

# CHANGES OF WIND WAVES IN THE NORTH ATLANTIC OVER THE LAST 30 YEARS

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## ABSTRACT

In order to evaluate long-term climatic changes in wind wave height, visual wave estimates available from the Comprehensive Ocean–Atmosphere Data Set (GOADS) were updated for the period from 1964 to 1993. Analysis of the accuracy of visual estimates shows that observations from merchant ships can be used for the study of climate changes in storminess. Climate changes obtained in significant wave height, computed on the basis of the voluntary observed data, are quite consistent with those shown by the instrumental records at OWS L, Seven Stones Light Vessel and NDBC buoys. The linear trends in significant wave height, as well as in the wind sea and swell heights, were computed for the entire North Atlantic. Significant wave height increases of 10–30 cm/decade over the whole of the North Atlantic, except for the western and central subtropics were found. Changes in the swell height are very consistent with those seen in significant wave height. Nevertheless, wind sea indicates strong upward tendencies only in the central mid-latitude North Atlantic and does not show any significant trends in the Northeast Atlantic, where instrumental records of Bacon and Carter report secular changes of about 1% a year. Wind waves of smaller occurrences show significantly negative changes in the Northeast Atlantic; that is in agreement with the wind sea periods changes. Possible mechanisms driving the swell changes with no pronounced increase of the sea height and wind velocity are discussed. Changes in the intensities of intramonthly variability in different synoptic ranges are considered as the major agent of the increasing swell. The conclusion is made that the upward swell changes are driven by the intensification of high frequency synoptic processes. Copyright © 1999 Royal Meteorological Society.

KEY WORDS: North Atlantic; wind waves; climate changes in storminess

## 1. INTRODUCTION

Secular changes in ocean wave characteristics are very important for climate studies and for practical needs. Instrumental records (Carter and Draper, 1988; Bacon and Carter, 1991, 1993) obtained by a Shipborne Wave Recorder at Ocean Weather Station (OWS) L and Seven Stones Light Vessel (SSLV) in the Northeast Atlantic, indicate increases in significant wave height in recent years, with a secular trend of about 1% per year. It is important to extend the geographical coverage of wave climate change estimates. At the same time, there are only a few long-term instrumental records that have climatological significance. In addition to the above cited series, there are several records obtained during the NOAA Marine Environmental Buoys Program for the period from the mid-1970s to the early 1990s. These series depict the variability in the area where the waves are quite small. Nevertheless, they will also be used in this paper.

Alternative sources of wave data are satellite observations, model products (hindcasts), and visual observations. Satellite observations are available at present from GEOSAT, ERS-1, and TOPEX/POSEYDON missions and already provide several years to decades of global-scale altimeter and scatterometer arrays (Cotton and Carter, 1994; Katsaros, 1996). However, the duration of remotely sensed wave

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parameters is still too short to be used for climate change studies, although future climate monitoring of waves will be based on satellite data. On the other hand, remotely sensed wave data have to be compared with each other and calibrated against instrumental measurements so as to be considered with confidence (Cotton and Carter, 1994). Model hindcasts (US Navy, 1983; Kushnir *et al.*, 1997; Sterl *et al.*, 1997; The WASA Group, 1998) and wave forecast charts (Neu, 1984) are also restricted in time by several years, and provide wave fields that are computed from wind fields using well-developed boundary layer models and parameterizations. In other words, hindcasted waves are not completely independent from the winds that come from atmospheric analyses.

In this sense, visual wave observations that provide global data for the period of several decades can be considered as an important source of alternative wave information. Usually visual observations are used to compute mean climatologies and statistics for numerous practical purposes. Products such as the US Navy Marine Climatic Atlas of the World (Naval Oceanography Command Detachment, 1981), Wind and Wave Summaries (Paskausky *et al.*, 1984), North Sea Climate (Korevaar, 1990), and very popular among sailors and naval engineers, Ocean Wave Statistics (Hogben and Lumb, 1967) and Global Wave Statistics (Hogben *et al.*, 1986) contain means and statistical distributions of the wave height for climatological months, which are based on a limited number of the voluntary observing ship (VOS) observations. Some results dealing with the changes in wave climate were obtained from the Ocean Weather Stations (OWS) data primarily for the 1960s and early 1970s (Walden *et al.*, 1970; Rodewald, 1972; Rye, 1976). These results were nicely reviewed by Bacon and Carter (1991). However, there has been no attempt yet to use for climate studies visual wave observations from the Comprehensive Ocean–Atmosphere Data Set (GOADS). This is the most complete collection of marine meteorological observations at present, which is widely used for the creation of different climatologies of individual variables and fluxes (Oberhuber, 1988; da Silva *et al.*, 1994; Gulev, 1995; Hasse *et al.*, 1996; Josey *et al.*, 1996). We attempt in this study to use visual wave observations in the North Atlantic from COADS in order to obtain basin-scale estimates of wind wave changes and to compare them with instrumentally measured changes at SSLV, OWS L and NDBC buoys. We will try to consider the relationships between the changes in the wave climate and the atmospheric circulation in the North Atlantic. Bacon and Carter (1993) found significant correlation between the large-scale sea level pressure (SLP) gradient and measured waves. However, this does not establish the direct link of the atmospheric conditions and shows the necessity of studying wave changes and atmospheric statistics over larger areas.

## 2. DATA AND METHODS

We used the collection of compressed marine reports (CMR) and long marine reports (LMR) for the period 1946–1993, available from the COADS Releases 1 and 1a (Slutz *et al.*, 1985; NCAR, 1983; Woodruff *et al.*, 1993). Besides the basic meteorological variables, CMR and LMR contain coded height, period and direction of wind waves and swell, taken visually by voluntary observing ships. This data set is the only source at present of the separate sea and swell estimates. The presence of reports with wave observations appears in COADS in 1963 and for later decades their contribution is usually about 60%. Gulev and Hasse (1998) updated COADS waves in order to evaluate annual mean climatologies of wave parameters and to compute the sea state-dependent wind stress fields over the North Atlantic Ocean. Decoded wave variables after quality control were validated against instrumental measurements at OWS L and C, SSLV and NDBC buoys. To provide relevant background for the intercomparison with *in situ* measurements in Gulev and Hasse (1998), we have computed significant wave height  $H_s$ , which is defined in terms of spectral moments as  $H_s = 4\sqrt{m_0}$ , where  $m_0$  is the zero moment of the spectrum, which is equal to the sea surface variance. From visual observations, significant wave height can be computed as (Hogben, 1988):

$$H_s = (h_w^2 + h_s^2)^{1/2}, \quad (1)$$

where  $h_w$  is sea height and  $h_s$  is the swell height. At the same time, some wave atlases used higher values of sea or swell heights ( $H_h$ ), as an estimate of significant wave height, which was justified by the comparison of visual observations with selected buoy data (Wilkerson and Earle, 1990). Barratt (1991) recommended to combine these two approaches using formula (1) for the cases when sea and swell are within the same  $45^\circ$  directional sector, and taking the highest of sea and swell in all other cases. Gulev and Hasse (1998) considered estimates for the directional sectors from  $30$  to  $60^\circ$  ( $H_c^{30}$ ,  $H_c^{45}$ ,  $H_c^{60}$ ) and estimates  $H_s$  and  $H_h$ . It has been found that the best estimate of significant wave height appears to be either  $H_h$  or  $H_{30}$ , which give the smallest 'buoy minus VOS' differences of about several centimetres. This is in agreement with Wilkerson and Earle (1990) who found  $H_h$  to be a better estimate than  $H_s$ , although they did not consider combined estimates. The estimate  $H_c^{30}$  fits better to the instrumental data in the regions with higher directional steadiness of sea and swell. Alternatively, in the west subtropical Atlantic where directional steadiness of waves is low, the estimate  $H_h$  fits better to the measurements. Thus, in addition to sea and swell heights, we have used significant wave height estimates  $H_c^{30}$  and  $H_h$  for the study of long-term changes. Gulev *et al.* (1998) intercompared the VOS significant wave height with the long-term WAM hindcast (Sterl *et al.*, 1997) and altimeter data available from TOPEX/POSEIDON, GEOSAT and ERS-1 instruments (Cotton and Carter, 1994) and also found the best agreement for the estimate  $H_c^{30}$ .

Wave variables were averaged into  $5^\circ \times 5^\circ$  boxes over the North Atlantic for individual months from 1964 to 1993. For each  $5^\circ$  box we obtained long-term series of monthly mean sea height, swell height and significant wave height. It is important to filter out the seasonal variability and to evaluate monthly anomalies in the climatic series. Thus, Sterl *et al.* (1997) computed trends from a 15 year WAM model hindcast for every individual month and found the trend estimates to be very flexible from month to month. Alternatively, when the long-term changes are computed from the annual means, the results may be influenced by short period month-to-month variations of a stochastic nature. To compute the long-term anomalies of wave variables, we have used the breakdown technique for monthly time series with a pronounced seasonal cycle, first suggested by Lappo *et al.* (1987), and recently used for the study of climate variability in the statistical characteristics at sea–air interface by Gulev (1997). According to Lappo *et al.* (1987) each time series has the following structure:

$$\mathbf{x}(\mathbf{t}) = \mathbf{S}(\mathbf{t}) + \mathbf{F}(\mathbf{t}) + \varepsilon(\mathbf{t}), \quad (2)$$

where  $\mathbf{S}(\mathbf{t}) = \sum A_i \cos(\mathbf{w}_i \mathbf{t} + \phi_i)$  is the multiharmonic seasonal cycle, which includes  $\mathbf{k}$  harmonics with divisible periods (12, 6, 4, 3, 2.4 and 2 months), amplitudes  $A_i$ , and phases  $\phi_i$ ;  $\mathbf{F}(\mathbf{t})$  is the long-term interannual change, and  $\varepsilon(\mathbf{t})$  is short period month-to-month variability, which is suggested to be a stationary random process. Similar approaches were used in radiotechnics by Levin (1974) and in the analysis of climate time series by Leith (1973) and Mobley and Preisendorfer (1985). The long-term components  $\mathbf{F}(\mathbf{t})$  were used to evaluate climatic trends and their statistical significance, estimated from a  $t$ -test for a certain number of degrees of freedom that result from the number of independent values.

### 3. ACCURACY OF VISUAL WAVE OBSERVATIONS

Visual wave estimates are usually assumed to be of a low accuracy due to many uncertainties inherent in the observational practice. On the other hand, wave parameters, observed visually, should not be worse than the Beaufort estimates of wind speed, which are still a considerable contribution of about 70–80% of the total number of marine wind observations. Sailors estimating Beaufort force make use of the sea state, and the latter is always under their considerable attention. There is evidence of inaccuracy of the visual estimation technique (Hogben and Lumb, 1967; Jardine, 1979; Hogben *et al.*, 1983; Wilkerson and Earle, 1990; Hogben, 1995). Gulev and Hasse (1998) compared visual estimates with the *in situ* measurements and found climatological values and seasonal dependencies to be in agreement for the wave heights and systematically biased for the periods. Gulev *et al.* (1998) comparing VOS wave climatology with the WAM hindcast and the altimeter data, also found general agreement between the spatial patterns

of the three products, although systematic overestimation of the VOS waves in the low ranges and a small underestimation in the high ranges have also been found.

Important questions of the reliability of visual wave observations are the observational error and the uncertainty of the separation between wind sea and swell. Liang (1985) introduced the dependence of the correlation between the log-transformed wave heights ( $r$ ) on ship separation ( $x$ ) as a measure of observational error in the visual wave data. Approximating this dependence as

$$r(x) = r_0 \exp(-kx), \tag{3}$$

he computed estimates  $r_0$  which are reasonably uninfluenced by the spatial variability and should characterize observational error. For the South Pacific Ocean, Liang (1985) got  $r_0$  estimates of 0.61, 0.58 and 0.57 for significant wave height, wind sea, and swell height, respectively, and concluded that from 60 to 70% of the variance of one observation is not explained by another nearby, and may result from the observational error. We applied the Liang (1985) method to the North Atlantic. We selected all simultaneous observations within 15 classes of ship-to-ship distances from 20 to 300 km, and then approximated the dependence obtained by the fit (3). Figure 1(A) shows the results for significant wave height estimate  $H_c^{30}$  for the North Atlantic Ocean. The large number of reports used (several orders larger than in Liang, 1985) provides very narrow confidence limits of about  $\pm 0.01$  for all classes (not shown in Figure 1). The resulting estimate of  $r_0$  gives 0.76 for significant wave height, 0.69 for the wind sea, and 0.73 for the swell height. This is 15–20% higher than the correlation obtained by Liang (1985). Differences may result from the reasonably poor collection used by Liang (1985), from the features of the observational techniques of sailors from different nations which contributed to the South Pacific and the North Atlantic reports, and from better control of the reports in the COADS in comparison with the Liang (1985) collection. When we consider the regional correlations for 20° areas, there is inhomogeneity in the space of the correlation estimates. Particularly, the lowest correlation from 0.50 to 0.60 is found in the Western Atlantic subtropics, and the highest (of about 0.83) in the North Atlantic mid-latitudes.

Lindau (1995) and Kent and Taylor (1997) introduced similar techniques for the evaluation of measurement error in the VOS wind speed. They recommended the computation of differences between simultaneous observations for certain classes of ship-to-ship distances. When the distance is equal to zero, natural variability does not contribute to the total variance, and the latter should represent error variance

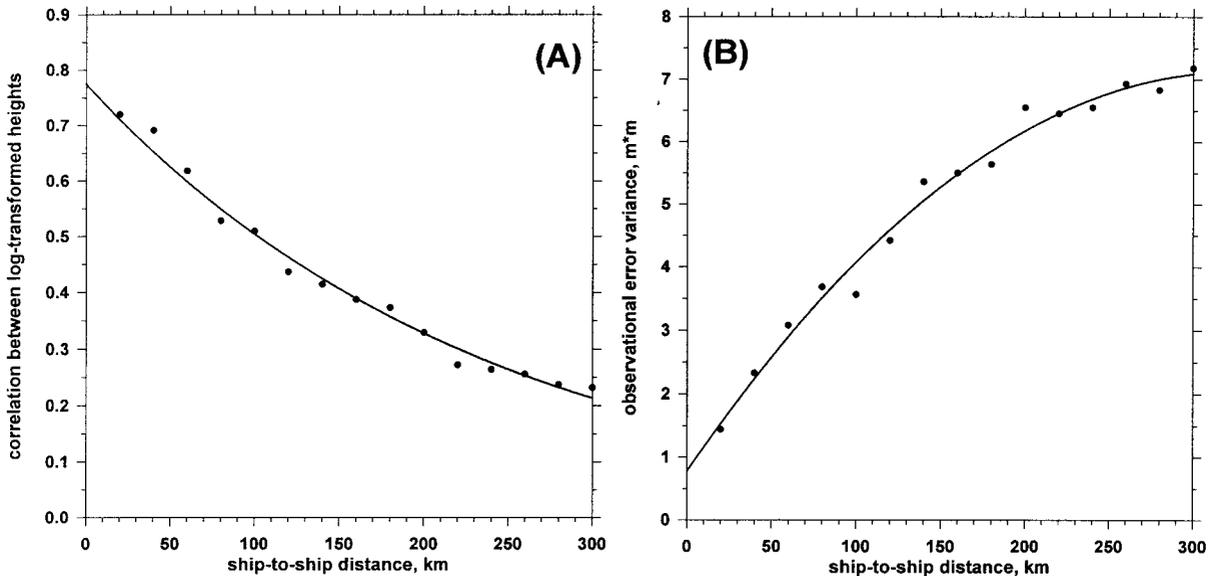


Figure 1. Correlogram for significant wave heights as a function of ship-to-ship distance (A) and the dependency of the observational error variance on the ship-to-ship distance (B). Solid lines show the best exponential (A) and polynomial (B) fits

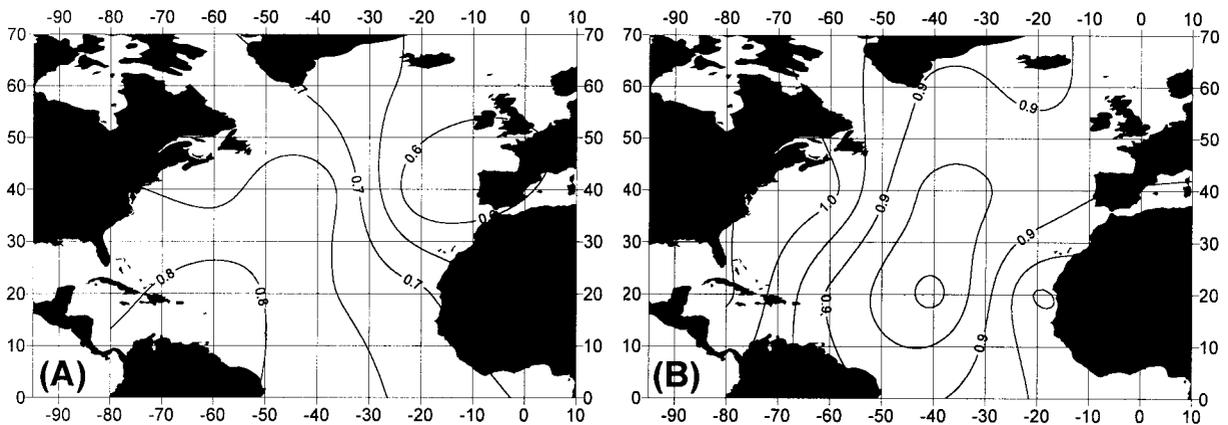


Figure 2. Spatial distribution of the random observational error in the wind sea (A) and swell (B) visual estimates over the North Atlantic ocean

only. Practically, variances  $\sigma^2$  have to be computed for each class of distance, and then the polynomial extrapolation is used to arrive at the  $\sigma_0^2$  estimate, which represents the variance of observations from the two ships. It has to be divided by 2 to get the squared measurement error:  $\varepsilon_m^2 = \sigma_0^2/2$  (Isemer, 1994; Lindau, 1995). Figure 1(B) displays the results for significant wave height estimate  $H_c^{30}$ . A polynomial fit gives a standard deviation (S.D.) error of about 0.85 m at  $\Delta x = 0$ . However, if we use only classes of distances from 20 to 180 km, this estimate will be lowered by about 0.07 m. We made an additional estimate for the class 0–10 km only and got  $\sigma = 0.81$ , which implies  $\varepsilon_m$  is a little bit less than 0.8. Figure 2 shows spatial distributions of the error estimates for the wind sea and swell heights over the North Atlantic Ocean. To produce maps in Figure 2, computations of error variances were performed for  $20^\circ$  boxes. The largest observational error of the wind sea height of about 0.8–0.85 m is obtained in the western subtropics, and the minimum (0.55–0.6 m) is located in the eastern mid-latitudes. Spatial distributions of the observational error in the swell height are quite different from those for the wind sea. A minimum error of about 0.8–0.85 m is in the eastern mid-latitudes and the central subtropics and tropics. The largest errors up to 1 m are observed in the western North Atlantic.

Beside the random observational errors, there is a known systematic bias of the small wave heights in COADS. Overestimation of primarily small sea heights results from the usage of the code figure '1', which is applied in COADS to all waves  $\geq 0.5$  m. Therefore, all sea heights coded as '1' should represent a value that is somewhat lower than 0.5 m. The problem can be probably recovered by the comparison of frequency distributions for small waves with instrumental data from NDBC buoys. However, the buoy records still do not provide separate measurements of sea and swell. This effect can be primarily pronounced in the tropics. Particularly, Gulev *et al.* (1998) found that the tropical VOS wave heights are slightly biased in comparison with the altimeter data and WAM hindcast.

Another possible source of the uncertainties is the lower accuracy of the night time observations. Particularly, for wind speed, Kent *et al.* (1993) found that moderate and strong winds can be underestimated at night time by 10–20%. In order to quantify this effect, we separated our collection into day time and night time measurements and computed day time and night time climatologies. Both climatologies of significant wave height as well as of the wind sea and swell demonstrate quite a good agreement with those given in Gulev and Hasse (1998). Figure 3 shows 'day time minus night time' differences in the climatological mean significant wave height, wind sea height and swell height. There is a systematic overestimation of the day time heights in comparison with the night time. The bias varies within the range 0.1 m and does not indicate any kind of regular spatial pattern. Local maxima are observed in the mid-latitudinal tropics, Labrador Sea and the eastern mid-latitudes. The opposite tendency (underestimation of the day time observations) appears in the high latitudes and can be explained by the considerable undersampling of the day time measurements during the winter time, and considerable oversampling of

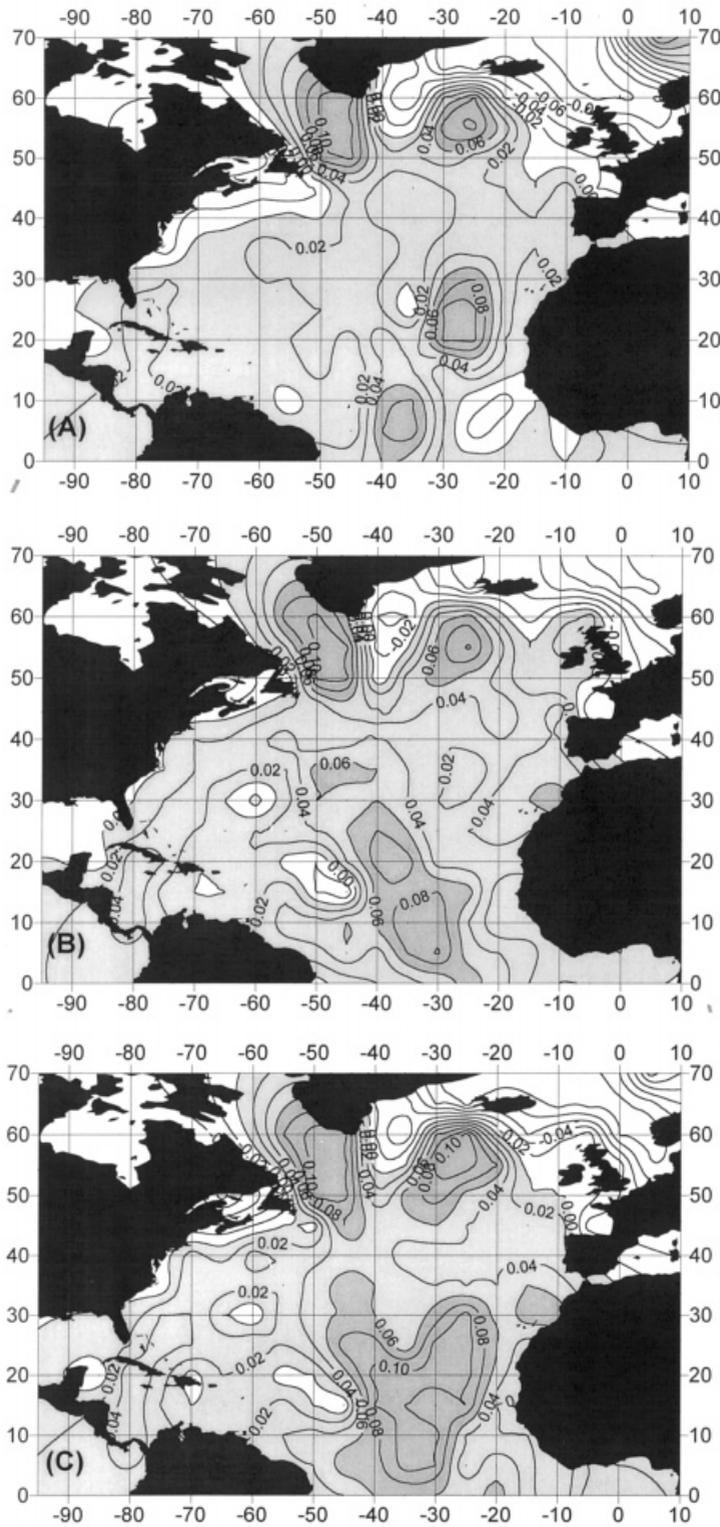


Figure 3. 'Day time minus night time' differences in the annual mean wind sea (A), swell (B) and significant wave height (C)

the day time observations in summer. For individual months, differences between the day time and night time observations are slightly higher and vary within the range of 0.24 m. There was no pronounced seasonal dependence found in the 'day time minus night time' differences. In general, the disagreement obtained was even smaller (with respect to the mean values) than those reported for the wind speed (Kent *et al.*, 1993). Wind is a more frequently reported parameter than waves, and probably when we use only the reports that contain wave information, we deal with the information from better trained officers who are concerned about the quality of meteorological observations. Remarkably, when computing 'day time minus night time' differences in the wind speed on the basis of reports with wave information (not shown here), we get 20–50% smaller biases than those based on the whole COADS collection.

Separation between wind sea and swell in the visual measurements can also lead to uncertainties in wave climatologies. This is especially important for the swell estimates that might be influenced by some portion of the well-developed wind sea cases reported as swells. In order to estimate this effect, we computed joint probability distributions of the wave height and wind speed for the wind sea and swell. Then we overplotted these distributions by the JONSWAP curves, representing wave height as a function of wind speed and duration in the formulation of Carter and Draper (1988). Figure 4 shows the results for the Marsden box 182 located in the Northeast Atlantic mid-latitudes. Most of the wind sea observations are reasonably bracketed by the JONSWAP curves corresponding to the 6 and 18 h durations. Alternatively, swell observations that are not dependent on the local wind, show very large scatter, and less than 20% of them are bracketed by the JONSWAP curves. Note here, that in the other regions of the North Atlantic this difference between the wind sea and swell distributions is even more pronounced, and swell shows nearly random scatter against wind speed. North Atlantic mid-latitudes are characterized by the high directional steadiness of winds and swell along the main North Atlantic storm track. Thus, winds in the Northeast Atlantic are highly correlated with winds in the central and western mid-latitudinal Atlantic, which are reasonably responsible for the swell propagating across the ocean. This can result in the slight dependence of the swell on the local wind, which is seen in Figure 4(B).

Analysis of the errors and uncertainties in the visual wave data show that errors could be quite high. On the other hand, when investigating climate changes we have to be more concerned about the time-dependent biases that may result in the artificial trends in the records, i.e. when dealing with the erroneous data we have to ensure that they are at least homogeneously erroneous. In Section 5 below we will analyse the possible effect of the errors and uncertainties on the estimates of long-term variability in the wave climate.

## 4. LONG-TERM TRENDS IN WAVE VARIABLES

### 4.1. Comparison with trends in instrumental records

First, it is important to compare the variability indicated by the VOS wave observations with the patterns shown by the instrumental records of Bacon and Carter (1989, 1991). We intercompared patterns of the long-term variability obtained from the VOS with instrumental records at OWS L (57°N, 20°W), SSLV (50°N, 6°W) and NDBC buoys. For this intercomparison we have produced monthly time series in the nearest vicinity of the locations of instrumental measurements in the same manner as was done by Gulev and Hasse (1998) for the calibration of mean climatological values. VOS observations were selected for individual months within the correlation ellipse 0.8 of the spatial correlation functions computed around the points of instrumental measurements. The linear dimensions of the ellipses along the major axis of the spatial correlation functions were from 80 to 150 km for SSLV and from 120 to 230 km for OWS L. The double correlation radius across the major axis of the spatial correlation functions was reasonably smaller and varied from 40 to 60 km at SSLV and from 55 to 120 km at OWS L. Since the Bacon and Carter (1989, 1991) records at SSLV contain a number of gaps, they have suggested to group the data into 14 sets, each containing 12 consecutive monthly mean values of significant wave height based on at least 80% of individual records. We decided to group VOS monthly means exactly in the same

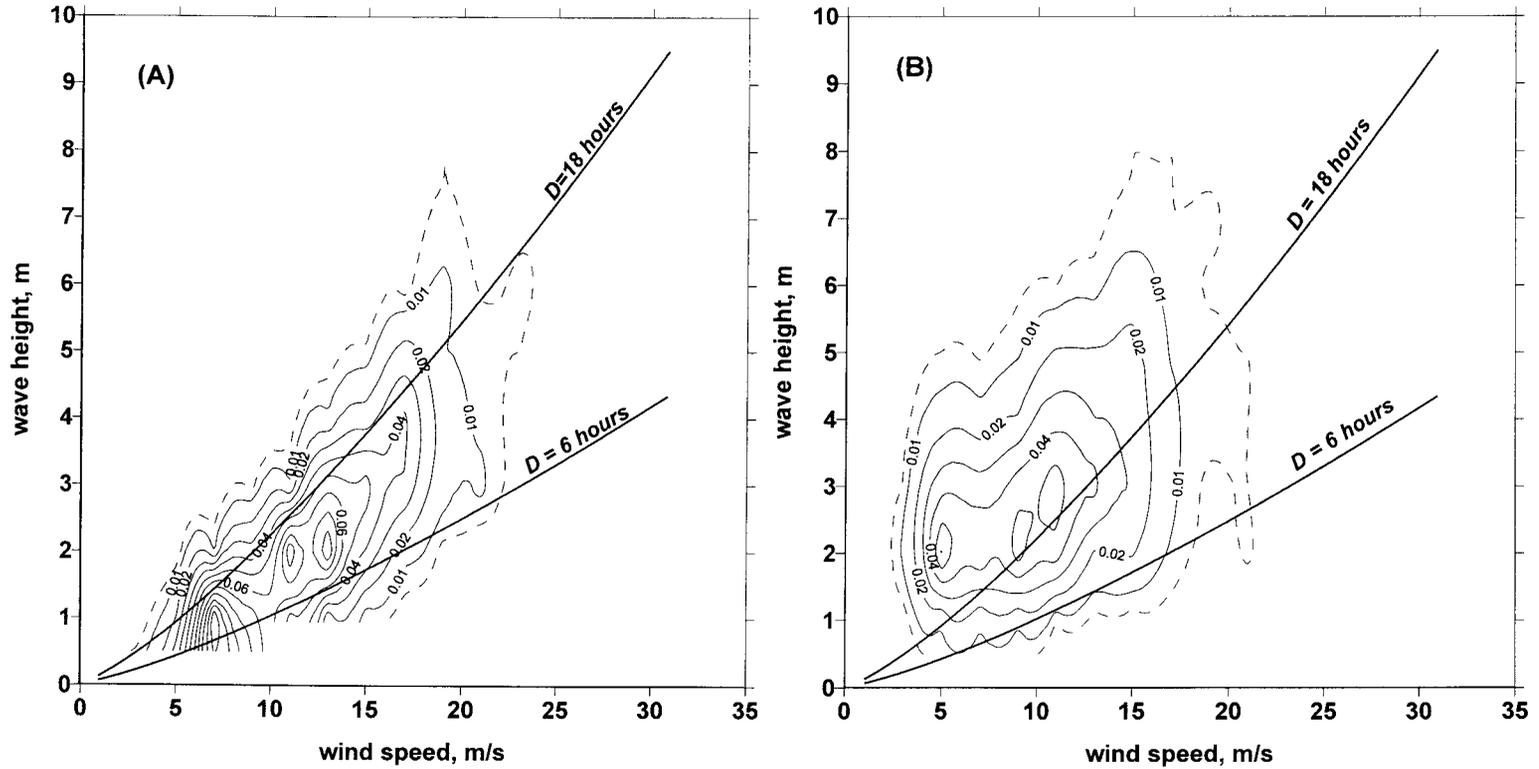


Figure 4. Joint probability distributions (portions of unity) of the wind sea and wind speed (A) and swell and wind speed (B). Solid lines correspond to the JONSWAP dependencies of the wave height of wind velocity for different durations, as given by Carter (1982)

manner and obtained 14 annual means of significant wave height from 1968 to 1986. For OWS L only 3 months were missing during 1986–1988 and we have used averaging over the calendar years for both instrumental and the VOS data. We used for the intercomparison significant wave height estimate  $H_c^{30}$ , which is less biased for the Northeast Atlantic in comparison with the others (Gulev and Hasse, 1998).

The results of the intercomparison are shown in Figure 5. Annual deviations of the computed visual significant wave height from the recorded heights at SSLV and OWS L vary within the range of 30 cm with the average departure of about  $\pm 0.1$  m. The total number of reports used for the evaluation of the monthly mean in the vicinity of the points with instrumental measurements usually overestimates several thousand for SSLV and several hundred for OWS L. Thus, the influence of the observational error on the results is quite small, especially taking into account that 12 months were then averaged to get the annual mean. On the other hand, the procedure of spatial averaging creates inadequate sampling error (Weare and Strub, 1981; Weare, 1989). In order to estimate sampling error in the annual estimates obtained on the basis of VOS reports, we used an approach first introduced by Cayan (1992) and then used by Gulev and Hasse (1998). We selected randomly for every individual month 72 samples, repeating this selection 20 times for SSLV and 10 times for OWS L. The results of these runs were then used for the computations of annual means. Standard deviations computed on the basis of these runs for each annual average give the measure of sampling error and are shown in Figure 5 as error bars. They usually do not overestimate  $\pm 0.1$  m for SSLV and 0.13 m for OWS L.

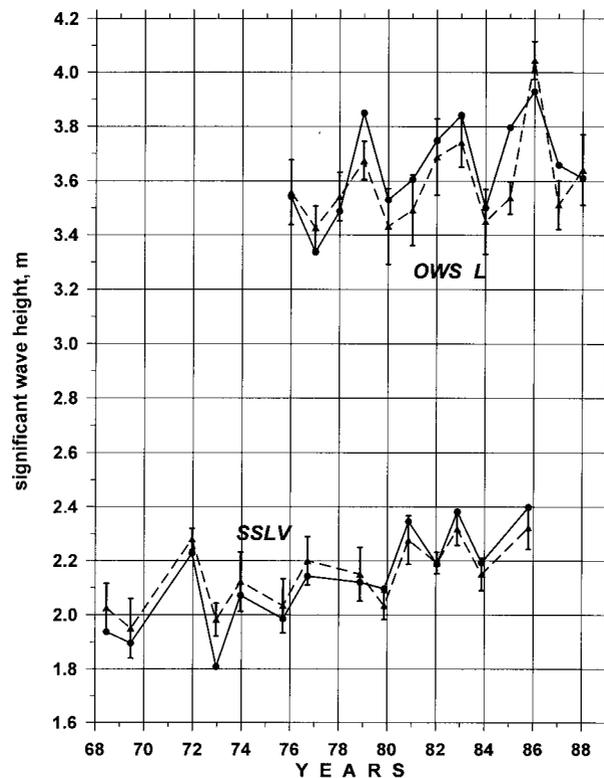


Figure 5. Comparison of the long-term interannual variability of significant wave height measured by Shipborne Wave Recorder at OWS L and SSLV (Bacon and Carter, 1991) and significant wave height computed from the VOS data in the nearest vicinity of OWS L and SSLV. Error bars correspond to inadequate sampling error

Table I. Observational periods and locations of the selected NDBC buoys in the North Atlantic and estimates of linear trends in significant wave height

Point	Latitude Longitude	Period (month/year)	Trend in $H_s$ (m/decade)	Number of months
41001	34.7°N 72.7°W	06/76 12/93	0.003	171
41002	32.3°N 75.2°W	12/73 12/93	0.026**	174
41006	29.3°N 77.4°W	05/82 12/93	0.007	118
42001	25.9°N 89.7°W	08/75 12/93	0.009	192
42003	25.9°N 85.9°W	11/76 12/93	-0.002	176
44004	38.5°N 70.7°W	09/77 12/93	0.003	161
44005	42.6°N 68.6°W	12/78 12/93	0.009*	167
44008	40.5°N 69.4°W	08/82 12/93	-0.006	111

\* Significant at 1% level; \*\* significant at 5% level; \*\*\* significant at 10% level.

Visual estimates of significant wave height at both SSLV and OWS L indicate upward changes, if only of a smaller magnitude than those reported by Bacon and Carter (1991). At SSLV, the VOS waves linear trend slope is 0.015 m/year and is significant only at the 90% level, although instrumental measurements indicate for this period (1969–1986) a linear trend of 0.025 m/year, which is significant at the 95% level. For OWS L, visual estimates give a positive trend of 0.014 m/year, which closely matches the 90% significance level. Instrumental data indicate upward tendency of 0.021 m/year, which is significant at 95% level. Bacon and Carter (1991) estimated the overall difference between the total annual averages of significant wave height for the periods 1975–1981 and 1982–1988 at OWS L (0.182 m). A similar estimate obtained from the VOS data (0.124 m) is 1.4 times smaller.

NDBC buoys provide wave measurements in a number of locations along the East coast of North America and in the Gulf region. We have selected eight buoys that have at least 10 year records and computed linear trends in significant wave height. Table I shows the information about observational periods and locations of the selected buoys and estimates  $\mathbf{a}$  of linear trends  $\mathbf{at} + \mathbf{b}$  together with their statistical significance, taken according to a Student  $t$ -test which has been used to test  $\mathbf{a} \neq 0$  against the null hypothesis (no trend in the record). Only buoy 42001 in the subtropical Atlantic indicates significant upward wave changes of 26 cm/decade. Other buoys show neither statistically positive nor negative trends. Figure 6 shows interannual changes in SWH at the buoy 42001 for selected months, which demonstrate the most pronounced increase. The largest upward tendencies of about 50 cm/decade are observed during late winter and early spring. In summer time, the upward changes are smaller (10–16 cm a decade), but nevertheless statistically significant. Time series of the VOS estimates of significant wave height were produced for eight NDBC buoys in the same manner as for OWS L and SSLV. Gulev and Hasse (1998) found quite a good agreement between buoy and VOS estimates of significant wave height. For the comparison with the data from NDBC buoys (not shown here) we used the significant wave height estimate  $H_h$ . There was a good agreement in the short-term interannual variability. Long-term trend estimates were compared only for the buoy 41002, which indicates visible upward tendency (Table I). The VOS trend estimate is nearly twice as small and underpredicts the 90% significant level. As we have mentioned above, this can result from the problem of the coding of low wave heights in COADS, that is most sensitive in the subtropics (location of NDBC buoys) and equatorial areas, where waves are

primarily small. Nevertheless, general agreement of the variability patterns seen in the VOS and instrumental data provide the possibility of using visual estimates for the study of changes in wave climate.

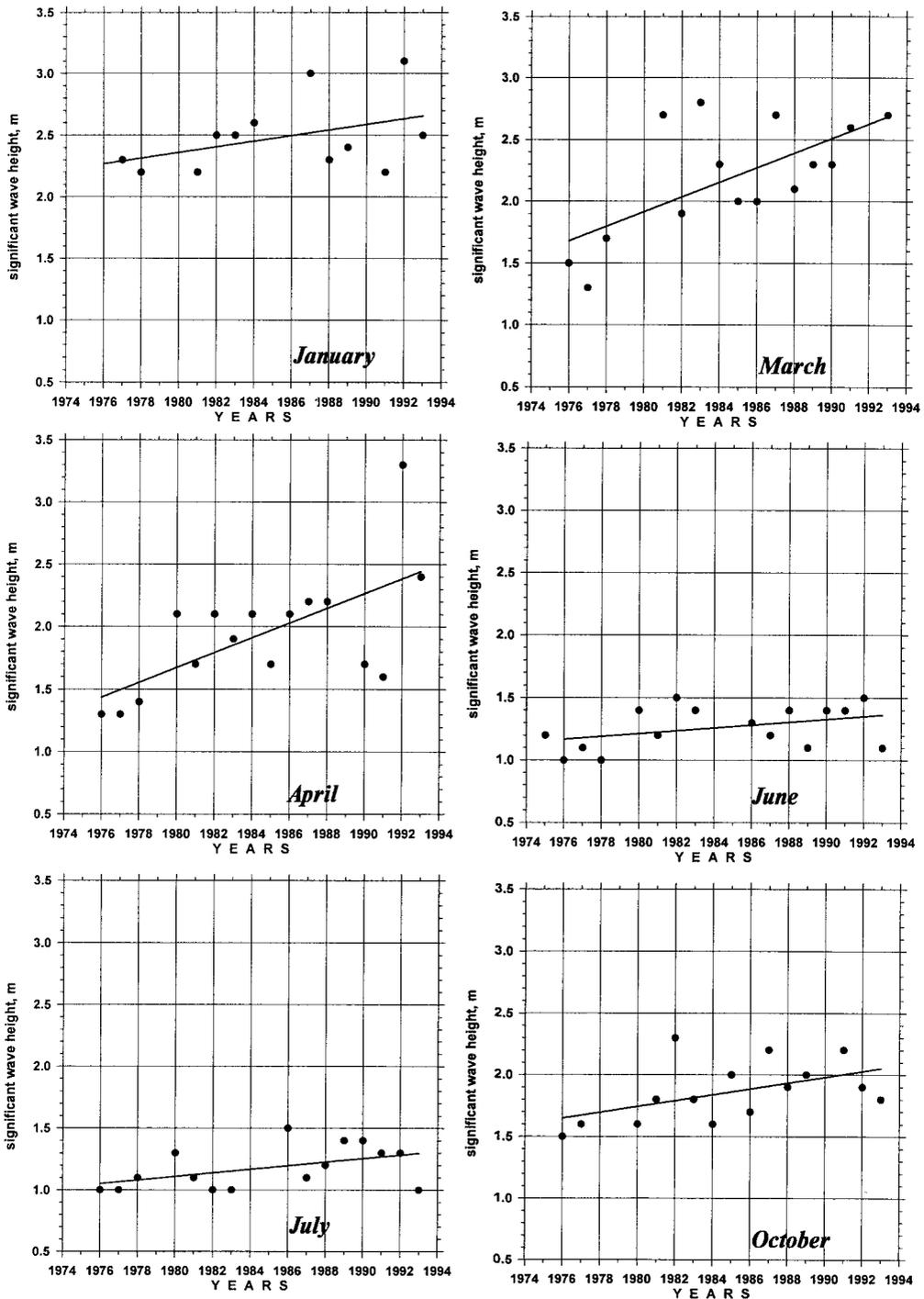


Figure 6. Interannual changes for individual months of the instrumentally recorded significant wave height at NDBC buoy 42001 from 1976 to 1993

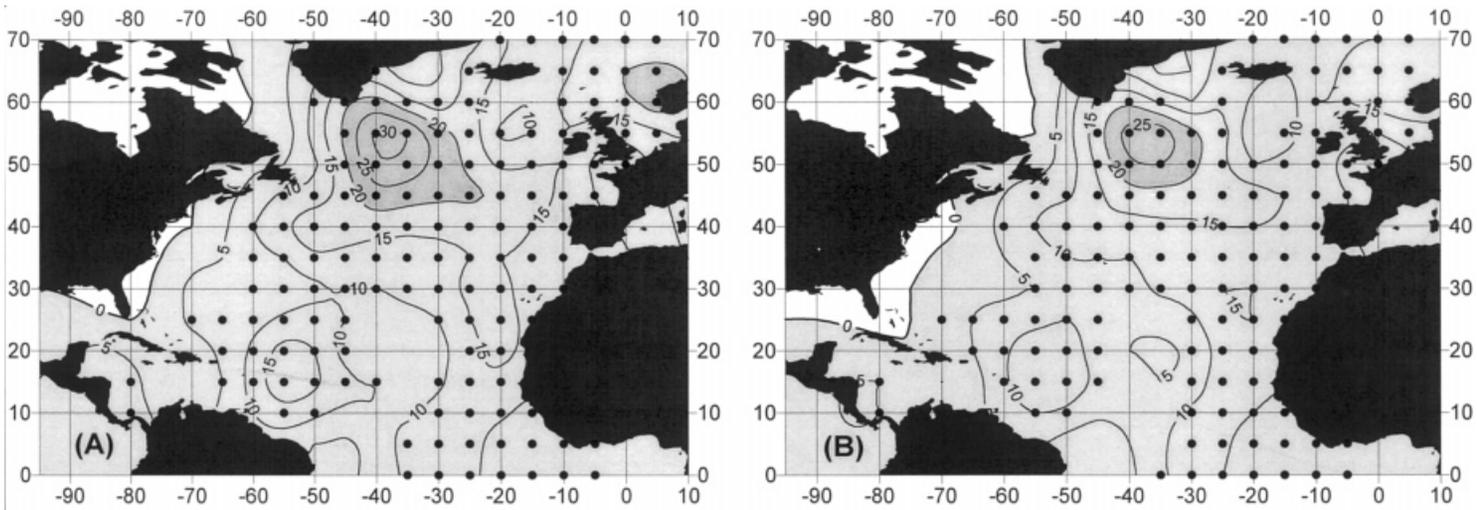


Figure 7. Estimates of linear trends (cm/decade) for the period 1964–1993 in the significant wave height estimates  $(h_w^2 + h_s^2)^{1/2}$  (A) and  $H_h$  (B) computed from the visual VOS data. Trends which are significant at the 95% level, are denoted by the black circles

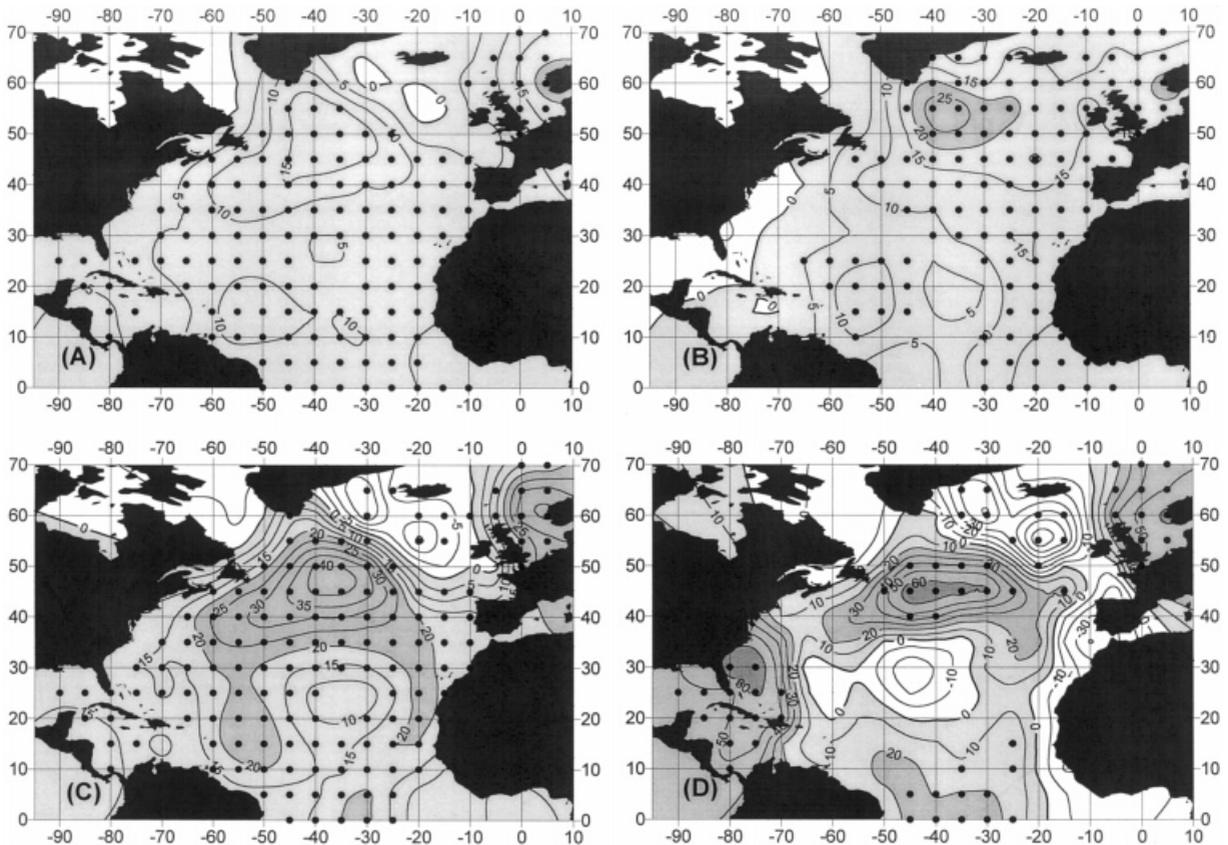


Figure 8. Estimates of linear trends (cm/decade) for the period 1964–1993 in the wind sea height (A), swell height (B), wind sea of 20% (C) and 0.14% (D) percentiles exceedances computed from the visual VOS data. Trends which are significant at 95% level, are denoted by the black circles

#### 4.2. Linear trends in the VOS significant wave height

Figure 7(A) and (B) represents linear trends in the estimates of significant wave height  $H_c^{30}$  and  $H_h$  with  $t$ -test significance for the period 1964–1993. Both estimates of significant wave height indicate primarily positive changes over nearly the whole North Atlantic, except for a limited area in the western subtropics, where the trends are weakly negative and statistically insignificant. Particularly, this fact explains the absence of any significant trends in the NDBC buoy data collected in this area. Spatial patterns of the secular changes are very similar for both significant wave height estimates  $H_c^{30}$  and  $H_h$ , although trends in the estimate  $H_c^{30}$  are from 5 to 15% larger than in  $H_h$ . Statistically significant positive changes are observed in the central mid-latitudes, eastern subtropics and western tropics. The largest changes of about 25–30 cm/decade appear in mid-latitudes between 30° and 40°W. Another local maximum of the positive changes in significant wave height appears in the tropics and indicates trends from 10 to 15 cm/decade. If we consider the Northeast Atlantic, where Bacon and Carter (1991) found the increase of significant wave height of about 20–30 cm/decade, there will be a local minimum of the positive trend estimates there, and the trends are primarily insignificant at least at the 95% level. There is a similarity in the locations of maxima of our trends with the net changes of the sea state computed by Neu (1984) for the period 1970–1982 from wave forecast charts. We have recomputed our trends for this period (not shown here), and have obtained also the largest changes in the mid-latitudinal central Atlantic, if only of a smaller magnitude than those shown by Neu (1984).

### 4.3. Linear trends in the VOS wind sea and swell

The outstanding feature of the visual data is the possibility of using separate estimates of the wind sea and swell heights for climate studies. Figure 8(A) and (B) shows estimates of linear trends of wind sea and swell height for the period 1964–1993 in the same manner as for significant wave height. Significant trends of mean wave height are obtained mostly in the West Atlantic mid-latitudes and tropics (Figure 8(A)) where they are within the range 0.10–0.18 m/decade. At the same time, we did not find any significant trends in the Northeast Atlantic, and particularly in the locations of OWS L and SSLV, where instrumental measurements (Bacon and Carter, 1991) indicate increases of about 1% per year since the 1960s. In the location of OWS L, we have even found a weak downward tendency. For wind sea we also computed monthly means for various percentiles (50, 20, 10, 5 and 0.14%) of distributions of wave height, because even if there are remarkable changes of mean wave heights, changes in certain percentiles exceedances may not necessarily be pronounced and *vice versa*. Long-term changes in the wave heights for the 20 and 0.14% exceedances (Figure 8(C) and (D)), indicate upward tendency in the Northwest Atlantic mid-latitudes of 0.4 and 0.7 m/decade, respectively. At the same time, there is even significant negative changes in the Northeast Atlantic of about  $-0.15$  m/decade for waves of 20% exceedance and  $-0.7$  m/decade for the maximum wind sea (0.14% exceedance). If we consider the trends of the swell height (Figure 8(B)), there will be a tendency of strong positive changes over nearly the whole North Atlantic with the exception of the western subtropics. The largest positive trends are obtained in the Central and East Atlantic mid-latitudes, where they are 0.2–0.3 m/decade (or about 1–1.5% per year) and significant at the 99% level. Another local maximum of the swell trends appear in the western subtropics, where the upward changes are 0.1–0.14 m/decade and are significant at the 95% level.

Figure 9 shows 30 year series of the anomalies of the COADS significant wave height estimate  $H_c^{30}$ , wind sea and swell for the selected locations in the North Atlantic Ocean. These plots indicate that the interannual changes in significant wave height are primarily influenced by the variability in swell rather than in the wind sea. Although the short-term year-to-year changes are quite consistent in both sea and swell records, long-term tendencies demonstrate quantitative and qualitative differences in a number of locations. In the Norwegian and North Seas, wind waves show secular upward changes of 0.21 and 0.15 m/decade, respectively. Positive trends in the swell estimates in these regions give 0.15–0.18 m/decade, respectively, but they result primarily from the influence of the first several years of the record. Table II shows estimates of the trends in the wind sea and swell heights, computed using shorter records between each of the first 7 years and each of the last 7 years for these two locations. For the mid-litudinal central Atlantic, sea and swell height trend estimates are consistent and indicate upward changes from 0.17 to 0.22 m/decade. If we consider the trend estimates between each of the first 7 years and each of the last 7 years for the location '3' (Table II), the largest trends of about 0.44 m/decade for swell and of about 0.19–0.21 m/decade for the wind sea appear for the period from the late 1960s to early 1990s. At the same time, wind sea does not show any statistically significant trends for the period from 1970 to the late 1980s. For the western subtropics and the tropics (locations '4' and '5' in Figure 9) swell trend is strongly influenced by the first several years of the records. Table II shows, that if we exclude the first 3 years, there will be a weakly negative tendency in the swell estimates in the subtropics, and in the tropics trends will be close to zero. Wind sea trend estimates are not so strongly influenced by the first years of the records in both locations, although the elimination of the first 4–5 years drops the trend estimates by nearly two times and makes them insignificant.

Figure 10 shows 30 year series of significant wave height, swell, mean sea, and different percentiles exceedances for the area in the Northeast Atlantic restricted by 60°N, 52.5°N, 22.5°W and 12.5°W, where instrumental measurements (Bacon and Carter, 1991) taken at OWS L and SSLV, give a secular trend in significant wave height. Mean wave height does not indicate any significant trends in this region. Fifty percent and higher percentile wave heights in the location of the OWS L show significantly negative changes, which give, for example for 10% exceedance, a 3.5 cm annual decrease. At the same time, swell height in this region (Figure 10) is growing with an overall increase of 0.018 m/year. In the SSLV area, wind sea indicates weak and insignificant positive tendencies, but for the already 20% exceedance, there

is a significantly negative trend of about  $-0.128$  m/decade. Swell in the vicinity of SSLV indicates a significantly positive trend of  $0.134$  m/decade. Note that in both OWS L and SSLV locations significant wave height trend estimates are highly correlated with trends in swell, and are not linked to the wind sea long-term changes.

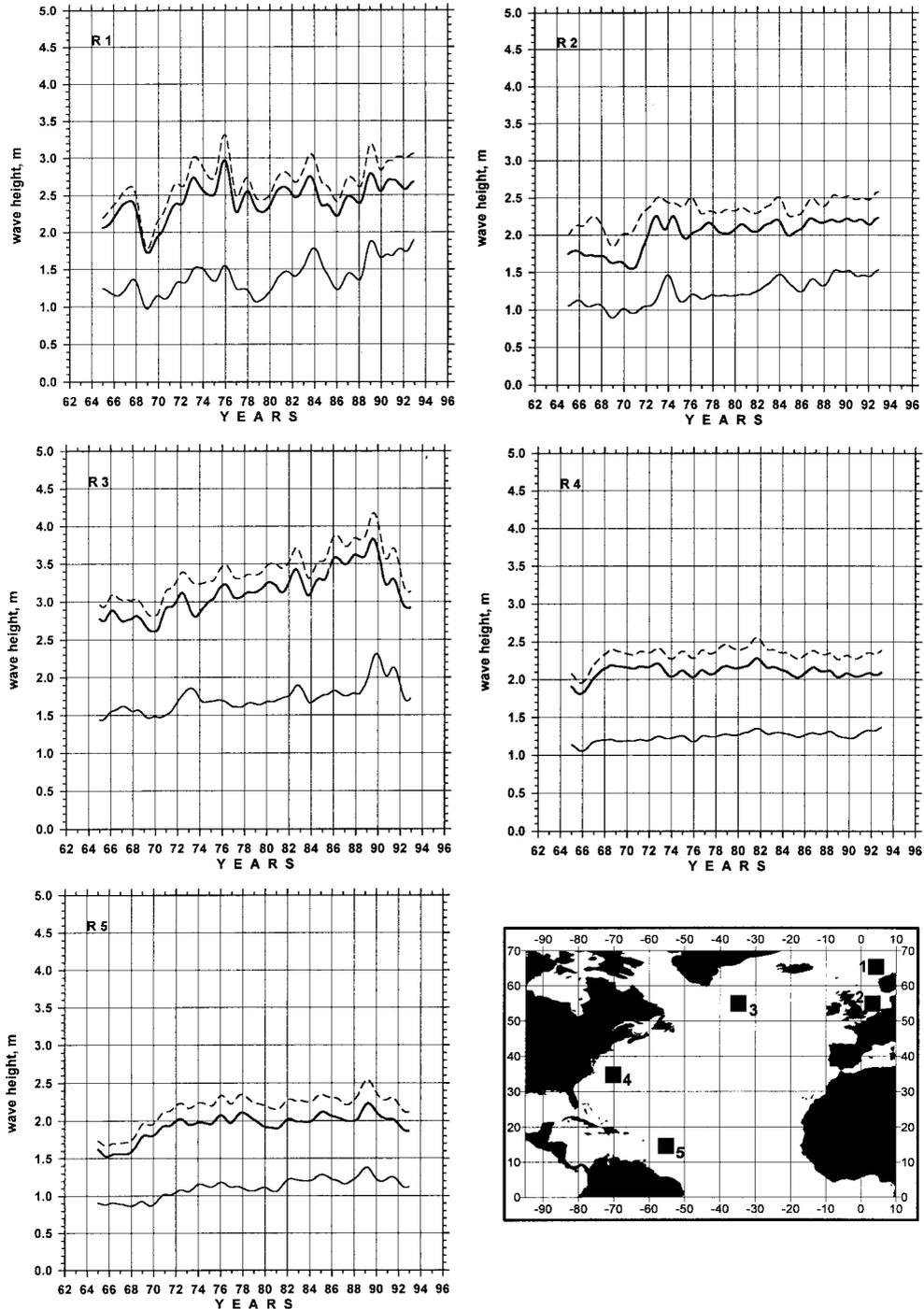


Figure 9. Long-term series of the anomalies of the wind sea height (thin lines), swell height (bold lines), and significant wave height (dashed lines) for 1964–1993 for five locations in the North Atlantic

Table II. Trends (cm/decade) of the wind sea and swell height between each of the first 7 years and each of the last 7 years for three locations in the North Atlantic

	Sea							Swell						
	1987	1988	1989	1990	1991	1992	1993	1987	1988	1989	1990	1991	1992	1993
Area 2 (North Sea)														
1964	17	<b>17</b>	<b>17</b>	<b>18</b>	<b>19</b>	<b>19</b>	<b>19</b>	<b>25</b>	<b>23</b>	<b>22</b>	<b>22</b>	<b>21</b>	<b>20</b>	<b>19</b>
1965	<b>18</b>	<b>18</b>	<b>18</b>	<b>19</b>	<b>20</b>	<b>20</b>	<b>19</b>	<b>24</b>	<b>24</b>	<b>23</b>	<b>22</b>	<b>21</b>	<b>20</b>	<b>20</b>
1966	<b>20</b>	<b>19</b>	<b>19</b>	<b>20</b>	<b>21</b>	<b>20</b>	<b>20</b>	<b>24</b>	<b>24</b>	<b>23</b>	<b>22</b>	<b>21</b>	<b>20</b>	<b>19</b>
1967	<b>21</b>	<b>20</b>	<b>20</b>	<b>21</b>	<b>22</b>	<b>21</b>	<b>21</b>	<b>24</b>	<b>23</b>	<b>22</b>	<b>21</b>	<b>20</b>	<b>20</b>	<b>19</b>
1968	<b>20</b>	<b>19</b>	<b>20</b>	<b>21</b>	<b>21</b>	<b>21</b>	<b>21</b>	20	<b>20</b>	<b>20</b>	19	19	18	17
1969	17	17	18	<b>20</b>	<b>20</b>	<b>20</b>	<b>20</b>	14	16	16	16	15	15	14
1970	15	16	16	18	<b>19</b>	<b>19</b>	<b>19</b>	6	8	9	10	10	10	9
Area 3 (mid-latitude central North Atlantic)														
1964	<b>13</b>	<b>12</b>	<b>12</b>	<b>16</b>	<b>18</b>	<b>19</b>	<b>17</b>	<b>34</b>	<b>35</b>	<b>36</b>	<b>38</b>	<b>36</b>	<b>33</b>	<b>28</b>
1965	11	11	<b>12</b>	<b>15</b>	<b>17</b>	<b>18</b>	<b>17</b>	<b>35</b>	<b>36</b>	<b>37</b>	<b>39</b>	<b>37</b>	<b>34</b>	<b>29</b>
1966	<b>12</b>	<b>12</b>	<b>12</b>	<b>16</b>	<b>18</b>	<b>19</b>	<b>17</b>	<b>37</b>	<b>38</b>	<b>39</b>	<b>41</b>	<b>39</b>	<b>35</b>	<b>29</b>
1967	<b>13</b>	12	<b>12</b>	<b>16</b>	<b>19</b>	<b>20</b>	<b>18</b>	<b>37</b>	<b>39</b>	<b>40</b>	<b>43</b>	<b>39</b>	<b>35</b>	<b>29</b>
1968	13	11	<b>12</b>	<b>17</b>	<b>19</b>	<b>21</b>	<b>18</b>	<b>38</b>	<b>39</b>	<b>41</b>	<b>44</b>	<b>41</b>	<b>35</b>	<b>29</b>
1969	10	9	10	15	<b>19</b>	<b>20</b>	16	<b>35</b>	<b>37</b>	<b>38</b>	<b>41</b>	<b>38</b>	<b>33</b>	<b>26</b>
1970	6	7	8	14	<b>17</b>	<b>18</b>	15	<b>32</b>	<b>34</b>	<b>36</b>	<b>40</b>	<b>36</b>	<b>31</b>	<b>24</b>
Area 4 (subtropical North Atlantic)														
1964	<b>8</b>	<b>7</b>	<b>7</b>	<b>6</b>	<b>6</b>	<b>6</b>	<b>6</b>	5	<b>5</b>	4	3	2	2	1
1965	<b>7</b>	<b>7</b>	<b>6</b>	<b>6</b>	<b>5</b>	<b>5</b>	<b>5</b>	2	2	1	0	-0	-0	-0
1966	<b>6</b>	<b>6</b>	<b>6</b>	<b>5</b>	<b>4</b>	<b>4</b>	<b>4</b>	-0	-0	-1	-2	-2	-3	-3
1967	<b>6</b>	<b>6</b>	<b>6</b>	<b>5</b>	4	4	4	-2	-2	-2	-3	-3	-4	-4
1968	<b>6</b>	<b>6</b>	<b>6</b>	<b>5</b>	4	4	4	-1	-1	-2	-3	-3	-3	-4
1969	<b>6</b>	<b>6</b>	<b>5</b>	4	3	3	4	-0	-0	-1	-2	-3	-3	-3
1970	<b>6</b>	<b>5</b>	<b>5</b>	4	3	3	4	-0	-0	-1	-2	-3	-3	-3

Bold indicates estimates that are significant at the 95% level (*t*-test).

#### 4.4. Trends in the VOS wind sea periods

Wave periods can be considered as an important relatively independent indicator of the changes in the wave heights. Although there could be physical mechanisms that lead to the opposite tendencies in the wave heights and periods, in general in the open ocean in mid-latitudes there should be relatively stable joint probability distributions of wave heights and periods (Srokosz and Challenor, 1987). Dacunha *et al.* (1984), Hogben (1988), and Gulev and Hasse (1998) noted that there is a systematic underestimation of visual estimates of periods in comparison with instrumental measurements by several tenths of a second. Gulev and Hasse (1998) suggested a correction for the wind sea and swell periods, based on fitting joint distributions of wave height and period for every calendar month in the 17 locations of the North Atlantic, which included 14 NDBC buoys, OWS C and L and the SSLV. For the whole North Atlantic, formulae obtained (Gulev and Hasse 1998) give better agreement with instrumental measurements than the Dacunha *et al.* (1984) method and the Ochi (1978) correction, which both give systematic overestimation of periods in the Northeast Atlantic, and systematically underestimate periods in the West Atlantic mid-latitudes and subtropics.

Corrected wind sea periods were used for computing long-term anomalies in the same manner as for the wave height (2). We did not use in this study estimates of the swell periods. There was a historical change in the COADS swell period codes in 1968. This change is hardly detectable, because it might not have been accepted simultaneously by all nations and ship owners. New codes (if decoded as old ones) give nearly twice as long swells, and even a small contribution of the wrongly reported periods can have the effect of a considerable increase of values for 1968–1970. Figure 11 shows linear trends in the sea periods for 1964–1993 together with a *t*-test statistical significance. Spatial patterns of the estimates of linear

trends in the wind sea height and periods (Figures 8(A) and 11) are in general agreement, although periods do not indicate pronounced mid-latitude maximum of the positive trends. At the same time, there is a very good agreement between the locations of areas of the negative trends in the heights and periods in the Northeast Atlantic. Wind sea periods show here significant downward tendencies ranging from 1 to 1.3 s/30 years. This indirectly supports the conclusion about the absence of the upward changes in the wind sea heights in this region. The largest positive trends in the wind sea periods (slightly higher than 1 s/30 years) are observed in the tropics, and the maximum is collocated with the local maximum of the positive trends in the sea height.

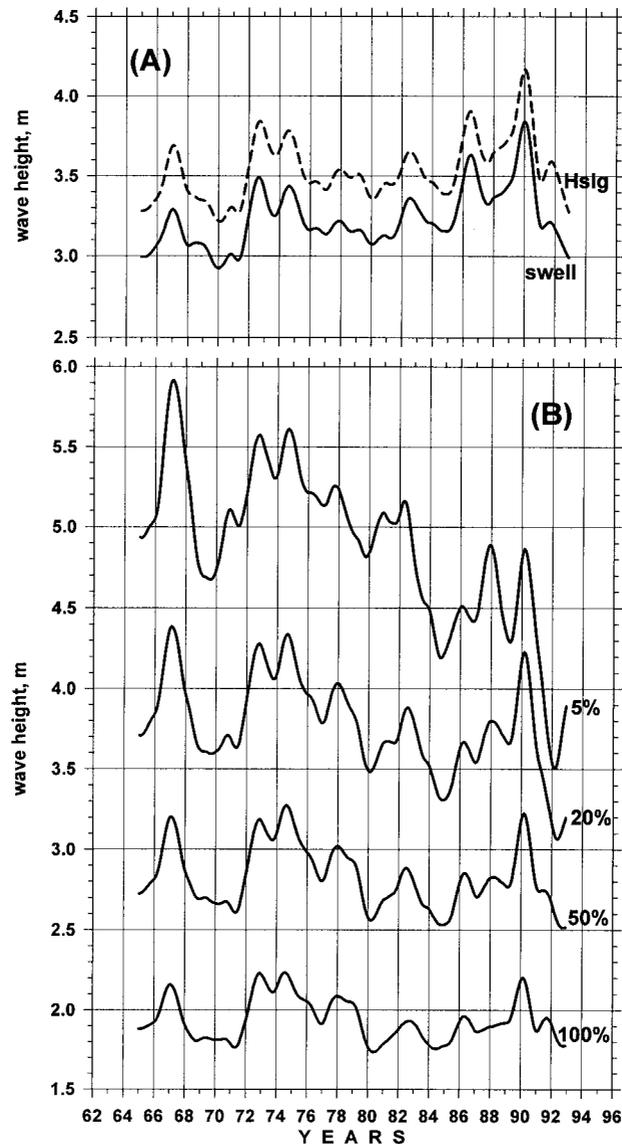


Figure 10. Long-term series of the anomalies of significant wave height and swell height (A) and the height of the wind sea of different percentiles exceedances (B) for 1964–1993 for the Northeast Atlantic

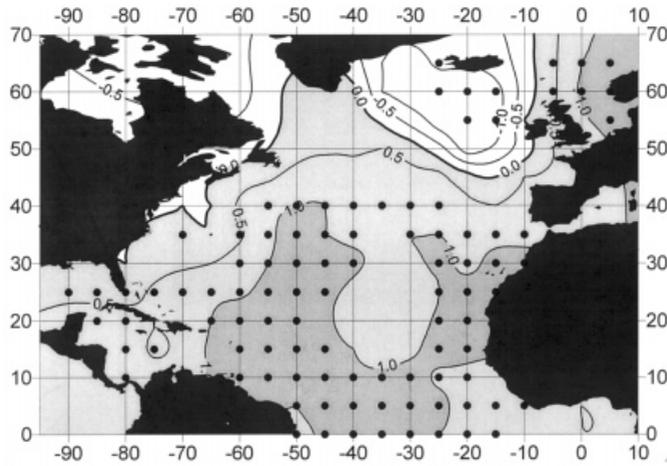


Figure 11. Estimates of linear trends (s/30 year) for the period 1964–1993 in the wind sea period from the visual VOS data. Trends which are significant at the 95% level, are denoted by the black circles

4.5. Long-term changes in the statistical distributions of sea and swell

Figure 10 demonstrates remarkable differences in the long-term variability of the wind sea for different percentiles exceedances in the Northeast Atlantic. Although the short period year-to-year changes are quite consistent for different percentiles, the long-term interdecadal tendencies are rather different, when computed for the mean wind sea and for the percentiles smaller than 50% exceedance. Neu (1984) on the basis of wave forecast charts, also noted significantly different tendencies in the waves that correspond to different percentiles. We have computed the probability distributions of the wind sea in the Northeast Atlantic. Figure 12 shows the occurrence histograms of the wind sea and swell height for three decades 1964–1973, 1974–1983 and 1984–1993. Remarkably enough, the occurrence histograms for the wind sea height were strongly changed through these three decades. Occurrences of smaller sea heights increased from 1964–1973 to 1984–1993 by 24% and by nearly 40% for the classes 0–1 m and 1–2 m, respectively.

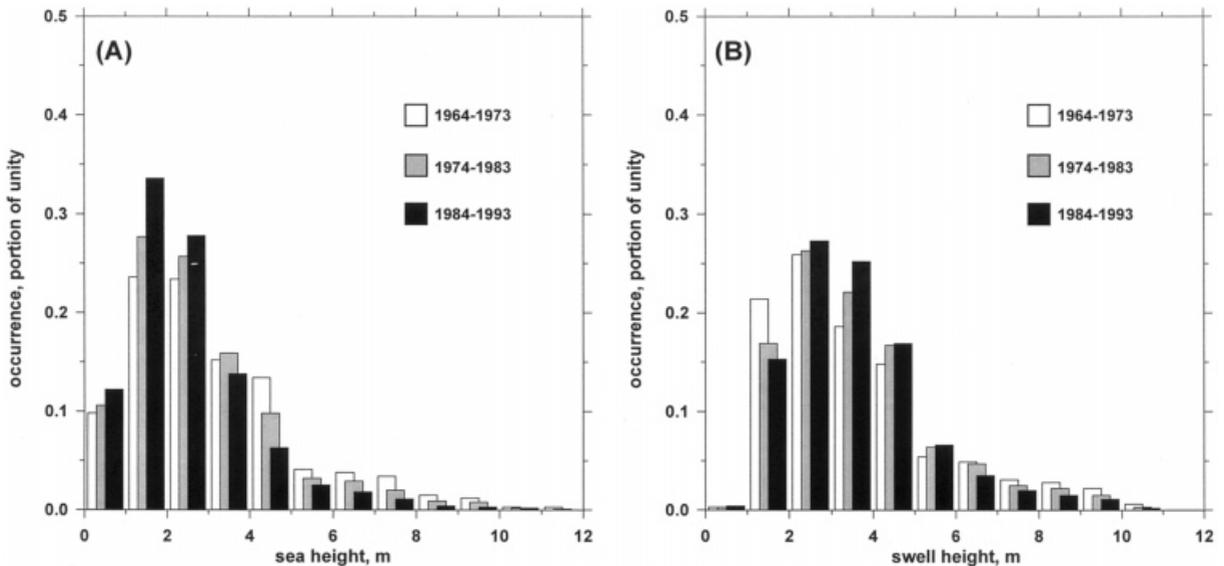


Figure 12. Occurrence histograms for the wind sea height (A) and swell height (B) in the VOS visual data for the periods 1963–1974 (white), 1974–1983 (grey), and 1984–1993 (black) in the Northeast Atlantic

Table III. Comparison of the linear trend estimates taken from the VOS visual data and the OWS visual data

OWS	Latitude	Period of observations	Trend in the wind sea (cm/decade)		Trend in swell (cm/decade)	
	Longitude		VOS	OWS	VOS	OWS
C	52.5°N 35.5°W	1964–1989	<b>4</b>	<b>15</b>	<b>34</b>	<b>36</b>
L	57.0°N 20.0°W	1976–1987	–3	–2	2	4
M	66.0°N 2.0°W	1964–1989	<b>16</b>	<b>15</b>	<b>14</b>	<b>14</b>
SECTIONS	40–45°N 40–50°W	1981–1991	<b>20</b>	<b>22</b>	<b>29</b>	<b>26</b>

Bold indicates significance at the 95% level; italic, at the 90% level.

At the same time, for the range of 3–12 m there has been a considerable drop in the occurrence of sea heights. Particularly, the occurrence of the high seas (higher than 4 m) decreased sharply more than twice during the three decade period. As a result, strong changes in the long-term variability patterns of the wind sea height of different percentiles appeared in Figure 10. Alternatively, occurrence histograms for the swell height (Figure 12(B)) demonstrate smaller interdecadal changes than those for the wind sea. An opposite tendency is observed for small swells. The occurrence of swells smaller than 2 m, decreased by about 40% during the period 1964–1993. At the same time, the moderate swells (2–6 m) appeared more frequently in the later decades than during the earlier ones. For the swells higher than 6 m (10–20% exceedances), the interdecadal tendency is similar to those for the wind sea. Interannual changes in the statistical distributions can result from the changes in the synoptic statistics of the forcing fields (first of all, wind) rather than from the climate changes in the mean monthly winds. In the discussion session below we will discuss the possible link between the changes in the wave height and statistical properties of the wind over the mid-latitude North Atlantic.

## 5. RELIABILITY OF THE TREND IN THE WAVE CLIMATE

Since the visual wave estimates contain a number of errors and uncertainties, the question remains whether even statistically significant changes are reliable, taking into account the questionable reliability of visual estimates. The study of the variability patterns gives the possibility of avoiding consideration of many systematic errors, assuming the homogeneity of systematic biases in time. On the other hand, this assumption has to be checked against independent data because the consistency of mean climatological values does not guarantee the similarity in the variability patterns.

To estimate observational accuracy of the VOS wave data, Gulev and Hasse (1998), and earlier Hogben and Lumb (1967) and Hogben *et al.* (1986), used visual observations that were done by well-trained (in comparison with the VOS officers) professional observers at OWS and from the SECTIONS experimental site in the Northwest Atlantic (Gulev, 1994, in press). Here we used OWS and SECTIONS visual data to test the trend estimates, obtained from the VOS collection. Trend estimates were computed using both OWS visual observations and the VOS data within a certain spatial correlation ellipse, which provides at least 100 VOS observations per month within the selected ellipse. For the SECTIONS experimental site, we selected a  $5 \times 10^\circ$  box in the Newfoundland basin. For this box all reports available from the SECTIONS collection were averages in the same manner as for the COADS data. The period of overlap of the SECTIONS data with the COADS is from 1981 to 1991. The periods of overlap of OWS data with the VOS observations are quite short for the majority of OWSs, and restricted by an 8 year period from 1964 to 1972 (Isemer, 1994). Thus, we used OWS C, L and M, which provide 25, 12 and 24 year periods

of overlap, respectively. Table III shows results of the comparison of trends for the OWS C, L, M, and the SECTIONS data with the VOS data in the nearest vicinity of OWS. In general, there is a very good agreement between the trend estimates taken from the VOS visual data and the professional measurements at the OWS and SECTIONS vessels. Deviations of trend estimates from each other are always within the range of 5 cm/decade. Statistically significant differences between the VOS and OWS trend estimates (at the 90% level) were obtained only for the swell height at OWS L. Trends in significant wave height (not shown here) are also reasonably consistent, as those computed from the sea and swell using the same unique approach. In the Section 4.1 we have also found very good agreement between the trend estimates in significant wave height from the VOS and instrumental measurements at SSLV and OWS L. Thus, we can conclude that the comparison with OWS and SECTIONS measurements as well as with instrumental records indicates the reliability of the trend estimates taken from the visual wave data.

In order to estimate the possible influence of the 'day time minus night time' differences on trend estimates, we have computed linear trends separately in the day time and night time climatology. Figure 13 shows the trend in wind sea and swell heights for the day time and night time in the same manner as Figure 8. We can point out that the spatial patterns and the quantitative estimates of day time and night time trends are nearly identical to each other and to the overall maps in Figure 8. The magnitude of trends is slightly higher for the night time collection for both sea and swell, although  $t$ -test results do not indicate statistically significant differences in the trend estimates. Both day time and night time charts indicate the absence of significant positive trends in the wind sea in the Northeast Atlantic, and show pronounced maxima of the secular changes in the swell heights ranging from 20 to 30 cm/decade. Thus,

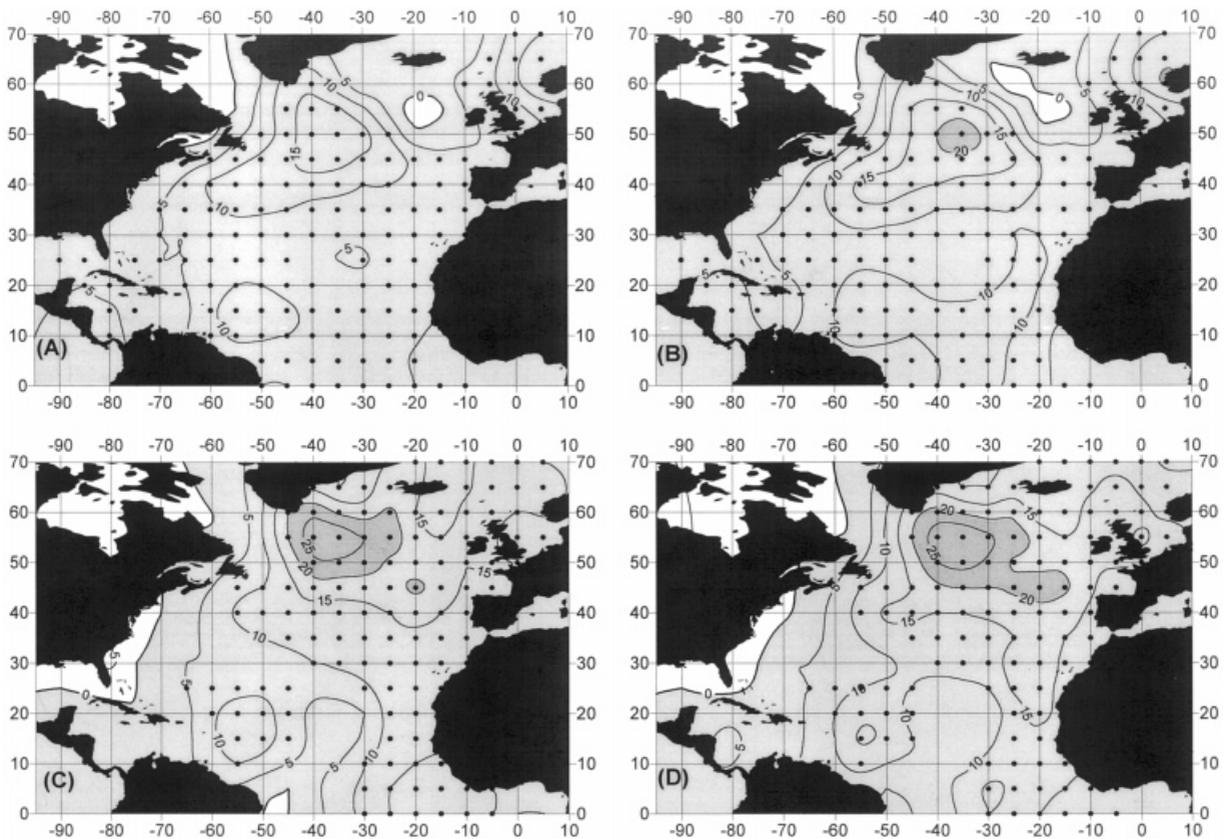


Figure 13. Estimates of linear trends (cm/decade) for the period 1964–1993 in the wind sea height (A, B) and swell height (C, D), computed for the day time (A, C) and night time (B, D) observations. Trends which are significant at the 95% level, are denoted by the black circles

'day time minus night time' bias does not affect the linear trend estimates in the wind sea and swell heights.

The separation between visual sea and swell estimates has been found to be successful in the COADS reports (Figure 5). Nevertheless, even if we assume that part of swell is reported as sea, that does not change our main conclusion about the growing swell in the Northeast Atlantic mid-latitudes with no pronounced upward tendency in the wind sea. Alternatively, wrongly reported seas (as swells) have to decrease positive trends in the Northeast Atlantic swell, and if we assume an ideal separation between sea and swell, we can only expect higher trends in the swell height. The same is with the biased small heights in the subtropics and tropics, which are lower than 0.5 m and coded as '1' in COADS. Positive trends assume that the number of reports within this range decreases with time. Thus, the contribution of positively biased heights in the beginning of the record is higher than in the end, and even if this effect is important it can result in the decrease of the positive trend estimates.

Houmb *et al.* (1978) reported about the possible influence of the change of meteorological assistants to mates (occurred in 1959) on the interdecadal changes in the visual estimates of wave heights. Particularly, he explained in this way the observed overestimation of significant wave height in 1972 in comparison with 1957. First, the Houmb *et al.* (1978) conclusion pertains to a limited area of the Norwegian Sea (OWS M) and is based on the interview of only one person who reported that his mates tended to underestimate wave height since they make the observations from the bridge which is located higher than the meteorological deck. Second, we did not use reports for the period prior to 1963. At the same time, the problem of possible changes in the observational techniques is very important. The first results from the pilot questionnaire SHIPMET distributed to 300 Russian and former Soviet officers (Gulev, in press) should provide suitable information for the evaluation of possible artifacts in the VOS observations of basic meteorological variables.

## 6. DISCUSSION

Our estimates of the climate changes in the North Atlantic wave fields based on visual observations, can be discussed from a number of viewpoints. Over nearly the whole North Atlantic except for the western and central subtropics, significant wave height indicates a significant upward tendency ranging from 10 to 30 cm/decade. These changes result primarily from the swell increase. Wind sea indicates strong changes in the central mid-latitudinal North Atlantic and does not show significant changes in the Northeast Atlantic, where instrumental records of Bacon and Carter (1991) report secular changes. Moreover, wind sea of 50% and higher percentiles exceedances indicate here significantly negative tendencies. Thus, the increase of recorded (Shipborne Wave Recorder) wave heights at OWS L and SSLV is connected with the growing swell rather than with the changes in the wind sea. Recently, Bouws *et al.* (1997) came to the same conclusion analysing different evidence of wave climate changes in the North Atlantic.

Observed changes in wind velocity ranging from 0.1 to 0.5 m/s per decade (Flohn *et al.*, 1992; Bigg, 1993; Diaz *et al.*, 1995) and in the severity of storms (Schinke, 1993; Stein and Hense, 1994) in the North Atlantic at first sight go hand in hand with the growing wave heights. At the same time, there is considerable debate (Ramage, 1984; Peterson and Hasse, 1987; Cardone *et al.*, 1990; Lindau *et al.*, 1990; Ward, 1992; Ward and Hoskins, 1996; Gulev, in press) about the reliability of upward wind trends, which probably results from the development of observational techniques. The increase of the relative contribution of anemometer measurements with time is considered as a possible reason of wind speed trends obtained from the VOS data. However, there are many other sources of artifacts, such as the growing ship size, and therefore the increase of the height of anemometer measurements, the effect of the computation (or its absence) of the true wind from the relative wind, and even the historical changes in the ship macrostructure. Many of these problems were studied in detail during the VSOP-NA project (Kent *et al.*, 1993), but not in the climate change context. Isemer (1995), Schmidt and von Storch (1993), and Gulev (in press) made a comprehensive comparison of the VOS winds with instrumental measurements and have found no evidence of the statistically significant and reliable trends in the wind speed over mid-latitudinal

North Atlantic during the last several decades. Growing storminess is also questionable, because it can result from the changing data coverage and analysis techniques (Agee, 1991; Ueno, 1993; von Storch *et al.*, 1993).

A reasonable question to ask is to how swell height could increase with no pronounced increase of mean wind and even downward changes of wind sea in this area west of Europe. Taking into account significant upward trends of the wave height in the West Atlantic mid latitudes (Figure 8(A), (C) and (D)), this is in agreement with the propagation of swell along the main Atlantic storm track with high directional steadiness, although in this case growing waves in the West Atlantic should be explained itself. Swell is an integrated space–time characteristic of wind speed in a higher degree than sea. Hogben (1995) first suggested a hypothetical qualitative mechanism of the growing swell without changing mean wind speed. In this way growing swell can result from the long-term changes of statistical distributions of scalar wind and sea level pressure (SLP), rather than from increasing mean wind speed. Increases in storm frequency reduces the time of the swell decay between storms and provides a higher residual swell level, as an initial condition for the generation of young waves (Hogben, 1995). On the other hand, increasing forcing frequency may not necessarily be associated with the growing forcing magnitude.

Note here that the hypothesis of Hogben (1995) was not supported completely and unconditionally by the model simulations with the WAM model. Recently, Bauer *et al.* (1997) performed an ingenious experiment with WAM driven by the ECMWF 6 hourly winds during six winter months from October 1992 to March 1993. In addition to the control run forced by the original 6 hourly winds, two ‘scenario’ runs were made that accounted for the increasing and decreasing of the storm frequency by respectively artificially reducing the temporal resolution of forcing to 4 h (‘fast’ run), and artificially enlarging the wind resolution to 8 h (‘slow’ run). Mid-latitude significant wave height has slightly increased in the ‘slow’ run and slightly decreased in the ‘fast’ run mainly due to the impact of the changes in the wind sea. Although swell indicated a 1–3% increase in the storm track area in the ‘fast’ run, it was not enough to overcompensate the considerable drop of the wind sea and to provide the growing significant wave height (SWH) (i.e. to prove the Hogben (1995) hypothesis). At the same time, the definition of ‘swell’ in the WAM model (Komen *et al.*, 1994) appears to be different from the swell defined by the sailors eye. Particularly, we have found systematic biases 0.2–0.7 m between the visual swell and the WAM swell, comparing two products for 1979–1993 (Gulev *et al.*, 1998). Sterl *et al.* (1997) computed significant wave height trends in the WAM runs driven by the ERA (European Reanalysis Project) winds for the period 1979–1993. Comparison of his trends with those seen in the North Atlantic VOS significant wave height for the same period (Gulev *et al.*, 1998) showed disagreement in the trends estimates in both the mid-latitudes and the tropics, which results primarily from the differences in swell.

Bacon and Carter (1993) found a significantly positive correlation of the instrumentally recorded wave heights at SSLV and OWS L with the SLP gradient between the Azores high and Iceland low, and therefore established a link between the Northeast Atlantic significant wave height and the North Atlantic Oscillation (NAO), which is one of the most pronounced modes in the interannual to interdecadal variability of the atmosphere over the North Atlantic Ocean (Rogers, 1984; Lamb and Pepler, 1987; Carleton, 1988; Hurrell, 1995a,b). Recently, Kushnir *et al.* (1997) using canonical correlations, found the link between the NAO and significant wave height hindcasted by the Canadian spectral model driven by ECMWF winds. Recently performed CO<sub>2</sub> sensitivity runs with the WAM model (The WASA Group, 1998) showed a decrease of significant wave height in the Northwest Atlantic in the case of the doubling of CO<sub>2</sub>. The NAO index indicates a significant increase over the last 30 years, which characterizes the transition from primarily anticyclonic to mainly cyclonic conditions from the 1960s to the 1990s (Kushnir, 1994; Hurrell, 1995a,b, 1996). Records of the frequencies of low pressure events over the North Atlantic (Schinke, 1993; Stein and Hense, 1994) and the intramonthly synoptic statistics (Gulev, 1997) show high correlations with the NAO index. Figure 14(A) and (B) compares the NAO index (as given by Hurrell, 1995a,b) and the winter swell height variability in the Northeast Atlantic for 1964–1993. The correlation between two records equals 0.63, and is higher than those for significant wave height (0.55), but this does not give unconditional evidence of the relationships between the forcing frequency and the growing waves in the Northeast Atlantic.

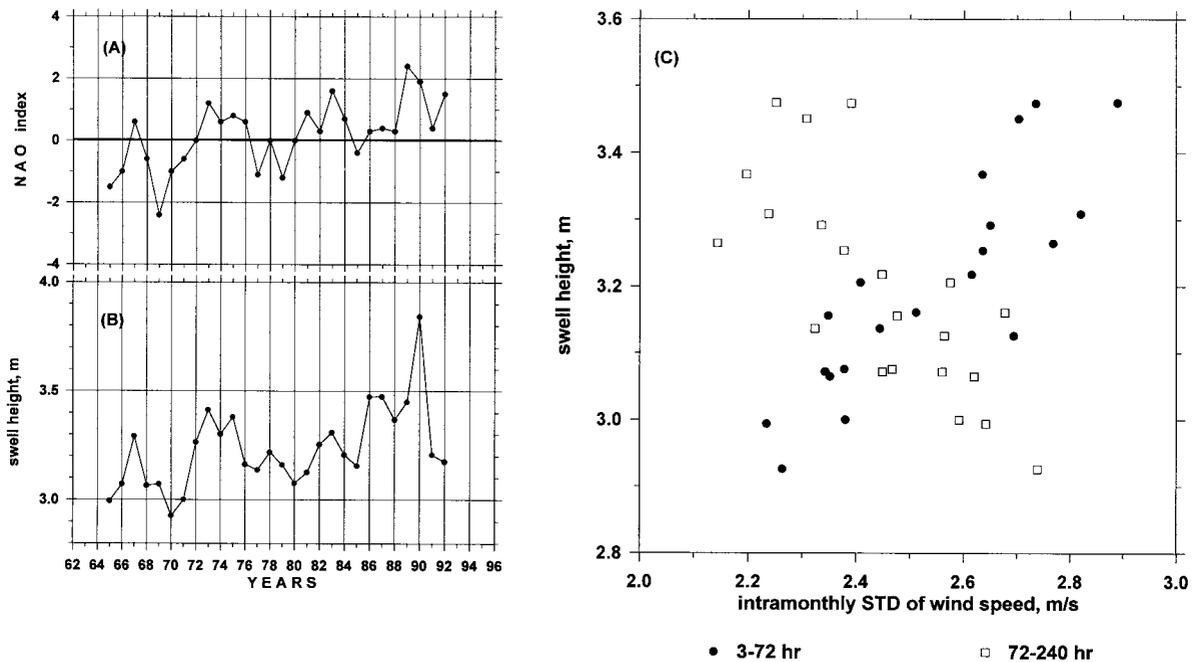


Figure 14. Interannual variability of the NAO index as given by Hurrell (1995a,b) (A), the winter swell height (B) in the Northeast Atlantic, and the dependencies of the winter swell height on the intramonthly S.D. of the wind speed for the ranges 3–72 h (black circles) and 72–240 h (squares) at OWS I and L from 1964 to 1987 (C)

To find an appropriate measure of the storm frequency in the wind data, we have band-passed the original wind records at OWS I (59°N, 19°W) for the period 1964–1973 and OWS L (57°N, 20°W) during 1975–1987. The locations of these stations are shifted from each other by only 200 km and for the rough large-scale estimates both records can be considered as those which characterize changes in the Northeast Atlantic atmospheric circulation. We have band-passed the original 3 hourly wind records for the winter months (December–February), using the Lanczos filtering (Lanczos, 1956; Duchon, 1979), which provides a very effective cut-off of the selected frequency. The total variability was broken down by band-passing into two ranges: 3–72 h and 72–240 h. The range 3–72 h corresponds to the subsynoptic ultra high frequency variability (UHFV) (Blackmon *et al.*, 1984; Ayrault *et al.*, 1995) and to the fast synoptic transients. The range 72–240 h depicts the main synoptic interval and partially the variability of the background flow (Ayrault *et al.*, 1995; Branstator, 1995; Gulev, 1997). Then for each range we have computed intramonthly S.D. Gulev (1997) on the basis of the OWS data showed different long-term tendencies in the intensities of the variability in these two ranges for the period from the early 1950s to the early 1970s. Figure 14(C) shows the high correlation between the winter time swell height and the intramonthly S.D. of the wind speed for 21 winters from 1964 to 1987 with the gap in 1974–1975. Synoptic variability in the range 3–72 h is positively correlated with the swell height with a correlation coefficient of 0.86. Alternatively, intramonthly S.D. in the range 72–240 h gives a significantly negative correlation ( $r = -0.74$ ) with the winter swell height. Thus, the growing swell is associated with the intensification of the relatively ‘fast’ synoptic processes, and simultaneous weakening of the relatively ‘slow’ synoptic processes in the Northeast Atlantic. Analysis of Ayrault *et al.* (1995) showed that for the primarily zonal regimes there is an intensification of the UHFV in the Northeast Atlantic, and the maximum of the intensity of synoptic scale transients (2–6 days according to the Ayrault’s branching) appears in the Northwest Atlantic. For the blocking regimes, both synoptic variability and UHFV indicate their maximum intensity in the Northwest Atlantic.

Thus, there is evidence that changing swell is driven by intramonthly statistics of wind. In this context, growing SLP gradient used by Bacon and Carter (1993) appears to be a very good indicator of the reason, but not the reason itself. It is reasonably correlated with synoptic baroclinic activity in mid-latitudes. Figure 15 represents winter time (December–February) synoptic spectra of zonal wind speed, averaged over the periods 1966–1970 and 1972–1973 at OWS I and for the periods 1978–1980 and 1986–1987 at OWS L, which are characterized by significantly different mean winter swell heights (Figure 14(A)). For example, between the periods 1978–1980 and 1986–1987, winter swell heights increased remarkably by 0.34 m. Spectra for the periods 1972–1973 and 1976–1977 overpredict significantly those for the periods 1966–1970 and 1978–1980 in the range 0.5–3 days. Alternatively, in the range 3–10 days, spectra for the periods 1966–1970 and 1978–1980 have more power than at least the spectrum for 1972–1973. Remarkably enough, mean winter wind at OWS L even decreased slightly between 1978–1980 and 1986–1987 by nearly 0.2 m/s, as well as the wind sea, which indicates the decrease of 0.04 m. Thus, the increase of the ‘fast’ synoptic and subsynoptic variances of SLP and wind speed provided growing swell in the Northeast Atlantic with no changes of mean wind speed.

One possible line of the future development of this study is connected with the use of the synoptic resolution products of different meteorological centres for finding relationships between the changes in the weather regimes and the wave parameters. NCEP and ECMWF nowadays provide reanalyses for 1958–1997 and 1979–1993, which contain 6 hourly wind and SLP fields for the entire globe (Kalnay *et al.*, 1996). OWS data as well the buoy records can provide the relevant background for the validation of the reanalyses. Band-passing and then computing intramonthly S.D. for different ranges from the reanalyses data, it is possible to obtain an adequate resolution and continuity for the forcing fields and the wave parameters and to apply effective procedures for finding interactive patterns. This can give the possibility of performing the basin-scale statistical hindcast of the wave climatology by scaling back the relations between synoptic intensities and the wave parameters. There is less hope with the VOS intramonthly statistics that depict the total synoptic variance (Zorita *et al.*, 1992) and do not provide the possibility of band-passing. Moreover, the VOS intrabox intramonthly S.D. accounts for both synoptic variability and random observational and sampling errors, and at present there is no way of separating synoptic variability from the errors.

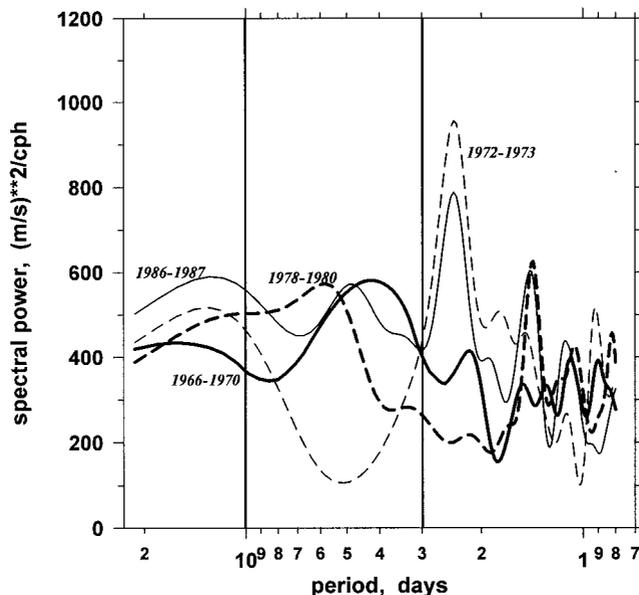


Figure 15. Synoptic wintertime spectra of the zonal wind speed, averaged for the periods 1966–1970 (bold solid line) and 1972–1973 (thin dashed line) at OWS I and for the periods 1978–1980 (bold dashed line) and 1986–1987 (thin solid line) at OWS L

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