Ministerie van Verkeer en Waterstaat

Directoraat-Generaal Rijkswaterstaat

Rijksinstituut voor Kust en Zee/*RIKZ*

National Institute for Coastal and Marine Management / RIKZ

To
Addressee

Contact
ir. W. Bijl

Telephone
070-3114240

Date
17 March 1995

Enclosure(s)
2

Our reference

Your reference

Project
EG*EPOCH

Subject
Forwarding of report "Impact of a wind climate change on the surge in the southern part of the North Sea"

Dear Sir/Madam,

A wide range of impacts may be induced by the greenhouse effect. One of these possible impacts is a wind climate change. Thus, computer based modelling of this forms an important element in studying the potential impacts of climate and other environmental changes upon coastal hydrodynamics.

Within the context of the EU-project "The Impacts of Coastal Changes Upon the Environmental Resources of the Coastal Zone", contract no. EV5V-CT93-0258, the National Institute for Coastal and Marine Management / RIKZ carried out a sensitivity study on this topic. Assuming a certain wind climate change scenario, the surge impacts of this have been computed for various water level stations in the southern part of the North Sea.

Enclosed you will find a copy of the final report of this sensitivity study, together with the project brochure "Coastal & Climate change".

Questions with respect to the report or the brochure can be addressed to ir. W. Bijl of the National Institute for Coastal and Marine Management / RIKZ.

Yours faithfully,

ir. J.G. de Ronde

Ministry of Transport, Public Works and Water Management
Directorate-General for Public Works and Water Management
National Institute for Coastal and Marine Management/ RIKZ

Impact of a wind climate change on the surge in the southern part of the North Sea

EU-project IMPACTS
contract no. EV5V-CT93-0258

report: RIKZ-95.016

author: W. Bijl
date: February 1995

Summary

This report considers the impact of a greenhouse-induced change of the extreme wind climate on the surge in the southern part of the North Sea.

It is however not possible to describe this greenhouse-induced extreme wind climate change unambiguously. Therefore, on the basis of some theoretical considerations and of numerical General Circulation Model experiments, a "scenario" of a possible greenhouse-induced extreme wind climate change is derived. This scenario can be described as follows:

The greenhouse-induced change of the extreme wind climate in the southern part of the North Sea consists of a northward shift of the present extreme wind climate in this area.

To study the impact of this scenario on the surge in the southern part of the North Sea, the present extreme wind climate in this area is modelled with the help of the principle of parametric storms.
On the basis of this principle, a parametric '53-storm is derived which is reasonably comparable with the real '53-storm.
By means of a systematical variation of 4 storm parameters of this parametric '53-storm, a set of 567 extreme parametric storms is derived.
This set of storms is combined with a distribution of probability of extreme storms in the southern part of the North Sea, which results into a model of the present extreme wind climate in this area.

The future extreme wind climate in the southern part of the North Sea is modelled by combining the set of 567 storms with a new (modified) distribution of probability of extreme storms in this area. This distribution, derived on the basis of the chosen extreme wind climate change scenario, is in fact the northward shifted distribution of probability of extreme storms in the present extreme wind climate.

The surge impact of both extreme wind climates in the southern part of the North Sea is determined with the help of the Dutch Continental Shelf Model. For each individual storm, the maximum storm surge effect is calculated for various water level stations in the area of interest.
Combining this surge data with the present and future distribution of probability of extreme storms in the southern part of the North Sea gives an indication of the surge impact of both climates in this area.
Comparison of this surge impact provides insight into the impact of a possible greenhouse-induced change of the extreme wind climate on the surge in the southern part of the North Sea.

Conclusion is that, compared to other greenhouse-related changes of the extreme wind climate, in the southern part of the North Sea the surge impact of the chosen extreme wind climate change scenario is small.

Contents

1. Introduction

1.1 Background and objective

A wide range of impacts may be induced by the greenhouse effect, whereby different aspects of climatic change play a role (sea-level rise, wind climate, etc.). Therefore the problem of the greenhouse effect and related impacts is typically complex. A number of reasons are [16]:

- Various greenhouse effects have to be considered.
- Much uncertainty exists to the extent, the evolution and the regional variability of the greenhouse effect.
- Many different impacts can be identified.
- Spatial variability of the different impacts has to be taken into account.
- The impacts have a long time-horizon, making it difficult to evaluate the consequences.

The impacts of the greenhouse effect, related to the water system, can be studied on the basis of the following subjects or scenario's [16]:

- Sea-level rise
- Temperature
- Wind climate
- Hydrological regime

These scenario's do not stand alone, but they are interlinked. A change in one of the scenario's or scenario-components affect the other ones. A system diagram is shown in Annex A.

From this diagram it follows that a change in the position of storm tracks and/or a change in the intensity of storms will have impact on the mean wind speeds, wind directions and on the duration of storms. It is clear that these latter impacts will affect the distribution of extreme storm surges in for example the low lying countries around the North Sea. In this area, storms and storm surges are the most damaging climatic features. Greenhouse-induced changes in the position of storm tracks and/or changes in the intensity of storms are therefore of great interest.

Historical documentation since about 1000 as well as instrumental observations over the last century show that variations in position of storm tracks and in storm intensities already do occur, even in the absence of external causes. These variations seem to be of random nature and can be seen as the natural variability of the climate system [21].

In view of a greenhouse-induced extreme wind climate change, it is no longer obvious that the variations in the position of storm tracks and/or in storm intensities will remain within the same, not clearly specified, bounds of natural variability. In some reports on recent storms, people already claim that developments are observed which are beyond this range of natural variability. The latter however, still has to be defined.

The study described in this report focuses on the impact of a greenhouse-induced change of the extreme wind climate on the surge in the southern part of the North Sea. Because up to now the bounds of natural variability of the present wind climate are not clearly defined, it is however not possible to predict this greenhouse-induced extreme wind climate change in terms of position of storm tracks and/or storm intensities. That is the reason why this study has the character of a sensitivity study.

This has been formulated as follows:

The objective of the study is to gain insight into the sensitivity of the surge in the southern part of the North Sea to a possible greenhouse-induced change of the extreme wind climate in this area.

1.2 Set up of the report

The report is built up as follows:

In chapter 2, first of all the greenhouse effect and its impact on climate is described in general terms. The second part of this chapter deals with climate forecasting and in the final part the results of climate forecasting experiments, related to a possible greenhouse-induced extreme wind climate change in the southern part of the North Sea, are outlined.

Chapter 3 deals with the modelling of a possible greenhouse-induced extreme wind climate change in the southern part of the North Sea.
In the first part of this chapter the "tool", used to generate a certain wind climate in terms of wind- and pressure fields, is described. In the second part the present extreme wind climate in the southern part of the North Sea is modelled with the help of this "tool" and in the third part of this chapter, on the basis of a chosen extreme wind climate change scenario, the future extreme wind climate in this area is modelled in the same way.

Chapter 4 describes the surge impact of a possible greenhouse-induced extreme wind climate change in the southern part of the North Sea (as modelled in chapter 3).
The first part of this chapter gives a description of the numerical model which is used to compute the surge impact of the present and future extreme wind climate. In the following parts of this chapter, the results of these surge computations are analyzed and the surge impact of the greenhouse-induced wind climate change in the southern part of the North Sea, based on the chosen extreme wind climate change scenario, is presented in terms of maximum water level frequency distributions.

Finally, chapter 5 contains concluding remarks.

1.3 Acknowledgements

The study described in this report is carried out within the framework of the ENVIRONMENT project "The impacts of climate change and relative sea-level rise on the environmental resources of european coasts", contract No. EV5V-CT93-0258.

The study was initiated in 1991 by the National Institute for Coastal and Marine Management, Rijkswaterstaat.

The following persons have contributed to the study:

- W. Bijl (National Institute for Coastal and Marine Management)
- M.E. Philippart (National Institute for Coastal and Marine Management)
- J.G. de Ronde (National Institute for Coastal and Marine Management)
- L.H. Holthuijsen (Delft University of Technology)
- B. Zwart (Royal Netherlands Meteorological Institute)

The present report has been written by W. Bijl (National Institute for Coastal and Marine Management).

2. Climatic change

In the first paragraph of this chapter the greenhouse effect and its impact on climate will be described in general terms (paragraph 2.1).
In paragraph 2.2 a general description will be given of (numerical) climate forecasting, and the final paragraph of this chapter will deal with the results of climate forecasting experiments, related to a possible greenhouse-induced change of the extreme wind climate (paragraph 2.3).

2.1 Greenhouse effect

2.1.1 Earth-atmosphere system

The earth is made habitable by the presence of certain gases in the atmosphere which trap long-wave radiation emitted from the surface of the earth. These gases are known as trace gases, because they make up only 1% of the atmosphere. Their presence gives a global mean surface temperature on earth of 15° C, as opposed to an estimated -18° C in their absence [15].
This phenomenon is known as the "greenhouse effect": a physical process whereby long wave radiation emitted by the warm earth is partly absorbed and remitted by certain gases in the atmosphere [9].
It should be emphasized that this greenhouse effect is a natural process, necessary for conditions of life on earth.

The driving force for the earth-atmosphere system is energy from the sun. This energy is intercepted by the atmosphere and the surface of the earth; about a third of it is being reflected, the rest is absorbed. The absorbed part must be balanced by outgoing energy in the form of emission of (long-wave) radiation to space.

The distribution of energy emitted with wavelength is a function of the temperature of the emitter; the hotter the emitter, the shorter the wavelength of peak emission. Thus the sun, which has a surface temperature of 5727° C, emits most short-wave (solar) radiation, whereas the earth emits mainly long-wave (thermal or infrared) radiation [15].

The afore mentioned trace gases are relatively inefficient in absorbing the short-wave radiation emitted from the sun. However, they are better in absorbing the long-wave radiation emitted from the surface of the earth and reradiate this both back to the surface, producing an additional warming, and to space, maintaining the balance with incoming short-wave radiation.

As a result, the current global mean surface temperature of the earth is substantially higher then it would be in case of no trace gases.

2.1.2 Greenhouse gases

In spite of its low concentration, carbon dioxide and several other gases present in even smaller amounts in the atmosphere, have an important role in determining the surface temperature of the earth. In contrast to for example nitrogen and oxygen, which together make up more than 99% of the atmosphere, these trace gases absorb the long-wave radiation emitted from the surface of the earth [12]. Since in this regard they act much like the glass over a greenhouse, they are commonly referred to as greenhouse gases.

The most important and effective greenhouse gases are water vapour and carbon dioxide [15]. This is mainly caused by the fact that both gases absorb the long-wave radiation, emitted from the surface of the earth, over a wide range of frequencies. Besides that, these two gases are present in the atmosphere in a relatively high concentration (compared to other greenhouse gases like ozone, methane, nitrous oxide and clorofluorcarbons).

The amount of energy which is absorbed by these greenhouse gases can be computed rather accurately, so if the concentration of a gas is subject to changes, the consequences can be computed in terms of the energy balance.

2.1.3 Human activities

Since the Industrial Revolution, usually taken as the middle of the 19th century, the global mean surface temperature of the earth has been increasing at the rate of about 0.5° C per century [25]. Up to now, it has however not been possible to determine whether this observed warming trend is attributable to a man-induced enhanced greenhouse effect.

The latter can mainly be attributed to the poor understanding of the natural variability of the climate.
Long temperature records for example show that a temperature increase as observed in this century is not very unique. Also in the period before 1700 till about 1750 the winter temperature rose to a level which is comparable to the present situation [19]. The reason for this temperature increase is not known, but for the time being it is assumed that such variations are part of the natural variability of the climate.

It is however clear that since the Industrial Revolution human activities are responsible for an increase in the concentrations of radiatively active gases. The atmospheric carbon dioxide concentration for example is increased by about 25% from pre-industrial estimates of about 280 p.p.m. to approximately 353 p.p.m. in 1990 [18].

In addition it should be mentioned that the concentrations of greenhouse gases in the atmosphere react very slowly to changes in emissions. This means that there is a large delay in possible climatic change if the emission patterns change. That is the reason why possible man-induced climatic change will partly be irreversible because significant increases in trace gas emissions have already been taken place since the Industrial Revolution.

2.2 Climate forecasting

2.2.1 One-dimensional models

The first one who recognized the possibility that absorption of long-wave radiation by atmospheric gases could influence the global mean surface temperature of the earth was Fourier in 1827. Tyndall tried in 1861 to measure the long-wave absorption by atmospheric gases and Arrhenius attempted in 1896 to estimate the changes in surface temperatures resulting from increased concentrations of carbon dioxide.

Later studies were mainly focused on the climate response to a doubling of the atmospheric carbon dioxide concentration and provided a range of estimates of the global mean surface temperature change, whereby the value derived was depending very much on the assumptions made.

In 1967, Manabe and Wetherald pointed out that the surface of the earth and the atmosphere are not in radiative equilibrium and they allowed for the convective transfer of heat from surface to atmosphere. They used a so called (numerical) radiative-convective model.

Many studies of climate sensitivity have been carried out using these radiative-convective models, producing increases in global mean surface temperature ranging from 0.48° C to 4.2° C in case of a doubling of the atmospheric carbon dioxide concentration [15].

This relative wide range of variation can be explained by the different feedback processes between the various components of the climate system which have been taken into account.
Many of those feedback processes originate from the fact that water can be present in 3 states (water, ice and vapour), which have large different physical properties, and from the fact that the atmospheric and oceanic currents affect each other [13]. The time scales of the various individual physical processes are largely overlapping and extend from less than hours to many years. On Mars, for example, everything is much simpler since there are no flowing oceans while water vapour and clouds are almost lacking.

The above mentioned one-dimensional models have been very useful in the determination of the radiative effects of increasing concentrations of trace gases, especially carbon dioxide. On the other hand however, these models do not provide information on the regional changes in climate.

2.2.2 General Circulation Models

In order to derive more detailed information, three-dimensional General Circulation Models (GCM's) have been developed. Like the one-dimensional models they are mostly used to determine the climatic effects of a doubling of the atmospheric carbon dioxide concentration.

These General Circulation Models can be seen as more elaborate versions of the global models which have been employed for weather forecasting. In one respect however, they differ completely from those numerical weather prediction models because in these climate models slow and subtle processes are incorporated which for the purpose of normal weather forecasts can be neglected. Without these processes a General Circulation Model is unrealistic and may even drift away from the observed means of the climate during numerical integration [13].

In general, the main prognostic variables of these models are temperature, precipitation and evaporation, surface pressure and the north-south and east-west components of the wind [15].
The values of these variables are obtained at regular locations on the globe (model grid) and at various levels in the model atmosphere.
They are determined by the Navier-Stokes equations (wind), the thermodynamic equation (temperature), and equations for the conservation of water substance and mass (humidity and surface pressure).
It should however be mentioned that many phenomena, like clouds, precipitation and evaporation, radiative heating and surface friction vary on a scale which is smaller than the model grid and thus have to be represented in an approximate manner.

If these General Circulation Models are run for several years with parameters and forcing appropriate to the present climate, the output should bear close resemblance to the observed climate. If parameters representing an increasing amount of the atmospheric carbon dioxide concentration are introduced, these models can be used to simulate or predict the resulting climate change.

The most elaborate climate model employed at present consists of an atmospheric General Circulation Model coupled to an ocean General Circulation Model [9]. The latter describes the structure and dynamics of the ocean. Added to this coupled model are appropriate descriptions of the other components of the climate system like land surface, ice and the interaction between them.
A problem with these coupled General Circulation Models is however the climate drift [20]. Without a systematical correction of the flux of heat exchange between the atmosphere and the ocean, the model drifts to a much colder climate than observed. A lot of research on this problem is yet going on.

2.2.3 General Circulation Model results

The first studies on the effect of doubling atmospheric carbon dioxide using General Circulation Models were carried out by Manabe and Wetherald in 1975. They carried out series of experiments using increasingly complex versions of this climate model, in order to isolate the influence of various features on climate sensitivity.

Initially they used a "simple" model with no orography, cloud amounts were prescribed and the ocean had no heat capacity nor did it transport heat. They repeated this experiment several times, introducing modifications like for example a variable (model generated) cloud cover or different radiation schemes.
From these experiments they concluded that the response of a General Circulation Model depends very much on the model used and that conclusions based on simplified models may be misleading qualitatively as well as quantitatively.

These experiments however have made clear the influence and importance of realistic orography, seasonal cycle and changes in cloud amount on climate sensitivity. That is the reason why in more recent studies General Circulation Models are used which incorporate these features.

Besides the "normal" double carbon dioxide concentration experiments, in recent studies also transient climate change experiments have been carried out with General Circulation Models. This means that in these experiments the carbon dioxide concentration is allowed to accumulate gradually, whereby the possible climate change for example is calculated for the next 100 year. Mostly a scenario is used in which the current trend of carbon dioxide concentration increase is continued unchanged into the future.

Considering the simulation results of these more elaborate climate models, especially those where General Circulation Models are coupled with a mixed layer ocean, the global mean surface temperature response to a doubling of the atmospheric carbon dioxide concentration is in the range 1.5° C to 4.5° C, with a most likely value of 2.5° C [11]. Up to now, the simulation results of transient climate change experiments do not show a significant different temperature response.

These simulation results also show a pronounced uncertainty of the regional temperature response [15]. (The same holds for the regional precipitation response, where in the northern latitudes generally an increase is expected.)
Most of these doubling carbon dioxide experiments predict however a maximum positive surface temperature response in the polar regions [8]. This can be seen as a reduction of the lower tropospheric pole-to-equator temperature gradient and can be explained by the following reasons [8,22]:

- *the (poleward) retreat of the highly reflective snow and ice cover.*
- the large gravitational stability of the atmosphere near the surface in the high latitude winter, which has the tendency to concentrate the warming at low levels.
- the moist adiabatic lapse rate feedback, which tends to produce smaller surface temperature changes in the tropics than in the high latitudes.
- the warmer, moister atmosphere is more efficient in transporting latent heat from the tropics to high latitudes, where it is released as latent heat of condensation.

On the other hand most of these experiments also predict a large positive temperature response in the tropical upper troposphere [8]. This causes in the upper troposphere exactly the opposite of the afore mentioned decrease of the lower-tropospheric pole-to-equator temperature gradient, namely an increase of the upper-tropospheric pole-to-equator temperature gradient.

2.3 Wind climate

A major worry about potential global warming due to the increasing concentration of greenhouse gases like carbon dioxide is that it could lead to more frequent and intense storms.

The idea behind this concern is that if long-wave radiation emitted from the surface of the earth is impeded by a buildup of greenhouse gases, the atmosphere will intensify other mechanisms of vertical heat transport, such as storms [1]. These storms remove energy from the surface of the earth via the latent heat of evaporation and return it to the higher levels of the atmosphere.

It is however equally as likely that just the opposite may be true [1], because General Circulation Models predict that the tropical ocean surface temperatures will increase very little in case of a doubling of the atmospheric carbon dioxide concentration. The tropical tropopause however will warm more than the tropopause anywhere else, and much more than the tropical ocean surface.
Consequently, the tropical troposphere will be more stable in case of doubling carbon dioxide than it is nowadays, which give rise to the conclusion that, in case of doubling carbon dioxide, storms will be less intense than they are presently.
In addition, with polar surfaces warming more than tropical surfaces in the General Circulation Model climate, there is also less need for storms to transport heat from tropical regions to polar regions.

Up to now it is not clear which of the above mentioned "scenario's" will be dominant.

Also General Circulation Model experiments do not give the ultimate answers. Although these models are able to reproduce many of the observed characteristics of storms, detailed comparison reveals numerous deficiencies [10]. The eddy kinetic energy in these models is for example only 1/2 - 2/3 of that observed, storms tend to continue into western Europe and blocking is underestimated.
This suggests that predictions of these models with respect to changes in storm intensity or frequency, associated with an increasing carbon dioxide concentration, must be looked at very critically.

In the following of this paragraph, the results of some of these General Circulation Model experiments with respect to a possible greenhouse-induced wind climate change in the North Sea area will be discussed.

- Temperature gradient

  Up to know it is not clear whether mid-latitude storms will respond primarily to the decrease of lower tropospheric pole-to-equator temperature gradient or the increase of the upper tropospheric pole-to-equator temperature gradient.
  Above that, this response is greatly complicated by the fact that these storms are strongly influenced by moisture in the atmosphere. This increase in moisture that accompanies the global warming (see paragraph 2.2.3) will itself have two distinct and competing effect on these storms and it is again not clear which effect will be dominant [8].

- Storm tracks

  The 500 hPa circulation determines in which direction weather systems near the surface and thus also storms propagate. The maxima in the geographical distribution of the temporal variability of the 500 hPa height are regarded as storm tracks [2].
  These storm tracks tend to coincide closely with regions of strong baroclinicity [22], which is related to the existence of large vertical

wind shear. Because large vertical wind shear occurs near the jet-stream, a change in the location and/or intensity of the jetstream may have important consequences for properties of storm tracks like location, intensity and frequency.
The problem is however that the storm track over western Europe not only exhibits a clear seasonal variation, but also shows changes from year to year and even decadal variations [21]. This causes that the significance of the predicted changes of the position and/or intensity of this storm track has to be compared with the natural variability of the storm track (which we do not know up to now).

- Circulation patterns

One factor determining regional climate change is a change in the statistics of regional atmospheric circulation patterns.
Using data from General Circulation Model experiments performed by Wilson and Mitchell in 1987, the response of the frequency distribution of 27 circulation types in the European winter climate to a doubling of the atmospheric carbon dioxide concentration has been analyzed by Siegmund [23].
From this analysis it follows that, due to a doubling of the atmospheric carbon dioxide concentration, there will be a significant decrease in the frequency of circulation patterns over western Europe with a strong westerly and southerly wind component. As outlined in [23], this can be explained by a northward shift of the storm track over western Europe.

3. Modelling of the wind climate change

The possible greenhouse-induced extreme wind climate change in the southern part of the North Sea will be modelled with the help of the principle of parametric storms. This principle will be explained in paragraph 3.1.
In paragraph 3.2 the modelling of the present extreme wind climate in the area of interest will be described with the help of these parametric storms.
In the final part of this chapter, paragraph 3.3, the modelling of the future extreme wind climate in the southern part of the North Sea will be outlined on the basis of a chosen greenhouse-induced wind climate change scenario.

3.1 Parametric storms

Parametric storms are asymmetric elliptical storms, of which the pressure fields can be described by a certain set of parameters [3,7]. These parameters are visualised in figure 3.1 and 3.2 and described below:

$\lambda_{c,b}$	=	position of the storm centre in degrees longitude (°)
$\varphi_{c,b}$	=	position of the storm centre in degrees latitude (°)
amb	=	ambient pressure of the storm (Pa)
$\delta p_{c,b}$, $\delta p_{c,e}$	=	pressure difference between ambient and central pressure (Pa)
$\theta_{c,b}$, $\theta_{c,e}$	=	orientation of the east-west axis of the storm in degrees CCW from east (°)
β	=	course direction of the storm in degrees CCW from east (°)
v_b, v_e	=	propagation speed of the storm (m/s)
$r_{xn,b}$, $r_{xn,e}$	=	radius to maximum wind along neg. x-axis (km)
$r_{xp,b}$, $r_{xp,e}$	=	radius to maximum wind along pos. x-axis (km)
$r_{yp,b}$, $r_{yp,e}$	=	radius to maximum wind along pos. y-axis (km)
$r_{yn,b}$, $r_{yn,e}$	=	radius to maximum wind along neg. y-axis (km)

With respect to the notation of these parameters the following has to mentioned:

- $X_{..,b}$ = value of parameter $X_{.}$ at begin simulation.
  $X_{..,e}$ = value of parameter $X_{..}$ at end simulation.
- The x- and y-as are locally defined through the centre of the storm, normal to the north-south axis of the storm.

On the basis of the calculated pressure fields the corresponding wind fields can be obtained by applying the geostrophic wind speed formula:

$$v_g = \frac{1}{2\omega_e \sin\varphi} \frac{\delta p}{\delta n} \qquad \text{(m/s)}$$

whereby:

v_g =	geostrophic wind speed	(m/s)
ω_e =	angular speed of the earth	(rad/s)
φ =	degree of latitude	(°)
δp =	pressure difference	(Pa)
δn =	distance perpendicular to the isobars	(m)

Figure 3.1
Storm-parameters (view from above).

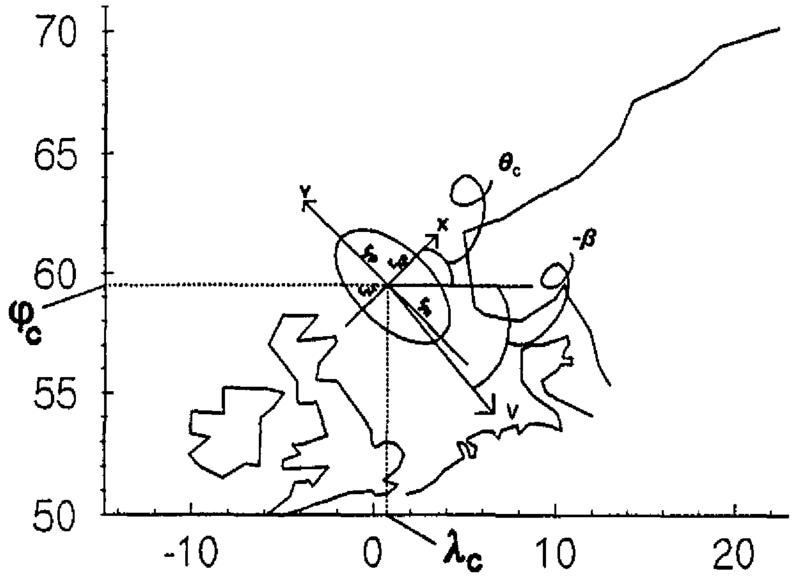
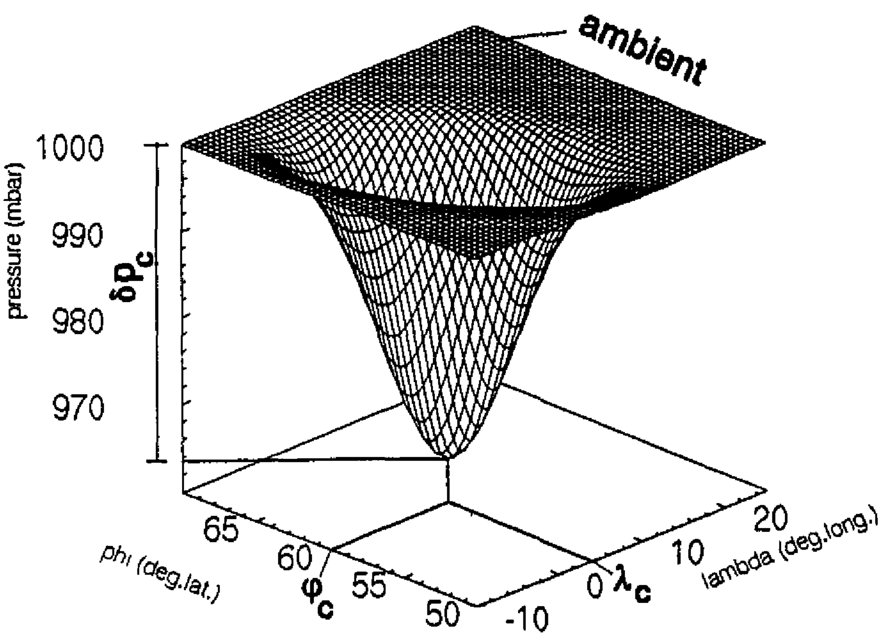


Figure 3.2
Storm-parameters (view from aside).



3.2 Present extreme wind climate

3.2.1 Parameterization of the '53-storm [4]

The modelling of the present extreme wind climate in the southern part of the North Sea area is carried out on the basis of the pressure fields of an extreme historic storm, namely the famous storm of 1 february 1953. During this storm especially the south-west coast of the Netherlands was strucked very hard. More than 135.000 ha. land was flooded and 1835 people were killed.
Also the east coast of England and the Thames Estuary were flooded, whereby 300 people lost their lives.

To parameterize the pressure fields of this storm with the in paragraph 3.1 described principle of parametric storms, the "real" pressure fields of the '53-storm are made visible from 30 january 1953 (12.00 hour) till 1 february 1953 (12.00 hour), with a time interval of 3 hour.
With the help of these "real" pressure fields and of weather charts of the Royal Netherlands Meteorological Institute (KNMI), a preliminary estimate is made of the storm parameters described in paragraph 3.1. They are visualised in table 3.1.

Table 3.1
Storm parameters of the parametric '53-storm.

Storm parameter	Begin simulation	End simulation
Depression track	12° WL, 64.4° NB	13° EL, 52.8° NB
amb (Pa)	101200	101200
δp_c (Pa)	4600	3000
v (m/s)	13.0	6.8
θ (deg)	10	50
r_{xp} (km)	275	250
r_{xn} (km)	900	50
r_{yp} (km)	800	400
r_{yn} (km)	600	500

Storm parameter β, which represents the course direction of the storm, is derived by determining the distance between (12° WL, 64.4° NB) and (13° EL, 52.8° NB) in both the north-south- and east-west-direction. With the help of the relation $\tan\beta = y/x$ it can easily be calculated that storm parameter $\beta = -45°$.

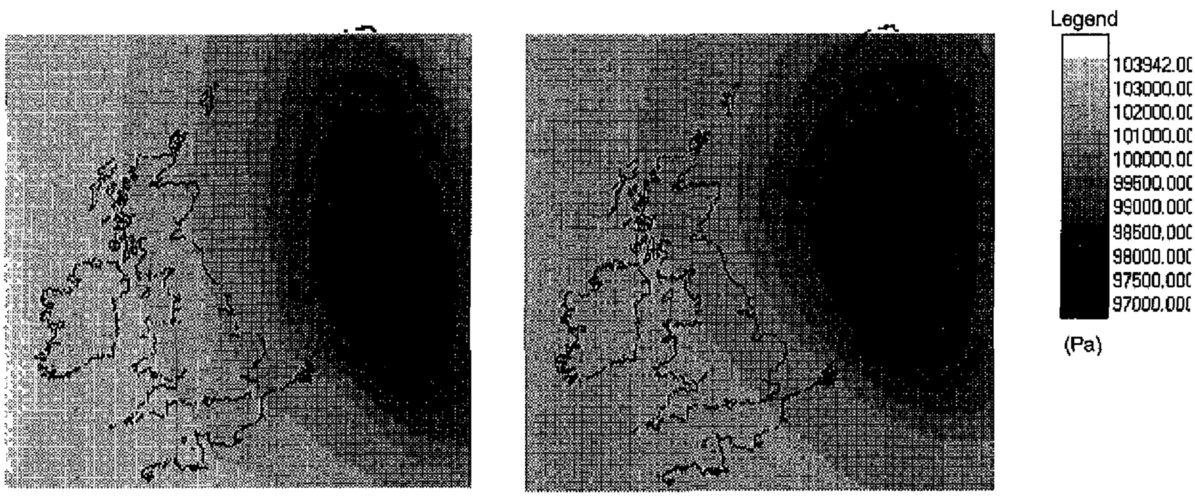
These storm parameters are the main input for the computer program which is used to calculate the wind- and pressure fields of parametric storms (program "Wind" [5]).

In this way a parametric '53-storm is obtained, based on the pressure fields of the real '53-storm and described by a specific set of storm parameters (as visualised in table 3.1).

The pressure fields of this parametric '53-storm are visualised in the same way as has been done in case of the real '53-storm, which makes it possible to compare the pressure fields of both storms.

From this comparison it turns out that, with respect to the pressure fields, the parametric '53-storm is reasonably comparable to the real '53-storm, see for example figure 3.3 at the following page.

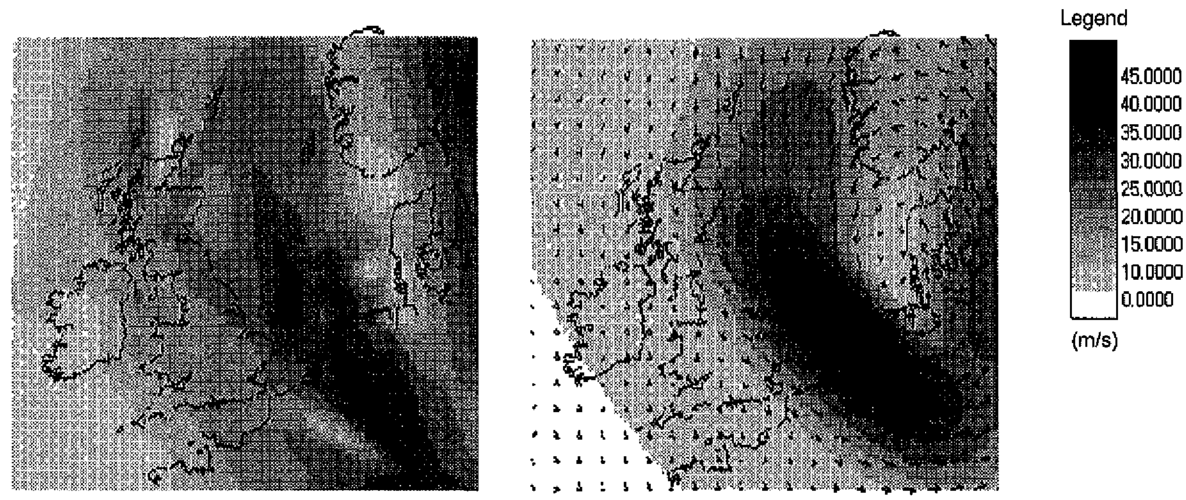
figure 3.3
Comparison of pressure fields of the real and parametric '53-storm at 1 february 1953 (0.00 h).



real '53-storm — parametric '53-storm

Comparison of the wind fields however shows that, although the pressure fields of both storms are reasonably comparable, the corresponding wind fields can be rather different, see for example figure 3.4.

figure 3.4
Comparison of wind fields of the real and parametric '53-storm at 1 february 1953 (0.00 h).



real '53-storm — parametric '53-storm

To investigate whether the parametric '53-storm nevertheless shows in general the same surge characteristics as the real '53-storm, for various water level stations in the southern part of the North Sea a comparison is made between the surge impact of both storms.

To determine this surge impact use is made of the Dutch Continental Shelf Model (CSM). A description of this model and the position of the water level stations is given in paragraph 4.1.

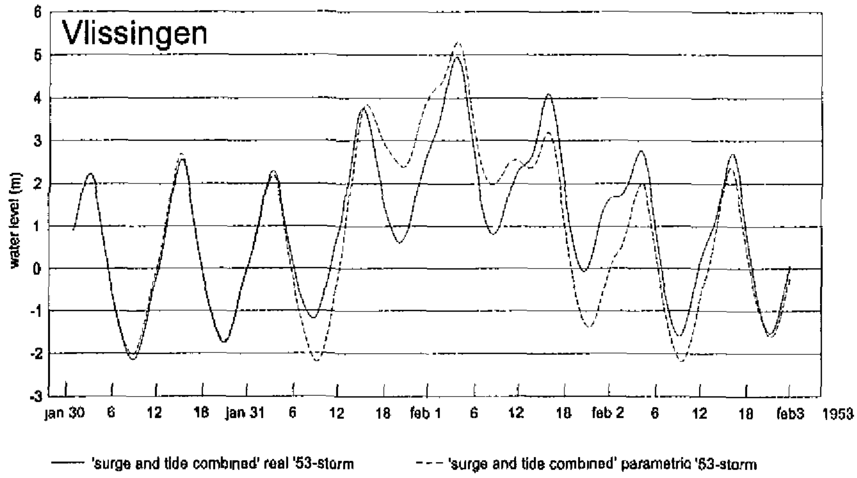
In order to be able to compare the surge impact of both storms in various ways, storm surge computations are carried out for "surge alone" and for "surge and tide combined", whereby

- "surge alone" means that during the simulation only the meteorological effect is taken into account, so there is no tidal influence.
- "surge and tide combined" means that both the tidal and the meteorological effect is taken into account.

From this comparison, which is illustrated in figure 3.5, it turns out that:

- The maximum storm surge effect throughout the model shows almost the same pattern for both the real as the parametric '53-storm.
- The surge in the southern part of the North Sea as a result of the parametric '53-storm is higher than as a result of the real '53-storm.
- The duration of the parametric '53-storm is shorter than of the real '53-storm.

figure 3.5
Comparison surge impact of real and parametric '53-storm for water level station Vlissingen.



So it can be concluded that the parametric '53-storm shows in general the same surge characteristics as the real '53-storm. The intensity of this parametric storm is however higher, while the duration is shorter.

This study is however focused on extreme storms, which means storms with return periods in the order of 10.000 year. The real '53-storm has however (especially for the southern part of the Dutch coast) a return period of about 250 year, so the differences between the real and the parametric '53-storm, as described above, are rather wished than unwished.

3.2.2 Wind climate model

The present extreme wind climate in the southern part of the North Sea area will be modelled with the help of the parametric '53-storm. On the basis of this storm, a set of extreme parametric storms will be generated and, because the individual storms of this set do not have equal chances of occurrence, also a distribution of probability of extreme storms will be derived for this part of the North Sea area.

Set of extreme parametric storms

At first thought, the set of extreme parametric storms can easily be obtained by a systematical variation of the storm parameters of the parametric '53-storm. This is however not feasible because there are 11 parameters to be varied, which means that in case of a systematical variation the set of storms will consist of n^{11} storms (whereby n is the number of variations per parameter).

It is however not necessary to vary all the available storm parameters in order to be able to generate a usable and realistic extreme wind climate in the southern part of the North Sea area. With the help of the following assumptions the number of parameters to be varied decreases from 11 to 5:

- Each individual storm is supposed to have the same course direction (storm parameter β). This can be made reasonable by the fact that storms which have caused in the past an extreme surge in the North Sea area, had always more or less the same course direction, namely north/northwest.
- The position of each storm track is sufficiently determined by the degree of latitude of the storm centre at the beginning of a storm simulation (storm parameter $\varphi_{c,b}$).
- The shape of each storm is varied by a joint increase or decrease of the 4 parameters which determine the shape of the storm (storm parameters $r_{x,p}$, $r_{x,n}$, $r_{y,p}$, $r_{y,n}$). They are treated as if they were just 1 storm parameter (storm parameter R).
- The ambient pressure of each storm (storm parameter amb) is supposed to be constant.

Taking these assumptions into account, the present extreme wind climate in the southern part of the North Sea area can be modelled by a systematical variation of the following storm parameters of the parametric '53-storm:

1) Storm parameter $\varphi_{c,b}$, representing the position of a storm track in degrees latitude at the beginning of a storm simulation.
2) Storm parameter θ_c, which determines the orientation of the east-west axis of a storm.
3) Storm parameter R, which represents the shape of a storm.
4) Storm parameter δp_c, which is the pressure difference between the ambient and central pressure.
5) Storm parameter v, representing the propagation speed of a storm.

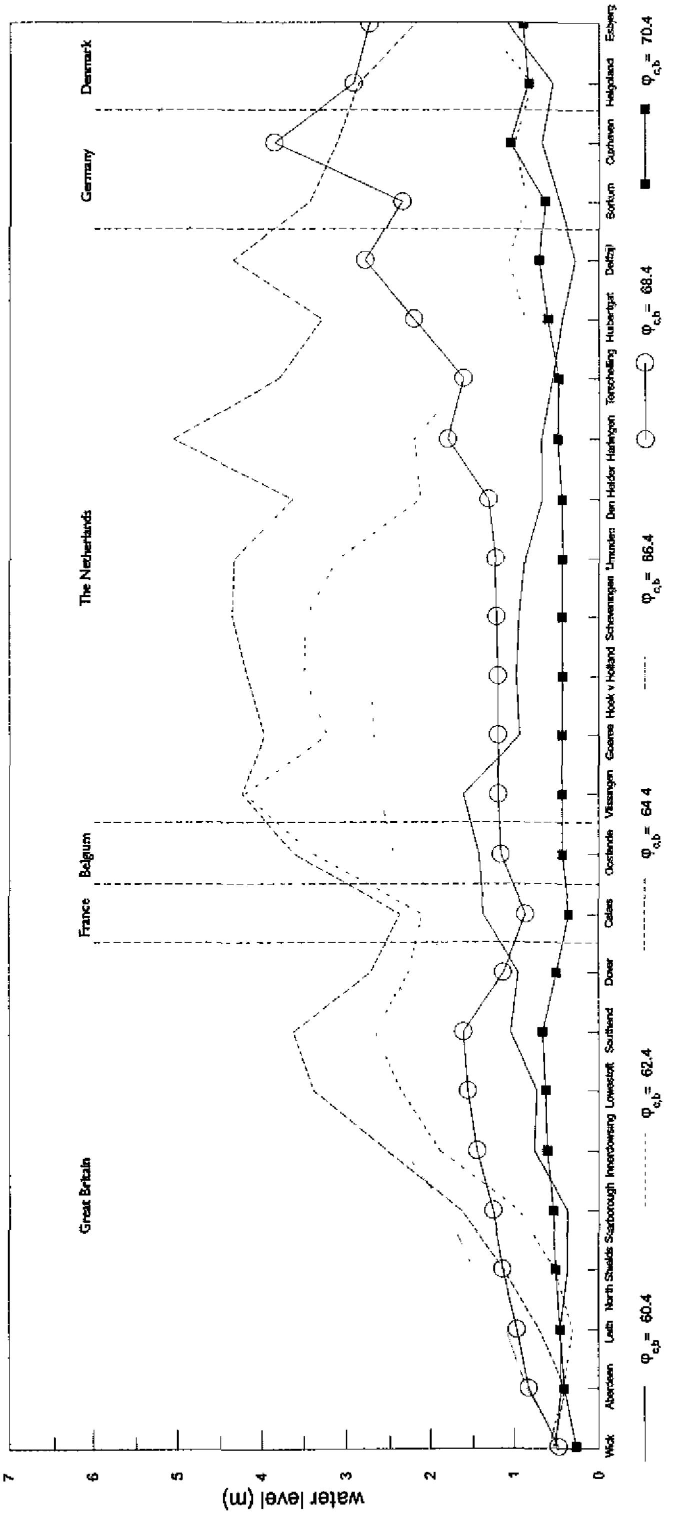
Which variation has to be carried out on each storm parameter separately is determined by means of a small sensitivity study, wherein each of the 5 chosen storm parameters is varied over a wide range of values (keeping all the other storm parameters constant).

For each individual storm parameter variation, the maximum surge impact is determined with the help of the Dutch Continental Shelf Model. A description of this model and the position of the water level stations is given in paragraph 4.1.

In the following, 2 examples will be given to illustrate the results of this sensitivity study. More detailed information about the storm parameter variations and the result of the sensitivity study is described in [6].

1) In figure 3.6, for various water level stations in the North Sea area, the simulation result of a relatively rough variation of storm parameter $\varphi_{c,b}$ is visualised in terms of maximum "surge alone".

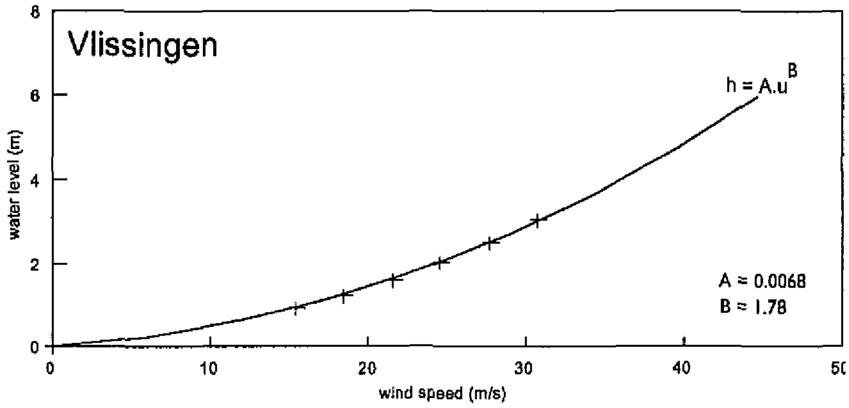
figure 3.6
Simulation result of varying stormparameter $\varphi_{c,b}$ in terms of maximum "surge alone".



This figure shows clearly that the maximum (70.4°) and minimum (60.4°) variation of storm parameter $\varphi_{c,b}$ can be ignored because these variations do not cause a substantial maximum surge in the North Sea area.
Besides that, it is also clearly visible that shifting the storm to the north results into a shift of the spatial distribution of the maximum storm surge from the British coast, via the Channel to the Dutch, German and Danish coast.

2) In figure 3.7, for water level station Vlissingen, the simulation result of varying storm parameter $\delta p_{c,b}$ is visualised. This is done in terms of maximum "surge alone" as function of the maximum wind speed in this water level station.

figure 3.7
Maximum "surge alone" as function of the maximum wind speed for water level station Vlissingen.



From this figure it follows that a relative small increase of the maximum wind speed (which is attributable to an increase of storm parameter $\delta p_{c,b}$) results into a relative large increase of the maximum "surge alone" in water level station Vlissingen.

For the Dutch water level stations the coefficients A and B of the formula $h = A.u^B$, which represents the relationship between maximum "surge alone" and maximum wind speed in a certain water level station, are visualised in table 3.2.

Table 3.2
Coefficients A and B of formula $h = A.u^B$.

Water level station	Coefficient A	Coefficient B
Vlissingen	0,0068	1,78
Goeree	0,0061	1,79
Hoek van Holland	0,0064	1,78
Scheveningen	0,0051	1,83
IJmuiden	0,0050	1,79
Den Helder	0,0064	1,66
Harlingen	0,0111	1,61
W-Terschelling	0,0050	1,72
Huibertgat	0,0100	1,58
Delfzijl	0,0080	1,72

From this sensitivity study the following is concluded:

- The surge response on varying the propagation speed of the storm (storm parameter v) is very small.

- The set of extreme parametric storms is obtained by a systematical variation of the following 4 storm parameters of the parametric '53-storm:

  1) Storm parameter $\varphi_{c,b}$, representing the position of a storm track in degrees latitude at the beginning of a storm simulation. This parameter is varied between 60.4° and 68.4° of latitude, with an interval of 1°.

  2) Storm parameter θ_c, which determines the orientation of the east-west axis of a storm. With respect to the reference values at begin and end of the parametric '53-storm, this parameter is varied between -45° and +45°, with an interval of 15°.

  3) Storm parameter R, which represents the shape of a storm. This parameter is varied by increasing the reference value at begin and end of the parametric '53-storm with 10% and 20%.

  4) Storm parameter $\delta p_{c,b}$, which is the pressure difference between the ambient and central pressure at the beginning of a storm simulation. This parameter is varied by decreasing the reference value of the parametric '53-storm (4600 Pa) with 400 and 800 Pa.

  This set of extreme parametric storms is schematically shown in chapter 4, figure 4.3.

Distribution of probability

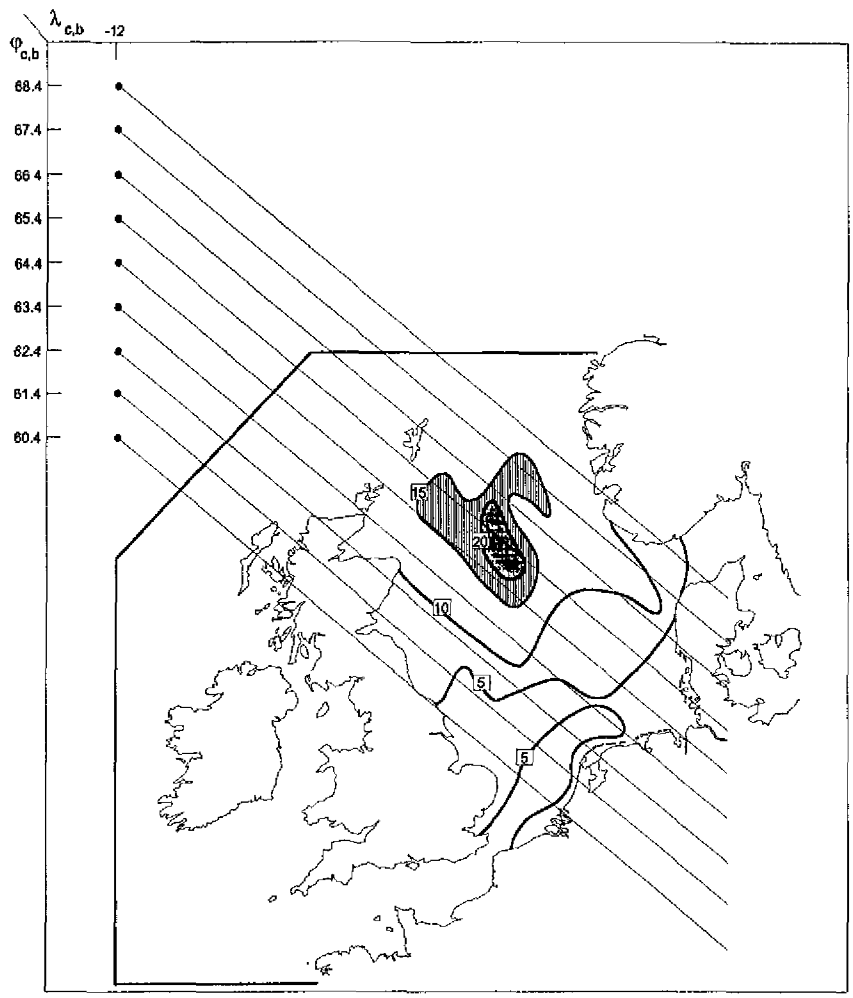
The individual extreme parametric storms in the southern part of the North Sea do not have equal chances of occurrence. Therefore a distribution of probability of these storms is derived for this area.

This is done on the basis of the exceedance frequency of wind force > 7 Beaufort in January, as derived for the North Sea area by Korevaar [14]. This monthly exceedance frequency is derived for each 1° square of the North Sea area and is based on observations from 1961-1980.

In order to be able to combine this exceedance frequency with the set of extreme storms, use is made of the assumptions described in the first part of this paragraph.
From these assumptions it can be concluded that it is possible to divide the set of extreme parametric storms into sub-sets of storms, which originate from a specific degree of latitude ($\varphi_{c,b}$), all having the same course direction (β).

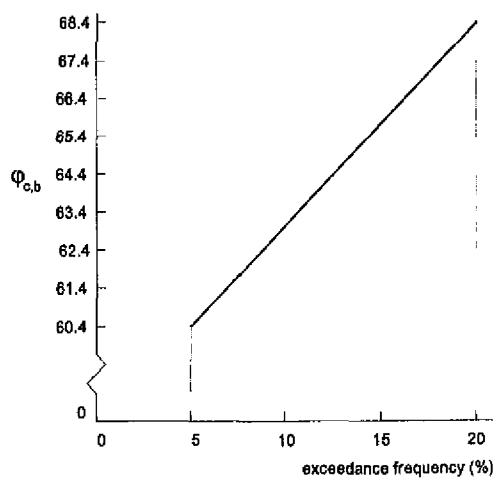
Next, the exceedance frequency of wind force > 7 Beaufort in the North Sea area is combined very roughly with the storm tracks of the afore mentioned sub-sets of extreme parametric storms in this area.
The result is visualised in figure 3.8.

figure 3.8
Storm tracks of sub-sets of extreme parametric storms, combined with the monthly exceedance frequency of wind force > 7 Beaufort.



On the basis of this figure, a (very rough) distribution of probability of extreme parametric storms in the southern part of the North Sea is derived for the present extreme wind climate, which is related to the degree of latitude at the beginning of these storms (figure 3.9).

figure 3.9
Distribution of probability of extreme parametric storms in the southern part of the North Sea (present climate).



So, the present extreme wind climate in the southern part of the North Sea is modelled as a combination of the following 2 elements:

1) A set of extreme parametric storms, derived by a systematical variation of the storm parameters $\varphi_{c,b}$, θ_c, R and $\delta p_{c,b}$ of the parametric '53-storm.
2) A distribution of probability of extreme parametric storms in the southern part of the North Sea area, as given in figure 3.9.

3.3 Future extreme wind climate

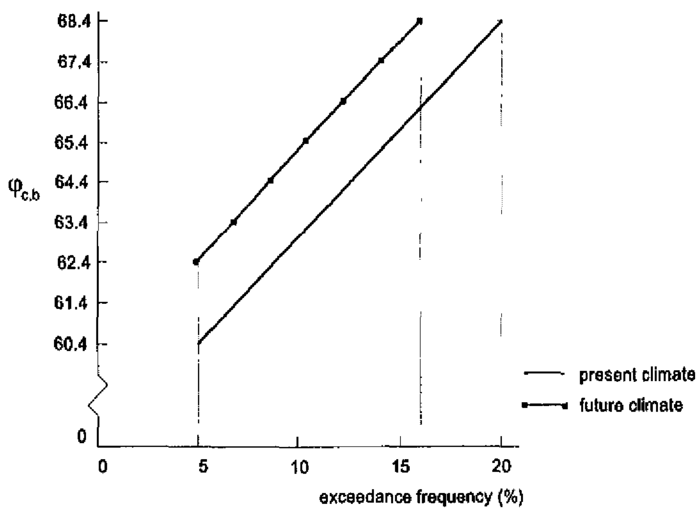
As outlined in chapter 2, both from theory as well as from General Circulation Model experiments it is not possible to describe unambiguously the greenhouse-induced extreme wind climate change in the southern part of the North Sea. That is the reason why in this paragraph the future extreme wind climate in this area is modelled on the basis of a possible greenhouse-induced extreme wind climate change scenario.

Like the modelling of the present extreme wind climate, also the modelling of the future extreme wind climate in the southern part of the North Sea consists of 2 parts:

1) A set of extreme parametric storms, derived by a systematical variation of the storm parameters $\varphi_{c,b}$, θ_c, R and $\delta p_{c,b}$ of the parametric '53-storm. This is the same set as derived for the present extreme wind climate.
2) A distribution of probability of extreme parametric storms in the southern part of the North Sea area, derived on the basis of a possible greenhouse-induced extreme wind climate change scenario. The scenario which is used is visualised in figure 3.10 and is described as follows:

   The greenhouse-induced change of the extreme wind climate in the southern part of the North Sea consists of a northward shift of 2 degrees of latitude of the present extreme wind climate in this area.

figure 3.10
Distribution of probability of extreme parametric storms in the southern part of the North Sea (present climate compared to future climate)



This scenario can be made reasonable by the following 2 reasons:

- General Circulation Model experiments indicate a significant decrease in the frequency of circulation pattern with a strong westerly and southerly wind component over western Europe in case of doubling of the atmospheric carbon dioxide concentration.
  As explained in chapter 2, paragraph 2.3, this can be explained by a northward shift of the entire wind climate system [23].

- General Circulation Model experiments indicate a decrease in the lower tropospheric pole-to-equator temperature gradient as a result of a doubling of the atmospheric carbon dioxide concentration. This can also be explained in terms of a northward shift of the wind climate system.
  It should however be taken in mind that these experiments also indicate an increase of the upper tropospheric pole-to-equator temperature gradient, which counteracts the effect of the above mentioned lower tropospheric decrease of this gradient.

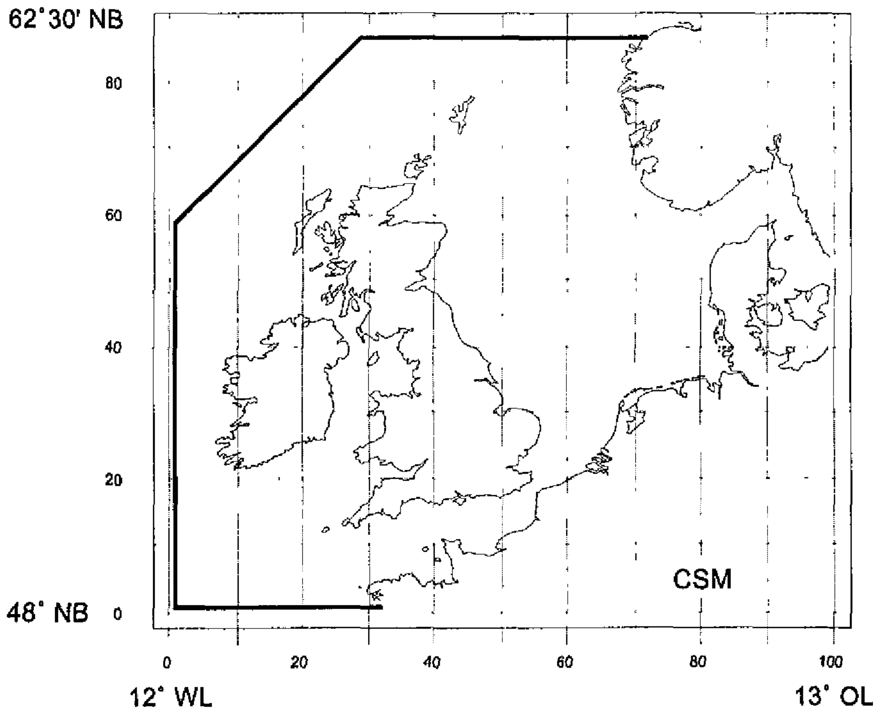
4. Surge impact of the wind climate change

The surge impact of the possible greenhouse-induced change of the extreme wind climate in the southern part of the North Sea will be determined with the help of the Dutch Continental Shelf Model (CSM). This model will be described in paragraph 4.1.
The results of the storm surge computations carried out with this model will be outlined in paragraph 4.2 and in the final paragraph of this chapter, paragraph 4.3, the above mentioned surge impact will be presented in terms of maximum water level frequency distributions.

4.1 Continental Shelf Model [27]

The surge impact of the possible greenhouse-induced change of the extreme wind climate in the southern part of the North Sea is determined with the help of the Dutch Continental Shelf Model (CSM).
This model is a non-linear model for tide and wind induced flow on the northwest European continental shelf, see figure 4.1, and is mainly used for storm surge computations, water quality computations and for the generation of boundary conditions for smaller models.

figure 4.1
Continental Shelf Model.

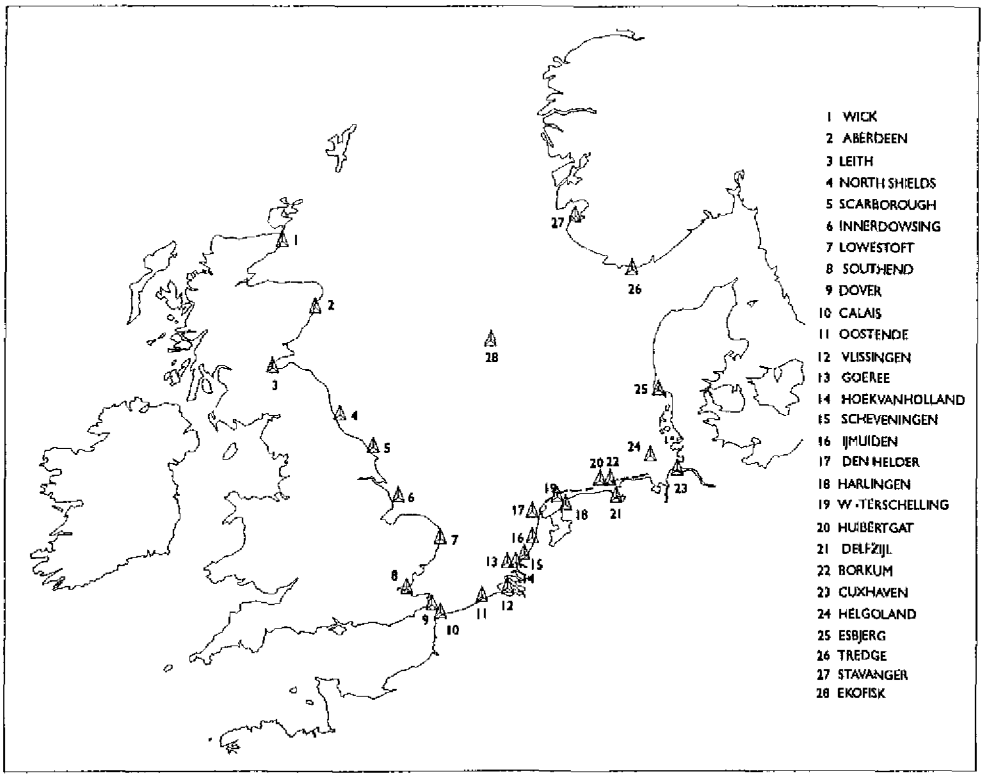


In this study the CSM-16 version of the model is used, which has a grid size of 1/6 degree of latitude and 1/4 degree of longitude (about 16 km.). *This version of CSM has been developed starting from a CSM-version* with a higher resolution; CSM-8 (grid size is about 8 km.).

CSM-16 is based on the WAQUA-system, which is a general purpose program system for solving depth integrated flow and transport problems in general geometries.
As visualised in figure 4.1, the model area covers a large part of the northwest European continental shelf. The bold lines in this figure are the open boundaries of the model, at which for example the tidal boundary conditions are situated.

The results of the storm surge computations (water levels) are performed at specific places in the model (water level stations) and the position of each water level station in the model is shown in figure 4.2.

figure 4.2
Position of the water level stations in CSM-16.



4.2 Storm surge computations

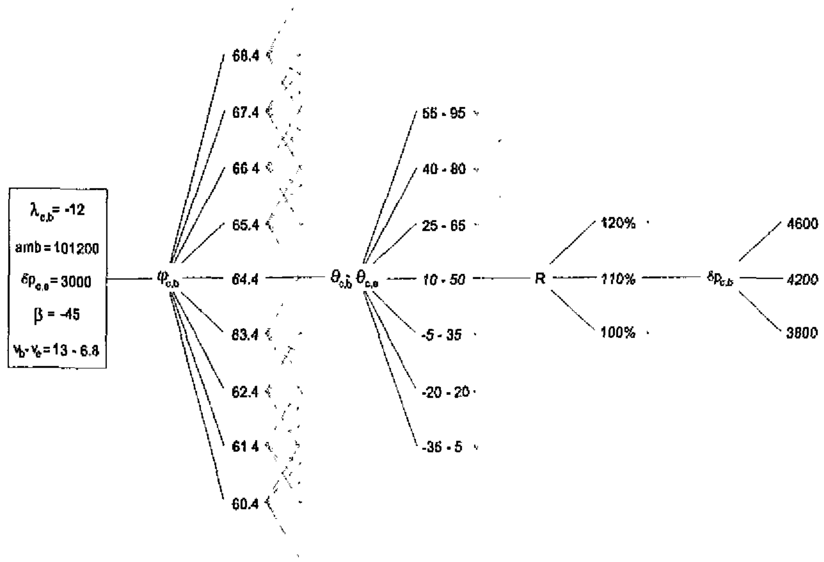
In this paragraph some results of the storm surge computations which are carried out with the Dutch Continental Shelf Model will be presented.
In paragraph 4.2.1 it will be described which storm surge computations are carried out and in paragraph 4.2.2 some results of these storm surge computations will be presented in terms of maximum water levels.

4.2.1 Simulations

As outlined in chapter 3, the extreme wind climate in the southern part of the North Sea (present and future) is modelled by a systematical variation of 4 storm parameters of the parametric '53-storm (in combination with a distribution of probability of extreme storms in this area for both wind climates).

The set of extreme parametric storms which is obtained in this way has already been described in chapter 3, paragraph 3.2.2, and is schematically shown in figure 4.3. It can easily be calculated that this set consists of 567 extreme parametric storms.

figure 4.3
Set of extreme parametric storms.



For this complete set of extreme parametric storms, storm surge computations are carried out for "surge alone" with the help of the Dutch Continental Shelf Model (CSM-16). As outlined in paragraph 3.2.1, "surge alone" means that only the meteorological (storm) effect is used as boundary condition. This implicates that the tidal boundary conditions, situated at the 4 open boundaries of CSM-16, are switched off.

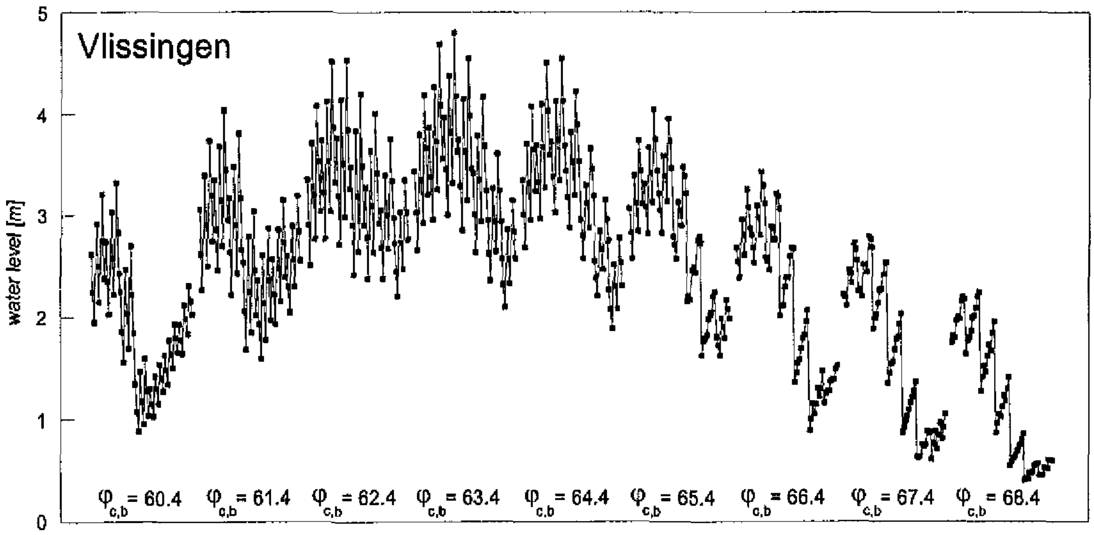
4.2.2 Simulation results

As outlined in paragraph 4.1, the results of the 567 storm surge computations are performed in various water level stations in the North Sea area, see figure 4.2.
This means that for each individual water level station in the model 567 water level time histories are available.
To reduce this enormous amount of information, the maximum of each water level time history is calculated. With the help of this (reduced) data set, the surge impact of the present and possible future extreme wind climate in the southern part of the North Sea will be presented in paragraph 4.3.
First of all however, in this paragraph, some analyses will be carried out on the data.

Taking the in paragraph 3.2.2 described modelling of the present extreme wind climate in the southern part ot the North Sea into account, the complete set of 567 maximum water levels is divided into 9 sub-sets of 63 maximum water levels. Each sub-set is related to a set of extreme parametric storms which have equal storm tracks (the same degree of latitude at the beginning of a storm simulation ($\varphi_{c,b}$)).

In figure 4.4 these 9 sub-sets are visualised for water level station Vlissingen.

figure 4.4
9 Sub-sets of maximum water levels, related to $\varphi_{c,b}$, for water level station Vlissingen.



To be able to compare the sub-sets of various water level stations in an adequate way, the "5%-mean" of each sub-set is calculated. This "5%-mean" is defined as the mean of the 3 (5% of 63) highest maximum water levels of each sub-set.

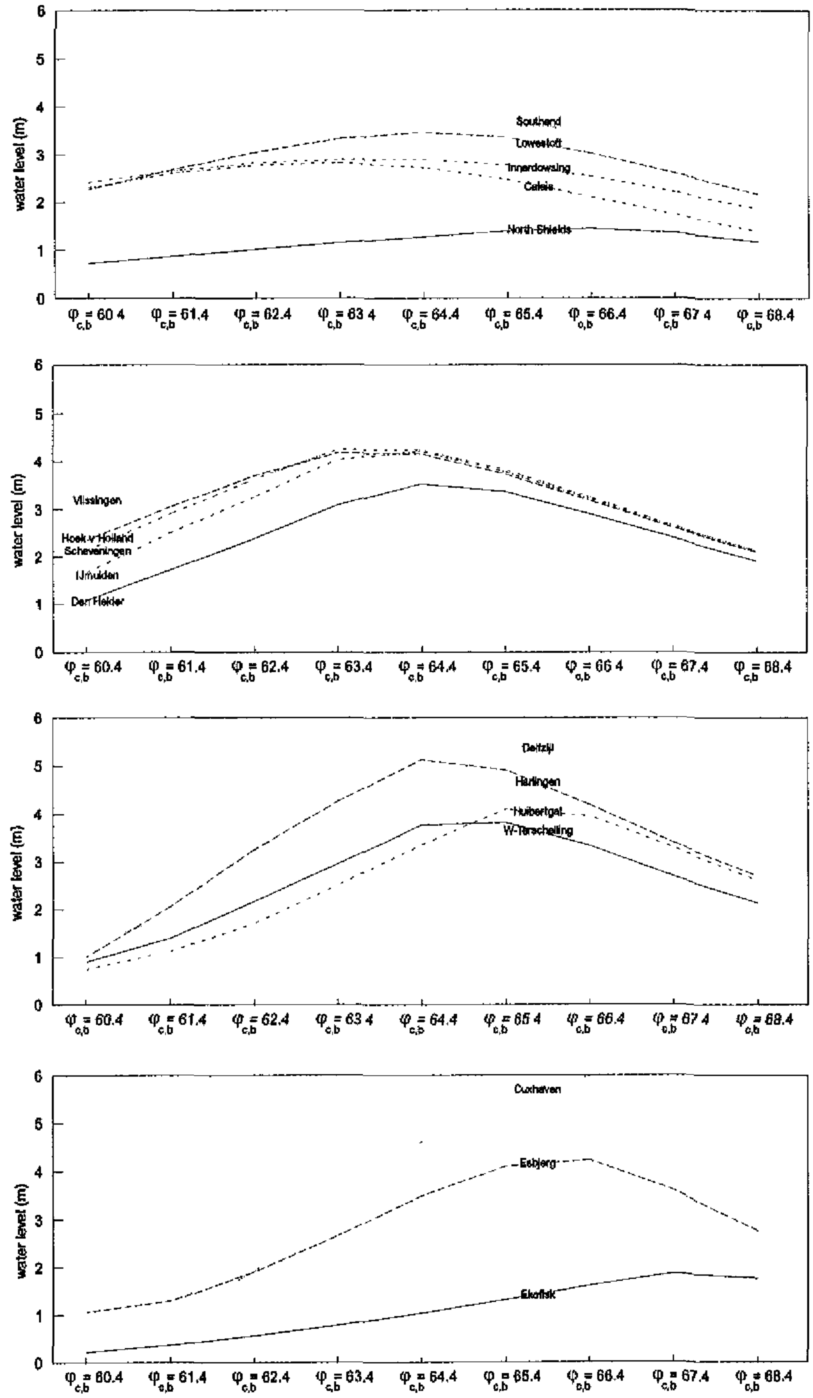
In figure 4.5 at the following page, a comparison is made between this "5%-mean" of each sub-set for various water level stations in the North Sea area.

From this figure the same type of derivations can be made as has been done from figure 3.6 (which shows the simulation results of a relatively rough variation of storm parameter $\varphi_{c,b}$ in case of the parametric '53-storm):

- The range of varying storm parameter $\varphi_{c,b}$ (60.4° to 68.4° of latitude) is wide enough, because for each individual water level station the maximum of the "5%-mean" is within this range.

- Shifting the sub-sets of extreme parametric storms to the north (60.4° to 68.4° of latitude) results into a shift (of the maximum) of the spatial distribution of the "5%-mean" from water level stations along the British coast, via the Channel to the Dutch, German and Danish coast.

figure 4.5
Comparison of the "5%-mean" of water level stations in the North Sea area.



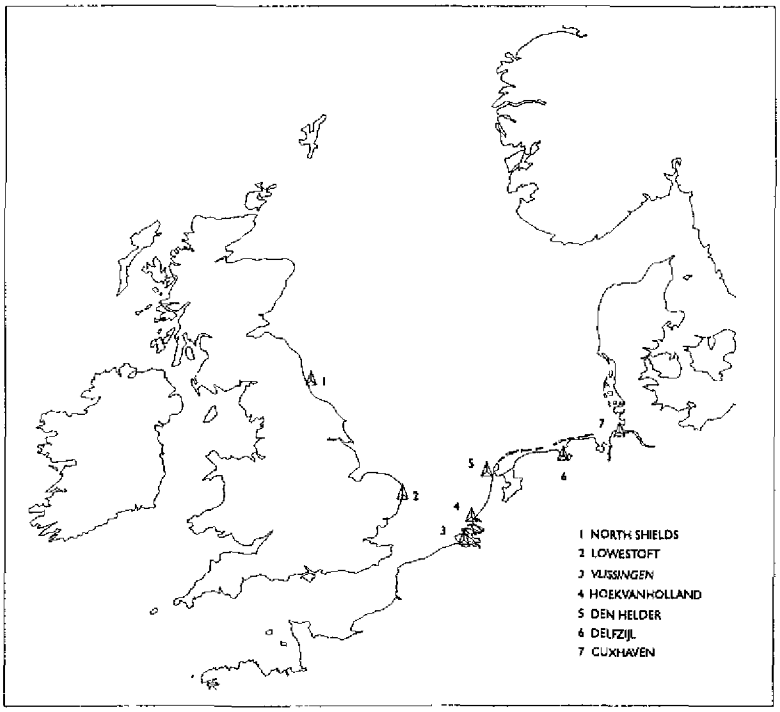
4.3 Extreme wind climate change

In this paragraph the surge impact of the possible greenhouse-induced extreme wind climate change in the southern part of the North Sea will be presented.

In paragraph 4.3.1 the surge impact of the present and in paragraph 4.3.2 the surge impact of the possible future extreme wind climate will be outlined in terms of maximum water level frequency distributions.
In the last paragraph, paragraph 4.3.3, a comparison between the surge impact of those 2 extreme wind climates will be made.

The surge impact of the 2 extreme wind climates is determined for a selected set of water level stations in the southern part of the North Sea area. These water level stations are visualised in figure 4.6:

figure 4.6
Water level stations in the southern part of the North Sea, used to determine the surge impact of the present and possible future extreme wind climate.



4.3.1 Surge impact present extreme wind climate

As outlined in paragraph 4.2.2, for each of the selected water level stations in the southern part of the North Sea, a set of 567 maximum water levels is available. Besides that, also a distribution of probability of extreme storms in this area is available for the present extreme wind climate (figure 3.9).

To determine the surge impact of the present extreme wind climate in the southern part of the North Sea, first of all for water level station Hoek van Holland a Weibull frequency distribution is derived on the basis of the complete set of 567 maximum water levels.

Because this set is obtained from extreme storm surge computations (storms with return periods in the order of 10.000 year), it is possible to "tune" this distribution on the "design level" of water level station Hoek van Holland (5.00 m.). This "design level" is defined as the water level which will be exceeded only once in 10.000 year [26].

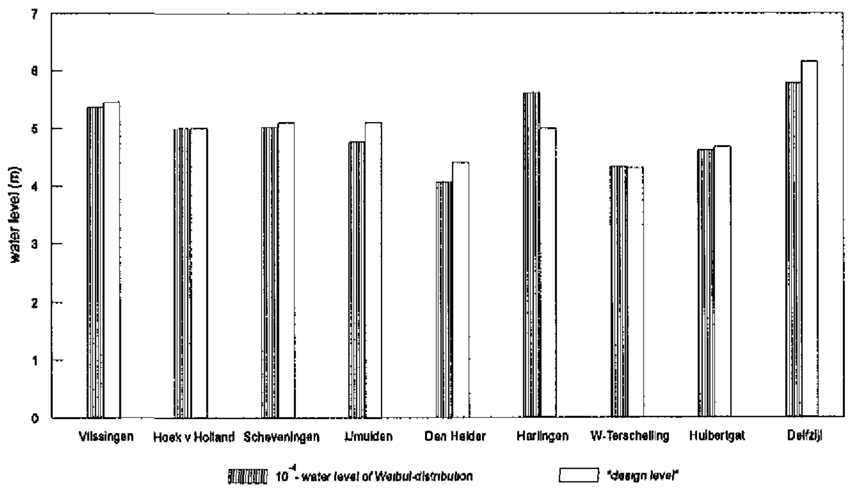
The Weibull frequency distribution of water level station Hoek van Holland is however obtained on the basis of storm surge computations whereby only the meteorological (storm) effect is taken into account ("surge alone"), while the "design level" besides this storm effect also incorporates a tidal effect and an interaction effect between surge and tide ("surge and tide combined") [4].

Therefore, the "design level" of water level station Hoek van Holland is corrected for mean high water (1.11 m.) and the interaction effect between surge and tide (0.27 m.). This results into a "design level" for "surge alone" which amounts to 4.16 m. This corrected "design level" is used to "tune" the Weibull frequency distribution, which means that this value is related to the 10^{-4} frequency of this distribution. More detailed information about this "tuning" is described in [6].

Subsequently it is assumed that the Weibull frequency distributions of the remaining selected water level stations can be obtained with the same Weibull parameter set as derived for water level station Hoek van Holland. The result is visualised in Annex B.

That this assumption is reasonable can be seen from figure 4.7. This figure shows that with the help of the Weibull parameter set of water level station Hoek van Holland it is possible to make a good estimation of the "design level" of the Dutch water level stations [6].

figure 4.7
Comparison between "design level" and 10^{-4}- water level of the Weibull frequency distribution.

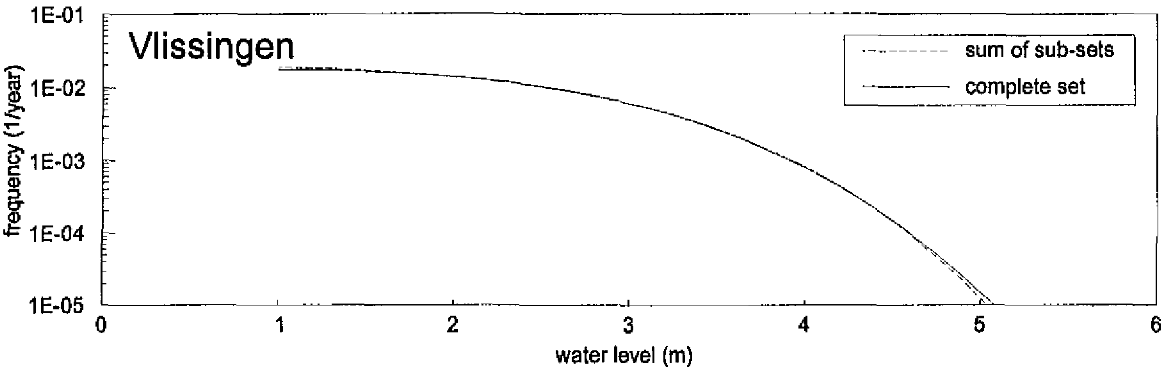


In order to be able to combine the 2 types of data (Weibull frequency distribution of maximum water levels and distribution of probability of extreme storms (present extreme wind climate), for each selected water level station the complete set of 567 maximum water levels is spit up into 9 sub-sets of 63 water levels (as outlined in paragraph 4.2.2).

Next, for each of these sub-sets a Weibull frequency distribution is derived on the basis of the same Weibull parameter set as is used for the complete set of maximum water levels.

Theoretically, the Weibull frequency distribution of the sum of these sub-sets has to be identical with the Weibull frequency distribution of the complete set of maximum water levels. As an example, in figure 4.8 for water level station Vlissingen it is shown that this "rule" is fulfilled.

figure 4.8
Comparison Weibull distribution of the sum of sub-sets and the complete set of maximum water levels.



Now, for each selected water level station in the southern part of the North Sea, the surge impact of the present extreme wind climate is obtained by combining the Weibull frequency distributions of the sub-sets of maximum water levels with the distribution of probability of extreme storms in this area for the present extreme wind climate.

In figure 4.9, this surge impact is visualised for the selected water level stations in terms of Weibull frequency distributions (continuous line).

4.3.2 Surge impact future extreme wind climate

In this paragraph, for the selected water level stations in the southern part of the North Sea, the surge impact of the possible future extreme wind climate will be outlined.
It should be mentioned that this future extreme wind climate is based on a chosen greenhouse-induced extreme wind climate change scenario. This scenario, described in paragraph 3.3, consists of a northward shift of 2° of latitude of the present extreme wind climate in the southern part of the North Sea.

The surge impact of this possible future extreme wind climate is obtained by combining the Weibull frequency distributions of the sub-sets of maximum water levels (described in paragraph 4.3.1) with the distribution of probability of extreme storms in the southern part of the North Sea for the future extreme wind climate (based on the afore mentioned extreme wind climate change scenario).

In figure 4.9, this surge impact is visualised for the selected water level stations in terms of Weibull frequency distributions (dotted line).

4.3.3 Surge impact extreme wind climate change

In this paragraph, for the selected water level stations in the southern part of the North Sea, the surge impact of the possible greenhouse-induced change of the extreme wind climate in the southern part of the North Sea will be presented.

In figure 4.9 is, besides the surge impact of the possible future extreme wind climate in the southern part of the North Sea (dotted line), also the surge impact of the present extreme wind climate in this area (continuous line) visualised for the selected water level stations.

From this figure it can be derived that a possible greenhouse-induced northward shift of 2° of latitude of the present extreme wind climate in the southern part of the North Sea, results into a slight decrease of the exceedance frequency of maximum water levels of the selected water level stations in this area.

For water level station Hoek van Holland for example, the "design level" decreases from 5.00 m. to 4.91 m. The same holds for the other water level stations; they all show a small decrease of the exceedance frequency of maximum water levels of about 0.1 m.

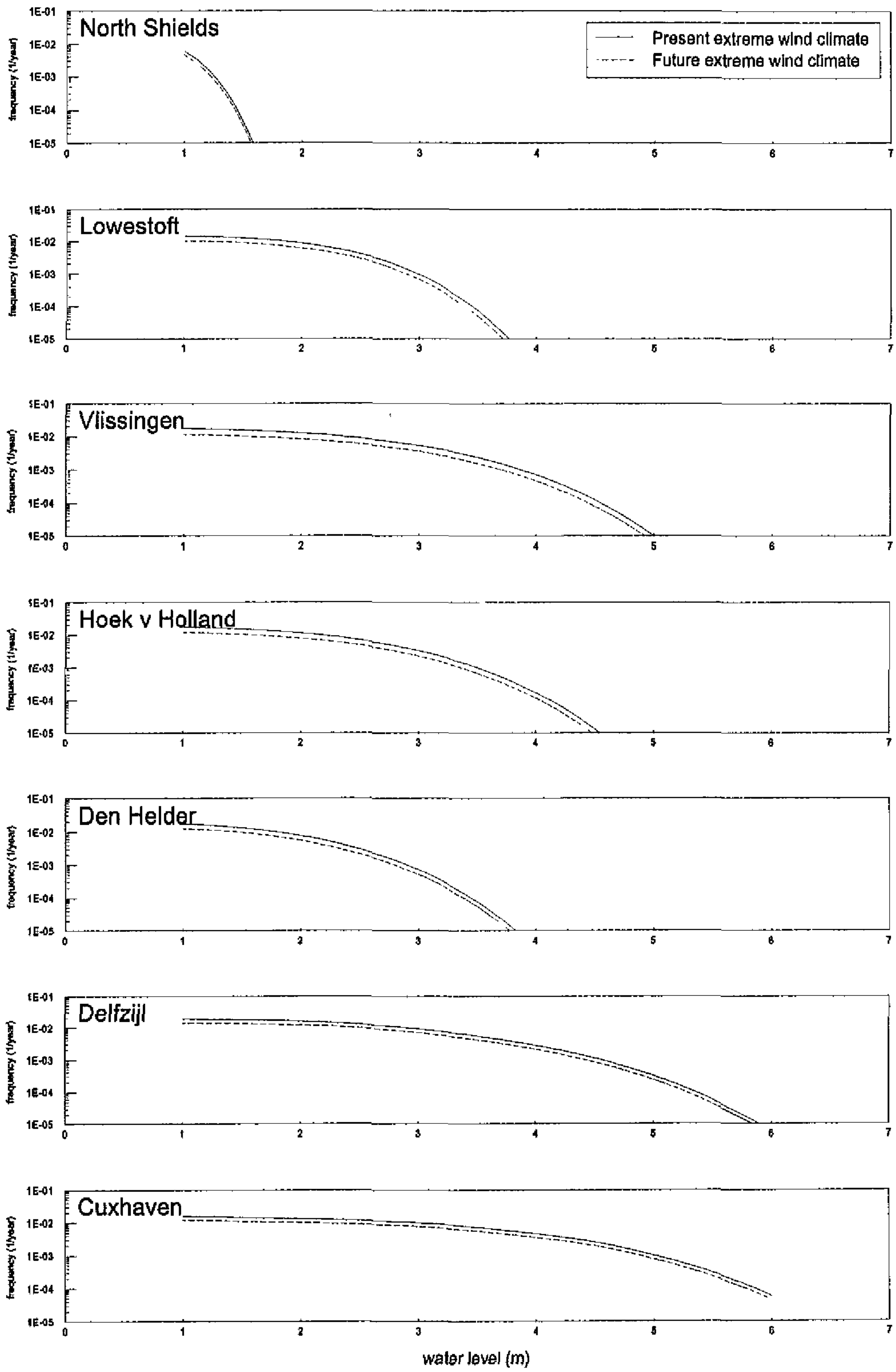
So, it can be concluded that a relative large northward shift of the present extreme wind climate in the southern part of the North Sea area (2° of latitude is about 222 km.) has a relative small effect on the extreme storm surge in this area (about 0.1 m.).

To illustrate this last conclusion, the relation between maximum wind speed and maximum "surge alone", visualised in figure 3.7 for water level station Vlissingen, has to be taken in mind.

With the help of this relation it can be calculated that a 10% increase of a maximum wind speed of 30 m/s, results into an increase of the maximum storm surge effect in this water level station of about 0.5 m.

So, from this relation it can be concluded that a relative small, greenhouse-induced change of the maximum wind speed (30 m/s to 33 m/s) has a relative large influence on the maximum storm surge effect in the southern part of the North Sea area.

figure 4.9
Comparison surge impact of present and possible future extreme wind climate.



5. Conclusions

The aim of the present study is to get insight into the impact of a possible greenhouse-induced change of the extreme wind climate on the surge in the southern part of the North Sea. In this chapter some concluding remarks will be made on the basis of subjects which play an important role in obtaining this insight.

Climatic change

The greenhouse effect is a natural process, necessary for the conditions of life on earth. It can be described as a physical process whereby long wave radiation, emitted by the warm earth, is partly absorbed and remitted by certain gases in the atmosphere.
Since the Industrial Revolution human activities are responsible for an increase in the concentration of these gases, resulting in an increase of the global mean surface temperature of the earth.
Within the "scientific community" there is no discussion about this temperature increase, although the predictions show a wide range of uncertainty (1.5° C to 4.5° C in case of a doubling of the atmospheric carbon dioxide concentration).

More discussion however exists on the regional pattern of this temperature increase. General Circulation Models (GCM's) play an important role in studies on this topic.
According to most of these models, in the lower troposphere, the largest temperature increase due to an increasing atmospheric carbon dioxide concentration, will be in the northern latitudes. This will lead to a decrease of the pole-to-equator temperature gradient, which can be explained in terms of a northward shift of the climate system (including the wind climate).
These models however also indicate that the upper tropospheric pole-to-equator temperature gradient will increase, leading to the opposite effect. Up to now, it is not very clear which effect will be dominant.

There are however more indications that the greenhouse-induced extreme wind climate change will consist of a northward shift of the entire wind climate system. Some of the General Circulation Model experiments for example indicate that the frequency of circulation patterns with a strong westerly and southerly wind component will decrease significantly in case of doubling carbon dioxide. As outlined in paragraph 3.3, this can also be explained by a northward shift of the entire wind climate system.

Conclusion: - Even with the most elaborate numerical climate models (General Circulation Models), it is not possible to describe unambiguously the greenhouse-induced extreme wind climate change in the southern part of the North Sea.

- On the basis of some theoretical considerations and of numerical General Circulation Model experiments it can be made reasonable that the greenhouse-induced change of the extreme wind climate in the southern part of the North Sea will consist of a northward shift of the entire wind climate system in this area.

Modelling of the wind climate change

The present extreme wind climate in the southern part of the North Sea is modelled starting from the pressure fields of the famous storm of 1953. With the help of the principle of parametric storms this storm is described by a specific set of storm parameters. This parameter set is called the parametric '53-storm, in contradiction to the real '53-storm.
Comparison of both storms in terms of surge impact leads to the conclusion that the parametric '53-storm shows in general the same surge characteristics as the real '53-storm. The intensity of this parametric storm is however higher, while the duration is shorter.

On the basis of this parametric '53-storm, a set of extreme parametric storms is generated by a systematical variation of the storm parameters of this storm.
From a small sensitivity study it turns out that, to be able to generate a realistic extreme wind climate in the southern part of the North Sea, the following 4 storm parameters have to be varied:

1) Storm parameter $\varphi_{c,b}$, representing the position of a storm track in degrees latitude at the beginning of a storm simulation. This parameter is varied between 60.4° and 68.4° of latitude, with an interval of 1°.
2) Storm parameter θ_c, which determines the orientation of the east-west axis of a storm. With respect to the reference values at begin and end of the parametric '53-storm, this parameter is varied between -45° and +45°, with an interval of 15°.
3) Storm parameter R, which represents the shape of a storm. This parameter is varied by increasing the reference value with 10% and 20%.
4) Storm parameter $\delta P_{c,b}$, which is the pressure difference between the ambient and central pressure at the beginning of a storm simulation. This parameter is varied by decreasing the reference value of the parametric '53-storm (4600 Pa) with 400 and 800 Pa.

So, the set of extreme storms consists of 567 extreme parametric storms (schematically shown in figure 4.3).

However, the individual extreme storms do not all have equal chances of occurrence. Therefore a distribution of probability of extreme storms in the southern part of the North Sea is derived for the present extreme wind climate (figure 3.9).
Combining this distribution of probability with the set of extreme parametric storms results into a model of the present extreme wind climate in the southern part of the North Sea area.

The possible future extreme wind climate in the southern part of the North Sea area is modelled in the same way by combining the set of 567 extreme parametric storms with a new (modified) distribution of probability of extreme storms in this area (figure 3.10). This distribution is derived on the basis of a possible greenhouse-induced extreme wind climate change scenario. This scenario is made reasonable in chapter 2 (climatic change) and is described as follows:

The greenhouse-induced change of the extreme wind climate in the southern part of the North Sea consists of a northward shift of 2° of latitude of the present extreme wind climate in this area.

Conclusion:
- With the help of the principle of parametric storms it is possible to derive a parametric '53-storm which shows in general the same wind and surge characteristics as the real '53-storm.
- The present extreme wind climate in the southern part of the North Sea is modelled by a systematical variation of 4 storm parameters of the parametric '53-storm, in combination with a distribution of probability of extreme storms in this area as given in figure 3.9.
- A possible future extreme wind climate in the southern part of the North Sea is modelled by the same systematical variation of storm parameters of the parametric '53-storm, in combination with a distribution of probability of extreme storms in this area as given in figure 3.10.

Surge impact of the wind climate change

The surge impact of the possible greenhouse-induced extreme wind climate change in the southern part of the North Sea is determined with the help of the Dutch Continental Shelf Model (CSM).

For the complete set of 567 extreme parametric storms, storm surge computations are carried out for "surge alone". This means that only the meteorological effect is used as boundary condition (no tidal influence).

The results of these storm surge computations (water level time histories) are performed at various places in the model area (water level stations).

For a selected set of these water level stations the maximum storm surge effect of each individual storm is computed.
These maxima are visualised in terms of Weibull frequency distributions, which are "tuned" on the "design levels" along the Dutch coast. These "design levels" are defined as the water levels which will be exceeded only once in 10.000 year.
It turns out that the 10^{-4}-water level of these "tuned" Weibull frequency distributions agrees reasonably well with these "design levels".

To combine the Weibull frequency distributions of the selected water level stations with a distribution of probability of extreme storms in the southern part of the North Sea (present or future extreme wind climate), the set of maximum water levels of each selected water level station is split up into 9 sub-sets. Each of these sub-sets is related to a set of extreme parametric storms which have equal storm tracks (the same degree of latitude ($\varphi_{c,b}$) at the beginning of a storm simulation).
For all these sub-sets a Weibull distribution is derived with the same Weibull parameter set as used for the complete set of maximum water levels.

Combining the Weibull frequency distributions of these sub-sets with the distribution of probability of extreme parametric storms in the southern

part of the North Sea area as visualised in figure 3.9, gives the surge impact of the present extreme wind climate for a selected water level station in this area.
Combining the Weibull frequency distributions of these sub-sets with the distribution of probability of extreme parametric storms in the southern part of the North Sea as visualised in figure 3.10, gives the surge impact of the possible future extreme wind climate for a selected water level station in this area.

Comparison of those 2 surge impacts provides insight into the impact of a possible greenhouse-induced change of the extreme wind climate on the surge in the southern part of the North Sea. From this comparison it turns out that a possible greenhouse-induced northward shift of 2° of latitude of the present extreme wind climate in the southern part of the North Sea, results into a slight decrease of the exceedance frequency of the maximum water levels in this area.

Conclusion: A possible greenhouse-induced northward shift of 2° of latitude of the present extreme wind climate in the southern part of the North Sea area results into a slight decrease of the exceedance frequency of maximum water levels in this area. In other words:

A relative large northward shift of the present extreme wind climate in the southern part of the North Sea (222 km.) results into a relative small storm surge effect in this area (0.1 m).

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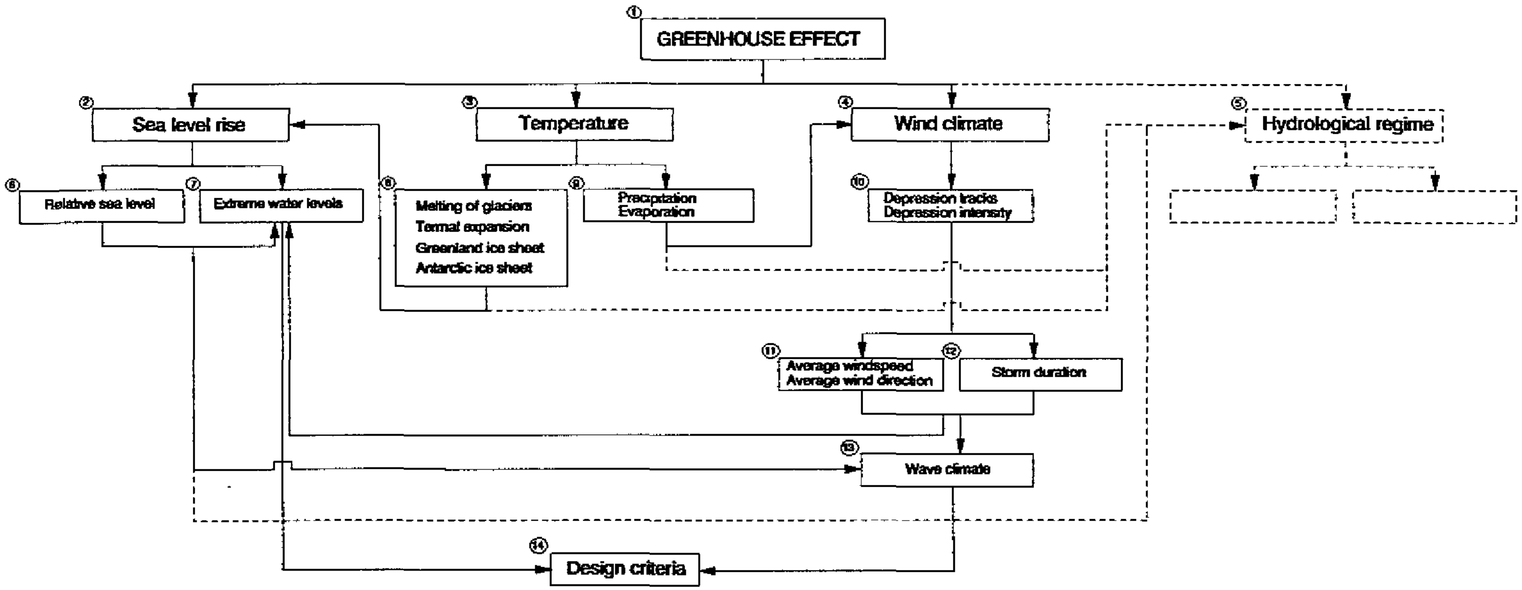
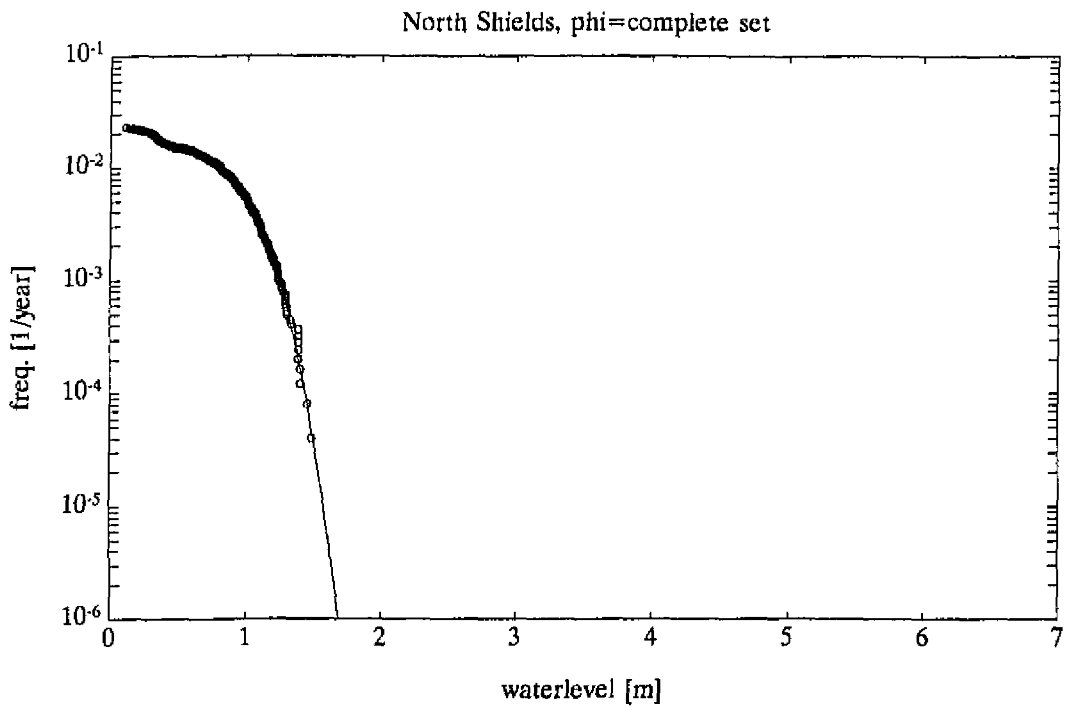
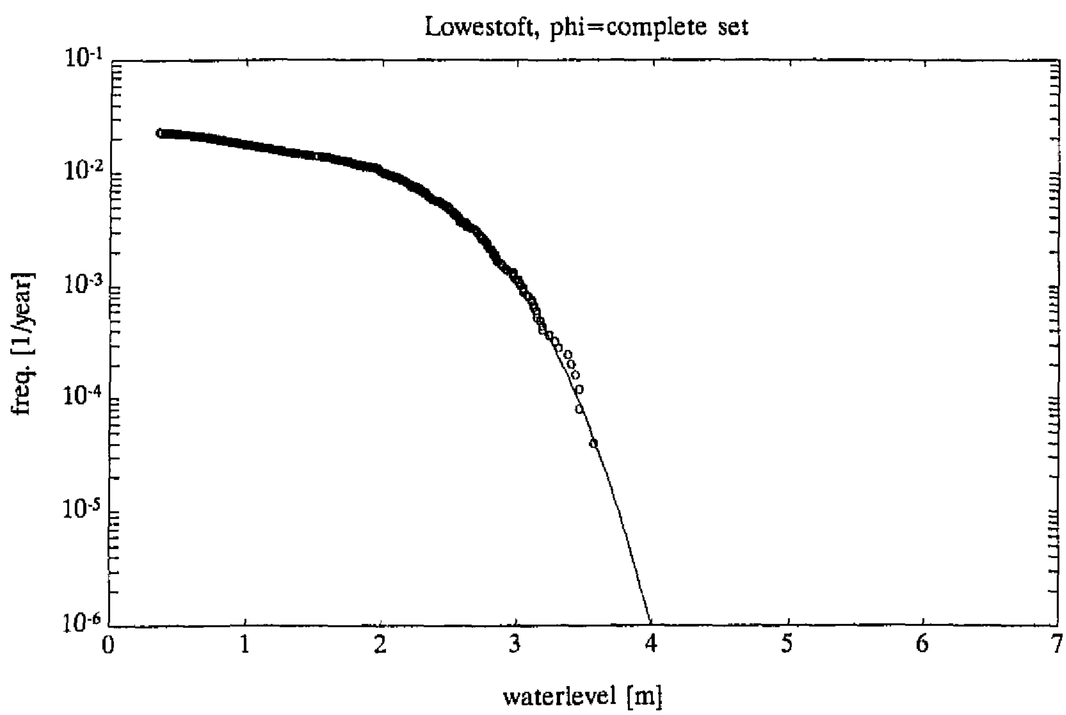
Annex A. System diagram

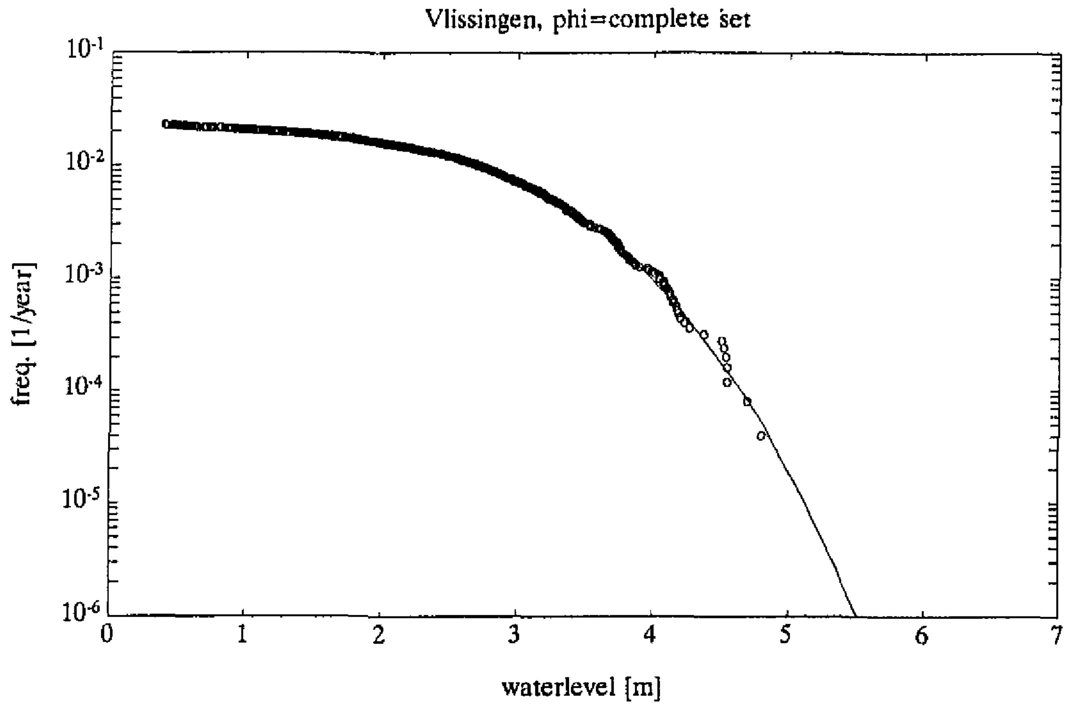


The dashed lines are connected to the hydrological regime. This subject does not play an important role in this study and will be ignored in the following.

Annex B. Weibull frequency distributions



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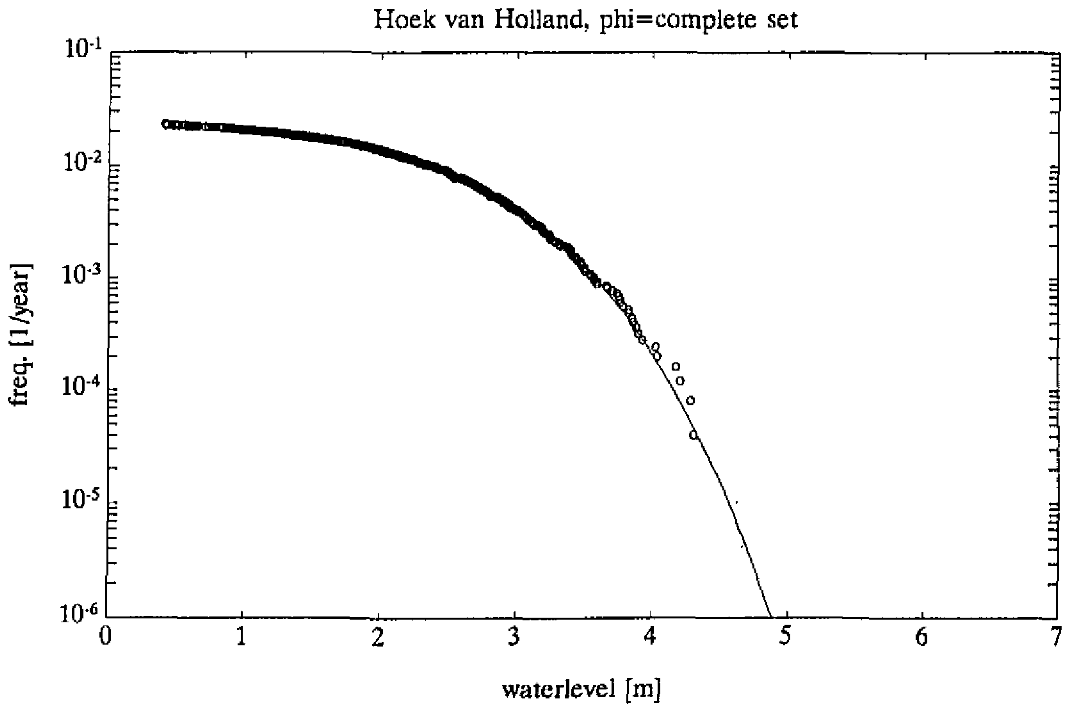
10-3
10-4
10-5
10-6
0
1
2
3
4
5
6
7
waterlevel [m]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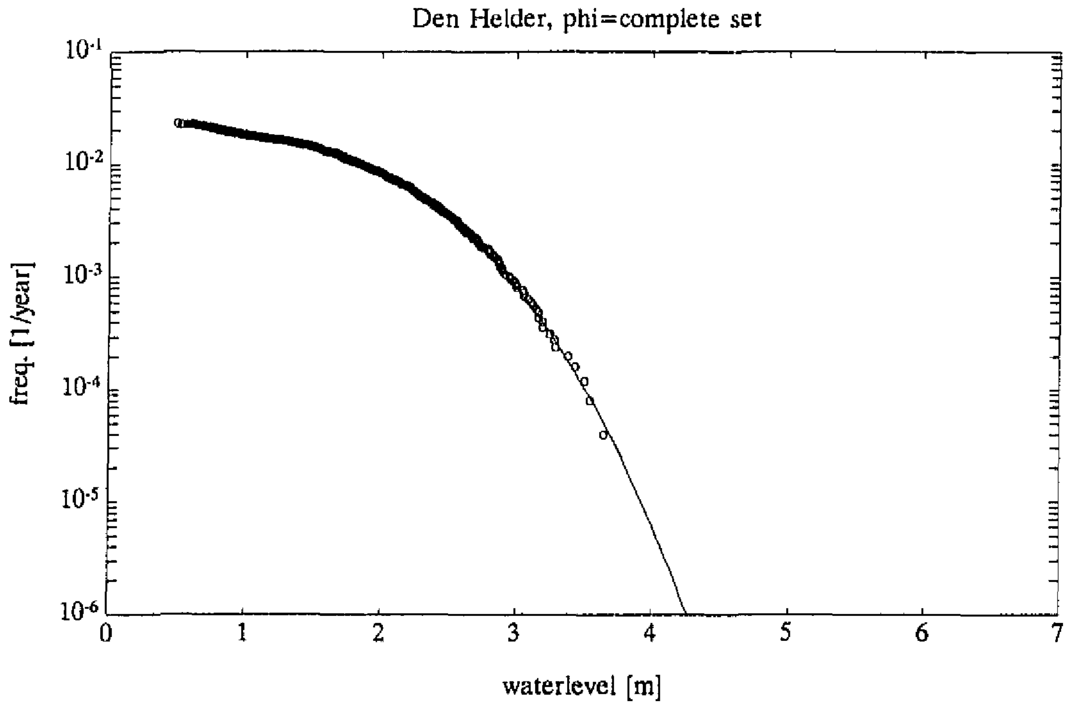
5
6
7
waterlevel [m]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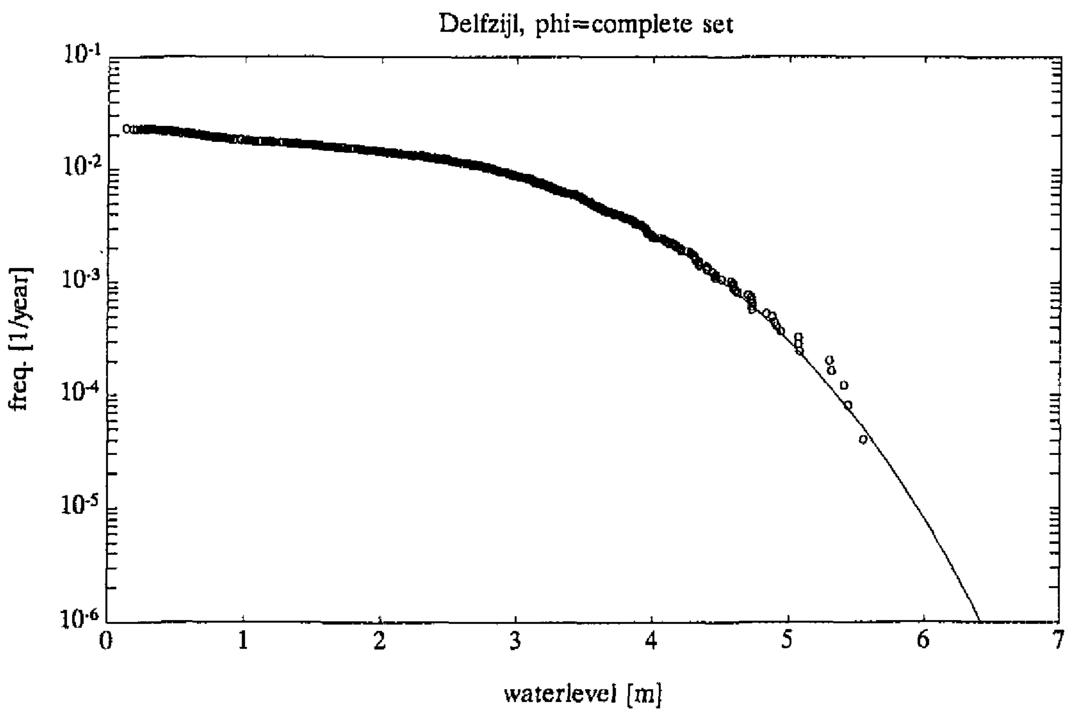
7
waterlevel [m]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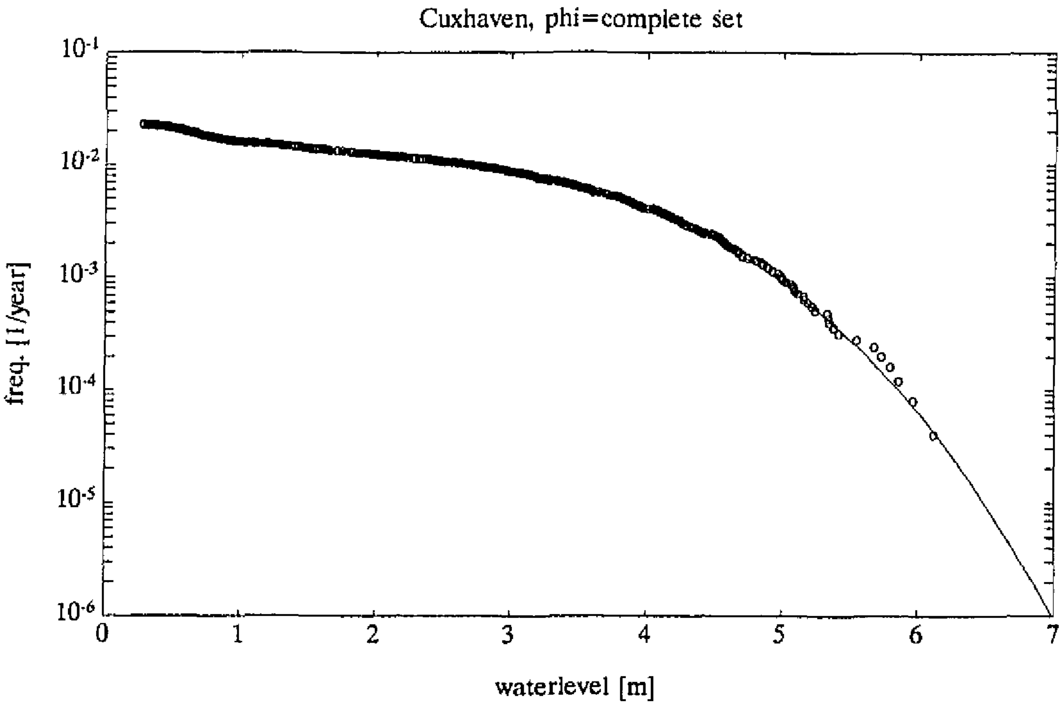
7
waterlevel [m]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10-6
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1
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4
5
6
7
waterlevel [m]