Investigation of surge-tide interaction in the storm surge model CSM-16

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Abstract

The Dutch Continental Shelf Model CSM-16 will be used for operational storm surge predictions in the Netherlands. In these predictions the non-linear interaction between surge and tide is an important feature for the whole southern North Sea and the Channel. The aim of the present study was to investigate the reproduction of interaction by CSM-16 and to describe and explain the characteristics of interaction.

For the storm surges of 31 January and 1 February 1953 and 1 and 2 February 1983, the variations in the computed and observed surge levels which are characteristic for interaction, were compared. In general, the agreement of the variations was satisfactory.

The characteristics of interaction were described and explained on the basis of literature and model experiments in which the phase of the surge and the tidal conditions were varied.
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List of Symbols

$A_S$ : surge amplitude
$C$ : Chézy coefficient of bottom friction
$C_D$ : wind drag coefficient
$g$ : acceleration due to gravity
$h$ : undisturbed water depth
$I$ : (total) interaction
$P_a$ : surface atmospheric pressure
$R$ : radius of the earth
$S$ : surge
$S'$ : surge with interaction from tide
$t$ : time
$T$ : tide
$T'$ : tide with interaction from surge
$u, v$ : components of $u$
$u^*$ : depth-mean current
$w$ : surface wind
$x$ : horizontal distance
$z$ : sea surface elevation
$\rho$ : density of sea water
$\rho_a$ : density of the air
$\tau_{bx}, \tau_{b\phi}$ : components of $\tau_b$
$\tau_b$ : bottom stress
$\tau_{wx}, \tau_{w\phi}$ : components of $\tau_w$
$\tau_w$ : wind stress on the sea surface
$x, \phi$ : coordinates in east longitude and north latitude
$\omega$ : angular speed of the earth's rotation
List of Abbreviations

CSM-8 : Dutch Continental Shelf Model, grid size $1/12^\circ$ latitude and $1/8^\circ$ longitude
CSM-16 : Dutch Continental Shelf Model, grid size $1/4^\circ$ latitude and $1/4^\circ$ longitude
HW : High water
GMT : Greenwich Mean Time
KNMI : Royal Netherlands Meteorological Institute
1. Introduction

The Tidal Waters Service of Rijkswaterstaat, Ministry of Transport and Public Works in the Netherlands commissioned a study on the reproduction of surge-tide interaction in the Dutch Continental Shelf Model CSM-16 to DELFT HYDRAULICS. CSM-16 is a non-linear model for tide and wind induced flow on the north-west European continental shelf with a grid size of $\frac{1}{4}^\circ$ latitude and $\frac{1}{4}^\circ$ longitude (approximately 16 km), see Figure 1.1. The model is based on the WAQUA programme system for the solution of the shallow-water equations. It has been developed by the Tidal Waters Service of Rijkswaterstaat and DELFT HYDRAULICS starting from a model with a higher resolution (CSM-8), described by Verboom et al (1987, 1989). At present Rijkswaterstaat is preparing CSM-16 for operational use in the storm surge prediction scheme of KNMI.

The non-linear interaction of tide and surge may lead to both reduction and amplification of storm surges. Investigations have shown that interaction plays a significant role in the whole southern North Sea, generally increasing the surge height at rising tide and decreasing the surge height at high tide, see for example the review on storm surges by Heaps (1983).

Consequently, a proper reproduction of interaction by CSM-16 is one of the requirements for the production of accurate storm surge predictions. Furthermore, the understanding of the phenomenon of interaction is important for the correct assessment of the surge predictions, as applied in the storm tide warning system.

In this context the following questions were raised:

(i) how realistic is the reproduction of interaction in the present model,

(ii) what are the characteristics of interaction and how do they develop, especially:
- how does interaction vary in space and time,
- which factors influence interaction, for instance
  - in what way does interaction depend on the meteorological boundary conditions, and
  - in what way does interaction depend on the tidal conditions?

The aim of the present work is to study these subjects by means of a literature investigation and numerical experiments with the model.
The contents of the report are as follows. First, Chapter 2 goes into the phenomenon of surge-tide interaction in more detail, starting with the definition of interaction and a first description of its characteristics based on literature. Possibilities for the verification of interaction computed by tide and surge models are also discussed. In Chapter 3 the reproduction of interaction by CSM-16 is investigated. The next two Chapters are dedicated to numerical model experiments to investigate the effect of the phasing of the surge relative to the phase of the tide and of the effect of variation in tidal conditions. Finally, in Chapter 6 the study is summarized and conclusions are presented.

The study was performed by DELFT HYDRAULICS Estuaries and Seas Division, Oceanography Group: dr. H. Gerritsen, project leader, A.C. Bijlsma, investigation and reporting, R. Bruinsma and D.K. Vatvani, numerical computations and programming. On behalf of Rijkswaterstaat, Tidal Waters Service, support was given by J.G. de Ronde, who also reviewed this report.
2. Problem analysis

2.1 Definition of interaction

The interaction between surges and the astronomical tide is caused by non-linear effects in the water motion. For tides and surges this motion is described by the depth-averaged shallow-water equations. Written in spherical coordinates the equations read:

\[
\frac{\partial u}{\partial t} + \frac{u}{R \cos \phi} \frac{\partial u}{\partial x} + \frac{v}{R} \frac{\partial u}{\partial \phi} - \frac{u \cdot v \tan \phi}{R} \frac{\partial}{\partial a} - 2 \omega \sin \phi v = \frac{g}{R \cos \phi} \frac{\partial \zeta}{\partial x} - \frac{1}{\rho R \cos \phi} \frac{\partial p}{\partial x} - \frac{\tau_{b\chi}}{\rho (h+\zeta)} + \frac{\tau_{w\chi}}{\rho (h+\zeta)} \tag{2.1}
\]

\[
\frac{\partial v}{\partial t} + \frac{u}{R \cos \phi} \frac{\partial v}{\partial x} + \frac{v}{R} \frac{\partial v}{\partial \phi} + \frac{u^2}{R} \frac{\partial}{\partial a} + 2 \omega \sin \phi u = \frac{g}{R} \frac{\partial \zeta}{\partial \phi} - \frac{1}{\rho R} \frac{\partial p}{\partial \phi} - \frac{\tau_{b\phi}}{\rho (h+\zeta)} + \frac{\tau_{w\phi}}{\rho (h+\zeta)} \tag{2.2}
\]

\[
\frac{\partial \zeta}{\partial t} + \frac{1}{R \cos \phi} \left[ \frac{\partial}{\partial x} \left( (h+\zeta) u \right) + \frac{\partial}{\partial \phi} \left( (h+\zeta) \frac{v \cos \phi}{R} \right) \right] = 0 \tag{2.3}
\]

where the notation is:

- \( t \) : time
- \( x, \phi \) : coordinates in east longitude and north latitude
- \( \zeta \) : sea surface elevation
- \( u, v \) : components of depth-mean current \( \bar{u} \)
- \( h \) : undisturbed water depth
- \( g \) : acceleration due to gravity
- \( \rho \) : density of sea water
- \( p_a \) : surface atmospheric pressure
- \( R \) : radius of the earth
- \( \tau_{b\chi}, \tau_{b\phi} \) : components of bottom stress \( \tau_b \)
- \( \tau_{w\chi}, \tau_{w\phi} \) : components of wind stress \( \tau_w \) on the surface
- \( \omega \) : angular speed of the earth's rotation
The bottom stress is defined by:

$$\tau_b = \rho g C^{-2} \left| \vec{u} \right| \vec{u}$$  \hspace{1cm} (2.4)$$

with a depth dependent Chézy coefficient $C$. In CSM-8 this coefficient is given by:

$$C = \begin{cases} 
65 \text{ m/s}, & h \leq 40 \text{ m} \\
62 \text{ m/s}, & 40 < h \leq 65 \text{ m} \\
90 \text{ m/s}, & h > 65 \text{ m}
\end{cases}$$  \hspace{1cm} (2.5)$$

In CSM-16 the fine tuning of the model resulted in slightly different values. Here, $C$ is generally described by:

$$C = \begin{cases} 
62 \text{ m/s}, & h \leq 42 \text{ m} \\
66 \text{ m/s}, & 42 < h \leq 66 \text{ m} \\
86 \text{ m/s}, & h > 66 \text{ m}
\end{cases}$$  \hspace{1cm} (2.6)$$

The wind stress is given by:

$$\tau_w = \rho_a C_D \left| \vec{v} \right| \vec{v}$$  \hspace{1cm} (2.7)$$

where:

$\rho_a$ : density of the air

$C_D$ : wind drag coefficient.

$\vec{v}$ : surface wind

In all storm surge simulations of this study $C_D$ is parameterized according to Smith and Banke (1975) and an air density of $1.205 \text{ kg/m}^3$ is used.

The total set-up, including effects of interaction, is defined by:

$$\zeta_{S+I} = \zeta_{T+S+I} - \zeta_T$$  \hspace{1cm} (2.8)$$

where $\zeta$ stands for the water level, and the subscripts denote:

$T$ : tide,

$S$ : surge,

$I$ : (total) interaction,

$S+I$ : (total) set-up,

$T+S+I$ : total water level.
This indicates that the total set-up, sometimes called residue, is obtained by subtracting water levels computed for tide alone from those computed for tide and surge together. The interaction effect of tide and surge, e.g. for water levels, is defined as:

\[ \zeta_I = \zeta_{T+S+I} - \zeta_T - \zeta_S \]  \hspace{1cm} (2.9)

The interaction effect results from subtracting water levels computed for surge alone from the (total) set-up computed by Eq. 2.8.

For current velocities, transports, etc., the same notation holds.

The specific non-linear terms related to:
- the advective interaction (a),
- the bottom friction interaction (f) and
- the shallow-water interaction (s)
are underlined in Eq. 2.1 to 2.3. The effect of shallow-water interaction is related to the change of the speed of the combined tidal and surge wave compared to the waves of tide alone and surge alone. The effect of (quadratic) friction interaction is related to differences in dissipation rates of the combined tide and surge wave compared to these waves individually. The advective terms are relatively unimportant.

2.2 Characteristics of interaction

The main characteristics of surge-tide interaction can be obtained from literature, in particular from Prandle and Wolf (1978a, b) and Wolf (1978), summarized by Wolf (1981), who examined the mechanics of interaction for the southern North Sea and the River Thames.

Prandle and Wolf (1978a) used coupled surge and tidal models to quantify the components of interaction due to quadratic friction only and shallow water only, see Figure 2.1. They carried out computations for tide alone (T), surge alone (S), tide with interaction from surge (T') and surge with interaction from tide (S'). Operating the latter two models simultaneously, the coupling between tide and surge was introduced by perturbation terms representing the influence of one model on the other. In the Southern Bight and the eastern Channel interaction results primarily from quadratic friction. The interaction develops most strongly in those
areas where both tidal and surge velocities are largest. Prandle and Wolf also found that the shallow-water interaction is generally restricted to the modification of the tidal propagation by the surge. Shallow-water interaction is significant in the Thames estuary and in the region between Oostende and Hoek van Holland. In these areas also the maximum total interaction occurred. This is related to the large amplitudes of both tide and surge in this region.

Wolf (1978) investigated the interaction between surge and tide based on the analytical solution of the equations of motion of two plane progressive waves travelling together along a semi-infinite uniform channel. This simplified analytical model reproduced the main observed features of interaction in the North Sea along the British east coast. It was used to study the effects of the individual non-linear terms in the dynamic equations over a range of water depths and surge amplitudes and a full range of phase lags of the surge input relative to the tide. The model indicates:

- interaction caused by quadratic friction is about twice the size of shallow-water interaction, which is again about twice the size of advective interaction,
- interaction increases with increasing surge height,
- the surge height $C_{S+I}$ increases at rising tide under the influence of shallow-water and advective interaction and decreases at high water by quadratic friction interaction,
- on the average, interaction increases with the distance over which the tidal and surge waves travel together, but with a super-imposed oscillation of increasing amplitude,
- the average magnitude of interaction increases with decreasing water depth.

The development of interaction with distance and water depth is shown in Figure 2.2. The minimum in interaction predicted by the model explains the low level of interaction near Lowestoft, see Figure 2.3.

From this it is recognised that the following factors may have a noticeable effect on the interaction:
- the tidal amplitude,
- the surge amplitude,
- the distance over which the tidal and surge waves travel together, starting from the point of negligible interaction,
- the water depth,
- the bottom friction coefficient and
- the occurrence of both large tidal and surge velocities.

Most of these factors are also related to the accuracy of the representation of the tide and the surge by the model. The parameters involved usually play a part in the fine tuning of the tidal and surge motion. In the case of CSM-16 for instance, the tidal boundary conditions, the bottom topography, the geometry of the coastline and the bottom friction coefficient were varied to optimize the representation of the tidal motion. The representation of the surge depends strongly on the accuracy of the surface wind and the parameterization of the wind friction. In view of this, the representation of interaction in the model is likely to be sensitive to the tuning process.

2.3 Method of verification of interaction

The verification of the reproduction of interaction in models like CSM-16 requires a direct comparison with prototype data. This is only possible in terms of time-series of water levels or currents of the combined surge and interaction effect (S+I). By consequence it is not very clear which part of the found differences is due to the interaction (I) and which part is due to the surge (S).

In the model S and I can be separated in a deterministic way by carrying out a computation for the surge alone (S), in addition to the usual computations for tide-and-surge (T+S+I) and tide alone (T). Such a simulation for surge alone is simply obtained by switching off the tidal boundary conditions in the T+S+I simulation run. By applying Eq. 2.9 to the simulation results, the total interaction can be made visible throughout the model.

In prototype data, interaction has to be quantified by statistical compilations, for example by the determination of the frequency of exceedance of $C_{S+I}$ for different phases of the tide. When 13 hourly phases relative to the time of high water are distinguished, at least one and preferably ten annual series of hourly $C_{S+I}$ would be needed. The differences in results of the successive phases produce a measure of interaction, namely:

- the difference in levels $C_{S+I}$ at a given frequency of exceedance, or
- the difference in frequencies at a given level.
From this kind of compilations it appeared that interaction varies in space and that interaction increases with the size of the (positive or negative) surge, see for instance De Ronde (1985) for the Dutch coast. Model and prototype may be compared on this basis. However, the required long model runs meet practical difficulties. In future, data from the operational storm surge prediction system running at the KNMI might be used for this kind of model validation.

2.4 Approach of further investigations

Insight in the accuracy and the spatial and temporal variation of interaction $z_I$ in CSM-16 will be obtained by comparing $z_{S+I}$ with prototype measurements and by computing the model interaction $z_I$ separately, see Chapter 3. Differences between model and prototype will be analysed.

In addition to Prandle and Wolf (1978a) and Wolf (1978) (see Par. 2.2) characteristics of interaction are explored further by model experiments.

The development of interaction as a function of the phasing of the surge relative to the phase of the tide is studied by a series of computations for a schematized storm which is shifted in time, see Chapter 4. The total dissipation of energy by bottom friction in the model area differs by a factor of about 8 for spring and neap tide conditions (Pugh, 1987). The (quadratic) bottom friction is also responsible for a large part of the interaction. Therefore the effect of varying tidal conditions (spring-neap cycle) is also investigated. The same storm will be used, see Chapter 5.

These experiments will also contribute to the understanding of the variability of interaction in space and time in the (whole) North Sea and the Channel.
3. Reproduction of interaction in CSM-16

To assess the accuracy of the interaction in CSM-16 and the variability in space and time, existing hindcasts of two storm surges were studied. The variability in time and space is addressed first.

3.1 Variability of interaction: the 1953 storm surge

A simulation for surge alone (S) was made for the 1953 storm surge in addition to existing simulations for T+S+I and T (Bavelaar, 1988). The interaction $\zeta_I$ was computed by applying Eq. 2.9 on the simulation results for T+S+I, T and S. The development in time of $\zeta_I$ is illustrated in Figure 3.1 for a series of twelve water level stations from Wick on the British east coast to Helgoland on the continental coast. The Dutch stations Harlingen and Delfzijl were not included. Due to the (necessarily) coarse schematization of the Waddenzee, these stations are not representative with regard to the interaction performance of CSM-16. During the 1953 storm surge the average effect of interaction is:

- on the rising flank of the surge a reduction of the surge, the largest reduction at the time of high water (HW), and
- on the descending flank of the surge an amplification of the surge, the largest increase near the time of LW and a minor increase or even reduction at HW.

At the time of the maximum total water level $\zeta_{T+S+I}$, the interaction $\zeta_I$ generally reduced the total water level in the order of 0.2 to 0.7 m, with the exception of IJmuiden where the effect was negligible.

The spatial variation of $\zeta_I$ is illustrated by Figure 3.2. From the successive contour plots it follows that the spatial structure of $\zeta_I$ moves along with the tidal wave, though the actual magnitude is subject to strong variations.

In the first half of the storm the negative effects of interaction dominate. Contributions below -0.5 m occur at the coast of Zeeland (31 Jan, 14 h), near The Wash (31 Jan, 20 h), in the Thames estuary (1 Feb, 1 h) and in the German Bight (1 Feb, 1 h). During the second half of the storm the positive contributions are more important. Interaction exceeds 0.5 m near Boulogne (1 Feb, 6 h), near the Belgium coast (1 Feb, 9 h), at the coast of Zeeland (1 Feb, 11 h) and in the German Bight (1 Feb, 8 h).
Figure 3.3 summarizes Figure 3.2 by showing the spatial distribution of the maximum and minimum interaction during the storm. In principle the extremes occur at different times, though some regional coherence exists. Although the most important contributions to interaction are found in the southern North Sea and the eastern Channel, the interaction effect is generated over the whole length of the North Sea and the Channel.

3.2 Verification of CSM-16 results

CSM-16 hindcasts by Bavelaar (1988) of $\zeta_{S+I}$ were compared with the observed time-series of $\zeta_{S+I}$ for the storm surges of 1 and 2 February 1983 and 31 January and 1 February 1953. Both computations used the wind drag formulation according to Smith and Banke (1975). Figures 3.4 and 3.5 show the results for the 1983 and the 1953 storm surge respectively. Data of older CSM-8 runs taken from Verboom et al. (1987) and Bijlsma (1988) and based on the same wind drag formulation, have been included in these figures as well.

In many stations the variations that are characteristic for interaction are clearly present in the CSM-16 results. Looking more closely at the Dutch stations, the differences in the variations seem largest at Vlissingen during the 1953 storm surge. Here, $\zeta_I$ shows relatively large oscillations (see Figure 3.1) that contribute significantly to the differences in $\zeta_{S+I}$. The reason is probably found in the local schematization which does not include the Westerschelde. At Hoek van Holland and Den Helder the surge $\zeta_S$ seems to be too small. This is partly due to set-up differences between open sea, where the model station is situated, and the location of the tide gauge.

At Southend probably the same problem as noticed at Vlissingen is present.

When $\zeta_{S+I}$ computed by CSM-16 and CSM-8 is compared for the 1953 and the 1983 storms, it appears that in most stations the differences between the two models are quite small, indicating that the differences in grid size and the related differences in schematization of bottom topography and coastal geometry and small differences in bottom friction coefficients do not severely affect the reproduction of interaction. The exceptions at Dover and Vlissingen, especially prominent in the 1953 storm surge, are attributed to the local schematization (geometry). At
the same time it can be seen that compared to CSM-8 the extra effort put into the local schematization near Vlissingen in CSM-16, resulted in a better hindcast at Vlissingen. The time-series of the instantaneous flow and the net transport through Strait Dover computed by CSM-16 and CSM-8 for the 1953 storm surge and presented in Figure 3.6, confirm the general picture.

3.3 Comparison with results in literature

The interaction computed for the 1953 storm surge was also compared with results obtained by Prandle and Wolf (1978a), who used coupled numerical models of the River Thames and of the southern North Sea and the eastern Channel to investigate interaction due to shallow-water effects and quadratic friction. The grid size of the sea model is approximately 12 km. Figure 3.7 shows the components of interaction \( S' - S \) and \( T' - T \) and the total interaction \( I = S' - S + T' - T \) for water levels at Lowestoft and Southend. Figure 3.8 shows the spatial distributions at 06:00 GMT 1 February 1953, including the total water level \( T' + S' \).

The results of both simulations agree with respect to the order of magnitude of the maximum and minimum interaction and the general trend of negative mean interaction during the first half and positive mean interaction in the second half of the storm surge. The obvious differences in the actual development of interaction are attributed to model differences, like the influence of the northern boundary near Lowestoft in Prandle and Wolf's model and the absence of the River Thames in CSM-16 near Southend.

In general, CSM-16 gives a satisfactory reproduction of interaction, except for stations like Southend and Vlissingen.
4. Variation of the phase of the surge

4.1 Schematized storm surge computation

The effect of the timing of the storm surge relative to the phase of the tide was investigated for spring tide conditions. Four simulations, which cover one tidal cycle, were performed by shifting the wind fields in time. The surge was generated by a schematic wind field, while the forcing by the atmospheric pressure gradients and the boundary condition of the surge was neglected. The simulations were carried out for the period of 00:00 GMT 28 January to 00:00 GMT 3 February 1953, because of the $M_2$ and $S_2$ spring tide in this period. Only the $M_2$ and $S_2$ tidal constituents were included in the boundary condition to eliminate the influence of varying tidal conditions (e.g. the diurnal inequality) as much as possible. Higher harmonics like $M_4$ and $MS_4$ are of course generated by the model.

The wind field was schematized in such a way that one of the primary features of severe storm surges, a northwesterly storm over the western half of the North Sea, is represented. Figure 4.1 shows the wind directions (time independent), the relative magnitude in space and the evolution of the maximum wind speed in time. The wind field was interpolated linearly in space and time. The atmospheric pressure was kept constant at the average level of 1012 mbar.

Four experiments were carried out. Starting from the wind field described above (denoted as phase = 0 h), the wind field was shifted in time by -3, +3 and +6 hours for the other simulations. Some features of the schematized surge are discussed first on the basis of the results of phase 0 h.

In many of the time histories of Figure 4.2 the maximum positive surge of the S-run is found after the period of maximum wind force in many stations. The explanation for this is that the surge energy generated during the period of maximum wind took some time to propagate into the shallow areas of the southern North Sea. The positive surge was followed by a substantial negative surge. Since by then the wind forcing had vanished, both features apparently demonstrate the resonance of the system. In the combined tide-and-surge computation this negative surge was reduced by interaction to approximately 25% of the original value. This can be seen from the values of $\zeta_S$ and $\zeta_I$ which have opposite signs in Figure 4.2. This in itself is an interesting result, since it shows
in an exceptional way the difference between methods of non-linear storm surge computation and methods based on linearised models. The latter can be regarded as models for surge alone ($S$) in which the formulations of wind and bottom friction have been adjusted to account for the average effect of the tide. Furthermore, concerning the subject of the oscillatory development (or resonance) of storm surges, it confirms the vision of British researchers, formulated by Heaps (1967), "... that although positive surges may develop in an oscillatory manner, they are so heavily damped that only the first rise and fall of the sea surface is of significance".

In agreement with the results of the 1953 storm surge, the average effect of interaction was a reduction of the surge both on its rising flank and at its maximum, and an amplification on the descending flank. In most stations this interaction led to a damping of about $0.1$ to $0.2$ m at the highest total water level $C_{T+S+I}$ in Southend even some $0.5$ m. Exceptions were Dover with a small increase and IJmuiden and Den Helder with negligible effects at the time of the highest level.

Another remarkable result follows from the contour plots of the S-run, Figure 4.3. Until 3:00 h at 1 February the gradients of the surge levels are almost perpendicular to the British east coast throughout the North Sea. Apparently, the surge levels reflect a geostrophic balance with the strong wind induced currents at the height of the storm. From then on the wind drag decreases rather quickly and from 6:00 h the disturbance is seen to move along like a progressive wave. The northwesterly wind produced the largest surge heights not along the Dutch coast as one would expect at first sight, but along the British east coast. At Southend the maximum surge height $C_S$ is approximately of the same magnitude as in the 1953 storm surge. However, the maximum $C_S$ along the Dutch and German coasts is appreciably smaller, see Figures 4.2 and 3.1. Apparently, different conditions are required to produce the largest surge levels along the Dutch coast, like for instance a longer duration of the storm and/or a more westerly wind in the southern part of the North Sea (see the 1953 storm surge).

Furthermore, the 1953 storm surge does not reveal a large negative surge in $C_S$, in contrast to the present schematized storm surge. It is concluded that the large negative surge is a feature of the schematized wind field as it originates from the west coast of Scotland and the Norwegian coast (see Figure 4.3).
Contour plots of the interaction at times corresponding to those of Figure 4.3 are given in Figure 4.4. Figures 4.8 b and 4.9 b present the maximum and minimum values of $\zeta_I$ that occurred during the schematized storm (phase = 0 h). Compared with Figure 3.3, the distributions of the maximum and the minimum interaction during the schematized storm agree with those of the 1953 storm surge in a general sense. However, the magnitude of the maximum interaction in the Southern Bight is much larger due to the large negative surge which developed in the S-run of the schematized storm. In line with the surge development, the magnitude of the minimum interaction along the Dutch coast and in the German Bight is smaller during the schematized storm.

4.2 Effect of phase shift

The phase shifts of -3, 0, +3, +6 hours of the four simulations provide the opportunity to study the variability of interaction effects over a complete tidal cycle. It must be remembered that in the first instance conclusions are valid for the schematized surge and spring tide conditions only.

Figure 4.5 shows the time-histories of the total water levels $\zeta_{T+S+I}$ of the computation of the combined tidal and surge wave. Attention is drawn to the remarkable change in the form of the tidal curve for the successive surge phases at some stations, e.g. see Southend. Generally, the level of the highest HW occurring in a station depends on the phase of the storm, as might be expected. Between North Shields and Southend the phase which produced the highest HW, differed from station to station as the tidal wave travelled faster than the surge. However, between Vlissingen and Helgoland the maximum levels occurred in the same phase (0 h). Over this distance the tidal wave and the (schematized) storm surge travelled more or less at the same rate (see also Figure 4.2). However, during the actual 1953 storm surge this did not happen (see Figure 3.1).

In Figure 4.6 time-histories of the (total) set-up $\zeta_{S+I}$ are presented. It shows that the tide has a strong effect on the set-up curves. The maximum height $\zeta_{S+I}$ of the surge and its particular evolution depends on the phase of the surge. In general, the phase producing the largest set-up does not necessarily give the highest total water level $\zeta_{T+S+I}$ as
well. Further, it is observed that between Oostende and Den Helder the same maximum surge height is reached in more than one phase, sometimes even at approximately the same time (see Vlissingen for example).

Looking at the time-histories of the interaction $\zeta_I$, given in Figure 4.7, a distinction can be made in variations on the time scale of the surge and on time scales of the tides, the latter including higher harmonics. The variations on the tidal scales are relatively strong and show at each station a certain similarity, independent of the phase of the surge. On the scale of the surge an average negative interaction is present at the beginning of the surge, and an average positive interaction is present in the second half of the surge (related to damping of the negative surge).

For the shifted storm surges interaction generally resulted in a reduction of the maximum total water level $\zeta_{T+S+I}$ as well. Except for phase = 0 h, Dover also showed damping at the time of the maximum total water level, while at IJmuiden the effect of interaction varied from (some) damping to (some) amplification and at Den Helder it remained small.

The spatial evolution of $\zeta_I$ is summarized by the maximum and minimum values that occurred in the computations for each phase, see Figure 4.8 (max. $\zeta_I$) and Figure 4.9 (min. $\zeta_I$). In the main areas of interaction, the Southern Bight and the eastern part of the Channel, positive interaction is about equally important for all phases. This is in agreement with the time-histories of $\zeta_I$ where the maximum and minimum values for the different phases are often of the same size. The highest value of $\zeta_I$ reaches over 0.9 m in a section along the coast near Dunkerque (Figure 4.8b, phase = 0 h). Negative interaction is particularly important in the Thames estuary, the lowest value reaching -1.0 m (phase = +6 h). The relative low level of interaction observed at Lowestoft (Wolf, 1978) is also clearly present.

Under the conditions of spring tide and the schematized storm, extreme values are found to be smaller than 0.1 m for water depths larger than about 100 m, except in the Skagerak.

In summary, for the schematized storm surge insight was gained in the variability of interaction over a tidal cycle, differences concerning the more or less regular variations on the scale of the surge and on the scales of the tide (including higher harmonics).
Translating phase shifts into uncertainties in predicted wind fields of storm surge forecasts, it is concluded that errors of 3 hours would have a severe effect on the locally predicted total water levels, for instance more than 0.5 m along the Dutch coast (see Figure 4.5). This effect is caused mainly by the shift of $S$; interaction is in this case of secondary importance.
5. Variation of tidal conditions

Interaction in storm surge computations under spring and neap tide conditions are compared to gain insight in the variation of interaction with tidal conditions.

In addition to the computations for the schematized storm surge (phase = 0 h) and the M_2 and S_2 spring tide conditions (Par. 4.1), the computations involving the tide were repeated for neap tide conditions. These conditions were obtained by increasing the phase of the S_2 tidal boundary conditions of the model by 3.1416 rad (180°). The simulation period was kept the same.

Figure 5.1 presents the time-histories of the total water levels $\zeta_{T+S+I}$. The figure shows that in a spring-neap cycle not only the amplitude of the tidal curve varies, but also the precise period. At spring tide, when the M_2 and S_2 waves are in phase, the actual tidal period is smaller than the M_2 period and at neap tide, when the M_2 and S_2 waves have opposite phases, the actual tidal period is larger than the M_2 period. The size of this variation in tidal period depends on the amplitude ratio of M_2 and S_2. In CSM-16 the variation is imposed via the boundary conditions.

Furthermore, the highest total water levels in the neap-run are found to occur at approximately the same HW's as in the spring-run. Attention is drawn to the total water level curves at the stations of Hoek van Holland to Den Helder, where the second HW on the third day of the neap tide case is virtually missing.

Figure 5.2 shows the time-histories of the (total) set-up $\zeta_{S+I}$ of the spring- and neap-runs and those of the run for surge only ($\zeta_{S}$). The effect of different tidal conditions on the set-up is especially prominent at Southend and Vlissingen, not only with regard to the size of the effect, but also because of the differences in the rates of damping and amplification of the surge at spring and neap tide. The differences at the time of the highest HW in $\zeta_{S+I}$ of spring and neap-runs are not systematically positive or negative. Furthermore, it is noticed that the computation for surge only ($\zeta_{S}$) produced oscillations with approximately a sixth-diurnal period at Vlissingen, which might otherwise be interpreted as an interaction effect. This might be related to the less satisfactory reproduction of interaction at Vlissingen noted in Par. 3.2.
The time-histories of interaction $\zeta_I$ are given in Figure 5.3. Although the general evolution of interaction at neap tide is not different from that at spring tide, unexpected differences are found locally. This usually takes place in the few hours before the maximum surge height is reached, see for instance Southend, Dover and Hoek van Holland in Figures 5.2 and 5.3. Comparing neap to spring tide conditions, differences in damping due to interaction at the time of the highest total water level ($\zeta_{T+S+I}$) were rather small from Wick to Southend. From Dover to Helgoland $\zeta_I$ at neap tide was generally about 0.1 to 0.2 in lower at that time than during spring tide.

Figures 5.4 and 5.5 present the spatial distribution of the maximum and minimum interaction $\zeta_I$ for spring and neap tide conditions, respectively. It follows that the spatial pattern is approximately the same, but the extreme values have been reduced by almost a factor two at neap tide.

In summary, for the schematized storm surge and the tide induced by the $M_2$ and $S_2$ boundary conditions, it was found that interaction generally decreases with decreasing tidal amplitude, with exception of the period of a few hours before the maximum surge levels in which at some stations unexpected differences were found.

In practice the variation of interaction due to tidal conditions will be more complicated since a much larger number of tidal constituents is present.
6. Summary and conclusions

The Dutch Continental Shelf Model CSM-16 has reached the semi-operational stage of storm surge predictions in the Netherlands. In these predictions the non-linear interaction between surge and tide is an important feature for the whole southern North Sea and the Channel. For water levels the effect of interaction is defined by the difference between total water levels obtained from a combined tide-and-surge computation and obtained from separate tide and surge computations. The aim of the present study was to investigate the reproduction of interaction by CSM-16 and to describe and explain the characteristics of interaction.

Reproduction of interaction in CSM-16

A comparison of computed and observed total set-up of the 1953 and the 1983 storm surges showed that CSM-16 reproduces the variations which are characteristic for interaction satisfactorily, except at stations like Southend and Vlissingen (see Figs. 3.4 and 3.5 in combination with Fig. 3.1). Here, the local schematization (geometry) is probably the reason of the deviations.

The differences between results of CSM-16 and CSM-8 prove to be quite small in most stations, except for Dover and Vlissingen (see Figs. 3.4, 3.5 and 3.6). This indicates that interaction is generally not dependent on the difference in grid size and related differences in schematization and bottom friction coefficients.

Characteristics of interaction

The characteristics of interaction were described and explained on the basis of literature and model experiments. Interaction is characterized by the following points.

a. Interaction between tide and surge is caused by the non-linear terms of the depth-averaged shallow-water equations. Distinction is made between advective interaction, bottom friction interaction and shallow-water interaction.

b. Interaction caused by quadratic friction is generally about twice the size of shallow-water interaction, which is again about twice the size of advective interaction (Wolf, 1978).
c. Quadratic friction interaction develops most strongly in those areas where both tidal and surge velocities are largest, like the Southern Bight and Strait Dover. Shallow-water interaction is generally restricted to the modification of the tidal propagation by the surge. Shallow-water interaction is significant in the Thames estuary and in the region between Oostende and Hoek van Holland. In these areas the maximum total interaction occurred as well (Prandle and Wolf, 1978a).

d. The spatial distribution of interaction changes with the progression of the tidal wave, while the actual magnitude is subject to strong variations (see Fig. 3.2). The largest negative levels of interaction were generally found in the Thames estuary and near The Wash (see Figs. 3.3, 4.9 and 5.5). The highest (positive) levels of interaction exceeding 0.5 m were found in the Southern Bight and the eastern Channel, particular in the Thames estuary and along the Dutch coast (see Figs. 3.3, 4.8 and 5.5). The German Bight is also of some importance.

e. Although the most important contributions to interaction are found in the Southern Bight of the North Sea and the eastern Channel, interaction is generated over the whole length of the North Sea and the Channel (see e.g. Fig. 3.3).

f. On the average, interaction increases with the distance over which the tidal and surge waves travel together, but with a super imposed oscillation of increasing amplitude. This explains the relative low level of interaction observed near Lowestoft (Wolf, 1978). In the 1953 storm surge and the schematized storm surges relatively low levels of interaction were computed in approximately the same area (see Figs. 3.3, 4.8, 4.9 and 5.5).

g. The average magnitude of interaction increases with decreasing water depth (Wolf, 1978).

h. At rising tide the surge height $C_{S+I}$ increases under the influence of shallow-water and advective interaction and at high water it decreases by quadratic friction interaction (Wolf, 1978). For the 1953 storm surge as well as for the schematized storm surges a general trend was found of negative mean interaction in the first half and of positive mean interaction in the second half of the storm surge (see Figs. 3.1, 3.2, 4.7, and 5.3).

i. At the time of maximum total water level the interaction generally reduces the total water level. In the 1953 storm surge this reduc-
tion is 0.2 to 0.7 m, while it is about 0.1 to 0.2 m in the schematized storm surge. In some computations exceptions to this rule in the form of negligible reduction or amplification were found at Dover, IJmuiden and Den Helder.

j. Imposed on the general trend (see point h), the interaction shows a strong variability at tidal frequencies (e.g. see Fig. 4.7).

k. Interaction increases with increasing surge height (Wolf, 1978; De Ronde, 1985).

l. For the schematized storm surge interaction generally decreased with decreasing tidal amplitude, except for a period of some hours before the highest surge levels, during which at some stations unexpected differences were found, e.g. Southend, Dover and Hoek van Holland (see Figs. 5.2 and 5.3).

**Improvement of interaction in CSM-16**

So far, most serious differences between observed and computed interaction were found for stations like Southend and Vlissingen, presumably caused by the limitations of CSM-16 to schematize the local (estuary) geometry. Improvement can only be reached by application of more refined local models. This is also true for the Waddenzee, where the stations Harlingen and Delfzijl were not included in the study.

The general reproduction of interaction by the model depends on the following factors:
- the tidal amplitude,
- the surge amplitude,
- the distance over which the tidal and surge waves travel together, starting from the point of negligible interaction,
- the water depth,
- the bottom friction coefficient and
- the occurrence of both large tidal and surge velocities.

Most of these are related to model features which are subject to the fine tuning of the tidal motion, like the tidal boundary conditions, the bottom topography, the geometry of the coast line and the bottom friction coefficient. The most serious inaccuracy is probably found in the surge as it depends on the accuracy of the surface wind and the parameterisation of the wind friction. This might limit further improvement of the general level of reproduction of interaction in the model.
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CONTINENTAL SHELF MODEL CSM-16
SPHERICAL COORDINATES x: 1/4 deg  y: 1/6 deg.

Figure 1.1: Lay-out of the continental shelf model CSM-16.
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Figure 3.1: continued.
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Figure 3.2: continued.
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Figure 3.4: continued.
Figure 3.4: continued.
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Figure 4.2: continued.
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Figure 4.3: continued.
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Figure 4.4: continued.
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Figure 4.5: continued.
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Figure 4.7: Time-series of interaction effect $\zeta_I$ computed for four phases of the schematized storm and spring tide conditions.
Tide = Spring
I (Phase in Hrs): -3 0 +3 +6

30-01-1953  31-01-1953  1-02-1953  2-02-1953  date

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Figure 4.7: continued.
Figure 4.7: continued.
Figure 4.8: Contours of the maximum interaction effect \( \zeta_1 \) (intervals of 0.1 m) during the schematized storm and spring tide conditions for the phases -3, 0, +3, +6 h.
Figure 4.8: continued.
Contour Shelves with annotations: 

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Figure 4.9: continued.
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Figure 5.1: continued.
Figure 5.1: continued.
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Figure 5.2: continued.
Figure 5.2: continued.
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Figure 5.3: continued.
Figure 5.3: continued.
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Figure 5.5: Contours of the minimum interaction effect $\zeta_r$ (intervals of 0.1 m) computed for spring and neap tide conditions of the schematized storm at phase 0 h.
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