PERGAMON

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Continental Shelf Research 23 (2003) 251–263

CONTINENTAL SHELF
RESEARCH

www.elsevier.com/locate/csr

Wave height variations in the North Sea and on the Norwegian Continental Shelf, 1881–1999

Frode Vikebø[a,*], Tore Furevik[a,b], Gunnar Furnes[c], Nils Gunnar Kvamstø[a], Magnar Reistad[d]

[a] *Geophysical Institute, University of Bergen, Allegt 70, Bergen 5007, Norway*
[b] *Nansen Environmental and Remote Sensing Center, Bergen, Norway*
[c] *Norsk Hydro, Research Center, Sandsli, Norway*
[d] *The Norwegian Meteorological Institute, Bergen, Norway*

Received 6 September 2001; received in revised form 24 October 2002; accepted 15 November 2002

Abstract

Analyses of overlapping Norwegian Meteorological Institute (DNMI) hindcast squared monthly mean wind speeds and monthly mean significant wave heights show a linear relation. Based on available time series of wind speed, computed from sea level pressure (SLP), this enables us to establish long and consistent time series of monthly mean significant wave heights. Data sets of monthly mean 10 m wind speeds from nine locations in the North Sea and on the Norwegian Continental Shelf have been investigated. The data sets include World Meteorological Organization (WMO) data, 1881–1982, DNMI hindcast data, 1955–1999, and National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) data, 1948–1999. From these time series it is evident that mean wave heights are subject to significant variations within a variety of time scales. There is a positive trend starting in the 1960s, mainly in northern parts of the North Sea, with significant regional variation. The increase is, however, not more dramatic than the decrease which occurred from 1881 and towards the beginning of the 20th century.

Analyses of annual maximum significant wave heights based on 6 h values of DNMI data, 1955–1999, strongly indicate increasing wave heights and rougher wave climate at the stations off the coast of mid-Norway. At the other stations the trends are only weakly positive or not apparent at all.

Keywords: Wave height; Trend; Variability; North Atlantic; North Sea and the Norwegian Continental Shelf, 2–38°E, 53–75°N

1. Introduction

Several authors have suggested that wave conditions in the North Sea and in the North Atlantic have become more severe with time. In a paper by Rye (1976) the consistency, significance and extent of linear climatic trends in various data sources related to the severity of the wave height conditions in the North Sea were analysed. The results indicated an increase in the wave severity for the North Sea during the winter season, 1951–1973, and a decrease in the wave severity during the summer season, 1952–1971. Neu (1984)

---

*Corresponding author.
E-mail address: frovik@imr.no (F. Vikebø).

0278-4343/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0278-4343(02)00210-8

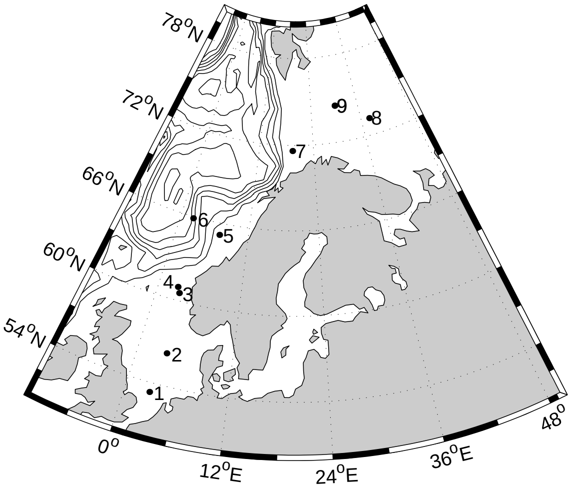
analysed synoptic charts of wave data, 1970–1982, consisting of visual observations reported every 6 h from ships, but also instrumental data from oil platforms and offshore meteorological buoys. The results showed continuously increasing wave heights during the period of investigation in the North Atlantic region, though in a spatially varying degree. Neu (1984) sees this increase in connection with a long-term variation with a period of several decades, probably related to an increasing north–south sea level pressure (SLP) gradient. Measurements of wave heights off Land's End, Cornwall, UK, have been made routinely by the Institute of Oceanographic Science, Surrey, UK. Carter and Draper (1988) presented analyses of the time series for the period 1962–1985. Even if only 12 years included at least 90 percent of the successfully recorded data, they indicate a long-term trend towards increasing wave heights. Bacon and Carter (1993) presented considerable experimental evidence supporting the hypothesis of zonal pressure gradient influencing wave heights. They established a link between the northeastern North Atlantic significant wave height and the mean atmospheric pressure gradient in the North Atlantic (early 1950s to 1980), which enabled them to generate a long-term hindcast mean wave climate for Seven Stones Light Vessel located at Land's End, England, suggesting that present conditions are as high as have been observed since 1873. Furnes and Reistad (1993) analysed time series of monthly mean World Meteorological Organization (WMO) and Norwegian Meteorological Institute (DNMI) hindcast SLP, 10 m wind speed (i.e. wind speed referenced to 10 m above the sea surface) and significant wave height along the Norwegian coast, from 1881 to 1982 and 1955 to 1989, respectively. They concluded that, though the wave climate has been subject to significant variation over time, there is no indication that the rough wave conditions in recent years are significantly different from earlier periods of rough wave conditions. Kleiven (1991) has investigated 6 h values of DNMI hindcast wave heights, from 1955 to 1989, and instrumentally collected wave heights, from 1973 to 1989, in northern parts of the North Sea at about 61°N, 2°E. Analyses of the DNMI hindcast significant wave heights indicate a positive trend, though the instrumentally collected data indicate a negative trend. Kleiven (1991) states that the instrumentally collected data are more reliable than the output from the model simulations and consequently there is no reason to assume any increasing wave heights. The time series are short and the conclusion is based on one station. However, the report demonstrates the necessity of comparing the model results with measurements. The European project group, Waves and Storms in the North Atlantic (WASA, 1998), states that the storm and wave climate variation in most of the northeastern North Atlantic and in the North Sea in the late 20th century seems to be comparable with that at the end of the 19th and the beginning of the 20th century, and that part of this variability is related to the North Atlantic oscillation (Hurrel, 1995). The main conclusion is that neither the storm climate nor the wave climate has undergone significant systematic trends during the last 100 years. Gulev and Hasse (1999) used visual wave estimates in the North Atlantic available from the Comprehensive Ocean–Atmosphere Data Set (COADS) to obtain basin-scale estimates of wind wave changes that were compared with instrumentally measured changes for the last 30 years. The visual wave estimates showed positive trends at the location of the time series presented in Carter and Draper (1988) and Bacon and Carter (1993), though smaller magnitude. Further, Gulev and Hasse (1999) displayed positive changes over nearly the whole North Atlantic, with an increase in significant wave height for the Norwegian and North Seas of about 0.15–0.18 m/decade, though they result primarily from the influence of the first several years of the record. Grevenmeyer et al. (2000) used a 40-year record of wintertime microseisms from Hamburg, Germany, which can be associated with ocean waves, to reconstruct the wave climate in the northeastern North Atlantic. The time series imply an increase in northeastern North Atlantic wave height, especially for the last 20 years.

One can ask whether the reported increasing wave heights are the result of local features or of the general behaviour of the North Atlantic, and whether oscillations of the ocean–atmosphere system are within the range of natural variations or due to climate changes. The answers to these questions will certainly concern fisheries and offshore operations in which the wave height is a limiting factor. The coastal zone is highly sensitive to the ocean surface state and increasing wave heights will have biological and geological impacts (coastal erosion, etc.). If the changes in the long-term mean state also affect the extreme values of the wave heights, it is of concern for the design of offshore constructions as well. Climatic changes are well documented in meteorological literature, and though there are fewer, long-term time series in the ocean, it is reasonable to assume that time series of oceanographic parameters are subject to the same climatic fluctuations due to air–sea interactions. Regular wave observation, visual appraisal or instrumentally recorded, have been carried out in Norwegian waters for several years, though the longest time series are not more than 30 years. In order to gain more information on possible changes in the wave climate, it is necessary to apply indirect methods. One such method is outlined by Furnes and Reistad (1993) where significant wave heights are calculated on basis of SLP. The main objectives for this work are to update the time series of monthly mean significant wave heights which were presented in Furnes and Reistad (1993), and to analyse six hour values of DNMI hindcast significant wave heights from 1955 to 1999.

The paper is organised as follows: Section 2 contains a description of the data sets used in this study, while Section 3 is a presentation of the analysis techniques applied. In Section 4 results are discussed and finally Section 5 contains a summary and conclusions.

2. Data

Several data sets of monthly mean significant wave heights based on 10 m winds, 1881–1999, and 6 h significant wave heights, 1955–1999, have been investigated. Focus has been on nine locations in the North Sea and along the Norwegian Continental Shelf from the North Sea in the south to the Barents Sea in the north (Fig. 1). The locations of the stations correspond to stations 3–11 in Furnes and Reistad (1993). The data sets include: (1) Monthly mean WMO 10 m wind speeds, 1881–1982; (2) Monthly mean DNMI 10 m wind speeds and significant wave heights, and 6 h SLP and significant wave heights, 1955–1999; (3) Six hour SLP and 10 m winds from



Sta. no.	Position
1	2.90 E, 53.29 N
2	3.67 E, 56.20 N
3	3.21 E, 60.49 N
4	2.07 E, 60.88 N
5	7.17 E, 65.14 N
6	2.15 E, 65.83 N
7	19.34E, 71.59 N
8	38.01E, 73.15 N
9	30.24E, 74.52 N

Fig. 1. Map over the area with stations 1–9 and bottom topography contour lines every 500 m and geographical coordinates for the chosen time series. The locations of the stations correspond to stations 3–11 in Furnes and Reistad (1993).

National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR), 1948–1999. These three data sets are originally stored on three different grids. The DNMI data are regional and are stored on a grid approximately 75 × 75 km, the WMO data on a grid 10° × 5° in longitude–latitude direction, while the NCEP/NCAR data are on a 1.9° × 1.9° grid. The WMO data were interpolated onto the DNMI hindcast grid for further analysis.

DNMI has been constructing historical wind and wave data since the 1970, but throughout these years the methods and tools have changed. The wave model used is the WINCH model, a deep water, discrete wave prediction model developed by Oceanweather Inc., which is a modified version of the SAIL model (Greenwood et al. 1985), one of the models in the SWAMP (1985) study. This is thoroughly discussed by Reistad and Iden (1998).

NCAR and NCEP have used a large number of observational data sets in a state-of-the-art global data assimilation system to provide spatial and temporal, homogeneous, atmospheric data from 1948 and onward. Changes in the observing systems and number of data sets being assimilated can still produce changes in the analysed climate, but this problem is approached by producing parallel reanalyses (at least 1 year long) with and without using the new observing system for the period immediately after its introduction (Kalnay et al., 1996). The NCEP/NCAR data is included as a comparison to identify possible inhomogeneities in the DNMI hindcast data set and to provide statistics of the wind fields for the entire North Atlantic.

The observational basis for the WMO time series changed significantly during the period 1881–1982. This makes the time series from WMO inhomogeneous, especially for the northern positions, where there were few observations during the beginning of the data set. The resulting WMO time series must therefore be interpreted with caution. The time series from the southern positions are more reliable, as the observational network was sufficiently closely spaced to reveal the synoptic pressure systems.

3. Methods

Both 6 h and monthly mean time series have been investigated. Time series of DNMI hindcast monthly mean significant wave heights are available for the period January 1955 to December 1999. In order to extend the significant wave height time series backward in time, it is necessary to apply indirect methods. We therefore follow the method by Furnes and Reistad (1993) and calculate significant wave heights by using the time series of WMO 10 m wind speeds for the period January 1881 to December 1955. Time series of 6 h DNMI hindcast significant wave heights January 1955 to December 1999 are further investigated to look for possible trends using extreme statistics.

3.1. *Extending time series*

The time series of wind speeds from two datasets are compiled. The first period, January 1881 to December 1955, uses the WMO data, continuing with DNMI hindcast data until December 1999. The correlation between the two data sets for the overlapping period is presented in Table 1a. Regression analysis indicates that monthly mean values of DNMI hindcast squared wind speeds and significant wave heights are close to linearly related (Table 1b). By this we do not intend to imply that a linear, physical relationship exists between these two variables. Wave conditions in a locality are a complex function of both local and distant wind speed, direction and persistence. Nevertheless, a simple linear relationship is a mean to extend the time series of significant wave heights beyond the period of available values. Scatter plots of WMO winds against DNMI hindcast winds, and DNMI hindcast significant wave heights against DNMI hindcast squared wind speeds, both at station 4, with and without seasonality, are shown in Fig. 2. This analysis only includes DNMI hindcast significant wave heights, thus it is necessary to adjust the squared wind speed from the WMO data set to the DNMI hindcast squared wind speed, in order be able to use the calculated linear relationship between DNMI hindcast squared wind speeds

Table 1
(a) Correlation coefficients C and regression factors a (slope) and b (y-intercept) calculated with linear regression between (a) monthly mean WMO squared wind speed (x-axis) versus monthly mean DNMI hindcast squared wind speed (y-axis), January 1955–December 1982 and (b) monthly mean DNMI hindcast significant wave height (x-axis) versus monthly mean DNMI hindcast squared wind speed (y-axis), January 1955–December 1999. Correlations are significant above the 99% confidence levels

Station	Data points	Seasonality			No seasonality		
		C	a	b	C	a	b
(a)							
1	336	0.92	0.97	16.40	0.83	0.91	1.02
2	336	0.89	0.89	25.72	0.77	0.77	−0.30
3	336	0.86	0.89	21.29	0.71	0.74	2.00
4	336	0.86	0.87	23.74	0.71	0.72	1.33
5	336	0.86	0.87	21.42	0.68	0.65	−0.39
6	336	0.81	0.87	28.19	0.56	0.58	−0.34
7	336	0.82	0.83	25.69	0.60	0.55	−5.53
8	336	0.86	0.95	19.83	0.65	0.66	−2.23
9	336	0.83	0.93	21.69	0.55	0.52	−6.97
(b)							
1	540	0.89	49.47	−17.96	0.80	44.35	0.00
2	540	0.93	47.95	−22.40	0.87	47.65	0.00
3	540	0.92	43.66	−23.25	0.84	46.46	0.00
4	540	0.93	40.18	−25.83	0.85	43.46	0.00
5	540	0.93	35.82	−14.83	0.84	33.98	0.00
6	540	0.94	36.84	−20.55	0.86	37.43	0.00
7	540	0.90	35.82	−7.89	0.76	33.20	0.00
8	540	0.84	39.36	−2.66	0.61	26.89	0.00
9	540	0.74	39.36	−2.66	0.44	26.89	0.00

and significant wave heights also for the WMO data. The overlapping period of WMO and DNMI hindcast data, 1955–1982, is used to remove possible systematic deviations in the WMO data compared to the DNMI hindcast data. This has been done by adjusting the WMO data so that it has the same mean value and standard deviation as the DNMI hindcast data. To assess the time series of wave heights based on DNMI and WMO 10 m wind are likely to be, scatter plots of significant wave heights based on DNMI and WMO 10 m winds versus DNMI hindcast significant wave heights for station 4, 1955–1982, are included (Fig. 3). The correlation coefficients are 0.92 and 0.82, respectively.

3.2. Extreme wave height analysis

Six hour values of DNMI hindcast significant wave heights at the nine positions shown in Fig. 1 have been analysed. The method used is described in Mathiesen et al. (1994) and Bjerke et al. (1990).

To look for trends in 6 h values of significant wave heights, the annual maximum values of moving 10-year periods from January 1955 to December 1999 have been investigated. Bjerke et al. (1990) noted that the annual maximum method is commonly used in the study of extreme states (significant wave heights, maximum wave heights) when hindcast data are available. Significant wave heights are random variables with a probability distribution often called an initial distribution. A number of different theoretical extreme value distributions have been used in the literature; however, it seems that the most common is the Gumbel distribution (Gumbel, 1958), also known as the Fisher–Tippet type 1 distribution (Wilks, 1995; Bjerke et al., 1990). The Gumbel probability density function $f(x)$ and the corresponding analytically integrated cumulative

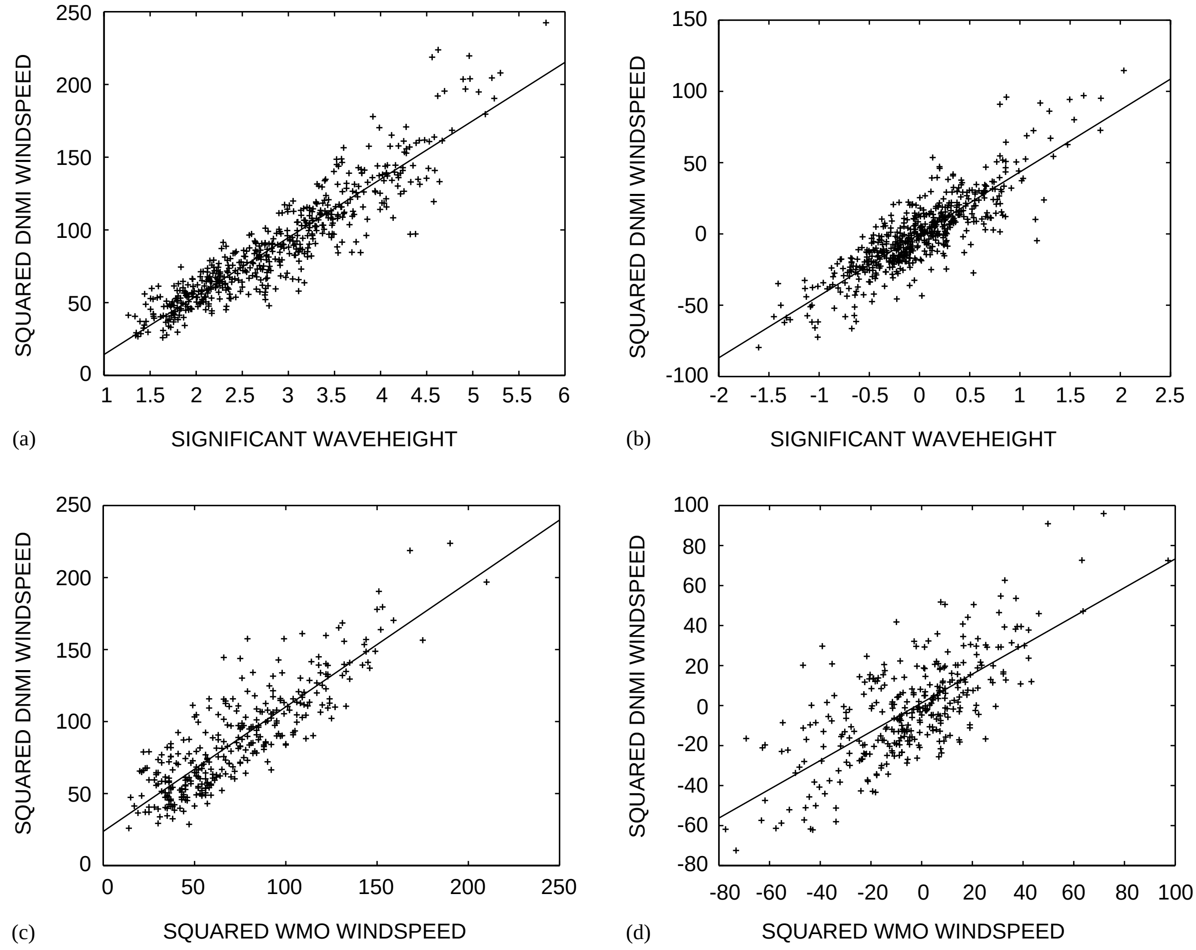


Fig. 2. Scatter plots of WMO winds against DNMI hindcast winds, with (a) and without (b) seasonality, 1955–1982. DNMI hindcast significant wave heights against DNMI hindcast squared wind speeds, with (c) and without (d) seasonality, 1955–1999. All plots are from station 4.

Gumbel distribution $F(X)$ are:

$$f(x) = \frac{1}{\beta}\exp\left\{-\exp\left[\frac{-(x-\zeta)}{\beta}\right] - \frac{(x-\zeta)}{\beta}\right\}$$
$$\leftrightarrow F(x) = \exp\left\{-\exp\left[\frac{-(x-\zeta)}{\beta}\right]\right\}, \qquad (1)$$

where ζ and β are known as the location and the scale parameters, and x in our case is the significant wave height. There are a number of ways to fit the model to the extreme values. As in Kleiven (1991), we used the least-squares method. When the model has been fitted to the extreme values, the y-abscissa gives the probability that any value (e.g. wave height) is beneath a certain value. In addition, one can find the return values, i.e. thresholds that on average are exceeded once per return period (upper part of the fitted extreme value distribution).

Assuming the model distribution is given by $F = F(x; \zeta, \beta)$, where x is the statistical variable and ζ and β the model parameters, Eq. (1) can then be rewritten in the form of a linear regression function:

$$Y(x) = a(\zeta,\beta)X(F) + b(\zeta,\beta), \qquad (2)$$

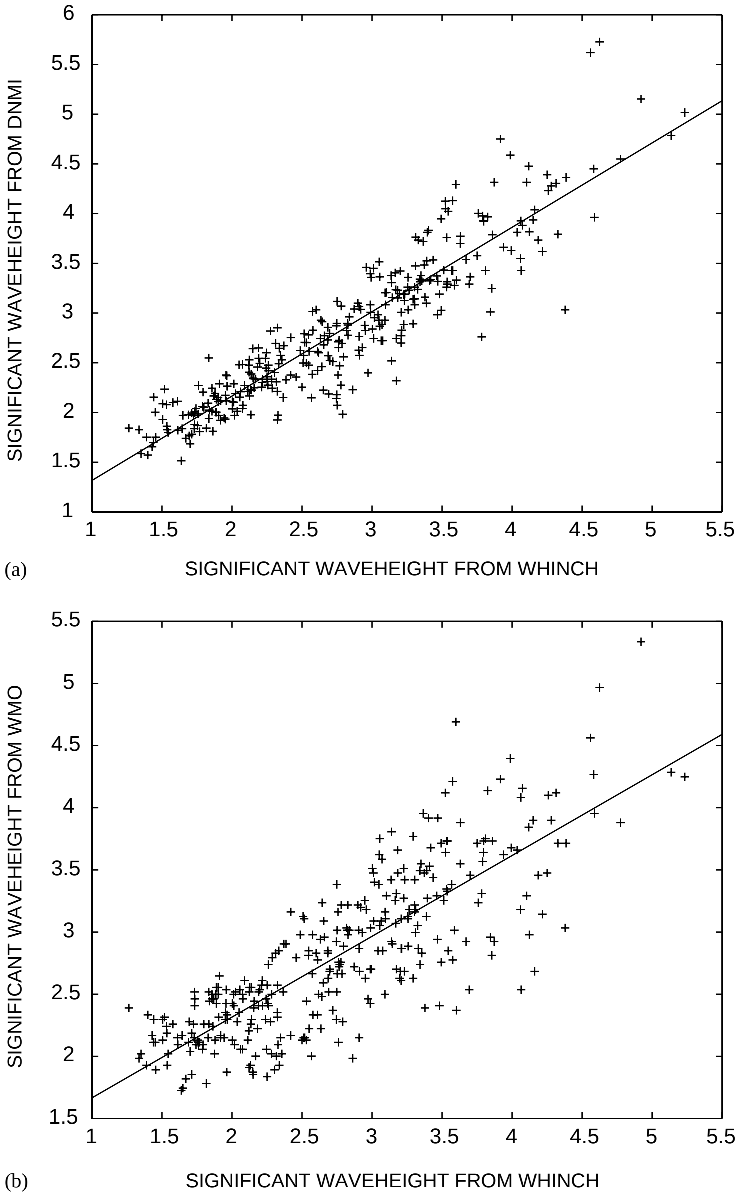


Fig. 3. Scatter plots of (a) DNMI hindcast significant wave heights versus calculated values of significant wave heights from DNMI hindcast 10 m winds and (b) DNMI hindcast significant wave heights versus calculated values of significant wave heights from WMO 10 m winds, both 1955 to 1982, station 4.

where

$$Y = -\ln\{-\ln[F(x)]\} \quad \text{and} \quad X = x. \tag{3}$$

An estimate of the cumulative distribution function F(x) was computed using the Gringorton (1963) plotting formula:

$$F(x_m) = (m - 0.44)/(n + 0.12), \tag{4}$$

where m denotes the index of observed data and n denotes the total number of data points. Estimates for the scale and location parameters are then obtained from

$$\beta = \frac{1}{a} \quad \text{and} \quad \alpha = \frac{-b}{a}, \tag{5}$$

where a and b are calculated using linear regression between Y and X. Mathiesen et al. (1994) have given a thorough description of sample selection methods, model distributions and fitting methods.

When it comes to the question of whether the dependent or independent nature of the data is an important issue, Bjerke et al. (1990) state that one should take great care when using methods that rely on plotting positions, like the method of least squares, when the observed data are partly dependent. When using the method of moments however, it does not seem important that the data are independent as long as the data have been sampled at regular intervals. We obtained the same results using the method of least squares and the method of moments, and time series analysis of independent instead of dependent data (moving five year intervals of non-overlapping data instead of moving ten years intervals of overlapping data).

4. Results and discussion

4.1. Statistics for the Northeast Atlantic region

Fig. 4a, c shows mean SLP of DNMI hindcast and NCEP/NCAR data for the period January 1955 to December 1999, respectively. The most noticeable feature is the Icelandic low, which stretches as a trough into the Nordic Seas, and the SLP gradient south- and eastwards into Central Europe, causing westerly winds towards northern Europe. There are minor differences between the two data sets, limited by the strength of the Icelandic low, the secondary low in the Norwegian Sea and features above Greenland. The trends in the annual mean SLP for the same period (Fig. 4b, d) are weakly positive at Central European latitudes and decrease towards negative higher latitudes, i.e. a strengthening of the north–south gradient and thereby the westerly winds. This is the SLP signature of the strengthened positive phase of the North Atlantic Oscillation during the last three decades (Hurrel, 1995). Comparison of the DNMI hindcast and the NCEP/NCAR data indicates that possible inhomogeneities in the DNMI hindcast data are not pronounced. Fig. 4e shows NCEP/NCAR 10 m mean wind speeds data for the period January 1948 to December 1999, with the largest wind speeds clearly reflecting the trough in the SLP. Fig. 4f shows the yearly trend in the annual number of extreme events of 10 m wind speeds for the same period. The criterion for an extreme event is that the wind exceeds twice the mean value for the entire period, and is thus stronger in an area with strong mean winds than in an area with weaker mean winds. Focusing on the Norwegian coast, we find the largest increase in a band extending north-eastwards from Great Britain towards Mid-Norway.

4.2. Correlations

The correlation between monthly mean DNMI hindcast and WMO squared 10 m wind speeds, and the correlation between squared monthly mean DNMI hindcast 10 m wind speeds versus significant wave heights are all high, close to or above 0.85 (Table 1). The variables correlate very well, but one can question whether this is due mostly to seasonal variations. However, subtracting the seasonal variations, the correlation coefficients of DNMI hindcast versus WMO squared 10 m wind lie between 0.5 and 0.8, and the correlation coefficients for wind speed versus significant wave height are still above 0.8 for stations 1–6, decreasing at stations 7 and 8 towards 0.4 at station 9. Thus the method can be justified, but it is a source of errors.

4.3. Monthly mean significant wave heights, 1881–1999

Time series of winds, deduced from atmospheric pressure, have been used to compute monthly mean significant wave heights from January 1881 to December 1999 at stations 1–9 (Fig. 5). Increasing westerlies are expected to correspond with increasing significant wave heights along the

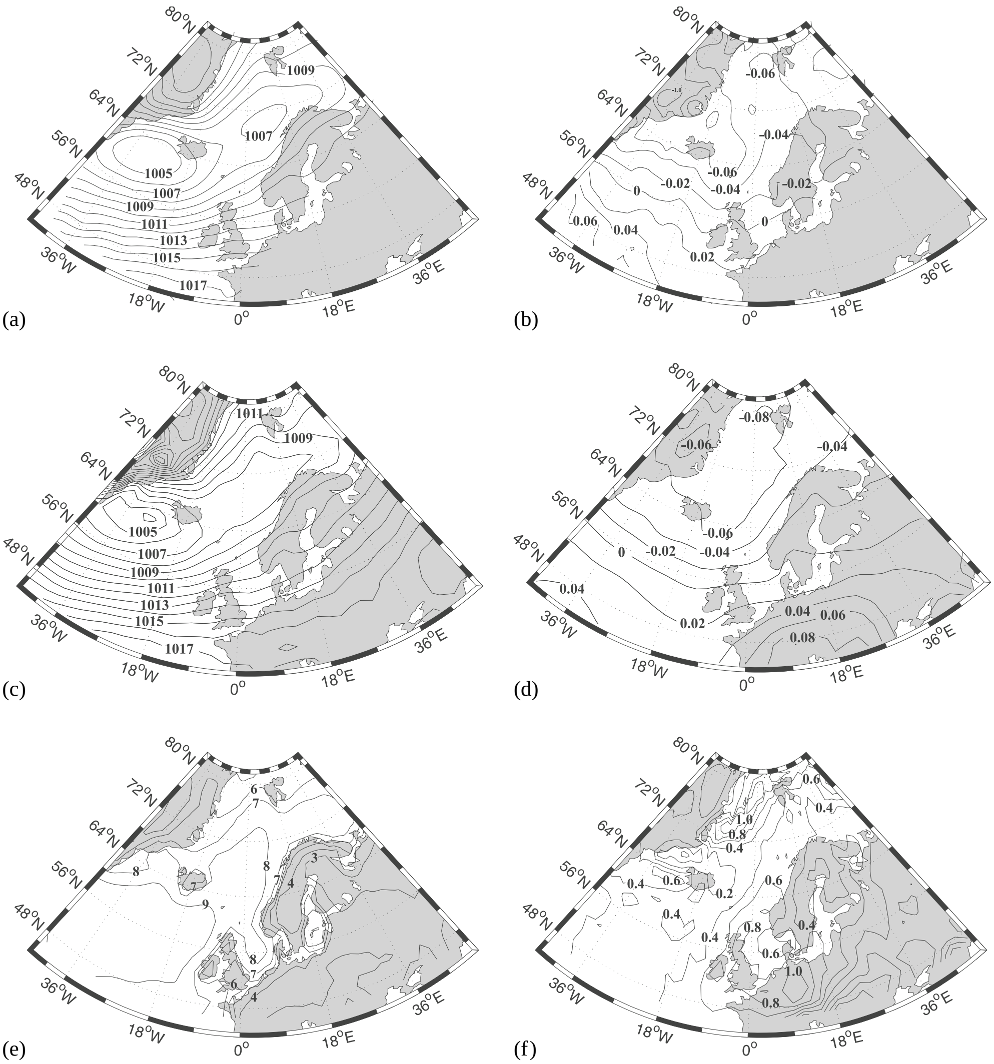


Fig. 4. (a) Mean DNMI hindcast SLP for January 1955–December 1999 (hPa), (b) trend in SLP for DNMI hindcast data, January 1955–December 1999 (hPa/year), (c) mean NCEP/NCAR SLP for January 1955–December 1999 (hPa), (d) trend in LSP for NCEP/NCAR data, January 1955–December 1999 (hPa/year), (e) mean NCEP/NCAR 10 m wind speed January 1948–December 1999 (m/s) and (f) trend in number of extreme events (defined in text) for NCEP/NCAR 10 m winds January 1948–December 1999 (events/year).

Norwegian coast. However, the characteristics of the time series depend on positions along the coast. Stations 1–6 and 8 are dominated by a rough wave climate during the last two decades of the 19th century (in agreement with Grevenmeyer, et al. (2000), Bacon and Carter, 1993 a.o.), with a distinct decrease of wave heights at the end of the 19th century (also the time series published by Bacon and Carter (1993) display decreasing maximum annual significant wave height, though the overall trend was positive). For the rest of the period the significant wave height show positive trends, though there have been significant variations on shorter time scales within this period. The overall trends for the entire period, as indicated by the linear regression lines, are dominated by the severe wave climate at the beginning of the period and are close to zero. The overall trends for the

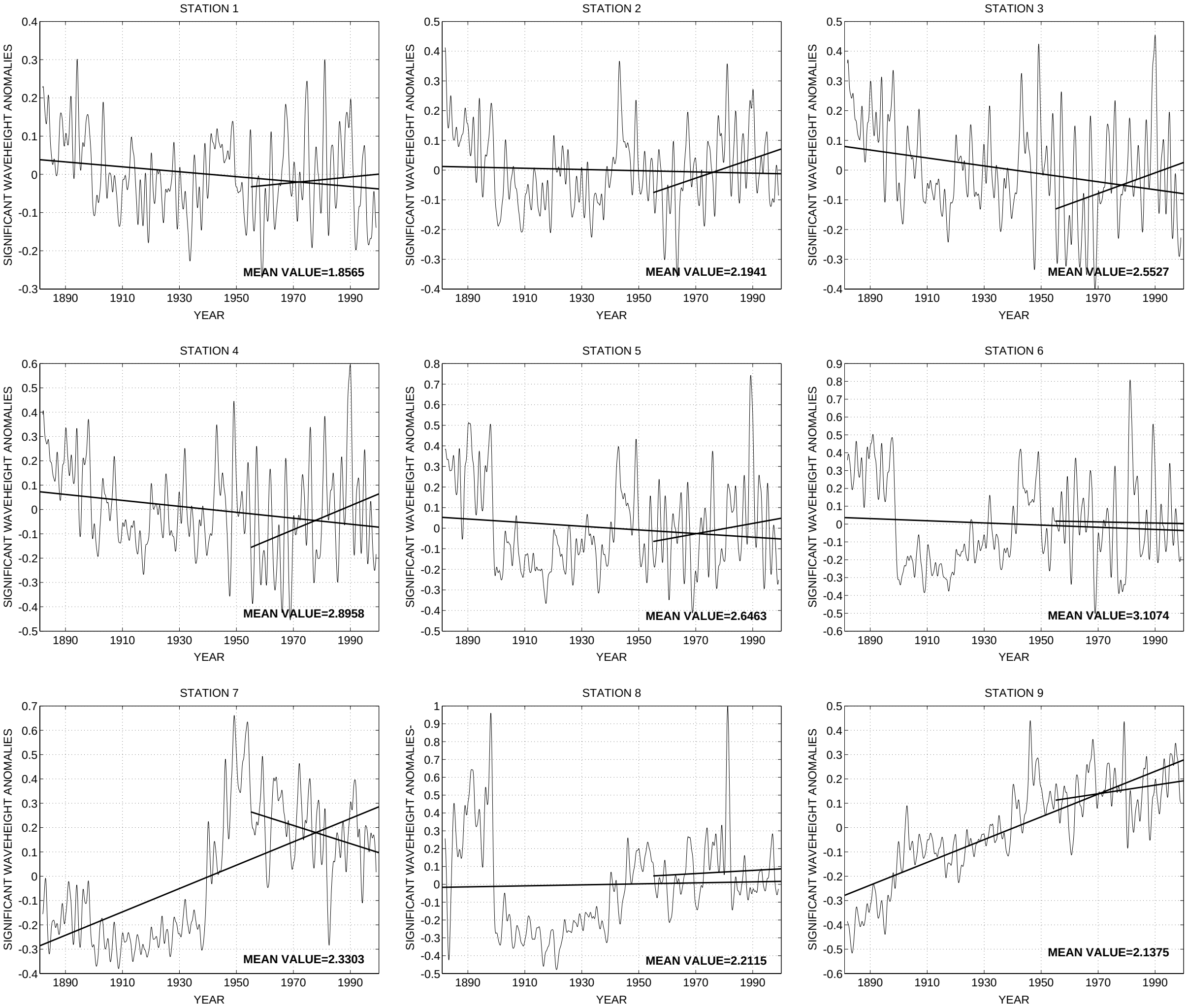


Fig. 5. Low pass filtered time series of DNMI hindcast monthly mean significant wave height anomalies (deviation from overall mean) at stations 1–9 January 1881 to December 1999, as derived from atmospheric data. Cut off period is 2 years. The two sets of regression lines indicate trends for the periods 1881–1999 and 1955–1999. The long-term mean values are given.

period 1955–1999, as indicated by the shorter linear regression line, show increasing significant wave heights at all stations but 6 and 7, with maxima of around 0.2 m during 1955–1999 along the mid-Norwegian coast (stations 3 and 4) (comparative to the results by Gulev and Hasse (1999) though less than the increase indicated by Bacon and Carter (1993)).

Station 7 indicates an increasing wave height of close to 0.5 m during 1881–1999, but with a negative trend for the period 1955–1999 showing a decrease of 0.15 m. At the same time, the northernmost station, station 9, shows an increasing trend for both the periods, above 0.5 m during 1881–1999 and 0.1 m during 1955–1999. As mentioned by Furnes and Reistad (1993), the three northernmost time series are not as reliable as the other time series for the earliest part of the period, both because of the moving ice edge and because of few and sparse observations. However, altogether the slopes for the entire time period give no indications of uniform increase in wave heights unless we choose to question the earliest WMO data. Then we find an increase of significant wave heights with a maxima in the area of maximum increase in the westerlies (Fig. 4d). On the contrary, if the WMO data set for the end of the 19th century is reliable, the increase for the period 1955–1999 is not more dramatic than the decrease which occurred from 1881 and towards the beginning of the 20th century, and consequently the increase of significant wave heights might be a part of the natural variability of the ocean–atmosphere system. This is contrary to the conclusion by Bacon and Carter (1993), that there is a positive trend in annual mean significant wave height, since the annual mean significant wave height was as high in the late 19th century as it is today.

4.4. Estimated hundred year return values of significant wave heights, 1955–1999

Estimated hundred years return values of significant wave heights (H_{EH}) are calculated using a Gumbel initial distribution on moving 10 years intervals of annual maximum significant wave heights (H_{AM}) from 6 h DNMI hindcast data for the period January 1955 to December 1999.

From Fig. 6 we note that there are different trends in the time series, stations 1–9, depending on whether we study H_{AM} or H_{EH}. Station 1, located in the southern North Sea, indicates a zero slope for the trend regarding H_{AM} but a positive trend for the time series of H_{EH}. The difference in the slopes can be explained by the fact that the variability around the mean H_{AM} is increasing. However, the large values of H_{AM} are weighted more than the low values when calculating H_{EH}, hence the increasing variability in H_{AM} contributes to the increased slope of the regression line for the H_{EH}. The same is true for station 2. The increase in H_{EH} for the entire period for stations 1 and 2 lie around 2.0 m.

Stations 3, 7–9 indicate an increase in H_{AM} of about 0.5–1.0 m for the entire period, though the slopes for the H_{EH} are varying, depending on the variability of H_{AM}. Stations 4–6 show an increase in both H_{AM} and H_{EH} of 1.5–2.0 m and 2.0–3.0 m, respectively. The slopes of the H_{EH} are larger than the slopes of the H_{AM} because there is an increase in H_{AM} and its variability at the same time. The trends at stations 4–6 are distinct and uniform indicating a trend towards a rougher wave climate in this area. This is consistent with the results presented in Fig. 4e showing an increasing number of extreme events. This is also consistent with the monthly mean significant wave heights as discussed above. Stations 1–3 and 7–9 give no conclusive trends in the significant wave heights, though the trends tend to be weakly positive.

5. Summary and conclusion

It is evident from the time series presented here that there is variability in the monthly mean significant wave heights on a broad range of scales, and apparent trends in time series of limited duration may be part of longer period variations. Yearly mean SLP changes, from 1955 to 1999, show a clear and distinct increase in the north–south SLP gradient, with a subsequent strengthening of the westerlies. Also, the yearly change in the number of extreme events of 10 m winds speed, 1948–1999, show a positive trend. For the North Sea and the continental shelf area we find the largest increase centred in a band extending northeastwards from Great Britain towards mid-Norway.

Although there is a sign of a positive trend in the DNMI hindcast monthly mean significant wave height data, from 1955 to 1999, mainly in northern parts of the North Sea and outside mid-Norway, the overall time series (1881–1999) shows no distinct trend, except for the northernmost stations. The increase in the DNMI hindcast data is not more dramatic than the decrease in the WMO data which occurred from 1881 and towards the beginning of the 20th century.

Analysis of annual maximum significant wave heights for the period 1955–1999, gives a strong indication of increasing wave heights and rougher wave climate at the stations in the northern parts of the North Sea and off the coast of mid-Norway. The other stations, positioned in the mid and southern parts of the North Sea and off the coast of northern Norway and in the Barents Sea, reveal

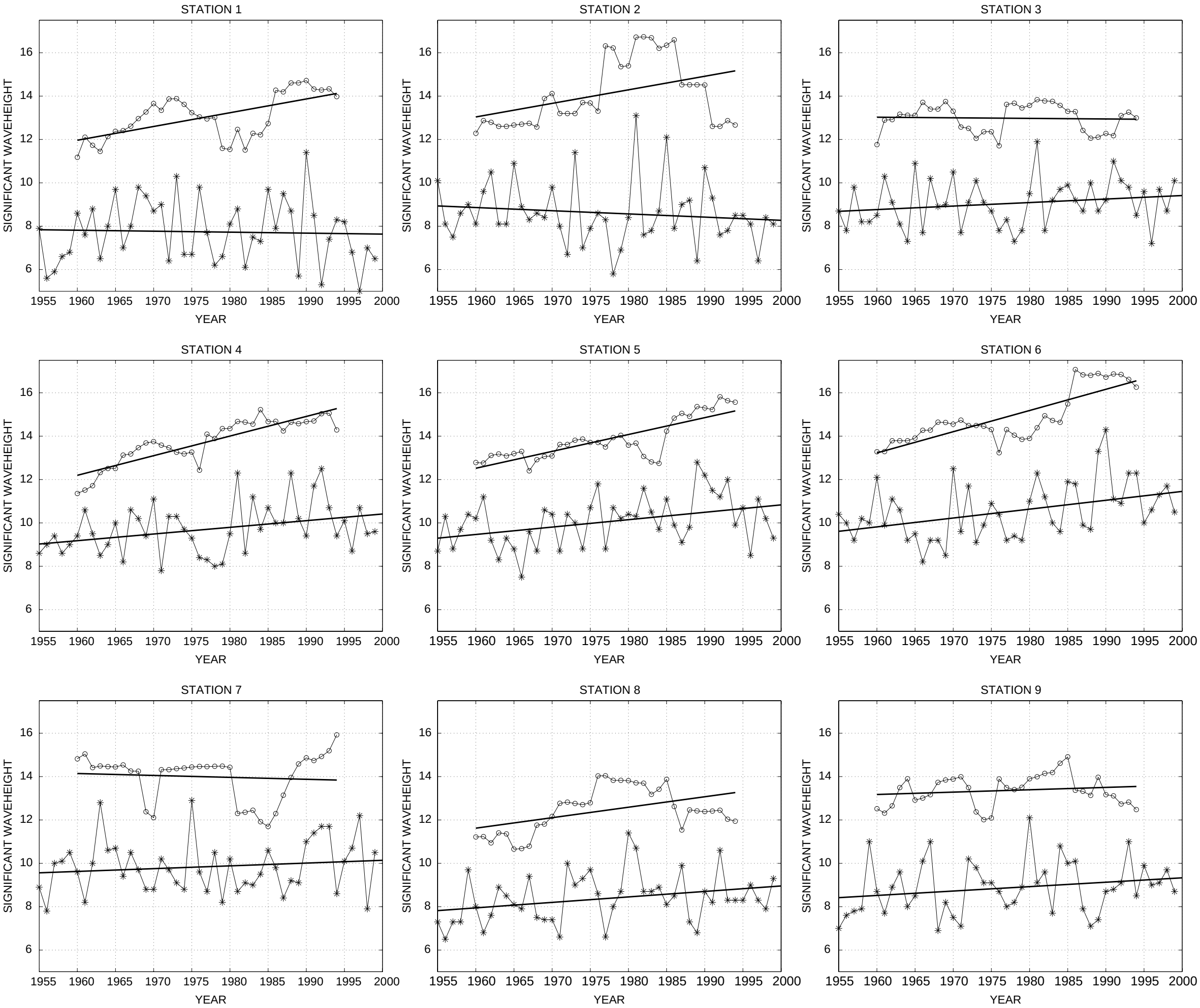


Fig. 6. Time series of DNMI hindcast annual maximum significant wave heights (-∗-) (m) with a linear regression line and estimated hundred years return values of significant wave heights (-⊖-) (m) on 10 years overlapping time interval using Gumbel cumulated density function and fitting the parameters to the data set with the least-squares method.

no distinct or uniform trend in wave heights, though the trends tend to be positive, possibly indicating a minor increase.

Acknowledgements

This project was funded by Norsk Hydro and partly by the Norwegian Research council funded Regclim project. NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, has provided data through the NCEP/NCAR reanalysis project (http://www.cdc.noaa.gov/).

References

Bacon, S., Carter, D.J.T., 1993. A connection between the mean wave height and atmospheric pressure gradient in the North Atlantic. International Journal of Climatology 13, 423–436.

Bjerke, P.L., Mathiesen, M., Torsethhaugen, K., 1990. Haltenbanken Metocean Study. Main Report. Appendix A. NHL-Rapport no. STF60 A90055, Arkiv-nr. NH: R-048951.

Carter, D.J.T., Draper, L., 1988. Has the North-East Atlantic become rougher? Nature 332, 494.

Furnes, G.K., Reistad, M., 1993. Mean wave height variations in the Northeast Atlantic (Jan. 1881–Dec. 1989). In: Proceedings of the Third (1993) International Offshore and Polar Engineering Conference. Singapore, 6–11 June 1993, pp. 71–75.

Greenwood, J.A., Cardone, V.J., Lawson, L.M., 1985. Intercomparison test version of the sail wave model. In: SWAMP Group (Ed.), Ocean Wave Modeling. Plenum Press, New York.

Grevenmeyer, I., Herber, R., Essen, H.H., 2000. Microseismological evidence for a changing wave climate in the northeast Atlantic Ocean. Nature 408, 349–352.

Gringorton, I.I., 1963. A plotting rule for extreme probability paper. Journal of Geophysical Research 68 (3), 813–814.

Gulev, S.K., Hasse, L., 1999. Changes of wind waves in the North Atlantic over the last 30 years. International Journal of Climatology 19, 1091–1117.

Gumbel, E.J., 1958. Statistics of Extremes. Columbia University Press, New York, p. 375.

Hurrel, J.W., 1995. Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. Science 269, 676–679.

Kalnay, E., et al., 1996. The NCEP/NCAR 40-year Reanalysis Project. Bulletin of the American Meteorogical Society 77, 437–471.

Kleiven, G., 1991. Trend i Bølgeklima: Innflytelse på ekstremverdier (Trend in wave climate: Influence on extreme values). Hydro forskningsrapport, U & P Forskningssenter, p. 31.

Mathiesen, M., Goda, Y., Hawkes, P.J., Mansard, E., Martin, M.J., Peltier, E., Thompson, E.F., Vledder, G.V., 1994. Recommended practice for extreme wave analysis. Journal of Hydraulic Research 32 (6), 803–814.

Neu, H., 1984. Interannual variations and longer-trem changes in the sea state of the North Atlantic from 1970 to 1982. Journal of Geophysical Research 89, 6397–6402.

Reistad, M., Iden, K., 1998. Updating, correction and evaluation of a hindcast data base of air pressure, wind and waves for the North Sea, the Norwegian Sea and the Barents Sea. The Norwegian Meteorological Institute, Research Report no. 9, p. 42.

Rye, H., 1976. Long term changes in the North Sea wave climate and their importance for the extreme wave predictions. Marine Science Communications 2, 419–448.

SWAMP Group, 1985. Ocean Wave Modelling. Plenum Press, New York.

The WASA Group, 1998. Changing waves and storms in the Northeast Atlantic. Bulletin of the American Meteorological Society 79 (5) 741–760.

Wilks, D.S., 1995. Statistical Methods in the Atmospheric Sciences. Academic Press, New York.