INCREASES IN WAVE HEIGHTS OVER THE NORTH ATLANTIC: A REVIEW OF THE EVIDENCE AND SOME IMPLICATIONS FOR THE NAVAL ARCHITECT

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SUMMARY

In common with other recent publications this review of evidence, based on both measured and visual data at a number of widely separated locations over the North Atlantic, leaves little room for doubt that mean wave heights have increased over the past 30 years or more at a rate of order 1 or 2% per annum. Indications that extreme wave heights may also have increased slightly are noted but the evidence for this is not conclusive.

A special contribution of this paper is that it considers also evidence that the corresponding mean wind speeds have not increased and analyses their consequent changing relation with wave heights in the light of experience gained by the author from compilation of 'Global Wave Statistics'. An interpretation in terms of increasing levels of swell possibly due to increasing storm frequency is offered.

As to implications, there are many aspects of the operation and design of ships which may be affected, notably the impact of increases in mean wave height on fatigue damage. Attention is however here concentrated on questions which have been raised by naval architects about the validity of data from wave atlases and of procedures for modelling wave conditions which use wind information. The importance of data covering long time spans is emphasised and the role of swell and its relation to locally generated wind sea is discussed with special reference to modelling of conditions in open ocean areas of interest to naval architects. Some recommendations for further investigations are included.

1. INTRODUCTION

Several reviews of the evidence for increases in wave heights over both the North Atlantic and the North Sea have recently been published and special mention may be made of papers by Bacon and Carter (1991) (Ref, 2) and Van Hooff (1994) (Ref. 16). There is moreover now wide acceptance that mean wave heights over the North Atlantic have been increasing substantially and persistently during the last 3 or 4 decades. Van Hooff's paper is a review of evidence and implications covering wave data for both the North Atlantic and the North Sea addressed primarily to the offshore industry and discusses the possible impact on fatigue damage to offshore structures in some detail. The present purpose is to review evidence for the North Atlantic only but covering both waves and wind, and to consider implications for the naval architect. There is inevitably some overlap, but the present paper is largely concerned with questions about the interpretation of wave data and their relation to wind data in open ocean areas which are not considered by Van Hooff.

An impressive feature of the available evidence is the consistency with which wave data from independent sources, including both measurements and visual observations from widely separated locations, show a continuous upward trend in average heights (of the order of 1 or 2% per annum) over a period of 30 years or more. There are also some indications of an associated but much smaller rise in extreme heights though the evidence for this is not conclusive. Another important feature is the lack of any corresponding rise in mean levels of wind speed which is also shown by data from independent sources for several locations. This inevitably implies a changing relationship between wave heights and wind speeds which will be the subject of some discussion.

In reviewing practical implications, particular attention will be devoted to questions which have been raised about the validity of data from currently available wave atlases and of assumptions regarding the relation between wave heights and wind speeds made by naval architects when using spectral models of wave conditions and estimating wave climate. It is suggested that in the case of spectra involving wind speed as a parameter some adjustment may be needed to the associated formula for computing the significant height when used in open ocean areas. Recommendations are also made for further investigations, which might aid understanding of the causes for the height increases and should include continuing programmes of long term measurement, to guide assessment of future prospects.

There are of course other questions of importance to naval architects such as implications for structure design with special reference to fatigue analysis, of increases in mean wave heights but the present writer leaves these to others to assess.

2. THE EVIDENCE

2.1 AVERAGE HEIGHTS

Early indications of substantial year to year variability in average values of wave height over the North Atlantic covering the period 1950 to 1967, based on visual observations from 9 weather ship stations were presented by Walden (1970) (Ref. 17) and further analysis of weather ship observations was undertaken by Rodewald (1972) (Ref. 14).

The first evidence of a strong and persistent upward trend was reported by Neu (1984) (Ref. 12) using analysis of synoptic charts. His data were derived from faired contours of height drawn every 12 hours, based mainly on input of visual observation but also including measurements where available. Table 1 summarises his findings for the annual rates of increase in the median (50% exceedance) height over the years 1970 to 1980 for 4 widely separated 5° square areas of the North Atlantic as shown in the map, Fig. 1. These were derived by fitting straight lines to the year to year variation in median height.

Since then the prevalence of an upward trend has been confirmed using instrumented data from shipborne wave recorders (Draper 1986, (Ref. 6) Draper and Carter 1988, (Ref. 5) and Bacon and Carter 1991) (Ref. 2) and has been further supported using visual data (Barratt 1991) (Ref. 3).

In these more recent investigations the height data have been derived in terms of mean rather than median values over specified periods (mostly 5 years). Tables 2 and 3 summarise the findings for annual rates of increase of mean height for various locations in the North Atlantic as shown in the map, Fig. 1, derived respectively from instrumental and visual data.

It is of course to be expected that the instrumental data shown in Table 2 are the most reliable and particular weight is lent to the results for Sevenstones because of the long duration of the records there. Thorough checks have been applied to all data to resolve possible sources of doubt about the validity of the measurements. In the case of the data from India and Juliett these are described by Draper (1986) (Ref. 6). He acknowledges that for these stations the data were necessarily drawn from a number of different ships on an intermittent basis and also that the values of significant height were derived from analog records by inspection methods involving period dependent correction factors. He expresses confidence however that since the same actual instruments and analysis procedures were used throughout the increases in wave height cannot be attributed to instrument error.

In the case of Sevenstones the annual rate of increase in mean height cited in Table 2 was derived by fitting a straight line through the year to year variation over the 23 year period 1962 to 1986. During this period there was considerable variability in the mean values and a number of special adjustments were made which are described in detail by Bacon and Carter 1989 (Ref. 1).

In particular a development affecting all the mean height values in Table 2 including those for India, Lima and Juliett must be mentioned. In 1989 a revised response function was introduced for deriving data from shipborne recorders (Pitt 1989) (Ref. 13) and a correction procedure involving a reduction of significant height has been applied retrospectively to all the data in Table 2. The rates of height increase quoted have not been affected but it is important to take the correction into account when comparing the mean heights with values cited in earlier publications. As an example it may be found that the mean heights quoted in Table 2 for India, Juliett and Sevenstones are more than half a metre less than corresponding values cited by the present author in Hogben (1989) Ref. 10).

The results based on visual data shown in Table 3 have been derived from plots in Barratt (1991) (Ref. 3) which are reproduced and discussed below (Fig. 2). The relevant source data were obtained from the Marine Data Bank of the UK Meteorological Office (Shearman 1983) (Ref. 15) in which observations from ships of the Voluntary Observer Fleet (VOF) are stored. The catchment areas for the respective locations which are shown in the map, Fig. 1, were:

Charlie	51°–54°N,	33°–39°W
Juliett	51°–54°N,	17°–23°W
Sevenstones	49°–51°N,	5°–7° W

The values of mean height plotted were computed for a series of 5 year periods with a total span of 30 years. The annual rates of increase cited in Table 3 are the total increases divided by 30.

It may be seen that the locations Juliett and Sevenstones are also covered by the instrumental results in Table 2 so that with the aid of Fig. 2a) direct comparison can be made between both the magnitudes and the annual rates of increase of the mean heights. Considering the very different and wholly independent derivations of the 2 data sets moreover, the agreement seems more than adequate to provide strong confirmation that mean wave heights over the North Atlantic have been increasing during the past 30 years or more. The results in the two tables indicate moreover that the rates of increase mostly lie between 1 and 2% per annum, though in places, as at OWS India, they may exceed 2% per annum at least for a time.

It may perhaps be wondered why the results in Table 1, whilst clearly confirming the upward trend, show annual rates of increase which are so much greater and the author can only speculate that the explanation may lie in the fact that the wave heights in this case are median values and not means.

2.2 EXTREME HEIGHTS

Estimates of extreme heights such as 50 year return values are subject to uncertainties inherent both in the relevant upper ranges of data and the methods of analysis. They also should be based on many years of data and cannot be assessed by any objective criterion of reliability. In Hogben (1989) (Ref. 10), the present author, on the basis of analysis of instrumental data from India, Juliett and Sevenstones raised doubts as to whether such extreme wave height estimates have increased at these locations but acknowledged that the case could not be proved for or against. Carter and Bacon (1991) (Ref. 2) present and discuss data for Sevenstones indicating that there may have been a small increase but they also concede that the evidence is not conclusive.

2.3 THE RELATION OF WAVE HEIGHT AND WIND SPEED

In an appendix to Draper (1986) (Ref. 6) Challenor showed that at India and Juliett the increases in mean wave height shown in Table 2 were not accompanied by any significant increase in mean wind speed. A similar finding applying to visual data from Charlie, Juliett and Sevenstones over the years 1950 to 1980 is moreover reported by Barratt as may be seen by comparing Figs. 2a) and b). It follows that the relationship between wave height and wind speed must have changed over the years and this is confirmed by the plots of mean lines relating them from Barratt (1991) (Ref. 3) reproduced here in Fig. 3.

This relationship is of considerable importance not only because of its crucial role in predicting and modelling wave conditions for engineering purposes as further discussed below but also because it may hold some keys to understanding why wave heights have been increasing and whether they may continue to do so. Referring to Fig. 4, the critical question arises as to why the average level of wave height corresponding to any given mean wind speed should have increased so substantially over the years.

The present author in Hogben (1989) (Ref. 10) has suggested that increases in levels of swell due to changes in wind speed or direction in other areas might offer some explanation. In so doing he noted that due to the square law for addition of sea and swell, swell has a relatively large effect on mean heights (of order 2 or 3m) but a negligible effect on extreme heights (of order 15 or 20m). This point and its relevance to Barratt's results may be clarified by reference to Fig. 4.

Fig. 4a) illustrates the square law for addition of wind sea height H_1 generated by a wind speed W and a mean swell height parameter

H_2, to derive a resultant significant height H_s, namely:

$$H_s = (H_1^2 + H_2^2)^{1/2}$$

(This relation applies because when wave systems combine, their energy which is proportional to the square of significant height is added linearly).

In the figure, based on experience from compilation of 'Global Wave Statistics' (Hogben 1988) it is assumed that:

$H_1 = aW^n$ (a = 0.06 and 0.09 = 'growth rate factor' : n = 1.2)

and

H_2 = 0.4, 0.6, 0.8 .... 2.0m = 'mean swell height parameter'

The ranges of a and H_2 and associated value of n are based on the distribution computed by best fitting of global data defined in Fig. 7b) of Hogben (1988) (Ref. 9). This shows that from analysis of 'Annual All Directions' data for all of the 104 areas covered, the mean value of n was 1.2 and over 90% of the a and H_2 values lay in the above ranges (see Section 3.2.2).

To assist the comparisons with Barratt's data in Figs. 4b), c) and d) it may be seen that the swell levels are divided into 2 bands. The upper band ($1.4 \leq H_2 \leq 2.0$m coupled with a = 0.09) is considered suitable for deep ocean locations such as Charlie and Juliett and the lower band ($0.4 \leq H_2 \leq 1.2$m coupled with a = 0.06) for more sheltered areas such as Sevenstones.

Figure 4a) clearly shows that at low wind speeds (W < 10 knots say) swell is the dominant component of the resultant height and wind speed has relatively little effect. At higher wind speeds on the other hand the effect of variation in wind speed and in the associated growth rate factor a is dominant and the contribution of swell is negligible. This explains how, if swell levels increase and mean wind speeds do not, the mean height will increase but the extreme height will not.

In Figs. 4b), c) and d) the curves of Fig. 4a) are superimposed on Barratt's data using the upper band for Charlie and Juliett and the lower band for Sevenstones. In all cases it may be seen that the year by year increases in wave heights for given wind speeds in the data could be explained at the lower wind speeds by increases in the swell parameter H_2. Possible reasons for such increases are not known but Barratt (1991) has suggested they could result from reduced decay time between storms which are known to have become more frequent. At higher wind speeds however, some other explanation is needed and this will be discussed in a later section (see Section 3.2.2).

3. SOME IMPLICATIONS

In the light of the foregoing evidence there seems little doubt that mean wave heights over the North Atlantic have increased substantially over the past 30 years or more but the mean wind speeds have not, so that the relationship between wave heights and wind speeds must have changed. These findings have a number of important implications but attention will here be concentrated on 2 areas of particular concern to naval architects, namely, the validity of available data sources and of current methods for predicting and modelling wave conditions based on use of wind data.

3.1 VALIDITY OF WAVE DATA

In assessing the validity of wave data an obvious implication of the above findings is that it is important to consider the derivation of any given compilation with special reference to the period of years covered and the extent of dependence on use of wind data. It may then be possible to make some approximate allowance for the effect of known long term trends such as have been described. In so doing it must be borne in mind however that such trends may be very different in the future and in other areas. In the North Sea for example the evidence for a continuing increase in wave heights (Bacon and Carter 1991) (Ref. 2) is much less clear.

In these circumstances it is to be expected that data derived from sources spanning long periods of years should offer the best basis for long term prediction. In this respect the validity of data from the book 'Global Wave Statistics' (Hogben et al. 1986) (Ref. 8), of particular concern because of its worldwide coverage, is exceptionally well founded. This claim may be justified by explaining that the wave statistics in the book were derived by use of a statistical relation between wave height and wind speed computed from wave and wind observations covering the years 1949 to 1984 applied to wind observations covering the years 1854 to 1984. They thus represent a long term average of wave conditions over a period of years which effectively spans the whole of the trend for mean height increase over the North Atlantic described above. Thus, bearing in mind also the validation of visual data offered by the comparisons with measured results in Tables 2 and 3 and Fig. 2a) they would seem to offer as good a basis as any for estimating long term statistics for the future.

3.2 WAVES FROM WINDS

Because of the abundant availability of wind data covering wide areas and long time spans, they are extensively used as a basis for hindcasting and predicting wave conditions and modelling of wave spectra. Not surprisingly therefore, questions have been raised regarding the effect of the above findings on the validity of prediction formulae and spectral models in common use.

These questions can be conveniently discussed by reference to methods derived from the 'JONSWAP' (Joint North Sea Wave Project) project (Hasselmann et al. 1973) (Ref. 7) since they cover both the prediction of wave height and the modelling of wave spectra in terms of wind field parameters.

3.2.1 Spectral Modelling

The most widely used spectral models are probably those known as Pierson-Moskowitz (PM) and JONSWAP. In common with a number of other models they share the same basic functional form but can be expressed in terms of different parameters and units. The JONSWAP spectrum was developed specifically for modelling wind seas and can be generated by use of wind speed, fetch, and duration parameters. It also contains a 'peakedness parameter' γ which when set to the value 3.3 defines a so called 'Mean JONSWAP' spectrum widely used for modelling wind seas. Setting $\gamma = 1$ defines a Pierson-Moskowitz spectrum which is somewhat broader and is commonly used for modelling open ocean spectra. All the above named spectra can also be expressed in terms of wave height and period parameters without any reference to wind speed using formulae promulgated by the ISSC and ITTC (Hogben 1990) (Ref. 11).

There seems to be no reason why changing relations between wave height and wind speed should require the functional forms of any of these spectra to be modified or to question the validity of models expressed in terms of height and period parameters only. In the case of spectra using wind speed as a parameter however, the validity of the relation between the corresponding significant height H_s, defined in terms of the spectral area m_0 by:

$$H_s = 4\, m_0^{1/2}$$

and the wind speed is important.

The formulae developed for use in modelling JONSWAP spectra are also widely used as a basis for estimating wave heights from wind speeds and it is therefore important to consider implications regarding their validity.

3.2.2 Prediction Formulae

Formulae for predicting the heights of wind seas need to take account of the effects of limited duration or fetch of the wind. Figs. 5a) and b) show plots of the relevant JONSWAP formulae for duration and fetch limited conditions respectively superimposed on the Barratt data for Sevenstones from Fig. 3c). In practice at any open ocean location the effects of ambient swell should be taken into account specially at lower wind speeds as shown in Figs. 4a) to d). Since however the concern here is with wind generated waves which are dominant at higher wind speeds where the effects of swell are relatively small these have for the sake of clarity been omitted. The key point illustrated by these plots is that the year by year increases in growth rate displayed by the Barratt data might at least in principle be explained by changes in the typical patterns of variation of duration and fetch rather than calling for any change in the basic formula.

In the case of the duration limit formula cited in Fig. 5a) it is indeed of interest to note that it corresponds very closely to the formula derived from 'Global Wave Statistics' used in the plotting of Fig. 4a), namely:

$$H_s = 0.06\ W^{1.2} \text{ and } 0.09\ W^{1.2}$$

Thus, setting D = 18 and 30 hours in the JONSWAP duration limited formula:

$$H_s = 0.00622 D^{5/7}\ W^{9/7} \quad \text{(D is duration in hours)}$$

yields respectively

$$H_s = 0.05 W^{1.29} \text{ and } 0.07 W^{1.29}$$

It could therefore be said that the increase in growth rate shown by the Barratt data could be explained by an increase in average durations from 18 to 30 hours. Unfortunately however this does not seem plausible. Even allowing for the fact that in the presence of swell the durations would tend to be shorter as the wind would not be starting with a calm sea as assumed in the formula, these durations seem excessively long. It must be noted furthermore that Barratt found indications that storms have been tending to get shorter and more frequent rather than longer.

Use of the alternative fetch limit formula plotted in Fig. 5b):

$$H_s = 0.0113 F^{1/2} W \quad \text{(F is fetch in nautical miles)}$$

is recommended (Carter 1982) when:

$$D > 2.344 F^{0.7}\ W^{-0.4}$$

and as an example when F = 100 nautical miles and W = 20 knots, D = 18 hours. According to Fig. 5b), the increased growth rate found by Barratt could be explained by an increase in average fetches from 100 to 200 nautical miles. This might seem slightly more plausible but unfortunately conflicts with Barratt's assessment that depressions have been tending to get smaller rather than larger.

Since increases in duration and fetch seem not to provide a plausible explanation for the rise in growth rate, other possibilities must be considered. An idea partly based on experience from compilation of 'Global Wave Statistics' is that the growth rate factor a may tend to increase with increasing levels of the mean swell height parameter H_2 (see Fig. 7b) of Hogben (1988) (Ref. 9). It is indeed to be expected than an existing swell could be equivalent to an added duration and hence to an increase in a. This idea is mentioned by Barratt (1991) at the suggestion of the present author who has meanwhile identified a further mechanism for swell dependent variation of the parameter a. This involves recognition first that the parameter H_2 is by definition the mean height only of swell components (which may be called 'old swell') which are independent of wind speed. It must be noted then that in practice there will generally be some components of swell (which may be called 'young swell') which are correlated with the local wind speed though not generated within its fetch. Thus if $H_1 = aW^n$ is redefined to include this 'young swell' as well as local wind sea, an additional mechanism for swell dependent variation of the parameter a is established. If such swell dependence of a is accepted it may be that when using the JONSWAP formulae in open ocean areas a growth rate enhancement factor related to the estimated mean swell height should be introduced. Further investigation would be needed before such a factor could be quantified.

It may be of interest to note however that analysis of the a and H_2 values derived from fitting 'Global Wave Statistics' data for the 'Annual All Directions' class of all 104 areas worldwide (Fig. 7b, Hogben 1988) (Ref. 9) yielded the following regression formula (see Fig. 6):

$$a = 0.011\ H_2 + 0.057 \text{ with a correlation coefficient } \rho = 0.353.$$

3.3 THE FUTURE

Key questions for the future are whether the trend for increasing wave heights will continue and if so what course it will take. The author is unable to answer these questions but recommends that investigations should continue to seek an understanding of the causes, which might offer some guidance on future prospects and to monitor trends in the data. Specifically it is suggested that analysis should be undertaken to determine trends in the variations with time of the swell height and growth rate parameters H_2 and a (as defined in Hogben 1988) by computing their values for selected locations at 5 yearly intervals over the past 30 years or so. This could help to clarify whether swell plays a role in causing the mean height increases and the extent of any correlation between growth rate and swell height. Such analysis could offer a basis also for monitoring future trends. It is strongly recommended however that programmes of long term wave measurement preferably linked with wind measurements should be continued at selected locations such as Sevenstones.

4. CONCLUDING REMARKS

Evidence has been reviewed based on independent data from both measurements and visual observations from a number of widely separated locations over the North Atlantic. They all yield very similar results and leave little room for doubt that mean heights have been increasing at a rate of order 1 or 2% per annum over the past 30 years or more but there has been no significant increase in mean wind speed during this period. Reasons for this have been discussed and a tentative explanation in terms of the effect of increased swell levels possible due to increased storm frequency has been offered. Indications of a corresponding small increase in extreme heights has also been noted but the evidence for this is not conclusive.

The review of implications has pointed to the need to consider the years covered when assessing the reliability of wave data and the reassurance bestowed by the exceptionally long time spans covered by the data in 'Global Wave Statistics'.

Implications regarding estimation of waves from winds and the validity of spectral modelling procedures have also been discussed. It is concluded that the validity of the basic form of the commonly used spectral methods is probably not affected so no change should be needed when wave height and period are the parameters. In the case of spectra involving wind speed as a parameter however it is suggested that some adjustment may be needed to the formula for computing the associated significant height. It is speculated that this might take the form of a swell dependent growth enhancement factor introduced when used in open ocean areas.

Finally, recommendations are made for further investigations including analysis of trends in swell and growth rate parameters and continuation of long term measurement programmes to guide assessment of future prospects.

There are of course many other implications of importance to naval architects such as those relating to structural design with special reference to fatigue analysis but these are left for others to assess.

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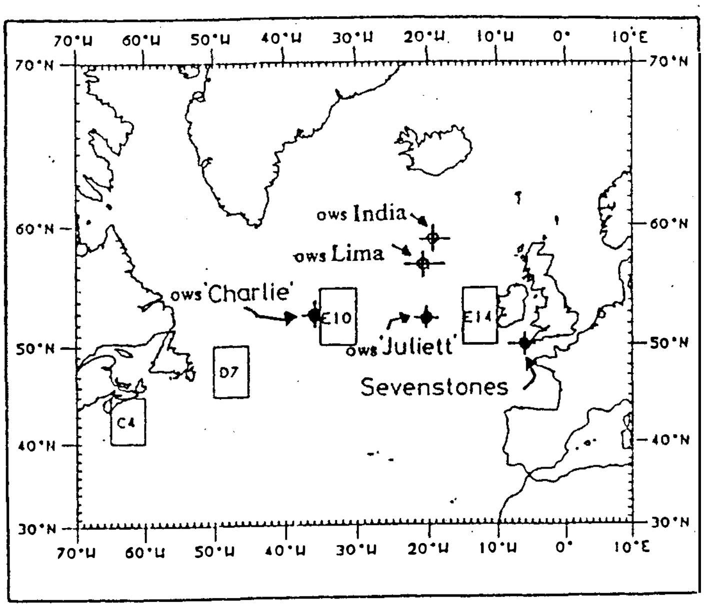


Fig. 1 Map of locations

TABLE 1

INCREASES IN MEDIAN HEIGHTS
(from Synoptic Charts, Neu 1984)

Location 5° Square No.	Date Ranges	Number of Years	H_c(m) Median	Increase of Height		
				m	m/year	%/year
E10	From 1970 To 1982	12	2.80 4.50	1.70	0.142	5.06
E14	From 1970 To 1982	12	2.65 3.65	1.00	0.083	3.14
D7	From 1970 To 1982	12	2.25 3.25	1.00	0.083	3.70
C4	From 1970 To 1982	12	1.75 2.50	0.75	0.063	3.57
Mean Values					0.094	3.93

TABLE 2

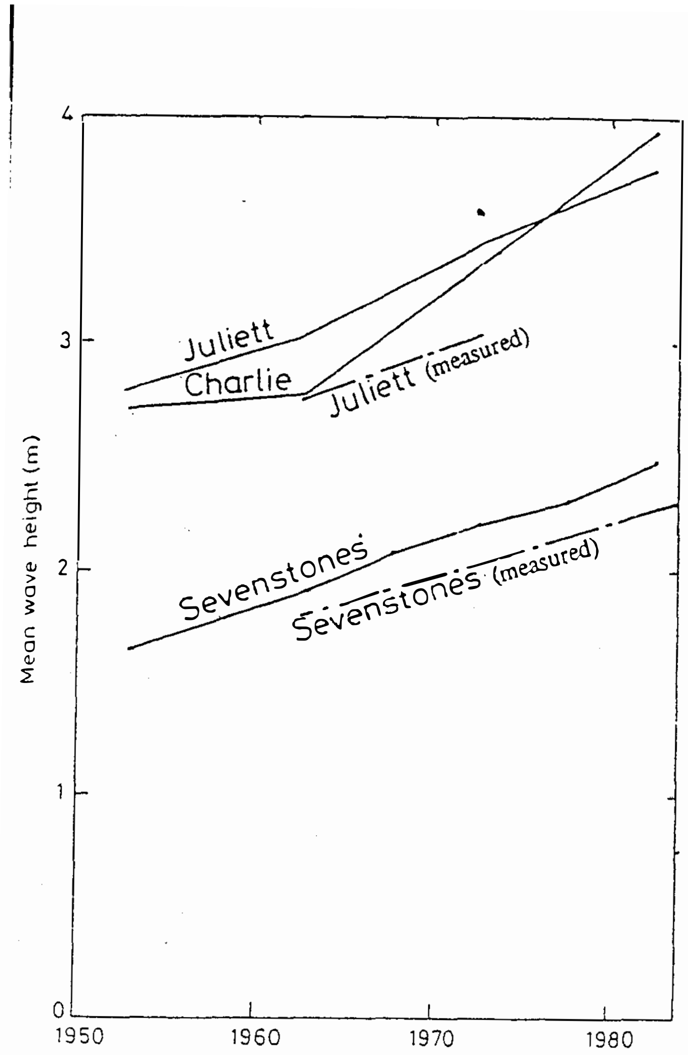
INCREASES IN MEAN HEIGHTS
(from measurements, Bacon and Carter 1991)

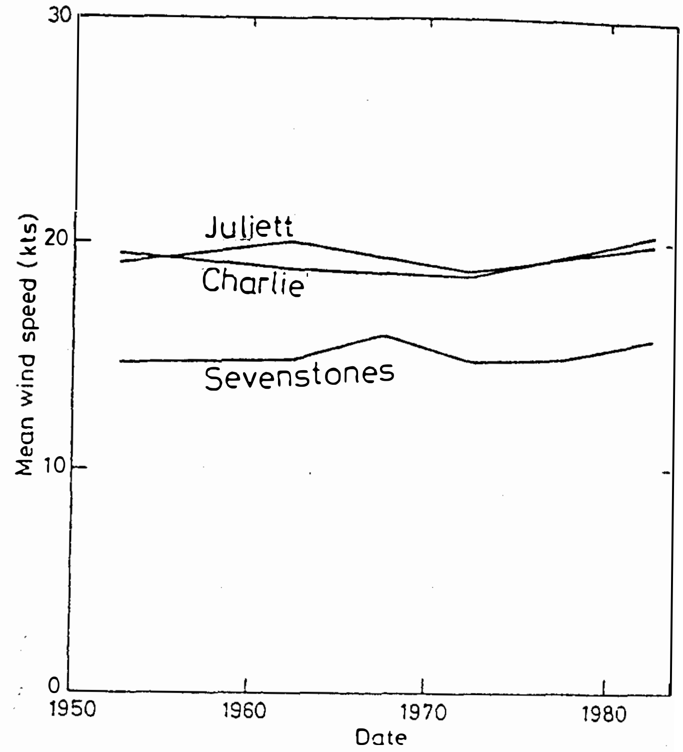
Location	Date Ranges	Number of Years	H_s(m) Mean	Increase of Height		
				m	m/year	%/year
OWS India	From 1960-65 To 1970-75	10	2.75 3.45	0.70	0.070	2.55
OWS Lima	From ca 1978 To ca 1985	7	3.50 3.75	0.25	0.036	1.02
OWS Juliett	From 1960-65 To 1970-75	10	2.75 3.03	0.28	0.028	1.02
Sevenstones	From 1962/63 To 1985/86	23	1.80 2.35	0.55	0.024	1.33
Mean Values					0.040	1.48

TABLE 3

INCREASES IN MEAN HEIGHTS
(from visual observations, Barratt 1991)

Location	Date Ranges	Number of Years	H_v(m) Mean	Increase of Height		
				m	m/year	%/year
OWS Charlie	From 1950/55 To 1980/85	30	2.70 3.94	1.24	0.041	1.53
OWS Juliett	From 1950/55 To 1980/85	30	2.78 3.78	1.00	0.033	1.20
Sevenstones	From 1950/55 To 1980/85	30	1.66 2.50	0.84	0.028	1.69
Mean Values					0.034	1.47





b) Mean wind speed

a) Mean wave height (including comparisons with measured data)

Fig. 2 Variation of mean wave height and mean wind speed (1950-1980) at Charlie, Juliett and Sevenstones from visual data (Barratt 1991)

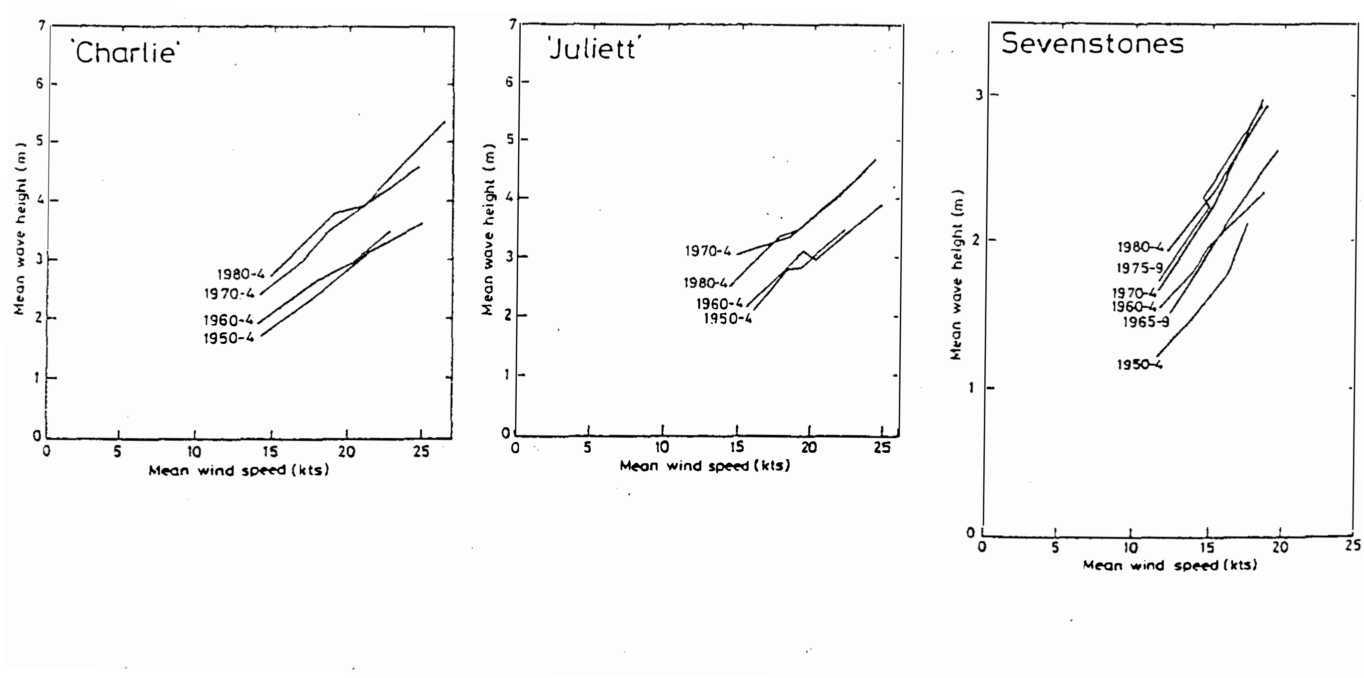
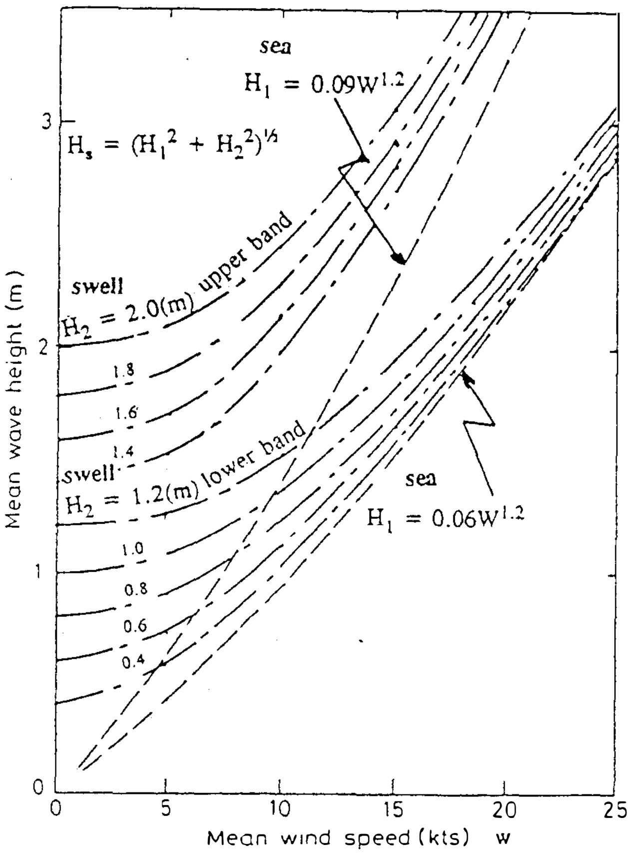
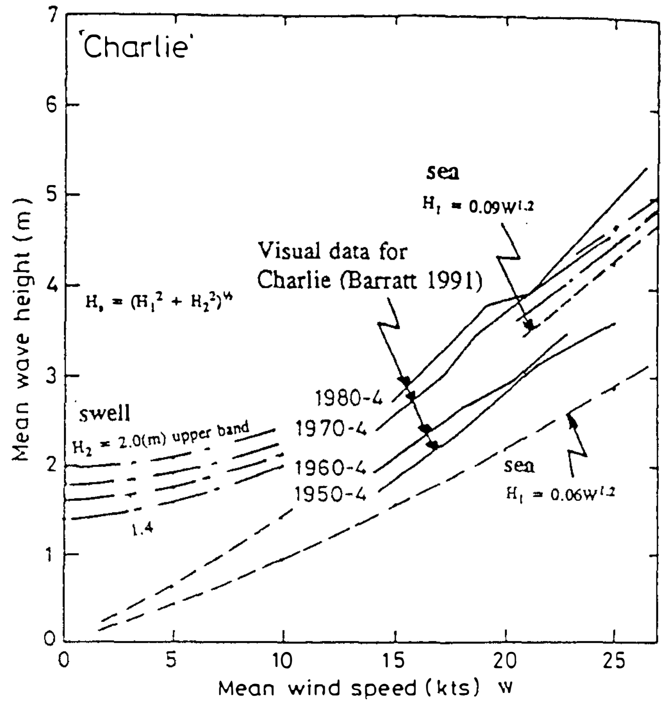


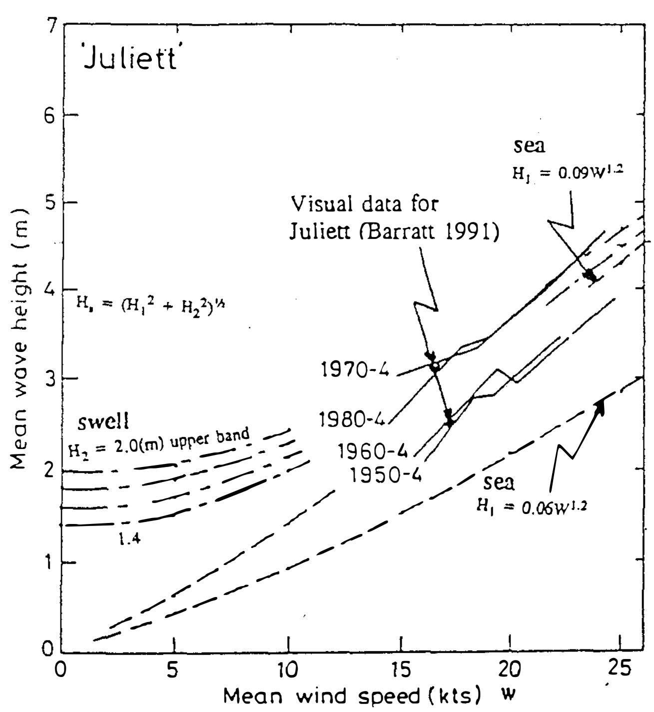
Fig. 3 Relation of mean wave height and mean wind speed at Charlie, Juliett and Sevenstones showing variations from 1950 to 1980 from visual data (Barratt 1991)



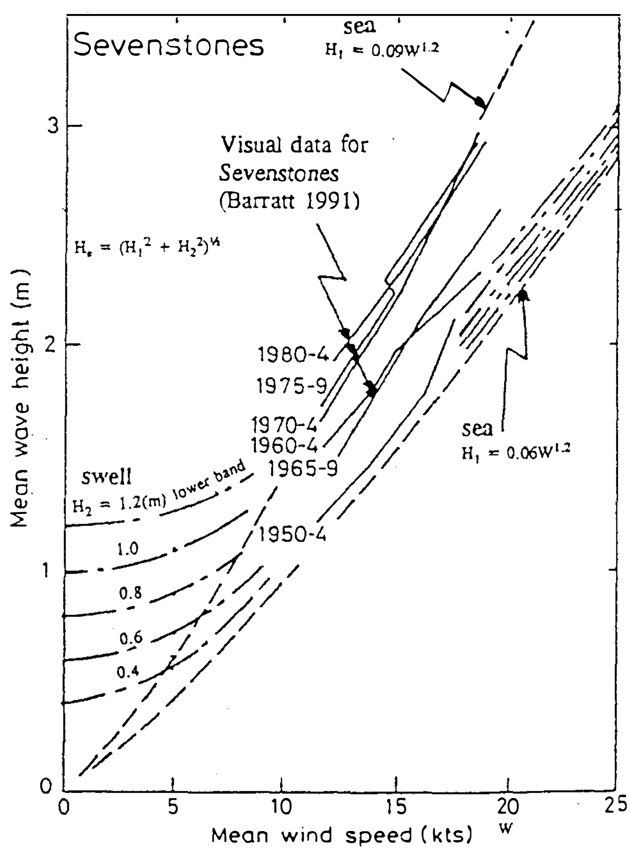
a) **Formulae based on experience from compilation of 'Global Wave Statistics' (Hogben 1988)**



b) **'Global Wave Statistics' formulae (upper band) superimposed on visual data for Charlie (Barratt 1991)**

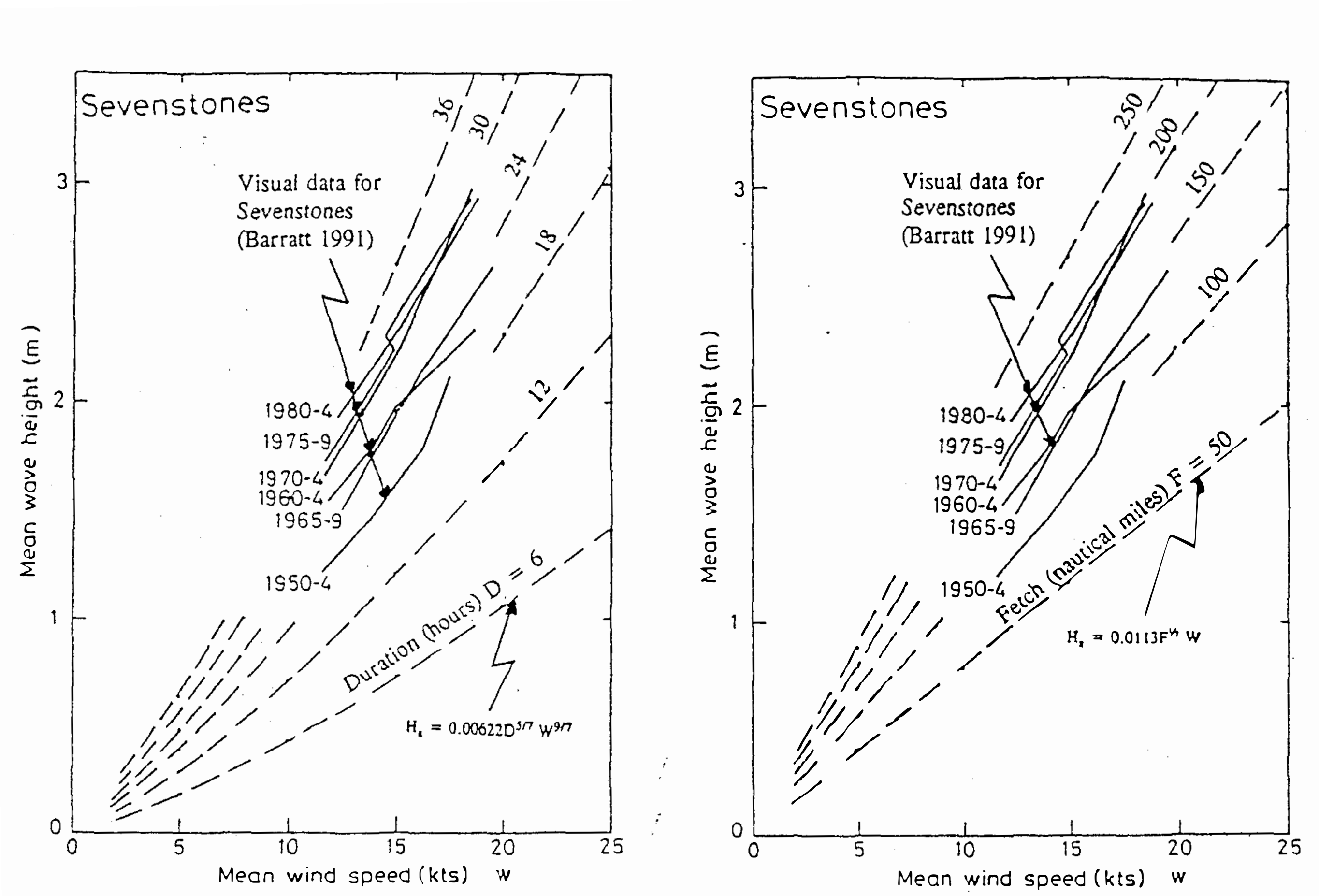


c) **'Global Wave Statistics' formulae (upper band) superimposed on visual data for Juliett (Barratt 1991)**



d) **'Global Wave Statistics' formulae (lower band) superimposed on visual data for Sevenstones (Barratt 1991)**

Fig. 4 Relation of mean wave height and mean wind speed showing the relative contributions from sea and swell



a) **Duration limited formula** b) **Fetch limited formula**

Fig. 5 Plotting of JONSWAP formulae for relating significant height and wind speed superimposed on visual data for Sevenstones from Barratt (1991)

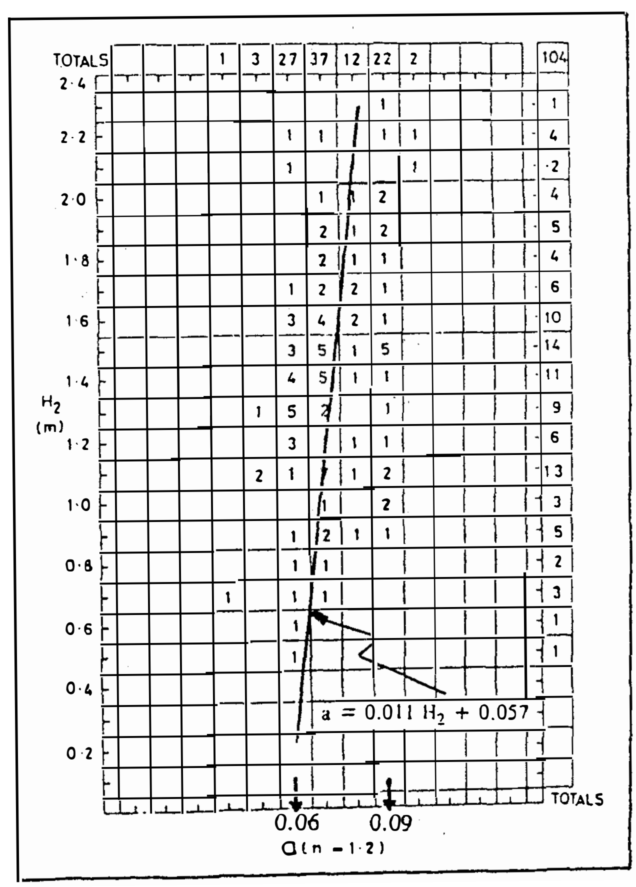


Fig. 6 Relation between growth rate factor a and mean swell height parameter H_2: regression of data from 'Global Wave Statistics' (Hogben 1988)

DISCUSSION

Professor K J Rawson, MSc, RCNC, FEng (Fellow): We are indebted, as always, to Dr Hogben for this advice on the waves likely to be met by our ships and structures, particularly, as in this case, because it was a generous response to our feelings of anxiety over reports that the sea had become considerably more fierce. That world climate has changed conforms to common experience, and it is no great surprise that seas have become worse; what is surprising is the magnitude of the changes in mean waveheight, some 50 per cent in 30 years. It would appear from Figs. 2 and 4 that both swell and wind components have increased although wind speed has not, and that in coastal regions, such as Sevenstones, wind has less effect.

It is difficult to accept that so great an increase in mean waveheight does not have a significant effect upon the maxima. Can waves have become more square? Evidence on the heights of extreme waves is naturally sparse, but with a general increase one would assume that those curious combinations of circumstances that cause extreme conditions would become more frequent. Significant waveheight and the energy spectra might also both be expected to show increases. Thus, the advice that the spectra do not need modification is puzzling, although it is accepted that a wind sea such as the North Sea is not much affected by an unchanging wind distribution.

Ships are designed to meet extreme conditions which statistics of losses have shown to be unlikely whether they are occasioned by a single extreme combination of waves or a fatigue condition of some sort. That losses have been steady over the last 30 years when seas have become more fierce is a tribute to the standards adopted for longitudinal strength and an indication that the section modulus requirements are at least just adequate for most types of vessel. Had losses increased over that time some correlation with change in wave climate might have been worthwhile. Furthermore, among the statistics of losses, those caused by fracture of the main hull girder are happily rare. However, fatigue failure and high local stresses due to poor local design or production could well be exacerbated by changes in mean waveheight and would warrant further investigation.

On balance, while puzzled, we may remain content that contemporary standards of ship strength have not been shown by this survey to be in need of urgent revision. For that reassurance, we may be grateful to Dr Hogben.

Mr N Lynagh (Noble Denton Weather Services Ltd): I have a number of comments to make which I shall do using the section numbering as given in the paper.

2.1 Average Heights

In the first paragraph Dr Hogben refers to indications of year to year variability based on visual observations from 9 weather ship stations. Speaking as someone with 3½ years experience of making such visual observations from 1964 to 1967, I would suggest that the poor quality of visual wave observations from Ocean Weather Ships (at least the British ones) makes any sort of analysis so unreliable as to be virtually useless. The observations were carried out by Meteorological Office personnel, mostly young and usually with no experience of the sea whatsoever, and with no prior training in the art of making wave observations.

Added to that there is the very great problem of actually seeing the waves during the long hours of darkness from a ship which had bright deck lights. On very many occasions a swell which was being reported at dusk continued to be reported unchanged throughout the night. Only after dawn did the 'new' swell conditions become apparent. Many of us tried very hard to provide accurate observations but the quality must be regarded as very low.

2.3 The Relation of Wave Height and Wind Speed

Dr Hogben points out that at the various sites where there is evidence of an increase in the mean wave heights there has been no corresponding increase in mean wind speed. This should not cause any particular surprise because the relationship between the wave height at a point and the windspeed at the same point is very loose.

The total wave height at a point is a combination of the wind-generated waves over the fetch to the point plus any swell reaching the point from other wind fields. The fetch of the wind generated waves can be limited in 3 ways:

- by geography, i.e. limited fetch length from the nearest land;
- by meteorology, i.e. by the shape of the pressure systems;
- by duration, i.e. the wind does not blow for sufficiently long to enable the seas to become fully generated.

A feature of the NE Atlantic is that the weather systems are very dynamic with very great changes taking place in the wind fields over periods of only a very few hours. Very seldom does the wind-generated sea become fully developed. Typically the sea state is very chaotic with swells from several different directions being present. This is quite different to the North Sea which tends to have a much more 'orderly' wave climate due to its relative shelter from most oceanic swell.

The increase in mean wave height at a point without any corresponding increase in mean wind speed could easily be caused either by an increase in mean meterological fetch lengths or by an increase in mean duration of wind from a constant direction over the fetch. Both of these imply some change in the climate of high and low pressure systems.

It would be interesting to examine whether or not the climate of wind direction has changed at any of the sites discussed by Dr Hogben.

3.1 Validity of Wave Data

Dr Hogben rightly points out that the trends observed are not necessarily an indication of what might happen in the future. Indeed, it is perhaps wrong to use the word 'trend' at all as it implies a permanent change. What has been observed may only be part of a natural fluctuation which has a period of several decades and there may not be any trend in the very long-term mean. Climate is never constant. It always fluctuates.

Dr Hogben points out that evidence for a continuing increase in wave heights in the North Sea is much less clear. This is not surprising because a change in weather patterns which would result in higher mean wave heights in the NE Atlantic could easily change the wind climate in the North Sea such that mean wave heights there decreased.

3.2.1 Spectra Modelling

As I have already stated the relationship between the wave height at a point and the wind speed at a point is only a very loose one. This is particularly so in open ocean areas.

I hope that these comments are useful and I would be happy to have direct discussions with Dr Hogben on the subject if he so wished.

Mr D K Brown, MEng, CEng, RCNC (Fellow): In my 1992 paper, 'History as a Design Tool', I was foolish enough to include the properties of the sea amongst the 'Eternal Verities' which do not change over recorded time. Clearly I was wrong and those attempting to use records of seakeeping from the past 30 years or more should be aware of the changes in wave height as must those estimating the fatigue life of present and future ships.

In an earlier paper (18), I attempted to assign a cash value to seakeeping from the loss of operational capability in high sea states. This came out as a high figure but must be increased considerably in the light of the increase in average wave height. The staffs of ocean going navies will need to attach higher priority to sea keeping in the future.

REFERENCE

18 BROWN, D K: 'The Value of Reducing Ship Motions'. Naval Engineers Journal. ASNE, March 1985.

Mr A W Stokes (Fellow): Until I read the paper I assumed the Offshore Industry had confidence that the early predictions on wave climate had been confirmed by the passage of time.

This paper raises several searching questions in the mind of an offshore engineer who has seen the industry grow from the early 70's. Can the Offshore Industry rely on predictions for extreme event and severity of wave climate made in the 70's and used for the design of the first generation of Northern North Sea Structures? Should all operators of offshore installations review their environmental design criteria? Is this case an exception or are wave heights increasing worldwide? Perhaps the author in his response could expand his paragraph 3.3.

In order to take the work forward I would suggest three research projects:

- Our instrumentation engineers should develop better measuring or analysing techniques for swell heights and periods.
- The author should repeat this exercise using the database of the North Sea held by Marex and UKOOA.
- The initiators of the NESS project should give a response on the implications of this work on their design tool.

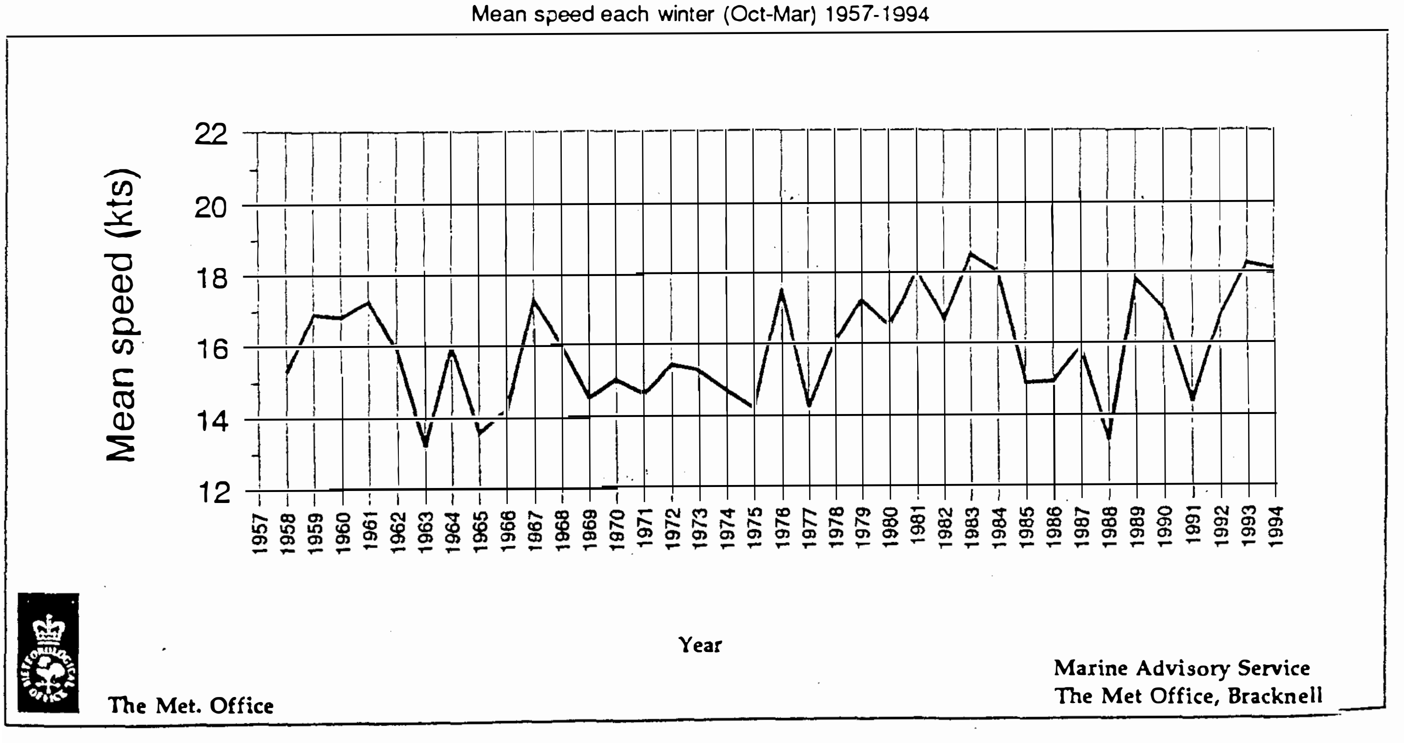
My main concern is on the data we use for fatigue design. We are asking North Sea Structures to last longer than their design life and we need to be confident on the wave heights used for the analysis.

Mr J S Hopkins, BSc, ARCS: To supplement the points made in this paper, it is worth emphasising that, in mid-latitudes, all meterological variables have a substantial year-to-year variability. We are all aware that some summers are sunny, some springs are wet, and some winters excessively stormy. This variability is due to the inherent complexity of global atmospheric behaviour, and the multiplicity of physical processes which combine to produce 'climate'. It is because of this complexity that forecasting on monthly and seasonal timescales has had minimal success until very recently.

Even without invoking mechanisms for climate trends (eg increases in greenhouse gases), the inherent year-to-year variability will give rise at times to relatively short-lived trends which, with the benefit of hindsight, prove to have no predictive value.

As an illustration of this effect, I include here the mean wind speeds over each winter (October to March) from 1957/8 to 199/4 recorded at the Met Office's Lerwick Observatory, Shetland. This data is derived from high-quality hourly wind speeds from a well-exposed and well-maintained instrument, and the record can be considered to provide a good representation of storm activity over the NorthEast Atlantic.

WIND SPEEDS AT LERWICK
Mean speed each winter (Oct-Mar) 1957-1994



It can be seen that the period 1969 to 1984 (the years shown are those of the January each winter) showed a notable upward trend in wind speed, approximating to 1.6% per year. If such an increase in wind speed were directly translated into wave energy, then an increase in mean wave heights of 2.56% per year might be expected - not inconsistent with the range of increases summarised by Hogben from studies mostly encompassing the same time period.

However, the main point to be made is that, after 1984, the trend disappeared; the year-to-year variability increased, and both very calm winters and very stormy winters were experienced. (January 1993, when the MV BRAER was lost, was the windiest month on record at Lerwick). The lesson here is that, without a fundamental understanding of *why* these climatic fluctuations occur over timescales of a few years, it may be misleading to over-publicise trends which may already have ceased by the time they are identified.

Institutes charged with the study of global climate changes (such as the Hadley Centre at the Met Office, Bracknell) are addressing the fundamental scientific issues and are modelling climate fluctuations to improve predictions on decadal timescales. However, results of practical value to those involved in marine planning and design are not expected for some years. Therefore, in the meantime, engineers are advised to base their designs on the most recent climatic data, and to bear in mind that fluctuations about the long-term mean may be as important as the mean conditions.

Mr Thor Haavie, BSc (Fellow), **Jerry Baker, PhD** (Member), **Greg Jones, MSc:** We would like to thank Dr Hogben for his most interesting and thought provoking paper.

Looking from the point of view of the offshore hydrocarbon industry, there appear to be two concerns:

In development of the West of Shetland and West of Ireland theatres (for it seems fairly certain that both will be developed in due course), installations will require a design life in excess of twenty years. Although any evidence for an increase in extreme wave heights is tenuous, an increase of 1 - 2% per annum in mean wave heights represents a 25 - 50% increase over the design life, and it is hard to believe that extreme wave heights would not follow the mean wave height trend to some extent. Thus, the growth in wave height will have implications for both fixed facilities (including Tension Leg Platforms or Compliant Tower variants) where under-deck clearances must still be adequate in as much as twenty-five years time, and for floating systems with regard to fatigue of flexible risers and mooring systems. Offshore operations such as tanker off-loading and subsea inspection and maintenance will also be constrained.

Another aspect of concern would be the effectiveness of life saving appliances: lifeboats or rafts may have to be launched into a sea state where the top of the mean waves could be nearer trusses or other structural obstacles. Presumably conservative growth factors must now be incorporated into the design codes while further investigations are carried out?

Structural fatigue is obviously common to both types of facility and herein lies the second area of concern. If Dr Hogben's plausible theory of increasing ambient swell levels is correct, might not the increase in the lower frequency but, presumably, higher stress components of fatigue so induced have more far-reaching implications on design life than the wave components?

These concerns also apply to non-hydrocarbon energy developments (such as offshore wave or wind power generation platforms), and also to offshore mariculture installations, which demonstrates that the field of influence of the Naval Architect spreads further afield than just ships.

Mr P A Frieze, MSc, PhD (Fellow): I have read the above with interest and have one main question and two recommendations with reference to editing.

With regard to the latter, page 2, last line of second last paragraph, there are too many right-hand parentheses, and page 3, line 3, add a comma after the word 'combine' otherwise it reads 'combine their energy'.

My question is: 'The evidence seems to clearly point to an increase in mean wave height over the 30 or so years considered. Is this an adequate length of time to ensure that the observations are not just natural variations in an otherwise considerably longer cycle of many decades or even centuries?'

Dr J C Brown, CEng, MIMechE: I was very interested to read Dr Hogben's paper reviewing the evidence of increases in wave heights over the North Atlantic and the implications for the naval architect. As a mechanical engineer carrying out research into wave induced loading of surface ships, I have an obvious interest in wave statistics and their effect on the statistics of hull loading.

DRA Dunfermline, formerly NCRE, has been conducting research into extreme wave induced loads in warships over a period of about forty years and as a result has an extensive database of extreme strains measured in ships in service. In 1988 my attention was drawn, by an article in Nature (Carter and Draper), to the possibility that wave heights in the Atlantic were increasing. Since this had obvious implications for the design of warship hulls, an investigation was undertaken to determine if the reported increase in wave heights had led to a corresponding increase in extreme wave induced stresses in Leander Class Frigates, the class for which we had most data. As will be seen from the results in Tables 1 and 2, they showed no evidence of the steady upward trend observed in wave heights. For extreme stresses the trend appears to be downward rather than upward.

There are several possible explanations for the downward trend in extreme stresses over a period of more than twenty years during which wave heights have apparently increased. Operational factors may have played a significant part. The increased cost of fuel following the oil crisis resulted in the imposition of speed restrictions which may in turn have reduced the incidence of slamming with a consequent reduction in hull loading. On the other hand, incidents such as the 'Cod War' in the winter of 1975/76 resulted in ships being deployed in high sea states around Iceland and may have led to increases in recorded stresses.

Another important factor which I have discussed in the past with Dr Hogben and other oceanographers is the longitudinal bending moment versus wavelength transfer function for a warship hull which as shown in (19) has a well defined peak for wavelengths of around 0.8 to 0.9 times the length of the ship. Since wave length is proportional to the square of the wave period, the period would have to change by only a small amount to have a significant effect. Consequently, if the observed increases in wave height have occurred at wavelengths which do not play a significant part in hull loading or if they have been accompanied by changes in mean periods or spectral shape, the observed reduction in wave induced strains would not be unexpected.

In relation to extreme wave heights, those likely to be associated with extreme loads, Dr Hogben states that there may have been a small increase but that the evidence is inconclusive.

On the topics of spectral modelling and wave height prediction he appears to suggest that there is no reason for modifying the spectral form and proposes the use of formulae for the calculation of old and young swell in predicting significant wave heights. Since this appears to imply that although wave heights have increased wave periods remain unaltered, I would be grateful for his views on my suggestion that increased wave heights may have been accompanied by increased wave lengths resulting in reduced wave induced stresses.

The findings of this paper and the difficulties I have experienced in trying to correlate in service stresses with assumed operating conditions and published oceanographic data in the form of tables or scatter diagrams of joint probability distributions of significant wave height and mean period convince me of the need for continued oceanographic research as proposed by Dr Hogben.

In my view there is a particular need for accurate statistics on the heights and increased resolution on the periods of waves, particularly extreme waves. For the design of warships more accurate data is required for extreme waves of around 100 metres in length since they are critical to extreme loads in ships of this length.

REFERENCE

19 LLOYD, A R J M, BROWN, J C and ANSLOW, J F: 'Motions and Loads on a Ship Model in Regular Oblique Waves'. Trans. RINA 122, 1980.

TABLE 1

NARROW BEAM LEANDER

MAXIMUM STRESS v YEAR

YEAR	MAXIMUM RECORDED	
	HOG	SAG
1968	31	46
1970	36	55
1971	35	52
1972	25	40
1973	44	55
1974	34	62
1975	40	64
1976	43	69
1977	35	44
1978	38	44
1979	38	81
1980	33	45
1981	27	46
1982	28	38
1983	22	31
1984	17	25

TABLE 2

BROAD BEAM LEANDER

MAXIMUM STRESS v YEAR

YEAR	MAXIMUM RECORDED	
	HOG	SAG
1971	34	62
1972	30	51
1973	27	49
1974	30	54
1975	21	45
1976	31	50
1977	22	39
1978	21	25
1979	21	28

Mr Sheldon Bacon, James Rennell Centre: I disagree with the approach by Dr Hogben to his material in two respects:

I discuss first changes in extreme wave heights. Dr Hogben doubts that extremes have risen, Bacon & Carter (1991; BC91 hereafter) suspect that they *have* risen, both sources readily concur that there is insufficient data to say *with confidence* whether they have or not. It is a very hard task to try to extract information on the matter from any data set, but in the Sevenstones Light Vessel (LV) data, we have the best presently available instrumental wave data set in the world, spanning the years 1962-1986. In BC91 we split the data into two (up to 1974, and 1975 onwards) and plot the cumulative probability distributions for the two halves (Figure 4), where it can be seen that the upper reaches of the two distributions diverge. The five-year return value, for example, is encompassed by measurements and not by extrapolation, and the value for the later half is a metre higher than the earlier value. Also, we inspect the distribution of annual maximum H_s (of which one may extract 14 values) and by fitting a suitable time-dependent extreme-value distribution, we find an increase of 10% over 25 years (compare with 28% over 25 years for annual mean H_s). We cannot say with confidence whether this is real because there is not enough data to do so; I am inclined to believe that the evidence, inconclusive as it is, is suggestive in the positive sense, unlike Hogben, who believes it is suggestive in the negative sense; and further, although it is almost certainly less than the increase in mean height, it is not 'small'.

My second point of departure is from Hogben's entire tack over the cause of the increase in mean heights. I make reference below to a companion paper to BC91: Bacon & Carter (1993), 'A connection between mean wave height and atmospheric pressure gradient in the North Atlantic', Int. J. Climat., 13:423-436, BC93 hereafter.

Hogben makes the case that mean wave heights have increased without increase in mean wind speeds (the essential problem) because swell has increased. This entirely begs the question. The review in BC91 examines all available long-term data sets, and these cover the entire North Atlantic.

The consistent picture which emerges (see BC91, Figure 5) is that wave heights have increased over the whole of the North Atlantic, not just at Sevenstones LV. It is likely therefore that swell has increased everywhere, and not just at Sevenstones LV. In BC93 we start from the simple position that if there is more energy in the wave field, it can only have been put there by the wind; and that, since the wave height in any place is a complicated result of non-local processes, it is worth inspecting a larger-scale measure of wind speed than just the local mean. Accordingly we selected the monthly and annual mean (sea surface) atmospheric pressure gradient between the positions of the Azores High and the Iceland Low, which is nearly the meridional (north-south) pressure gradient. We compared these data with Sevenstones LV and OWS Lima monthly and annual mean H_s and found highly significant correlations at both sites for annual and winter month data (the spread of H_s values was insufficient for determining correlations in the summer months). As a by-product of the correlation of annual means of pressure gradient and H_s at Sevenstones LV, we were able to make a simple wave climate hindcast back to 1873, when Met. Office records began.

Now all this is not a solution to the problem of increasing wave heights; but given that the solution must lie in the behaviour of the atmosphere, it gives a sensible starting point. Why does it work? I can only speculate, but changes in storm tracks, weather system translation speeds, weather system sizes and growth and decay rates may all be involved, and are all the sorts of phenomena one would expect to 'wrap up' into the meridional pressure gradient. Put simply, given that conditions seldom favour the production of fully-developed seas, for the same winds to produce higher waves, they only need to stay in the same direction longer. Finally, to say that the evidence "inevitably implies a changing relationship between wave heights and wind speeds" is misleading in the extreme. What is needed is the inclusion of some missing physics into the existing parameterisations.

Mr I M Leggett: Detailed analysis of wave data collected by Shell U.K. Exploration and Production in the Brent area of the Northern North Sea 1973-1993, and wind data from Lerwick 1957 - 1993 tend to support Hogben's findings.

The main conclusions from the Shell work complementing Hogben's are as follows:

1) The average increase in mean significant wave height (H_s) is 0.5% per year.

2) The average increase in mean H_s for winter months only (October to March) is 1% per year.

3) There is no corresponding increase in wind speeds.

However the above conclusions should be put into context with the other findings from the Shell work:

4) There is evidence of a cyclical trend in wave heights with an average period of circa 10 years. Thus the mid 1970's and mid 1980's are less severe than average, whereas the early 1980's and early 1990's are more severe. From these findings it is apparent that there will be significant variation in perceived annual increases in wave height depending on your start and end year.

5) Seasonal changes are apparent in the wave data with Autumn becoming less severe compared to increased severity in late Winter/early Spring.

6) The 5 highest recorded H_s values in separate storms have occurred over the last 6 years.

7) Evolution of data sampling from the standard 20 minutes every 3 hours of the 1970's to the more frequent 34 minutes on a rolling 10 minutes basis since the late 1980's, together with changes in instrumentation and data processing will affect the homogeneity of the dataset. This could distort some of the findings. For example, the increased sampling of recent years may partially explain the reason for 6 above.

Shell is continuing to measure and record meteorological and oceanographic data at its offshore installations, and will be updating the above analyses every 2 years.

Professor M Mano (Fellow): First of all, I would like to offer my sincere congratulations to the author on a wonderful paper. Now is the environment of the human being changing slowly or quickly? If the latter, it is important to sound the alarm well in advance for the preparation of countermeasures, and from this point of view this paper will be very important.

Increases in wave height will bring about important problems not only on ships but also offshore structures and even on land.

As the author mentions in the paper, fatigue strength of the hull structure is one of the important problems to be discussed. The evaluation method of fatigue strength of hull structures is now being established, and authorised, based on a cumulative fatigue damage ratio concept. Data concerning the increases in wave heights to meet the evaluation method of fatigue strength of hull structures will be very much appreciated.

Mr Christopher Grigson (Fellow): Dr Hogben is to be thanked for an interesting paper, but his claim in the summary that the paper has implications: "...for many aspects of the operation and design of ships ... notably the impact of the increase in mean wave height on fatigue damage", is rather sensational.

The author bases his case mainly on visual observations of wave heights. This suggests that Kinsman's verdict on the determination of wave heights still applies: "Each instrument preserves a signal which is related to the true sea surface but is distorted from it in many ways." Moreover there was then not one satisfactory method for the calibration of wave gauge systems (20).

Would oceanographers put their faith in visual observation of height if there were measuring systems available? If it was necessary to measure the undulations of a piece of land which was to be used as an airstrip and an observer drove across it at 20 mph in order to determine the wave heights by visual observation, would any credence be given to the estimates? If visual observation could determine wave height, then it should be possible to obtain the heights of waves in any photograph of the sea. But although the angle subtended by the height of any wave can be determined, the actual height cannot, since the distance to the wave is unknown. Visual observations assign numbers to unknown heights at unknown distances.

However, there are also results from wave recorders which seem to show that annual average wave heights in part of the North Atlantic have risen from 2.7m to 3.1m. The recorders are installed on three ocean weather ships and a light vessel, Sevenstones, the latter moored by heavy chain in a very exposed position. The records were taken in 1960-75 (India and Juliett), 1962-86 (Sevenstones), and on Lima from 1978-85. All those instruments were designed before the days of large scale silicon integrated circuits and digital processing of the sensor signals. Presumably India, Juliett and Sevenstones had Tucker wave recorders. Were not all those instruments based on sensing the acceleration at the recorder itself, integrating it twice and displaying it on chart recorders? What you require is the surface elevation h(x) as the random waveforms stream past the observing sensor; what you get is a different signal h_1 (t) involving the response of the ship to the waves; h_1 (t) has frequency components with periods down to 20 seconds, so that the overall response of the system, including the integrations, must be flat to 0.02 Hz. Thus the systems must be direct coupled and at these very low frequencies DC drift and gain stability are the same thing.

How was the problem of drift solved? The author claims to measure a change in the average amplitude of the waves of 1.48% per annum. To achieve this the overall gain stability must be 0.1% per annum. In the days before LSI and digital processing, a stability of 0.1% per day in laboratory conditions would have been considered remarkable. How was the overall gain stability established? Were the recorders taken ashore at each vessel refit and put on an acceleration table with excitation in the range 0.02 - 2 Hz and their response recorded?

In getting 'average annual height', how much waveform was processed and how was this done?

It is characteristic of many observations to do with climate, that results from a limited number of observing stations are held to represent a vast area of the globe. The four wave recorders lie within a radius of some 420 sea miles centred on Juliett. The population of observing stations is rather small to represent 'the North Atlantic'.

For the sake of discussion, consider the consequences for the strength of ships of an increase in the annual average height of waves from 2.7 to 3.1 metres in the period 1960 - 75, or 1978 - 85. The author implies that it is the 40cm change which must have a notable impact on fatigue damage. According to Principles of Naval Architecture (21, p214) scantlings are sized to ensure stress levels below 130MPa when the ship is on a wave of height $1.1\sqrt{L_{pp}}$ and length L_{pp}, a wave 15m high on a vessel 200m long. The hulls are all welded which degrades the endurance limited of mild steel from above 200MPa to 50MPa (type F and F_2 welds (22 pp79-102). Certainly the average waves whether of height 2.7m or 3.1m, contribute to high-cycle fatigue, but below the endurance limit.

> "Fortunately fatigue cracks have been mostly of the nuisance variety occurring in poorly designed brackets and other details" (21, p288).

The nuisances will in any case be kept under observation by the Class and dealt with periodically at special survey.

REFERENCES

20 KINSMAN: 'Wind waves, their generation and propagation on the ocean surface'. Prentice Hall, 1965, pp 427-433.

21 Principles of Naval Architecture, edited by Lewis, Vol. 1, SNAME, 1988.

22 MADDOX: 'Fatigue strength of welded structures', The Welding Inst. and Abington publishing, 2nd edition, 1991.

Messrs K Iden, H Reichardt, M Reistad, W Rosenthal, A Ruiz de Elvira and H von Storch (WASA group):

1. Reply to Dr Hogben's Main Points

In his review paper Hogben deals with the North Atlantic wave climate and makes the following main points:

1) The mean wave height has increased in the past: "Little room for doubt that mean wave heights have increased over the past 30 years or more at a rate of order 1 or 2% per annum"[1].

   There are indications that the extreme wave heights may have increased but the data are too poor to make a definite statement.

2) There is no obvious change in the wind statistic over the North Atlantic in the past decades.

3) The empirical relationship between wind speed and wave height has changed since 1950 so that weaker winds go with taller waves (see in particular Hogben's Figure 3).

4) The additional wave energy may stem from swell which has been created somewhere else. The alternative explanations of a changed fetch statistic due to different wind directions and storm durations is unlikely.

The WASA[2] research group appreciates the opportunity to comment on this fine assessment of the state of knowledge concerning the mean wave height statistic in the North Atlantic. In the following we comment on the four points listed above.

2 "Mean Wave Height Has Increased."

Hogben supports this rather general statement with data from a series of locations mainly between 50° and 60°N obtained from ships of opportunity and visual and instrumental observations from Ocean Weather Stations ("OWS") C, L, I and J from the light vessel Sevenstones. His numbers, condensed in his Figure 2a, support this notion of increased mean wave height.

Nevertheless we challenge this notion for two reasons.

- Observations from other locations do *not* show an increase of the order of 1 to 2% per annum. For instance for OWS M (66°N, 2°E) the net increase over 40 years should be of the order of 40 to 80% - if we start with a mean wave height of about 2m in the early 50s the numbers in the late 80s should be somewhere between 2.8m and 3.6m. In Figure 1 we have plotted the temporal evolution of various percentiles of the reported wave height. We do not claim that the wave data from that position are homogeneous (in the early 50s the numbers seem to be systematically too low; before 1979 the reports were based on visual assessments and after 1979 on instrumental data) - but Figure 1 does not contain any hint towards a roughening of the wave climate at OWS M.[3]

  If we limit our attention to the last 15 years, the increase of annual mean wave height at OWS M is marked with a rate of approximately 1m/15 years (Figure 2). In the context of the longer observational record of Figure 1, though, this recent increase appears as a transient evolution, which is not uncommon compared to previous developments. For three other locations, in the North Sea, namely at Statfjord/Gullfaks (61°N, 2°E), Frigg (60°N, 2°E) and Ekofisk (56°N, 3°E) the last 15 years' trend is smaller than that at OWS M or even absent.

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[1]Similarly categorical statements, such as "... an indisputable increase in wave height measured out there!", have been put forward by van Hooff (1993). However, van Hooff refers to about the same material as Hogben so that Hogben's and van Hooff's results do not represent independent evidence.

[2]WASA stands for "Waves and Storms in the North Atlantic". It is a European Consortium of scientific institutions from the United Kingdom, Norway, Denmark, Sweden, Spain, The Netherlands and Germany and is funded in part by the Commission of the European Community in its ENVIRONMENT programme. Coordinator of the project is Hans von Storch, Max-Planck-Institut für Meteorologie, Bundesstrasse 55, 20146 Hamburg, Germany.

[3]We do not know whether the dramatic increase in the last year of the record, 1993, is real or not.

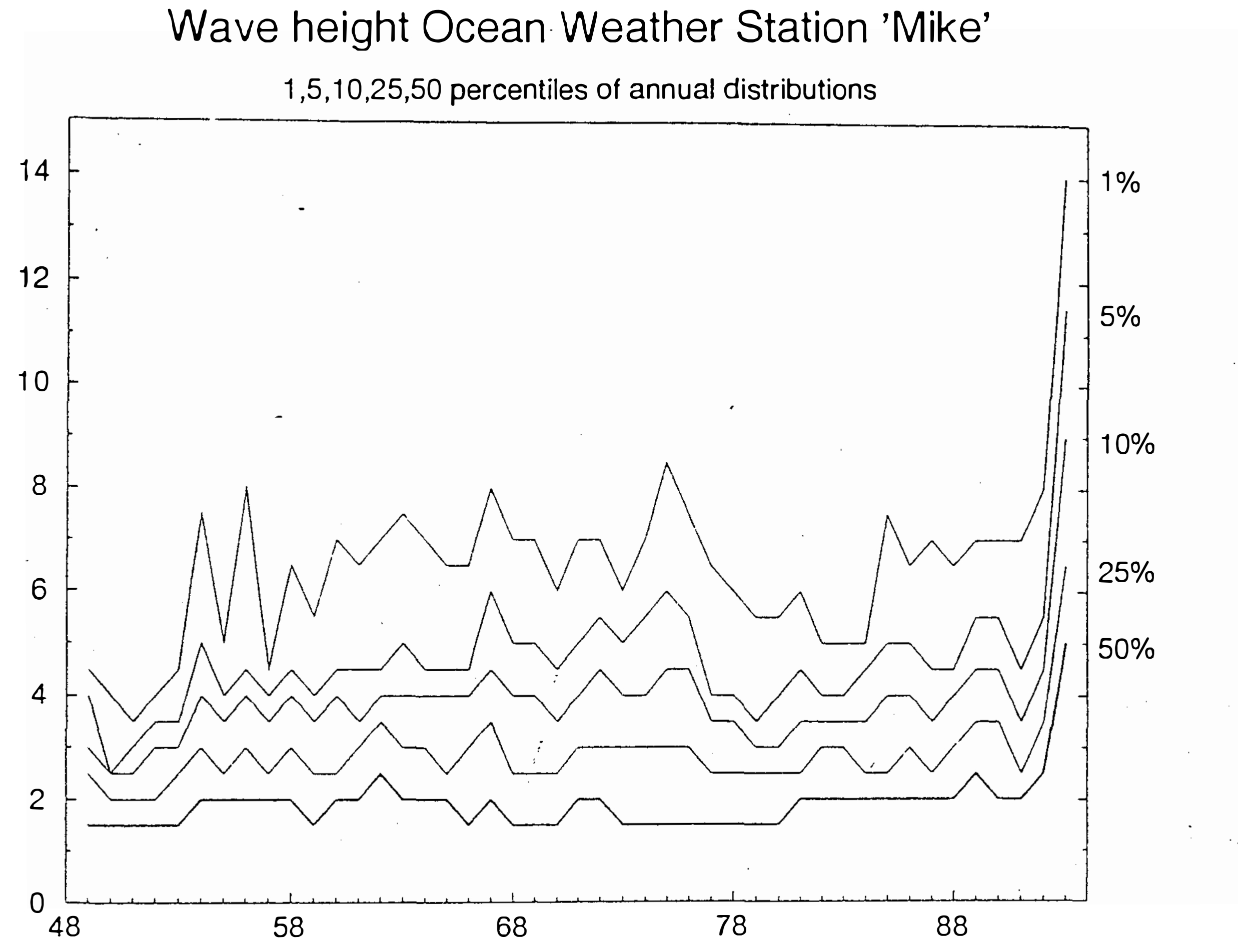

Fig. 1 Time Series of percentiles of the annual wave height distribution at Ocean Weather Station M. Units: m.

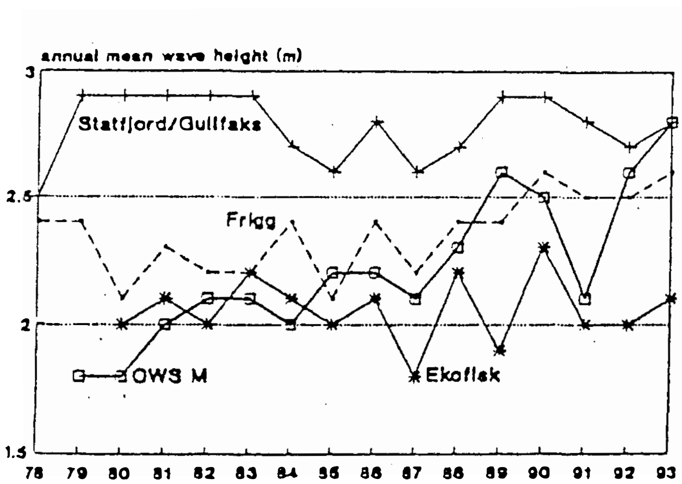

Fig. 2 Time series of annual mean wave height at OWS M, Statfjord/Gullfaks, Frigg and Ekofisk. Units: m

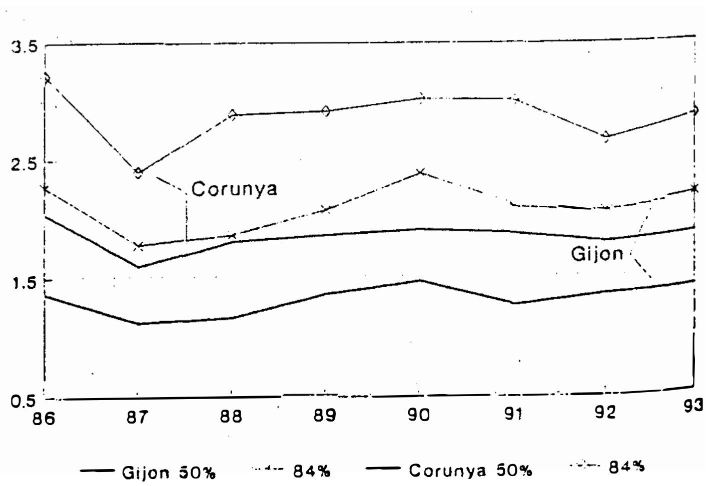

Fig 3 Time series of the annual mean wave height and of the 85%-percentile of the annual wave height distribution (i.e. mean plus one standard deviation) at the buoys 'Gijon' and 'Corunya' in the Spanish coastal waters. Units: m.

Another unfortunately rather short but homogeneous data set at our disposal consists of instrumental reports from buoys in the Spanish coastal waters. Figure 3 shows again temporal developments of percentiles derived from data from the two buoy "Gijon" (6°W, 44°N) and "Corunya" (8°W, 43°N) (1985 - 1993). A general increase cannot be detected.

- The increase of reported wave height could be due to improvements and changes of instrumentation and observational practices in the course of time.

  - For visual data the training of the observers in estimating wave heights has changed over the years, especially by comparison estimates with the steadily improved objective methods. On the light vessel Sevenstones a shipborne wave recorder was first installed in the early 60s - therefore the parallel increase of reported wave height at that location does not necessarily represent two independent observations but possibly only one gradually improving observation (see below).

  - The wave statistic is affected by 'ship down' -times. Especially in heavy sea states the measurements were interrupted. This occurred more often in the early years so that the mean wave height in the early years will exhibit a negative bias and the temporal development will show up a spurious upward trend.

  - Early shipborne wave recorders, as used at OWS J or light vessel Sevenstones, were unable to catch the effect of high frequencies. This deficiency has been improved in several steps. Such a gradual improvement leads to a slowly decreasing bias and to a slow increase of the mean and extreme wave heights.

In the early 90s, reports about wave crests reaching the working decks of oil rigs in the North Sea created concern in the European oil industry. This concern prompted the Norwegian Weather Service to organize two workshops: 'Climatological Trends and Future Offshore Design & Operation Criteria' in Bergen (30 November to 1 December 1992) and Reykjavik (28 to 31 March 1993) with participants from research institutions, the oil industry and certifying agencies. These workshops came to the same conclusion as Hogben, namely that there are reports which are consistent with the concept of increasing extreme heights, but that the available data is far from being sufficient to allow for a definite assessment. The creation of the WASA group was an immediate result of the two workshops.

3 "Wind Statistic Has Not Changed."

The two above mentioned workshops also dealt with the problem of whether the storm statistic might have changed or would be changing right now. The discussions are summarized in von Storch et al (1994). All available estimates derived from fixed platform-data, for instance weather ships or geostrophic wind derived from air-pressure triangles, or the statistic of high-frequency coastal sea-level statistics, do not point to a change. Estimates derived from sources such as weather maps or ships of opportunity showed an increase in storminess, but in this case the spurious effect of better analyses of the weather state and of the effect of changing sizes and routes of ships cannot be distinguished from a real effect.

4 "The Empirical Relationship Between Wave Height and Local Windspeed has Changed."

Hogben argues for a change in wave climate without a change in wind climate over the North Atlantic. The strongest argument is Hogben's Figure 3 which shows regression lines of local wave height versus local wind speed. The most dramatic changes occur between 1960 and 1970. This was the time period where wave measurements became more and more frequent and more and more reliable.. Especially weather ships were equipped with shipborne wave recorders which were continuously improved. We had already formulated our suspicion that this instrumental improvement might have led to the observed particularities.

From this observed change of the regression coefficients, Hogben derives implications for wave modelling methods. As a consequence he proposes a growth enhancement factor for open ocean wave modelling in case that swell is present. This would be really a far reaching consequence which is not supported by the very positive experience with recent activities in numerical wave modelling. We think that the physical laws for wave growth in dependence from the local wind speed W have not changed in the past decades. They are implemented in numerical wave models in the growth relation of wave energy E(f):

$$\frac{dE(f)}{dt} - b\left(\frac{W}{c(f)} - 1\right)E(f) \qquad (1)$$

- dissipation

+ Wave-wave interaction

(with c(f) denoting the phase speed at the frequency f).

This growth law is completely based on local environmental parameters. Waves from different areas and different times (swell) are propagated into other areas and give rise to locally changing wave growth. The arrival of swell energy is therefore taken into account in the source functions of numerical models. The regression coefficients between local wind speed and local waves, that are derived by Hogben are not necessarily stationary if the local wind is constant in time, since the waves do not depend on the local wind speed alone but depend on the wind history along their travel route.

If all artifacts are removed and if the climatology of the waves at any location has changed, the conclusion from the presented data can only be that the climatology of the wind fields over the North Atlantic has changed somewhere, not necessarily at the weatherships. There is no implication for changing the algorithms of numerical wave models.

For a review of modern wave modelling see Komen et al (1994).

5 "The Swell-Component of the Wave Height Has Increased."

WASA agrees that intensified swell might be one mechanism to increase mean wave heights. However, this intensified swell must come from somewhere. An adequate answer requires an analysis of the variability of the storm tracks at least in the North Atlantic. Such an analysis is, however, loaded with great methodological problems because of the above mentioned homogeneity problem in historical weather maps. It is hoped that the recently begun projects to 'reanalyse' weather maps in a homogeneous manner, will allow for such an assessment. With such a data base and with modern numerical wave models, such as WAM (WAMDIG, 1988), it will be possible to sort out the different possible explanations put forward by Hogben and others.

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AUTHOR'S REPLY

It is gratifying to receive so many thoughtful contributions to this discussion which are a most valuable addition to the paper. As a preface to my reply it may be of interest to mention that a follow up paper (Hogben 1995) has been written which reports some significant further investigation of the changing relation between wave heights and wind speeds over the North Atlantic.

Prof. Rawson's comments are particularly welcome since the paper was written in response to concern expressed by the RINA 'Safety Committee' of which he is Chairman.

His query about the plausibility of an increase in mean height without a corresponding change in maximum height of wave is, I suspect, based on a misunderstanding. By referring to an associated change of wave shape (to a square wave) he appears to be considering the relation between the peak height and mean elevation of an individual wave which is not the issue here. The concern of the paper is with the relation between the mean value of a population of significant heights spanning several years, and the extreme value of significant height and associated maximum individual wave height in the most severe storm during those years.

As explained in Hogben (1989) and further discussed in the present paper, since mean wind speeds have not increased it is quite plausible that the mean heights, which are dominated by the influence of swell (see also Hogben (1995)) have increased without a corresponding rise in extreme heights, which are caused by very high wind speeds.

The plausibility of the suggestion that spectra do not need modification is also queried. I must emphasise in reply to this point that the advice given is that there seems to be no reason why the changing relation between wave height and wind speed should call for a change in the functional form of the widely used JONSWAP family of spectra. It is noted, however, that the associated prediction formulae for estimating wave height from wind speed may need to be modified when used in ocean areas. Also, when using the parametric form of spectrum entered by wave height and period it will be advisable to ensure that the values chosen for these parameters take account of the reported variability (see also reply to Dr. J.C. Brown).

Finally, Prof. Rawson draws some reassurance from the lack of increase in ship loss statistics over the past thirty years. This is consistent with the suggestion in the paper that there may not have been any significant rise in extreme heights. The reported increase in mean heights may, of course, have caused some increase in fatigue damage. Since, however, estimates of fatigue life are, I believe, notoriously imprecise, it seems reasonable to assume that there has been sufficient conservatism in design to avoid corresponding increases in ship losses. It may be prudent nonetheless, as suggested by Prof. Rawson, to investigate whether safety margins have been unacceptably eroded.

Mr. Lynagh begins by citing his own experience of observing waves from weather ships to cast doubts on the evidence of wave height variability based on the analysis of visual data from weather stations by Walden (1970). In reply to this point, I should emphasise that the visual data from Barratt (1991) cited as evidence of increasing mean heights in Table 3 and Figures 1 to 5 of the present paper, were derived entirely from ships of the Voluntary Observing Fleet (VOF). The significance of this point is that the reliability of statistics from such data in comparison with measurements has been extensively documented (see for example Hogben and Dacunha (1985) and Hogben et al. (1986)). Further evidence of their reliability is moreover offered by comparisons with measured data cited in the present paper (Tables 2 and 3, and Figure 3a)). In support of Mr. Lynagh's case, however, it should be noted that Hogben (1963) found large differences between statistics derived from weather ship observations and those from VOF ships for the same area.

The remainder of Mr. Lynagh's comments are broadly supportive of the paper's findings and do not call for any reply beyond endorsement of his point that in the long term (but how long is long?) trends become episodes in a fluctuating history.

Mr. Stokes expresses concern about the impact of the paper's findings on design of North Sea structures. In reply, I should emphasise that the present paper relates only to the North Atlantic and notes (see also Hogben (1989)) that evidence as to increases in extreme heights, most important for structure design, is inconclusive and suggests that any rises have been relatively small. North Atlantic experience may, of course, have some relevance for planned developments 'West of Shetlands', but for assessment of implications for design of North Sea structures I recommend reference to Van Hooff (1994).

This indicates that trends for increasing wave heights are much less marked in the North Sea (see also Bacon and Carter (1991) and the contribution to the present discussion by Mr. Leggett). It draws attention, however, to the possibility that increases in mean height could change the balance between design for extremes and design for fatigue, such that satisfaction of extreme criteria may no longer, as now, tend to ensure acceptable fatigue life. As to the situation in other areas of the world I am not myself aware of any evidence for comparable trends elsewhere.

Mr. Stokes asks for expansion of paragraph 3.3 of the paper and, to save space, I simply recommend that he should consult the follow up paper (Hogben (1995)) which, I hope, he will find meets this requirement. He also suggests three research projects all of which I would strongly support and I hope those able to provide the necessary funding and resolve the confidentiality problems can be persuaded to do so.

Mr. Brown offers some interesting comments on the financial implications of the paper's findings and refers to a paper he has written which assesses the cash value of good seakeeping. No reply seems to be needed but I imagine many readers will wish to consult his paper.

Mr. Hopkins has submitted comments supported by some measured wind speed data which are a particularly valuable addition to the paper. His contribution also includes some general remarks about the complexity of the processes involved in climate change. These lead to a warning against too much attention to trends and the recommendation that adequate allowance for fluctuations about mean values may be as important as estimation of mean values themselves, which I strongly endorse.

Concerning his wind data, such a long run of good quality measured results is of great practical interest. I have two points to make about the data, the first concerning comparison with other findings and the second regarding his estimates of corresponding wave height changes.

In the paper, measured data reported by Challenor in an appendix to Draper (1986) and visual (VOF) data from Barratt (1991) plotted in Figure 2b), are cited as evidence that mean wind speeds in the North Atlantic have shown little change over a period of thirty years or so. Reference may also be made to comments in contributions to this discussion by Mr. Leggett about Lerwick winds and by the WASA group citing a review of fixed station data by Von Storch et al. (1994) indicating no change in mean wind speeds. It need not, of course, be assumed that conditions in the Atlantic should be the same as those at Lerwick, but if a comparison is made between Figure 2b) of the paper and the Lerwick data, it is important to note that Figure 2b) shows five year averages plotted above a zero datum, whereas the Hopkins figure plots annual values above a 12 knot datum. When this is taken into account, the difference is less marked than might at first appear. Also, it should be noted that the 1.6% per annum rate of increase which is cited, relates to a span of years chosen to yield a high rate, an interesting illustration of the deceptiveness of trends.

A more direct comparison to which I should refer is with Mr. Leggett's comments mentioned above. He states that at Lerwick 1957 to 1993 "There is no corresponding increase in wind speeds". This seems to be in conflict with the Hopkins data and I would be interested to know the explanation for this apparent anomaly. Presumably it is a matter of interpretation including assumed averaging periods and choice of time span as well as the meaning of 'corresponding increase'.

Regarding estimates of corresponding wave height changes, I note that Mr. Hopkins translates his 1.6% per annum increase in mean wind speed to an estimated 2.56% per annum increase in mean wave height, which implies an assumption that wave heights are proportional to the square of wind speed. This is indeed true for fully arisen wind seas but, in practice, due to the influence of swell and of limited duration and fetch of the wind, wave heights tend to be proportional to a much lower power of wind speed, close to unity, as shown in the paper. I believe, therefore, that the corresponding mean height increases should be nearer to 1.6% per annum and thus in closer agreement with most of the results in Tables 2 and 3 of the paper.

Haavie et al. raise two questions about implications for design of offshore structures. The first is a concern that extreme heights may have increased by amounts comparable with the reported rises in mean heights. For reasons explained in reply to Prof. Rawson (see also Hogben (1989)), this is not necessarily so and, furthermore, such increases may not continue in the future. It may nonetheless be prudent to review safety margins to ensure that adequate allowance is made for long term variability.

Their second question concerns the implications for fatigue design of the assessment that higher levels of ambient swell are the main cause of increased mean wave heights in the Atlantic. In reply to this question it may be helpful to refer to the accompanying Tables R1 and R2.

The results in Table R1 were derived from analysis of measured wave and wind data reported by Hogben (1984) and show the relation between mean zero-crossing period and wind speed at OWS India over the years 1957 to 1965. The relative invariance of mean period at a level close to the overall mean value of 9½ seconds supports the assessment that swell waves which are independent of local wind speed play a dominant role in determining mean wave conditions in ocean areas (see also Hogben (1995)).

The results in Table R2 were computed from measured wave data and show changes in mean height and period between two spells spanning the years 1952 to 1975 at OWS India and OWS Juliett. It may be seen that, whereas mean heights have increased by the amounts already reported in Table 2 of the paper, the corresponding mean periods have decreased by 9% in both cases. I initially found this surprising. On reflection however, since the mean periods of swell waves tend to increase with time, it is an expected result of the increased storm frequency and associated reduction in swell decay time mentioned in the paper.

I am not competent to assess the full implications of these results for fatigue design. I imagine, however, that the reduction in average period which means an increase in wave frequency and hence of the stress cycle count will tend to aggravate the effect of increasing mean height. The question as to whether any modification of design codes is needed is a matter for careful consideration by relevant experts taking account of the available data. It may also be useful to note some of the comments contained in this discussion specially the warning of Mr. Hopkins against too much attention to trends and his advice to make adequate allowances for fluctuations.

Finally, as in reply to Mr. Stokes, I recommend reference to Van Hooff (1994).

Dr. Frieze's main point concerns the length of time needed to differentiate a trend from a cycle. This is a 'length of string' question and in reply I recommend again reference to the sound advice in the contribution of Mr. Hopkins, to avoid too much attention to trends and concentrate on allowing for fluctuations.

Dr. Brown seeks an explanation for his finding illustrated by the results in his Tables 1 and 2 that the trend of extreme stresses tends to be downward rather than upward. In so doing, he recalls discussions with myself concerning the influence of wave length on bending stresses and suggests that some increase in wave period and hence of wave length might help to provide the required explanation. I have a pleasant memory of our discussion though it was a long time ago (15 or 20 years?), and am most interested in the question now raised.

It has, in fact, stimulated me to undertake some analysis of measured wave data to assess the changes in mean wave period associated with the reported increases in mean height. Some results of this analysis have already been cited in reply to Haavie et al (see Table R2) and results relevant to Dr. Brown's question are shown in Table R3.

It may be seen that there has been a reduction rather than an increase in the wave length corresponding to the mean period, towards the 100m level cited as critical for bending stresses. Thus, although extreme stresses may not be caused by waves corresponding to the mean period, since according to Table R1 (see reply to Haavie et al.) mean period is relatively insensitive to wind speed, the results suggest that change of wave length is not the required explanation. I fear, therefore, that Dr. Brown must seek the answer to his question among the other possible explanations which he mentions.

Mr. Bacon disagrees with the paper in two respects. The first of these relates to the possibility that extreme wave heights have increased. On this, however, I think we are not much further apart than the difference between a half full and a half empty glass. He thinks it likely that they have, I think it possible that they have not and we both agree that we do not know.

The second point of disagreement concerns explanation of the cause for increases in mean wave heights, and he cites a reference which describes his views on this. I have read the paper in question with interest, and again, I believe we are not very far apart and may even be able to arrange a meeting of ideas and possibly some synergy between them.

Mr. Bacon's main points seem to be that the ambient swell has increased over the whole North Atlantic and that this additional energy must have been put there by the wind by some process which has been found to involve a correlation with the north/south pressure difference across the Atlantic referred to as the 'meridional pressure gradient'. Significantly, however, it is acknowledged that the physical explanation for the correlation is not known and, in particular, I could find no evidence in the reference as to whether any increases in mean local wind speed are involved.

This assessment seems to me to be entirely consistent with the findings of the present paper. These include confirmation that the mean height assumed to be dominated by swell (see Hogben (1995)), has increased at a number of widely separated locations across the Atlantic. They also include the suggestion that these increases are a result of increasing storm frequency which reduces the swell decay time between storms. This concept is more fully explained in Hogben (1995) which presents further evidence in support of the link between ambient swell height and wind wave growth rate illustrated by Figure 6 of the present paper and also derives a direct relation between ambient swell height and overall mean wave height. It is acknowledged, however, that the cause of the increased storm frequency is not known which is where the synergy referred to earlier may help.

It occurred to me that it would be interesting to consider the possibility that Mr. Bacon's 'meridional pressure gradient' works by increasing the storm frequency rather than the mean wind speed. This would mean that we are both right and would, at the same time, help fill the acknowledged gaps in both our explanations. Could this be some of the 'missing physics' mentioned by Mr. Bacon.

But what causes the increases in meridional pressure gradient? Global warming perhaps?

Finally, I am surprised that Mr. Bacon finds the claim for a changing relation between wave heights and wind speeds based on evidence such as Figures 2 and 3 to be so misleading.

Mr. Leggett's contribution is specially appreciated because of his extensive experience of analysing metocean measurements spanning long periods of years. Most of his comments are complementary to, but broadly supportive of the present paper and do not call for any detailed reply, so I merely draw attention to a few points of particular relevance.

It is of interest to note that the Shell data from the northern North Sea shows that mean wave heights have increased but at a lower rate than those in the North Atlantic. This is consistent with the expectation that levels of ambient swell are lower in the Northern North Sea than in the Atlantic. The conclusion that there has been no corresponding increase in wind speeds is also of interest as it supports findings of the present paper for the Atlantic. I must, however, note the apparent conflict with data presented by Mr. Hopkins to which I have already referred in my reply to his contribution, with a plea for an explanation.

The conclusion number 4 reinforces a recurring theme of the preceding discussion that trends must be treated with great caution. It also underlines the importance of continued monitoring and it is reassuring to learn from the last sentence that the collection of Metocean data by Shell will be continuing with updating of the analyses every two years.

Prof. Mano's favourable comments on the paper are appreciated. He expresses particular concern regarding implications of its findings for fatigue strength of both ships and offshore structures. As noted earlier, I am not competent to offer any detailed advice on this question. I can therefore only suggest that he may find it helpful to study parts of the previous discussion which have considered this question. Also, as in reply to other contributors, I recommend that he should consult Van Hooff (1994) which devotes particular attention to implications for fatigue design of offshore structures of increases in mean wave height.

Mr. Grigson supports a charge of sensational claims regarding implications of increased wave heights for fatigue design with very detailed criticisms of both the visual and measured data and their interpretation, which I believe are an overstatement of his case.

Regarding the reliability of visual observations, for example, his airstrip analogy and reference to the limited concept of photographic analysis of the sea surface are, I believe, highly misleading and betray a serious lack of understanding of the data collection and analysis procedures. It would be more realistic to consider a very large number of experienced observers reporting estimates of mean heights using techniques based on a well established code of practice (Meteorological Office 1977) not confined to photographic types of assessment. It should be noted, moreover, that statistics derived from the massive archives of those observations now available have been extensively validated by comparison with measured data (see for example Hogben and Dacunha (1985) and Hogben et al. (1986)). Further support for the reliability of the visual data is moreover offered by the correspondence with measured data illustrated by comparison of the results shown in Tables 2 and 3 and Figure 3a) of the present paper.

Regarding the measured data, Mr. Grigson is correct in saying that the results reported in the paper were all derived using Tucker wave recorders. Again, however, I believe his comments about the degree of uncertainty inherent in use of this instrument are highly misleading. It is true that its mode of operation calls for quite complicated signal processing involving a number of frequency dependent calibration factors and that a revised analysis procedure was recently introduced (Pitt (1989)). Nonetheless, on the basis of extensive comparisons with buoy measurements it is widely regarded as reasonably reliable if due care is taken in its operation and in the data analysis.

The question of instrument reliability is discussed in Section 2.1 of the paper and it is noted that Draper (1986), in presenting the data showing increased wave heights at OWS India and Juliett, undertook a thorough investigation of possible sources of error which reassured him that their results were valid. In particular, he affirms that the same actual instruments and analysis procedures were used throughout both of the two periods of years concerned. This would appear to offer some confidence that though the mean wave heights may not be quantitatively as accurate as might be expected using modern instruments, comparative results and percentage increases are likely to be valid. This view draws some support from the results presented in the accompanying Table R4.

This shows a comparison between measured mean heights for the two periods of years at OWS India and OWS Juliett derived before and after introduction of the revised analysis procedure. It may be seen that, although the revised mean heights are substantially lower, the percentage increases from Period 1 to Period 2 are relatively unchanged at both stations.

Concerning the possible impact of increased mean wave heights on fatigue damage, I am not competent to challenge Mr. Grigson's assessment. Possibly, as suggested in the reply to Prof. Rawson, in the case of ships it is only a matter of a slight erosion of safety margins which is tolerated by conservatism in design and has apparently not led to any increase in ship losses. In the case of offshore structures, however, the impact on design may be more significant as noted in reply to Mr. Stokes on the basis of Van Hooff (1994).

The WASA Group (Iden et al.) have made a collective contribution to the discussion which is particularly appreciated because of the wealth of relevant experience and specific concern as a group with study of trends.

1. Main Points

The discussion is presented under five headings, Section 1 being a summary of the main points in the paper with which I agree. It will be convenient to follow their section numbering for the remainder of my reply.

2. Mean Height Increases

They challenge the increases of mean height presented in the paper, partly on the grounds that such increases are not found in data which they display for other locations and partly on the basis of doubts raised about the consistency of the instrumental and observing practices.

I do not accept the concept that doubt can be cast on the results in the paper by lack of increases in other very different areas. Thus, considering first their data for OWS M (65°N 2°E), this relates to a location off the coast of Norway far removed from those in the paper, an area where the level of ambient swell is believed to be much lower (Hogben 1981) and the expectation of increasing wave heights correspondingly much less. As to the Spanish coastal data, they are irrelevant for two reasons. The first is that they also relate to a very different area from those in the paper where the ambient swell level may be lower. The second, and most important, is they cover a period of years starting in 1986, whereas the results in the paper do not extend beyond 1985.

Regarding doubts about the consistency of the observing and instrumental practices, the question of data reliability has been discussed in some detail in the replies to Mr. Lynagh and Mr. Grigson. In particular, attention has been drawn to the extensive validations of visual data including the comparisons with measured results in the paper (Tables 2 and 3 and Figure 2b)). Also, as to the measured data, it has been noted, citing Draper (1986), that in the case of the OWS India and OWS Juliett data, the same actual instruments and analysis procedures were used throughout the two relevant recording periods.

In the last paragraph of this section of their contribution, reference is made to the question of increasing extreme heights and it is gratifying to learn that the two workshops mentioned both came to the same conclusion as the present paper, namely that they may have increased but the evidence is inconclusive.

3. Wind Statistics

It is reassuring that the comments in this section and, specifically the review of platform data by Von Storch et al. (1994) which is cited, broadly support the finding of the paper that there has been little change in mean wind speeds.

4. The Relation between Wave Heights and Wind Speeds

Objections are raised to the suggestion in the paper that a growth rate enhancement factor should be applied to the JONSWAP formula for predicting wave height from wind speed when used in ocean areas. These are, however, based on a crucial misunderstanding, and since this may be shared by others, I welcome this chance to resolve it and, in so doing, to show that the WASA argument actually serves to justify the proposed use of an enhancement factor.

The key point is that the paper is not referring to employment of the JONSWAP formula for numerical wave field modelling as discussed by WASA. Its concern is with its common use by engineers as a simplex prediction formula for individual estimates of wave height from the relevant wind parameters at a specific time and location. I freely acknowledge that in wave field modelling the relevant swell dependent enhancement is inherent in the working of the modelling equation (1). This is indeed apparent from the form of the equation which involves an energy growth rate term proportional to the prevailing energy level E(f), which will include ambient swell.

In the case of the prediction formulae cited in Section 3.2.2 of the paper, however, no such allowance for the influence of swell is included. I believe, therefore, that when such formulae are used for prediction as described, in ocean areas, it is to be expected not only that an estimate of the ambient swell height should be included but also that the effect of that swell on the growth rate of the wind sea should be taken into account. As is more fully explained in Hogben (1995), the empirical formula relating to the growth rate factor a to the ambient swell parameter H_2 offers a basis for making such predictions which are shown to correspond closely to use of the JONSWAP formula with a growth enhancement factor.

5. Increase of Swell Height

WASA agrees that intensified swell might be one mechanism for increasing mean heights but notes that the additional swell must come from somewhere. This is indeed recognised and in the paper it is suggested that it could result from increased storm frequency reducing the swell decay time between storms. This idea is more fully explained in Hogben (1995). Also, in reply to Mr. Bacon's contribution to this discussion it is further tentatively suggested that the increased storm frequency may be due to a rise in meridional pressure gradient (Bacon and Carter (1993)) and more tentatively that this may in turn be related to global warming.

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TABLE R1

Relation between Mean Zero Crossing Period and Wind Speed Measured at OWS India (1957-1965) (from Hogben 1984)

Wind Speed W (knots)	Zero Crossing Period		Number of Values N
	Mean Value $\bar{T}_z$ (s)	Standard Deviation σ (s)	
2.5	9.29	0.95	106
7.5	9.38	1.16	248
12.5	9.32	1.25	423
17.5	9.30	1.31	392
22.5	9.40	1.26	391
27.5	9.51	1.33	285
32.5	9.51	1.35	175
37.5	10.20	1.36	112
42.5	10.74	1.19	63
47.5	11.38	1.18	25
52.5	11.72	0.92	9
57.5	11.00	0.50	2
62.5	-	-	-
67.5	13.00	0.50	2
72.5	13.50	0	1
All	9.50	1.33	2234

TABLE R2

Changes in Mean Significant Wave Heights and Zero Crossing Periods Measured at OWS India and OWS Juliett

Station Co-ordinates		OWS India 59°N 19°W	OWS Juliett 52°N 20°W
Years	Period 1 Period 2	1952 - 1965 1970 - 1975	
Mean Significant Height $\bar{H}_s$(m) % Change	Period 1 Period 2	2.75 3.45 +25%	2.75 3.03 +10%
Mean Zero Crossing Period $\bar{T}_z$(s) % Change	Period 1 Period 2	9.43 8.61 -9%	9.54 8.72 -9%

TABLE R3

Changes in Wave Lengths Equivalent to mean Zero Crossing Periods Measured at OWS India and OWS Juliett (see Table R2)

Station		OWS India	OWS Juliett
Years	Period 1 Period 2	1952 - 1965 1970 - 1975	
Wave Length λ^* (m) equivalent to $\bar{T}_z$ % Change	Period 1 Period 2	138.8 115.7 -16.6%	142.1 118.7 -16.5%

* $\lambda = (g/2\pi)\ \bar{T}_z^2$

TABLE R4

Effect of Revised Analysis (Pitt 1989) on Increases in Measured Mean Heights at OWS India and OWS Juliett

Station		OWS India		OWS Juliett	
Years	Period 1 Period 2	1952 - 1965 1970 - 1975			
Before or After Revision		Before	After	Before	After
Mean Significant Height H_s(m) % Increase	Period 1 Period 2	3.37 4.15 23%	2.75 3.45 25%	3.37 3.73 11%	2.75 3.03 10%