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The wave climate of the Northeast Atlantic over the period 1955–1994: the WASA wave hindcast

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36 pages with 14 figures and 11 tables

Abstract

The European project "Waves and Storms in the North Atlantic" (WASA) has been set up to prove, or to disprove, hypotheses of a worsening storm and wave climate in the Northeast Atlantic and adjacent seas in the present century. A major obstacle for assessing changes in storm and wave conditions are inhomogeneities in the observational records, both in the local observations and in the analysed products, which usually produce an artificial increase of extreme winds and waves. Therefore, changes in the wave climate were assessed with a state-of-the-art wave model using wind analyses. Within the scope of the WASA project, a 40 year reconstruction (1955–1994) of the wave climate in the North Atlantic was completed using the WAM wave model.

The input wind fields were assumed to be reasonably homogeneous with time in the area south of 70 °N and east of 20 °W, and it was expected that the hindcast wave data would reliably describe the space-time evolution of wave conditions in this area. The results of the hindcast experiment are presented in this article. The main conclusion was that the wave climate in most of the Northeast Atlantic and in the North Sea has undergone significant variations on time scales of decades. Part of variability was found to be related to the North Atlantic Oscillation. As a general result we noted an increase of the maximum annual significant wave height over the last 40 years of about 5 to 10 cm/year for large parts of the Northeast Atlantic, north of the North Sea. There was also a slight increase of probabilities of high waves derived from conventional extreme value statistics in northwest approaches to the North Sea. Similar trends of the extreme waves were found in a scenario of future wave climate at a time of doubled CO_2 concentration in the atmosphere.

Das Wellenklima im Nordostatlantik von 1955 bis 1994: Rekonstruktion von Wind und Seegang im Rahmen des WASA-Projektes

Zusammenfassung

Das europäische Projekt WASA ist initiiert worden, um die Hypothese zu prüfen, ob das Sturm- und Wellenklima im Nordatlantik und den europäischen Randmeeren sich in den vergangenen hundert Jahren deutlich verschlechtert habe. Das wesentliche Problem bei der Beschreibung von Änderungen im Sturm- und Wellenklima besteht in den Inhomogenitäten der Beobachtungsdaten, sowohl im Hinblick auf lokale Daten als auch im Hinblick auf analysierte Daten. Diese Inhomogenitäten deuten häufig fälschlich auf Zunahme der extremen Windgeschwindigkeiten und Wellenhöhen hin. Deshalb wurden Änderungen des Wellenklimas mit Hilfe eines Standard-Wellenmodells und Windanalysen untersucht. Im Rahmen des WASA-Projektes wurde das Wellenklima über eine Periode von 40 Jahren (1955–1994) mit dem WAM-Wellenmodell rekonstruiert.

Im Gebiet südlich von 70° N und östlich von 20° W scheinen die Winddaten homogen zu sein, daher erwarten wir, daß die Ergebnisse der numerischen Simulation verläßliche Aussagen über die räumliche und zeitliche Entwicklung des Wellenklimas in jenem Gebiet erlauben. Die Resultate des Modellexperiments sind hier präsentiert. Das wesentliche Ergebnis der Untersuchung ist, daß das Wellenklima im genannten Gebiet auf Zeitskalen von Dekaden signifikanten Änderungen unterworfen ist. Ein Teil der Variabilität ist mit der Nordatlantischen Oszillation verbunden. In großen Gebieten des Nordost-Atlantiks, nördlich der Nordsee, haben die maximalen jährlichen signifikanten Wellenhöhen in den letzten 40 Jahren etwa 5 bis 10 cm/Jahr zugenommen. Dort ist auch eine leichte Zunahme der Wahrscheinlichkeit des Auftretens von hohen Wellen zu verzeichnen. Ähnliche Trends bei den extremen Wellen wurden mit einem Klimaänderungsexperiment unter der Annahme der Verdopplung der atmosphärischen Kohlendioxidkonzentration festgestellt.

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1 Introduction

In recent years there has been a growing concern among many people, especially in coastal areas and in the marine industry, about a climate change over the past several decades. There have been many reports of increased wind speeds, wave heights and storm surges heights, as well as increased storm frequency. Several workshops were organized (e.g. "Climate Trends and Future Offshore Design and Operation criteria" in Reykjavik and Bergen) in which the question of a worsening wave and storm climate was discussed. However, the historical data exhibit increasing accuracy with time, and this trend in data quality limits the usefulness of extrapolating historical time series into the future.

Climate changes for wind and waves over the past several decades have received special attention, and there has been a wide variety of estimates of these changes. Because there are basic physical relationships between air pressure gradients, wind fields and wave fields, the project WASA (Waves and Storms in the North Atlantic), funded by the European Union's Environment Program, was established to investigate the consistency of various historical data sets and the variation of the statistical distribution of marine meteorological parameters. The main aim of the project was the reconstruction of the storm, wave and surge climate of the North Atlantic for past decades and the prediction of the possible future wave climate of this area. This article presents the ocean wave subtask of WASA, in which the numerical wave model WAM was used to produce a 40 year wave hindcast for the North Atlantic Ocean from historical data of surface pressure and wind distribution. In addition, a wave hindcast for a wind climate of a doubled CO_2 ($2xCO_2$) atmosphere was compared with a control run of present CO_2 to evaluate the possible influence of greenhouse gases. To derive changes in extreme wave conditions from the hindcast data, the distribution function of extreme values of significant wave heights (SWH) was calculated for each decade of the hindcast period. The secular shift towards larger and in some regions lower extremes was investigated.

The results of the hindcast experiment presented here focus on significant wave height. The reconstruction of the wave climate in the North Atlantic for last 40 years was achieved by running the WAM model in two nested grids: a coarse grid (1.5^ox1.5^o) covering the whole North Atlantic and a fine grid (0.5^ox0.75^o) covering only the Northeast Atlantic. For running the numerical simulation, two different wind data sets were used: operational analyses of the Fleet Numerical Meteorology and Oceanography Center (FNMOC) for the coarse grid, and wind estimates from the air-pressure analyses prepared routinely by Det Norske Meteorologisk Institutt (DNMI) for the fine grid. The homogeneity of the input wind fields is an important aspect for the assessment of changes in the wave climate obtained from the hindcast data. We considered a data set to be "homogeneous" if it is free of artificial signals due to changing instrumental accuracies, observational practices or analysis routines. These signals do not reflect real changes in the local and remote wind conditions. With a homogeneous wind data set we may expect, within the limitations of the wave models, to receive a detailed space and temporal evolution of wave parameters, such as significant wave height, which may be considered to be a "substitute" reality. Even if the hindcasted substitute reality does not capture all details of the past wave history, it is expected that the low-frequency variations of wave statistics, including interdecadal variability and trends, are reliably reproduced. Indeed, these assumptions were found to be valid in the present analysis, when multi-year time series of in-situ observed SWH statistics were compared with hindcast wave heights in areas and time intervals with approximately homogeneous wind field analyses.

Inhomogeneities, i.e. changing non-physical factors influencing the weather analyses, can be either "creeping" or "sudden" (Karl et al., 1993; Jones, 1995). Creeping inhomogeneities are present in operational analyses, which are prepared with operational weather forecast schemes subjected to ongoing improvements of the numerical weather prediction models. Another source of creeping inhomogeneities are ongoing modifications of the observational network, i.e. changes in the density of stations or the replacement of instruments. For instance, the availability of satellite imagery in the 60s may have persuaded human weather forecasters to describe a low pressure system over the Atlantic as more intense than if he had only ship observations as in the 50s. In marine weather statistics, creeping inhomogeneities are brought into the analysis procedure by gradually changing ship routes, increasing ship speeds and instrument heights, and other aspects.

Sudden inhomogeneities are introduced by abrupt, often documented, changes in the analysis scheme. These may be the change from manual to automatic analysis techniques; the rectification of outright errors in the analysis procedure; the creation or the withdrawal of an observational platform in a data sparse area (such as ocean weather stations). If sudden changes are not already known from the documentation, they may often be identified by screening the time series for jumps in the moments of the time series calculated for moving windows.

In our case, we could not completely assess the degree of homogeneity in the driving wind fields. We objectively identified sudden inhomogeneities, but for creeping inhomogeneities we had to refer to plausibility arguments. The comparison with observed records is in many cases inconclusive as these data have already entered the analysis, so that they do not offer independent information about the success of the analysis for providing useful information in data void areas and time intervals. Furthermore, local observations, which in many cases are not instrumental observations but are based on subjective assessments (wind force estimated from wave heights), may already suffer from the creeping inhomogeneities, which are then inherited by the 2-d mapped analysis.

We argue in section 3 that the FNMOC winds are homogeneous enough for producing boundary conditions for our 40 year hindcast. This view is supported by the relative uniformity of the monthly mean statistics in this data set; while over the whole 40 years of the hindcast the frequency of strong wind events has undergone changes which are not supported by the DNMI analyses and analyses from pressure gradients, the hindcast created with these analysis results in wave statistics that compare favourably with in-situ wave data collected in the Bay of Biscay since mid 80s. We therefore consider the hindcasted wave heights produced with the FNMOC winds in the Bay of Biscay since the 80s as a plausible reconstruction of the wave history for that area and time.
The degree to which the DNMI analyses were contaminated by creeping inhomogeneities was examined with the help of maps of the ratio of storm-related standard deviations of air pressure calculated for consecutive 10 year intervals. It was found that this standard deviation has undergone a steady increase in data from sparse areas far from coasts, while it remained almost constant in an area surrounding the British Isles and covering the North Sea (see Section 3.2). Based on this observation, we concluded that the DNMI analyses suffer from an artificial worsening of the storm climate in data sparse areas, and that we could expect minor inhomogeneities in the area covering the North Sea and the Atlantic adjacent to the British Isles, approximately between 70°N and 40°N and east of 20°W.

For quality control of the production runs, model output was compared with weather ship measurements and other observational data sets, i.e. wave buoy records. Furthermore, the data obtained from the numerical simulation were compared with data retrieved from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) ship routing charts (Bouws et al., 1996). In general there was a good agreement between model results and observations. But there were partly, sometimes severe, overestimations by the model, especially at high wind speeds in shallow water or for islands (e.g. Shetland and Faroe Islands) not accurately resolved by the grid. As a conclusion from this comparison, we believe that the real trends of wave statistics are reliably reconstructed by the hindcast.

To examine the hypothesis of worsening of the wave climate in the North Atlantic published by many authors in last years (i.e. Carter and Draper, 1988; Bacon and Carter, 1991; Hogben, 1994), time series from different locations were extracted from the model data and analysed. The trends in average wave heights derived from model data were much smaller than those given in recent publications. Annual mean SWH in the Northeast Atlantic increased since 1955 at a rate of 0.25-0.75 cm/year, which corresponds to about 0.2%. A continuously upward trend in average wave heights on the order of 1% or 2% per annum reported in recent years cannot be confirmed using WASA wave model output. Small changes in average SWH could be seen as a result of small changes in mean wind speeds. The computed trends in mean wind speed in the Northeast Atlantic are almost negligible. Besides mean wave conditions, extreme conditions were also analysed. The annual maxima, along with 99th and 90th percentiles of SWH and wind speed were computed for each grid point, and the two-dimensional distribution of changes per year were computed. The maxima, and 99th and 90th percentiles of significant wave heights have steadily increased in the Northeast Atlantic, while in the near-coastal areas of Northwest Europe the storm climate has not systematically worsened. The upper estimates for this increase are 7-10 cm/year for the maxima, 3-4 cm/year for the 99th percentile and 2-3 cm/year for the 90th percentile of annual wave height distribution.

Another objective of the WASA project described in this paper is extreme value analysis (section 7). The extreme wave analysis was performed in four slices of ten year each: 1955-64, 1965-74, 1975-84 and 1985-94. The values of SWH with a return period of 100 years obtained in each decade showed a clear spatial pattern. Two distinct regions can be identified: one between Iceland and Scotland with a tendency towards higher extreme waves, and another southwest of Ireland with a slight decrease. These trends took place during the four decades without interruption or large oscillations.

Extreme value analysis was also applied to a scenario of future surge and wave climates in a 2xCO_2 atmosphere, also as part of the WASA project. The anomalies found with the climate change scenario showed the same pattern as the trends of the extreme waves for the 40 year hindcast. An area south of Iceland exhibits a tendency towards higher extreme waves, while in another area, southwest of Ireland, extreme waves decrease.

2 Model set-up

Because of the limited amount of reliable homogeneous wave data from the North Atlantic, a 40 year reconstruction, 1955 to 1994, of wave conditions was prepared by running the WAM (cycle four) wave model. The WAM model is a third generation wave model which solves, in contrast to the first and second generation models, the wave transport equation explicitly without any presumption on the shape of the wave spectrum (for a detailed description see WAMDI, 1988; Günther et al., 1992 and Komen et al., 1994). In the WASA project the wave model was applied to two nested grids:

- A coarse grid in the North Atlantic: resolution 1.5°x 1.5° latitude x longitude, covering the whole North Atlantic from 80°N to 9.5°N and from 78°W to 48°E with 2094 active grid points.

- A nested fine grid in the Northeast Atlantic: resolution 0.5° x 0.75° latitude x longitude covering the Northeast Atlantic: 77°N to 38°N, 30°W to 45°E with 4105 active grid points (Fig.1).

The deep-water version which neglects bottom effects was applied on the coarse North Atlantic grid and the shallow water version which includes bottom effects was run on the fine grid in the Northeast Atlantic. Both models were run with an angular resolution of 15° and 25 logarithmically spaced frequencies from 0.042 to 0.411Hz.

The standard WAM model was modified to handle variable sea ice cover updated once per simulation month. The sea ice data was provided by the Norwegian Meterological Office (DNMI). The output routine of the model was extended to store the proposed output most effectively. To follow the aims of the

WASA project and to facilitate possible future analysis, the following model data were stored for both grids at all sea points every three hours for the entire 40 year hindcast period:

- 23 integrated spectral parameters (cf. Appendix A)
- two-dimensional wave spectra in the full frequency-angular resolution

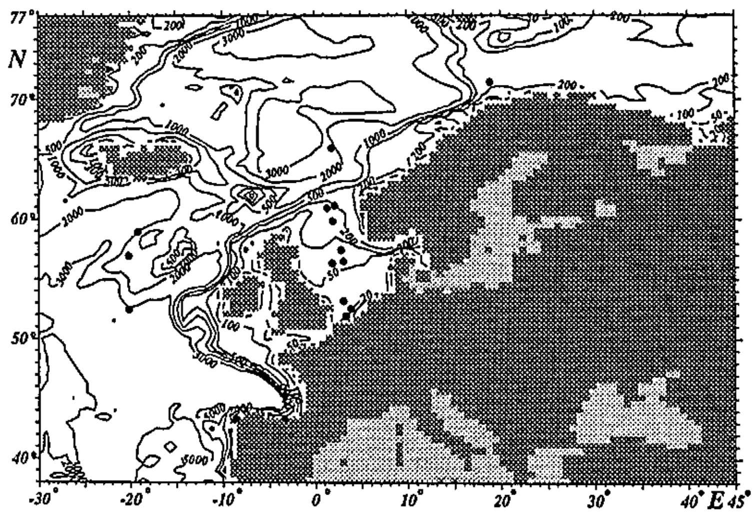

Figure 1: WASA fine grid topography. Dots indicate measurement sites

A number of consistency checks were carried out for the quality control of the production runs. In addition, model results were compared with measurements (see section 4) at several sites. These stations were located in the fine grid are marked in Fig. 1 and are listed in Appendix B.

3 Hindcast wind fields

3.1 FNMOC winds

The operational wind analysis done by FNMOC was used for the coarse grid resolution model. The FNMOC data cover a 63x63 cartesian grid drawn over a polar stereographic projection centered on the North Pole and were taken four times daily since 1946.

Unfortunately, the FNMOC winds suffer from a few gaps, i.e. all of 1994 is missing. These gaps were filled by temporal interpolation if the gaps were one day or less. The European Centre for Medium-Range Weather Forecasts (ECMWF) analysis was used to fill longer gaps.
The wind fields were interpolated on the WASA 1.5^ox1.5^o coarse grid using a polynomial method. An alternative bilinear interpolation was also tested. The results of the wave model forced by the different wind fields were compared with buoy data from the open ocean and close to the coast. It was found that the wave peaks were better fitted by the polynomial interpolation method. For interpolation over time, a linear method (standard WAM cycle 4) was applied. An example of FNMOC wind field is shown in Fig. 2.

Two inconsistencies in the wind data set were found:

- Surface winds for the period 1954 to 1977 were geostrophically derived, while afterwards they were produced using a Planetary Boundary Layer Model (PBLM). The overlapping period of eight months, April 1977 to December 1977, was used for consistency tests. It was found, that the wind directions of both data sets, PBLM winds and geostrophical winds, agree very well, while the geostrophic wind speeds were found to be systematically lower than the PBLM wind speeds. The conclusion of this study was that the geostrophic winds were given at 10m (the reference level required by the WAM model) and the PBLM winds at 19.5m. This inconsistency was removed by applying a standard logarithmic wind speed profile assuming neutral stratification.
- Until 1971 the pressure maps were prepared by manual analysis, while from 1972 to today numerical models are used. This change was associated with an abrupt change of about 1 ms^{-1} in average wind speed.

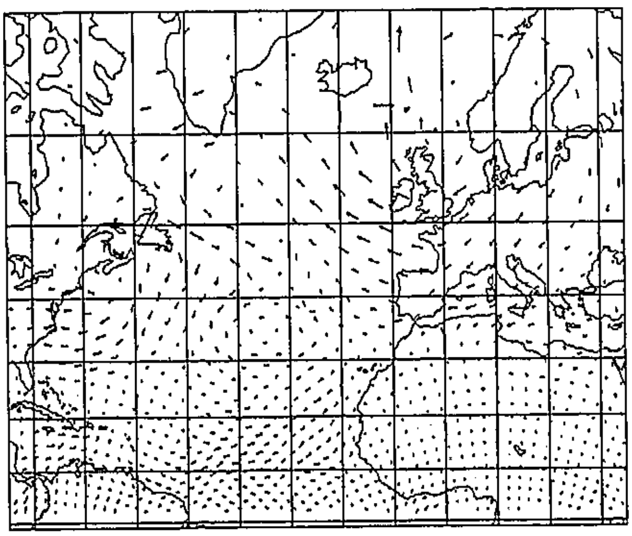

Figure 2: An example of a FNMOC wind field.

Comparisons between PBLM and ECMWF winds showed good agreement in direction and modulus for values of up to 15 ms^{-1}. Higher values were found to be lower in the ECMWF winds. For the comparison between model wind data and observation the Comprehensive Ocean-Atmosphere Data Set (COADS) was used. Time series were extracted from the model data and compared with mean values of the observations from ships in the area (square box of $1^o x 1^o$). All extracted points were located in areas with high density of observations and in general there was a good agreement between both data sets.

Comparison (Fig. 3) between model coarse grid data and measurements at Ekofisk (position: 56.5°N, 3.2°E) from 1980 to 1994 also showed a good agreement in annual mean wind speeds and annual 90th percentiles (up to values of around 15m/s). The annual 99th percentiles of the model wind were slightly overestimated. Mean errors in wind speed at Ekofisk vary between 1.6 m/s and 2.9 m/s (see Fig. 3). Comparison with wind observations at Gulfaks (61.2°N, 2.3°E) over the same period gave similar results.

From wind measurements done on board the Ocean Weather Ships (OWS), time series of wind speeds were extracted and compared with wind speeds used in the model coarse grid run. For the comparison between input and OWS data a German data archive at the Seewetteramt (SWA) and DNMI data were used. In the following, some typical examples of these comparisons are given:

- OWS Mike: 1955 to 1994:
  The comparison between 99th and 90th percentiles of the annual model input wind speeds and observed wind speeds showed mixed results (Fig. 4). In the period 1955 to 1970 input wind speeds seem to be underestimated. In this period the mean wind speeds error vary between 2.6 and 3.7 ms^{-1} (see Fig. 4). The agreement is better after 1970, but there are still periods (e.g. 1982-85, 1990-93) with rather poor agreement between model and observations.

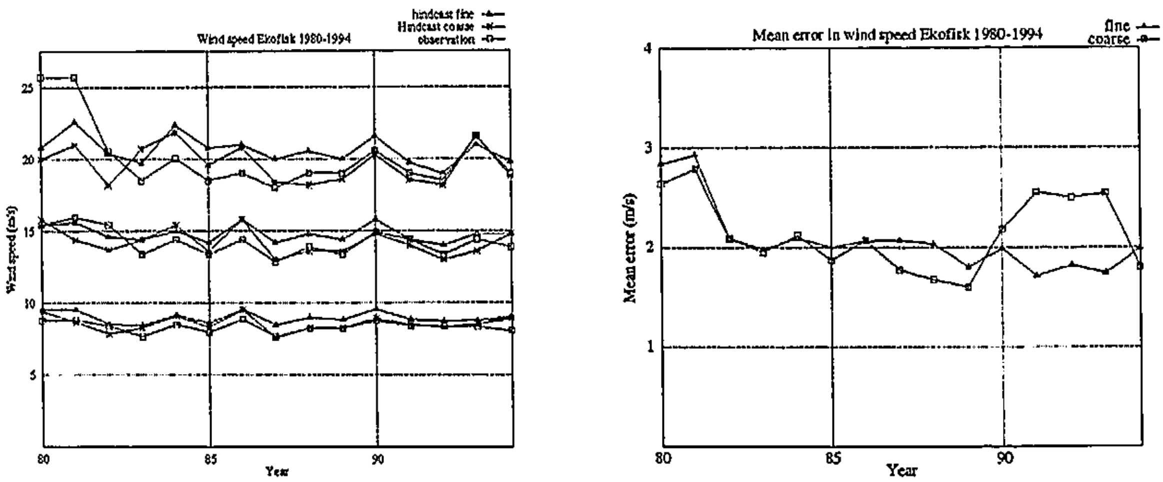

Figure 3:
Comparison between model input wind (coarse and fine grid) and observation at Ekofisk for 99th and 90th percentiles, and mean (from top to bottom), right side: mean error in wind speed for both coarse and fine grid hindcast.

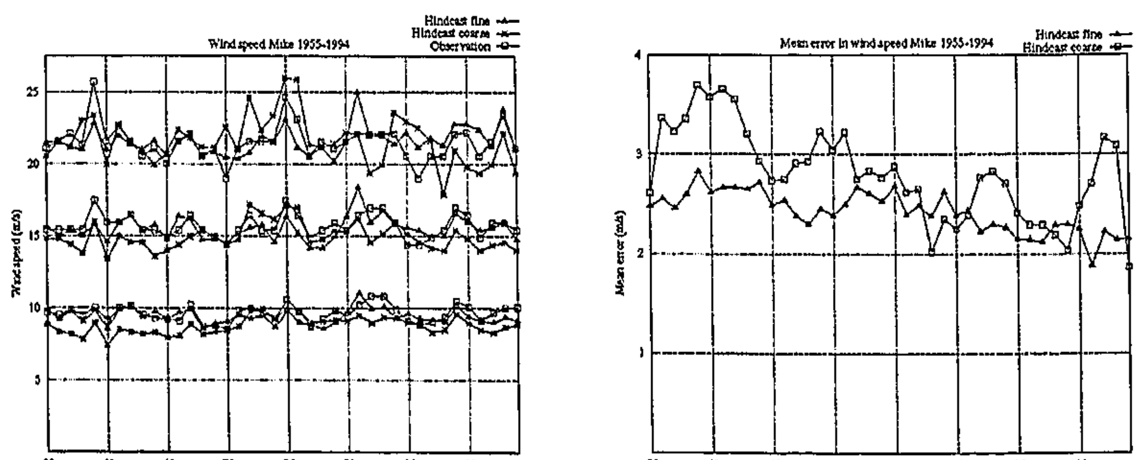

Figure 4:
Comparison between model wind speeds (coarse and fine grid) and observations for the annual 99th, 90th percentiles and annual mean (from top to bottom); right side: mean error in wind speed for both coarse and fine grid hindcast.

Agreement between model and observed wind speeds vary at other locations too. Fig. 5 shows time series of the monthly 90th percentiles of both model winds and observations at OWS India and OWS Lima:

- OWS India: 1955-1971:
  Monthly 90th percentiles of the model wind speeds accorded well with observations from OWS's in the period 1962-71. Before this there are partly underestimations by the model winds (see Fig. 5). The data from OWS Juliett showed similar results. The monthly mean wind speeds showed good agreement at both locations.

- OWS Lima: 1975-1990:
  There was a good correlation between coarse grid model winds and observations in the period for which observational records are available (Fig. 5)

However, it should be noted that the comparisons between the model wind fields and observations are often problematic due to the assimilation of observational data into the analysis. The documentation of the FNMOC wind fields is poor, so we do not know whether or not observations entered the FNMOC data. We suppose that the assimilation of the observed data took place from the beginning of the 70s. It would explain that the agreement between input winds and observations is, in general, better after 1970.

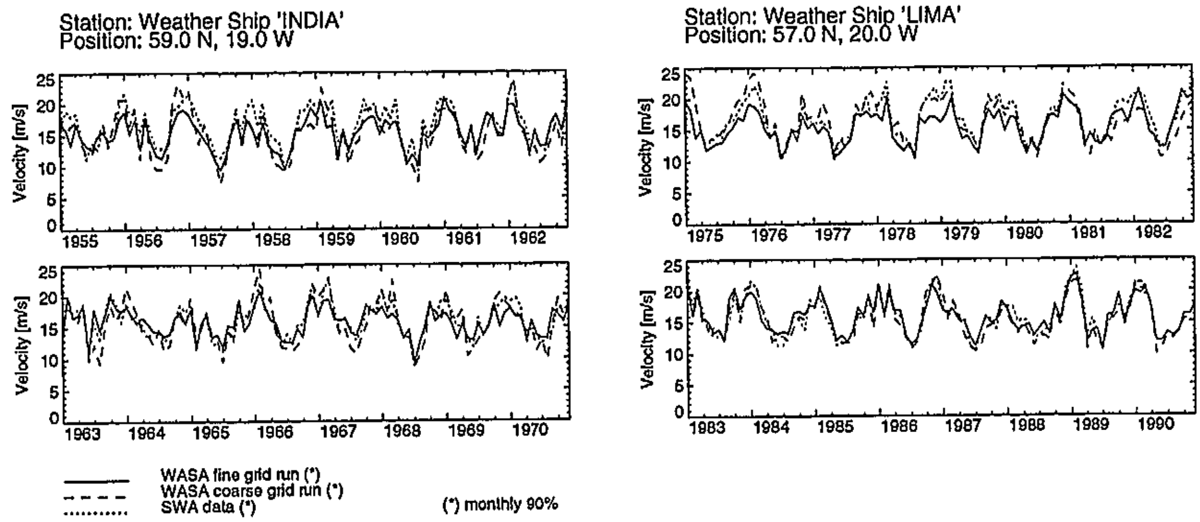

Figure 5:
Comparison between coarse and fine grid model wind speeds and observations (monthly 90%); left side: at OWS India 1955-71, right side: at OWS Lima 1975-90.

3.2 DNMI winds

The fine resolution simulation was forced with wind data from DNMI (Reistad and Iden, 1995). These winds were calculated from mean sea level air pressure fields. The data were taken at 6-hour intervals on a rectangular grid with a stereographic map projection with a grid distance of 75km at 60°N. The data were interpolated to the WASA fine grid. The DNMI wind data do not cover the most southern part of the WASA fine grid model area, so the DNMI wind data were supplemented by the wind data from FNMOC. At the boundaries between the DNMI grid and the FNMOC grid the wind fields were spatial smoothed to avoid discontinuities.

For the years 1955-1981 the DNMI pressure fields were obtained by numerical reanalysis using available pressure observations from ships and land stations. For the period 1955-1979 the first guess fields in the pressure analyses were pressure fields digitized from manually analysed weather maps, and for the years 1980-1981 the first guess fields were taken from operational pressure analysis made for weather prediction models. For the years 1982-1995 the pressure data were taken directly from operational analyses in numerical weather prediction models without any reanalysis. From January 1982 to May

1987 the pressure data were obtained from the global model at ECMWF, and from June 1987 to December 1995 from DNMI's regional weather prediction model.

The winds at 10m above sea surface are based on calculation from geostrophic wind from the pressure data and a two-layer boundary layer model. The geostrophic wind is used as the wind at the top of the boundary layer. The two-layer model is based on the formulation by Brown (1978). The surface roughness is calculated from a slightly modified version of the formula proposed by Charnock for surface roughness over the sea (Charnock, 1955). The reduction and turning of the geostrophic wind due to eddy viscosity is calculated assuming neutral stratification of the lower layer.

The DNMI data were considered to be more accurate than the FNMOC wind fields, but the data were not homogenous for the whole 40 year period. The most severe inhomogeneity was in 1982, coinciding with the first use of pressure fields from numerical weather prediction systems. There were also inhomogeneities in the pressure and wind data due to changing numbers of observations used in the analyses through the years 1955-1981, and after 1982 there were changes and improvements of the numerical weather prediction systems that affect the pressure analyses.

The degree of contamination of the DNMI analyses by creeping inhomogeneities was examined with the help of maps of the ratio of storm-related standard deviations of air pressure calculated for consecutive 10 year intervals. It was found that this standard deviation has undergone a steady increase in data-sparse areas far from the coasts, while it remained almost constant in the areas surrounding the British Isles and covering the North Sea (Fig. 6). Based on this observation, we concluded that the DNMI analyses suffered from an artificial worsening of the storm climate in data-sparse areas, and that we may expect minor inhomogeneities in the area covering the North Sea and the Atlantic adjacent to the British Isles, approximately between 70°N and 40°N and east of 20°W.

Comparison between fine grid model winds and observations at Ekofisk from 1980 to 1994 (Fig. 3) showed a good agreement in annual mean and 90th percentiles of the wind speed. The agreement between 99th percentiles of model and observations is worse, especially in the period 1980-81. However, observed value show much uncertainty in this time. The mean error in wind speed varied between 1.7ms^{-1} and 2.9 ms^{-1} (see Fig. 3). The analysis of the wind speed at Gulfaks showed similar results but the agreement for the 99th percentiles was better.

Comparisons between wind speed records of different OWS's and DNMI winds also showed that, generally, model and observed winds agreed well. Fig. 4 shows time series of the annual wind speed at OWS Mike as well as the mean error between model and observation.

Also locations in the central North Atlantic, such as OWS India, OWS Juliett or OWS Lima, showed generally good agreement between model and observed estimates. There were periods with worse agreement and periods when hindcast wind speeds agreed very well with observed wind speeds. Fig. 5 shows examples of time series with monthly 90th percentiles of wind speed records of the OWS's Lima and India and corresponding DNMI winds.

- India 1955-1970: The 90th percentiles showed that the model winds were underestimated in the period 1955-1960 but there was good agreement between input and observed winds after 1960. The behaviour of the time series of monthly mean values was similar.

- Lima 1975-1990: The 90th percentiles were generally in good agreement with the observations. After 1983 the agreement was excellent. We don't know whether or not this was due to an improvement in the analysis method . The agreement between monthly mean wind speeds was also good.

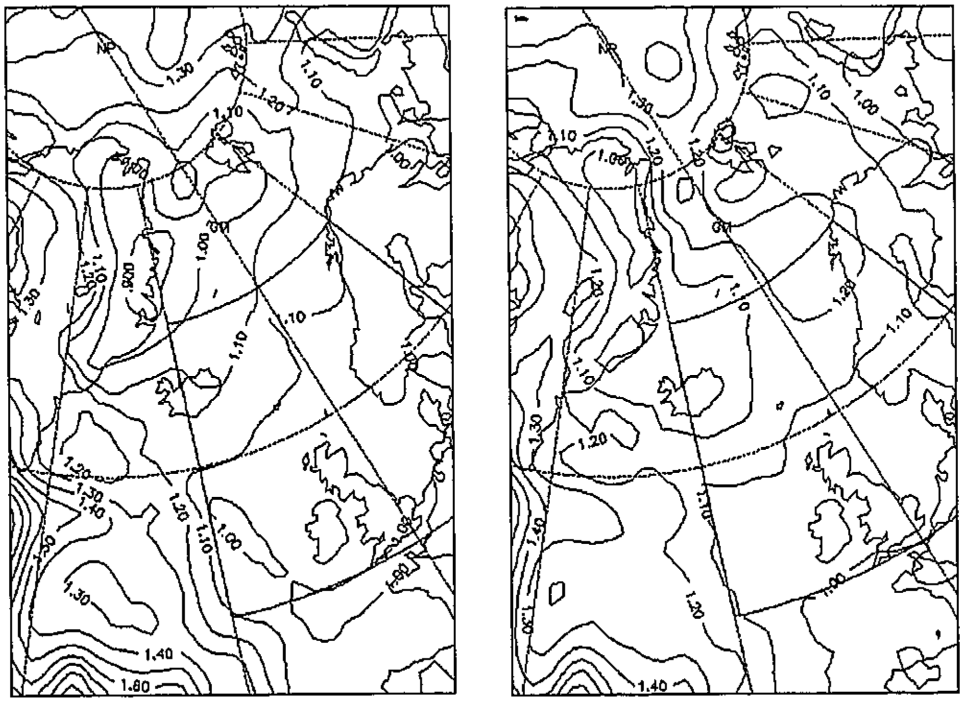

Figure 6:
Ratio of synoptic scale standard deviation of air pressure variations in winter (DJF) as derived from DNMI analysis for 10-year intervals, left side: decade 1984-93 vs. decade 1955-63; right side: decade 1984-93 vs. decade 1964-73. The area south of 70°N and east of 20°W is marked (courtesy: S. Kharin).

In general the model winds and the observations at various sites were in quite good agreement. This holds for coarse (FNMOC) and fine (DNMI) winds and for the comparisons of the mean wind speeds and the checked percentiles. Only the mean errors indicated a small advantage in the quality of DNMI winds over some periods. It has to be taken into account that the comparison between model winds and observation is inconclusive if the observed winds have entered the analysis. In case of the FNMOC wind fields we do not know whether observations were assimilated. But in case of the DNMI winds the wind observations were not used to generate the wind fields. The driving wind fields were computed from the pressure field. Though the pressure observations were used in the analysis and they had some limited influence on the computed wind, the wind measurements and model winds are widely independent.

The most important aspect of the reliability of computed trends in wave conditions in the North Atlantic is the homogeneity of the wind fields used in the wave hindcast. The analyses of both FNMOC and DNMI wind fields showed that the DNMI winds seemed to be homogeneous in most parts of the fine grid area, approximately between 70°N and 40°N and east of 20°W. The ratio of high-pass filtered standard deviations of air-pressure variations in winter in the decade 1984-93 and in the decade 1964-73 showed small variability in this area. In contrast, the variability increased greatly after the 1960's in areas where few or no in-situ observations were available (WASA, 1995). We concluded that the high quality and homogeneity of the DNMI wind fields in the area mentioned above allowed us to make reliable predictions about the development of wave conditions in this area over the past 40 years. However, the possible inhomogeneity of the wind fields in areas near the boundary of the fine grid (west of 20°W, north of 70°N and south of 40°N) indicated that the trends obtained there had to be handled with great care.

4 Model output - waves

The wave parameters obtained from the numerical simulations were compared to the observational data and to the data retrieved from the KNMI ship routing charts. Two-dimensional distribution of the wind and wave parameters were also computed. Because the WAM model is a state-of-the-art wave model which was tested many times for different wind conditions, we do not discuss the quality of the model. The comparison between model and observations shown here is intended to give a first impression about the agreement between simulated and observed data. Even if the simulated wave conditions did not capture all details of the reality, it is expected that the variability and trends of the wave climate are reliably reproduced.

The coarse grid wave model forced by the FNMOC winds was checked for a number of storms on the coast of Spain and the Canary Islands, where buoy measurements were available in deep water. Fig. 7 shows a typical comparison of computed and measured significant wave heights (SWH) for storm periods in February 1982 and 1992 at a site close to Bilbao in the Bay of Biscay. In general, the agreement between model and measurement is fair. This indicates that the coarse grid wave computations provide realistic boundary values for the fine grid.

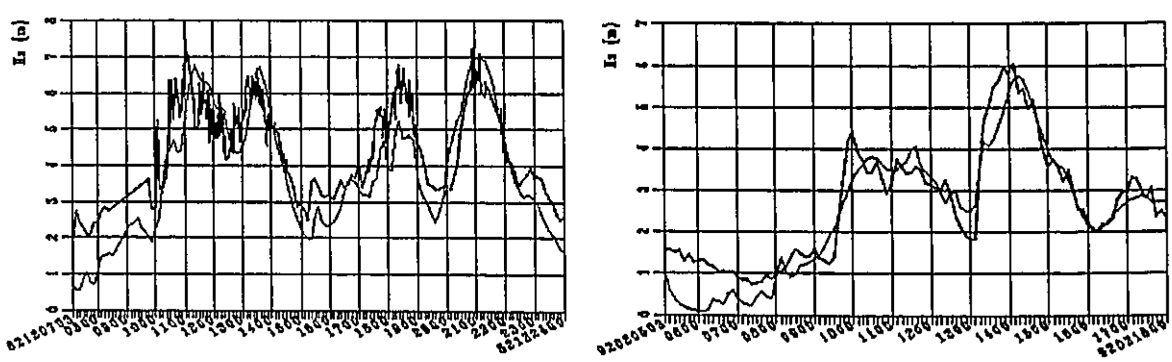

Figure 7:
Hindcast of SWH for the location of the buoy "Bilbao" (43.40°N, 3.14°W), left side: two weeks in February 1982, right side: two weeks in Feb 1992. The heavy line represents measurements,the light line represents hindcast using the FNMOC wind analyses.

A number of storms hindcasted with the fine resolution model were also compared to observational records. The agreement between model data and observation was fair (Fig. 8). Statistics of year-to-year variation were also computed and compared to those of observations. Some of the statistics for the Northern North Sea and for the Northeast Atlantic show good correlation between model and observation, while others show severe overestimations by the model (see Fig. 9). This may be partly due to the tuning of the WAM model to the ECMWF-wind fields, which are usually lower than the wind fields used in this study. Other reasons for the overestimation were insufficient resolution of the grid to show sheltering from islands (e.g. the Shetland and Faroe Islands are not resolved) and some model problems with wave dissipation in the shallower southern parts of the North Sea. Fig. 9 shows the comparisons of the monthly maximum SWH, the monthly 90th percentile and the monthly mean SWH at Statfjord for two different five year periods. The systematic difference (bias) and the standard deviation of data set (std) is shown in Tab. I.

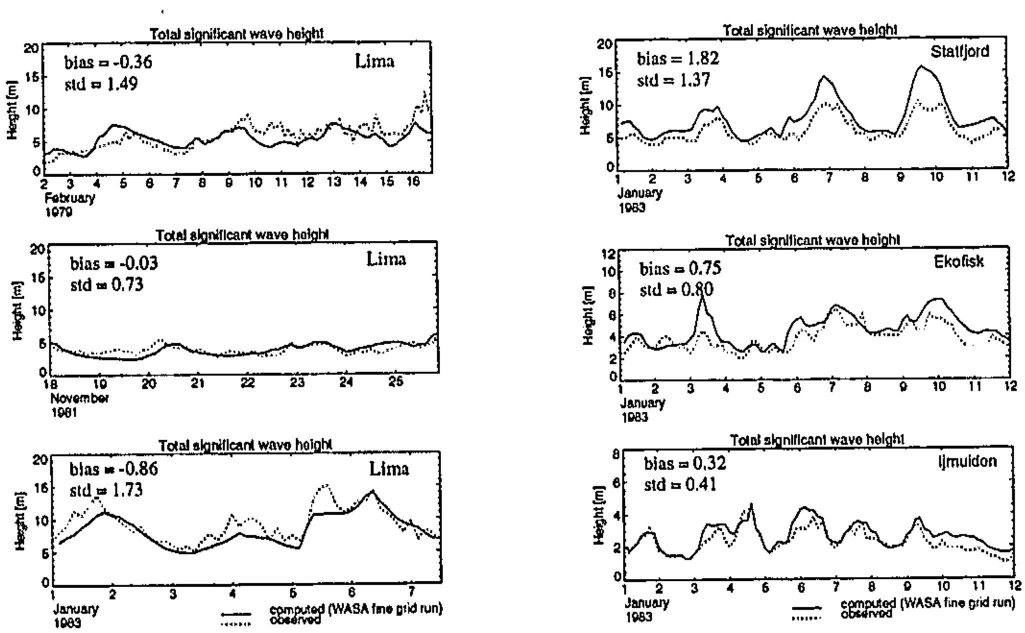

Figure 8:
Comparison between hindcast (fine grid) and observation; left side: for three selected periods at OWS Lima, right side: for 12 days in Jan 1983 at three selected points in the North Sea (std means standard deviation of data set).

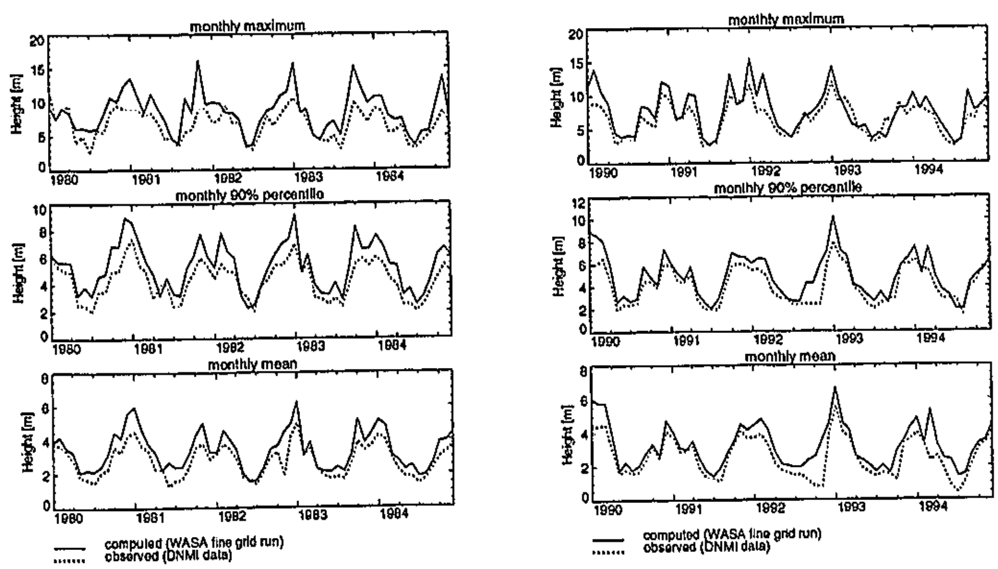

Figure 9:
Multi-year statistic for SWH at Statfjord, left side: period 1980-84; right side: period 1990-94.

Table I: Bias and standard deviation of simulated and observed SWH in Fig. 9

	Period 1980-84			Period 1990-94		
	max	90%	mean	max	90%	mean
bias	1.81	1.02	0.61	1.11	0.83	0.66
std	1.80	0.67	0.45	1.50	0.79	0.60

Also within the framework of WASA, wave heights were retrieved from a set of wave charts produced by KNMI Ship Routing Office during its existence between 1960 and 1988 . These wave charts were produced every 12 hours. They show contours of significant wave height with steps of 1 meter; wave heights less than 2 meters were neglected. For data retrieval, the maximum and minimum significant wave height within each of three selected areas were taken (Bouws et al., 1996). The results based on maximum SWH for one of the selected areas: west of Ireland (50°N-55°N, 20°W-10°W) over the period 1961-1987 are presented in Fig. 10. Positive trends in yearly maxima, 99th, 90th and 50th percentiles of significant wave height were found. Yearly averages (not shown in the figure) also increased in this period.

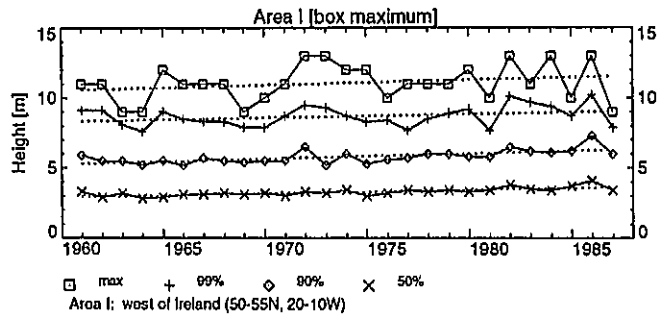

Figure 10:
Time series of maximum, 99th, 90th and 50th percentiles (from top to bottom) of the annual SWH (box maximum) retrieved for the area west of Ireland from ship routing charts

The regression coefficients obtained from a linear regression representing the yearly change of the wave height for the given exceedance levels are listed in Tab. II. The trends seem to be persistent during the whole period. It should be noted that the procedures for making wave charts at the KNMI Ship Routing Office hardly changed during this whole period. The increase during the period 1970-1982 was found to be about 15%, compared to 30% found by Neu (1984).

Table II: Statistics of SWH west of Ireland based on ship routing charts (box maximum) over the period 1961-1987.

	maximum	99%	90%	50%
average [m]	11.07	8.69	5.80	3.28
change/year [cm]	3.8	2.7	3.8	3.0
st.deviation [m] *	1.29	0.70	0.37	0.19

(*) standard deviation due to linear regression

Tab. III shows statistics from the WASA data in the area west of Ireland over the same period and over the entire simulation period 1955-94. The computed averages for the years 1961-87 were generally greater for all exceedance levels. The trends found for the yearly maxima, 99th, 90th and 50th percentiles of SWH were positive as well. Except the yearly maxima, where WASA data resulted in the greater trend (5.48 cm/year compared to 3.8 cm/year obtained from wave charts), trends computed for 99th, 90th and 50th percentiles of SWH were smaller. If we look at the changes per annum over the last 40 years, only maxima of SWH increased about 2.2 cm/year, while the 99th and 90th percentiles of SWH decreased during that time by about 1.5 and 0.4 cm/year respectively (Tab. III).

Table III: Statistics of SWH west of Ireland based on WASA fine grid data (box max), period 1961-1987 and whole simulation period 1955-1994

	Period 1961 - 1987				Period 1955 - 1994			
	max	99%	90%	50%	max	99%	90%	50%
average [m]	17.42	13.04	8.43	4.50	17.33	12.89	8.26	4.37
change/year [cm]	5.48	1.01	0.54	1.01	2.18	-1.51	-0.38	0.05
st.deviation [m] *	2.00	1.00	0.65	0.27	2.02	1.01	0.62	0.29

The differences between average wave heights from ship routing charts and from the hindcast were probably caused by the different methods of estimating wave height. Ship routing charts were compiled with the input of voluntary ship observations. The ships tended to avoid stormy weather conditions and their reports were therefore biased low.

The statistical analysis of the WASA model data made for two selected areas is shown in Fig. 11. The areas (the same areas selected for the data retrieval from wave charts) were defined as follows: area I: 50°-55°N, 20-10°W (west of Ireland), area III: 60°-65°N, 10°-0°W (north of Scotland). The wave maxima in both areas increased; this increase was more significant north of Scotland (about 8.7 cm/year) than that west of Ireland (about 2.2 cm/year).

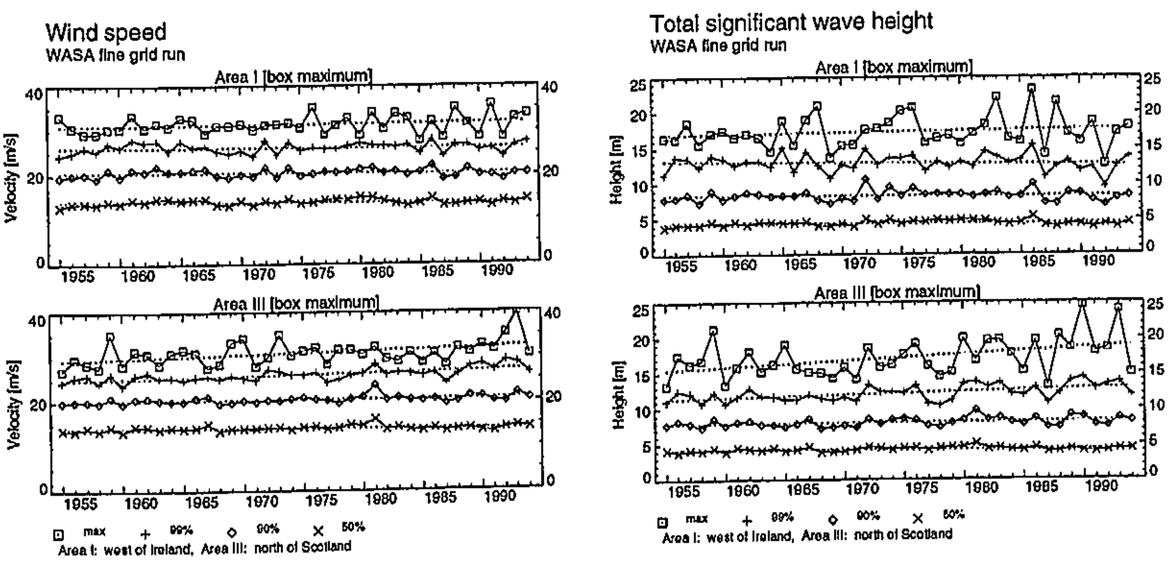

Figure 11:
Time series of maximum, 99th, 90th and 50th percentiles (from top to bottom) of annual wind speed and significant wave height computed for two selected areas (based on box maximum).

Other representatives for the aspect of possible changes in the wave climate are 99th or 90th percentiles of SWH. The regression coefficients obtained for these percentiles were much smaller than those for wave maxima (see Tab. IV). The changes in SWH corresponded very well to changes in wind speed in the chosen areas.

Table IV: Regression coefficients for maximum, 99%, 90% and 50% of SWH and wind speed (box maximum) for two selected areas

Percentile	Change per annum of SWH [cm]		Change per annum of wind speed [cm/s]	
	Area I	Area III	Area I	Area III
max	2.18	8.73	2.46	7.78
99	-1.51	4.03	0.31	5.94
90	-0.38	1.00	-0.10	1.34
50	0.05	0.04	-0.10	-0.31

Spatial distributions of the rate of changes per annum for wind speed and total significant wave height computed from the model data over the whole simulation period of 40 years for the maxima, and the 99th and 90th percentiles are given in section 7.

5 Statistics of significant wave height and wind speed at selected points

At selected locations, time series of significant wave height and wind speed were extracted from the model data. Fig. shows the annual maxima, 99th, 90th and 50th percentiles. The computed trends are presented in Tab.V and in Tab.VI. Generally, the variability of the wave climate was great and there were sometimes significant changes in the statistics of wave and wind fields over time scales of decades.

- Southern North Sea - Euro location: Trends for maxima and 99th percentiles of the wind speed and total significant wave heights slightly decreased, 90th and 50th percentiles were mostly constant. At this station the maxima are definitely overestimated by the model.
- Central North Sea - Ekofisk location: Wind speed maxima and 99th and 90th percentiles increased (4.8, 3.9 and 3.1 cms^{-1}/year). The increase in the wind speed could be determined by the increase of total SWH. The trend for the maxima is 3.5 cm/year, and the 99th and 90th percentiles also increased slightly.
- Northern North Sea - Brent location: Wind speed slightly increased: max 4.9 and 99th percentile 3.2 cms^{-1}/year, 90th percentile 2.6 cm/s/year. Total SWH also increased: 3.4, 2.2 and 1.1 cm/year respectively.
- Northeast Atlantic - Mike location: Wind max, 99th percentile: 6.3, 2.6 cms^{-1}/year, total SWH: 8.4 and 2.6 cm/year respectively.
- North Atlantic: Juliett (west of Ireland): Relatively strong increase in wind speed. Trend for the maxima is 13.7, for the 99th percentile 6.8 cms^{-1}/year. But the total SWH at this position increase only slightly: max 0.9 cm/year. 99th percentile decreased by 1.9cm per year.
- North Atlantic: India, Lima (northwest of Ireland): at India wind speed and SWH increased significantly. The maxima of the wind speed increased on the order of 17.5 cms^{-1}/year, SWH 9.4 cm/year. However, the statistics of wind speed and SWH at Lima were quite different. The maxima of wind speed decreased, as well as the maxima of total SWH.

We conlude that there was a slight positive trend for high wind speeds and large wave heights for most of the selected positions.

Table V: SWH statistics at selected points - fine grid area (see Fig.12)

	Euro					Ekofisk				
	max	mean	99%	90%	50%	max	mean	99%	90%	50%
average [m]	6.46	1.23	4.13	2.35	0.93	10.45	2.32	6.95	4.11	1.94
change/year [cm/a]	-0.89	0.00	-0.96	0.12	0.00	3.47	0.41	1.73	1.04	0.28
st.deviation [m] *	1.39	0.10	0.51	0.23	0.08	1.77	0.13	0.62	0.28	0.13
	Brent					OWS Juliett				
	max	mean	99%	90%	50%	max	mean	99%	90%	50%
average [m]	12.87	3.24	8.83	5.59	2.77	14.94	3.81	10.66	6.49	3.31
change/year [cm/a]	3.38	0.57	2.18	1.10	0.41	0.90	0.43	-1.99	0.55	0.49
st.deviation [m] *	1.64	0.19	0.72	0.40	0.18	2.13	0.33	1.28	0.71	0.31
	OWS India					OWS Lima				
	max	mean	99%	90%	50%	max	mean	99%	90%	50%
average [m]	15.98	3.94	10.85	6.75	3.41	16.60	4.00	11.26	6.83	3.45
change/year [cm/a]	9.40	0.18	0.16	0.11	0.08	-3.40	-0.08	-3.99	-0.38	0.06
st.deviation [m] *	2.71	0.26	1.06	0.56	0.24	2.63	0.27	1.28	0.62	0.24

Table VI: Wind speeds statistics at selected points - fine grid area (see Fig.12)

	Euro					Ekofisk				
	max	mean	99%	90%	50%	max	mean	99%	90%	50%
average [m/s]	24.03	7.87	18.98	13.23	7.16	25.23	8.77	19.94	14.36	8.29
change/year [cm/s/a]	-2.97	-0.12	-2.70	-0.02	-0.07	4.81	1.65	3.86	3.08	1.61
st.deviation [m/s] *	2.36	0.42	1.26	0.80	0.42	2.27	0.37	0.94	0.52	0.41
	Brent					OWS Juliett				
	max	mean	99%	90%	50%	max	mean	99%	90%	50%
average [m/s]	26.43	9.13	21.03	15.22	8.59	27.03	9.40	21.04	15.20	8.95
change/year [cm/s/a]	4.92	1.54	3.17	2.62	1.61	13.68	2.83	6.75	5.73	2.37
st.deviation [m/s] *	2.03	0.41	0.90	0.60	0.45	2.29	0.43	1.06	0.76	0.45
	OWS India					OWS Lima				
	max	mean	99%	90%	50%	max	mean	99%	90%	50%
average [m/s]	28.64	10.17	22.59	16.48	9.70	29.45	10.14	22.89	16.45	9.62
change/year [cm/s/a]	17.49	1.10	6.28	2.16	0.68	-3.83	0.37	-2.56	0.90	0.37
st.deviation [m/s] *	2.36	0.39	1.23	0.71	0.41	1.81	0.49	1.37	0.87	0.50

(*) standard deviation due to linear regression

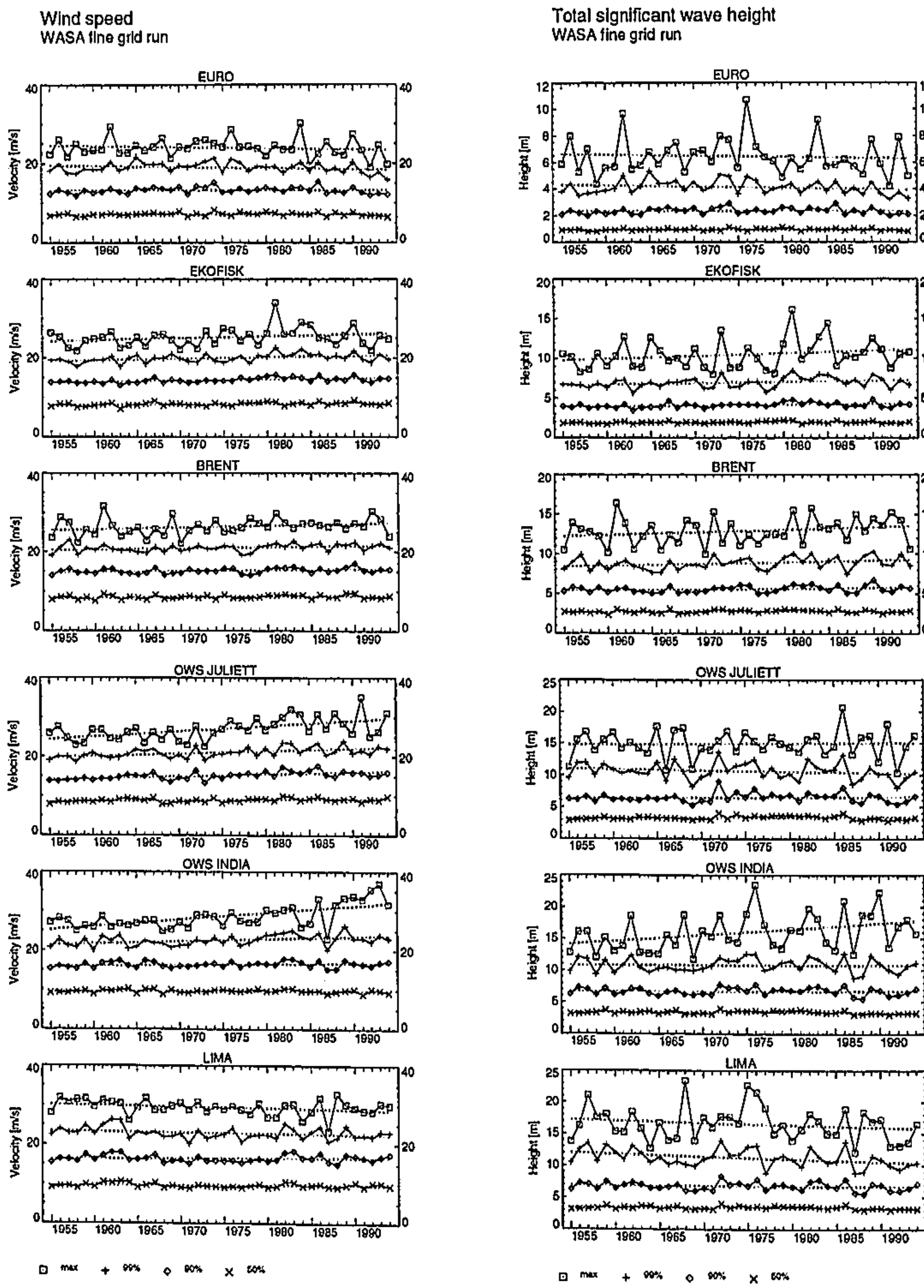

Figure 12:
Trends for maxima and chosen percentiles for wind speed and SWH computed over the WASA period 1955-94 at selected positions (cf. Appendix B).

Past analyses of data on wave height, gathered from ships of opportunity or from ocean weather stations, had led to the conlusion of a substantial worsening of the wave climate in the North Atlantic (Carter and Draper, 1988; Bacon and Carter, 1991; Hogben, 1994). Hogben maintained that mean wave heights have increased at a rate on the order of 1 or 2% per annum since 1950. He supported this with data from a series of locations mainly between 50 and 60° N. However, such local data must be considered with great care. Upward trends could have various non-physical reasons (WASA, 1994). For example, before 1979 wave height data were based on visual assessments, and they seem to be systematically too low, while after 1979 they were based on instrumental data. The poor quality of visual wave observations (especially at night) makes any analysis of year-to-year variability unreliable. To examine Hogben's and other authors' hypotheses of increasing wave heights in the North Atlantic, time series from different locations, i.e. OWS Mike, OWS Juliett, OWS India, OWS Lima, Ekofisk, were extracted from model data and analysed.

In fact, there was an increase in model SWH at OWS Mike (Fig. 13) over the whole simulation period 1955-1994 on the order of 8 cm/year for the annual maxima, or a rate of 0.7% per annum. Other representatives for the aspect of the possible changes in the wave climate are 99th or 90th percentiles of wave height. The regression coefficients obtained for these percentiles were much lower: 2.6 cm/year for the 99th and 1 cm/year for the 90th percentile (see Tab. VII).

The increase in wave height at OWS Mike was more significant in second part of the simulation period, 1975-1994. During that time the maxima of SWH increased by more than 17 cm/year (1.4% per annum) and 99th percentile by about 3.5 cm/year (0.3% per annum). For the mean values, there was no evidence of a significant trend over the last 40 years. The simulated mean SWH at OWS Mike increased by 0.3 cm/year, which correlates to 0.09% per annum. The median of SWH increased by 0.2 cm/year.

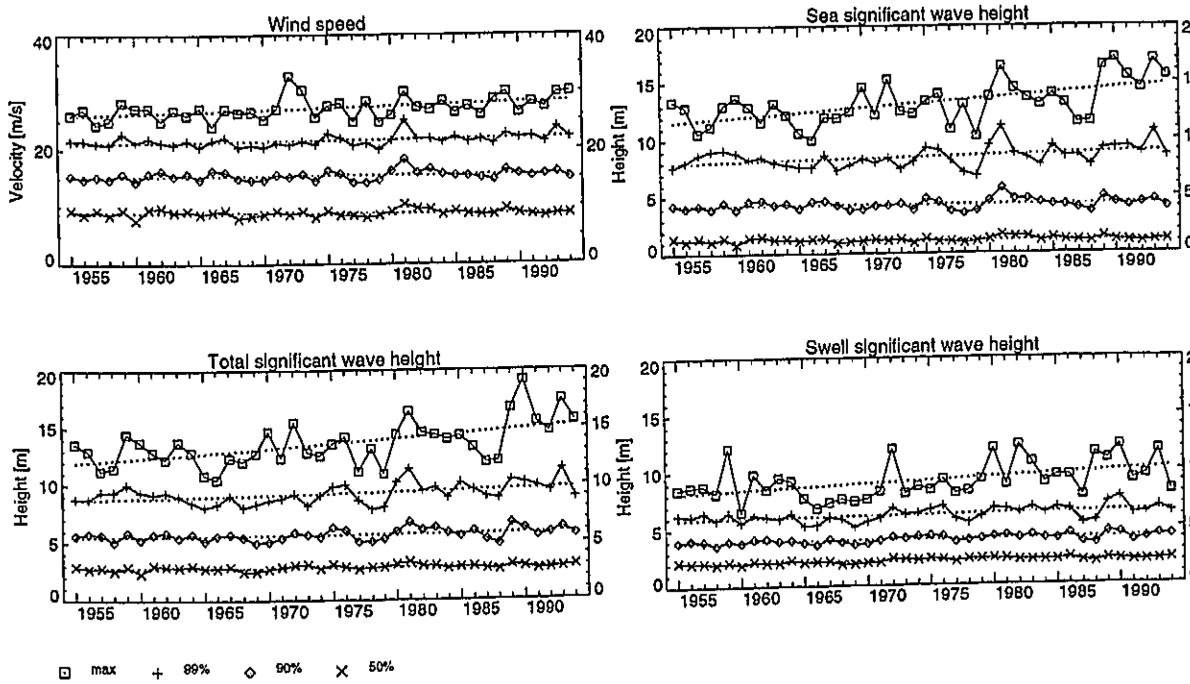

Figure 13:
Trend for the simulated wind speed and wave heights at OWS Mike over the period 1955-94.

The model data confirmed that swell waves were dominant at low wind speeds. The slight increase in mean SWH at OWS Mike could, in fact, be explained by the increase in the mean swell height, especially since mean wind speed at this station decreased by an annual rate of 0.25 cms^{-1}. Also mean sea waves decreased slightly (0.026 cm/year) but mean swell height increased by 0.44 cm per annum.

Table VII: Change per annum of wind speed and wave heights at OWS Mike

Quantile	Change per annum			
	wind speed [cm/s]	total swh [cm]	sea swh [cm]	swell swh [cm]
max	6.30	8.39	8.40	5.37
99%	2.56	2.62	2.58	1.66
90%	0.89	1.00	0.35	0.80
50%	-0.57	0.22	-0.25	0.28
mean	-0.25	0.38	-0.03	0.44

There have been many other publications, based both on measurements and visual observations, with evidence of an increase in average wave heights over the Northeast Atlantic. Analyses made by Barratt (1991) based on visual estimates at the three stations OWS Charlie, OWS Juliett and light vessel Seven Stones showed an upward trend in the annual mean value of significant wave height from 1950-54 to 1980-84 of about 1.5%/year. A review of the measured data at several OWS's by Bacon and Carter (1991) also showed clear indications of an increased level of wave heights from 1960-64 to 1970-74 (OWS India, OWS Juliett) and from ca. 1978 to ca. 1985 at OWS Lima. These rates of increase were between 1 and 2%/year, while at OWS India a rate of 2.55% per annum was reached. The analysis of WASA wave data at the same locations did not confirm such large trends in annual mean wave height. Tab. VIII summarises statistics of mean wave heights for various locations in the North Atlantic based on model data. The periods in Tab. VIII were chosen to ease comparison with trends previously published.

Table VIII: Increases in mean wave heights based on WASA model data (fine grid).

Location	Dates	Increase of mean SWH per annum	
		[cm]	[%]
OWS India	1960-74	2.1	0.5
OWS Juliett	1960-74	3.4	1.0
	1955-84	1.9	0.5
OWS Lima	1978-85	-1.8	-0.4
OWS Charlie *	1955-84	1.5	0.3
Brent	1973-93	-0.5	-0.2
Statfjord	1973-93	-0.5	-0.2

(*) based on coarse grid resolution

The trends for average wave heights derived from model data were much smaller than those found in recent publications. Similarly, the annual rates of increase in mean wave heights computed over the whole simulation period 1955-94 were small. The following rates were obtained:

OWS India: 0.1cm/y
OWS Juliett: 0.4cm/y
OWS Lima: ~0.0cm/y
Brent and Statfjord: 0.5cm/y

Evidence of a strong upward trend in the wave heights was also reported by Neu (1984). His analysis based on data derived from synoptic charts for separated 5° square areas of the North Atlantic from 1970 to 1982. He found that the annual 50th percentiles of wave heights increased during this period by an average 3.93% per year. For the area west of Ireland (15-10°W, 50-55°N) he found an increase in median wave height from 2.65m to 3.65m, an annual rate of 8.3cm or 3.14%. The analysis of WASA data for selected areas in the North Atlantic did not verify Neu's rates of increase. Fig. 14 show trends in annual maxima, the 99th, 90th and 50th percentiles of significant wave height for the 10°x5° square west of Ireland (20-10°W, 50-55°N) over the same period. The results were based on area maximum values. For the 50th percentiles of SWH an annual rate of increase of about 4.3cm/year was obtained. This was almost 50% smaller than Neu's rate of increase. The annual rates of increase computed for selected parameters in the area west of Ireland (1970-1982) are presented in Tab. IX.

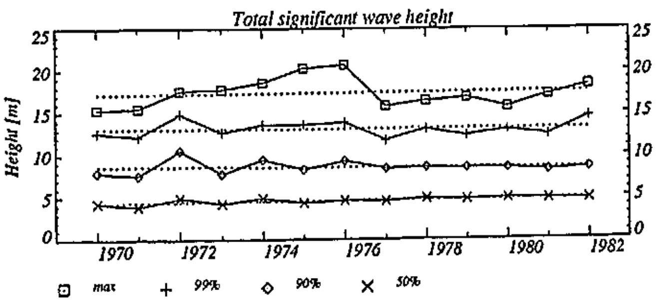

Figure 14:
Trends of WASA total SWH (box maximum) west of Ireland over the period 1970-1982.

Table IX: Change per annum of selected parameters west of Ireland, 1970-82.

Parameter	Change per annum			
	maximum	99%	90%	50%
wind speed [cm/s]	3.4	11.1	7.6	9.1
total swh [cm]	3.2	0.2	-1.2	4.3
sea swh [cm]	14.6	11.2	2.9	4.7
swell swh [cm]	-33.2	-15.3	-3.0	1.6

The differences between the WASA hindcast results and earlier estimates of wave height trends described in this chapter were partly significant. There are several possible explanations for these discrepancies. Two of these are:

- The development of the shipborne wave recorder, which took place between 1962 and 1980. This instrument was improved over the years and visual observations of wave heights on weather ships were probably influenced by its objective measurements of wave heights.
- The bias of ship observations towards lower waves, since ships tend to avoid storms. However modern ships have improved seakeeping capability and can now sail more often under heavy storm conditions than previously without risk to ship and cargo.

6 Changes in significant wave height and wind speed in the fine grid area

The detection of possible changes in the wave and storm climate in the North Atlantic was focussed on regional changes in the trends of SWH and wind speed. The annual maxima, averages and the 50th, 90th and 99th percentiles were computed for each grid point in the 40 year wave hindcast (1955-1994). To study possible trends, a straight line was fitted to the yearly variation. The linear regression coefficients are presented for the homogeneous part of the fine grid area as contour plots in figures 15, 16 and 17. The contour line "Ice" marked the maximum extension of the sea-ice.

6.1 Extreme conditions

The significant wave height and wind speed maximum, and the 99th and 90th percentiles have steadily increased in the Northeast Atlantic in the last 40 years, while in the near-coastal areas of the North Sea the storm climate has not systematically worsened. In the southwestern part of the fine grid area the significant wave height and wind speed maximum, 99th and 90th percentiles have decreased (Fig. 15 and Fig. 16).

The most characteristic feature in the trend distribution for annual maxima of SWHs was the area between Iceland and Scotland. The tendency towards higher extreme waves there is quite distinct. The annual rates of increase in maximum SWH lie between 7.5 and 10 cm/year, partly between 10-12 cm/year. Positive trends are also found in the Norwegian Sea, where upper-bound estimates were 7.5-10 cm/year. The maxima of the wind speed also clearly increased in this area. Upper-bound estimates were 10-14 cms^{-1}/year. In contrast, in the area southwest of Ireland wind maxima became lower and wave heights became smaller. The distribution in the North Sea was quite complex. In the central part wind speed showed a tendency towards higher maxima, while in the Southern North Sea they decreased. The trends for the maxima of SWH were similar: increased waves in the central part and decreased waves along the south coast from the Netherlands to Denmark. The spatial distribution of changes per annum of the maximum wind speed and maximum SWH is presented in Fig. 15.

The 99th and 90th percentiles of significant wave height and wind speed have also undergone a steady increase in the Northeast Atlantic (north of the Faroe Islands) in the last 40 years, while in the coastal areas of Northwest Europe the wave climate has not systematically worsened (see Fig. 16).
In the Northern North Sea and in the Norwegian Sea, the 99th percentile of wind speed increased over the last 40 years on the order of 2-6 cm/s per year, the 90th percentile on the order of 1-4 cm/s per year. The 99th and 90th percentiles of significant wave heights increased on the order of 1 -3 cm/year and 0.5-1.5 cm/year respectively. In contrast, west of Spain and west of Ireland wind speeds became lower and waves became smaller. The differences in the distribution of the wind and wave changes computed over the 20 year period, 1975 to 1994 (not shown here), were considerable. They pointed to a great variability of the wave climate over time scales of decades.

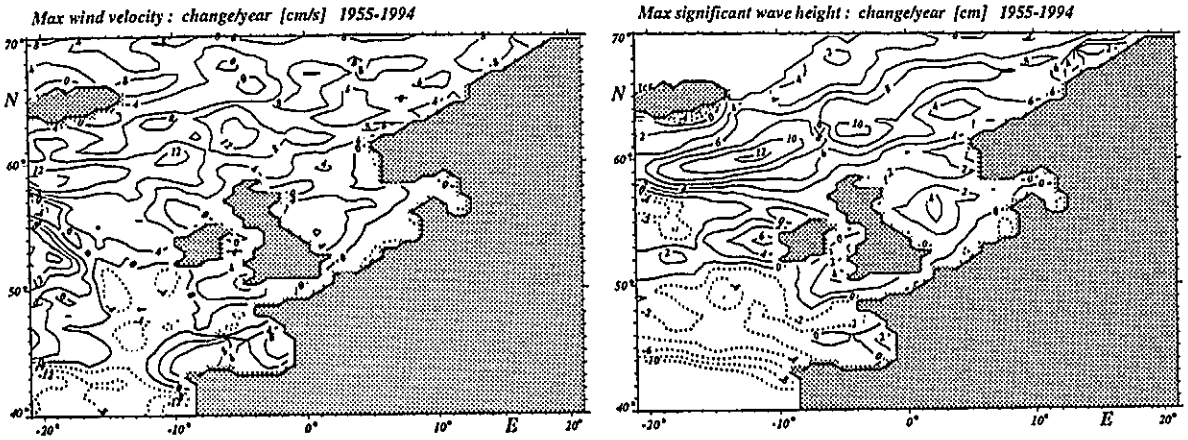

Figure 15:
Two-dimensional distribution of changes per annum of the maximum wind speed and maximum SWH over the period 1955-1994.

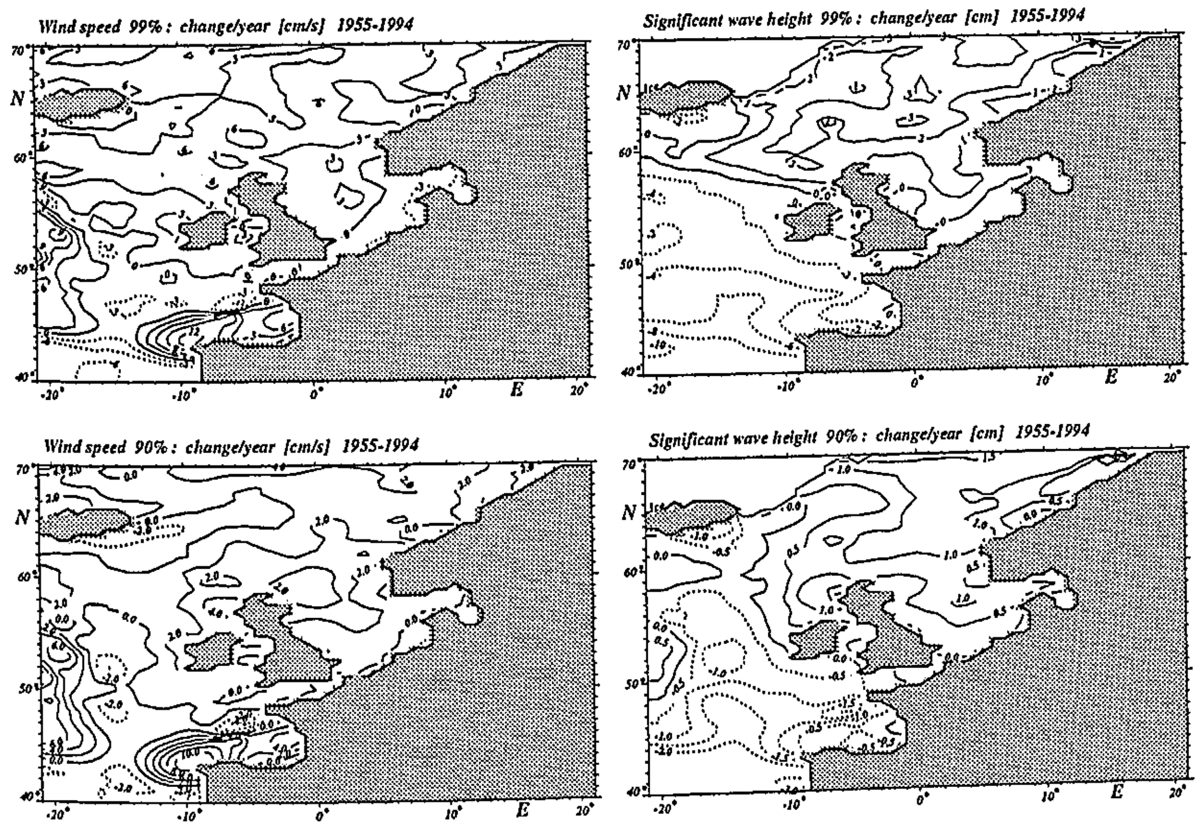

Figure 16:
Two-dimensional distribution of changes per annum of the wind speed and SWH over the period 1955-1994; above: 99th percentiles, below: 90th percentiles.

6.2 Mean conditions

The trends in average SWHs derived from model data were likewise small. Only in the Northern North Sea, in the Northeast Atlantic (north of the Faroe Islands), and on the northwest coast of Ireland were the trends in average SWH slightly greater, between 0.5 and 0.75cm/year. In the Central North Atlantic (west of OWS Juliett) the rates were between 0.75 and 1cm/y. The small changes in average SWH could be seen as a result of small changes in mean wind speeds. The computed trends in the mean wind speed in the Northeast Atlantic were almost negligible (Fig. 17). Only on the northwest coast of Spain and in the central North Atlantic the mean wind velocity increased significantly and the rate of year-to-year variation exceeds 6cms^{-1}/y, an increment in the mean wind speed of about 2.5ms^{-1} over the 40 year period. However, the average wave parameters showed comparable variability over time scales of decades as discussed for the 90th percentile of wind speed and SWH. In contrast to the whole simulation period, the average annual SWH decreased almost everywhere over the last 20 years. A positive trend in mean SWH over the last two decades was computed in the Irish Sea and on the west coast of Norway. The rate of changes obtained for these areas reached 0.5cm/y. More significant increases in annual mean SWH took place on the northwest Norwegian coast (Fig. 17).

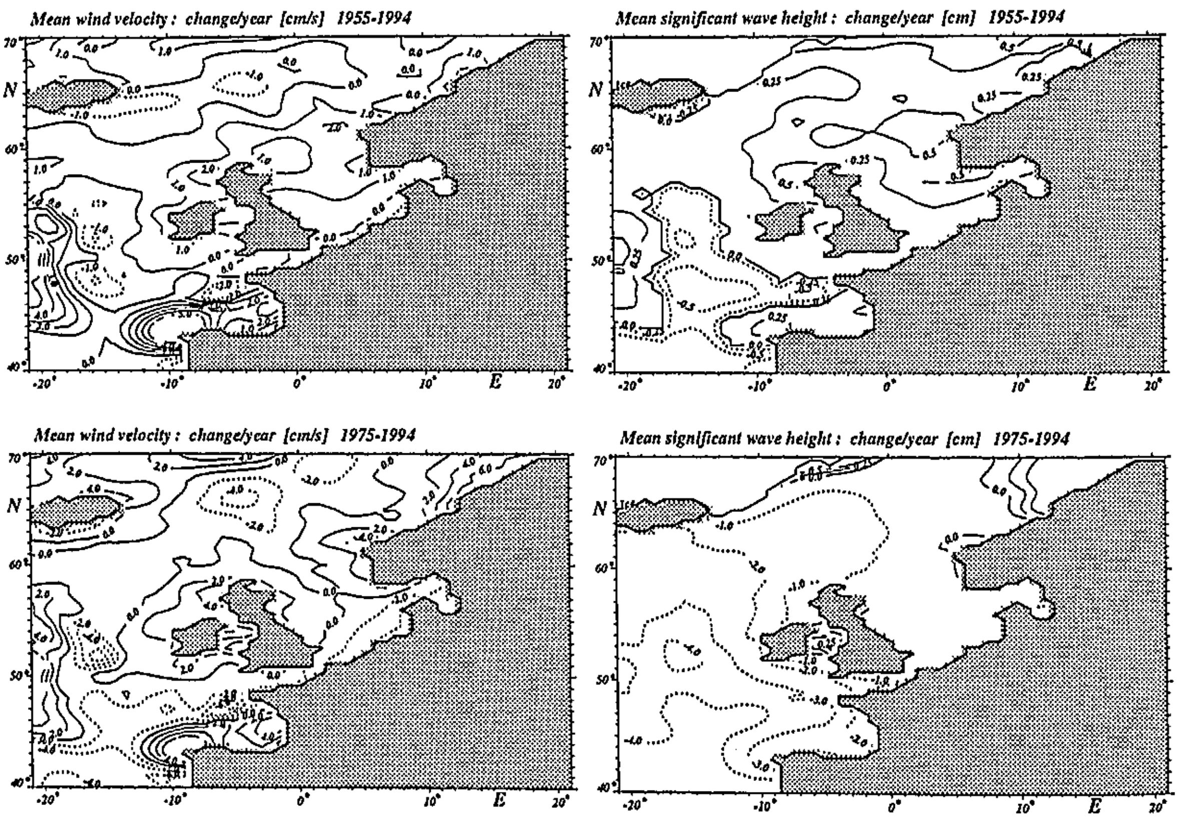

Figure 17:
Two-dimensional distribution of changes per annum of the mean wind speed and mean SWH, above: over the period 1955-1994, below: over the period 1975-1994.

The trends in extreme and mean wave conditions presented in this section were not reliable for the whole fine grid model area. The computed variability in SWH and wind speeds near the boundary of the grid area, approximately west of 20°W, north of 70°N and south of 40°N, were questionable. In these areas only few, if any, in-situ observations were available and the wind fields seemed to be non-homogeneous. But there were several indications that the hindcast data and therefore also the computed trends were reliable for most of the fine grid area, approximately between 70°N and 40°N and east of 20°W. This is the area where wind fields seemed to be homogeneous over the whole 40 year simulation period. The computed changes of wave conditions surrounding the British Isles and west of Norway showed a good agreement with observations and the spatial variability of computed trends are reliable. Also the trends obtained from hindcast data near the coast of Spain agreed well with trends obtained from buoy data. We conclude that the changes of the wave conditions in the area mentioned above were trustworthy.

7 Trends in the extreme values

This section describes the process carried out to verify the hypothesis of a possible change in the highest values of significant wave height during the period 1955-1994.

Primarily, some non-parametric tests of tendency were applied using the mean of the four highest significant wave heights that occurred every year, so as to reduce the problem of considering only the yearly maximum in model data subjected to error. As a result of these tests, it turned out that there could be a certain tendency towards higher or lower values in some parts of the grid covered in the hindcast.

To confirm the evolution hinted by the non-parametric tests and to have a deeper look into the way in which the tails of the distributions, representing the extreme events, might have changed during the period 1955-94, use was made of the well known methods of extreme analysis, as is explained here.

The 40 years hindcast was split into four slices of ten years each (1955-64, 1965-74, 1975-84, 1985-94) in order to have a minimum and sufficient number of data in each slice and to be able to compare results from different periods. An extreme wave analysis was performed for the Northwest Atlantic on every point of the fine grid for each 10-year slice. The grid was limited in the North to avoid the variable ice cover and some areas without much interest. Then, the area covered by this analysis was 25^{o}W-6^{o}E and 44^{o}N-69^{o}N.

The common approach to calculate the risk of extreme wave conditions is the theory of 'extreme value statistics'. The typical parameter in this theory is the average return period of an extreme significant wave height.

Extreme wave distribution functions have been calculated from wave hindcasts for several times and areas (e.g. first calculation for the North Sea is described in Ewing et al., 79). The method is well established and the output has been used as the environmental characteristic for loads on offshore construction, shipbuilding, downtimes of ship-operation etc. Here, we follow the methods described by several authors (Ewing et al., 79; Goda, 88; Goda and Kobune, 90) and we are not going into details, but restrict ourselves to the necessary facts.

It should be kept in mind that the use of extreme analysis in this paper has the only objective of making a comparison and search of the possible evolution of the tails of the distributions for the highest values. It is not our aim to get the best estimation of the values associated to a certain return period for the forty years but to compare them in the four slices.

We decided to use the method of "peak over threshold" to sample the data since it is more often used and avoids the large dependence of the "annual peak method" from single peaks that may be artifacts of the wave model or of the wind field construction. Since the threshold will be determined by the number of peaks used, using the same number of independent peaks for every point in the grid, for every 10-year slice, we can assure that we are working always within the same probability level and so we will be able to compare significant wave heights associated to one or several probability levels.

To fit the data the least-square method was used which is a standard method and fast algorithm (it has to be considered the great amount of points in the fine grid where the analysis is carried out) that guarantees the convergence when fitting multi-parametric distributions regardless of the number of data. The quality of the fit to different distributions (Gumbel, Weibull and Fisher-Tippet III) is determined from a Monte-Carlo simulation of new samples of the derived extreme value distribution via the normalised correlation Rc, which takes into account the statistical significance of the fit.

The result of the fitting showed that the Fisher-Tippet III distribution was the best option in most of the points. This distribution makes the assumption of an upper limit to the data. This fact helps to control the possibility of any outlier produced by the wave model as a response to a misleading wind field.

7.1 Trends of return values

For the extreme analysis performed over the 10-year periods, 50 peaks were used per slice (five peaks per year, in average, which seems a reasonable number) in order to make the analysis with a sufficient number of peaks.

The values of SWH obtained in each decade for 100 years return period shown a clear spatial pattern when fitted to a linear regression model and the slope was depicted for every point in the grid. Two distinct regions can be identified: one, between Iceland and Scotland, where there appears a tendency towards higher extreme waves, and another area, Southwest of Ireland, with a slight decrease in SWH (Fig. 18).

These trends took place along the four decades without interruption or great oscillation, as could be seen in the exhaustive analysis done in eight control points, representative of the whole fine grid, and the linear regression coefficient derived fitting the 10-yearly variation to a straight-line model, which has a value very close to 1 in most of the points, in particular, in the first of the two mentioned regions, confirming the suspected behaviour from the non-parametric tests of tendency.

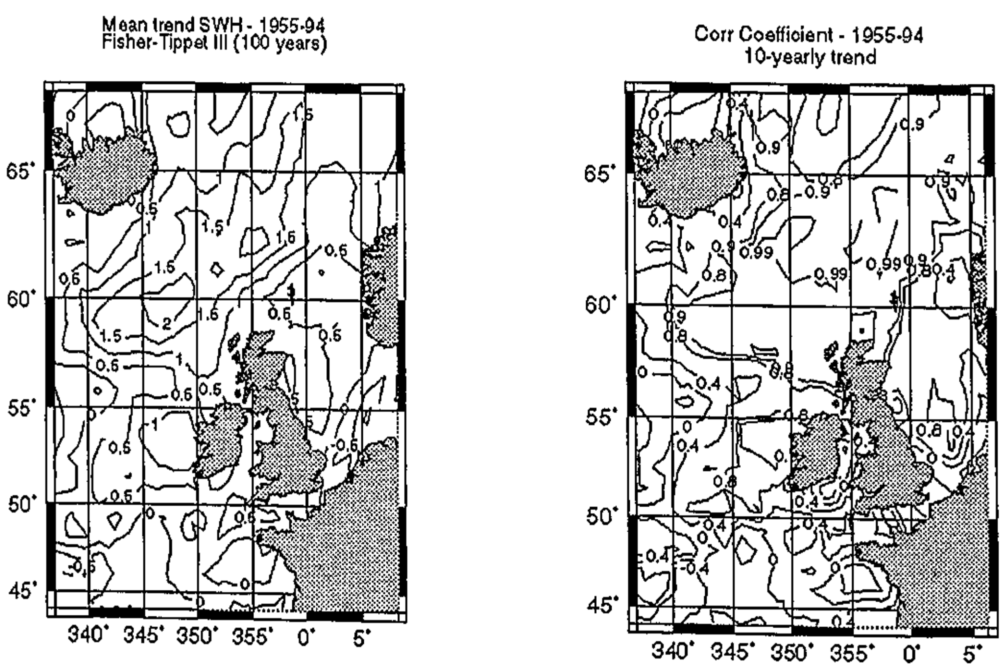

Figure 18:
SWH mean trend in the period 1955-1994 (left, units: m/decade). Linear regression coefficient derived by fitting the 10-yearly variation to a straight-line model (right).

Figure 18 shows the mean slope of the trend found during the four decades for the extreme SWH with a return period of 100 years and the correlation coefficient of the regression fit to a strait-line model.

7.2 Extreme wave analysis in a double CO_2 scenario

The same method of comparison between SWH associated to certain return period was applied to a scenario of future surge and wave climates at a time of doubled CO_2 ($2xCO_2$) concentration in the atmosphere to study possible effects on the extreme waves. The scenario was based on two 5-year time slice experiments with a T106 atmospheric GCM: a "control" run with current level atmospheric CO_2 concentration and a "$2xCO_2$" run (for more details, refer to Beersma et al., 1996 or Rider et al., 1996). In general, the wind and wave climate produced by the $2xCO_2$ run is partly significant different from that produced by the control run.

Due to the short period simulated with this data set the extreme analysis was performed to calculate SWH with a return period of 20 years. The analysis was applied to the control and the $2xCO_2$ runs and the results are shown in Fig. 19 for the Fisher-Tippett distribution. There is a clear pattern with two separated regions: one south of Iceland, where the 20-year return wave height grows, and other south-west of Ireland, where there is a decrease.

The confidence intervals for the SWH values of the extreme analysis in the control and the $2xCO_2$ runs, have similar magnitudes, point to point, to the anomalies ($SWH_{2xCO2\text{-}Control}$). This means that there is an overlap between the SWH values estimated for the two runs.
This could lead one to believe that there is no (significant) difference between both extremes, but, despite these overlapping confidence intervals, the information given by the return values map (Fig. 19) should not be ignored. There is a large area where the difference keeps the same sign (growth or decrease) and is organized in a clear pattern.

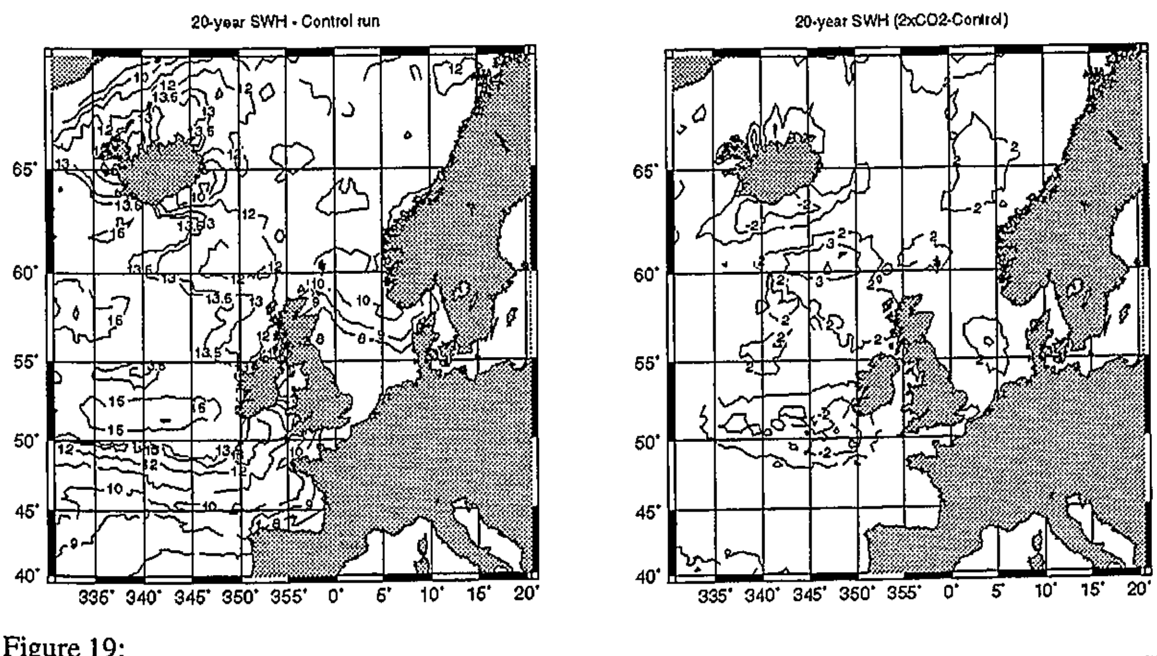

Figure 19:
20 year return period SWH for the control run (left) and differences in the 20 years return period SWH between the control and the $2xCO_2$ runs (right). Distribution is Fisher-Tippett III in both cases.

The anomalies found with the climate change scenario (double concentration of CO_2) show the same pattern as the trends of the extreme waves for the 40 year hindcast. There is an area South of Iceland with positive values for the anomalies (growth) and an area Southwest of Ireland with negative values (decrease).

8 Conclusion

The wave data obtained within the WASA project enable us to make more reliable predictions of changes in wave conditions in the North Atlantic since 1955 than other wave data sets allow. The analysis of the model output data revealed that statistics of significant wave height in the Northern North Sea and in the Norwegian Sea have undergone a steady increase in the last 40 years. Upper bound estimates were 3-4 cm/year for the 99th and 1-2 cm/year for the 90th annual percentiles. But average SWH increased during this time only at a rate of 0.25-0.75 cm/year, which corresponds to ca. 0.2% per annum. Consequently a continuously upward trend in average wave heights of the order of 1% or 2% per annum reported in recent years cannot be supported using WASA wave model output. For the credibility of the trends in SWH and changes in wave climate obtained from the WASA hindcast data the homogeneity (i.e. absence of non-physical signals) of the input wind fields play a key role. Without uniform quality throughout the entire hindcast period the predicted changes are unreliable. The results of the analyzed hindcast data showed that the trends obtained from the WASA data are reliable for most of the fine grid model area, the area approximately between 70°N and 40°N and east of 20°W. The comparison between model data and observations in this area showed good agreement. Previous analyses have also shown that the DNMI winds are relatively homogeneous in this area (WASA, 1995). The ratio of high-pass filtered standard deviations of air-pressure variations in winter in the decade 1984-93 and in the decades 1964-73 and 1955-63 showed small variability in the area mentioned above. In contrast, the variability greatly increased since the 1960's in areas where little or no in-situ observations were available. The spatial distribution of trends obtained from WASA data showed that changes and trends based on hindcast data are rather unreliable in area west of 20°W and south of 40°N.

The regional variability of the trends computed from the WASA data shows that wind speed and wave height tendencies are closely correlated. In areas where SWH increased (i.e. between Scotland and Iceland) wind speed increased as well. Consequently, the upward trend in significant wave height in the WASA hindcast can be explained by the increase in wind speed. However, further analysis of the derived data set is necessary to confirm the one-to-one correspondence between the increases of these two parameters. The increasing wind speed in the region of interest is also shown by the WASA investigations on changes of the geostrophic wind (Alexandersson et al., 1997). The 90th percentile of the large-scale geostrophic wind has changed in the Torshavn-Aberdeen-Bergen triangle in the period 1960 to 1995 from about $26 ms^{-1}$ to about $30 ms^{-1}$. The regional variability of our data indicates that a one-parameter description for the change of wind and wave climate is not appropriate. Nevertheless, it is interesting that the North Atlantic Oscillation index (NAO), which is built from the pressure difference between Iceland and Azores and is a major mode of atmospheric variability, has significantly intensified in the past 30 years (Hurrel, 1995). The analysis of wind and wave variability showed that variations in wave climate in the North Atlantic may be related to variations in the NAO (Kushnir et al., 1995). The WASA hindcast results supported the connection between NAO index and wind and wave climate in the North Atlantic over the last four decades, so the wave climate changes in this period are explainable by the large scale feature of the circulation. In contrast to that, the stormy decades around and before 1900 were, in general, years with low or normal NAO index (Alexandersson et al., 1997).

Interesting results with regard to the possible changes in the wave climate in the North Atlantic were given by the extreme value analysis. We used the well-established extreme value statistic to construct return periods for extreme waves from the 40 year hindcast. These return values are used as design parameters for offshore constructions. The underlying assumption is the stationarity of the extreme wave statistic over the involved return period. We checked this assumption for the return period calculation a posteriori in four slices of ten years. The results showed that the values of SWH for prescribed return periods have been growing during the last four decades in a distended area southeast of Iceland and in a small area west of Ireland. Southwest of Iceland a slight tendency towards smaller extreme waves appeared. These results fit very well with the analysis of percentiles of SWH performed in the fine grid area for the same period. All three distributions (Weibull, Gumbel and Fisher-Tippet III) produced similar results. The most important differences between them occurred in the area between Iceland and Scotland where strong storms pass the North Atlantic and where the highest peaks of SWH appeared. SWH's with the return period of 100 years reached there values of about 22m. South of this area 100 year waves decreased up to about 14m at the Atlantic coast of France. In the North Sea values between 14 and 17m were obtained. The results of the extreme value analysis showed also that the presented method of return period calculation does not take into account the long term changes of the extreme wave statistics.

It is also notable that the anomalies found with the climate change scenario (double concentration of CO_2) show the same pattern as the trends of the extreme waves for the 40 year hindcast. There is an area south of Iceland with positive values for the anomalies (growth) and an area southwest of Ireland with negative values (decrease).

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Appendix A

Within the WASA project the following integrated spectral parameters were stored:

Table X: WASA Integrated Spectral Parameter and the accuracy of stored data.

No.	Parameter	Accuracy
1	Wind speed	0.2 m/s
2	Wind direction	rad/40
3	Total sig. wave height	0.1 m
4	Total peak period	0.1 s
5	Total M1-period	0.1 s
6	Total M2-period	0.1 s
7	Total mean period	0.1 s
8	Total mean wave direction	rad/40
9	Total directional spread	rad/40
10	Sea sig. wave height	0.1 m
11	Sea peak period	0.1 s
12	Sea M1-period	0.1 s
13	Sea M2-period	0.1 s
14	Sea mean period	0.1 s
15	Sea mean wave direction	rad/40
16	Sea directional spread	rad/40
17	Swell sig. wave height	0.1 m
18	Swell peak period	0.1 s
19	Swell M1-period	0.1 s
20	Swell M2-period	0.1 s
21	Swell mean period	0.1 s
22	Swell mean wave direction	rad/40
23	Swell directional spread	rad/40

The data were stored using HDF (Hierarchical Data Format). It minimizes the size of the output files and is computer independent which facilitates the exchange of data between the different institutes. The total data set contains about 260 GByte.

Appendix B

For the quality control of the production runs the model results were compared with measurements at several sites listed in the following Table. The stations located in the fine grid are marked in Fig. 1, too.

Table XI: Position of measurement sites.

Station	Position	
	Latitude	Longitude
Brent	61.0°N	1.5°E
Gulfaks	61.2°N	2.3°E
Statfjord	61.2°N	1.8°E
Frigg	59.9°N	2.1°E
WS Famita	57.5°N	3.0°E
Ekofisk	56.5°N	3.2°E
Pennzoil	53.2°N	3.2°E
Ijmuiden	52.6°N	4.1°E
Euro	51.98°N	3.5°E
Buoy Bilbao	43.40°N	3.14°W
Buoy Biscay	43.41°N	8.38°W
Tromsø	71.5°N	19.0°E
OWS Mike	66.0°N	2.0°W
OWS India	59.0°N	19.0°W
OWS Juliett	52.5°N	20.0°W
OWS Lima	57.0°N	20.0°W
OWS Charlie	53.0°N	35.0°W