CHAPTER 107

NEPTUNE—AN INTEGRATED APPROACH TO DETERMINING NW EUROPEAN COASTAL EXTREMES

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Abstract

NEPTUNE is an EU-research project under the MASTII framework. It involves seven partners: British Maritime Technology, Delft Hydraulics, Department of Mathematics & Statistics, University of Lancaster, Climate Research Unit, University of East Anglia, Econometrics Institute, Erasmus University, National Institute for Coastal and Marine Management of Rijkswaterstaat (RIKZ), and Forschungszentrum Geesthacht GmbH (GKSS). The purpose is to investigate ***a new integrated approach for modelling the statistics of NW European coastal extremes*** by first characterising the coastal impact and then *linking it through a process model chain with the causative storm involved*. The project methodology recognises that the North-European storm climate is made of several different storm types which impact on the coastline in different ways. The project strategy is described and some of the main results are presented.

1. Introduction

Information requirements for modern coastal management and engineering design need a statistical characterisation of the impact of storms on the shoreline or coastal structure. The impact is related to the combined influence of waves, tides and surges which are the hydraulic parameter inputs into functional relationships that describe the loading and response of the structure. The relationships describe the *limit-state* conditions that provide for the *design formulae* which are the basis of the modern approach to structural design and risk analysis (CUR/TAW 1990). Traditionally, estimates of the frequency distribution of extreme sea levels are based on analysis of historical tide gauge measurements of still water levels. These data are always site-specific and cover historical periods which are rarely consistent from site-to-site. The principal extreme value methods used to compute the *return periods* are the *annual maxima method* (Wemelsfelder 1961, Lennon 1963 a, Suthons 1963, Führböter 1976, Graff 1981) and the *joint probability method* (Pugh and Vassie 1980, Walden *et al.* 1982, Tawn 1992). Although the statictical methods have been extensively developed over recent years (de Valk 1991, Smith 1994, Coles and Tawn 1994) they are applied only to sea state observations without consideration to the influence and variability of the causitive storm events involved.

The NEPTUNE project originated from the conviction that an integrated approach allowing for storm climate influence is called for. Changes in global weather climate

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will naturally influence storm climate which will induce consequential changes in the severity and frequency of regional coastal extremes. This may help explain the historical time variation in the probability of extreme sea levels around Great Britain and along the German coast identified independently by Graff (1978,79) and Führböter (1976,78) in the late 1970's. Ultimately, a stochastic description of the regional storm climate could form the common basis for the required joint statistics of coastal extremes, in which a combination of numerical models is used to parameterise the transformation from storm climate to local statistics. Such a description can serve as a solid basis for assessment of the consequences of changes in storm climate. Recently this same philosophy has been adopted by a number of other European research project groups (WASA, IMPACT) which will no doubt help to accelerate progress and development.

2. Project Methodology

The methodology seeks to develop an integrated approach for modelling the statistics of coastal extremes by first characterising the coastal impact and then linking it through a process model chain with the causative storm involved which in turn is attributed a statistical form within the global climate of storms.

The cause-consequence process chain linking the causative storm with impact on a coastal structure can be summerised in the following diagram:

Storm Weather & Tide State Pressure-wind field history, phase in the tidal cycle.

↓

Sea State Offshore Still water level (surge+tide), wind-wave field (given by directional spectrum or by selected integrated parameters describing the wave height, period, direction and directional spread), current.

↓

Sea State Nearshore Still water level (surge+tide+wave set-up), wave field and current with their interaction taken into account, and dependence on coastal exposure and bathymetry. The parameters describing the sea state nearshore compose a set of sl hydraulic parameters which are usually input for the hydraulic/geotechnical and structure response model.

↓

Loading and Response of Coastal Structure The loads and response depend on type of structure or system of structures and are described by basic functional relationships. These relationships describe the *limit-state* conditions that provide for the sl design formulae and are the basis for the structural design and risk analysis. The design formulae have usually the form of a relation between the strength and load functions. The basic strength variables are determined by material characteristics and by the geometry of the structure which compose the set of *design parameters*. The loading variables of marine structures originate from the environmental boundary conditions and are either the input hydraulic parameters themselves or the parameters describing the hydraulic and geotechnical response (e.g. wave run-up, overtoping, transmission, reflection, set-up, pore pressures) which are determined by hydraulic input.

The cause-consequence chain is represented as follows:

$$\mathbf{W}_t \xrightarrow{\mathcal{F}_1} \mathbf{X}_t \xrightarrow{\mathcal{F}_2} \mathbf{Y}_t \xrightarrow{\mathcal{F}_3} D_t \tag{1}$$

where $\mathbf{W}_t$, $\mathbf{X}_t$, $\mathbf{Y}_t$ and D_t denote the random wind field, offshore variables, nearshore variables and design variable respectively, each indexed by time t. $\mathcal{F}_1$ is the superposition of the offshore tide-surge model and numerical wave generation model run on deep water up to 20 m depth. $\mathcal{F}_2$ is the superposition of the tide-surge model and wave model that transforms the offshore variables to the nearshore environmental variables (hydraulic parameters). Finally, $\mathcal{F}_3$ is a function of the nearshore variables which gives the design parameter D_t, assumed to be scalar. The function $\mathcal{F}_3$ (design formula) is usually determined by a *boundary function* of a failure region defined as a sub-set of $\mathbf{Y}_t$ space. In order to develop a statistical model integrating the $\mathbf{W}_t$, $\mathbf{X}_t$, $\mathbf{Y}_t$ and D_t variables the simplified versions of $\mathcal{F}_1$ and $\mathcal{F}_2$ need to be developed; in the case of $\mathcal{F}_3$ we assume that it is a known function. These are simple parametric models $\widetilde{\mathcal{F}}_1 : \mathbf{W}_t \to \mathbf{X}_t$ and $\widetilde{\mathcal{F}}_2 : \mathbf{X}_t \to \mathbf{Y}_t$. The parametric models $\widetilde{\mathcal{F}}_1$ and $\widetilde{\mathcal{F}}_2$ are designed and calibrated based on the data hindcast for the storms selected for both demonstrator zones.

NEPTUNE assumes that, on a European *coastal cell scale*, the extreme water levels generated at the shoreline are due to the impact of a particular type of storm. These storm types may vary for different coastal cell regions. Because wave effects play a critical role in maximising the water level at the shoreline it is obvious that storm directionality is important. It is assumed that the different coastal storm types which arise can be characterised into sub-classes of the overall climate of European storms.

Two distinct demonstrator zones were established, one on the west coast of Great Britain and the other on the north coast of Holland as shown in Fig. 1. Each zone has a particular type of region-specific storm climate associated with the generation of extreme coastal impact events and each is characterised by different physiography which would be used to investigate the relative influence of regional features affecting the storm-wave transformation to shore. In each demonstrator zone a review was made of the historical coastal flood events within the period 1955–1993 and the worst 20 events were selected independently for each region. The period 1955–1993 was chosen because high quality gridded digital meteorological data covering the NE Atlantic were available from DNMI—Norwegian Meteorological Institute. The DNMI data would provide a consistent set of boundary conditions both for analysing the storm weather directly and for modelling the sea state processes $\mathcal{F}_1$ and $\mathcal{F}_2$ associated with each of the 40 storm events.

3. Structure of Project

The project objectives span four main task areas of which three cover detailed research and investigation namely:

T100 Identify and analyse extreme sea state data

Establish a database of field measurements and information describing coastal physiography and sea state associated with historical coastal flood events in two selected coastal zones. One demonstrator zone was chosen on the west coast of Great Britain and the other on the Dutch coast. The extreme flood events in each zone are characterised by different types of storm.

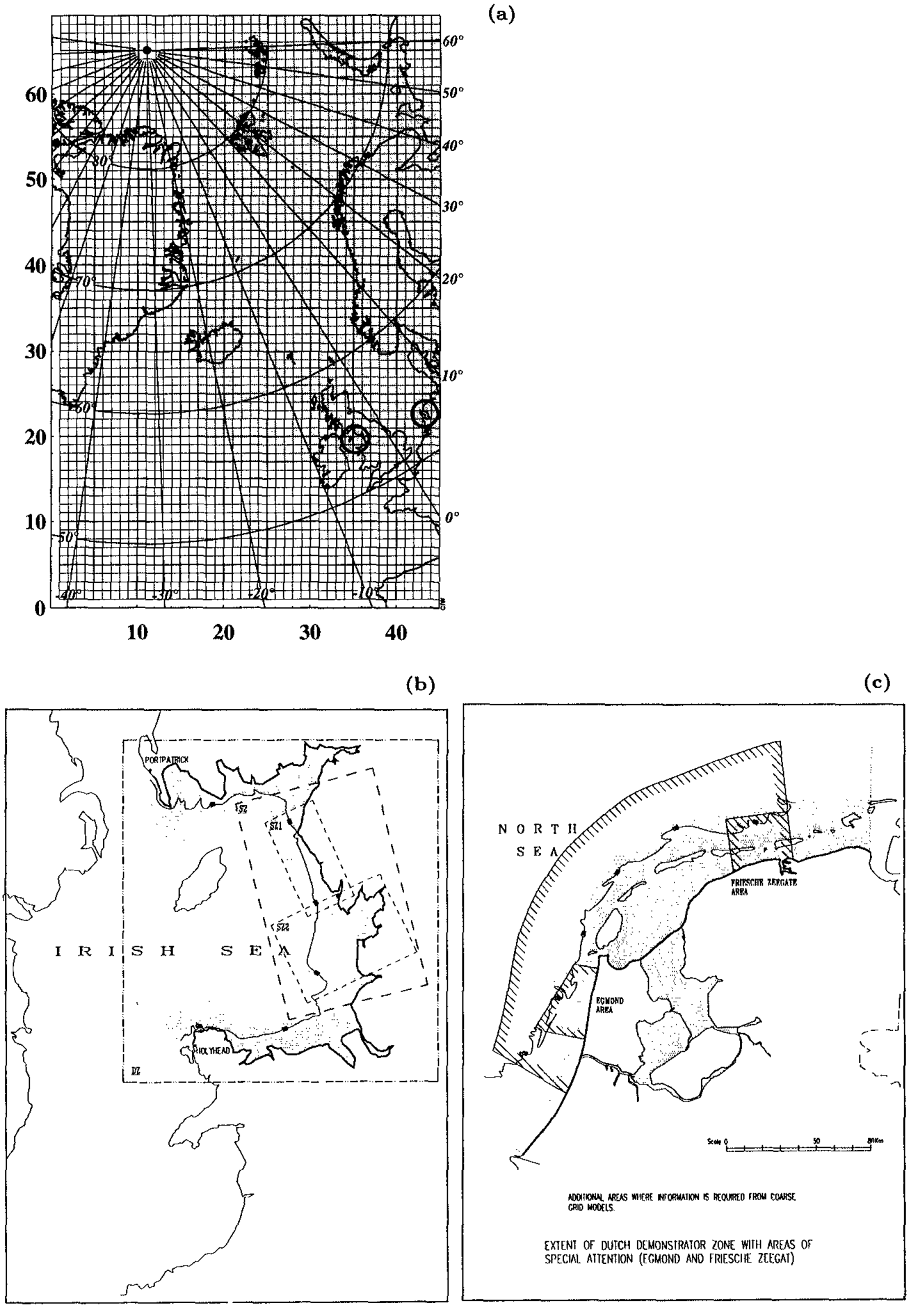


Fig. 1. **(a)** DNMI grid co-ordinates and study demonstrator zones; **(b)** UK demonstrator zone; **(c)** Dutch demonstrator zone.

T200 Identify and analyse storm weather data

Investigate the local and regional storm climate associated with generation of extreme coastal impact in respective demonstrator zones. The aim is to develop a parametric representation of the storm weather for input to sea state models and evaluate trends in storm character and frequencies of occurrence of different types of storms.

T300 Simulate extreme sea state processes and coastal impact

Use established operational hydrodynamic models to simulate the storm generated sea states offshore and their transformation to shore and investigate ways to parameterise the model responses and assess modelling uncertainties.

T400 Develop methods for determining joint statistics

The main goal is to develop, using the results from the two different demonstrator zones, a generic framework and associated multivariate models for describing joint statistics of coastal extremes allowing for relationships between storm climate and coastal response.

4. Key Features and Results

T100 Identify and analyse extreme sea state data

For each demonstrator zone the criteria for individual storm selection differed between the UK and Holland. The UK events were selected on the basis of regional coastal tide gauge records and documented public reports of the flood impact whereas the Dutch coast selection was made directly from available full scale measurements of winds, waves and tides monitored at a number of offshore platforms. The Dutch storm selection procedure is described in Dunsbergen (1994) and is based on metocean measurements recorded near Den Helder which was selected as representative location for the Dutch demonstrator zone. Many of the UK Irish Sea storm-surge events have been extensively studied and modelled at the Institute of Oceanographic Sciences (IOS), Bidston Observatory—now Proudman Oceanographic Laboratory (POL) (e.g. Amin 1982, and Heaps 1983) however, supporting wave measurement were rarely available.

T200 Identify and analyse storm weather data

Storm weather data

The primary data set used is the North Sea – NE Atlantic gridded pressure and wind data prepared by the DNMI covering the period 1955–1993. The coverage is shown in Fig. 1 (a) and represents a rectangular grid on a polar stereographic projection with grid size 75km at 60° N. These data were processed to provide coverage for all storm events in the study and were also used as common boundary data to model both the storm surge and storm wave simulation.

Storm classification and parameterisation

A key objective of NEPTUNE is to identify, characterise and classify storms affecting the two different demonstrator zone and seek to develop a parametric link between the causative storm features and the resulting hydraulic response (waves, tides and surges) at the shoreline. In part, this requires a need to parameterise the storms in order to exploit the digital DNMI database. The approach adopted was based on the recent work of Ferrier *et al.* (1993) which assumes that the storm pressure field (affecting the Dutch coast) can be represented as a Gausian bell of elliptical cross section whose geometry and motion are determined by a set of 11 parameters. The DNMI gridded data were processed to produce colour contoured pressure field maps at 6hrly intervals extending over a 20 day period for each of the 40 selected storms. These maps were used to study and classify the storms and to determine the parameters required for their characterisation and modelling. Preliminary analysis of the storms suggests that they can be divided into three classes each characterised by specific features associated with track and form of isobar distribution and dynamics. The assumption of a generic form of elliptic bell shaped storm structure proves to be an oversimplification. The findings reafirm the view that UK west coast extremes are associated with a particular type of storm first identified by Lennon (1963 b) and that the great 1953 storm does in fact characterise the worst-case storms affecting the Dutch coast. The contrasting structure of the two types of storm at moment of maximum coastal impact are shown in Fig. 2.

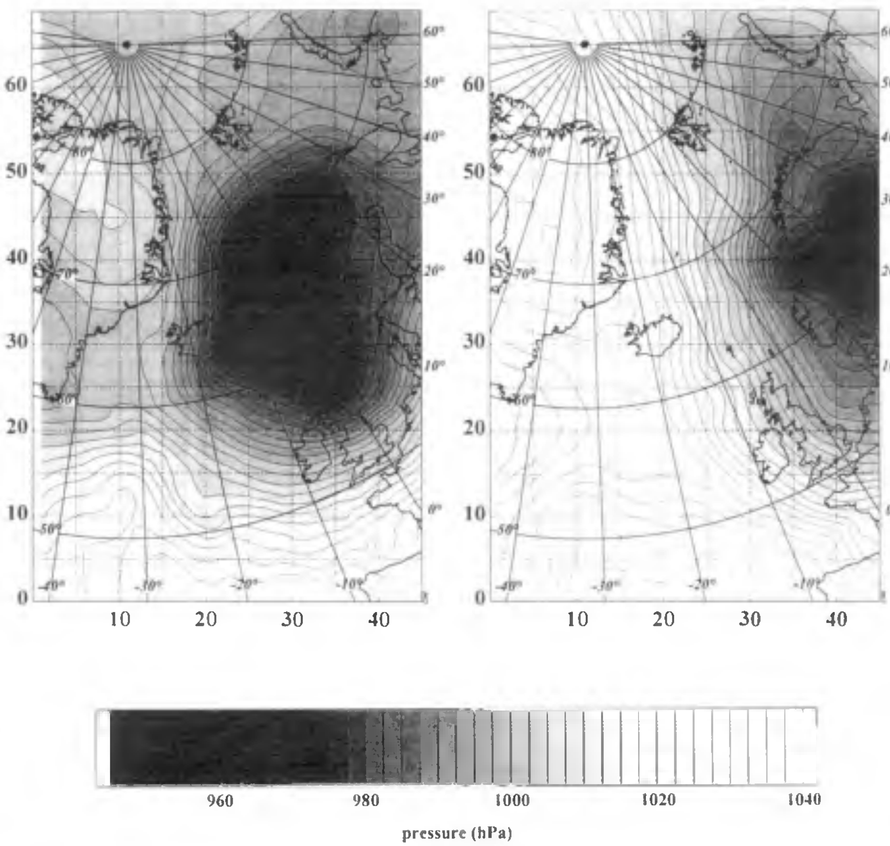


Fig. 2. Pressure distribution at time of coastal extreme for two contrasting storm types; Irish Sea extreme at 0:00h on 12/11/77 (left) and Dutch coast extreme at 6:00h on 13/02/62 (right).

T300 Simulate extreme sea state processes

Simulate offshore extremes

A conventional hybrid scheme involving the separate modelling of tide-surge and wave-current interaction processes was used to simulate the offshore storm induced sea state in each demonstrator zone. The DNMI gridded data were used to provide the boundary conditions associated with the forty storms selected. Storm surge levels were computed by POL using their CSX model and the associated wind-wave field was computed by GKSS using their hybrid parametrical surface wave prediction model (HYPA) in a nested model chain. The POL CSX model has a uniform grid resolution of 1/3° latitude by 1/2° longitude (approximately 36km) whereas the GKSS HYPA model chain coupled grid resolutions of 150km, 30km and 10km. HYPA (Günther *et al.* 1979) is a second-generation wave forecasting model that includes parametric prediction of the one-dimensional wind-sea spectrum with the mean wave direction as an additional prediction parameter. At each grid point the model generates the directional wave spectra as well as a set of 24 integrated spectral parameters.

Verification of hindcast wave and still water levels has been performed in detail for nine severe storm events using the independent field measurements available at five Dutch zone monitoring stations. The results were extremely good and an example of surge and wave comparison for a Dutch zone station is shown on Fig. 3.

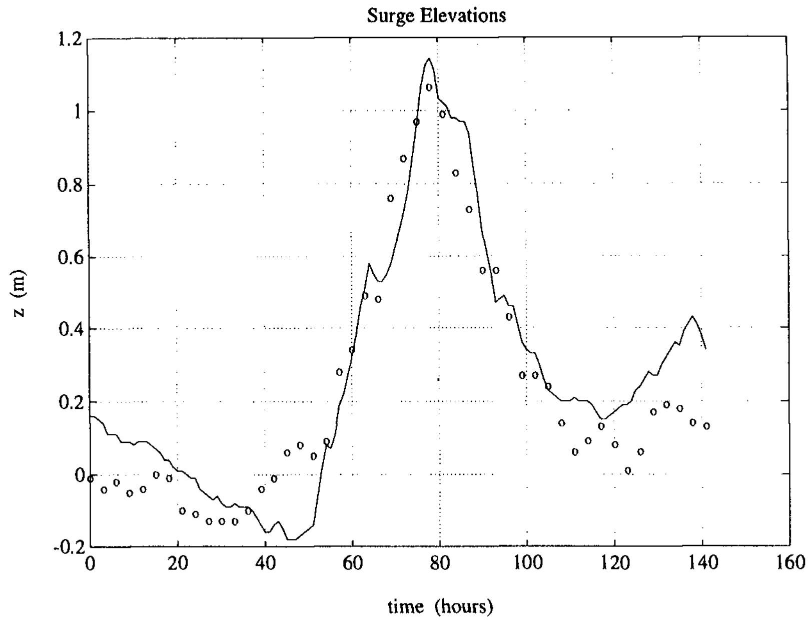


Fig. 3. Comparison of surge hindcast (solid line) and observed (circles) at SON, 21–28 Nov, 1981. Time is counted from 00h of first day of storm period.

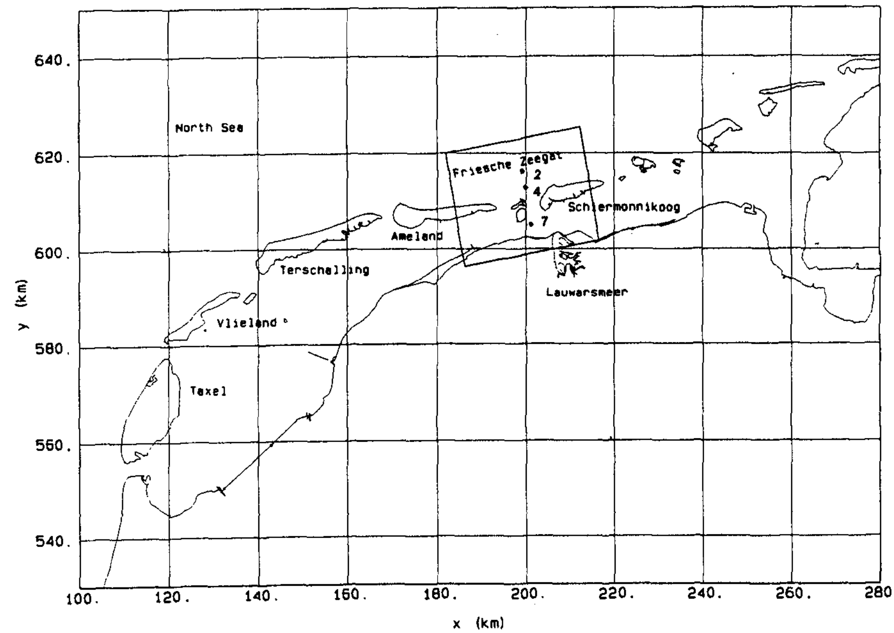


Fig. 4. Friesche Zeegat modelling area (ref. Spaan *et al.* 1996).

Transfer offshore extremes to shore

The transfer of offshore extremes to shore represents a strategic task since it forms the basis for developing the parametric relationships $\widetilde{\mathcal{F}}_2$ between physical parameters which are required to develop appropriate statistical models for the transfer of statistics to shore.

The Friesche Zeegat area in the Dutch demonstrator zone shown in Fig. 4 was used to undertake a number of detailed simulations and sensitivity studies involving different state-of-the-art models. The area is a special focus for ongoing coastal research modelling trials and associated field measurement experiments. The two principal models were HISWA (Holthuijsen *et al.* 1989) a 2nd generation stationary wave model and SWAN (Holthuijsen *et al.* 1993, 1994) another stationary but fully spectral 3rd generation wave model. Additionally the more advanced 3rd generation non-stationary wave model PHIDIAS (van Vledder *et al.* 1994) which is still under development was also used. The models were configured to provide grid cell resolution over various scales down to 100 m. The results (Dunsbergen 1995, Otta 1995, van Vledder 1994, van Endt 1996) show that in complex coastal regions such as Friesche Zeegat it becomes necessary to employ the very latest advances in shallow water wave modelling in order to approach the degree of reality needed to correctly simulate wave transfer processes.

In association with the HYDRA project a special study was performed (Booij *et al.* 1996) to investigate in detail the nearshore wave conditions in the Friesche Zeegat during a suprestorm. The superstorm (Bijl 1995) was an adapted version of the parameterised 1953 storm. The wave simulation was carried out using two models. First the SWAN model was used to compute the wave conditions at the height of the storm when the highest still water levels occurred in the central part of the Friesche Zeegat. The PHIDIAS model was then used to compute the time variation of the wave conditions over a period of 8 hours around the peak of the storm. The results show that the wave field along the Friesche Zeegat shoreline is mainly determined by local winds and by depth limitation on the tidal flats in the Waddensea. The offshore storm wave boundary conditions have little or no effect on the nearshore wave effects. Figs. 5 (a)–(c) show the storm wave spectra computed at the three locations marked on Fig. 4. The results clearly illustrate the form of double-peak spectra which may be associated with shallow water non-linear wave interaction.

Parameterisation of the modelling response

It has been assumed that full scale modelling of the process chain described in section 2 may lead to relatively simple parametric relationships linking $\mathbf{W}_t$, $\mathbf{X}_t$, $\mathbf{Y}_t$ and design variables $\underset{\sim}{D_t}$. The objective is to represent the model responses $\mathcal{F}_1$, $\mathcal{F}_2$ in simplified form $\widetilde{\mathcal{F}}_1$, $\underset{\sim}{\mathcal{F}_2}$ to allow transformation not only of input data but also of statistics.

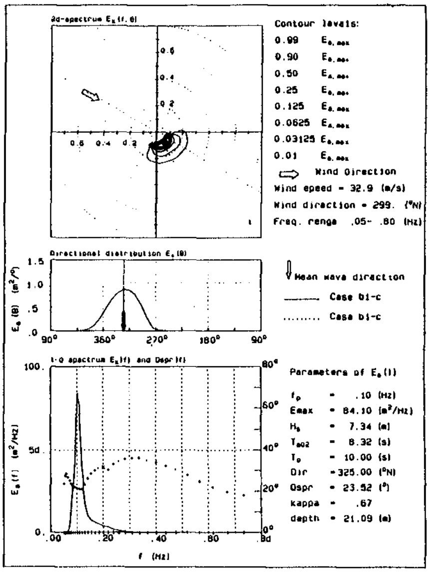
For the $\mathbf{W}_t \rightarrow \mathbf{X}_t$ link a parametrisation scheme has been developed (Cieślikiewicz and Graff 1996) which can effectively relate the NE Atlantic wind and pressure field with the consequential NW European coastal surge and wave climate response. The novel approach involves use of empirical orthogonal functions (EOF) to transform the DNMI based NE Atlantic wind field into principal components targeting the UK and Dutch demonstrator zones and system identification techniques (SI) to develop the wave and surge field response. The scheme which involves linear system simulation techniques such as ARX and ARMAX has been trialed successfully for the Dutch demonstrator zone where 13 years of offshore metocean measurements are available in addition to the hindcast modelled data. Some results showing EOF wind field transformation and subsequent wave climate simulated using the SI technique are presented in Figs. 6 and 7. The scheme provides a potentially powerful tool for fast and efficient simulation of sea state parameters in response to weather field input.

A simple parameterisation scheme for the $\mathbf{X}_t \rightarrow \mathbf{Y}_t$ link specific to the Pettemer Zeewering shoreline was also developed. In this case available wave measurements were used to develop a parametric transformation matrix linking offshore storm waves with their shoreline response. The wave transform relationship needed to develop the multi-regression based matrix was determined using the 1-D version of the HISWA model. The transform matrix was then used to synthesise multivariate hydraulic parameters and associated statistics required to develop the $\mathbf{X}_t \rightarrow \mathbf{Y}_t$ association. Subsequently a family of seventy storms consisting of 22 historical storms and 48 ficticious conditions were used to compute $\mathbf{X}_t \rightarrow \mathbf{Y}_t$ wave transforms in the Friesche Zeegat region (Spaan *et al.* 1996) as a basis for the transfer of hydraulic parameter statistics.

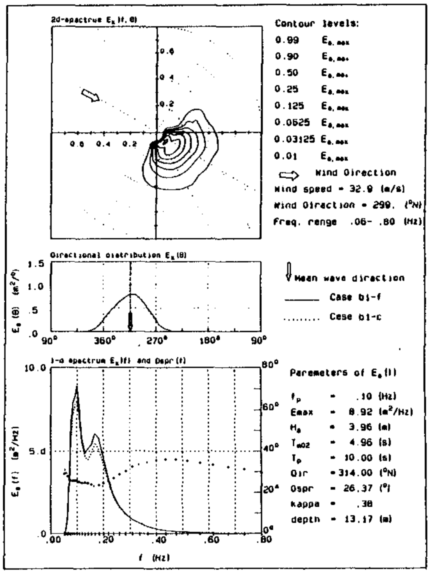
T400 Determining joint statistics of extremes

The project methodology has been already outlined in section 2 and relations between the fields of random variables $\mathbf{W}_t$, $\mathbf{X}_t$, $\mathbf{Y}_t$ and design variable D_t were discussed. The integration of a suitable multivariate extreme value model is dependent on the success of developing simple parametric models $\widetilde{\mathcal{F}}_1$ and $\widetilde{\mathcal{F}}_2$ of low dimension.

(a)



(b)



(c)

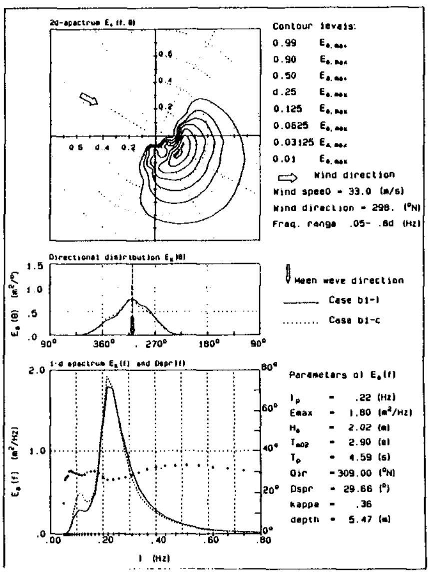


Fig. 5. Wave spectra in Friesche Zeegat computed by SWAN (ref. Booij *et al.* 1996) at locations 2 **(a)**, 4 **(b)** and 7 **(c)**.

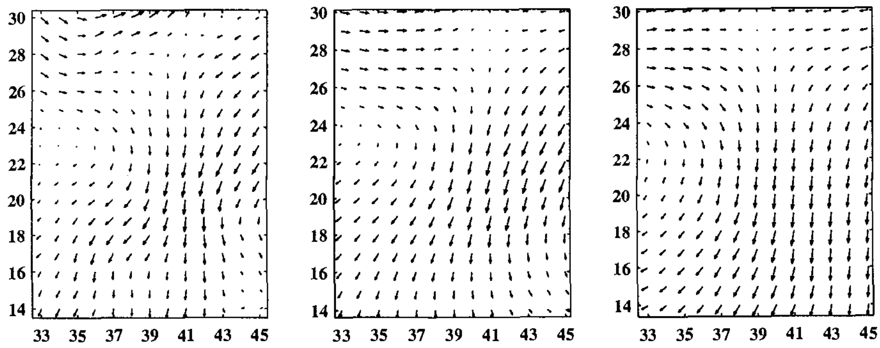


Fig. 6. Comparison between spatial distribution of DNMI wind velocity field at 12h on 16 May, 1988 and wind obtained via EOF analysis; original distribution (to left), and recalculated using first eight principal components (in the middle) and first four (to right).

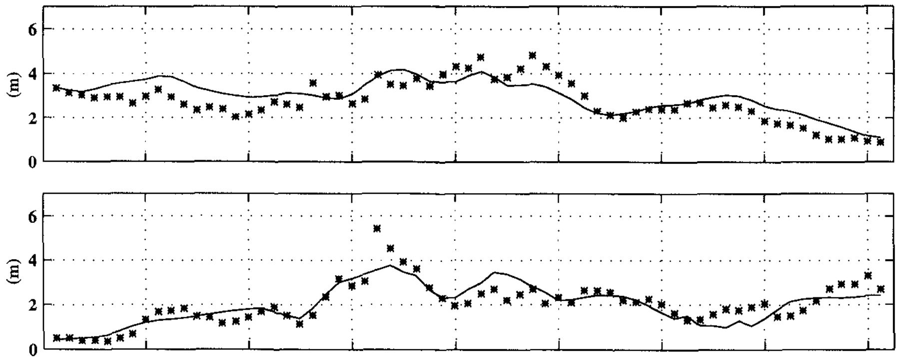


Fig. 7. Comparison between modelled (solid line) and recorded at EUR station (stars) time series of significant wave height for storm periods 15–22 Jan, 1983 (top) and 11–18 Feb, 1989 (bottom).

The hydraulic parameters $Y_{1,t}, Y_{2,t}, \ldots Y_{d,t}$, which compose the d-dimensional random vector $\mathbf{Y}_t$, determine the design variable D_t through $\mathcal{F}_3$

$$\mathbf{Y}_t = [Y_{1,t}, Y_{2,t}, \ldots, Y_{d,t}] \xrightarrow{\mathcal{F}_3} D_t \tag{2}$$

If we assume that the marginal distributions of $Y_{1,t}, Y_{2,t}, \ldots Y_{d,t}$ are known then we can analyse the joint dependent structure of the multivariate data $[Y_{1,t}, Y_{2,t}, \ldots, Y_{d,t}]$ and extrapolate, or create a structure variable D_t through $\mathcal{F}_3(\mathbf{Y}_t)$ and study the univariate structure data. One aim of the project has been to compare the accuracy of joint probability models (analysis of $\mathbf{Y}_t$) to the structure variable approach (analysis of D_t) in estimating the return level for given probabilities of failure for D_t.

Considerable progress has been made in advancing both theoretical and practical aspects of the alternative approaches namely, the structured variable approach favoured by the Dutch research partners de Valk (1995, 1996) and Draisma and de Haan (1995, 1996) and the joint probability method favoured by the UK research partners Ledford and Tawn (1996 a, b) and Bruun and Tawn (1996). Issues examined cover multivariate dependency between the different parameters, temporal behaviour of the joint distributions and spatial dependency.

A practical case study application of the Structure Variable approach was developed and trialed by de Valk (1996) for a seawall dyke structure at Pettemer Zeewering in Holland. Only one failure mechanism was considered namely, wave overtoppiong of the crest of the seawall. Based on the expression for the 2 percent run-up level $z_{2\%}$ from Van der Meer (1993) a reliability function z was defined as the difference between the crest level z_{crest} and $z_{2\%}$; $z = z_{\text{crest}} - z_{2\%}$. If z is positive the overtopping is acceptable, whereas if z is negative , the structure fails. Contours of the reliability function involving nearshore wave height and period for two different still water levels are shown in Fig. 8.

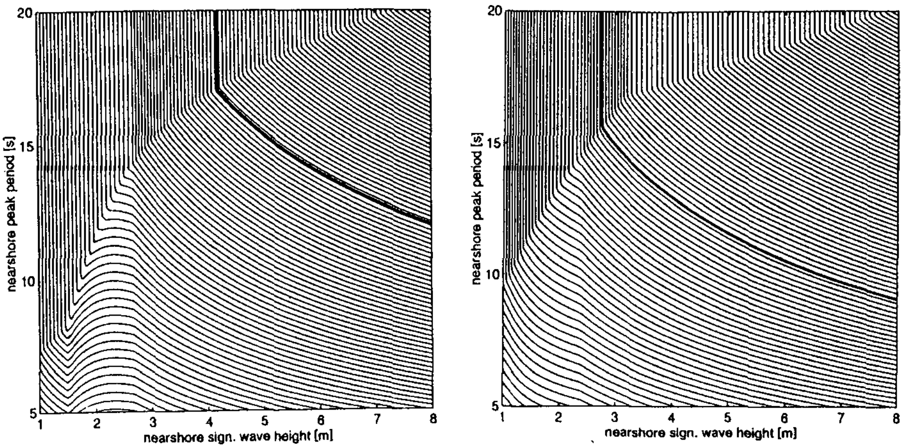


Fig. 8. Contours of run-up reliability function z as function of nearshore significant wave height and nearshore peak wave period for sea level 3.0 m (left) and 5.0 m (right) at Pettemer Zeewering (ref. de Valk 1996).

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