CHAPTER 56

On the Occurrence of Abnormal Storms and Its Implications on Design Parameters (Statistical Analysis of Same)

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Abstract

The assessment of design parameters has a fundamental importance for port planning and design of coastal structures. Special emphasis has to be put on the importance of the occurrence of abnormal storms. The authors' experience from investigations of port projects has revealed that on many sites it is storms with unusual tracks or otherwise unusual behaviour that are determinant for the design events. This experience is documented by two case stories. The importance of unusual weather systems is discussed and statistical methods for investigation of such phenomena are discussed.

1. Introduction

The design parameters for ports and coastal structures are usually established by statistical analysis of environmental data on extreme events from measurements or hindcast or a combination of these methods.

Traditionally statistical analysis is based on the application of a probability distribution such as: Gumbel, Exponential or Weibull etc. The theory of statistical distributions requires that the data to be introduced in the statistical analysis all belong to the same stochastic/statistical population. This is usually assumed to be the case if for example the data originate from wave measurements at a specific site.

On some sites, it is, however, evident that two wave regimes occur. This is for example the case for the coasts of the Indian Ocean where both normal monsoon waves and tropical storm waves occur. The two types of waves have clearly

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different origin and may thus be expected to be of different populations as has been documented by many studies. For such sites, it has since long been known by coastal engineers that it is necessary to separate the two regimes of waves when performing statistical analyses. Experience shows that two regimes of storms or storms leading to two statistical populations may also occur on sites exposed to cyclones. (Examples will be presented from Europe and North Africa).

2. Statistical Method for Analysis of Storms

In Ref. /6/, Rosbjerg et al. present the so-called POT-estimation of Extreme Sea States. The POT-method, i.e. peak-over-treshold, considers the distribution of peaks (for example wave heights, H_s) over a preselected treshold level. The following description is an extract from Ref. /6/.

The appropriate treshold is introduced and the recorded wave heights below this level are deleted, the remaining data constitute a partial duration series. This series is likely to represent independent storm events provided that the threshold is reasonably selected. Within each storm the peak value is used for further analysis. The POT-method focus on the relevant statistical variable for extreme events. A basic requirement of further analysis is that selected peaks are independent and identically distributed (i.e. that in any period of time there is the same probability of occurrence of a given wave height. Since for example the waves in the winter and summer season are quite different, it is normally most accurate to separate the two seasons and to consider the waves for example in the winter season, on the Northern Hemisphere October to March, both months included (about 180 days).

Denote either the storm peak itself or some suitable transformation by H_s' and the threshold level by h_*, the distribution function for H_s' is then introduced as

$$P\{H_s' \leq h \mid H_s' > h_*\} = F(h) \tag{1}$$

Further assume that the occurrence of wave peaks takes place according to a Poisson process with a seasonally varying intensity. This implies that the number of storms per year follows a Poisson distribution with the parameter equal to the integral of the intensity over a year. If this quantity is denoted by λ, the expected number of storms in t years with wave peaks greater than an arbitrary level $h (> h_*)$ becomes

$$\nu_h = \lambda\ t\ (1 - F(h)) \tag{2}$$

The T-year event, h_T, is now defined as the level which, on the average, will be exceeded once per T years. Since this situation corresponds to $\nu_h = 1$ for $t = T$, the T-year event is obtained by solving Eq. (2) under these conditions leading to

$$h_T = F^{-1}\left(1 - \frac{1}{\lambda T}\right) \tag{3}$$

By use of the above mentioned assumtions implying that the number of storms with wave peaks greater than h in t years follows a Poisson distribution with ν_h as parameter, the distribution for the maximum value of H_s' in t years, $H'_{s_{max,t}}$ becomes

$$P\{H'_{s_{max,t}} \leq h\} = e^{-\nu_h} = e^{-\lambda\, t\, (1-F(h))} \tag{4}$$

Now denote by R the probability (the risk) that the level $h_{R,L}$ will be exceeded once or more during a time period of L years (for example the lifetime of the structure). Accordingly, the left hand side of Eq. (4) equals 1-R for t = L, and a relation between R, L and the corresponding value of T can then be obtained by solving the equation for $h_{L,R}$ and equalizing the expression with Eq. (3). Hereby the following relationship is obtained

$$R = 1 - e^{-L/T} \tag{5}$$

In case of exponentially distributed wave peak exceedances i.e.

$$F(h) = 1 - e^{-\frac{h-h_*}{\alpha}} \tag{6}$$

where the parameter α is equal to the expected value of the exceedances above the threshold value h_*, the expression for the T-year event becomes particularly simple. Combining Eqs. (3) and (6) results in

$$h_T = h_* + \alpha \ln \lambda T \tag{7}$$

which can be used in order to exemplify an approximate method for calculating the standard error of the T-year estimate. In Ref. /6/ it is shown that the approximate standard error of T-year estimate can be written

$$\hat{s}_T = \frac{\alpha}{\sqrt{\hat{\lambda}_1}} \left(1 + (\ln \hat{\lambda} T)^2\right)^{\frac{1}{2}} \tag{8}$$

It is important to notice that the POT-approach is not limited to the exponential distribution assumption applied above. If another type of distribution, (e.g. lognormal or gamma) is justified, a similar procedure can be applied leading to revised expressions for the standard error of the T-year estimate. For other types of statistical distributions special care should be taken when the threshold level is selected.

3. Storms Caused by Cyclones

In many parts of the world including Europe and the Mediterranean, the severe storms are of the cyclone-type, being roughly circular low-pressure areas with a diameter that may range from hundreds to perhaps two thousand kilometers.

Most storms are associated with cold and warm fronts separating different air masses, but storms also occur when depressions form within the same air mass. The most severe cyclones are normally generated in the Atlantic Ocean east of New Foundland (Ref. /2/) and travel eastwards over the Atlantic Ocean to Europe and the Mediterranean following typical tracks as seen in Fig. 1. These cyclones occur due to unstable waves on the polar front and are therefore always associated with fronts separating different air masses with a difference in temperature. Besides these "Atlantic Cyclones" other cyclones affect Europe and the Mediterranean. Cyclones are sometimes generated on the southwest or southeast side of a cyclone, so-called secondary lows, which sometimes develop into major cyclones (Donn, Ref. /3/).

Many "Atlantic Cyclones" reach the Mediterranean, but in addition cyclones are also generated locally. Ref. /8/ presents an attempt to characterize cyclones in the western Mediterranean after their generation area and track characteristics. The most well known "local" Mediterranean cyclones are those generated within or near the Gulf of Genoa. They usually move southeast across the Tyrrhenian Sea. Fig. 2 from Ref. /5/ shows typical tracks of depressions affecting the western Mediterranean.

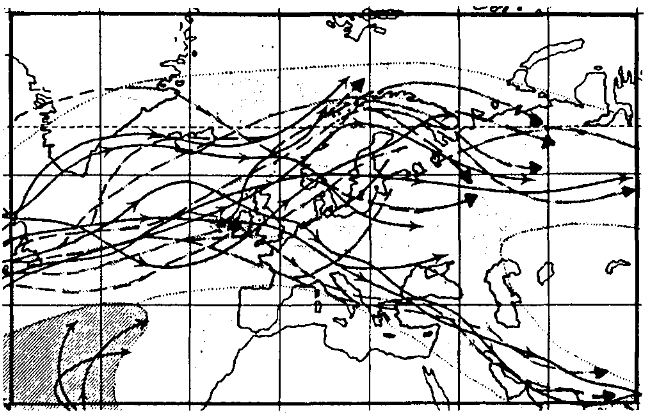


Figure 1. Typical tracks of Atlantic cyclones, Ref. /2/.

When making data analyses of wind velocities, wave heights, or water levels it is assumed that the cyclone generated physical data belong to the same statistical population. It is the authors' practical experience that in many cases the assumption of all data originating from the same homogeneous data population may be questioned. On some sites, it appears that the most extreme events are due to abnormal cyclone storm tracks leading to unusual weather situations and extreme wind, wave or water level conditions.

When dealing with sites with more than one statistical population of storm waves, it is necessary to separate the analyses into two distributions. A serious problem often arises in this respect, as although there may be sufficient data for the estimate of the distribution for the "normal" waves, the data available for the determination of the parameters of the unusual or abnormal waves will normally be very scarce as shown in the following examples from case studies.

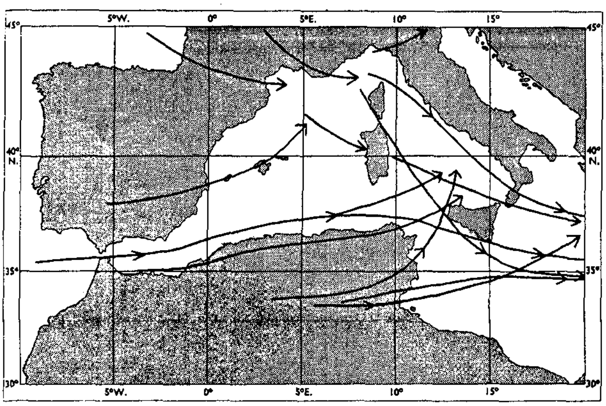


Figure 2. Typical tracks of depressions affecting the Mediterranean.

4. Examples of Abnormal Storm Events

4.1 The Western Part of the Mediterranean (the Coast of Algeria)

The most severe storm situations in the western Mediterranean area are due to Atlantic cyclones entering the Mediterranean after passage of the southern part of France (see Fig. 1 and 2). The cyclones usually follow a track towards ESE passing Italy and propagating further eastwards over Greece and Turkey. For the most severe of this type of cyclones the waves can be relatively high in the western Mediterranean, but due to the relatively fast propagation time of 30-50 km/h the duration of high winds is generally short and hence storms are not fully utilizing the geographical fetch. It appears, however, that the cyclones/depressions causing the largest waves especially on the central and western part of the Algerian coast (see example from the Oran/Arzew area) follow less frequent tracks which are more southerly than the typical patterns described above. Sometimes the cyclones even become stationary as will be seen in some of the following examples.

Based on local information, literature, available measurements and hindcast results from numerical hindcast models, the storms in Table 1 have been found to be among the most severe in the last say 50-60 years. Table 1 shows results of numerical hindcast studies as well.

Table 1. Extreme storms selected for analysis. (Western Mediterranean).

Storm No.	Date/year	Offshore Waves H_s (m) a) Arzew/Oran area	Betw. a&b	b) Alger	Betw. b&c	c) Algeria/Tunesian Border
i	1934,Feb.1-5	4.3		4.8		8.6*
ii	1965,Jan.5-6	5.8**	8.4*	7.2		4.1
iii	1967,Dec.10-12	7.3	7.6	6.6	9.3*	7.2
iv	1969,Nov.30-Dec.2	3.4	5.8	5.3	9.6*	7.8
v	1979,Dec.19-23		Wave height not known			
vi.	1980,Dec.27-29	7.0*				

* Maximum value found by hindcast study.

** Wave measurements near Port of Oran, H_s = 5.5 m.

i. The Feb. 1934 storm caused the failure of Jetêe Mustapha in Port d'Alger, Ref. /9/ & /10/ in Port of Oran displacement of several blocks on the main breakwater, wave direction NNE. (Note highest waves towards east in Algeria). Wave direction observed, NNE.

ii. In Port Oran, about 200 blocks displaced. Wave height measured by LCHF, France, at H_s = 5.5 m.

iii. In Port of Oran, damage to the wave wall in several points and some blocks displaced from the armour layer. Wave direction NNE.

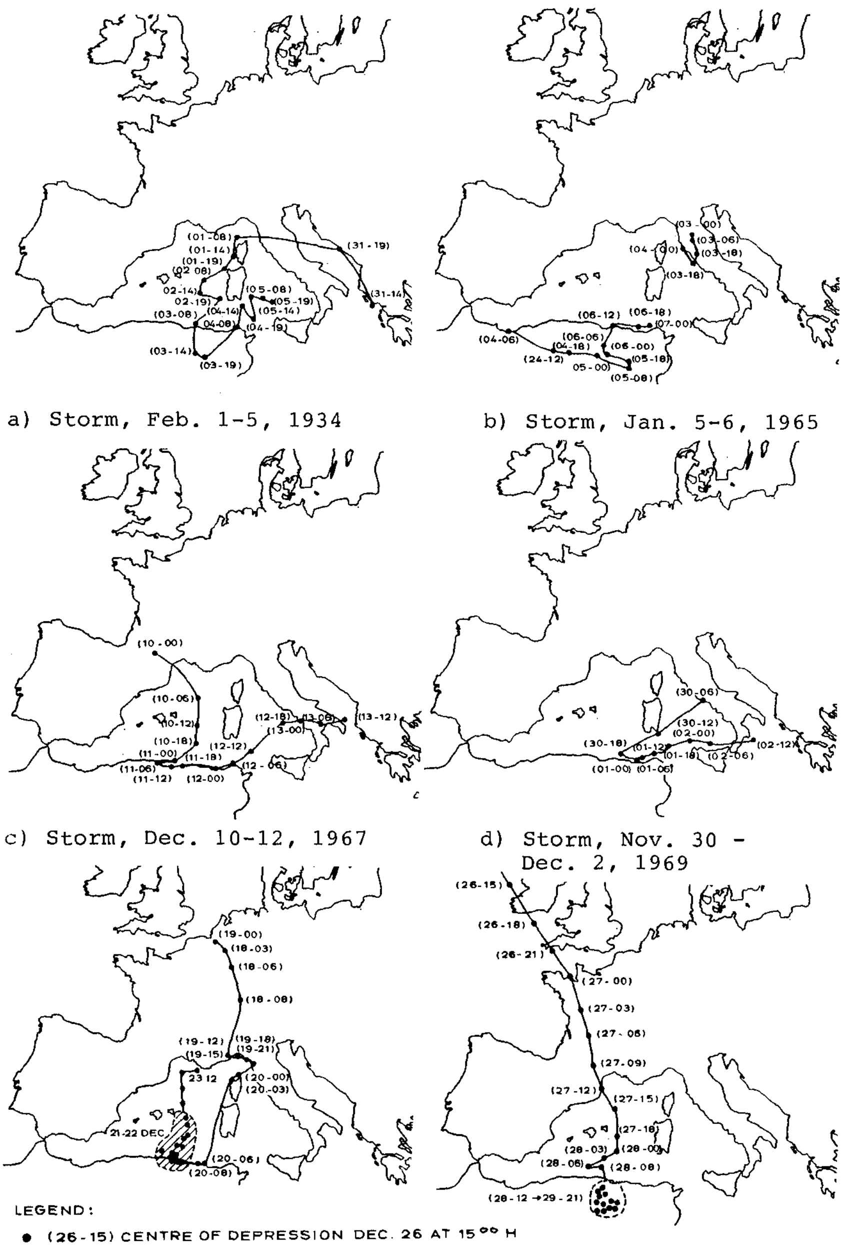
v. Many blocks (in the order of 150) displaced on the main breakwater in Port of Oran, wave direction NNE.

vi. Failure of the new breakwater in Port d'Arzew el Djedid and damage on other ports in Algeria and Morocco. Wave direction at Arzew/Oran, NNE.

The tracks of all these storms have been analysed and the results are shown in Fig. 3. Figs. 4 and 5 show examples of the results of numerical hindcast studies of the 1967 and 1986 storms.

All the storms are caused by depressions with rather unusual tracks. The centres of the depressions arrived in all cases at or very close to the Algerian Coast. The configuration of the wind field being almost circular with the wind blowing anti-clock-wise results in a curved fetch larger than the apparent geographical fetch, see Fig. 4.

It is further interesting to notice that although they all exhibit this common feature, the tracks are all very different. It appears that the tracks of the depressions to a large extent are unpredictable i.e. the atmospheric air flow is highly irregular and once the depressions deviate from their normal track their propagation becomes extremely



a) Storm, Feb. 1-5, 1934

b) Storm, Jan. 5-6, 1965

c) Storm, Dec. 10-12, 1967

d) Storm, Nov. 30 - Dec. 2, 1969

e) Storm, Dec. 19-23, 1979

f) Storm, Dec. 27-29, 1980

Figure 3. Tracks of cyclones for selected storms over the Mediterranean.

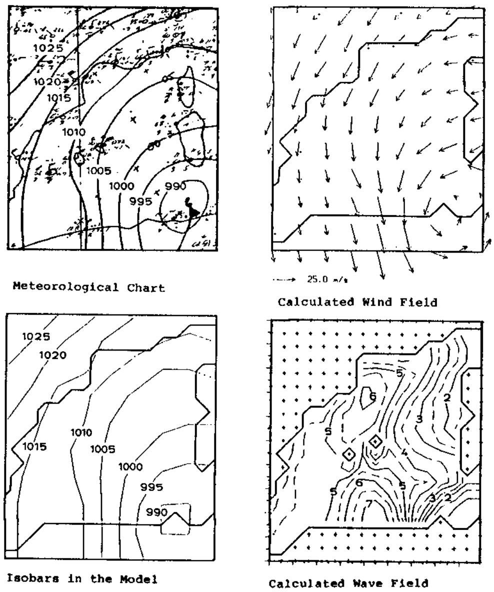


Figure 4. Example of hindcast results of storm on Dec. 10-12, 1967. Situation in the Western Mediterranean on Dec. 12 at 00GMT.

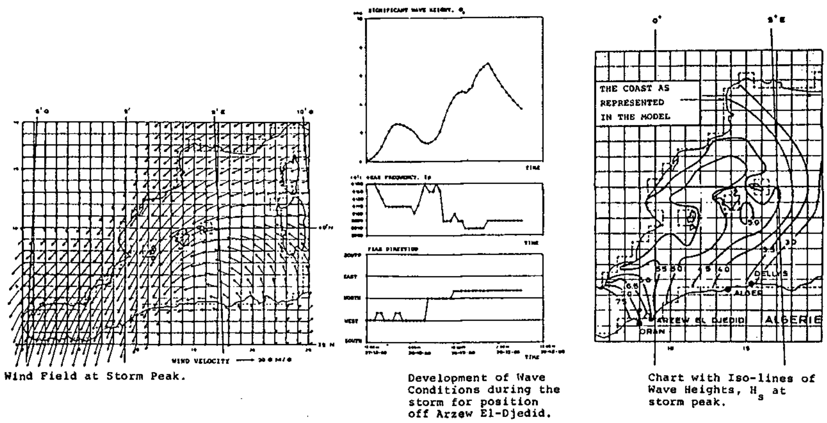


Figure 5. Example of hindcast results of storm on Dec. 27-29, 1980 from Ref. /1/.

complex.

The wave data available from the western part of Algeria show that the storms belong to two populations and further that all the most severe storms occur from NNE and further that they are rather rare. Those storms are associated with the abnormal depressions as seen in Fig. 3.

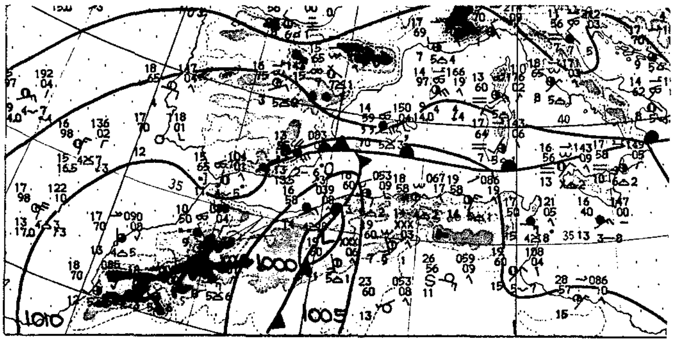


Figure 6. Weather situation May 1, 1976.

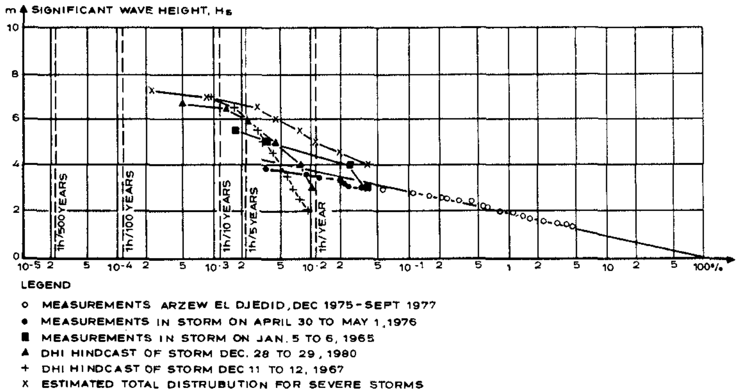


Figure 7. Wave statistics for Arzew El Djedid.

This may be proven by a wave statistics for Arzew El Djedid in the western Algeria. The statistics come partly from wave measurements in the period December 1975 to September 1977 and from the hindcast study shown in Table 1. The most severe storm in the measuring period was due to a low pressure originating from the Gulf of Cadiz (Type B2 in Ref. /8/ propagating straight eastwards through the Strait of Gibraltar (see typical storm tracks in Fig. 2). The situation at the peak of the storm appears on the weather map in Fig. 6. The center of the depression is near the site, but the fetch to the north is disturbed by the presence of a front running west to east. The statistics appears in Fig. 7. Wave measurements were not available in a form allowing for a POT-analysis. The available data were therefore plotted on logaritmic paper.

It is clear from the statistics that the "normal" wave conditions covered by the measurements did not include any severe storms from NNE of the more stationary type shown in Fig. 3. The statistics for these storms lie above the statistics of the normal storms and two distinct populations of storms are identified although the upper one is not well defined. In this case it is seen to be highly risky to base the long term statistics on two years of measurements where only one regime (population) of the storms occurring on that site is included.

4.2 Extreme Waves from SE in the Faroe Islands

The main harbour in the Faroe Islands is Torshavn. This harbour is exposed to waves from SSE and NE. Torshavn is partly sheltered by the island of Nolsoe, see Fig. 8, which shows the position of Torshavn and of the wave recording station, East, mentioned in the following.

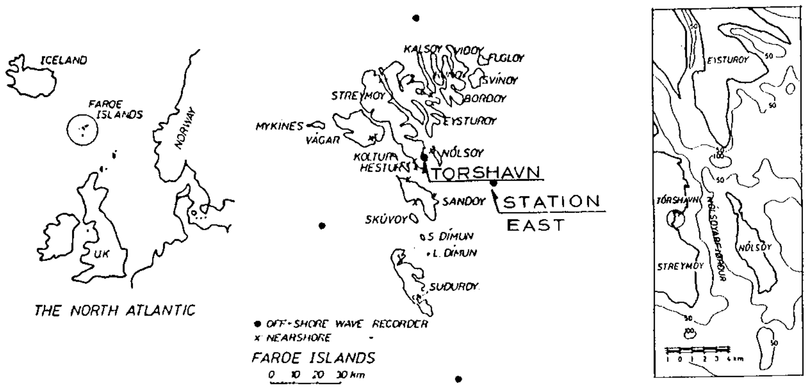
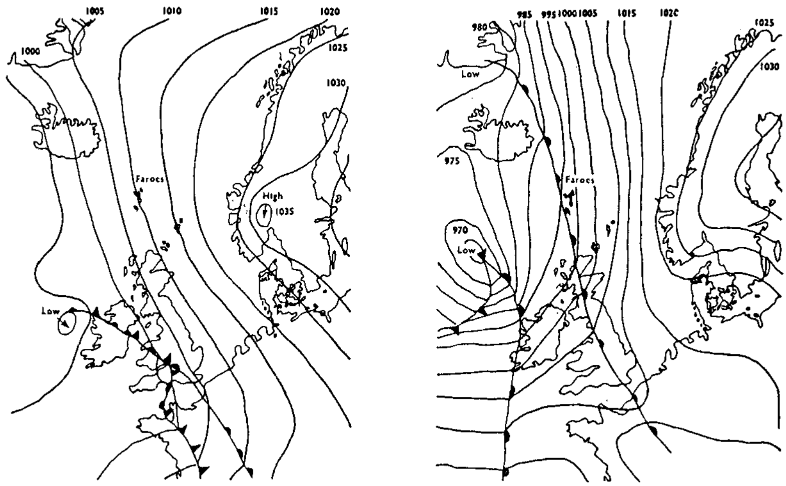


Figure 8. Location of Torshavn.

The design storms occur from SSE and they are associated with the occurrence of unusual depressions, unusual not with respect to the storm track but in the sence that they become stationary. The two most severe storms from SSE since 1930 occurred on Jan. 15-19, 1972, and on Jan. 21-22, 1984. Both storms created very large waves from SSE due to a depression over Ireland that could not move eastwards because of blocking high pressure over Norway. The depression consequently became stationary.

In Figs. 9 & 10 the weather situation for the two storms is described by weather maps.

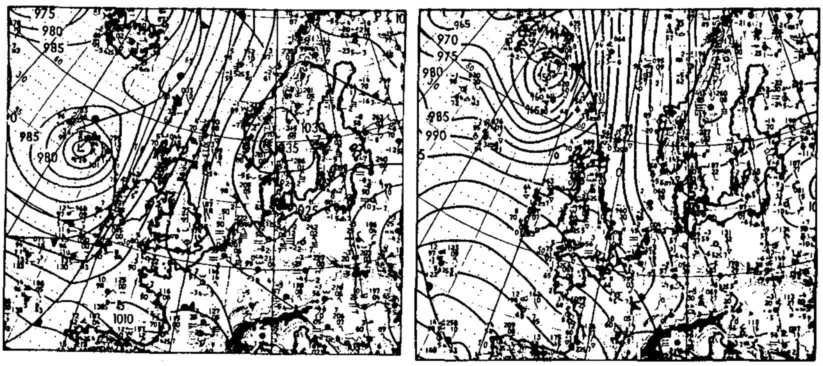
A detailed survey of the weather maps of storms from SSE in the period 1930 to 1972 has revealed that no other storms in this period are as severe. The two storms caused offshore waves in the order of $H_s = 11$ m. In the storm of Jan. 21-22, 1984, the waves were measured at $H_s = 11.3$ m at the peak. A desk hindcast study using the SMB-method has shown that the third and forth most severe storm since 1930 occurred in 1959 ($H_s \sim 9.5$ m) and 1941 ($H_s \sim 9.0$ m). Both storms were of the same type as 1972 and 1984, but with lower wind velocity. In Fig. 11 a POT analysis of measurements from station East is shown for the period Oct. 1980 to April 1987. The threshold level used is $H_s = 5.0$ m.



Weather situation 12.00 GMT, 15 Jan., 1972

Weather situation 12.00 GMT, 18 Jan., 1972

Figure 9. Weather maps of 1972 storm.



21 Jan., 1984, 1200 GMT

22 Jan., 1984, 1200 GMT

Figure 10. Weather maps of 1984 storm.

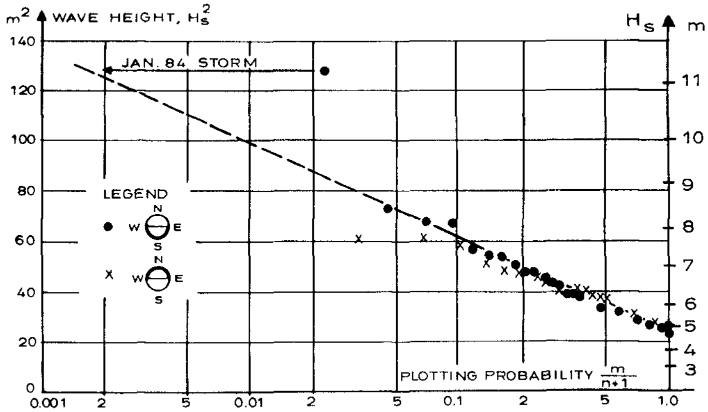


Figure 11. POT analysis of wave measurements. Station East.

It is seen that the data for "northern" and "southern" directions are following the distribution except the storm of January 1984, which falls well above the rest of the distribution. In order to see whether the distribution is actually a double distribution composed of two distributions the available information on the storms has been plotted in Fig. 12 where the abscissa has been changed to show the number of storms per year instead of the probability. The storms in question appear in Table 2. In this presentation the two severe storms of 1972 & 1984 are still above the distribution of measured data while the two storms of 1941 & 1959 are below.

Table 2 Ranking of the four most severe storms.

Ranking m	Storm	H_s (m)	Return Period years $\frac{n+1}{m}$	Probability of Occurrence per year $\frac{m}{n+1}$
1	1984	11.3	59	0.017
2	1972	11.0	29	0.034
3	1959	9.5	19	0.05
4	1941	9.0	14	0.07

It is seen that also in this analysis the wave data indicate two distributions. The analyses were performed under the assumption that the wave climate has not changed in the period 1930 to 1987, while from other sources there are certain indications from the Northern Atlantic and the North Sea that the wind and waves have been more severe in the last 10-15 years.

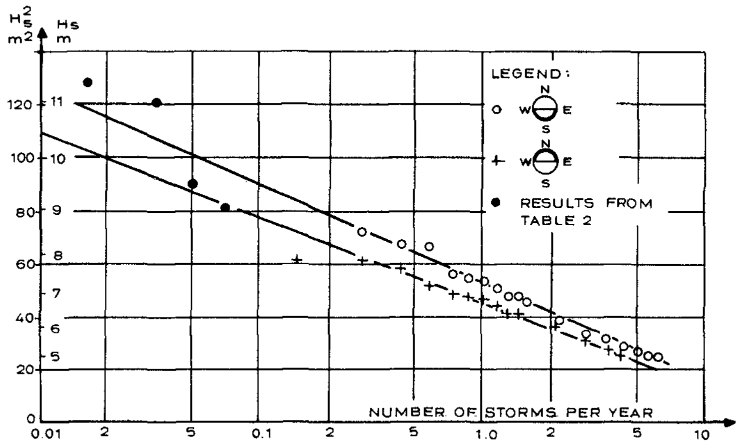


Figure 12. Statistics of number of storms per year.

5. Conclusions

The paper has shown that the occurrence of storms and high waves and water levels at many sites is highly complex and that it can be risky to assume all data belonging to one statistical population.

It is consequently the hope that the paper will encourage meteorologists and coastal engineers to embark on detailed co-operation for improving the understanding of the occurrence of abnormal storm events in order to provide more reliable assessments of extreme design events. The above are only a few examples of sites where mixed distributions occur. It is the author's feeling that on many sites, the same is the case.

The meteorological data bases that are set up these years and the advanced wave hindcast techniques on numerical models now available enable more profound studies to determine more accurate design data for man made marine and maritime structures and for assessing the risk for existing installations. The paper has shown the necessity for such investigations.

6. Acknowledgement

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