delfzijl	-0.01	0.18	-0.02	0.39	41	-0.01	0.24	-0.07	0.28	36

Table 4.3: Forecasts between 0 and 12 h for October 1989

Station	high tides					low tides				
	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N
	[m]	[m]	[h]	[h]		[m]	[m]	[h]	[h]	
Vlissingen	0.02	0.12	-0.02	0.14	41	0.04	0.10	-0.07	0.20	43
Oosterschelde	0.03	0.11	0.26	0.31	40	-0.03	0.11	0.39	0.61	42
Hoek van Holland	-0.02	0.12	-0.06	0.28	40	0.07	0.12	0.00	1.87	43
Den Helder	-0.01	0.11	-0.28	1.12	42	0.04	0.11	-0.09	0.37	37
West Terschelling	0.11	0.12	0.03	0.44	30	0.09	0.18	0.12	0.39	32
Huibertgat	0.07	0.11	-0.07	0.29	34	0.06	0.16	-0.19	0.33	41
Harlingen	0.07	0.12	-0.07	0.33	35	0.13	0.14	0.03	0.29	37
Delfzijl	0.08	0.11	-0.17	0.27	42	0.07	0.18	-0.24	0.28	44

Table 4.4: Forecasts between 0 and 12 h for November 1989

Station	high tides					low tides				
	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N
	[m]	[m]	[h]	[h]		[m]	[m]	[h]	[h]	
Vlissingen	0.01	0.11	0.00	0.15	45	0.04	0.14	-0.14	0.29	49
Oosterschelde	0.04	0.11	0.32	0.18	43	0.01	0.13	0.06	0.43	48
Hoek van Holland	-0.01	0.10	-0.01	0.21	42	0.08	0.11	0.50	1.42	49
Den Helder	0.04	0.16	0.16	1.00	40	0.07	0.14	-0.11	0.36	36
West Terschelling	0.15	0.13	-0.07	0.47	36	0.22	0.10	-0.07	0.18	32
Huibertgat	0.01	0.10	-0.10	0.28	45	0.11	0.12	-0.12	0.23	40
Harlingen	0.11	0.12	-0.07	0.35	42	0.22	0.10	-0.01	0.20	39
Delfzijl	0.03	0.11	-0.07	0.25	48	0.15	0.16	-0.14	0.21	43

Table 4.5: Forecasts between 0 and 12 h for December 1989

Station	high tides					low tides				
	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N	$< \Delta H >$	σ_H	$< \Delta T >$	σ_T	N
	[m]	[m]	[h]	[h]		[m]	[m]	[h]	[h]	
Vlissingen	-0.01	0.14	0.01	0.23	52	0.01	0.12	-0.07	0.28	60
Oosterschelde	-0.01	0.13	0.26	0.25	51	-0.05	0.11	0.22	0.58	58
Hoek van Holland	-0.04	0.10	0.09	0.24	46	0.03	0.08	0.43	1.21	53
Den Helder	-0.03	0.12	0.01	1.44	56	0.00	0.24	-0.02	0.57	53
West Terschelling	0.10	0.13	-0.23	0.48	47	0.08	0.14	0.10	0.48	39
Huibertgat	0.00	0.10	-0.07	0.27	45	0.06	0.09	-0.21	0.22	38
Harlingen	0.07	0.13	-0.16	0.42	52	0.11	0.12	0.00	0.33	43
Delfzijl	0.01	0.10	-0.13	0.31	55	0.06	0.13	-0.21	0.20	48

Chapter 5

Management

The WAQUA system has been designed to need a minimum of management in an operational set up. It is safeguarded against most of the errors one can think of. This especially holds for runs that were skipped for whatever reason, or missing wind input. The **initwaqua** module can take proper action on this kind of errors. However, when the model is used in day to day forecasting of water levels, operators have to keep an eye on the model, checking whether the products arrive in time, and, if not, trying to find the cause. The logfiles might be helpful in this case. For the operators there is a special manual available, which describes the system in much more detail on this level [16].

Another point for consideration is the availability of the tables with the harmonic analysis of the astronomical tides. Each table contains the data for one year. That means that well before the end of the year new tables have to be made available. The format of these tables is given in appendix G.

Chapter 6

Outlook

When this report was finished the testing phase was gradually being ended and preparations were made to run the model under operational responsibility. Already for some time the results from WAQUA are being presented at the HMR in Hoek van Holland to give the meteorologists the opportunity to acquire some experience with the new products. It also enables a comparison of the model with its predecessor, the IOS model. A systematic comparison of the results of both models will be made for the year 1990 and the winter months of 1991.

The WAQUA model is driven by the 10 m winds from LAM, which are converted to friction velocities with a quadratic drag-relation. The effect of using 10 m winds or even the friction velocities from the boundary layer module DVM is still negligible [1].

Data assimilation in the storm surge model will not become operational before it has been thoroughly tested, e.g. by running the models with and without data assimilation in parallel and by a careful study of some interesting cases. The Kalman Filter is, however, already completely embedded in the WAQUA system and switching it on is simply a matter of a single parameter in the DTM file (see appendix E).

From the first results (cf. sect. 4) it seems that the translation of the water levels just outside the Waddenzee to the coastal stations Harlingen en Delfzijl, hardly gives better forecasts than these stations in the model itself. Part of the explanation is that the model itself has already been tuned to give optimal results for Harlingen and Delfzijl [15], but a more sophisticated translation might still help to improve the results.

Uncertainty intervals are already calculated using the sector model. Before they can really been used, however, the parameters in this model should be tuned. When the WAQUA system has been used for some time and the results have been archived, the tuning can be performed using the statistics.

Apart from water levels, the WAQUA system also produces depth-averaged currents in the North Sea. At the moment these currents are not yet used, but there are various possibilities. One could think of assistance in off-shore activities that are limited by the strength of the current. To this end a study has already been carried out to investigate the use of a $2\frac{1}{2}$ D model to calculate the depth-dependency of the current from the WAQUA results [8]. Another application could be assistance of decision makers for the North Sea in case of calamities. When an accident occurs that involves the spill of chemicals or oil, information is needed to determine the displacement and dispersion of the pollutant. In this field much work has already been carried out by Rijkswaterstaat, but their models only use measured winds and elementary current information. By supplying forecasts of winds and currents, the APL models could add to the quality of the decision support.

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Appendix A

File names in the WAQUA system

This appendix lists the names of all files, used in the WAQUA system. The file names conform to the APL standard. The model version, indicated by v, can be

G	File for general use
T	Tidal run
L	Surge run, driven by LAM
V	Surge run, driven by VIMOLA
B	Surge run, driven by Bracknell/UK6
D	Surge run, driven by LAM/DVM

For *yy*, *mm*, *dd* and *hh* the year, month, day and hour have to be substituted.

LAMF_FMT_*yymmddhh*00_00000_AB	Database produced by LAM
UKMO_ARG_*yymmddhh*00_00000_AB	Database from the Bracknell Fine Mesh model
VAKA_INP_0000000000_00000_VB	Sector model database
VAKA_INP_*yymmddhh*00_00000_VB	Idem, saved old version
WAQG_DTM_0000000000_00000_LC	WAQUA DTM file
WAQG_SIM_0000000000_00000_LC	CSM-16 model description
WAQG_GRD_0000000000_00000_SW	WAQUA grid description
WAQG_TID_*yy*00000000_00000_DW	Harmonic tide analysis (10 min values)
WAQG_ODC_*yymmddhh*00_00000_OC	Observations
WAQ*v*_HIS_*yymmddhh*00_00000_HW	Time series produced by sim2d11
WAQ*v*_HLW_*yymmddhh*00_00000_LC	Table with high and low tides
WAQ*v*_INP_*yymmddhh*00_00000_AB	Wind input database on WAQUA grid
WAQ*v*_INP_*yymmddhh*00_00000_SW	Wind input for sim2d11
WAQ*v*_KFL_0000000000_00000_LC	Kalman filter (ascii)
WAQ*v*_KFL_0000000000_00000_SW	Kalman filter (binary)
WAQ*v*_KFO_*yymmddhh*00_00000_LC	Kalman filter input (ascii)
WAQ*v*_KFO_*yymmddhh*00_00000_SW	Kalman filter input (binary)
WAQ*v*_LOG_*yymmddhh*00_00000_LC	Log file from sim2d11

WAQ*v*_MAP_*yymmddhh*00_00000_AB	Maps database from vultab
WAQ*v*_MAP_*yymmddhh*00_00000_SW	Maps from sim2d11
WAQ*v*_MTH_*yymm*000000_00000_LC	WAQUA forecast results, gathered for one month
WAQ*v*_PRT_*yymmddhh*00_00000_LC	Print file
WAQ*v*_RST_*yymmddhh*00_00000_SW	Restart file
WAQ*v*_SUM_*yymm*000000_00000_LC	Verification summary
WAQ*v*_STX_*yymm*000000_00000_LC	Verification summary as input for LaTeX. (Used for tables 4.1 to 4.5.)
WAQ*v*_TMS_*yymmddhh*00_00000_TW	Time series (TSF/BUFR)
WAQ*v*_VER_*yymm*000000_00000_LC	Verification results
WAQ*v*_VER_*yymm*000000_00000_SW	Verification results for summarizing purposes
WAQ*v*_WAD_*yymmddhh*00_00000_SW	Data for Waddenzee correction

Appendix B

Description of the WAQUA MAP file

The WAQUA MAP files are called `WAQ`*v*`_MAP_`*yymmddhh*`00_00000_AB`. These ASIMOF databases contain the tidal and residual water levels and the u and v components of the tidal and residual currents for every three hours (see table B.1).

Table B.1: Contents of the WAQUA MAP file

WMO identification	parameter	unit
231	Tidal water level	[m]
232	Tidal current (East component u)	[m/s]
233	Tidal current (North component v)	[m/s]
237	Residual water level	[m]
238	Residual current (East component u)	[m/s]
239	Residual current (North component v)	[m/s]

Appendix C

Description of the WAQUA time series file

The WAQUA time series files are called `WAQ`*v*`_TMS_`*yymmddhh*`00_00000_TW`. These TSF files contain time series for all selected stations in the model. Currently these stations are Wick, Aberdeen, North Shields, Scarborough, Innerdowsing, Lowestoft, Southend, Dover, Newhaven, Portsmouth, Cherbourg, Calais, Oostende, Vlissingen, BG-2 (Oosterschelde), Goeree, Hoek van Holland, Scheveningen, IJmuiden, Den Helder, Harlingen, West-Terschelling, Huibertgat, Delfzijl, Borkum, Helgoland, Esbjerg, Stavanger, Ekofisk and Station K13a (see table F.1). The time step is 20 min. For each of the stations the elevation with WMO identification 0 54 001 and the tidal water level with WMO identification 0 54 002 are stored.

Appendix D

Description of the WAQUA tidal table

The post processing program **vultab** produces a table with the most important results of a WAQUA run. Its name is `WAQ`*v*`_HLW_`*yymmddhh*`00_00000_LC`. The table contains the following information on high and low tides for the successive stations: Vlissingen, Oosterschelde, Hoek van Holland, Den Helder, West Terschelling, Huibertgat, Harlingen, and Delfzijl.

dtg	Date/time group of the WAQUA run. All time values are given with respect to this time. A negative dtg signals a missing RWS tidal table.
t_{RWS}	The time of the RWS table with respect to the dtg.
h_{RWS}	The water level according to the RWS table.
t_{obs}	Observed lag or advance of the tide with respect to the RWS table.
h_{obs}	Observed increase or decrease of the water level for this tide with respect to the RWS table.
t_{mod}	Calculated lag or advance of the tide with respect to the RWS table.
h_{obs}	Calculated increase or decrease of the water level for this tide with respect to the RWS table.
dh_+	Calculated uncertainty in the level of the tide, upper boundary.
dh_-	Calculated uncertainty in the level of the tide, lower boundary.
u	East component of the wind stress at the calculated extreme.
v	North component of the wind stress at the calculated extreme.

The items t_{RWS} to v are repeated for at most 10 successive tides. Missing data are indicated by the value 99.999.

Appendix E

Description of the WAQUA DTM file

The DTM file, called `WAQG_DTM_0000000000_00000_LC`, contains the control parameters for a WAQUA run. Each parameter occupies exactly three positions with no extra interleaving space. The parameters are:

yy	
mm	
dd	
hh	date and time *dtg* for the run.
its	control for run type 0 : tidal run 1 : run with LAM winds 2 : run with VIMOLA winds 3 : run with Bracknell winds
ianal	analysis period, preceding the *dtg* [h]. In the operational environment this parameter indicates the last WAQUA surge run that was completed successfully, i.e. the current *dtg* minus *ianal* is the *dtg* of the last successful WAQUA run.
iforcp	forecast period from *dtg* [h].
ipmflg	permanent restart flag 0 : 'cold' start 1 : start with initial fields
kamflg	Kalman Filter flag 0 : Kalman filter off: no data assimilation 1 : Kalman filter on
ihinca	hindcast parameter 0 : operational run 1 : hindcast run
ipm	interval [h] to write restart file.

Appendix F

Water level stations

In this appendix the water level stations which are available for verification of the model and data assimilation are listed. Table F.1 gives the names of the stations, the index N_{WAQUA} in the model, the gridpoint indices m and n and the identification code for the SQNT42 observation bulletins. In the SQNT42 bulletins only the last three digits of this code are used. When the gridpoint indices are not given the station is not used for verification or data assimilation. When the identification code is not given observations for the station are not available (in real time).

Table F.1: Water level stations

Name	N_{WAQUA}	m	n	code
Wick	1	37	64	03075
Aberdeen	2	41	56	–
North Shields	3	44	43	03262
Scarborough	4	48	39	–
Innerdowsing	5	51	33	–
Lowestoft	6	56	28	03496
Southend	7	52	22	03791
Dover	8	55	20	03796
Newhaven	9	49	17	03880
Portsmouth	10	45	18	–
Cherbourg	11	43	11	–
Calais	12	56	19	–
Oostende	13	61	21	–
Vlissingen	14	64	22	06520
BG-2 (Oosterschelde)	15	64	24	06516
Goeree	16	64	25	06320
Hoek van Holland (MNZ)	17	65	25	06330
Hoek van Holland (MSW)	–	65	25	06514
Scheveningen	18	66	26	06517
IJmuiden (MNZ)	–	67	28	06225
IJmuiden (MSW)	19	67	28	06522
Den Helder	20	67	31	06512
Harlingen	21	71	32	06513
West Terschelling	22	70	33	06518
Huibertgat	23	75	35	06515
Delfzijl	24	77	33	06511
Borkum	25	76	35	–
Helgoland	26	81	38	–
Esbjerg	27	82	46	–
Stavanger	28	72	67	–
Ekofisk	29	62	52	–
K13a	30	62	32	06550
Cadzand	–	–	–	06510
Texel Noordzee	–	–	–	06519
West Kapelle	–	–	–	06521
Auk Alpha	–	–	–	06551
Euro platform	–	–	–	06553
Meetpost Noordwijk	–	–	–	06554
North Cormorant	–	–	–	06555

Appendix G

Format of the yearly tidal tables

The tidal tables are stored in a binary direct-access file to ensure an optimum access time to the required data. The file is called `WAQG_TID_`*yy*`00000000_00000_DW`. It consists of records according to the Pascal definition:

```
TYPE    integer_2 =  { a 2-byte integer } ;
        integer_4 =  { a 4-byte integer } ;
        rec_type =   (statlist, data);
        day =        RECORD
                       CASE class:  rec_type OF
                          statlist:  (     n_stat:   integer_4;
                                         stations:   ARRAY [1..73] OF integer_4;);
                              data:  (       date:   integer_4;
                                          station:   integer_4;
                                       tidal_data:   ARRAY [1..144] OF integer_2;);
                     END;
```

Every record has a length of 296 bytes. The first record of the file is of the `statlist` type. It contains the number of stations `n_stat` in the file and a list `stations` with the station codes according to table F.1. All other records are of the `data` type and contain the tidal information for one station and one day, stored per station and ordered according to the `stations` array. The `date` field has the form *yymmdd*. The `station` field is the code as in the `stations` list. The `tidal_data` are water levels for every 10 minutes in cm, starting at 0h MET (!). Because of the ordering of the data the record number of the required data can be found as:

$$n_{rec} = N_{31\,Dec} \cdot (i_{stat} - 1) + N_{day} + 1,$$

with

n_{rec}: Record number

$N_{31\,Dec}$: Daynumber of 31 December (365 or 366)

i_{stat}: Index of the station in the `stations` array.

N_{day}: Number of the day under consideration.

This means that the `date` and `station` fields are redundant, but they are used as an extra check to ensure that the data for the correct day and station are returned.