Changing Waves and Storms in the Northeast Atlantic?

The WASA Group*

ABSTRACT

The European project WASA (Waves and Storms in the North Atlantic) has been set up to verify or disprove hypotheses of a worsening storm and wave climate in the northeast Atlantic and its adjacent seas in the present century. Its main conclusion is that the storm and wave climate in most of the northeast Atlantic and in the North Sea has undergone significant variations on timescales of decades; it has indeed roughened in recent decades, but the present intensity of the storm and wave climate seems to be comparable with that at the beginning of this century. Part of this variability is found to be related to the North Atlantic oscillation.

An analysis of a high-resolution climate change experiment, mimicking global warming due to increased greenhouse gas concentrations, results in a weak increase of storm activity and (extreme) wave heights in the Bay of Biscay and in the North Sea, while storm action and waves slightly decrease along the Norwegian coast and in most of the remaining North Atlantic area. A weak increase in storm surges in the southern and eastern part of the North Sea is expected. These projected anthropogenic changes at the time of CO_2 doubling fall well within the limits of variability observed in the past.

A major methodical obstacle for the assessment of changes in the intensity of storm and wave events are inhomogeneities in the observational record, both in terms of local observations and of analyzed products (such as weather maps), which usually produce an artificial increase of extreme winds. This occurs because older analyses were based on fewer observations and with more limited conceptual and numerical models of the dynamical processes than more recent analyses. Therefore the assessment of changes in storminess is based on local observations of air pressure and high-frequency variance at tide gauges. Data of this sort is available for 100 yr and sometimes more. The assessment of changes in the wave climate is achieved using a two-step procedure; first a state-of-the-art wave model is integrated with 40 yr of wind analysis; the results are assumed to be reasonably homogeneous in the area south of 70°N and east of 20°W; then a regression is built that relates monthly mean air pressure distributions to intramonthly percentiles of wave heights at selected locations with the help of the 40-yr simulated data; finally, observed monthly mean air pressure fields from the beginning of this century are fed into the regression model to derive best guesses of wave statistics throughout the century.

*The WASA Group:
J. C. Carretero, M. Gomez, I. Lozano, A. Ruiz de Elvira, and O. Serrano, Clima Maritimo, Madrid, Spain.
K. Iden and M. Reistad, Det Norske Meteorologiske Institutt, Bergen, Norway.
H. Reichardt, V. Kharin, M. Stolley, and H. von Storch, Max-Planck-Institut für Meteorologie, Hamburg, Germany.
H. Günther, A. Pfizenmayer, W. Rosenthal, and M. Stawarz, Institut für Gewässerphysik, GKSS, Geesthacht, Germany.
T. Schmith, E. Kaas, and T. Li, Danmarks Meteorologiske Institut, Copenhagen, Denmark.
H. Alexandersson, Sveriges Meteorologiska och Hydrologiska Institut, Norrköping, Sweden.
J. Beersma, E. Bouws, G. Komen, and K. Rider, Koninklijk Nederlands Meteorologisch Instituut, De Bilt, the Netherlands.
R. Flather and J. Smith, Proudman Oceanographic Laboratory, Bidston, United Kingdom.
W. Bijl and J. de Ronde, Rijkswaterstaat, the Netherlands.
M. Mietus, Institute of Meteorology and Water Management, Gdynia, Poland.
Eva Bauer, Potsdam Institut für Klimafolgenforschung, Potsdam, Germany.
H. Schmidt, Seewetteramt, Hamburg, Germany.
H. Langenberg, Institut für Meereskunde, Universität Hamburg, Hamburg, Germany.
Corresponding author address: Hans von Storch, Institute of Hydrophysics, GKSS Research Centre, P.O. Box 21502, Geesthacht, Germany.
E-mail: storch@gkss.de
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1. Background

In the public debate concerning climate change due to increasing concentrations of radiatively active gases into the atmosphere, many people are concerned about the possibility of an intensification of extratropical storms. Even though the Intergovernmental Panel on Climate Change (IPCC) took a cautious stand in this matter because of lack of evidence (Houghton et al. 1990; Houghton et al. 1992; Houghton et al. 1996), a mixture of indirect evidence (van Hooff 1993; Hogben 1994) and misleading scientific statements (Schinke 1992) created a substantial uneasiness in the public (Berz 1992; Berz and Conrad 1994; Greenpeace 1994). The offshore oil industry in the North Sea was confronted with reports of extreme waves higher than had ever been observed. The insurance industry organized meetings with scientists because of greatly increased storm-related damages. Newspapers in northern Europe were full of speculations about the enhanced threat of extratropical storms in early 1993.

In this atmosphere the Norwegian Meteorological Institute organized two workshops, "Climate Trends and Future Offshore Design and Operation Criteria," in Reykjavik and Bergen, bringing together people from the oil industry, certification agencies, and scientists to discuss the reality of a worsening of the wave and storm climate. The workshops did not issue definite statements, but the general impression was that hard evidence for a worsening of the storm and wave climate was not available (for a summary see von Storch et al. 1994). A group of workshop participants then established the Waves and Storms in the North Atlantic (WASA) project.

In the present paper the results obtained in WASA are summarized and the main conclusions are drawn. The results are documented in detail in a series of papers (Alexandersson et al. 1998; Bauer et al. 1996; Beersma et al. 1997; Bijl 1997; Kaas et al. 1996; Rider et al. 1996; Schmith 1995; Schmith et al. 1997; Schmith et al. 1998; Günther et al. 1998; Schmidt and von Storch 1993; von Storch and Reichardt 1997; Bouws et al. 1996). Preliminary assessments were published by von Storch et al. (1994) and WASA (1994, 1995). Part of the work reported here also originates from studies outside of WASA.

The present paper is organized as follows. In section 2 the fundamental methodological problem of WASA is addressed, namely, the presence of creeping inhomogeneities. These inhomogeneities render the seemingly most suitable collections of weather maps useless for the description of trends and interdecadal variability in storm and storm-related statistics. Instead local data, unaffected by improving analysis procedures, are studied. Two variables seem to be little affected by instrumental and environmental changes, namely, air pressure and sea level variations around a multiyear mean. We present time series of intrayearly statistics of geostrophic winds, air pressure tendencies, and variances of storm-related water level variations in section 3.

In the case of the wave climate, analyses, such as ship routing maps derived manually from wind analyses, suffer to an unknown degree from inhomogeneities. Local observations are sparse and have achieved a high level of high and uniform accuracy only in the past 10 years or so. Prior to, say, 1980, the observational techniques have changed from visual assessment to shipborn instruments, which in their early days covered only part of the energy spectrum (and thus underestimated the significant wave height, which is proportional to the integral over the energy spectrum). Thus, in the WASA project a strategy suggested by Kushnir et al. (1995) and Kushnir et al. (1997) was adopted, namely, of first generating a consistent dataset describing the variations of the wave field for 40 yr with a state-of-the-art wave model and multiyear wind analyses. The simulated wave data in areas where the wind forcing is thought to be sufficiently homogeneous is considered as "substitute reality." In section 4 the model simulation and the results obtained within the 40 yr of simulation in the "homogeneity" area (around the British Isles, the Bay of Biscay, and the North Sea) are presented. In section 5 the substitute reality wave statistics are linked to monthly mean air pressure analyses, which have been collected since 1899 and are thought to be sufficiently homogeneous (Trenberth and Paolino 1980). This is done for two locations in the northern and central North Sea (oil fields Ekofisk and Brent). With the help of this regression model and the observed monthly mean air pressure fields, a best guess of wave statistics earlier in this century is derived.

In section 6 possible implications of an increased CO_2 concentrations in the atmosphere on storminess, wave, and storm surge statistics are examined. Specifically, a high-resolution (T106) paired atmospheric GCM time-slice experiment on the impact of doubled CO_2 concentrations in the atmosphere is studied. The simulated change in storminess is discussed, and the impact of this (moderate) change in storminess on waves and storm surge statistics, as estimated through dynamical wave and storm surge models as well as through the regression model derived in section 5, are presented.

In the concluding section, the main results are summarized and the major caveats of the analysis are listed and discussed.

2. The problem of homogeneity

a. General

The methodological challenge with the analysis of historical datasets is the discrimination between signals, reflecting real changes as opposed to changes due to changing instrumental accuracies, environmental conditions, observational practices, and analysis routines. We call a dataset homogeneous if it is free of such artificial contaminations. Inhomogeneities, that is, changing nonphysical factors influencing the weather analyses, can be characterized as being 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 subject to ongoing improvements of the numerical weather prediction model. Another source of creeping inhomogeneities consists of ongoing modifications in the observational network, be they changes in the density of stations or the replacement of instruments. For instance, the availability of satellite imagery and reports from intercontinental flights in the 1960s may have persuaded human weather analysts and forecasters to describe a low pressure system over the Atlantic as being more intense than when they had only ship observations as was the case in the 1950s. The number of forecasters that wholeheartedly accepted this additional information may have gradually increased as more conservative forecasters retired and were replaced by younger colleagues. In marine weather statistics, based on reports from voluntary observing ships, creeping inhomogeneities are brought into the analysis procedure by gradually changing ship routing routines and by increasing ship speeds and heights and other aspects. The standard technique for identifying such creeping inhomogeneities is to compare the suspected time series with data from neighboring stations known not to be affected by the inhomogeneity (Alexandersson 1986; Alexandersson and Moberg 1997). However, such neighboring stations are not always available, particularly in marine weather data.

Sudden inhomogeneities are introduced by abrupt, often documented, changes in the analysis scheme. Such changes may include the change from manual to automatic analysis techniques, the rectification of outright errors in the analysis procedure, or 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.

b. Storm climate

When assessing the temporal evolution of the storm climate, principly two different types of data may be considered. One source of information is the archive of weather maps, which covers about 100 years. Indeed, several attempts have been made to count the number of storms, stratified after the minimum core pressure, in the course of time (Schinke 1992; Stein and Hense 1994). These studies are useful in describing the year-to-year fluctuations for a period of, say, 10 years. However, for a longer perspective this approach is rendered inconclusive simply because the quality of weather maps has steadily improved. Thus any steady worsening of the storm climate apparent in the weather maps (as reported by Schinke 1992) might reflect a real signal or might result from the ever-increasing quality of the operational analyses due to more and better observations, more powerful diagnostic tools, and other improvements in the monitoring of the state of the troposphere. A more detailed mapping of the pressure distribution, however, automatically yields deeper lows. This problem is severe for weather maps; when dealing with monthly mean maps, the inhomogeneity becomes less significant because of the greater smoothness of monthly mean fields.

The inhomogeneity problem is illustrated by Fig. 1, in which the ratio of high-pass filtered standard deviations of air pressure variations in winter in the decade 1984–93 and in the 9-yr interval 1955–63, as derived from the Norwegian Meteorological Institute (DNMI) analyses (see section 5), is plotted. Variability obviously increased since the 1950s in areas where few or no in situ observations are routinely available; this increase is likely to be spurious. Note the local maximum of enhanced variability, with a ratio > 1.1, in the data-sparse area between Svalbard and Greenland and over Greenland. Of course, this increase may be real, but it is suspicious that it takes place in areas of little

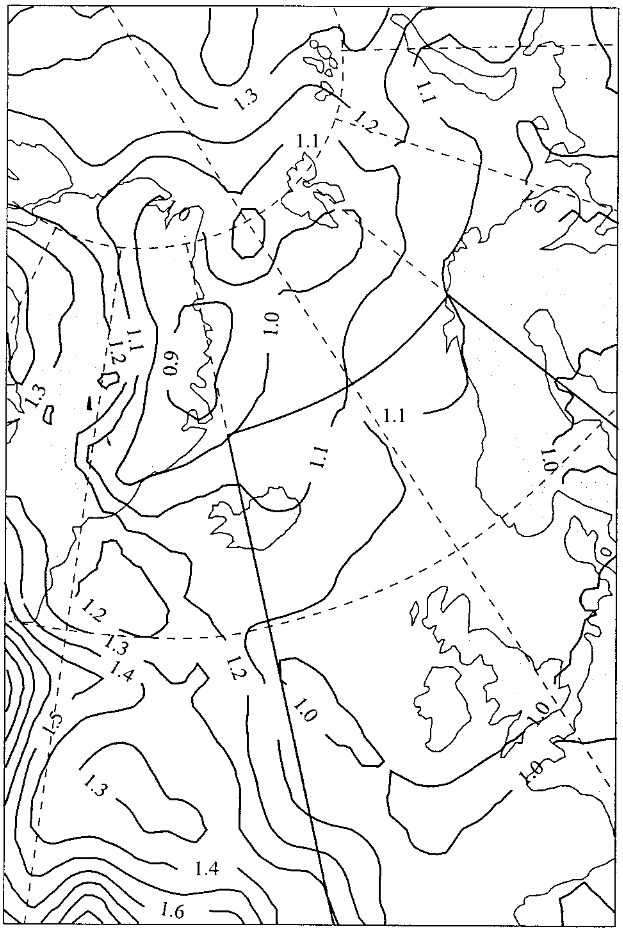

FIG. 1. Ratio of synoptic-scale standard deviation of air pressure variations in winter (DJF) as derived from DNMI analyses in the decade 1984–93 and in the decade 1955–63. The analyses in the marked area south of 70°N and east of 20°W seem to be relatively homogeneous.

high quality observational data. Note that the comparison with observed records is often inconclusive as these data have 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, the local "observations," which are sometimes not instrumental observations but reports based on subjective assessments (wind force estimated from wave heights), may already suffer from the creeping inhomogeneities (cf. Peterson and Hasse 1987), which are then inherited by the 2D mapped analysis.

Any analysis of changes of the storm climate should be supported by an analysis of local observations that are unaffected by improvements in the process of mapping the weather. A good parameter would be wind speed, since it relates directly to damages and impact of waves and surges. However, wind observations—either determined instrumentally or estimated—are usually of limited value due to inhomogeneities such as the change of scale, change of observer, change of surroundings, etc. (cf. Peterson and Hasse 1987).

Therefore one must look for other and more homogeneous proxies for storminess. An obvious choice is to base these on station air pressure, the time series of which are considered to be rather homogeneous because more or less the same instrument (mercury barometer) and procedures have been used throughout the entire observation period.

From air pressure several proxies for storminess may be formed, namely, the annual (seasonal, monthly) distribution of the geostrophic wind speed derived from three stations in a triangle (Schmidt and von Storch 1993; see section 3a) or the annual (seasonal, monthly) distribution of the pressure minima or tendencies, possibly after suppressing the nonsynoptic variations by means of a digital filter (Schmith 1995; Kaas et al. 1996) (see section 3b). Also the frequencies of "pressure events," such as pressure readings below a threshold, geostrophic winds, or pressure changes larger than a threshold, may serve as a measure of storminess.

Alexandersson et al. (1998) compared the different measures for the geostrophic wind triangle "Bergen–Stockholm–Nordby" (for the locations, see Fig. 2) and for the station Oksøy in the middle of the triangle. Using data from 1881 to 1995, Alexandersson et al. (1998) calculated correlations between annual 99% and 95% percentiles of geostrophic winds (labeled *p*% in the following table), the frequency of geostrophic winds above 25 m s^{-1} (F_{25}) and of the frequency of 24-h pressure tendencies ($|\Delta_p| > 16$ hPa) and of deep pressure readings ($p < 980$) at Oksøy.

	95%	F_{25}	$\|\Delta_p\|$	$p < 980$
99%	0.75	0.90	0.38	0.08
95%		0.64	0.44	0.15
F_{25}			0.34	0.07
$\|\Delta_p\|$				0.35

The indices related to pressure gradients (99%, 95%, and F_{25}) are well correlated, whereas the frequency of deep pressure readings ($p < 980$) is only loosely linked, which may in part be due to the fact that the large-scale low-frequency variability of air pressure shifts local pressure distributions to smaller or larger values without necessarily affecting the storm regime. This finding casts additional doubts on the approach of counting "deep cyclones," as a deep core pressure is not necessarily connected with a strong spatial or temporal gradient.

Another homogeneous proxy data time series is provided by high-frequency sea level variations at a tide gauge. The variance of such variations is controlled by the variance of the synoptic atmospheric disturbances (see section 3c).

The proxy data geostrophic wind, high-frequency pressure tendency, and sea level variations cannot be used to reliably estimate actual wind speeds; however, changes in the annual (monthly) distributions of the wind speed are well reflected with similar changes in the distributions of geostrophic wind speed. This is demonstrated in Fig. 3 by a percentile–percentile plot of 5 yr of daily wind speeds (observed at a station) and daily geostrophic wind speeds (derived with the triangle method using three surrounding pressure readings). Thus changes of statistical moments and percentiles of the wind speed distribution may be deduced from changes of the same statistical moments of the geostrophic wind speed distribution.

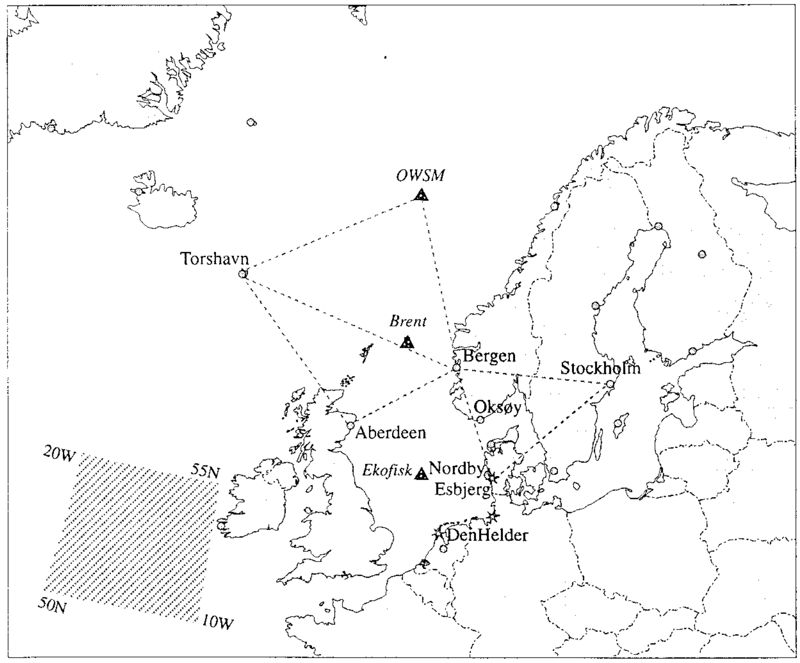

FIG. 2. Location of in situ data used in the WASA studies. Locations explicitly used in the present paper are marked by their names. Dots represent pressure gauges used for geostrophic wind calculations by Alexandersson et al. (1998). Triangles: Tide gauges for which high water level percentiles were calculated, and offshore stations and ocean weather stations. Geostrophic triangles used in the present article are marked by dotted lines; the wave chart area west of Ireland is marked by hatching.

c. Wave climate

Data about wave height are available from reports of visual assessments from ships of opportunity and lighthouses, from wave rider buoys and shipborne wave recorders at ocean weather stations; also wave height maps have been constructed for the purpose of ship routing from wind analyses. These data are sparse and suffer from inhomogeneities of various kinds (cf. WASA 1994). Analyses of these data have revealed a substantial worsening of the wave climate in the North Atlantic (Neu 1984; Carter and Draper 1988; Bacon and Carter 1991; Hogben 1994; Bouws et al. 1996).

A recent estimate is offered by Bouws et al. (1996), who studied operational analysis of wave analysis prepared by the Koninklijk Nederlands Meteorologisch Instituut (KNMI) Ship Routing Office from 1961 to 1987. The procedure for preparing the analyses did not change in the course of time, but the data used as base material for the analyses did change. Thus, the KNMI wave charts suffer from similar hidden inhomogeneities as the DNMI pressure analyses. Thus, any trend derived from the KNMI wave charts should be considered as an upper bound and not as an unbiased best guess.

For a box west off Ireland, in 50°–55°N, 20°–10°W, maximum wave heights were read from the wave charts (1961–87) and annual percentiles (labeled 99% and 90% in the following table) as well as the annual maximum (max) were determined. From these annual time series, the mean heights and mean annual changes were calculated.

	Max	**99%**	**90%**
Time mean (m)	11.1	8.7	5.8
Change 1961–87			
cm yr^{-1}	3.8	2.7	3.8
% yr^{-1}	0.3	0.3	0.7

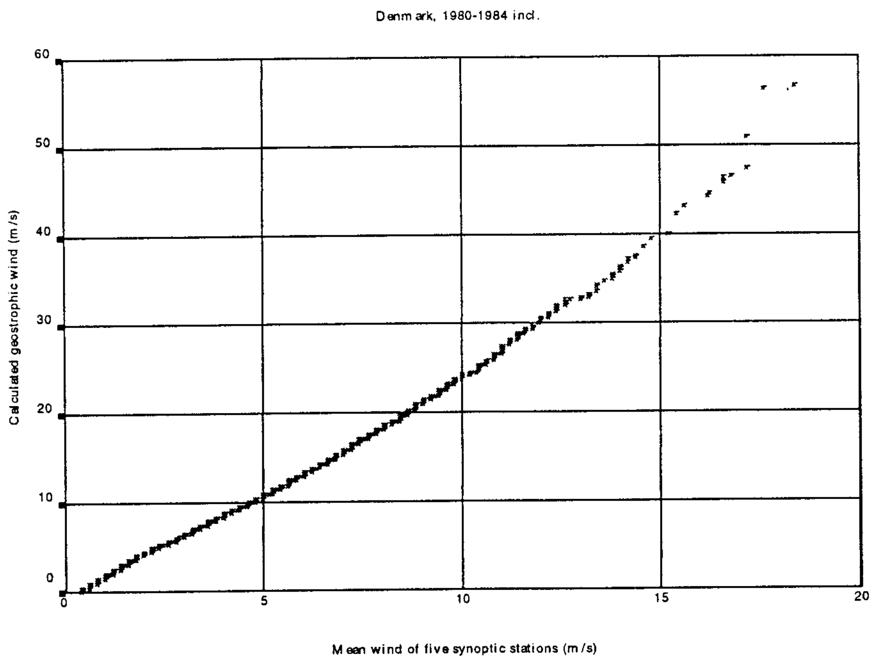

FIG. 3. Percentile–percentile plot of station wind speed and geostrophic wind speed for a Danish station, derived from 5 yr of daily data.

These numbers show changes considerably smaller than those given by others, such as Neu (1984), Bacon and Carter (1991), who report increases of the order of more than 1% yr^{-1}. We will later see in section 4b that the WASA reconstructions return even smaller trends in that area.

Using a downscaling approach, Kushnir et al. (1995) and Kushnir et al. (1997) built an empirical model relating wave hindcast data, generated with 10 yr of European Centre for Medium-Range Weather Forecasts (ECMWF) analyses of surface winds, with the mean air pressure field. This statistical model was then used to estimate the mean wave field from the air pressure field from 1962 onward. This procedure confirmed the presence of an increase in wave heights during the past few decades as inferred from the observational data. In the present paper a similar approach is pursued.

3. Analysis of the historical storm climate

In the next sections we deal in some detail with time series of intraannual percentiles and pressure tendencies. In the last subsection, we discuss two time series derived from tide gauges at the southern and eastern North Sea coast.

a. Geostrophic wind analyses

For 20 stations (see dots in Fig. 2) situated in northwestern Europe and the northeast Atlantic, the WASA project identified an uninterrupted pressure record of three or four daily observations for about the last 100 yr that could be homogenized. (The influence of changing instruments and gradually changing environments are less severe in case of air pressure measurements, but there are several other sources of potential inhomogeneities, such as relocations with a vertical displacement of the instrument or changing observational times.)

For these stations, triangles were set up and daily geostrophic winds were derived. Time series of annual 95% and 99% quantiles for various triangles are presented by Alexandersson et al. (1998) and for a triangle in the German Bight by Schmidt and von Storch (1993). They all exhibit marked interdecadal variability, with an intensification in the past decades. The findings are summarized by Figs. 4 and 5, which show standardized annual quantiles time series for triangles in the Scandinavian–Finland Baltic Sea region (Fig. 4) and in the British Isles–North Sea–Norwegian Sea region (Fig. 5). The quantiles are standardized; that is, for each triangle and each percentile, first the long-term mean and the standard deviation are determined, then the mean is subtracted and the time series is divided by the standard deviation.

There has indeed been an increase in the strong geostrophic wind speeds in the past decades, but this increase does not appear to be alarming when compared with conditions earlier in this century and at the end of the last century. There is a considerable amount of interdecadal variability, and an assessment using only data from 1960 onward leads to misleading result of dramatic increases.

Note that the interdecadal variability in the two considered quantiles are very similar, indicating that the annual geostrophic wind speed distribution is not becoming broader or narrower but is shifting as a whole to smaller or larger values.

Mietus (1995) examined annual mean geostrophic wind speeds derived from the triangle "Jan Mayen–

Svalbard–Bjørnøya" in the northernmost North Atlantic and likewise found an upward trend from 1960 onward, with a magnitude of 2 (cm s^{-1}) yr.

An important factor characteristic for the large-scale state of the atmospheric circulation in the North Atlantic area is the North Atlantic oscillation (NAO) (van Loon and Rogers 1978; Hurrell 1995), so that it appears plausible that the identified variations in storm frequency may be related to variations in the NAO. This is really the case, but the correlations are not large although statistically significant: For the 95 and 99 percentiles in Fig. 4 the correlations are only 0.49 and 0.37 only and, similarly, for Fig. 5, only 0.56 and 0.38.

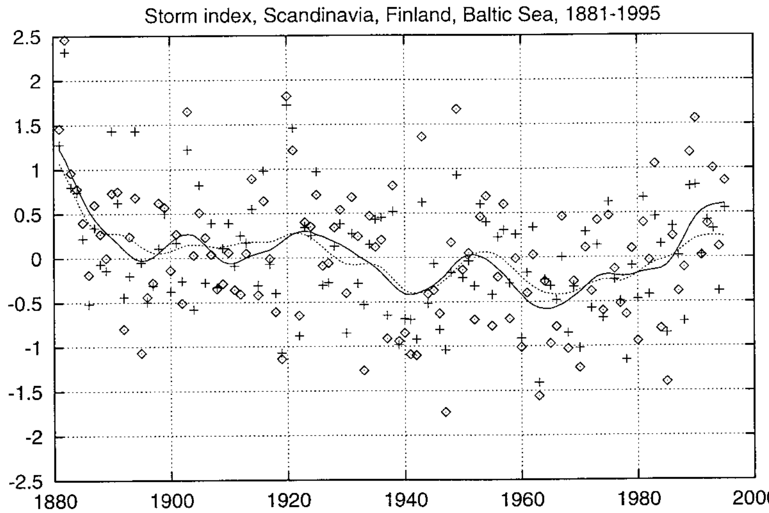

FIG. 4. Standardized annual 95% (diamonds and full line) and 99% (crosses and dotted line) quantile time series from pressure triangles in the Scandinavian, Finnish, and Baltic Sea regions. The lines are obtained from the yearly data by applying a Gaussian filter with standard deviation of 3 yr. Dimensionless units. (From Alexandersson et al. 1998.)

b. Pressure tendency analysis

Kaas et al. (1996) calculated 12-h absolute pressure tendencies for eight North Atlantic–Scandinavian stations for the period 1961–87. By means of a downscaling technique utilizing canonical correlation, the monthly mean (winter months only) of these absolute pressure tendencies for each station were related to North Atlantic monthly mean. The relations found were used to hindcast the time series of monthly means of absolute pressure tendency for the period 1903–87. For two of the stations the pressure tendencies could be calculated directly from observations so a direct comparison between observed/hindcasted values was possible. The result of this exercise is shown in Fig. 6 with a low-frequency appearance similar to that found for the geostrophic wind speed curves in Fig. 5.

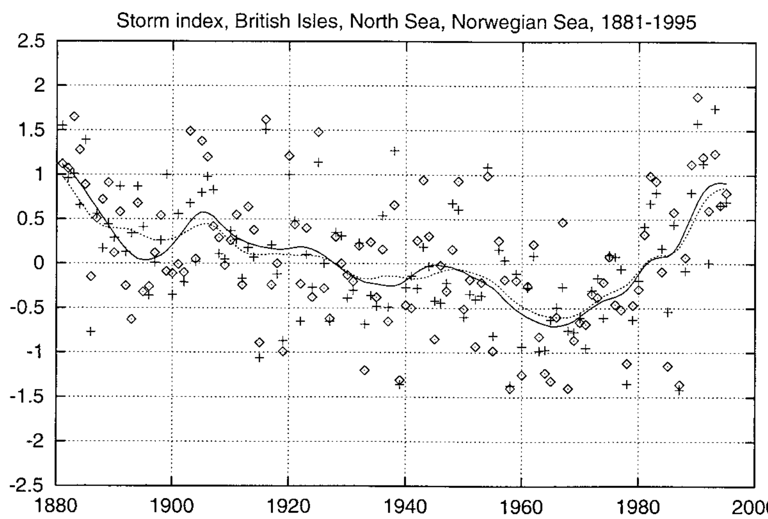

FIG. 5. Standardized annual 95% (diamonds and full line) and 99% (crosses and dotted line) quantile time series from pressure triangles in the British Isle, North Sea, and Norwegian Sea regions. The lines are obtained from the yearly data by applying a Gaussian filter with standard deviation of 3 yr. Dimensionless units. (From Alexandersson et al. 1998.)

The method was developed further in Schmith et al. (1998). However, the scope was somewhat different: namely, to investigate in detail the hypothesis that high-frequency variability and low-frequency variability of the mean sea level pressure are closely interlinked.

For eight stations in the North Atlantic (Schmith et al. 1997) 24-h tendencies were calculated, and for each winter during the period 1875–1995 50%, 10%, and 1% exceedance levels were calculated. The time series of these levels showed no dramatic behavior at any of the stations, although there was some increase during the past two decades. A similar downscaling to that in Kaas et al. (1996) was carried out but for the period 1900–95 and with canonical correlation analysis replaced by multilinear regression analysis. It was found that the exceedance levels were linked to the winter mean sea level pressure, with highest correlation coefficients for stations close to the North Atlantic storm track.

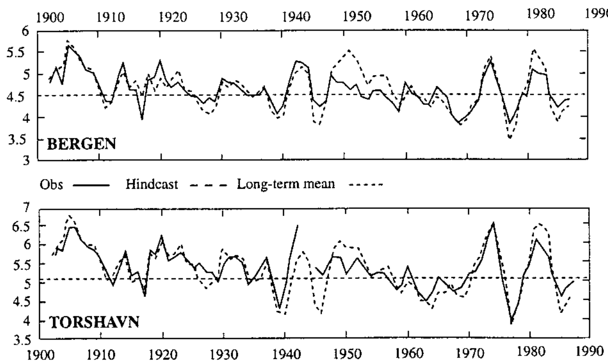

FIG. 6. Monthly mean of absolute values of pressure tendencies for Bergen and Thorshavn (see Fig. 2). Means derived from in situ data are given as a continuous line, and means derived indirectly via downscaling by the dashed lines. (From Kaas et al. 1996.)

The residual, that is, the signal not explained by the model, was also investigated. If the residual time series has a systematic trend, it would be a sign of changing physics not incorporated into the model, for instance systematic change in sea surface temperatures leading to decreased stability of the atmosphere and therefore increased baroclinic activity. The residual time series was found to be without any trend, indicating that no factors are missing in the model.

c. Storm-related sea level variations

The idea of using high-frequency variations of sea level as a proxy for storm activity was suggested by de Ronde (cf. von Storch et al. 1994). To do this, the annual mean water level is subtracted from the data, because changes in the mean water level are thought to reflect processes unrelated to the storm activity, such as local anthropogenic activity (e.g., harbor dredging), mean sea level rise, or land sinking. After subtraction of the annual mean, intraannual distributions of the water level variations are formed, as in the case of geostrophic winds discussed above, and intraannual quantiles are determined.

By now, the observational record at a series of tide gauges around the North Sea coast has been examined (Langenberg et al. 1997). At Cuxhaven (von Storch and Reichardt 1997), as well as at other locations, increases of the storm-related intraannual quantiles in the past decades were found, but the water levels vary still in a range comparable to historical levels. As examples, we present the time series for Den Helder (the Netherlands) and Esbjerg (Denmark) in Fig. 7. The Den Helder record is inhomogeneous because of the building of the the Ijsselmeer dam in the 1930s in the vicinity of the tide gauge (a rough correction was applied to the data).

4. Generating a "substitute reality" for wave statistics

As discussed above, an analysis of reported wave observations is of limited value because of the inhomogeneities hidden in such datasets. Therefore, an attempt was made to reconstruct the time–space statistics of the wave field with the help of a wave model integrated over 40 yr using a sequence of 6-h wind analysis. A detailed account of this simulation is offered by Günther et al. (1998).

With a homogeneous, realistic wind dataset we can expect, within the bounds of the skill of the wave model, to receive a detailed space–time evolution of wave parameters, such as significant wave height, which may be considered a substitute reality (see, for instance, Bauer et al. 1996). Even if the hindcasted substitute reality does not capture all details of the past wave history, we can expect that low-frequency variations in the wave statistics, including the interdecadal variability and trends, are reliably reproduced. Indeed, this assumption is found to be valid in the present analysis, when extended time series of in situ observed significant wave height statistics are compared with hindcasted wave heights in areas and time intervals with approximately homogeneous wind field analyses (Günther et al. 1998).

a. Wave model and forcing data

In the following we describe some technical details of the wave hindcast 1955–94. For details refer to Günther et al. (1998).

In the hindcast the fourth-generation wave model WAM (Komen et al. 1994) was used. It was run twice for the whole simulation interval 1955–94. First a "coarse-resolution" northern North Atlantic version (1.5° lat × long resolution, 9.5°–80°N, 78°W–48°E) was integrated using the operational wind analysis by the Fleet Numerical Operational Center (FNOC). The purpose of this simulation is to generate adequate time-dependent lateral boundary conditions for the "fine-resolution wind" run. (The results of the coarse simulation are of only limited use for the assessments of changes of the tall wave statistics in European coastal waters. The wind analyses exhibit some inhomogeneities, in particular in 1972 when the operation system was changed from manual analysis to numerical analysis. Also, the spatial resolution in the near-coastal areas of northern Europe is insufficient. Therefore, the results of this coarse run are not further considered.)

The hindcast itself is done on a "high-resolution" grid, covering the northeast Atlantic (0.5° lat × 0.75° long, 38°–77°N, 30°W–45°E) for 1955–94, using the operational air pressure analysis of the DNMI. From the air pressure field, surface winds were derived and used as forcing in the wave hindcast.

The DNMI analyses were prepared four times a day from 1955 until present. The pressure fields for the years 1955–81 were obtained by a numerical reanalysis on a 75-km grid using available pressure observations from ships and land stations. For the years 1955–79 the first-guess fields in the analysis were pressure fields digitized from manually analyzed weather maps on a 150-km grid, and for 1980–81 the first-guess fields came from operational analyses in a numerical weather prediction model system. From 1982 the pressure data were taken from operational analyses without any reanalysis. From January 1982 to May 1987 the pressure data were obtained from the global model at ECMWF, and those for June 1987–1995 from DNMI's regional weather prediction model.

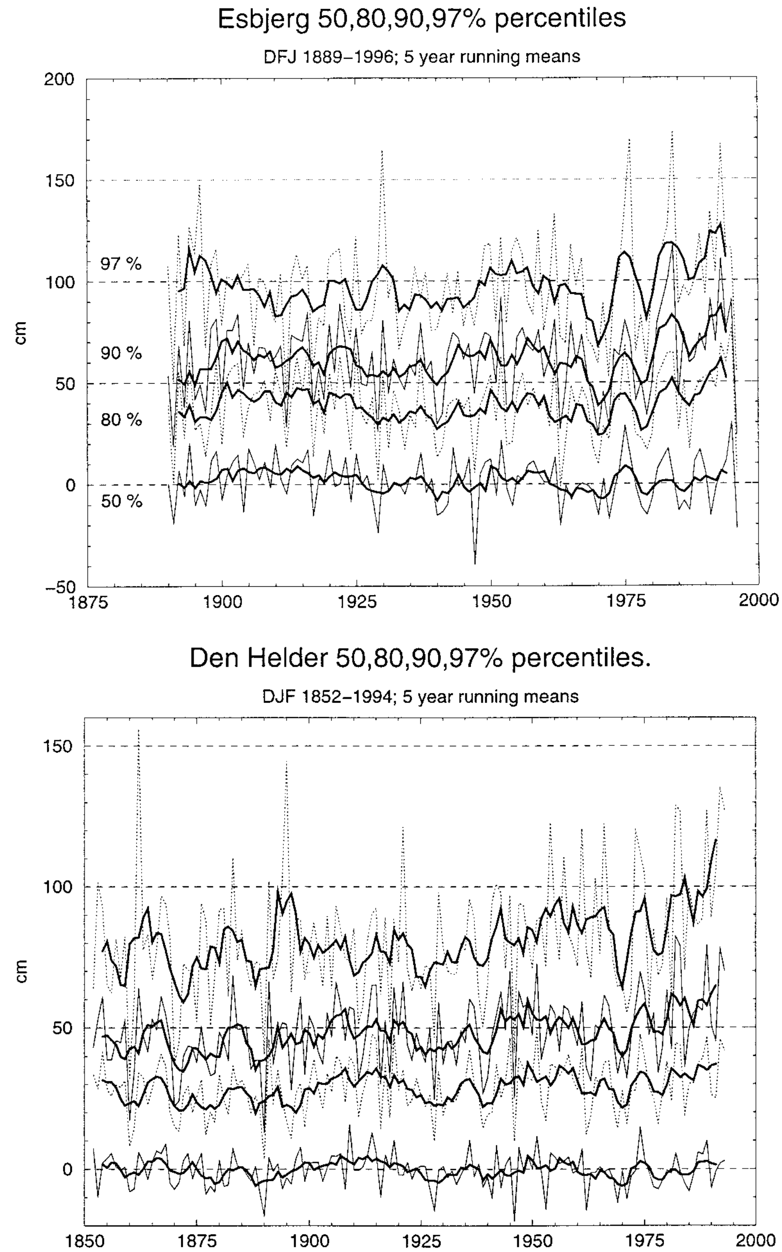

FIG. 7. Time series of the intraannual quantiles of storm-related water level variations (defined as deviation from the annual mean) at the gauges in Den Helder and Esbjerg (see triangles in Fig. 2). Units: cm.

The degree of contamination of the DNMI analyses by creeping inhomogeneities is examined with the help of maps of the ratio of storm-related standard deviations of air pressure calculated for consecutive 10-yr intervals. It is found that this standard deviation has undergone a steady increase in data-sparse areas far off the coasts, while remaining almost constant in an area surrounding the British Isles and covering the Norwegian Sea, the North Sea, and the Bay of Biscay (cf. Fig. 1). Based on this observation, we conclude that the DNMI analyses suffer from an artificial worsening of the storm climate in data-sparse areas.

In the area marked in Fig. 1, between 70° and 50°N and east of 20°W, the bias seems to be less severe. For this area slightly more storms were found in the decade 1984–93 than in the previous decades (348 as opposed to 339, 336, and 330). We do not know to what extent changes in the analysis scheme are responsible for the changing storm numbers in that area; therefore the result of this storm count should be taken as an upper bound of an increase of storm frequency and intensity.

To further examine the degree of inhomogeneities, we calculated time series of annual percentiles of geostrophic wind speeds derived from triangles, formed by in situ pressure gauges, and in the DNMI analyses. Figure 8 displays the result for the 90% quantiles for neighboring triangles. In case of the triangle "Thorshavn–OWS M–Bergen," no systematic differences between the two time series emerge, but in the case of the southern triangle "Bergen–Thorshavn–Aberdeen," the analysis exhibits a trend toward stronger winds that is absent in the in situ data. (The intercomparison between geostrophic winds derived from in situ observations with those calculated from the DNMI winds has only limited power in detecting inhomogeneities, as most of the surface pressure data available for geostrophic triangle wind calculations have entered the DNMI pressure analysis. In the present case, it may be that Aberdeen was not used for the DNMI analyses, while the other sites, Thorshavn, Bergen, and Ocean Weather Station M, were used.) Note that the trend in both triangles

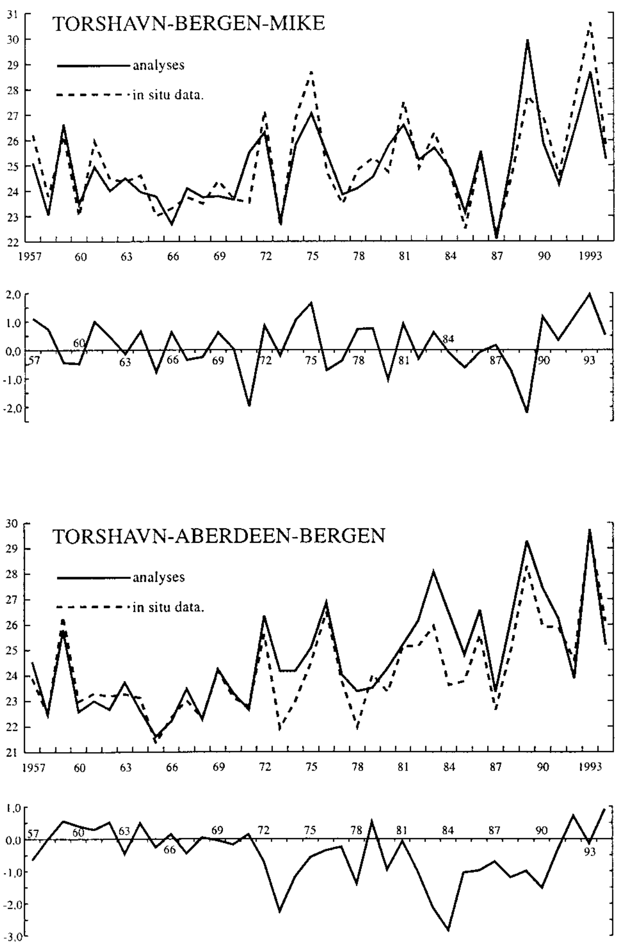

FIG. 8. Time series of annual 90% percentiles of geostrophic wind speeds derived from in situ data (top: Thorshavn–Ocean Weather Station M–Bergen; bottom: Thorshavn–Aberdeen–Bergen) and from the operational DNMI analyses. In the lower panels, the difference between the two curves in the upper panels in given. Units: m s^{-1}.

amount for about (2.5 m s^{-1}) (38 yr^{-1}), that is, ≈ 0.06 m s^{-1} yr^{-1}.

We conclude that the DNMI data to some extent describe an artificial worsening of the storm climate, not only in data-sparse areas but also over the North Sea; in particular, the analyses changed in 1982 and this seems to have introduced an inhomogeneity. This artificial worsening of the wind climate will, of course, be immediately transferred to the wave hindcast, so that all trends toward taller waves in the hindcast should be considered as upper bounds of any real upward trends.

b. Analysis of wave hindcast 1955–95: Selected locations

In Figs. 9 and 10 time series of annual maxima, means, and 99% and 90% December–January–February (DJF) quantities of local wind speeds and significant wave heights are shown for three selected locations: between Scotland and Norway (oil field Brent; 61°N, 1°E; for the locations, see Fig. 2), in the central North Sea (oil field Ekofisk; 56°N, 3°E, and in the Norwegian Sea (Ocean Weather Station M). In all three locations, there are upward (December–February, DJF) trends in the local winds and in the significant wave heights (in centimeters per second per year and centimeters per year).

Statistic	OWS M	Brent	Ekofisk
WIND SPEED			
Maximum	2.8	3.7	2.5
99%	5.3	3.4	4.6
90%	2.4	3.0	4.0
Mean	0.8	3.1	2.9
WAVE HEIGHT			
Maximum	7.7	4.3	1.9
99%	4.3	2.9	1.9
90%	0.9	0.6	1.1
Mean	1.1	1.0	0.6

A characteristic of these numbers is that the distributions have become wider in the past four decades.

The general increase in strong wind speeds is consistent with the increase in wind speed found for the triangles Thorshavn–Bergen–OWS M and Thorshavn–Bergen–Aberdeen (see Fig. 8), but the increase in geostrophic wind speed percentiles is much larger. This is due to the difference between wind speed and geostrophic wind speed.

The largest increases are found for the maxima of both the wind speeds and the wave heights. At Ocean Weather Station M the changes, derived from the ongoing in situ wind–wave observations, the hindcast compares well (Günther et al. 1998). For the mean wave height increases are 0.1–0.2 m during the 40 yr of hindcast, relative to mean heights on the order of 2–3 m; the signal is stronger for the maxima, for which accumulated increases of 1.30–3.30 m are simulated (on the background of 10–14-m averages).

Also, the temporal evolution of wave heights in the area west off Ireland considered by Bouws et al. (1996) was analyzed. The simulated increases, if any, are much smaller than those derived from the ship routing wave charts.

The trends are very sensitive to the time interval considered. The following table lists trends for the time interval 1961–87 (on the same time interval the ship routing map analysis discussed in section 2c was done) and for the full hindcast time interval 1955–94.

	Max	99%	90%
1961–87			
Time mean (m)	17.4	13.0	8.4
Change (cm yr^{-1})	5.5	1.0	0.5
(% yr^{-1})	0.3	0.1	0.1
1955–94			
Time mean (m)	17.3	12.9	8.3
Change (cm yr^{-1})	2.2	–1.5	–0.4
(% yr^{-1})	0.1	–0.1	0.0

The difference between the changes of the annual maxima (max) and of the annual percentiles (99% and 90%) between the wave charts (section 2c) and the WAM reconstruction is remarkable. The wave charts indicate an annual increase of 2.7 cm yr^{-1} for the 99% percentiles, whereas the hindcast simulates for the same time interval an increase of only 1 cm yr^{-1}, which becomes a decrease if the trend is calculated over the full 40 yr. These peculiar observations point to creeping inhomogeneities in the ship routing maps and in the frequency of extreme wind situations in the wind analyses used in the wave hindcast. Only the trend in the maximum is not changing its sign when extending the 1961–87 time series by about 10 yr to the 1955–94 time series.

At the present time, we cannot determine to what extent the increases in wave height are due to improved air pressure analysis techniques and how much is due to a real worsening of the wave climate. However, the lesson to be learned from Fig. 8 is that there is indeed

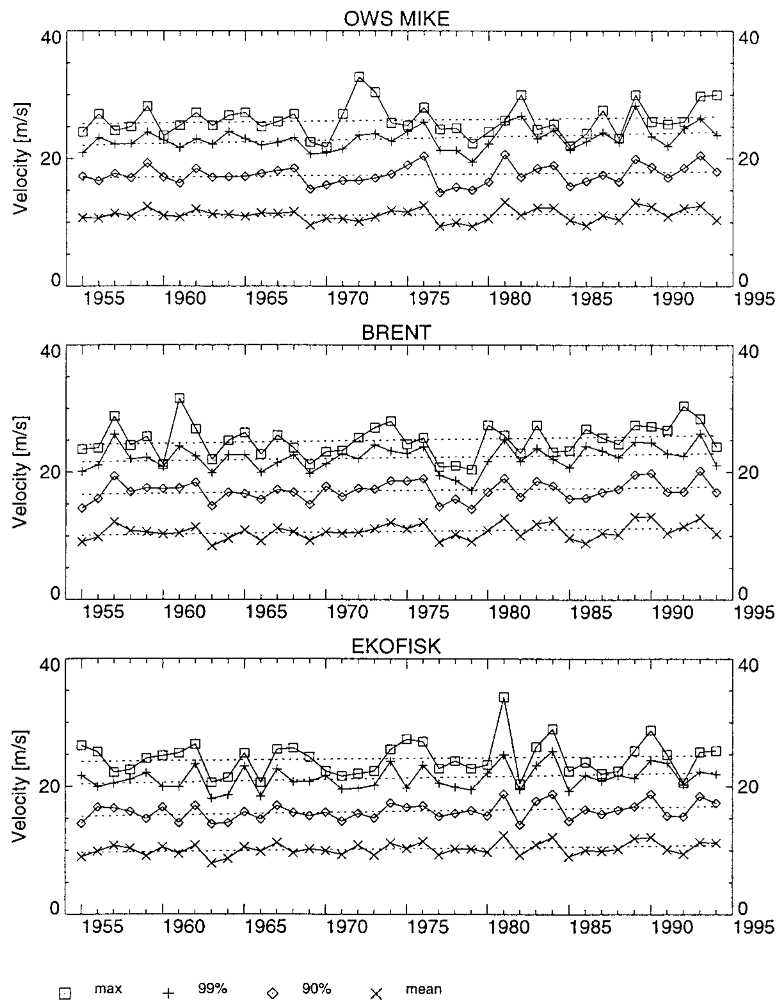

Fig. 9. Annual maxima, means, and 99% and 90% percentiles of wind speed percentiles (for OWS Mike, Brent, and Ekofisk, see Fig. 2) as derived from DNMI analyses. Trends are given as dashed lines. Units: m s^{-1}.

an upward trend in the past 40 yr at the locations of OWS M, Brent, and Ekofisk. Another characteristic of the time series is the presence of irregular temporal variations on all timescales, from year to year to interdecadal.

c. Analysis of wave hindcast 1955–94: Overall statistics

A convenient summary of systematic changes in the frequency of tall waves is a map of the trend in the 90% quantiles, as shown in Fig. 11. In both the North Sea and the Norwegian Sea, the trend is upward with an increase of about 1 cm yr^{-1} (or, equivalently, 40 cm over the considered time interval 1955–94). A local maximum of the trend is obtained northwest off Scotland, with mean annual increases of about 2 cm yr^{-1}. Otherwise, the trend is mostly negative, with decreases of about 1 cm yr^{-1} in the area west of Ireland, in the open Atlantic Ocean, and, with somewhat slower decreases, in the Bay of Biscay. On the boundary of the considered area, in particular on the southern and northern boundaries, larger trends appear, which may partly reflect boundary effects or inhomogeneity problems with the wind fields in these data-sparse areas.

5. Reconstruction of past wave statistics at selected locations

Von Storch and Reichardt (1997) developed a statistical technique that allows the backward reconstruction of intramonthly percentile time series of some local variable and the construction of scenarios for these intramonthly percentiles consistent with a given global climate change scenario. The basic idea is to first build a statistical model that links the intramonthly percentiles to planetary-scale monthly mean air pressure (or other) fields, and then to use this link to derive estimates of intramonthly percentiles from historical monthly mean air pressure maps or from air pressure fields changes simulated in climate change scenarios.

The base model is explained in section 5a; it deviates from the technique used by von Storch and Reichardt (1997) in that redundancy analysis is used rather than canonical correlation analysis. Since this model is nonstandard and has not yet been described in the open literature, section 5a is somewhat more detailed than the other parts of this paper. The model is applied to two locations, the oil fields Brent (between Scotland and Norway) and Ekofisk (central North Sea). The results for the two positions are discussed in some detail in section 5b. Scenarios for plausible future statistics are derived in section 6b.

a. The statistical model for extending the data in time

A regression model is built that relates two sets of random vectors $\mathbf{S}_t$ and $\mathbf{Q}_t$. In the present cases, the vector time series $\mathbf{S}_t$ represents the winter (DJF) monthly

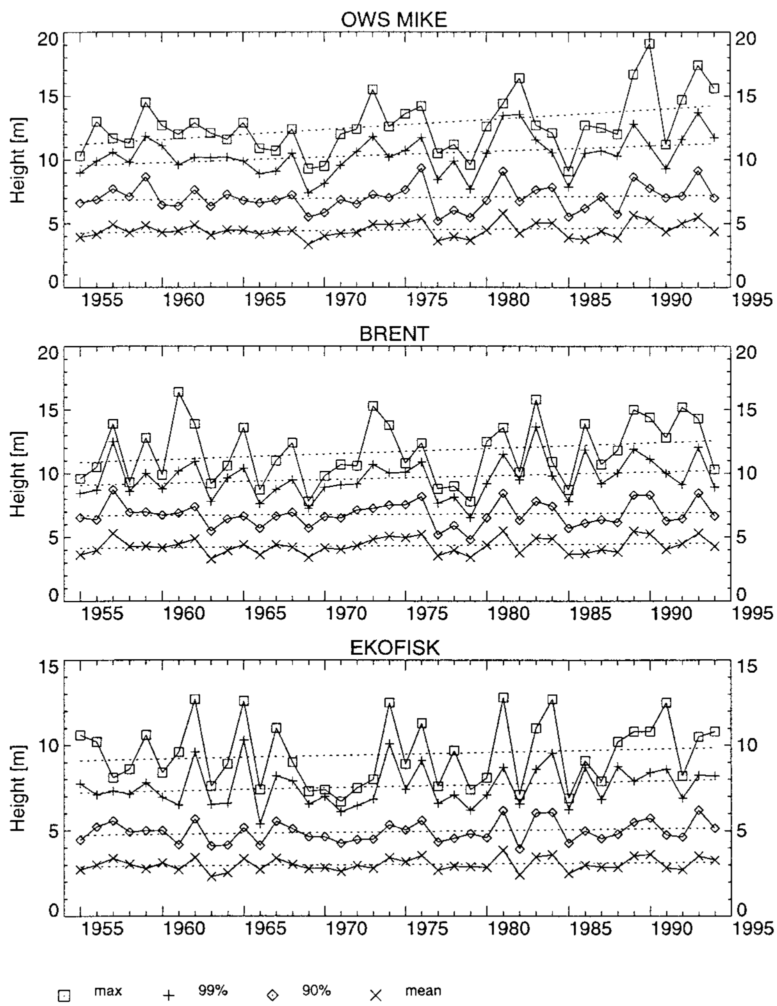

FIG. 10. Annual maxima, means, and 99% and 90 % percentiles of significant wave height percentiles (for OWS Mike, Brent, and Ekofisk, see Fig. 2) as derived from the wave hindcast. Trends are given as dashed lines. Units: m. (From Günther et al. 1998.)

mean air pressure (sea level pressure, SLP) distributions. The other vector time series $\mathbf{Q}_t$ is formed by the 50%, 80%, and 90% intramonthly quantiles of significant wave height at a given location (Brent or Ekofisk):

$$\mathbf{Q}_t = \begin{pmatrix} q_{50\%} \\ q_{80\%} \\ q_{90\%} \end{pmatrix}_t . \qquad (1)$$

Both vectors are assumed to be centered; that is, their time means are subtracted prior to the analysis. Also, compression of the data with the help of EOFs is done prior to the analysis in order to avoid artificially enhanced correlations. Four EOFs are used for SLP and two for the intramonthly percentiles.

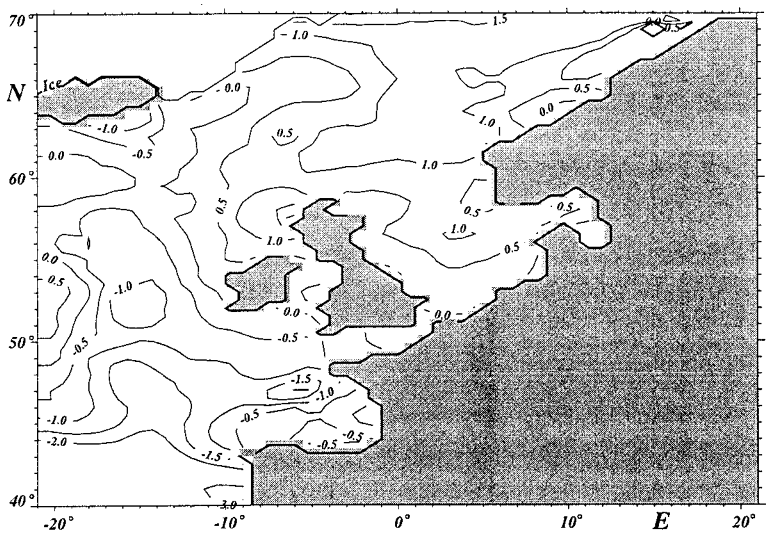

FIG. 11. Map of the 1955–94 trends in the intraannual 90% quantiles of significant wave height, as derived from the 40-yr hindcast executed with the WAM wave model. Units: cm yr^{-1}. (From Günther et al. 1998.)

A redundancy analysis (RDA) (Tyler 1982; von Storch and Zwiers 1998) is performed with the two vector time series. The result of an RDA are pairs of vectors ($\mathbf{p}^{s;k}$,$\mathbf{p}^{q;k}$) and time coefficients $\alpha_{s;k}(t)$ and $\alpha_{q;k}(t)$ so that

$$\mathbf{S}_t = \sum_{k=1}^{K} \alpha_{s;k}(t)\mathbf{p}^{s;k}, \qquad (2)$$

$$\mathbf{Q}_t = \sum_{k=1}^{K} \alpha_{q;k}(t)\mathbf{p}^{q;k}. \qquad (3)$$

The patterns $\mathbf{p}^{s;k}$ and $\mathbf{p}^{q;k}$ are determined such that the regressed expansion

$$\hat{\mathbf{Q}}_t = \sum_{k=1}^{K} \rho_k \alpha_{s;k}(t)\mathbf{p}^{q;k} \qquad (4)$$

describes an optimum of variance of **Q** for a given number, *K*. In order to have uniquely determined solutions, the expansion patterns $\mathbf{p}^{q;k}$ of the *predictand* are required to be orthonormal, whereas the patterns $\mathbf{p}^{s;k}$ are required to be linearly independent. The first pair of patterns are chosen such that a maximum of **Q** variance is explained, the second pair such that a maximum of additional variance is represented [because of the orthonormality of the $\mathbf{p}^{q;k}$ patterns, the variance contributions in (4) may simply be added].

The coefficients are obtained by the projections

$$\alpha_{s;k} = \mathbf{S}^{\mathrm{T}}\mathbf{p}_A^{s;k}, \qquad (5)$$

$$\alpha_{q;k} = \mathbf{Q}^{\mathrm{T}}\mathbf{p}^{q;k}, \qquad (6)$$

where $\mathbf{p}_A^{s;k}$ are the adjoints to the patterns $\mathbf{p}^{s;k}$. In (6) the patterns $\mathbf{p}^{q;k}$ appear, since these are constructed to be orthonormal and thus self-adjoint. The patterns $\mathbf{p}^{s;k}$, on the other hand, are not orthonormal and therefore not self-adjoint.

The coefficients are normalized to one,

$$\mathrm{VAR}(\alpha_{q;k}) = \mathrm{VAR}(\alpha_{s;k}) = 1,$$

so that the three components of $\mathbf{p}^{q;k}$ may be interpreted as anomalies that occur typically together with the "field distribution" $\mathbf{p}^{s;k}$.

The downscaling model that relates the large-scale air pressure information to the intramonthly wave height information is a regression model $\alpha_{q;k} = \rho_k \alpha_{s;k}$ for the RDA coefficients $\alpha_{s;k}$ and $\alpha_{q;k}$. A reconstruction in the three-dimensional space is then obtained using (3):

$$\hat{\mathbf{Q}}_t = \widehat{\begin{pmatrix} q_{50\%} \\ q_{80\%} \\ q_{90\%} \end{pmatrix}} = \sum_{k=1}^{K} \rho_k \alpha_{s;k}(t)\mathbf{p}^{q;k}. \qquad (7)$$

The regression model (7) may be applied to anomalies of observed or simulated air pressure fields $\mathbf{S} = \Sigma\alpha_{s;k}\mathbf{p}^{s;k}$.

The success of the reconstruction of intramonthly wave height percentiles is quantified by two measures of skill, namely, the correlation skill score ρ_κ and the percentage of represented variance ε_κ for $\kappa = 50\%$, 80%, and 90% (Livezey 1995):

$$\rho_\kappa = \frac{\mathrm{Cov}\left(\hat{q}_{\kappa;t}, q_{\kappa;t}\right)}{\sqrt{\mathrm{Var}\left(\hat{q}_{\kappa;t}\right)\mathrm{Var}\left(q_{\kappa;t}\right)}},$$

$$\varepsilon_\kappa = 1 - \frac{\mathrm{Var}\left(\hat{q}_{\kappa t} - q_{\kappa;t}\right)}{\mathrm{Var}\left(q_{\kappa;t}\right)}, \tag{8}$$

where $\hat{q}_{\kappa;t}$ is the estimated κ percentile in the month t.

b. Results for Brent and Ekofisk

In this section the paired patterns $\mathbf{p}^{q;k}$ and $\mathbf{p}^{s;k}$ are shown and discussed for the wave height percentiles for the oil fields Brent and Ekofisk. The results for Brent are shown in some detail, whereas those for Ekofisk are only summarized.

Figure 12 and Table 1 display the first two RDA patterns of the monthly mean air pressure fields and wave height quantiles for Brent. The first air pressure pattern is related to the NAO (van Loon and Rogers 1978; Hurrell 1995). An intensified NAO in the monthly mean is associated with enhanced wave heights. In effect, this pattern describes a shift of the intramonthly distribution toward taller waves. The second pattern describes a mean southerly flow across the northern North Sea; the 50% quantile of the wave height distribution is enhanced, whereas the 90% is reduced by 26 cm, so that the overall distribution becomes narrower.

For Ekofisk similar patterns are found (not shown); the wave height anomalies are smaller than at Brent, and the second pair is slightly more relevant at Ekofisk for representing wave height variance.

In the second step, the observed monthly mean air pressure anomaly fields from 1899 until 1994 were fed into the regression model (7) and time series of the quantiles of wave height distribution at Brent are estimated. The last 40 yr may be compared with the hindcast data, whereas the first five decades represent our best guess and cannot be verified at this time.

For the 90% quantiles of wave height distribution, the reconstructed time series 1899–1994 and the hindcasted time series 1955–94 are displayed in Fig. 13. (The results for the other percentiles are similar and not shown for the sake of brevity.) In the past four decades, the similarity between hindcast and statistically derived heights is good (cf. Table 2), and the statistical model confirms the hindcasted increase. However, this increase appears “normal” when compared to the changes that may have taken place earlier in this century. Indeed, waves as tall as those nowadays seem to have occurred in the first two decades, when the NAO was strongest; in the 1920s the NAO weakened significantly (van Loon and Rogers 1978), and our statistical model indicates that concurrently the height of the waves dropped by several tenths of a centimeter per year.

TABLE 1. Characteristic anomalies of intramonthly percentiles of significant wave height at the oil field Brent (61°N, 1.5°E) north of Scotland in winter (DJF) as obtained in a redundancy analysis. The k row is the kth redundancy vector $\mathbf{p}^{q;k}$. This vector represents ε_k of the variance of $\mathbf{Q}$ within the fitting interval January 1955–February 1995. Its coefficient $\alpha_{q;k}$ shares a correlation of ρ_k with the coefficient of the air pressure pattern $\mathbf{p}^{s;k}$ within the fitting interval.

κ =	Wave height (cm)			ε_k (%)	ρ_k
k	50%	80%	90%		
1	−86	−114	−122	94	0.84
2	33	3	−26	5	0.08

TABLE 2. Correlation between hindcasted and reconstructed quantile time series, and proportion of described variance of wave height accounted for by the RDA model (7) at Brent and Ekofisk.

Quantile	Wave height 50%	80%	90%
BRENT			
Correlation (%)	84	82	78
Described variance (%)	70	67	61
EKOFISK			
Correlation (%)	73	69	63
Described variance (%)	52	47	40

Note that the trends in Fig. 11 cannot directly be compared with those in Fig. 13. Figure 11 is based on time series of annual quantiles, whereas Fig. 13 is derived from intramonthly quantiles in winter months (DJF).

6. Scenarios for the expected time of doubled carbon dioxide concentrations

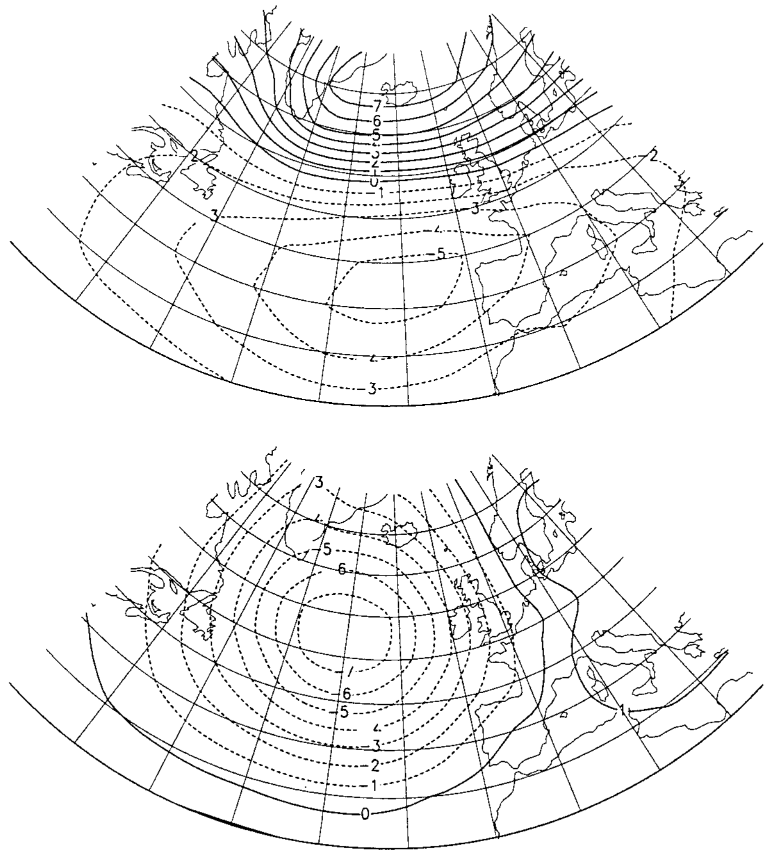

FIG. 12. First two monthly mean air pressure anomaly distributions identified in a redundancy analysis as being most strongly linked to simultaneous variations of intramonthly quantiles of significant wave height at Brent (61°N, 1.5°E). The anomalies of the quantiles at that position are listed in Table 1.

In order to determine a consistent scenario of expected future wave height statistics in the northeast Atlantic, use is made of a a paired "2 × CO_2"/"control" time-slice experiment with a T106 atmospheric GCM (Bengtsson et al. 1995; Bengtsson et al. 1996; Cubasch et al. 1996). In the control time-slice experiment, the atmospheric GCM simulates the equilibrium response to present-day sea surface temperature and sea ice distribution and present carbon dioxide concentrations. For the 2 × CO_2 experiment, SST and sea ice distributions from a simulation with a coupled low-resolution atmosphere–ocean GCM with gradually increasing carbon dioxide concentrations are determined from the time of doubled carbon dioxide concentrations at about the year 2050 (Cubasch et al. 1992). These SST and sea ice distributions are then used as specified, time-constant lower boundary conditions for the T106 atmospheric GCM. Additionally, the carbon dioxide concentrations are doubled.

The time-slice experiments control and 2 × CO_2 were integrated for 6 yr. Clearly, an integration of only 6 yr is rather short (enforced by the enormous computational costs of such simulations), and the discrimination between interdecadal variability and the response to the changed boundary conditions and radiative forcing will be difficult. In fact, in turns out that the derived scenarios for storminess, wave climate, and storm surge statistics can hardly be distinguished from the natural variability (see below).

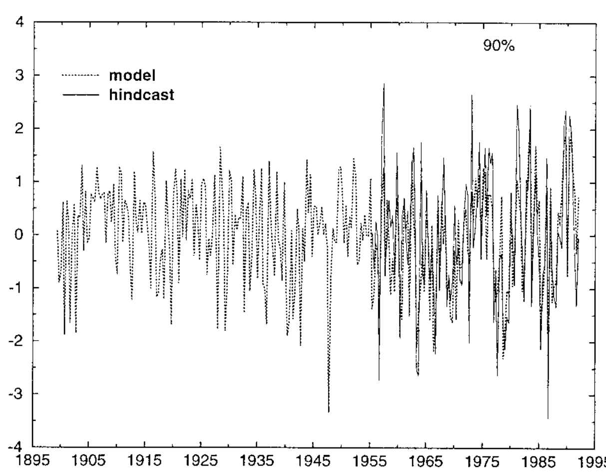

FIG. 13. Reconstructed (dashed line) and hindcasted (continuous line; 1955–94) anomalies of 90% quantiles of significant wave heights at Brent (61°N, 1.5°E). Units: m.

The output of the time-slice experiments is used for deriving scenarios of changing storminess, wave climate, and storm surge statistics. This is done with two different approaches. First, the simulated weather streams, in terms of near-surface wind, are considered (Beersma et al. 1997) and fed into the WAM wave model (Rider et al. 1996) and into a storm surge model (Flather and Smith 1998; Langenberg et al. 1997). The results of this exercise are presented in section 6a. The other approach makes use of the RDA model presented in section 5: The time mean difference of SLP in the two time-slice experiments is fed into (7) (see section 6b).

a. Dynamically derived scenarios

The T106 atmospheric GCM operates with a horizontal resolution of approximately 75 km, which is thought to be sufficient for modeling a realistic weather stream, that is, storms and high pressure systems that are consistent with observed weather in terms of duration, frequency, strength, and track. Therefore, this specific climate change experiment was used in the WASA project in spite of the short simulation time.

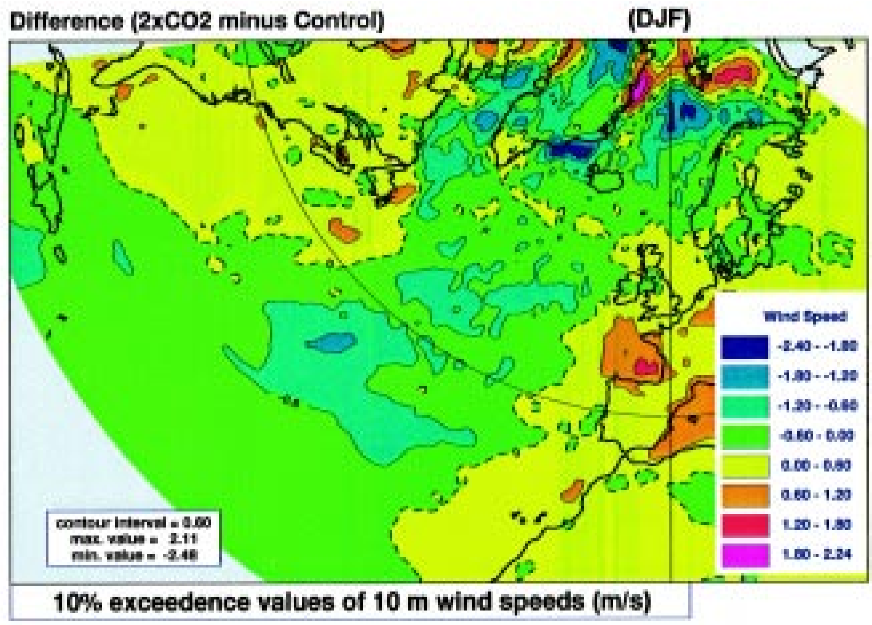

FIG. 14. Change in the intraannual 90% quantiles of wind speed as derived from a paired atmospheric circulation model run with present and doubled carbon dioxide conditions. Units: m s^{-1}. (From Beersma et al. 1997.)

Beersma et al. (1997) examined the output of the T106 simulations and found the simulated weather stream to be consistent with observations during a positive phase of the North Atlantic oscillation, that is, a phase with westerlies stronger than on average.

The intercomparison of the two simulations, control and $2CO_2$, yielded only few changes between the present and prospective future storm climate (Fig. 14). In the Bay of Biscay the 90% quantiles of wind speed are simulated to be increased by up to 1.5 m s^{-1} and in the central North Sea up to 0.5 m s^{-1}. Over most of the Atlantic, however, the wind speed in the climate model is decreased by as much as 1 m s^{-1}.

Both weather streams, from the control run as well as the 2 CO_2 run, were used as forcing fields for the wave model WAM (Rider et al. 1996). The 90% wave height quantiles are found to increase in the Bay of Biscay and in the North Sea by up to 0.5 m, whereas in most of the North Atlantic, the wave heights are decreasing (Fig. 15).

Flather et al. (1998) and Flather and Smith (1998) ran a storm surge model with the wind and air pres-

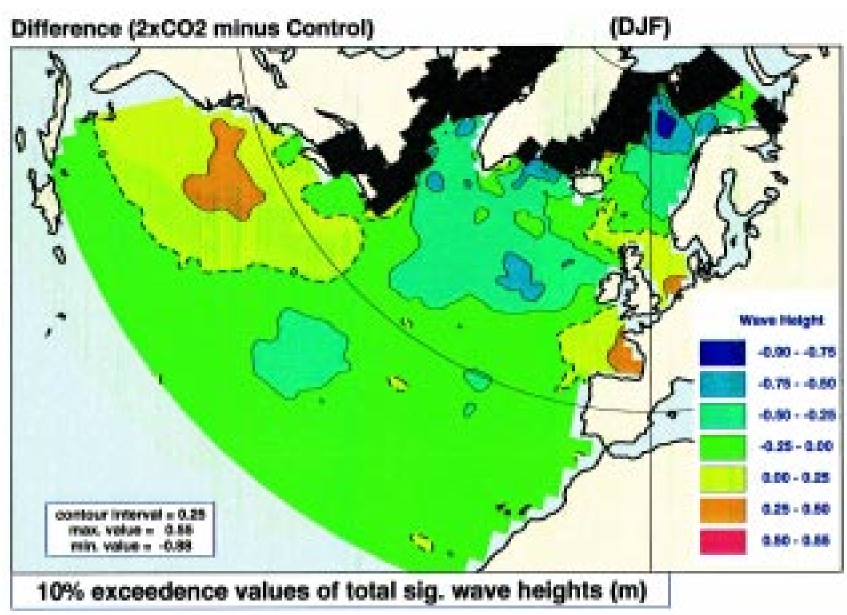

FIG. 15. Change in the intraannual 90% quantiles of significant wave height simulated by a wave model as a response to weather streams derived from a paired atmospheric circulation model run with present and doubled carbon dioxide conditions. Units: m. (From Rider et al. 1996.)

sure data from the DNMI analysis 1955–94 (reference run) and from the two time-slice experiments. It was found that the reference run quite successfully reproduced the storm surge statistics derived from various tide gauges along the North Sea coast as well as the along Irish and British coasts. The control time-slice experiment significantly underestimated the height of the severe storm surges. The difference, in terms of 5-yr return values, between the 2 CO_2 and the control run surges was everywhere positive, with maximum values of 65 cm in the German Bight and 30 cm along the Dutch coast (see Fig. 16). When compared with the variability of 5-yr return values calculated from different 5-yr chunks of the reference (DNMI wind) run, these changes appeared within the range of natural variability. However, without further data, Fig. 16 may be considered as a best estimate at this time.

Langenberg et al. (1997) also integrated a storm surge model with the T106 weather streams and found a moderate increase of severe storm surges in the North Sea consistent with Flather's results. According to their analysis the increase is mainly due to an increase of the mean water level and not caused by storm-related short-term variations around the mean.

b. Empirically derived scenarios

An alternative scenario for possible future modifications of the surge climates is the use of the regression model (7). To do this, the mean difference of air pressure 2 CO_2–control from the paired T106 time-slice experiments is calculated (Fig. 17) and fed into the regression model for anomalies of intramonthly quantiles of wave heights at Brent in the northern North Sea and at Ekofisk in the central North Sea. This exercise yields the following results.

		Change (cm)	
Quantile	**50%**	**80%**	**90%**
Brent	13	18	20
Ekofisk	14	19	22

The statistical models predicts a small, almost uniform, shift of 10–20 cm of the wave height distribution toward taller waves. Thus, the projected changes of the wave height distribution at the two locations are small and qualitatively consistent with the results obtained in the dynamically derived estimates. Note, however, that the numbers cannot be compared one to one, as the dynamically determined numbers refer to annual quantiles whereas the statistical model returns intramonthly percentiles.

An advantage of the statistical method is that it does not require the availability of a realistic weather stream as only mean fields are processed. Therefore global climate change scenarios generated with coarse resolution, such as T42 (horizontal resolution approximately 300 km), can also be used as input. A time-slice experiment, formally identical to the one considered so far but integrated over 30 yr with a T42 resolution, is available and has been used for the derivation of another, equally plausible scenario. This results in decreases of the significant wave height percentiles at Brent of the order of 50–70 cm; at Ekofisk the reduction is about 10 cm for all three percentiles.

The T106 mean air pressure field was also used to estimate changes of storm-related surge percentiles at a number of southern and eastern North Sea coast tide gauges (Langenberg et al. 1997).

		Change (cm)	
Quantile	**50%**	**80%**	**90%**
Den Helder	6	7	8
Esbjerg	8	11	13

These numbers compare well to the estimate given by von Storch and Reichardt (1997) for Cuxhaven. If the T42 time-slice experiment is used instead of the T106, then the changes of storm-related percentiles are still positive but considerably smaller.

7. Conclusions

a. Analysis of past hundred years

Our joint efforts for determining whether the storm and/or wave climate in the North Atlantic Ocean and adjacent seas have roughened resulted in two findings.

- *The storm and surge climate along the European coasts has not roughened in the past hundred years.* This result is consistent with other analyses based on local data. For instance, Jónsson (1981) studied the number of "storm days" on Iceland, as defined by local observations, and found no systematic changes (cf. von Storch et al. 1994).

  The Koninklijk Nederlands Meteorologisch Instituut published an assessment on the state of climate and its change for the territory of the Neth-

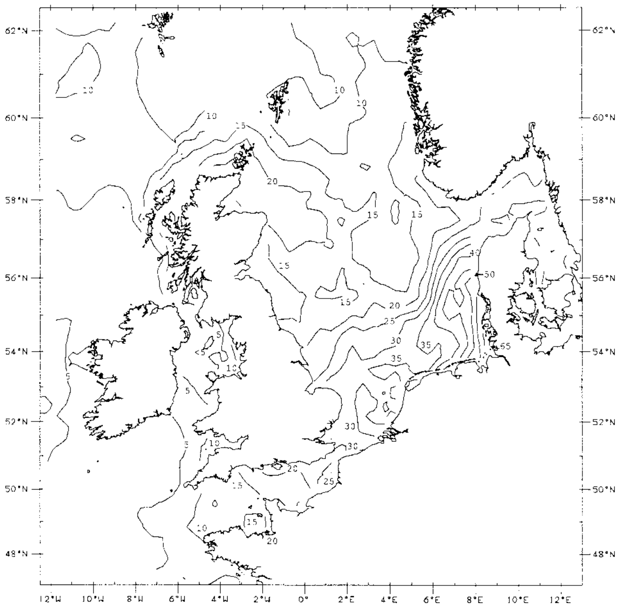

FIG. 16. Difference of 5-yr return values of water level heights, derived from simulations of a storm surge model, forced with winds and air pressure from the 2 CO_2 and the control T106 time-slice experiments. The difference is within the bounds of natural variability. Units: cm.

erlands (KNMI 1993). According to that report the maximum wind speeds observed during severe storms have not increased between 1910 and today.

- For the wave statistics, hardly any reliable estimates about systematic trends can be derived for in situ data, and all numbers established on these grounds should be considered as upper bounds of any real roughening.

To overcome this situation, the Waves and Storms in the North Atlantic (WASA) project has executed a four-decade-long hindcast. This hindcast suffers again from inhomogeneities inherited from the wind–air pressure analyses. It is hoped, however, that the derived empirical model is less affected by these problems.

The empirical model confirms the finding of a roughening wave climate in the past four decades and relates it in part to a change of the strength of the North Atlantic oscillation (cf. Hurrell 1995).

However, the increase of the last decades does not appear alarming when compared to the reconstruction of the wave field earlier this century.

In summary, it is claimed that neither the storm climate nor the wave climate has undergone significant systematic changes in this century. Instead, the situation is masked by the presence of natural variability on all timescales, ranging from year to year to interdecadal. This low-frequency variability violates the basic assumption of stationarity in conventional extreme value analyses and coastal engineers should be aware of this violation as a potential pitfall in conventional data analysis.

The recent increase in wave heights, the reality of which is still questionable, might well be another swing in the never-ending sequence of ups and downs of natural variability. Further close monitoring of the development is required to eventually evaluate whether the other possible explanation—systematic changes because of anthropogenic climate change—might be adequate (cf. von Storch and Hasselmann 1995).

Our study has a number of caveats. The analysis of geostrophic winds, pressure tendencies, and high-frequency sea level variations covers only the near-coastal areas of northern Europe, and no robust analysis is available for open ocean regions. Also, one may speculate whether the link between these proxy data and the wind speeds holds for extreme wind speeds. Another caveat refers to the wave hindcast. This has been performed with wind analysis that over the course of time resolved more details (i.e., strong wind events); thus the diagnosed roughening of the wave climate in the past decades may still be artificial to some extent.

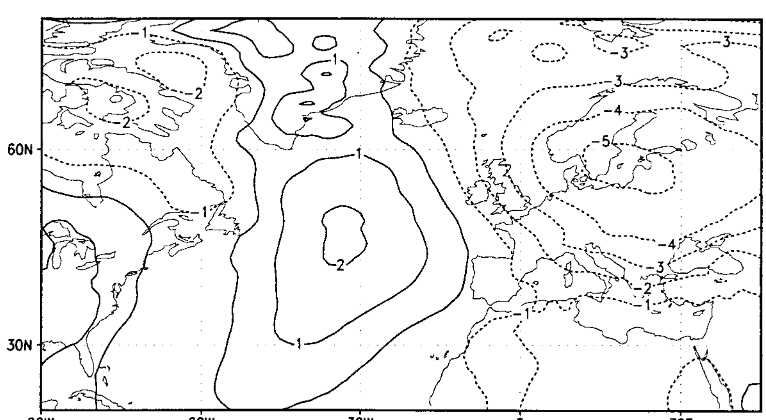

FIG. 17. Simulated atmospheric response to doubled carbon dioxide concentrations, as derived from a T106 time-slice experiment. The variable shown is air pressure at sea level, given in hPa.

b. *Outlook for the next century*

Our scenario for the expected time of doubled carbon dioxide concentrations points to moderate increases of surges along the North Sea coast and of wave heights in the Atlantic.

At this time, a word of caution is required. The scenarios given above are consistent with, and within, the range of previously observed variations. As such, they are plausible. However, they depend crucially on the validity of the driving GCMs; if these GCMs turn out to be inadequate then our numbers will be inadequate as well. Thus, these scenarios should not be given too much informational weight.

Also, no error bars are given for the scenarios. Such error bars are often considered by physicists to be indispensable but cannot be given with any degree of confidence for scenarios. The expected error is composed of many factors, such as the natural variability of the system, the uncertainty in the timing of the expected atmospheric doubled carbon dioxide concentration, or errors originating from the various parameterizations in the used climate model. Since the climate models are tuned to the observational record and only one such record exists, rigorous statements about errors cannot be made.

c. Other aspects

A topic not within the focus of the WASA project, but of related interest, is the Baltic Sea. Here as well, increased storm surge levels have been reported, but Backmann and Tetzlaff (1998) showed that the increase since the 1950s is mainly due to the increased volume of the Baltic as a result of intensified mean westerly winds (cf. Heyen et al. 1996). Also, levels of wave activity were found to be more or less constant (Mietus and von Storch 1997).

Other aspects examined in the WASA project concern the potential of changing storm surges at the southern North Sea coast (Bijl 1997) and a process study demonstrating that an acceleration of the weather stream does not cause a significant intensification of the heights but rather a reduction (Bauer et al. 1996).

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