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Interannual Variations and Longer-Term Changes in the Sea State of the North Atlantic From 1970 to 1982

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A 13-year (1970–1982) time series of 12-hourly wave charts of the North Atlantic has been analyzed for variations in the sea state. Two types of variation were determined: first, strong 3- to 7-year fluctuations; second, a continuous increase in the sea state during the 13 years. It appears that the former is the result of variations in cyclonic activities over the western North Atlantic and that the latter is caused by a steady increase in the strength of the prevailing westerly winds. The existence of such fluctuations and changes in the wave activity will affect long-term predictions and are expected to have an important impact on the upper-level physical, chemical, and biological processes of the ocean.

1. Introduction

The atmosphere and the underlying ocean are closely, though complexly, coupled. Wind-driven surface waves are an important aspect of this coupling. In the North Atlantic the "Prevailing Westerlies" are one of the prime features in generating the sea state in this body of water. Their strength is determined by the atmospheric pressure difference between the Icelandic Low and Azores High and is much stronger during the winter than in summer. In winter these prevailing winds are interrupted by cyclonic disturbances that form along the cold front of continental North America, then propagate northeastward along the Atlantic seaboard and out either toward Iceland or the Labrador Sea. On average, nearly 200 of these disturbances, referred to as extratropical cyclones, are counted each year. Tropical cyclones or hurricanes, occur in the westerly North Atlantic, usually six to eight times in late summer. Low and medium sea states are generated by the "Prevailing Westerlies," while the high and extreme sea states are produced primarily by cyclonic disturbances and mid-Atlantic storms.

In the late sixties, when oil exploration commenced in Canadian waters, the need became apparent for a wave climate of this region. In 1970 the Bedford Institute of Oceanography (BIO) initiated a wave study for the Scotian Shelf and the Grand Banks of Newfoundland [*Neu*, 1971, 1972] and later expanded it to cover the entire North Atlantic [*Neu*, 1976; *Walker*, 1976, 1977, 1978]. In light of the sinking of the oil exploration platform Ocean Ranger on the eastern Grand Banks in February 1982, a more detailed study, based on 11 years of data, was undertaken for the Canadian Atlantic region [*Neu*, 1982]. In addition to the well-known seasonal cycle in wave conditions, these were marked year-to-year variations in sea state. Similar interannual variability has been noted at North Atlantic weather ships [*Walden*, 1970; *Painting*, 1979], in Delaware's coastal waters [*Yang et al.*, 1974], in the North Sea [*Rye*, 1976], and at Seven Stones light vessel off England's southwest coast [*Fortnum and Tann*, 1977].

This investigation has been extended to include 13 years of data and to cover the entire North Atlantic between 25° and 70°N (Figure 1).

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2. Data Base and Method of Analysis

The wave data were taken from synoptic charts published every 12 hours by the Meteorological and Oceanographic Centre (METOC) in Halifax, N.S., Canada. These charts are based mainly on visual observations reported every 6 hours from 100 to 200 ships across the North Atlantic but also include instrumental data from oil exploration platforms and deep-ocean meteorological buoys.

The question of whether the wave height derived from visual observation is related to the significant wave height H_{sig}—which is the mean height of the highest 1/3 of the waves in a record—has been addressed by a number of researchers [*Wiegel*, 1964; *Bretschneider*, 1966; *Nordenstrom*, 1972; *Jardine*, 1979] who concluded that they are, for all practical purposes, equal. The same conclusion was reached by *Neu* [1976] after comparing the METOC charts with long-term measurements from the SEDCO H oil exploration platform near Sable Island. Other researchers, such as *Pierson* [1982], disagree with this conclusion, particularly for short-term data, but the results analyzed from continuous instrumental recordings at the Hibernia oil field on the Grand Banks and from concurrent METOC data are in close agreement. A comparison of the exceedance distributions for a period of 1.25 years indicates that the average visual wave height H_v is within $\pm 3\%$ of the average instrumental data H_{sig}. The conslusion that $H_v \simeq H_{sig}$ is therefore considered to be valid and is applied here.

The method of processing the wave data is described by *Neu* [1976, 1982]. As specified in Figure 1, for each center of the 5° by 5° areas, annual wave height exceedance distributions were developed on the basis of 730 observations (732 for a leap year). With the exception of the highest value (which might be the height of a wave with a return period of greater than 1 year, e.g., 5 or 10 years, and therefore will not fit the average distribution of the year in which it was recorded), the data follow the straight-line log-normal distribution extremely well, with correlation coefficients in excess of 0.98. This straight-line distribution forms the basis for further analysis, and its relative location and slope are an indication of the severity of the sea state during the year.

3. Results

The individual annual wave height exceedance distributions from 1970 to 1972 and the integrated 13 years distribution for the center of grid box C4 on the Scotian Shelf are shown in Figure 2. The slopes of the annual lines decreased from 1970 to 1972, indicating an increasing trend in the sea state over the

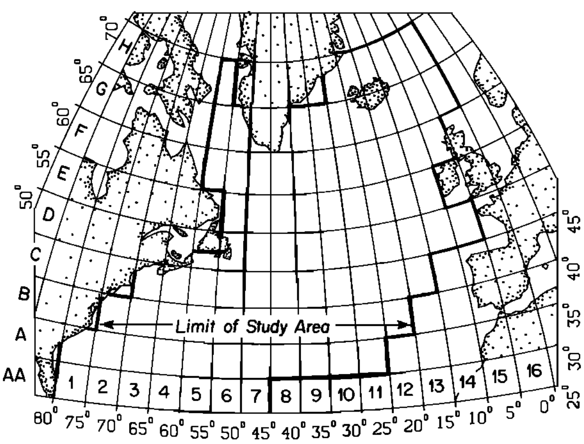

Fig. 1. North Atlantic Ocean with BIO grid system.

3-year period. By expressing the largest 1-year H_{sig} on each line as an indicator for the severity of the sea state, it can be seen that the severity has increased in 3 years from 7.5 m to 9.2 m and 10.2 m. Comparing these annual lines with the 13-year mean distribution line, 1970 was below, 1971 slightly above, and 1972 above average for area C4. Predicting long-term values by extrapolating each 1-year data set yields a 13-year wave from the 1970 and the 1972 data of 10.9 and 15.6 m, respectively; however, the mean value obtained from the entire 13 years of observations was 12.6 m. A deviation of this magnitude from the mean demonstrates that the data from any single year are unsuitable for stable and consistent long-term predictions because of interannual variability.

The variation in annual significant wave height from 1970 to 1982 for four areas of the North Atlantic is shown in Figure 3. Two types of variation are apparent: the first, 2- to 3- and 6- to 7-year fluctuations, particularly in the high and medium wave ranges; and the second, an overall upward trend in the sea state during the 13 years. With few exceptions, both were present across the entire North Atlantic. While it seems highly probable that this 13-year trend is merely an indication of the presence of fluctuations on a time scale of several decades, it is also possible that the period is one of transition toward a new 'mean' of wave severity.

The lowest and highest values of the annual largest H_{sig} in the 13 years were, 7.5 m and 11.5 m on the Scotian Shelf, 8.9 m and 12.9 m on the Grand Banks, 9.4 m and 17.7 m in the mid-Atlantic, and 10.3 m and 16.4 m west of Ireland. In Figure 4 these two values are presented for the entire North Atlantic. In general terms the range between these lowest and highest values increased from 2.5 m in the southern North Atlantic and along the coast of North America to about 6 m in the central and northeastern North Atlantic. These ranges are similar in magnitude to the range of the normal cycle between winter and summer [*Neu*, 1982] for the respective areas.

The spatial variation year by year across the North Atlantic is best demonstrated in Plate 1, where the annual anomalies relative to the local 13-year means are presented. The data used are not the largest annual wave height but that wave height exceeded by the highest 1% of the waves. The figure clearly shows the long-term increasing trend and the shorter-term fluctuations: 1970 was well below and 1971 slightly below the 13-year average condition; 1972 was a noteworthy exception, with conditions well above normal in the northern and well below normal in the southern part of the North Atlantic; 1973, 1974, and 1975 were more or less below average, but 1976 and, in particular, 1977 form a transition from below to above average. From 1978 onward, conditions were, first, above and then well above average in 1979, 1980, and 1981, primarily in the south, and in 1982 in the central and northern North Atlantic.

The sequence and magnitude of the fluctuations varied greatly from location to location. Coastal regions frequently differed in their behavior from that of the open ocean. In most cases the variations alternated between the northern and the southern and, in two cases, in 1980 and 1981, between the western and eastern North Atlantic. Therefore, the dividing lines, or regions of no fluctuations, were more from east to west than from north to south.

The lowest and highest sea states in the central part of the North Atlantic occurred in 1970 and in 1982, respectively. In 1970 it was 20% to 25% below, and in 1982, 40% to 45% above, the mean—a total difference of more than 60%. Expressing this difference as wave energy, there was 2.5 to 3 times more wave energy in the central North Atlantic in 1982 than in 1970.

The average long-term changes in the 1% exceedance sea state and in the 50% exceedance sea state are shown in Figure 5. The change is determined by the ratios of the 1982 and 1970 wave heights taken from the least squares mean lines based on the 13 years of data. North of 60°N and east of 25°W along the coast of North America, there was little or no increase in the large sea state; however, there was a significant increase, between 30 and 40%, in the western part of the North Atlantic. The zone with the greatest increase was between the Gulf Stream and the mid-Atlantic, generally lying between Bermuda and 35th meridian and roughly north to Greenland and into the Labrador Sea. Since the area of the increased sea state activity of the large waves is also the region where extratropical cyclones grow and travel, it appears that enhanced cyclonicity during this period is responsible for the higher wave activity. It also appears that more cyclones entered the Labrador Sea than before. The low sea state, which is exceeded 50% of the time, shows an increase that is even larger, proportionally, than that of the high sea state. It extended over the entire main body of the North Atlantic, including the coastal regions of North America but excluding the northern

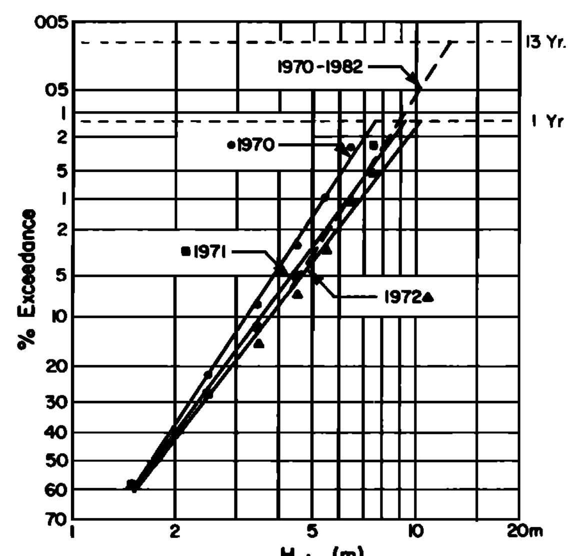

Fig. 2. Annual (from 1970 to 1972) and 13-year wave height distributions for C4.

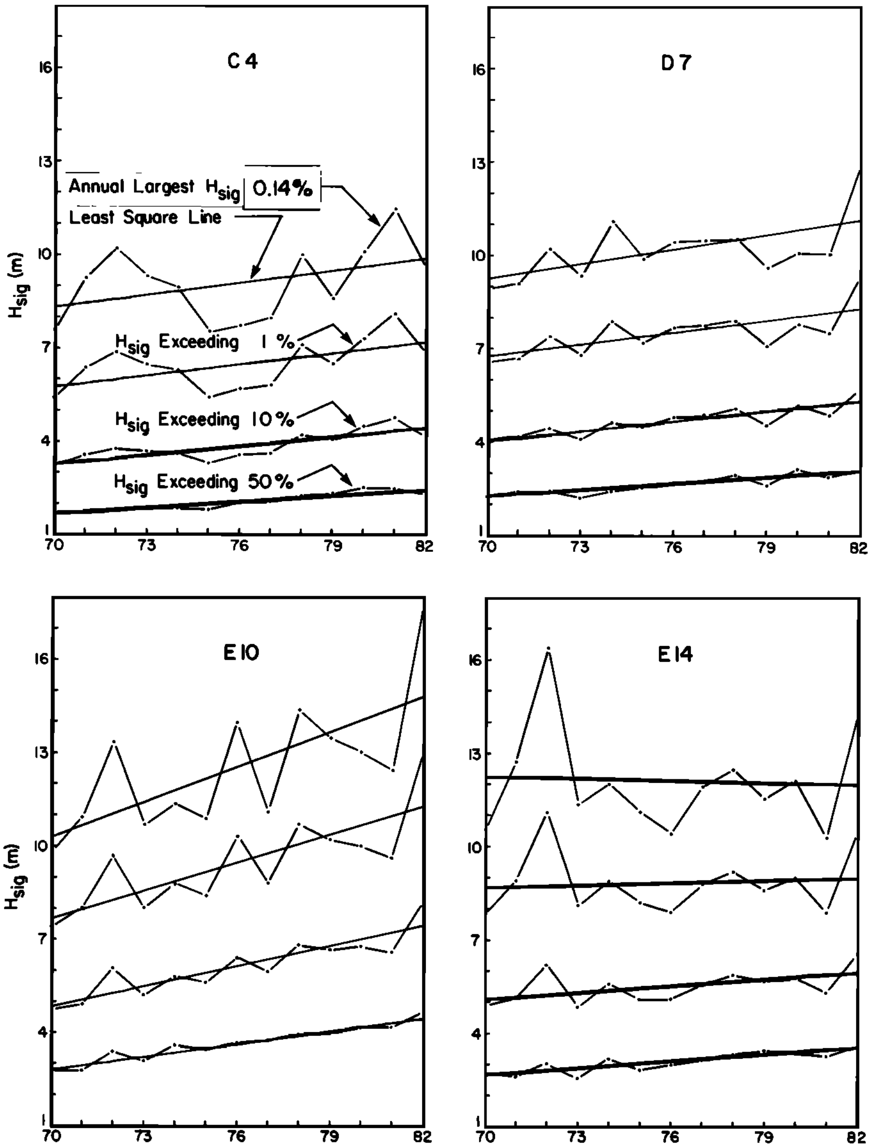

Fig. 3. Variation in annual significant wave height (H_{sig}) for four areas of the North Atlantic (Scotian Shelf, C4; Grand Banks, D7; mid-Atlantic, E10; and west of Ireland, E14) from 1970 to 1982. For each area, wave heights for the 0.14% (highest annual H_{sig}), 1%, 10%, and 50% exceedances are plotted in addition to the least squares fit.

waters where polar easterly winds prevail. The height of the waves generally increased from north to south with regions of 55% growth at mid-Atlantic, along the south-eastern coast of Atlantic Canada and in the southwestern North Atlantic. These results indicate that the prevailing westerly wind increased during these 13 years and shifted southward into the Horse Latitudes, which usually occupy the zone at about 20° to 30°N.

Surface waves are a kinetic energy system arising from wind activity, and since these winds are the result of inequalities in barometric pressure, the variations in wave activity must be related to atmospheric fluctuations. An analysis by *Saulesleja*

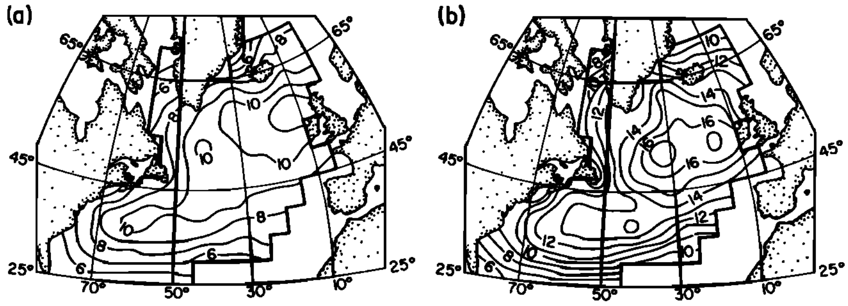

Fig. 4. Lowest (*a*) and highest (*b*) annual largest H_{sig} from 1970 to 1982.

Plate 1. Annual anomalies from the mean of the 1% exceedance sea state from 1970 to 1982.

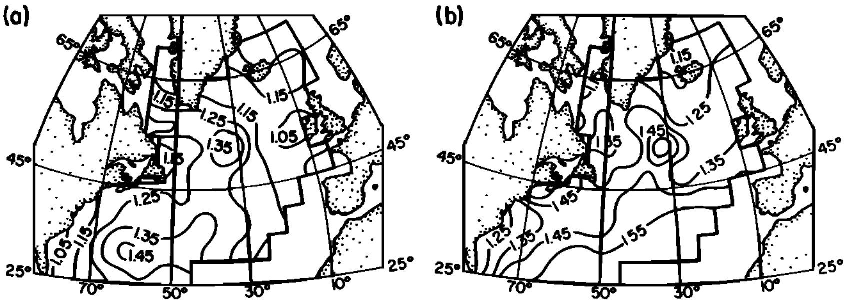

Fig. 5. Net change of sea state exceeding 1% (*a*) and 50% (*b*) occurrences from 1970 to 1982.

and Phillips [1981] of geostrophic wind in the Canadian waters over the two decades ending in 1968 and 1978 confirms a general increase in wind speed of 10% to 20%. This, however, covers only part of the wave analysis and does not include the period from 1978 to 1982, which contained exceptionally high wave activity.

According to *Wallace and Gutzler* [1981], there is abundant evidence of the existence of fluctuations with characteristic time scales of a year to a few years. One such fluctuation, referred to as the North Atlantic Oscillation, is defined by the mean surface temperature in the Greenland-Labrador region and northwestern Europe, and the sea-level pressure difference between the Icelandic Low near 65°N and the Azores High, which is a broad belt of high pressure from the east coast of the U.S. to the Mediterranean. The standing oscillation in winter temperature has been documented by *Van Loon and Rogers* [1978], and the oscillating pattern in sea level pressure has been noted by many authors over the years, including *Defant* [1924], *Walker and Bliss* [1932] and *Kutzbach* [1970]. In Figure 5 the general pattern of fluctuations in wave activity and the prevailing location of the nodal zone across the North Atlantic bear great similarity to the sea-level pressure system and its oscillation. This invites further study.

Fluctuations in sea-level pressure, wave activity, and air and sea temperature all have an impact on oceanic processes. According to *Longuet-Higgins* [1977], waves strongly influence the transfer of heat, momentum, water vapor, gases (O_2 and CO_2), salt particles, and microorganisms between ocean and atmosphere, and they stir the ocean surface through their oscillations, breaking, and surface drift. The larger the sea state, the stronger the mixing, and thus the greater the thickness of the upper layer. *Perry and Walker* [1977] report that mixing by wave action and convective stirring can lead to large changes of sea temperature, which in many areas of the ocean can amount to as much as 1.5°C over a 2-day period. For instance, during the Ocean Ranger storm (February 14, 1982) at the Hibernia oilfield on the Grand Banks of Newfoundland, the surface temperature of the water increased by 2°C within 24 hours [*Richards*, 1982]. Similar fluctuations, though smaller in magnitude, can result from interannual variations in storm and sea state that can, in turn, affect the formation and ablation of ice in northern waters of the Atlantic.

On the biological side, related variations in productivity can be expected from long-term fluctuations in the sea state. *Lafond and Lafond* [1971] state that surface waves assist in the vertical and horizontal redistribution of nutrients, bringing them from the thermocline into the euphotic layer, thereby creating conditions favorable to the growth of marine organisms in the surface layer. Variations here should be reflected, with some time lag, in the fish population.

Thus long-term changes in sea state produce responses in the ocean that must be determined before sensible interannual comparisons of oceanographic variables can be made.

4. CONCLUSIONS AND RECOMMENDATIONS

1. Based on a 13-year data set for the North Atlantic, the annual sea state displayed large variability, particularly in the higher waves. All regions of the ocean were affected. The total range of variation of the largest (0.14%) annual H_{sig} increased from about 2.5 m along the coast of North America and in the southern North Atlantic to about 6 m in the mid-Atlantic and west of Ireland. This represents 30% to 50% of the initial wave height and is similar in size to that of the annual cycle between winter and summer.

2. There were basically two types of variation: first, strong 3- to 7-year fluctuations that were more pronounced in the higher seas than in the lower; second, a continuous increase in the sea state during the 13 years that was present in all the wave height ranges, except the larger sea state in the eastern North Atlantic, along the coast of North America, and in the northern waters. This steady increase is probably part of a long-term variation with a period of several decades.

3. The increase of the large sea state in the western North Atlantic (that is in a zone between the Gulf Stream and the mid-Atlantic) indicates an intensification of the cyclonic activity in this region, while the increase of the smaller sea states, which affected the entire North Atlantic, implies that the prevailing westerly wind increased significantly during this period, particularly at more southerly latitudes.

4. Long-term extreme value predictions that do not take these fluctuations and long-term changes into account may differ by as much as 50%, depending on the year the data were taken. To reduce this, predictions should be based on much longer data sets. Even with 12–14 years of data, there may be uncertainties caused by longer-term shifts or fluctuations, such as seen in the North Atlantic data.

5. The energy input from waves into the upper layer of the ocean at any location varies considerably from year to year, sometimes two- to threefold. This undoubtedly affects mixing and thus the physical, chemical, and biological processes of the North Atlantic. Therefore, long-term studies of these processes need to consider the variation in wave/wind energy over various intervals of time.

6. The atmosphere and underlying ocean are closely, though complexly, coupled. Ocean wave studies, particularly with regard to cycles and long-term changes in the sea state, can throw light on and assist in the explanation of related meteorological phenomena in the ocean.

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