** Not Completed*

14. Air-sea energy exchange

Solar radiation

Some energy from the sun is absorbed in the oceans from whence it passes to the atmosphere and finally back to the ocean again as winds drive waves and currents - the air-sea interface is therefore crossed three times by these energy exchanges.

The seasonal variation in heat content of the upper ocean is primarily determined by the net heat flux across the interface between the atmosphere and ocean. Short-wave radiation from the sun is mainly absorbed in the upper 10-20 m of the ocean but this heat is redistributed in the vertical by turbulent mixing brought about by strong winds.

The mechanical energy source for this process is proportional to the third power of the wind speed. Increasing winds cause a rapid cooling and deepening of the oceanic boundary layer as shown in Fig. 14. In the winter, the high frequency of storms causes the mixed layer to be deep, and usually near 100 m whereas, in the summer, the mixed layer is shallow and usually less than 20 m in depth. The change from a summer to winter regime and vice versa takes place in the autumn and spring and at any place can occur quite quickly in the order of a few days.

Ref. Niiler and Kraus 1977

14. Temperature anomalies due to cyclones

Namias (1959 and 1972) and Bjerknes (1966 and 1969) have related anomalous weather patterns to anomalies in sea surface temperature. On the other hand, Ramage (1974), Davis (1976) and Bell (1976) have suggested that temperature anomalies develop more frequently from anomalous atmospheric circulations, rather than the other way round. In this connection, Elsberry and Garwood (1978) have shown how an extended period without storms may result in upper-ocean temperature anomalies that persist for months. The predominance of either anomalously high or low temperatures is related to the thermal structure in the ocean that is established on the transition date between the deep mixed layer of the winter regime and the shallow mixed layer in the summer.

Elsberry and Garwood (1978) suggest that persistent anomalous sea surface temperatures are caused not by anomalous solar radiation but by anomalous redistribution of heat in the vertical. They show that the distribution of heat is governed by oceanic turbulence on two time scales. The first associated with diurnal heating in light wind conditions and the second associated with the time-distribution of storms. During the autumn cooling, when solar heating is decreasing the passage of a storm can cause a sudden deepening of the mixed layer and marked surface cooling as shown in Fig. 14. . In addition to the upper cooling a warming of almost 5°C is shown in a shallow layer near 50 m. This warming is caused by the downwind transport of heat due to turbulent mixing. In strong storms the downward flux of heat at the base of the mixed layer can be 5 to 10 times the value of the upward flux of heat lost to the atmosphere. Both effects cause surface cooling which, from one strong storm, can amount to a significant fraction of the seasonal cooling.

During periods of light winds the diurnal solar heating cycle produces a layer of warmer, less dense water near the surface. This stable stratification inhibits deep turbulence. A critical period occurs during the spring when solar heating is increasing and the frequency of high wind speeds is diminishing. The stratification near the surface then increases and isolates the subsurface ocean layers from the turbulent energy sources near the surface. Thus the strength of the storms at this time, and the duration of weak winds between them, influence strongly the

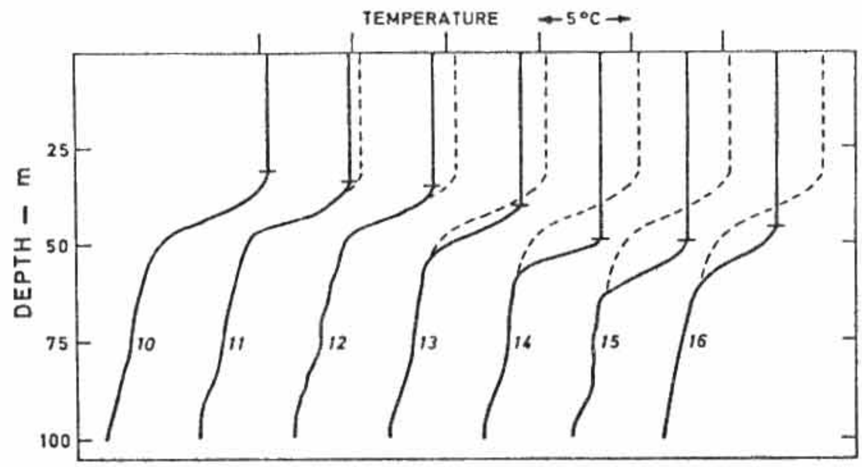


Fig. 14. .1. Ocean temperature profiles (solid lines) at 50°N, 145°W from 10 to 16 October 1954 with the initial profile repeated as a dashed line to indicate the cooling and deepening of the oceanic boundary layer (horizontal ticks) during the passage of a weak and a strong storm. (After Elsberry and Garwood 1978.)

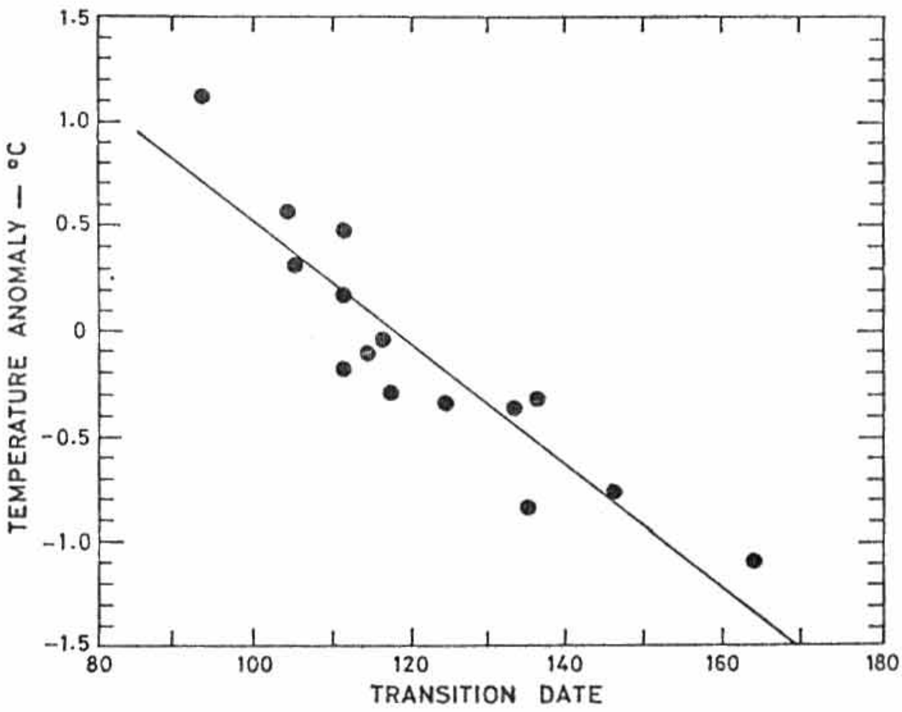


Fig. 14. .2. Relative sea-surface temperature of 50°N, 140°W averaged over March-December as a function of transition date. (After Elsberry and Garwood 1978.)

day on which the ocean thermal structure makes the change from winter to summer regime. Once the transition is made, the shallow surface layer, only 25% or 33% of its previous depth, warms rapidly with the increasing solar heating. An early transition to a summer regime would therefore be expected to be followed by warm temperature anomalies. Using data from Ocean Weather Ship P (50^{o}N 145^{o}W), Elsberry and Garwood (1978) showed that the surface temperature averaged from March to December did indeed depend on the date of transition as is illustrated in Fig. 14. . At this station the median transition date is Julian day 117 (27 April) with a range of ~ 70 days in their 19-year sample. One role of atmospheric storms is to determine the timing of the transition from the deep isothermal layers of winter to the shallow summer time boundary layer. This change, coupled with the diurnal heating cycle, determines the nature of the subsequent anomalies.

14.4 Waves and swell

Most of us have at sometime been fascinated by ocean waves and their rhythmic movements. Some of us have probably tried to confirm that every seventh wave is larger than the others - a long-standing myth. During storms many may have wondered how large would be the greatest possible wave. The most famous reliable report of an extreme wave came from the crew of the USS Ramapo. This Navy tanker, 146 m long, was en route from Manila to San Diego on 7th February 1933 when it met a disturbance in which the pressure fell to 992 mbar and the wind rose from 15 to 30 m/s over several days. The ship was running with a high sea when the top of an approaching wave was seen to be level with the horizon and the crow's nest. From the geometry of the situation it was possible to calculate that the wave was 34 m high (trough to crest) and its period was timed at 14.8 seconds. Arakawa and Suda (1953) gave an interesting account of the seas encountered by a Japanese Fleet which steamed through a typhoon on 26th September 1935. One ship reported wave heights of 25 m and another reported waves up to 30 m but this report was discounted. Arakawa and Suda reported that wave heights above 20 m were extremely rare. The life of these extreme waves is transitory being not much more than a minute or two. They owe their height to the addition of a number of component waves each travelling at slightly different but constant speeds which, by chance, all arrive at the same place in step; the component waves separate as they continue on their journey, and the wave subsides.

The British Ocean Weather Ship "Weather Reporter" was instrumented to measure wave heights at its station in the North Atlantic. The original instrument could record waves up to 15 m in height but this limit was soon found to be inadequate and was extended to 18 m. On the 12th September 1961 the ship lay close to the track of the dying hurricane Betsy when the recording pen hit the stops in a giant wave. By drawing a crest on the wave trace it was found to have had a height of at least 20 m. The ship had risen 20 m in 7½ seconds and dropped a similar distance in the next 7½ seconds. Draper (1965) considered that because the instrument was only operated for 8% of the time the highest wave at that station was probably about 24 m. The 20 m wave was the highest instrumentally recorded wave until the centre of hurricane Camille 1969 passed within 23 km of an offshore oil platform standing in 104 m of water in the Gulf of Mexico. The central pressure of the hurricane was 901.8 mb and it was moving north at 6.6 m/s. The highest wave on the recorder was 23.6 m and its period was 12.5 s (Earle 1975). It is clear from the foregoing that the highest waves produced by tropical cyclones are amongst the highest encountered on the oceans and are of prime importance to mariners and engineers.

Mention should be made of the so called "freak" waves although the frequency of reports received during the last decade has prompted the use of the term "episodic" wave, because an episode is a recurring event. Episodic waves are defined as waves of very considerable height ahead of which there is a deep trough. Thus it is the unusual steepness of the wave which is the outstanding feature dangerous to shipping. Ship tend to drop into the trough and, at best, loose their bows. The area off the southeast coast of Africa between Cape St. Lucia and Port Elizabeth favours the formation of episodic waves. The strong Agulhas current there flows south-west over the 100 fathom line with an average speed as high as 2 m/s in places. The extreme waves occur when gale-force south-westerlies blow against the current ~~and~~ in the presence of a long swell from the southwest. Gales also blow against strong currents over the Gulf Stream off the east coast of America and over the Kuroshio current off the east coast of Taiwan but episodic waves are much less frequent in these areas. It is probable that some other feature such as sea bed topography or wind sequence enhances their formation over the Agulhas current.

The detailed mathematical description of ocean waves and sea state is a rather complicated subject that came of age in the late nineteen fifties, ~~1950s~~, it will not be pursued here. The reader requiring more complete information will find it in the papers to which reference is made. However, it is ~~if~~ fortunate that a simplified theory which omits many of the complicating factors is adequate for many practical applications including the description of some of the more important aspects of tropical cyclone waves.

14.4.1 Definitions and relationships

Ocean waves are primarily generated by the wind blowing over the water although earthquakes under the sea-bed can also give rise to long waves known as "tsunamis". Oscillatory waves are described by their height, length and period. Wave height is the vertical distance from the top of the crest to the bottom of the trough. Wavelength is the horizontal distance between successive crests whilst the wave period is the time between successive crests passing a given point. The wave frequency is the inverse of period i.e. the number of crests passing a given point in one second. As sea waves advance in deep water, only their shape and part of their energy move forward; the water particles themselves do not advance with the waves. The motion of the water particles is confined to whatever current is flowing and to movement around a vertical circular path as they are displaced by successive waves. Particles below the surface also describe circular orbits but the diameter of the orbits decreases exponentially with depth. For practical purposes the motion of water due to surface waves is confined to a layer of depth equal to about one half a wave length. In water less deep than this the particle orbits are flattened and become elliptical.

The distance over which the wind maintains an approximately constant speed and direction while generating waves is known as the "fetch". In the open sea the height, length and period of the formed waves depends on the fetch, wind speed and the time during which it blows (Fig.14.1). Waves in the generating area that is, those still being driven by the generating wind, are steep and have wavelengths of 10 to 20 times the wave height; such waves are called "seas". A sea is a mixture of all wavelengths up to a maximum that depends on the greatest wind speed in the generating area. The sea in the storm area therefore has a relatively confused appearance as the many different waves reinforce or cancel one another as they progress at different speeds. In general, the fastest moving waves i.e. those with the longest wavelength, advance at a speed slightly less than that of the wind which generates them. If typhoon winds apply more force than a wave can accept it steepens until its crest becomes a wedge of less than 120° at which time, the "steepness" of the wave i.e. the ratio of height to wavelength, will reach the critical value of one-seventh (0.14) and the crest will be blown off by the wind to form a breaking wave at sea. Mariners have many times described how, near the

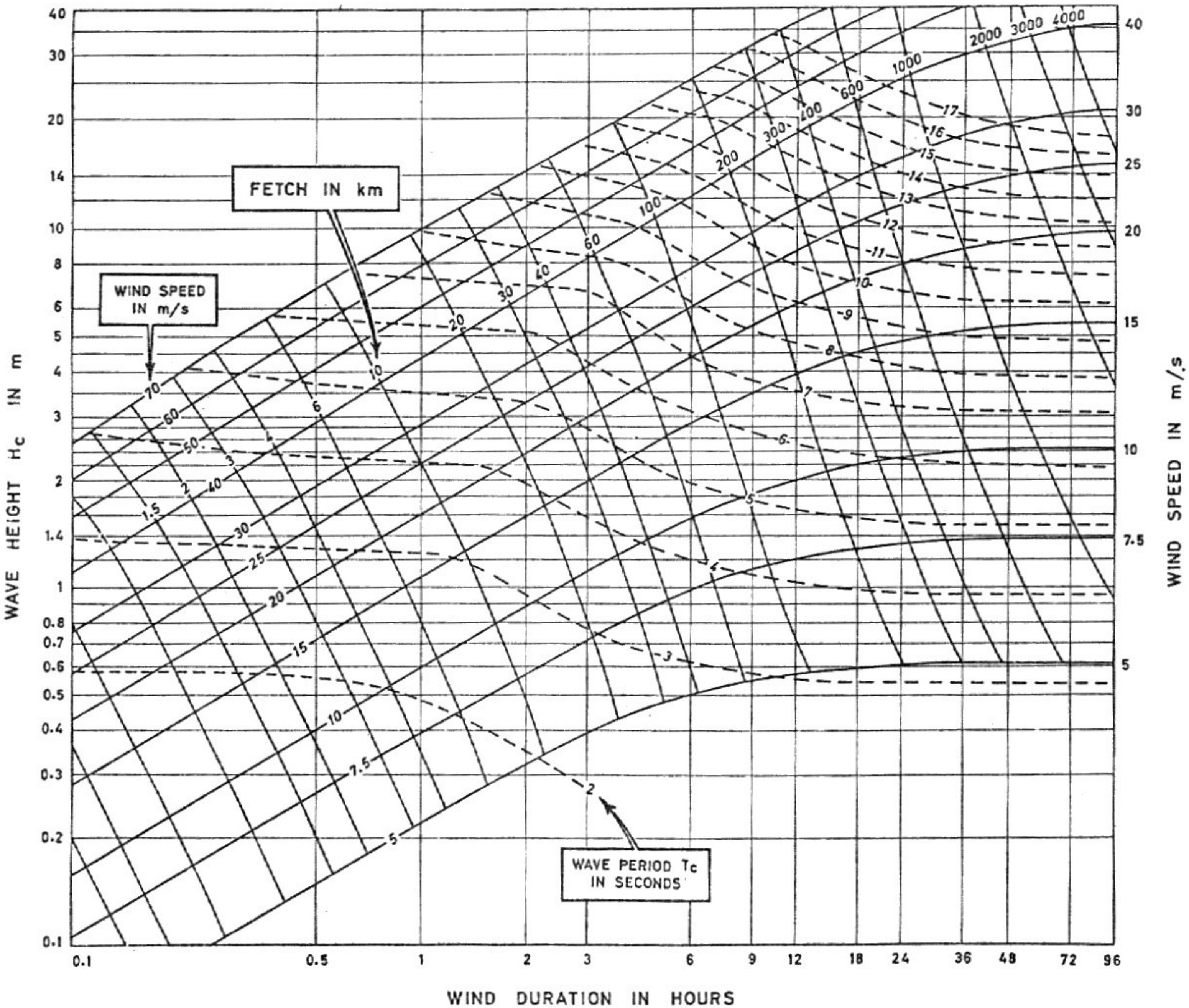


Fig. 14.1 Deep water wave forecasting chart. Enter on the left of the appropriate wind speed curve move to the right to the intersection with the appropriate fetch or duration line, whichever comes first, and read off forecast characteristic wave height Hc (or Hs see text) and period Tc. These curves were obtained in the Joint North Sea Wave Project (See Hasselman et al 1973) and have been extrapolated to wind speeds above 30 m/s.

? No figure is shown here.

centre of a typhoon, the tops of waves are blown off by the fierce winds as shown in Fig.' . The abundance of spray and foam together with the torrential rain, often blurs the demarcation between sea and air. A long wave can accept more energy from the wind and so rises higher than those of shorter wavelength. The waves which grow most rapidly are those having a component of the wind speed in the direction of wave motion equal to the speed of wavc propagation.

When waves move out of the area where they are being forced by the wind they become free moving waves known as "swell". These waves are relatively well defined and "long crested" i.e. they are extensive across the direction of propagation, and they have a distinct rhythmic rise and fall. The distance over which swell travels after leaving the generating area is known as the "decay distance" and may amount to several thousand kilometres. During this period the waves become lower and their crests more rounded and they assume a more symmetrical shape with lengths 30 to more than 500 times their height. Besides losing height, swell tends to increase both in length and period as it progresses. This is caused by the phenomena known as "dispersion" in which the long period waves travel faster than those of shorter wavelength. Consequently, the first swell to arrive at a distant point are those of greatest length and period. Fig. 14.2 shows how the period and height of swell changes with distance of travel.

There are several kinds of surface water wave and their classification, together with the relevant primary disturbing and restoring forces, are illustrated in Fig. 14.3. Also shown is the relative amount of energy found in ocean waves having a particular frequency. Most energy is seen to occur in gravity waves having periods between 1 and 30 seconds. Much of the energy of typhoon winds is used to produce such waves particularly those with periods around 10 seconds (Fig. 14.1).

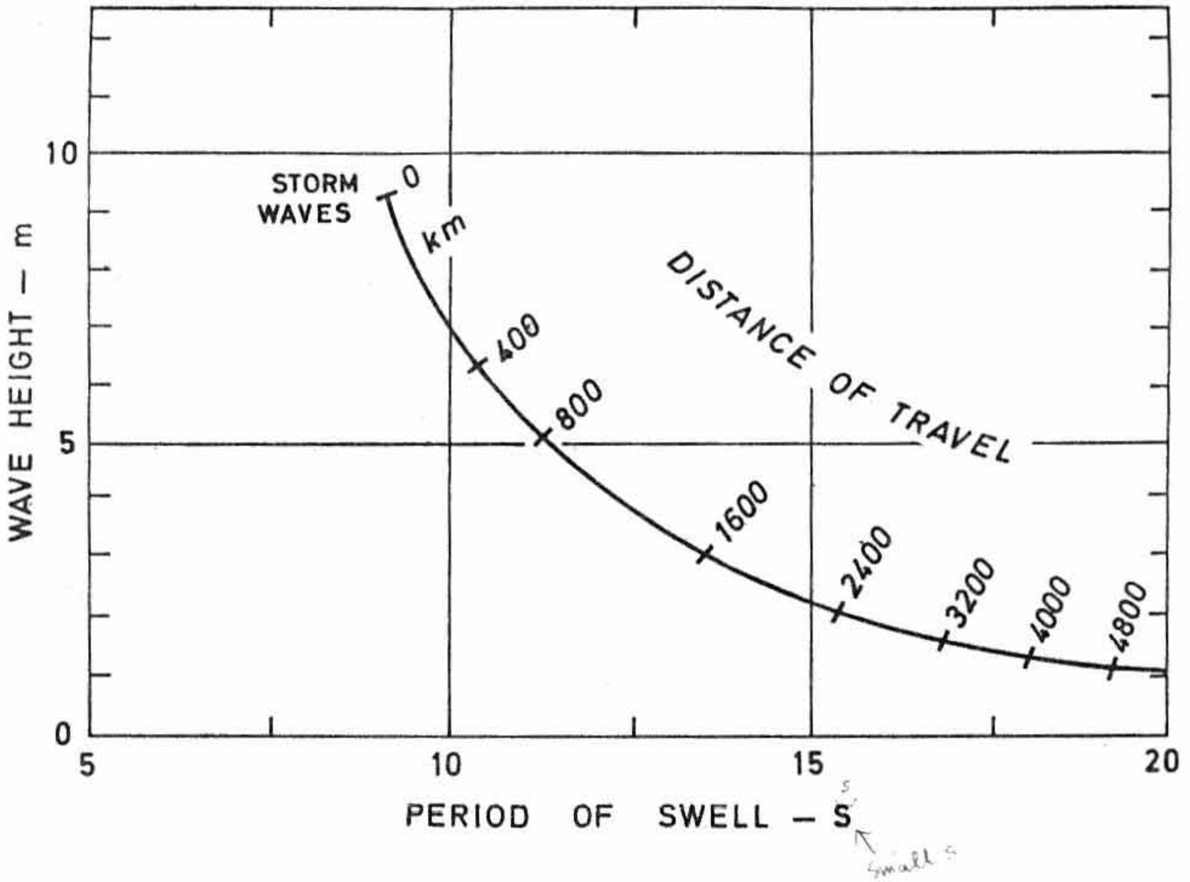


Fig. 14.2 . Height of swell diminishes while period increases with increasing distance of travel from a storm area. (After Sverdrup and Munk 1947).

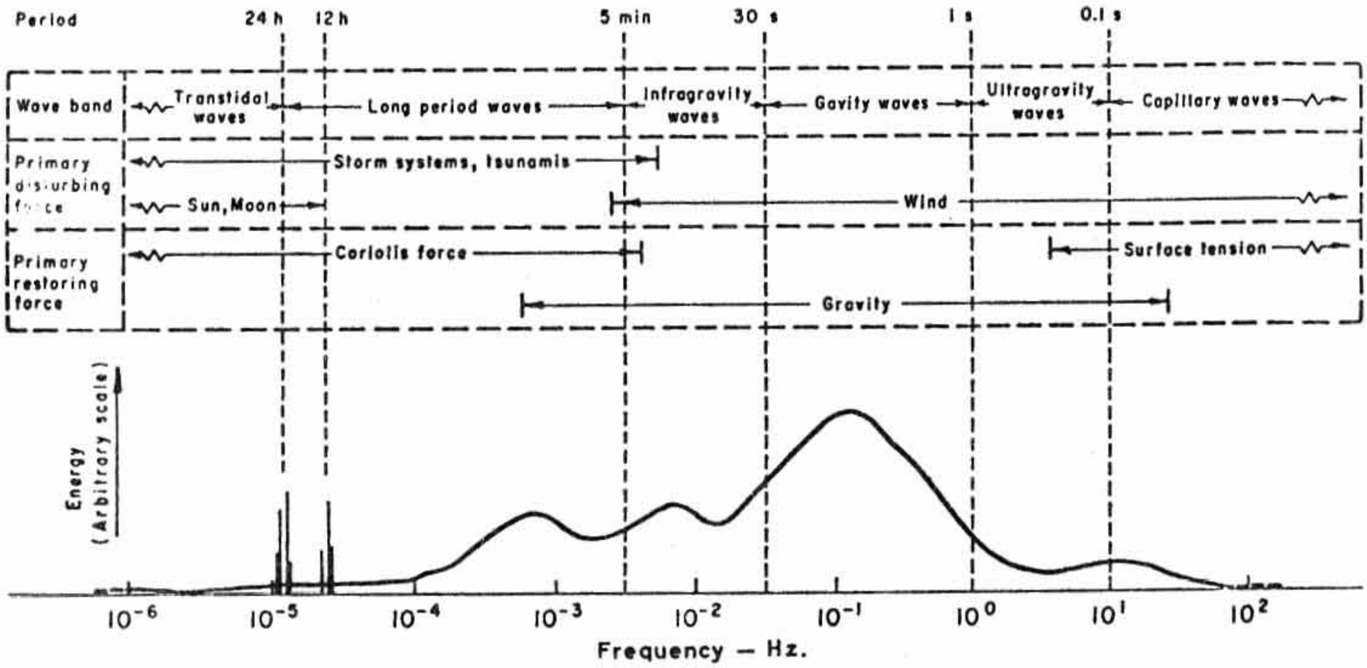


Fig. 14.3 . Approximate distribution of ocean surface wave energy illustrating the classification of surface waves by wave band, primary disturbing force and primary restoring force. (After Kinsman 1965).

The speed at which a wave form propagates is called its phase speed or wave celerity C and ~~it~~ is related to ~~its~~ wavelength L and period T such that

$$C = L/T \qquad (14.1)$$

Small amplitude gravity waves can be shown to propagate in water of depth d at a speed C given by

$$C = gT/2\pi \,.\, \tanh\,(2\pi d/L) \qquad (14.2)$$

where g is the acceleration due to gravity ($9.8\ m/s^2$). Gravity waves may be classified into three groups 1) deep water waves in which the ratio d/L is greater than 1/2; 2) shallow water waves in which the ratio d/L is less than 1/25 and 3) transitional waves in which d/L lies in the range 1/25 to 1/2. Equation (14.2) can be simplified for both deep water and shallow water waves, as defined, because $\tanh\,(2\pi\, d/L)$ will then be approximately equal to one and $2\pi\, d/L$ respectively. The deep water wave speed C_o will then be given by

$$C_o = gT/2\pi = L_o/T \qquad (14.3)$$

where L_o is the wavelength. No suffix is required on T because, for oscillating waves, the period remains constant and independent of the water depth.

From equations 14.1 and 14.3 it is possible to express C_o, L_o and T in terms of each other. This has been done in Table 14.1. ~~and on the right of the table the equations are expressed for use with metres and seconds.~~

Table 14.1 Read down to express the quantity in the top row in terms of the quantity in the left hand column. Use metres and seconds.

	L_o	C_o	T	L_o	C_o	T
L_o	L_o	$(gL_o/2\pi)^{1/2}$	$(2\pi L_o/g)^{1/2}$	L_o	$1.25\ L_o^{1/2}$	$0.80\ L_o^{1/2}$
C_o	$2\pi C_o^2/g$	C_o	$2\pi C_o/g$	$0.64\ C_o^2$	C_o	$0.64\ C_o$
T	$gT^2/2\pi$	$gT/2\pi$	T	$1.56\ T^2$	$1.56\ T$	T

From this table, for example, it is seen that

$$C_o = 1.25\ L_o^{1/2} \quad \text{or} \quad 1.56\ T \qquad (14.4)$$

Table 14.1 Read down to express the quantity in the top row in terms of the quantity in the rows below. (Unit: metre and second)

L_0	C_0	T
L_0	$(gL_0/2\pi)^{\frac{1}{2}} = 1.25 L_0^{\frac{1}{2}}$	$(2\pi L_0/g)^{\frac{1}{2}} = 0.80 L_0^{\frac{1}{2}}$
$2\pi C_0^2/g = 0.64 C_0^2$	C_0	$2\pi C_0/g = 0.64 C_0$
$gT^2/2\pi = 1.56 T^2$	$gT/2\pi = 1.56 T$	T

Going back to eqn (14.2) and using the shallow water ($d/L < 1/25$) approximation the shallow water speed is

$$C = \sqrt{gd} = 3.13\sqrt{d} \qquad (14.5)$$

and is seen to depend only on the depth of the water. Tsunamis have a wavelength long compared to the depth of even the Pacific ocean so that over the deeper parts of the ocean where d may be 5 km the speed of propagation will be about 220 m/s.

Swell waves consist of a train of waves which can be considered as a moving "wave group". It is observed that the leading wave of a group weakens and disappears whereas new waves appear at the rear of the group. This is readily observed in the case of a bow wave caused by a ship. The term "group speed" is applied to the rate of motion of the wave group as a whole and according to the theory of gravity waves in deep water this speed is one half of the phase or wave speed. The group speed is important because it is the speed with which energy is propagated and, of course, it will determine the time of arrival of swell at a location from a distant typhoon. In shallow water the group and phase velocities are equal. The swell received on a shore will be remote descendants of the waves which left the storm.

The total energy of a wave system is the sum of its kinetic energy (due to the water particle velocities) and its potential energy (due to part of the fluid mass being above the trough). If the potential energy is determined relative to mean water level and the waves are all propagating in the same direction then the kinetic energy is equal to the potential energy and their sum in one wavelength per unit crest width is given by

$$\mathcal{E}' = \rho g H^2 L/8 \qquad (14.6)$$

where ρ is the density of the water and H is the wave height from trough to crest. The total average wave energy per unit surface area is called the energy density and is given by

$$\mathcal{E} = \mathcal{E}'/L = \rho g H^2/8 \qquad (14.7)$$

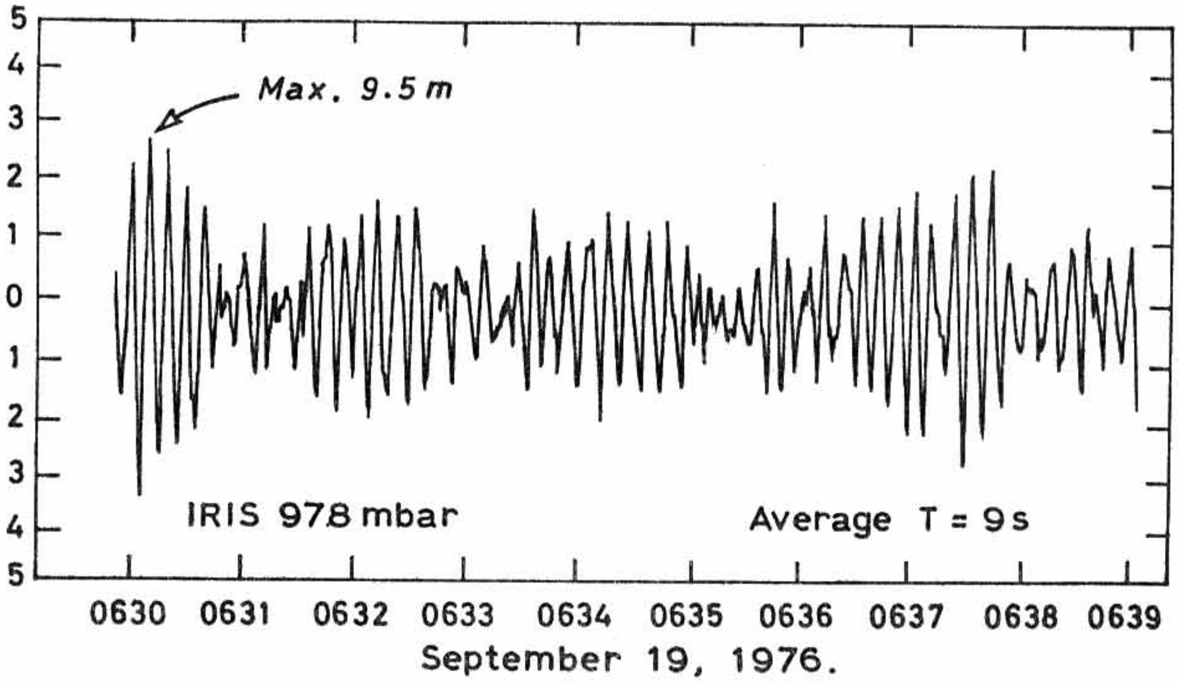
It is thus seen that the total energy beneath unit area of a sea wave depends mainly on its height. Large waves have large energy which has been derived from the wind. Some additional wind energy is also absorbed in water turbulence and white caps.

As an oscillatory wave moves into shoaling water only the period remains constant, the wave height becomes ~~progressively~~ greater; the crests become shorter and more pointed and the trough becomes longer and flatter. Eventually the wave will attain the critical steepness (0.14) and break; this happens when the wave reaches a still water depth of about 1.28 times the wave height. The actual value depends on the beach slope and wave period. The ratio of breaker height (H_b) to deep water wave height (H_o) is given approximately by

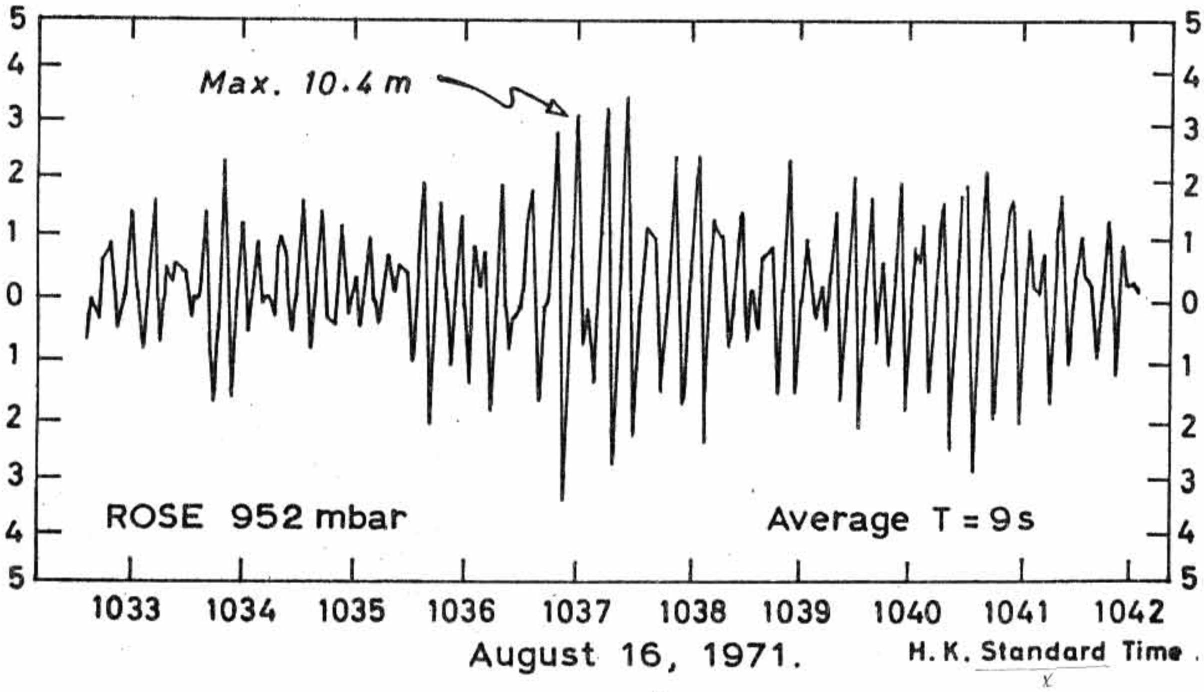
$$H_b/H_o = 0.3\ (L_o/H_o)^{1/3} \qquad (14.8)$$

and is seen to be greater for long, low swell. However, in practice, the ratio seldom exceeds two. As depth decreases beyond L/2 the wave speed and length also decrease and there is, at first, a slight fall in wave height. The original height is regained when d/L is approximately equal to 0.06 after which the height grows again until breaking depth is reached.

The foregoing simple description of waves was confined to idealised cases in which the waves were small and monochromatic that is, of only one period. In practice, the wind generates waves with a wide spectrum of periods and wave lengths and their directions of motion may also differ. The state of the sea then becomes confused as these various wave trains interfere with each other. This is illustrated by the wave records in Fig. 14.4 ~~which~~ were obtained in 28 m of water near Waglan Island, just south of Hong Kong, during the approach of typhoons. Nevertheless, a dominant wave train is usually apparent to an observer. The concept of a "significant wave height" (H_s) was introduced by Munk (1944) to represent the characteristics of the real sea in the form of waves of one period. He defined the significant height as the average of the one-third highest waves and stated that it was about equal to the average height of the waves as estimated by an experienced observer. This latter wave height is sometimes called the "characteristic height" (H_c) when it is necessary to differentiate



(b)



(a)

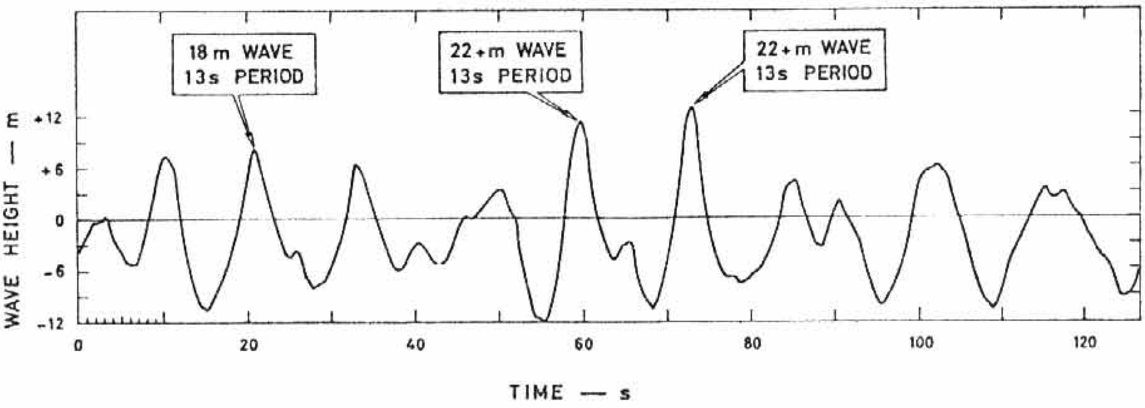
Fig. 14.4 . Records of wave heights and periods off Waglan Island when (a) typhoon Rose was centred 185 km to the south and (b) typhoon Iris was centred 185 km to the SW. Indicated wave heights have to be corrected for attenuation in the water above the gauge and for the frequency response of the instrument which detects waves with periods between 4 and 25 seconds. Corrected heights of the largest wave in each recording are shown.

between it and a measured significant height ($\overline{H}_{1/3}$). Apps and Chen (1973) compared instrumental determination of wave heights in typhoons at Hong Kong with visual estimates. They found that, in the cases studied, the visual reports were indeed close to the significant wave height as defined, notwithstanding the fact that there are sometimes more than one wave train present.

The characteristic wave period observed visually (T_c) is not well related to the average period ($\overline{T}$) of the waves. An average of the periods of the waves used to determine $H_{1/3}$ can be formed although it does not exist in nature. This average ($\overline{T}_{1/3}$) is often called the significant period (T_s) although the name is not altogether a happy one. In hurricane Camille 1969 T_s, as defined, was on average equal to 1.24 $\overline{T}$ (see Fig. 14.7) with a standard deviation of 0.04. A somewhat lower ratio close to unity is found in Hong Kong typhoons.

Tsunamis and other waves resulting from large displacements of water, such as might occur in some landslides, approximate to the form of a "solitary wave" in which the wave form is predominantly above the still water level. A true solitary wave is difficult to form in nature because smaller dispersive waves are generated at the trailing edge of the wave. Laboratory measurements indicate that the speed of propagation of a solitary wave is given by the formula

$$C = \sqrt{g\,(H + d)} \qquad (14.9)$$



This figure was not mentioned in the text originally, a few words are added on P.7 at present.

Fig. 14.4 (c). Wave heights in hurricane Camille at about 1600 h on 17th August 1969 as measured by a variable inductance staff gauge on an oil rig in 104 m of water in the Gulf of Mexico. The pressure on the rig at the time was 951.6 mbar and the mean wind speed was 30 m/s equivalent to 24 m/s at the 10 m level. Gusts of 53 m/s were being experienced. (After Patterson 1971).

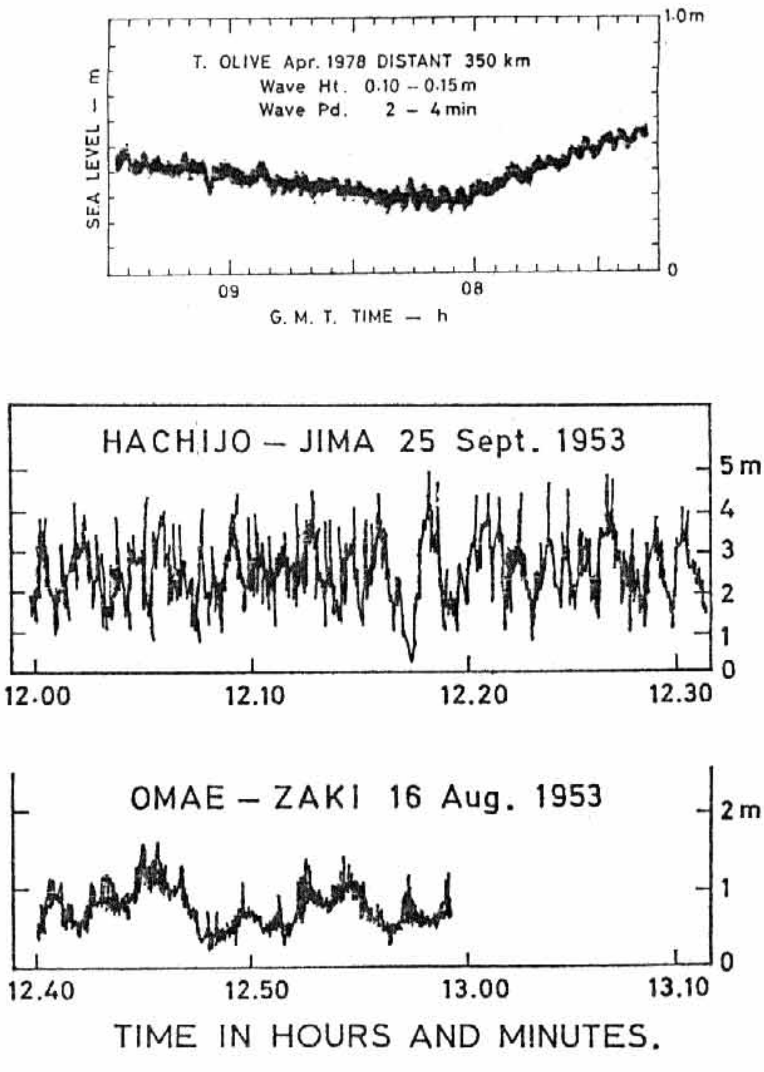


Fig. 14.5 Examples of long swell with periods of a few minutes produced by typhoons. The upper record is from the tide gauge in Hong Kong harbour on 24 April 1978. The lower two are redrawn from Unoki and Isozaki 1966.

14.4.2 Typhoon waves and swell

.1 Waves on the coast

One of the early precursory signs of a typhoon is often the slow heaving of water in harbours and the foaming around islands or cliffs due to a very long, low swell. The period of these waves can be as long as one or ~~two~~ more minutes and they are sometimes known as "forerunners". They often arrive during the fine weather and light wind conditions which frequently precede the storm. It was the arrival of this long low swell which used to send coastal fishermen scurrying for shelter. The forerunners, travelling fast, often arrive some time before meteorologists consider it necessary to hoist signals to warn the approach of a typhoon.

Instrumental recordings of these long waves are shown in Fig. 14.5. Over deep water they have small heights and are not easily noticed by observers on ships but, the wave heights increase in shallow water near the shore. Although it is probable that these waves are somehow generated by extreme winds near the typhoon centre the exact mechanism is not known. Pierson (1955) shows that in a fully developed sea there is, theoretically, no appreciable amount of energy associated with waves having group velocities greater than or equal to the windspeed. In a typhoon with 70 m/s winds a maximum period of about 45 seconds would be indicated but, in practice the period will be less because the sea is not fully developed. Additionally, Pierson shows that the greatest energy is associated with waves having a phase speed of 1.22 times the wind speed and that the energy of waves faster than this drops off rapidly. Because a fully arisen sea is not achieved in a typhoon, waves with greatest energy have periods around 12 seconds and a speed of the order of 20 m/s or only 0.3 times the wind speed. The current theory of wind generated waves does not therefore adequately account for the long period forerunners. Bascom (1959) reported that the longest swell period observed was 22.5 s but subsequently the British Ocean Weather Ship "Weather Reporter" recorded a swell with a period of 36 s in the dying hurricane Betsy during 12-15 September 1961 (Chakrabarti 1976). This swell may have originated in hurricane Debbie about 3 000 km to the southwest.

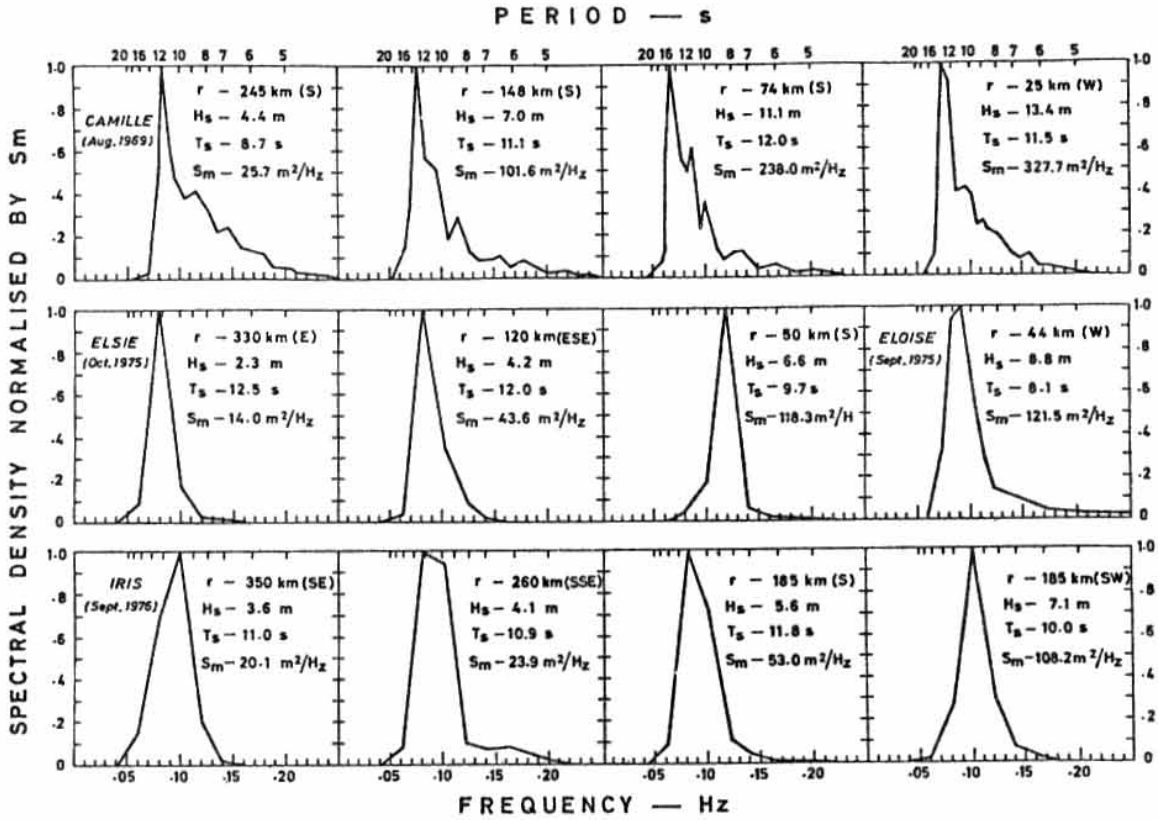


Fig. 14.6 Spectra from hurricanes Camille and Eloise and typhoons Elsie and Iris. The distance (r) together with direction of each cyclone from the recording station (see text) is indicated along with the height of the significant waves (H_s), their period (T_s) and the peak spectral density (S_m) at the frequency peak. Spectral densities at other frequencies can be obtained by multiplying the ordinate by S_m.

generated by the maximum winds to the right of the centre

All the waves generated by the wind near the centre of a typhoon propagate ~~radially~~ outwards. The longer ones may travel fast enough (see Table 14.2) to move out of the gale area (ahead of the storm) and arrive at a shore, as a long low swell, many hours before the strong winds and gales.

Table 14.2 Characteristics of deep sea waves

Period s	Wave length m	Wave speed m/s	Group speed m/s
20	624	31.2	15.6
15	351	23.4	11.7
10	156	15.6	7.8
8	100	12.4	6.2

This long swell arrives quite suddenly and usually has a period in the range 15 to 20 seconds. As time goes by the swell is reinforced by others with shorter period and greater height that have taken a longer time to travel and the periods of the significant waves then decrease to 10-15 seconds and their height increases greatly. This increase in height and decrease in period of the significant swell is well illustrated by the spectra (a spectrum shows the energy of waves of different frequency) for typhoon Elsie in Fig. 14.6. As the swell moves on shore, it increases in height and breaks to pound on the beach with a noise which can sometimes be heard several kilometres inland. The fairly regular boom, arriving during the otherwise quiet conditions of fine weather and light winds, is ominous. Many accounts of historical t-c-s around the world start with reference to the initial fine weather and the noise of pounding of the surf. For example, the Annual Report of the Royal Alfred Observatory for 1892 carries a description of the severe cyclone of April 29th that year which took a toll of 1100 lives; it states that "During the night of the 26th and the morning of the 27th, the sea was making some noise on the reefs at northwards, ...".

While not referring specifically to forerunners, Gherzi (1936) proposed that typhoon swell was generated by "pumping" or vertical pulsations of the air column over the central regions of a typhoon. Bascom (1959) has suggested that such pulsations might be the cause of forerunners. However, any such oscillations of atmospheric pressure would have to have an amplitude of several millibars and although variations of pressure are found near the centre of typhoons (sect.   ) oscillations of the kind believed to be needed to generate forerunners have not been observed. Munk (1949) showed that waves with very long periods are caused by variations in the shoreward transport of water by breaking surf with irregular height. However, the long waves ahead of typhoons are most noticeable when the sea surface offshore is relatively quiet. Yoshida (1950) showed theoretically that variations of water level with periods of a few minutes could be caused on the open sea by non-linear interaction between short waves. Because of their long period, forerunners propagate at high speeds around 70 m/s and arrive at a coast long before the normal typhoon swell and seas. Forerunners are not detected ahead of all typhoons.

Waves with an even longer period than forerunners are sometimes produced by tropical cyclones. They are called "edge waves" and have periods from several minutes to several hours. They are discussed in sect.   .

It is appropriate to note here that the direction from which the swell arrives has many times been shown to be NOT a reliable indicator of the current bearing of a typhoon. Neither does the amplitude of the swell give reliable indication of the distance to the storm. The rate of change of swell frequency at a coast can give an indication of the distance to a typhoon by using the relationship

$$\text{Distance} = 4.9/\text{rate of change of frequency} \qquad (14.10)$$

However, even this method can be greatly in error. A distant storm produces a long crested swell as opposed to the short crested more confused swell from closer storms. A long period swell indicates that the storm is intense unless there are strong intervening winds as may happen during the northeast monsoon (Sect.). Finally, if a tropical storm or typhoon moves as fast as its longest waves none of them will propagate ahead of the storm to give warning of its approach. This condition usually occurs when the storm speed is more than about two-thirds of that of its maximum significant waves.

As a typhoon moves closer to a station on the coast a more confused, short-crested sea arrives and at this time, on the periphery of a typhoon, the period of the significant waves will decrease to a minimum of about 8 s, or 6-7 s in the case of a tropical storm. The continued approach of the tropical cyclone results in the further increase in height of the significant waves but their period begins to rise again as winds at the station increase. The significant waves obtain maxima in height and period in the ring of hurricane force winds around the eye as illustrated in the Eloise case of Fig. 14.7. The period of the significant waves increases because the tops are blown off short-period waves at high wind speeds and relatively more wind energy goes towards increasing the height of the longer period waves. The spectrum becomes more peaked with most of the energy in a relatively narrow band of long period waves as shown for hurricane Camille in Fig. 14.6 (Earle et al 1974). At the height of the storm the period of the significant waves is usually found between 10 and 13 s which is less than the 15-18 s periods associated with deep extratropical cyclones.

The spectra shown in Fig. 14.6 for typhoon Elsie 1975 were obtained from recordings made in 28 m of water off Waglan Island to the south of Hong Kong. The spectra for hurricane Camille 1969 were obtained from a recorder on an oil drilling platform standing in 104 m of water in the Gulf of Mexico. In 1975 hurricane Eloise passed over a meteorological buoy (sect.) anchored in 2.4 km of water in the Caribbean. A time series of the wave

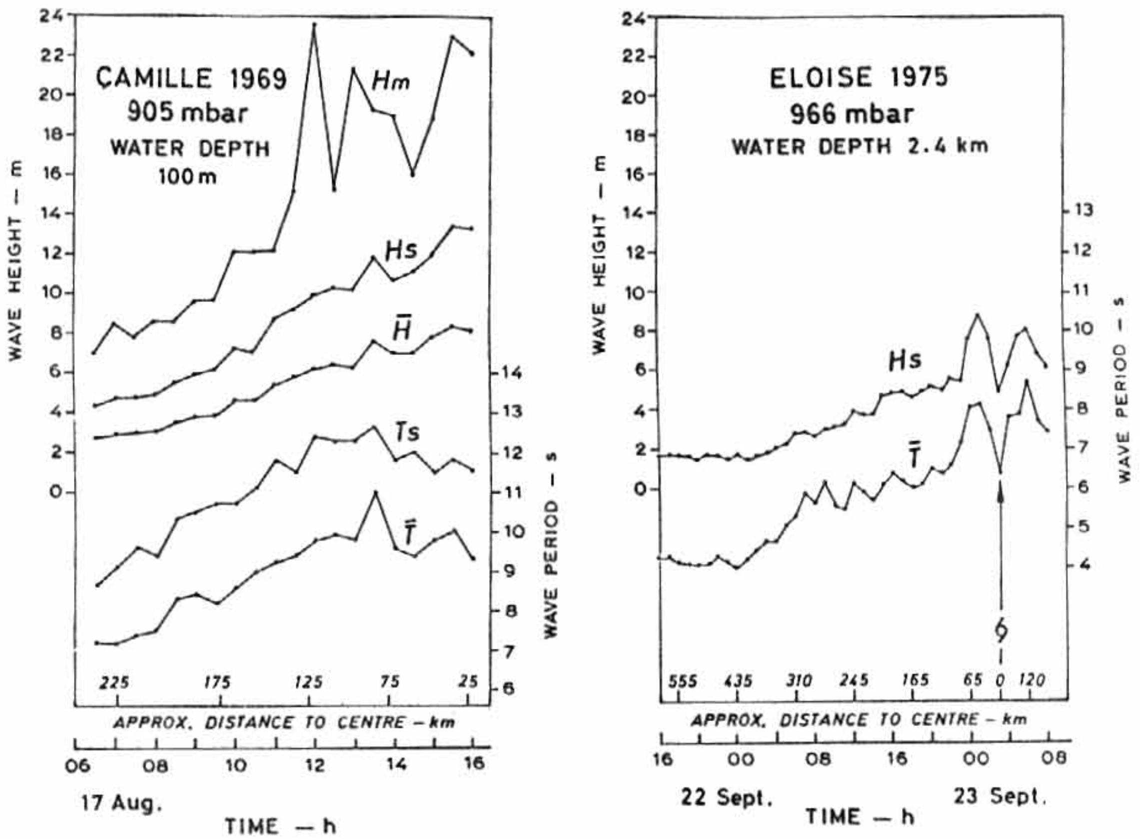


Fig. 14.7. Heights and periods of waves recorded during the approach of hurricanes Camille and Eloise to an oil rig and instrumented buoy respectively. (Data from Earle (1975) and Withee and Johnson (1975) respectively.)

height spectra during the passage of this hurricane is shown in Fig. 14.8 along with the 15 minute mean wind speeds. This diagram shows, on the vertical lines corresponding to different times, the distribution of energy amongst the waves of different frequencies. The dashed lines shows the wave frequency having the greatest energy at any time. Eloise was weak at the beginning of the record, when it was centred 650 km to the south over the Yucatan peninsula, so that no early long-period swell was recorded. Note the sudden increase of the height and period of the waves with greatest energy around 0500 GMT on the 22nd September - some 16 hours before gale force winds arrived - and the decrease in both their height and period in the eye of the hurricane.

Just off the southwest end of Waglan Island in 28 m of water, about 15 km from Hong Kong harbour and in its southeast approaches, a wave recorder is mounted about 7.8 m below mean sea level on a massive 20 m tower weighing about 60 tonnes ~~[illegible]~~ to prevent overturning. It was found that instrumental recordings of maximum wave height were about 1.43 times greater than wave heights reported visually (Apps and Chen 1973). Fig. 14.9 shows the maximum wave heights recorded at this site during the period 1959-1971 when typhoons or severe tropical storms, which passed south of Hong Kong with a westerly movement, were centred in the indicated two degree areas. The instrumental recordings have been supplemented by visual estimates of the significant wave height multiplied by 1.43.

The diagram shown in Fig 14.10 ~~No satisfactory relationship could be found between the visual estimates of the period of the significant waves and those measured instrumentally. Fig. 14.10~~ is based on the instrumental records for the summer of 1971, the higher waves in this period were due to tropical cyclones in the South China Sea.

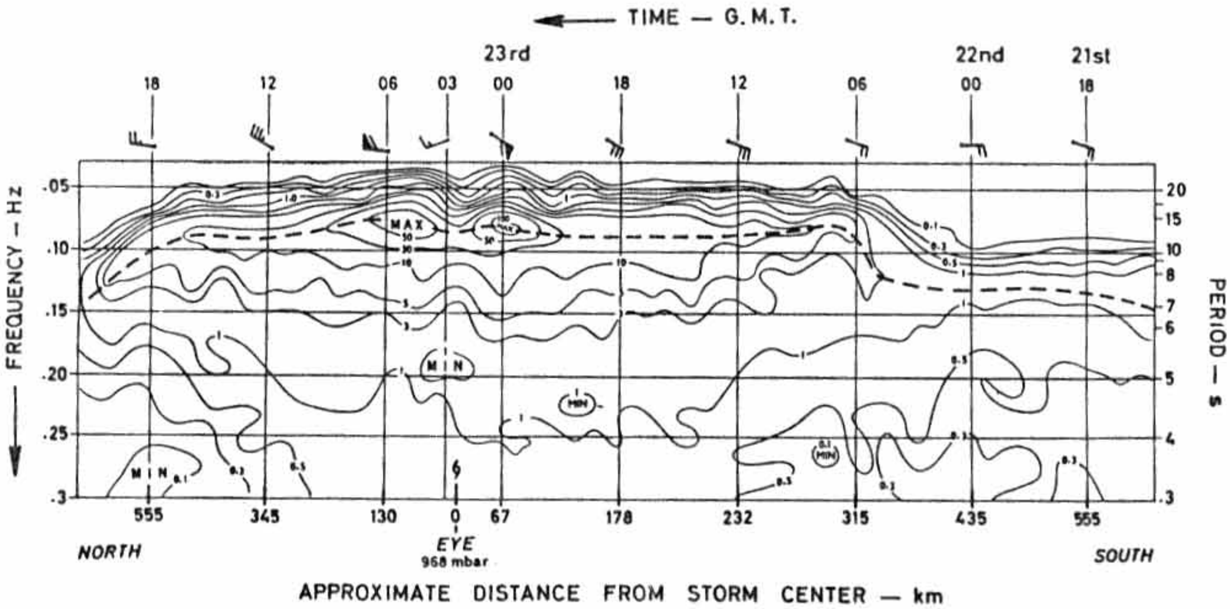


Fig. 14.8. The time series of wave height spectra during the passage of hurricane Eloise 1975 over an instrumented buoy (EB 10) anchored in 2.4 km of water. The spectral densities are given in m^2/Hz. (Based on Withee and Johnson 1975.)

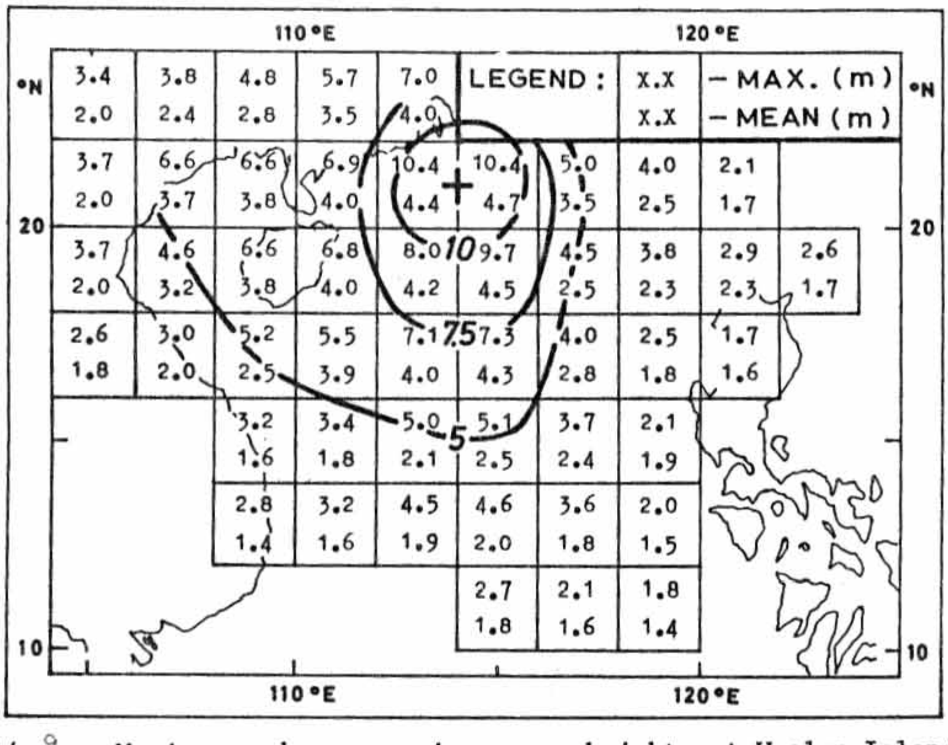
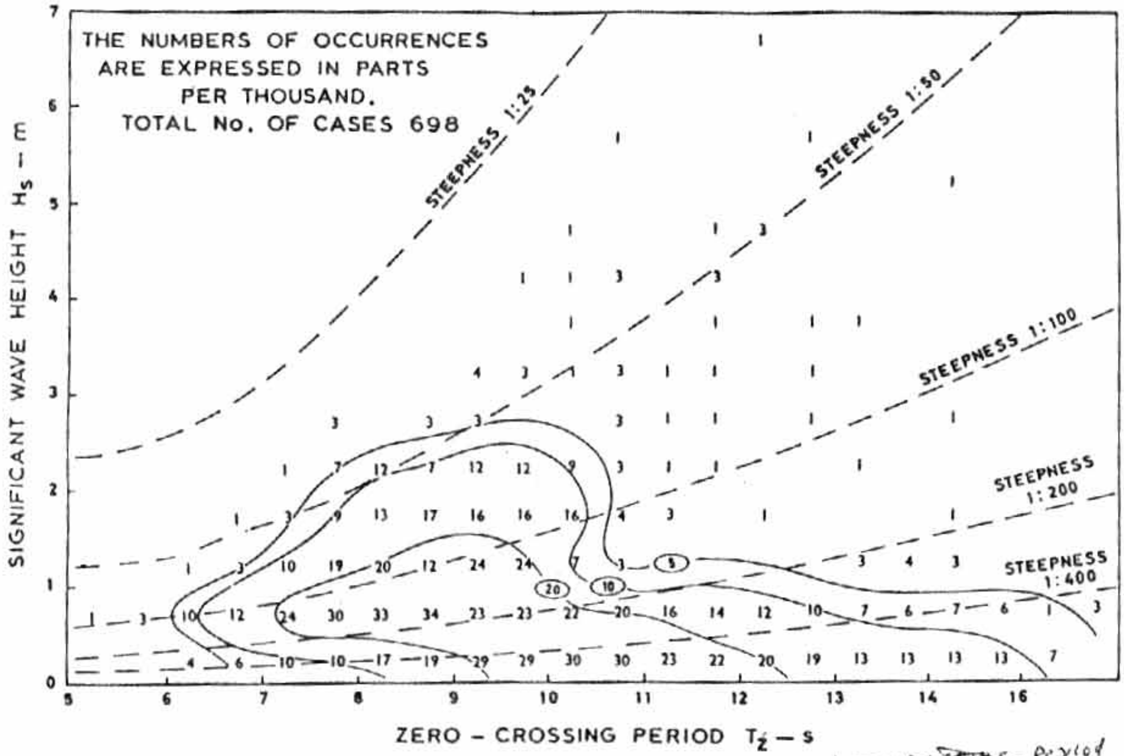


Fig. 14.9 Maximum and mean maximum wave heights at Waglan Island caused by westerly moving typhoons and tropical cyclones in the indicated two degree areas during 1959-1971. The isolines refer to the maximum wave heights. (After Apps and Chen 1973)



and crossing period

Fig. 14.10 Scatter diagram of significant wave heights recorded at Waglan Island during the sumer of 1971. (From Apps and Chen 1973)

.2 Waves in the open sea

In a typhoon circulation the sea never attains the fully arisen state indicated on the right-hand side of Fig. 14.1 because both the fetch and the duration in the generating areas are severely limited. The areas of a typhoon in which both the wind direction and speed remain reasonably constant are small when compared with extratropical cyclones or the trade winds. Fetches of only 20-40 km and durations of only 1 to 2 hours are typical for wave generating conditions near the centre of tropical cyclones. There are exceptions of course, a few very large typhoons have gale areas as extensive as those in deep extratropical cyclones. In addition, typhoons can interact with monsoons (sect.) to form wave generating areas having long fetches and duration. For example, a typhoon in the South China Sea can enhance the northeast monsoon in autumn as is shown in Fig.13. or the southwest monsoon in the South China Sea in summer as shown in Figs. 3.19 and 13. In the former case, a ship in the Taiwan Straits encountered waves of height 9.5 m and period 12 seconds. In the southwest monsoon case, winds of gale force, reaching 20 m/s at times, extended nearly 2 000 km from just east of Malaya to Manila, generating waves of about 6 m height with period 9-11 seconds. These large waves crashed over Roxas Boulevard in Manila Bay causing flooding and much damage.

Notwithstanding the limited fetch and duration of the winds in the wave-generating area the extreme winds in a tropical cyclone can nevertheless raise seas of record height.

The total energy of the waves associated with a typhoon usually amounts to between 10^{16} and 10^{17} Joules. This corresponds to about ten per cent of the kinetic energy of the typhoon as a whole (sect.). Of the total wind energy dissipated by surface friction in a typhoon about five per cent goes towards increasing and maintaining the waves (Unoki 1957b).

Suggest 2 paragraphs in connection with JONSWAP to be inserted here

During the Joint North Sea Wave Project (JONSWAP) in 1968-1969, it was found that most of the properties in connection with wave growth could be explained by the non-linear energy transfer due to resonant wave-wave interactions (Hasselmann, K. et al. 1973). The principal energy balance was between the input by wind in the central region of the spectrum and the non-linear transfer of energy away from this region to longer and shorter waves. The rapid growth of waves on the forward face of the spectrum was associated primarily with the non-linear energy flux across the peak due to resonant wave-wave interaction. The non-linear energy transfer controlled not only the rate of growth of the newly developing waves, but also the form of the spectrum, in particular the development of a pronounced peak, and the migration of the peak towards lower frequencies. For short fetches approximately ~~For~~ 80% of the momentum trasferred across the air-sea interface went into the principal components of the wave spectrum. About 80-90% of the wave-induced momentum flux passes into currents via the non-linear transfer to shorter waves and subsequent dissipation; the rest remains in the wave field and is advected away. At larger fetches, the interpretation of the energy balance became ambiguous on account of the unknown dissipation in the low frequency part of the spectrum.

The result of JONSWAP also showed that the swell attenuation could not be explained simply by the generally accepted bottom friction law, as the extensive swell data available through the experiment contracted the theory. They suggested that either the friction law needed to be modified or that some other mechnism, such as backscattering ~~scattering~~ by bottom irregularities, was ~~is~~ the cause of the attenuation.

Tr. 1st inserted at the end of p. 12

was, until quite recently, entirely dependent

The ~~For a~~ description of the sea surface in typhoons in the open ~~sea we rely almost entirely~~ on shipboard visual observations of sea and swell. The accuracy of many of these observations will of necessity be poor. The visibility in storms is limited by rain and sea spray and there are many distractions. In addition, the waves in most areas of a tropical cyclone consist of a locally generated sea and swells from other regions of the storm. Consequently, several wave trains will usually be in evidence at a given location and the determination of the predominant swell height and direction from on board ship is often a very difficult task. For example, the recording of wave heights in Fig. 14 . (b) shows strong rhythmic variations indicative of beats between wave trains; these are often clearly identified in wave spectra as illustrated in Fig. 14. 6 . Verploegh (1961) estimated that the average observational error for a visual determination of the height of a 5.5 m wave was 1 m. Nevertheless, good observations are available in sufficient number to permit us now to describe the sea state in these storms.

In a classic paper Arakawa and Suda (1953) presented the observations of the Imperial Japanese 4th Fleet as it passed through a typhoon near 41°N 144°E in September 1935. The typhoon, with central pressure of about 960 mbar, was moving rapidly at 21 m/s on a north northeasterly course and beginning to take on extratropical characteristics. The diameter of the eye was about 31 km. The distribution of wind velocity, sea, swell and the tracks of the various flotillas are shown in Fig. 14.11. The wind speeds are averages over 20 minutes and the maximum observed was 42 m/s. The highest wave was over 20 m. Two features are noteworthy, the very high asymmetry of wind speed, attributable to the high speed of movement of the typhoon centre, and the high seas in the right rear sector. The unusually pyramidal, confused and mountainous seas in the right rear quadrant were attributed to the sudden change of wind direction in this sector, from S.E. to S.W. which, in turn was attributable to embryonic fronts in the storm. The bows of two destroyers were broken off during this encounter and total angles of roll i.e. from port to starboard, of up to 100° were recorded.

In 1939 the Royal Dutch Meteorological Institute published an analysis of 3 300 Netherlands ship observations made in typhoons between 1910 and 1935 (K.N.M.I. 1939). The average direction of swell determined from these observations is shown in Fig. 14.12. Tannehill (1936) propounded the rule that if you stood with your back to the wind in a northern hemisphere hurricane or typhoon then the swell will be moving off to the right. The results from the Dutch ships and from Arakawa and Suda show that this rule is not always valid in the right rear quadrant within about 350 km (200 n miles) of the centre. Swell waves are not deflected by the earth's rotation because the water body carrying them has no significant, sustained velocity.

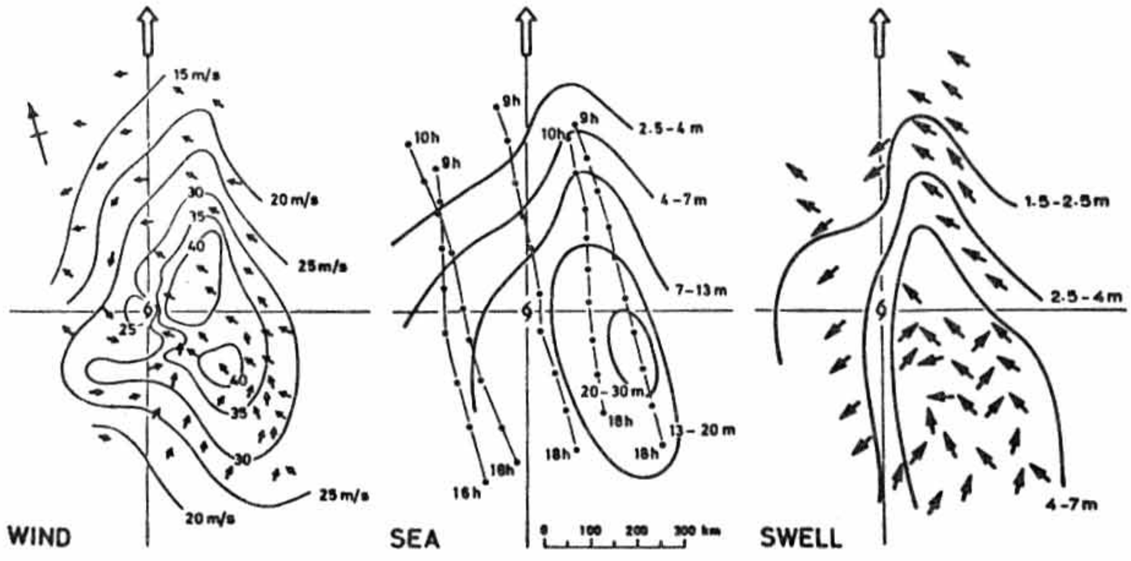


Fig. 14.11 . The distribution of wind, sea and swell determined ~~by~~ from ships of a Japanese fleet on 26 September 1935. (Redrawn from Arakawa and Suda 1953).

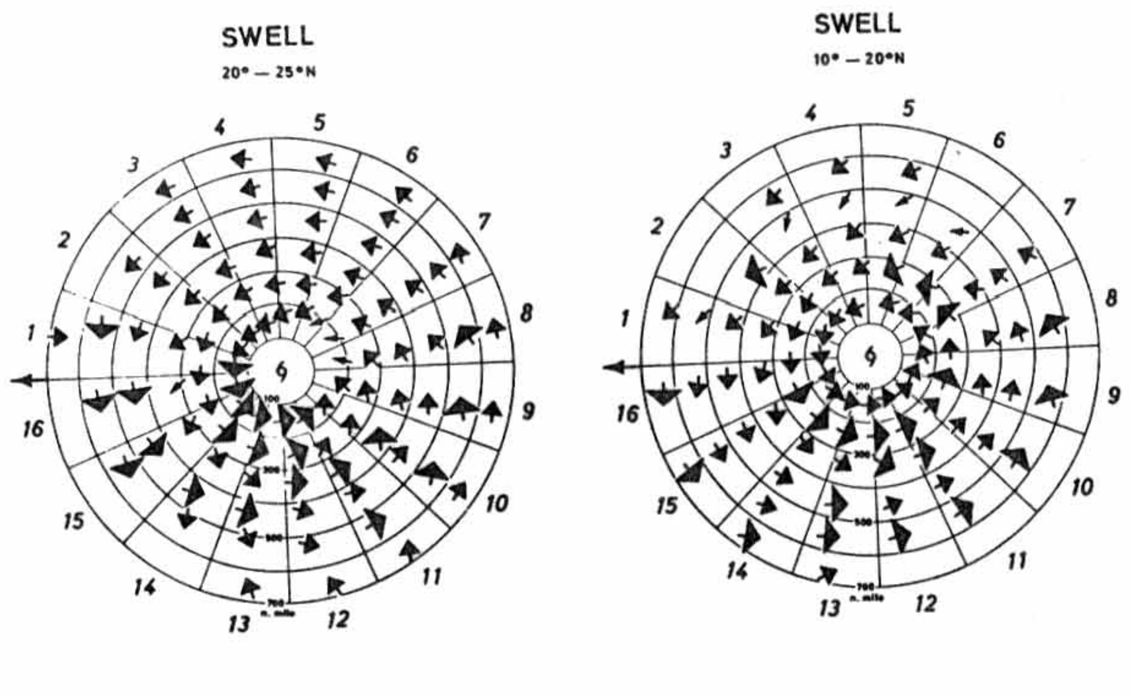


Fig. 14.12 . The average direction towards which swell runs is indicated by the arrow. The spread of the observations is indicated by the angle of the arrow head; there is a 50% probability that a single observation will not lie outside this angle. (Data from K.N.M.I. No. 119, 1939).

Tannehill (1936), Arakawa and Suda (1953), Pore (1957), Unoki (1957a) and Harris (1962) all agree that the highest waves are found in the right hand semicircle. The high seas in this semicircle are due to the stronger winds found there - see Fig. - and the increased effective fetch and duration caused by the storm movement. When the speed of the storm centre approximates the group velocity of the larger waves - usually around 8 m/s - then both the fetch and period during which the strongest winds act on these waves is greatly increased. A dangerously high and steep sea is produced to the right of the centre as waves build up in a kind of resonance effect. There is disagreement in the literature as to which of the two right hand quadrants usually contains the highest waves. Unoki (1957a) finds that the right rear is the preferred place whereas Pore (1957) finds that the highest waves are found about equally frequently in the right front and right rear quadrant. It is probable that the difference arises from the different ratios of maximum wind speeds to speed of travel of the tropical cyclones studied. The case of the fast moving typhoon studied by Arakawa and Suda (1953) illustrated in Fig. 14.11 is a good example, and shows the highest waves in the right rear quadrant. The right hand semicircle is referred to by mariners as the "dangerous semicircle" while that on the left of the track is euphemistically called the "navigable semicircle".

The sea conditions in the rear semicircle are usually worse than those in the front semicircle for two reasons. Firstly, for a point on the sea surface at the rear of a storm, the high winds would have blown for a longer time and at a higher average speed - over a few hours - than at a point an equal distance ahead of the typhoon. Secondly, the sea in the rear semicircle will be raised on a swell left behind by the winds in the front semicircle, so causing the confused seas found in the rear (Fig. 14.13).

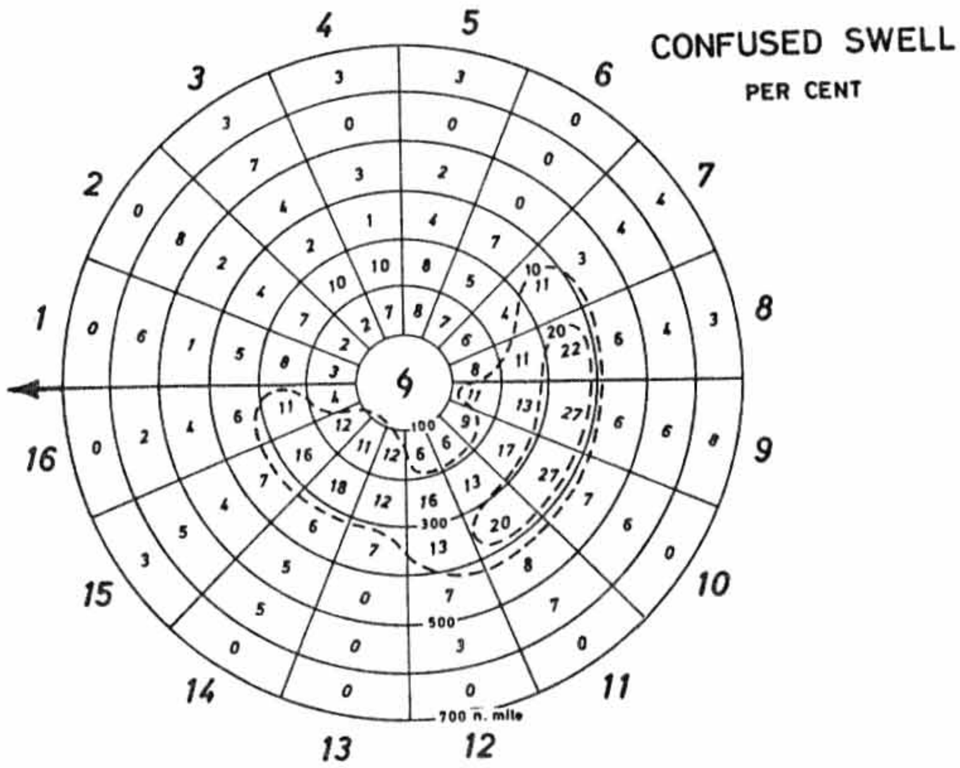


Fig. 14.13 . The percentage of observations from the indicated areas which include reports of "confused swell". Isolines for 10 and 20 per cent are shown. (Data from K.N.M.I. No. 119, 1939)

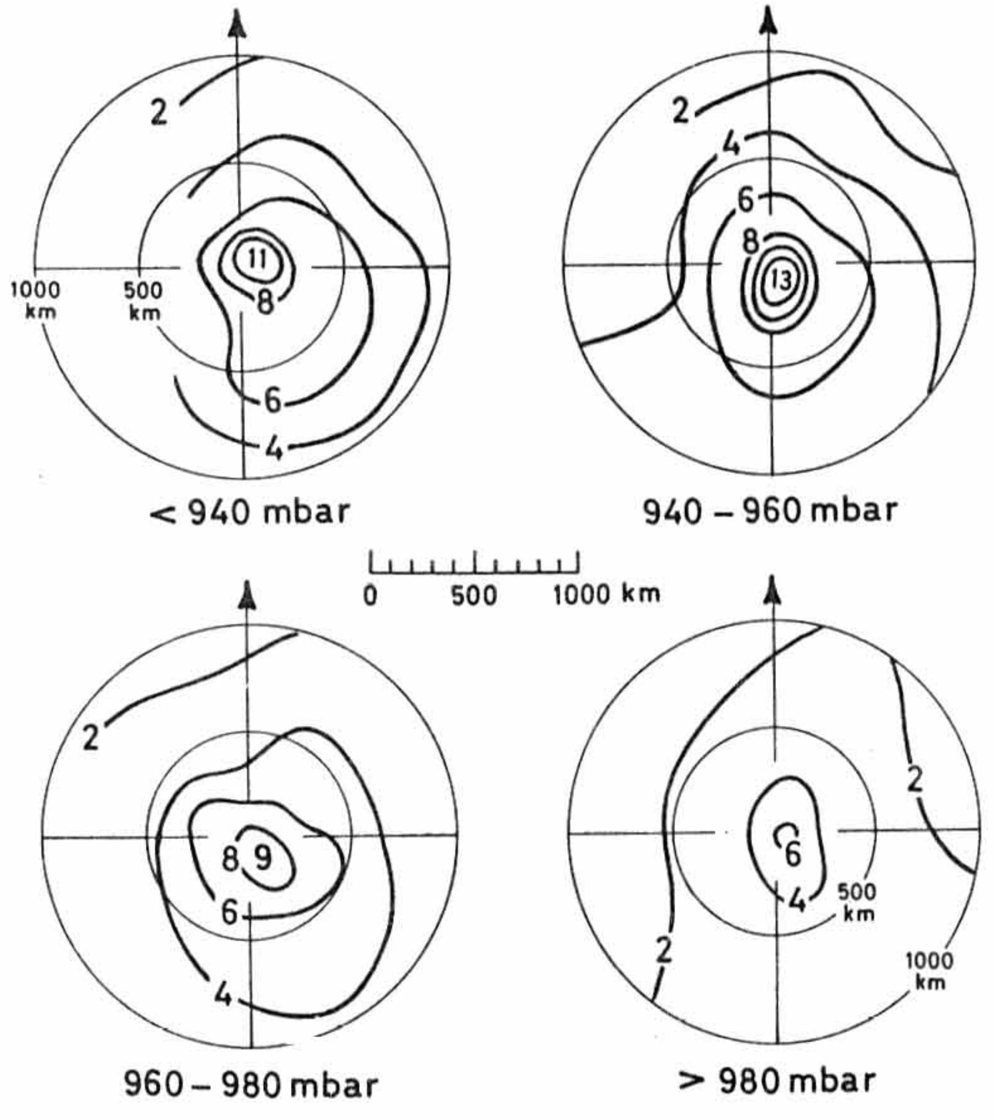


Fig. 14.14 Distribution of mean wave heights (H_s) in metres shown with respect to the direction of motion of the typhoons. (Redrawn after Unoki 1957a)

Unoki (1957a and 1957b) analysed visual observations of waves in 47 typhoons made on board Ocean Weather Station Tango (20°N 135°E) and Ocean Weather Station Extra (39°N, 153°E) and from special low level flights made around eight typhoons in 1946 by aircraft of the U.S. Navy. In addition, observations from the weather ship "No. 4 Kaiyo-maru" when it passed through the eye of a typhoon of central pressure 898 mbar in October 1944 have been analysed. From this data the distribution of waves in terms of direction of typhoon movement, speed of typhoon movement and central minimum pressure are shown in Figs. 14.14 and 14.15. The distribution of wave steepness is also shown in Fig. 14.16. Because of the difficulty involved in determining wave periods and the few observations near the centres of typhoons no distributions for wave periods are presented but, it can be said that 1) waves of long period are more frequent in the rear semicircle than in the front semicircle; 2) the maximum wave period increases as the central minimum pressure decreases; 3) the period of the significant waves decreases with distance from the centre from 10-12 seconds to about 8 seconds at 1 000 km (See Fig. 14.7) or 6 seconds for weaker storms with lowest central pressure greater than 980 mbar; and 4) the overall distribution pattern is similar to that for wave height.

Fig. 14.16a shows the wave patterns in hurricane Gloria on 30 September 1976. The photographs were obtained using an L-band synthetic-aperture radar on board the NASA Convair 990, the longest waves of 275 m wave length are found near "A" in the front right quadrant. These waves would have a period of about 13.3 seconds [Table 14.1]

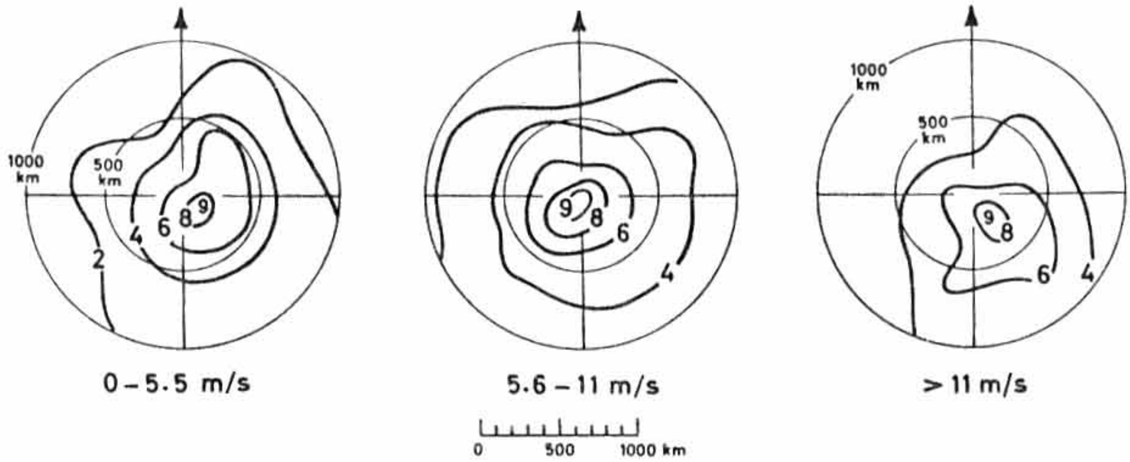


Fig. 14.15 . The distribution of mean wave heights (H_s) in metres in typhoons having a central pressure between 960 and 980 mbar and the indicated speeds of progression.

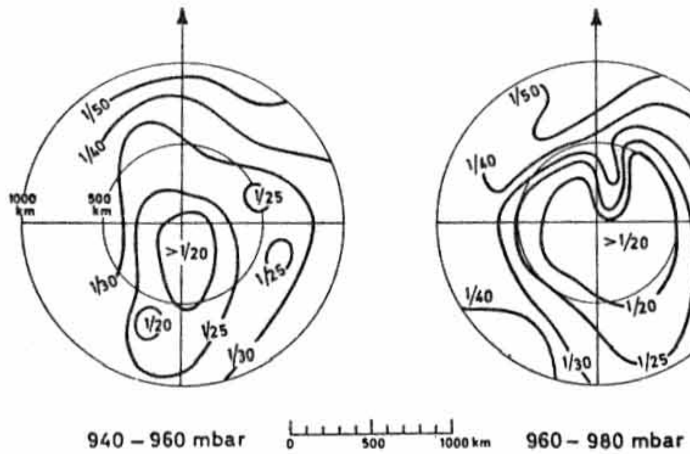


Fig. 14.16 . The distribution of mean wave steepness relative to the direction of movement in typhoons of indicated intensity. (Redrawn from Unoki 1957b)

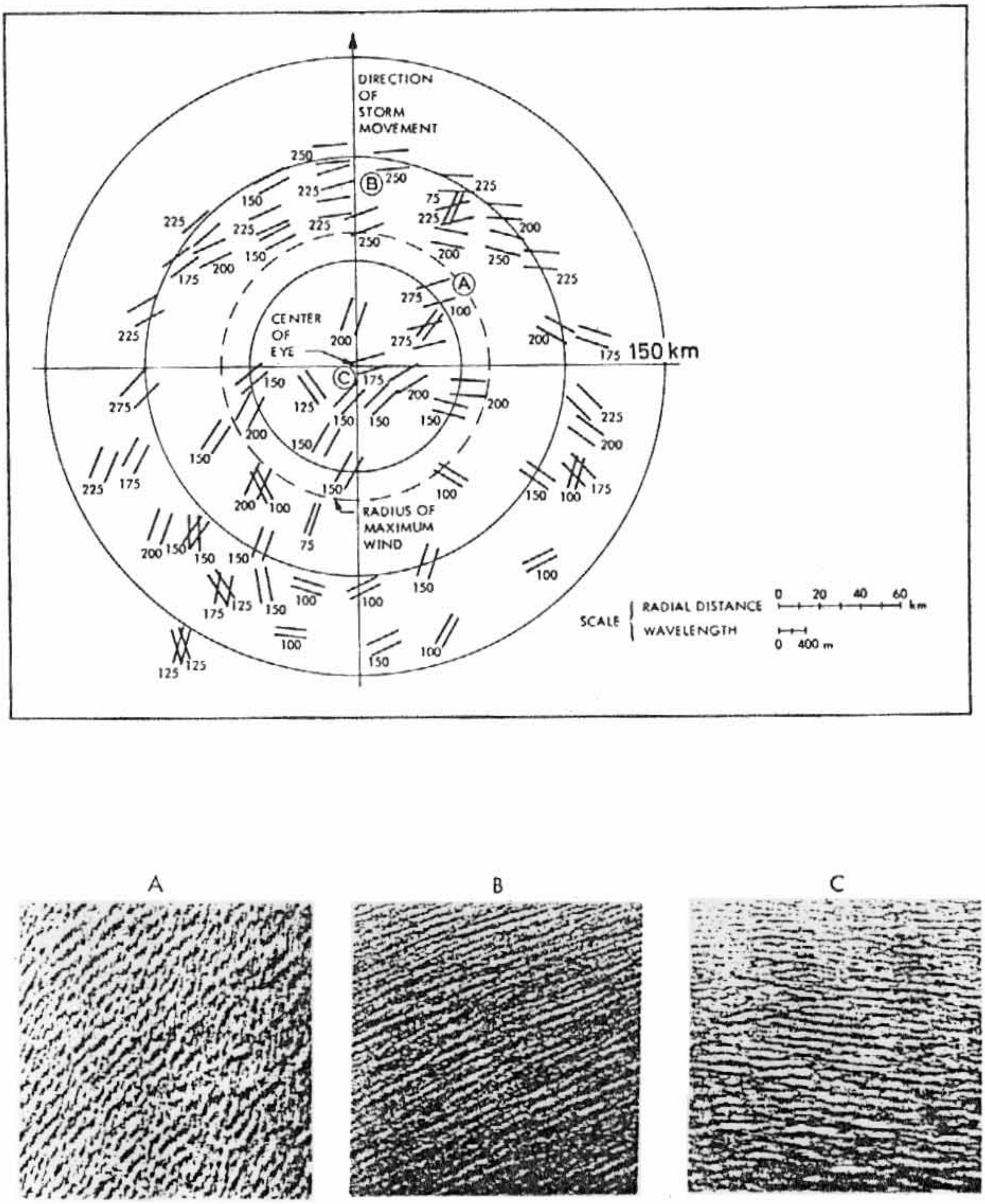


Fig. 14. 16a Wave patterns in hurricane Gloria on 30 Sept. 1976 as seen by L-band synthetic-aperture radar mounted on an aircraft. Wave fronts are shown as two parallel lines with separation proportional to the wave length which is also indicated in metres. The dashed circle of radius 65 km corresponds to the ring of maximum winds. The maximum low-level wind measured was 50 m/s. The three images A, B and C are the radar presentations of sea waves in 7 by 7 km squares at the corresponding locations marked in the diagram. (Courtesy of C. Elachi, Jet Propulsion Laboratory 1976)

To assist both ship captains and meteorological forecasters in determining the sea state Brand et al (1975) analysed the sea height reported by ships in 21 tropical storms and typhoons in 1971 in the Western Pacific (excluding the South China Sea). The reports included estimates of the height of swell and sea separately. The characteristic height - called "combined height" by Brand et al (1971) - is obtained by taking the square root of the sum of the squares of the sea and swell heights. Altogether 173, 12-hour analyses of the combined sea height were obtained. The average distance from the storm centre to combined seas of height 2.7, 3.7 and 4.6 m were determined and they are shown in Table 14.3 and Fig. 14.17. There was insufficient data to extend the analysis to seas over 4.6 m in height.

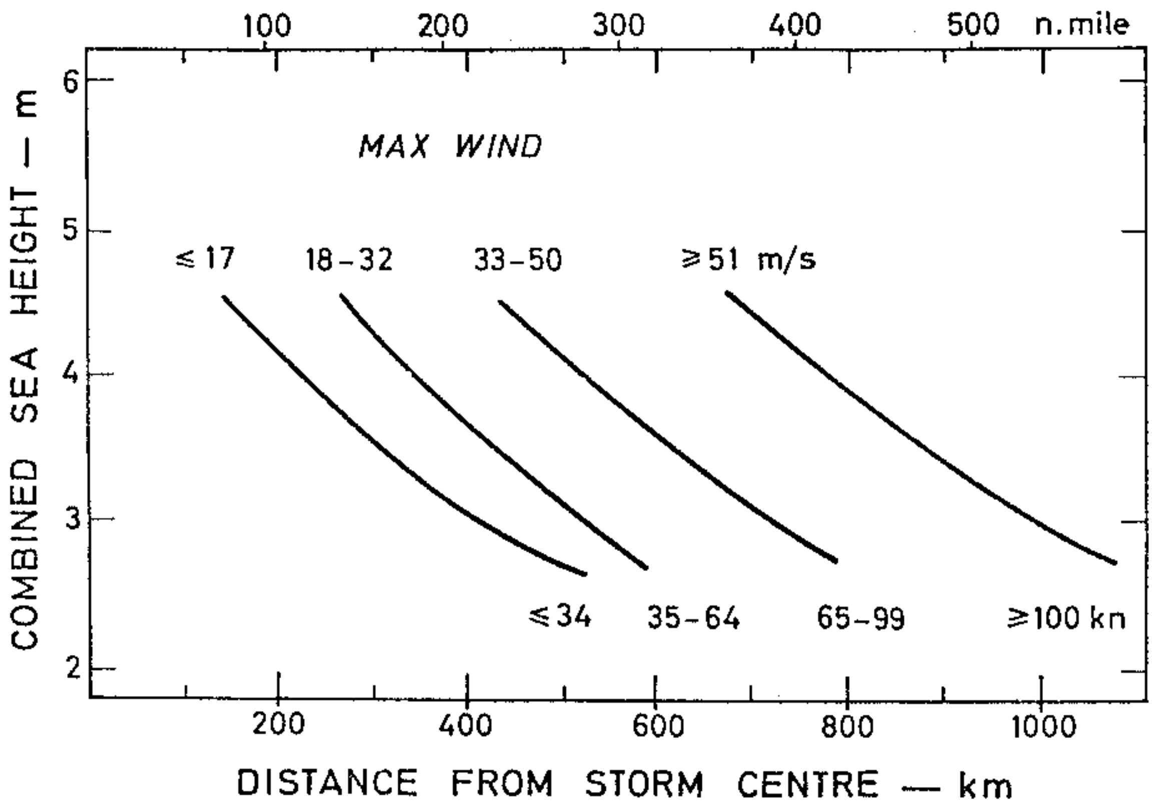


Fig. 14. . The combined sea height (mean values radially averaged) from 21 tropical storms and typhoons plotted against distance from the storm centre for four categories of storm intensity. (After Brand et al 1975).

Table 14.3 Mean and standard deviation of the distance from the storm centre of the 2.7, 3.7 and 4.6 m combined sea heights in tropical storms and typhoons having maximum wind speeds in the indicated ranges (From Brand et al 1975)

Max. Wind Speed m/s	Combined Sea Height m (ft)	Mean Distance km	Standard Deviation km
≤ 17	2.7 (9)	515	274
	3.7 (12)	291	232
	4.6 (15)	143	169
18–32	2.7 (9)	587	315
	3.7 (12)	402	261
	4.6 (15)	265	228
33–50	2.7 (9)	780	389
	3.7 (12)	580	328
	4.6 (15)	439	269
≥ 51	2.7 (9)	1067	297
	3.7 (12)	841	254
	4.6 (15)	671	213

The values of combined sea height in Fig. 14.17 and Table 14.3 are radially averaged means over all the storms examined. The results are in reasonable agreement with those of Unoki (1957a) shown in Fig. 14.14. Deviations from the means in individual cases were considerable as is indicated by the relevant standard deviations in Table 14.3. Two-thirds of the observations should lie within plus or minus one standard deviation from the mean so that, for a typhoon with maximum winds of 50 m/s (equivalent to a central pressure of about 950 mbar), a 3.7 m combined sea would be found within 587-1095 km of the storm centre on two-thirds of occasions.

Brand et al (1975) found that the chosen sea heights were about 200 km further out to the right and rear of the storm centre, relative to the direction of motion, and the greatest asymmetry was found in storms which had recurved. In addition, it was found that the radius of the chosen wave heights was markedly dependent on the length of time for which the storm had existed but not on its speed of propagation. Regression equations were developed to assist in forecasting the average radius to seas of 2.7, 3.7 and 4.6 m. The average radius to the 3.7 m combined sea height in degrees of latitude (111 km) was

$$56.61 + 0.19\ (\text{duration}) + 0.06\ (\text{max. wind}) + 0.48\ (\text{size}) - 0.18\ H_7 \qquad (14.11)$$

where the duration is expressed in the number of 12 h periods since gale force winds first developed, the maximum wind is in m/s, the size is the average radius to the outer closed isobar in degrees of latitude, and H_7 is the geopotential height of the 700-mbar ridge line to the north of the storm, in decametres. The corresponding coefficients in eqn. (14.11) for 2.7 and 4.6 m seas are 60.72, 0.24, 0.06, 0.55, 0.19 and 44.21, 0.16, 0.06, 0.42, 0.14 respectively. A schematic example of the seas around a tropical typhoon is shown in Fig. 14.18 .

Longuet-Higgins (1952) proposes that if the spectrum is sufficiently narrow, the wave heights should be approximated by a Rayleigh distribution. Recently there has been controversy over how well the Rayleigh distribution matches the observed distribution of wave heights. Most of this controversy stems from comparisons based on different definitions of the significant wave height. Once consistent definitions are used, all available data support the conclusion that the Rayleigh distribution overpredicts the heights of the higher waves in a record. Forristall (1978) analysed 116 hours of hurricane-generated waves in the Gulf of Mexico and showed that the results permitted the empirical fitting of the data to a Weibull distribution. Statistics developed from the empirical distribution show that the significant wave height is 0.942 times that calculated from the Rayleigh distribution and the expected value of the maximum wave in 1000 is 0.907 times the height calculated from the Rayleigh distribution.

Longuet-Higgins 1952 $H_{max} = 0.707 H_s \sqrt{\ln N}$ ← N = sample size

$= .707 H_s \sqrt{\ln 10^3}$

$= 1.86 H_s$ See p. 21

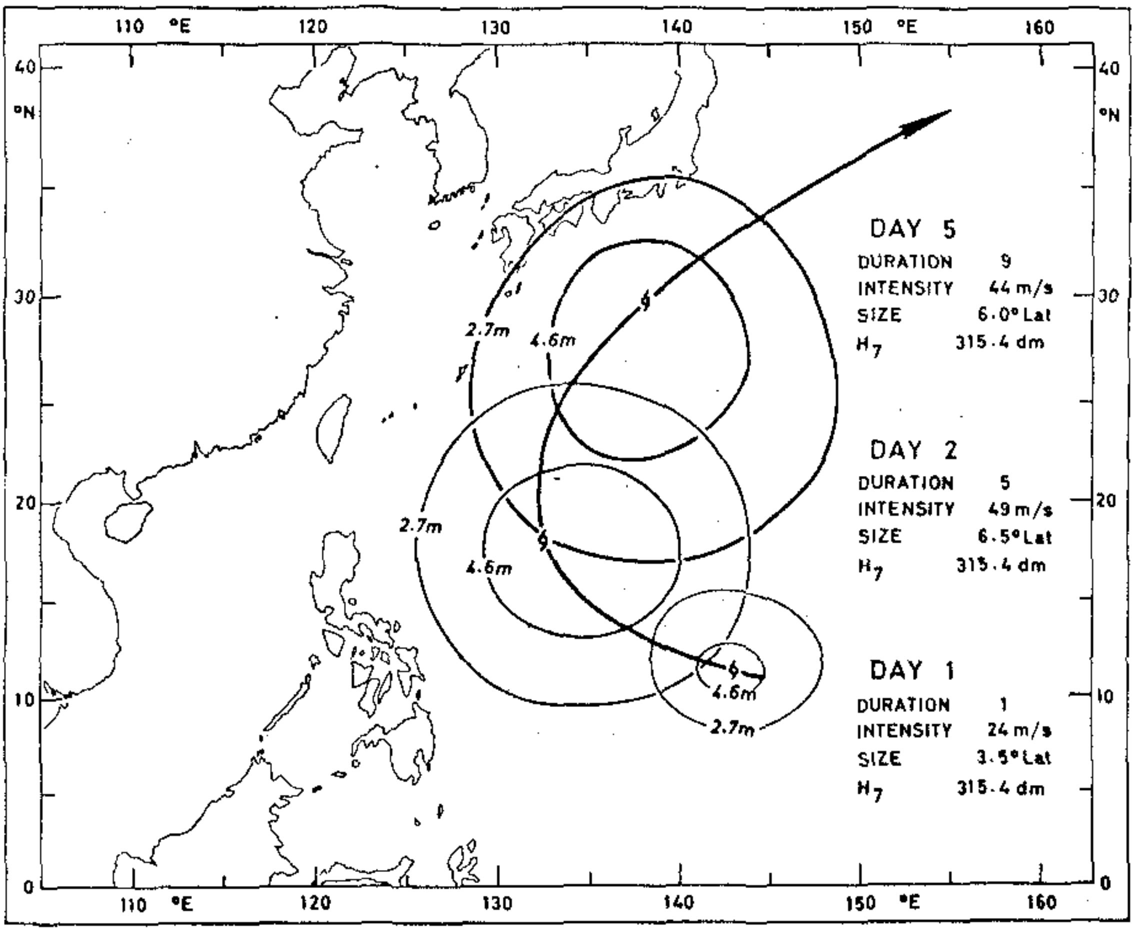


Fig. 14.~~16~~17. The distribution of sea height values of 2.7 m (9 ft) and 4.6 m (15 ft) around a typical recurving typhoon. (Redrawn from Brand et al 1975)

.3 Waves in the eye

In the region of the calm eye there is no sea but only swell. This radiates inwards, from all directions, from the generating area in the surrounding ring of hurricane force winds. The swells from different directions have similar periods so causing a marked reinforcement and cancellation of waves going in different direction; this results in the sea rapidly rising in huge pyramids, appearing from nowhere and collapsing just as suddenly, as the component waves move on. ~~Mariners have often described~~ Such seas have been likened to the water surface ~~sea states as being like conditions~~ in a boiling cauldron. Masters of old sailing ships found these ~~seas~~ conditions extremely dangerous because, although they acknowledged that the waves were not as high as in the region of hurricane force winds, there was, in the eye, no wind to hold the ship steady or to give it way consequently, the sea took complete charge violently tossing the vessel and often causing severe structural damage and loss of masts. The following passage from John Eliot's "Handbook of Cyclonic Storms of the Bay of Bengal" (1900) describes conditions in the eye of a China Sea typhoon on 21st September 1869 as experienced by the ship "Idaho".

> " Till then the sea had been beaten down by the wind, and only boarded the vessel when she became completely unmanageable; but now the waters, relieved from all restraint (in the calm center), rose in their own might. Ghastly gleams of lightning revealed them piled up on every side in rough, pyramidal masses, mountain high, - the revolving circle of the wind, which everywhere enclosed them, causing them to boil and tumble as though they were being stirred in some mighty cauldron. The ship, no longer blown over on her side, rolled and pitched, and was tossed about like a cork. The sea rose, toppled over, and fell with crushing force upon her decks. Once she shipped immense bodies of water over both her bows, both quarters, and the starboard gangway at the same moment. Her seams opened fore and aft. Both above and below the men were pitched about the decks and many of them injured."

After analysing the experiences of several weather ships and military vessels in the calm eye of typhoons, Arakawa (1954) wrote: " It is definitely concluded that, in nearly all typhoons, the most dangerous sea is always that found in the right or dangerous semi-circle and not that found in the calm centre. The sea is usually very high and dangerous in the calm centre, but the sea in the right or dangerous semi-circle is always more pyramidal, mountainous and confused than the sea in the calm centre. This is an established truth well confirmed for about three fourths of a century (75 years)."

The wave records from the buoy EB10 in hurricane Eloise (Fig. 14.7 and 14.8) show that waves in the right semicircle of this hurricane were considerably higher than in the calm eye. The spectral peak in the right semi-circle had a period of 11 s and an amplitude of 121 m^2/Hz corresponding to waves of 11 m height. In the eye the peak was at the same frequency but had decreased in amplitude to 31 m^2/Hz, corresponding to 5.5 m waves. Fig. 14.7 shows that the height of the significant waves were 9 m and 5 m just outside and in the eye, respectively.

Fig. 14.15 shows that there are most probably considerable differences between sea states in the eyes of slow and fast moving typhoons. The figure indicates that slow moving eyes contain swell from all directions whereas the faster moving eyes contain swells only from the right hand semicircle with a very high dominant swell from the right rear.

.4 Waves and local wind

In a fully arisen sea the theoretical relationship between the maximum wave height H_m and the local wind speed V has been derived by different authors, in different ways, and is approximately

$$H_m = 0.26\ V^2/g \qquad (14.12)$$

However, in a typhoon, a fully arisen sea does not form and eqn (14.12) would greatly overestimate the wave heights. Cline (1926), neglecting other factors which influence wave height, gave a simple rule of thumb (here converted to S.I. units) that the wave height (in metres) is given by dividing the wind speed (in m/s) by 3. This is in remarkable agreement with Unoki's finding, illustrated in Fig. 14.19 , that the significant wave height H_s in typhoons is given by

$$H_s = 0.31\ V \qquad (14.13)$$

This equation is not meant for use in places where the fetch of the wind could be decreased by land.

Simultaneous instrumental recordings of wave height and wind speed in nine typhoons at Hong Kong and in hurricane Camille 1969 suggest a value of 0.29 for the constant in eqn 14.13 . Points for hurricanes Camille and Eloise and typhoon Rose are entered in Fig.14.19 for comparison. The good agreement between the instrumented recordings and Unoki's shipboard, visual observations is a tribute to the seamen who made them. Fig.14.19 shows that at high wind speeds the "probable wave height" (0.75 times H_m in this case) given by the WMO version of the Beaufort Wind Scale is considerably greater than is found in typhoons. This cannot be attributed entirely to fetch and duration limitations in typhoons because, at the wind speeds in question, Roll (1954) obtained even lower heights from observations made on ten Ocean Weather Ships in the North Atlantic. Unoki (1957b) showed that, as might be expected, the wave height for a given wind speed was lower when the wind was increasing than when it was decreasing; eqn 14.13 gives a compromise height.

Eloise 35.3 m/s
Hs 8.8 m

Frederic buoy 42003
34 m/s
10.4 m

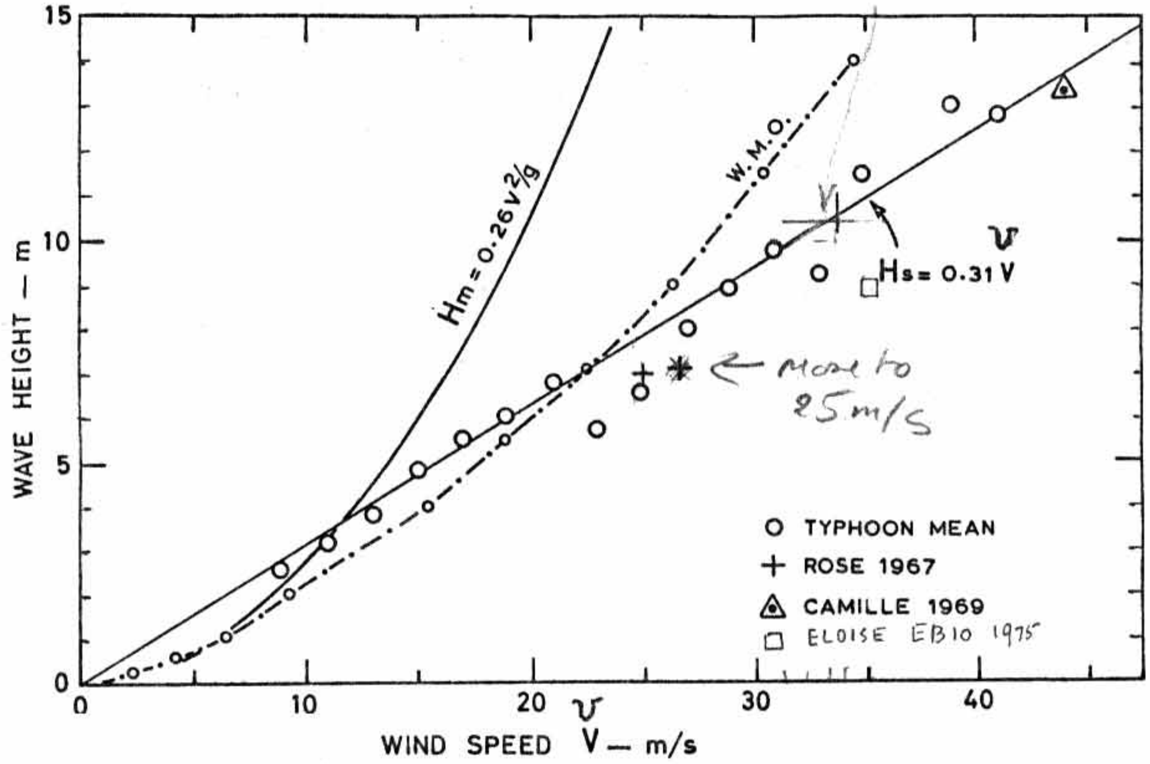


Fig. 14.A . Mean relation between wind speed and significant wave height in typhoons. The results of Sverdrup and Munk (1947) and the W.M.O. are not specific to typhoons. (Redrawn from Unoki 1957b)

Fig. 14.19. Mean relation between the local wind speed and significant wave height in typhoons, from shipboard observations, after Unoki (1957b). The curves from the WMO Beaufort wind scale and for Hm – from Sverdrup and Munk (1947) are not specific to ~~typhoons~~ t-c-s.

Wave heights and wind speeds measured instrumentally in ~~four~~ three storms are also shown.

The most probable maximum wave depends upon the state of the sea and the number of waves observed. If we describe the state of the sea by the significant wave height H_s then the most probable maximum wave H_m is found by putting n equal to one in the equation

$$H_m = 0.707\ H_s\ (\ln N/n)^{\frac{1}{2}} \qquad (14.14)$$

where N is the number of waves used to find H_s. When using instruments to determine H_s it is usual to consider runs of from 10 to 30 minutes. Near the centre of typhoons these runs usually contain about 70 and 210 waves respectively giving approximate ratios of H_m of 1.5 and 1.6. Using 10 minute records in typhoons Apps and Chen (1973) found a ratio 1.5. Earle (1975) presented data from 30 minute records from Camille yielding an average ratio of 1.63; the number of waves in the records varied from 162 to 249. When H_s is determined visually it is found that the ratio of H_m/H_s usually lies between 1.4 and 1.6; accepting the latter value and substituting for H_s in eqn (14.13) yields

$$H_m = 0.5\ V \qquad (14.15)$$

In other words the maximum wave height in metres in a tropical cyclone is approximately equal to one half the wind speed given in metres per second. Again, this formula is in reasonably good agreement with others found for the maximum wave height in storms other than tropical cyclones (Unoki 1957b). In the extreme hurricane Camille the maximum ten-minute wind at the oil rig, corrected to 10 m height, was 43.6 m/s; this speed was recorded at the height of the storm just before recordings ceased. The wave height given by half the wind speed is 21.8 m, the highest wave recorded in the previous hour was 22.99 m, this is better agreement than should be expected in general and indeed, the foregoing rule-of-thumb formulae should be used with caution because they do not take account of factors which affect wave heights in typhoons other than wind speed.

The period of the significant waves in a typhoon also increases with wind speed, rising from a mean value of about 8 seconds at 10 m/s to a mean around 12 seconds at 40 m/s.

.5 Wave height and period relationships

A number of relationships between various wave statistics in tropical cyclones are useful and they are shown in Table 14.4 . Some of them can be deduced from the assumption that wave heights are distributed according to a Rayleight distribution law, others have been determined empirically. The root mean square height H_{rms} is the square root of the mean of the squares of all the wave heights in the sample. The standard deviation σ is the square root of the mean of the squares of the departures of all wave heights from the average wave height $\bar{H}$.

Table 14.4 . Height and period relationships in tropical cyclone waves

$\bar{H}/H_{rms} = 0.89$	$H_m/H_s = 1.68$	$T_m/T_s = 0.98$
$H_s/H_{rms} = 1.41$	$H_{rms} = 2.83\,\sigma$	$\bar{T}/T_s = 0.81$
$H_m/H_{rms} = 2.36$	$H_s = 4\,\sigma$	$T_s/\sqrt{H_s} = 3.85$

Most of these ratios were reported by Earle (1975) from 20 wave recordings, each of thirty minutes duration, made in hurricane Camille. The two ratios containing σ are theoretical but consistent with the Camille observations. The value of $T_s/\sqrt{H_s}$ is given by Bretschneider (1957) as an approximate relationship. In Camille this ratio varied from 4.40 to 3.15. For H_s less than 9 m ratios were equal to 4 or more, above 9 m they were all less than 4 with the value 3.85 corresponding to significant waves of 10 m height.

An equivalent wave can be found having the same total energy as that under a spectral curve. It has been shown that the height of this equivalent wave should be multiplied by $\sqrt{2}$ to give the height of the significant wave. From which it follows that

$$H_s = 1.41\sqrt{E_H} \qquad (14.16)$$

where E_H is the area under the spectrum having a vertical axis expressed in H^2. The period of this wave is given by

$$T_s' = 0.88\,T_e \qquad (14.17)$$

where T_e is the period with the maximum energy.

If the area under the spectrum having a vertical axis expressed in $\frac{1}{2}a^2$ is E, where a is the wave amplitude, then

$$H_s = 4\sqrt{E}$$

14.5 Forecasting tropical cyclone waves

Engineers often wish to know the probability of occurrence of extreme waves at a given location because this is a critical factor affecting the design of coastal and offshore structures. If an area is subject to visitations by tropical cyclones it is usually found that these give rise to the extreme waves there. The problem of assessing the recurrence period for these waves can be solved by using extreme-value statistical techniques on a large sample of wave heights from historical storms. Unfortunately, the necessary wave sample is seldom available. It is therefore necessary to estimate the wave conditions which would have prevailed in past storms. Historical meteorological conditions are used for this purpose. This technique is known as "wave hindcasting". It is applied to as many past storms as are required to form an adequate sample for the statistical techniques. A variety of methods of hindcasting are available but the choice of method for a particular application must depend on the meteorological data available. The distribution of wind velocity is all important in determining the greatest wave height in tropical cyclones but this is seldom known to the desired degree of accuracy. The fetch of the maximum winds is usually taken as being proportional to the radius of maximum winds (r_m). However, in the typhoon region it is almost impossible to estimate this factor for early historical typhoons. The storm characteristics most generally known are its track, speed of movement and estimated central pressure deficit (Δ p).

The data deficiencies are usually circumvented by assuming some model distribution for the maximum winds and their fetch in terms of the storm the central pressure deficit Δ p and the radius of maximum winds r_m and then using empirical wave accretion relationships such as those depicted by the curves in Fig. 14.1.

14.6.1 / 14.4.2/6.1 Energy Index wave methods

Bretschneider (1957) analysed thirteen east coast hurricanes and found that a reasonable representation of the significant wave field in a steady state storm could be given in terms of the highest significant wave. He found that if the distributions were expressed in dimensionless form with $H_s/H_{s\,max}$ plotted in terms of R/R_m where R is the radial distance to a point, then the results of his

14.5.1 Energy Index Method

Reid (1954) proposed the concept of an Energy Index, $r_m.\Delta P$, for classifying hurricanes. Since the kinetic energy of the low level circulation of a tropical cyclone is proportional to $r_m.\Delta P$ and the wave energy is proportional to H^2, various relationships between the wave characteristics and the Energy Index can be derived.

Bretschneider (1957) analysed thirteen east coast hurricanes and found that a reasonable representation of the significant wave field in a steady state storm could be given in terms of the highest significant wave. He found that if the distributions were expressed in dimensionless form with $H_s/H_{s\ max}$ plotted in terms of r/r_m where r is the radial distance to a point, then the results of his investigations could be represented by a single set of curves. The distribution is shown in Fig. 14.20 and permits H_s to be estimated at any point if $H_{s\ max}$ is known. He found that $H_{s\ max}$ in the open sea could be estimated from the following equation here expressed in S.I. units in terms of Energy Index, $r_m.\Delta P$, and other variables:

$$H_{s\ max} = 5.03\, e^{(0.16\ r_m.\Delta P\ 10^{-6})}(1+0.29\alpha\, V\, v_m^{-\frac{1}{2}}) \qquad (14.18)$$

where $H_{s\ max}$ is the maximum significant wave height in m,

r_m is the radius of maximum wind in m,

ΔP is the central pressure deficit in mbar,

V is the forward speed of the storm in m/s,

α is a coefficient whose value depends on the variations in effective fetch with storm motion, its value is taken as one for normal speed in the tropics,

v_m is the storm maximum sustained wind speed in m/s at 10 m above the sea which is found at radius r_m and is determined using the formula:

$$v_m = 4.84\ (\Delta P)^{\frac{1}{2}} - 0.12\ r_m f\ 10^{-3} + 0.5\ V \qquad (14.19)$$

where f is the Coriolis acceleration.

The corresponding period T_s is derived from the relationship $T_s = 3.85\sqrt{H_s}$ discussed in sec. 14.4.2.5. The distribution of wave heights over the storm area is obtained from the model in Fig. 14.20.

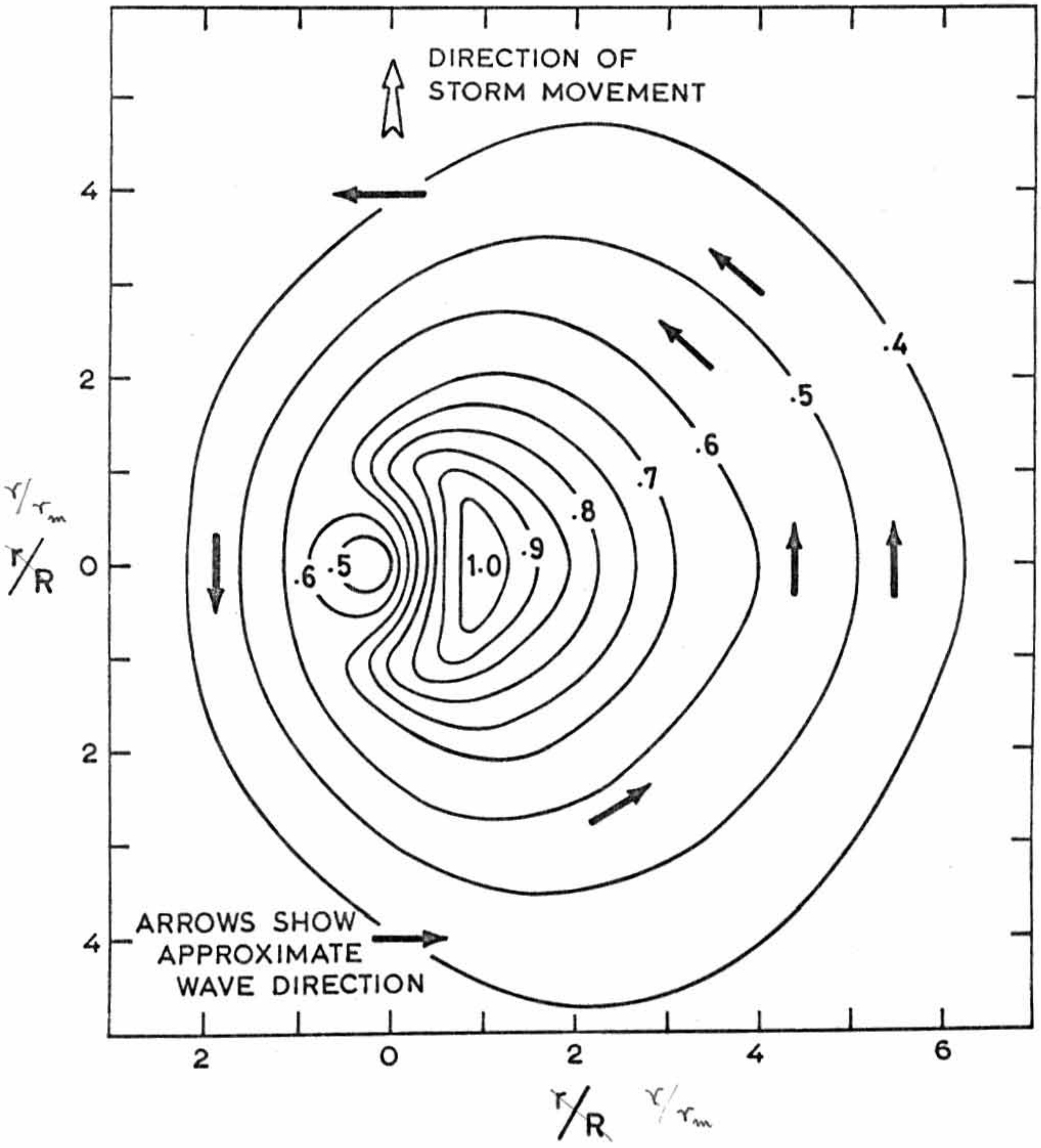


Fig. 14.20 Isolines of the significant wave height relative to the maximum significant wave in a slow moving tropical cyclone. (After ~~C.E.R.C. 1973.~~ Bretschneider 1957)

Maximum significant ($H_{s\,max}$) eqn 14.18

Wave heights, calculated by this method are very sensitive to the value chosen for R. The determination of R is not always straight forward and storm structure can vary considerably from the model adopted. In addition, it is not clear how the coefficient "a" should be chosen. The wave height will be a maximum when the forward speed of the storm is close to the group velocity of the largest waves - about 8 m/s - the appropriate value for the coefficient "a" should therefore be expected to decrease for slower and faster storms. (With "a" set equal to 0.5 good agreement is obtained between the observed and calculated waves in the fast-moving typhoons of 1935 but, in general, variation of the value of "a" as a function of V_F only, does not yield results which are better than those using a = 1.) It is of interest that the calculated wind speeds V_R agree with the near-sea-level observations in Eloise and the 1935 typhoon. However, in all the other cases the anemometer readings have been reduced to the 10 m by the 0.2 power law and these winds are less than those calculated. The best procedure for reducing winds in the eye wall to the 10 m level has not yet been ascertained (See sect 5.)

To be inserted here

Table 14.4 contains the calculated $H_{s\,max}$ using $\alpha = 1$ and $\alpha = 0.5$. It shows that the calculated wave heights with $\alpha = 1$ are very close to the actually observed values for H. Camille, H. Eloise, T. Rose and T. Elsie, which moved at near average speeds but were much too high for the fast-moving typhoon of 1935. The calculated values with $\alpha = 0.5$ are on average about 10% lower then those with $\alpha = 1$.

Table 14.4. Observed ~~and calculated (in brackets)~~ wave heights in tropical cyclones. Wave heights and maximum wind speed calculated by Bretschneider's method+ are shown in parenthesis.

Tropical Cyclone	Date	Latt	Speed of Storm	P_c	ΔP	Radius of eye	Radius of Max Winds R	Max. 10m 10 min. Wind Speed V_R	H_s max	H_m	Remarks
		°N	m/s	mbar	mbar	km	km	m/s	m	m	
H. Camille	17 Aug 1969	29	7.1	905	108	9	35	44+(53)	13.5 (11.8)	23.6 (20.3)	Inner eye wall 9-16 km Outer eye wall 28-37 km Oil rig 10 min ~~10m~~ wind 54.5 m/s at 150 m, equivalent ~~was~~ 44 m/s at 10 m. Fastest averaged radar echoes 60 m/s at 35 km.
H. Eloise	23 Sep 1975	28	7.7	966	47	22	28	35 (35)	8.8 (8.5)	- ( )	Buoy EB 10
T. Rose	17 Aug 1971	22	5.2	952	58	13	18	~~37~~ 27 (38)	7.0 (7.4)	10.4 (12.5)	Wave recording ceased just before max. wave conditions. A nearby ship estimated 14 m wave. The wind at 75 m was 40 m/s
T. Elsie	14 Oct 1975	22	4.6	950*	60	7.5	12*	~~40~~ 23 (40)	6.6 (6.8)	9.5 (11.4)	~~[illegible]~~ R estimated from radar photographs. ~~A~~ Wind speeds of 40 m/s and 35 m/s were ~~was~~ recorded at 152 m and 75 m a.m.s.l. respectively, ~~at~~ at 35 km from centre.
Typhoon near Japan	26 Sep 1935	41	21	957	53	17	100	42 (42)	11.8* (22.8)	20+* (37.8)	* Estimated from ships. See section 14.4.2.2

+ ΔP is based on an environmental pressure of 1010 mbar for Atlantic hurricanes and 1013 mbar for typhoons. The fetch coefficient, a, is taken as unity.

For more accurate work the graphical method of Wilson (1955, 1961) can be used. In this method a model wind field is described by Δp and R and is then moved in equal time steps along the path of the hurricane at the forward speed of the storm V_*. The components of the wind along given vectors to a site are used to generate wave heights there so that a time history of the sea state at the site is generated and expressed as the height of the significant waves from different directions.

Bea (1974) used Wilson's method on the 43 hurricanes in the Gulf of Mexico during the 70 years 1900–1969. He compared his result with such measured data as were available and found that the median ratio of observed to hindcast waves heights was 0.85, an overestimate of 15%. 95% of the results were within the limits 0.70 to 1.42. The largest hindcast wave height (H_m) was 26.8 m in hurricane Betsy (10th September 1965). Bea was able to use these hindcast data to obtain a relationship of the form $H_{s\,max} = e^z$ where z was expressed in terms of Δp, R, V and their logarithms. The relationship was used to generate the curves of Fig. 14.20. The importance of the forward movement of the hurricane in determining the maximum wave height is clearly shown in Fig. 14.20 where the biggest waves occur with forward speeds of 6 – 11 m/s. This is about the speed of the major wave groups (Table 14.2).

After an intensive study of the Gulf of Mexico hurricanes the U.S. Department of Commerce (1968) proposed a set of "maximum credible" values for Δp, R and V of 103 mbar, 29 km and 9.3 m/s respectively. For a hurricane with this specification Bea (1974) derived a hindcast $H_{s\,max}$ of 20.1 m whilst Bretschneider (1972) obtained 20.9 m. This values correspond to a maximum wave of about 34 m. Ackers et al (1972) applied the significant wave methods to South China Sea typhoons to obtain an estimate of the deep water significant wave heights off Hong Kong. Their results are shown in Fig. 14.30.

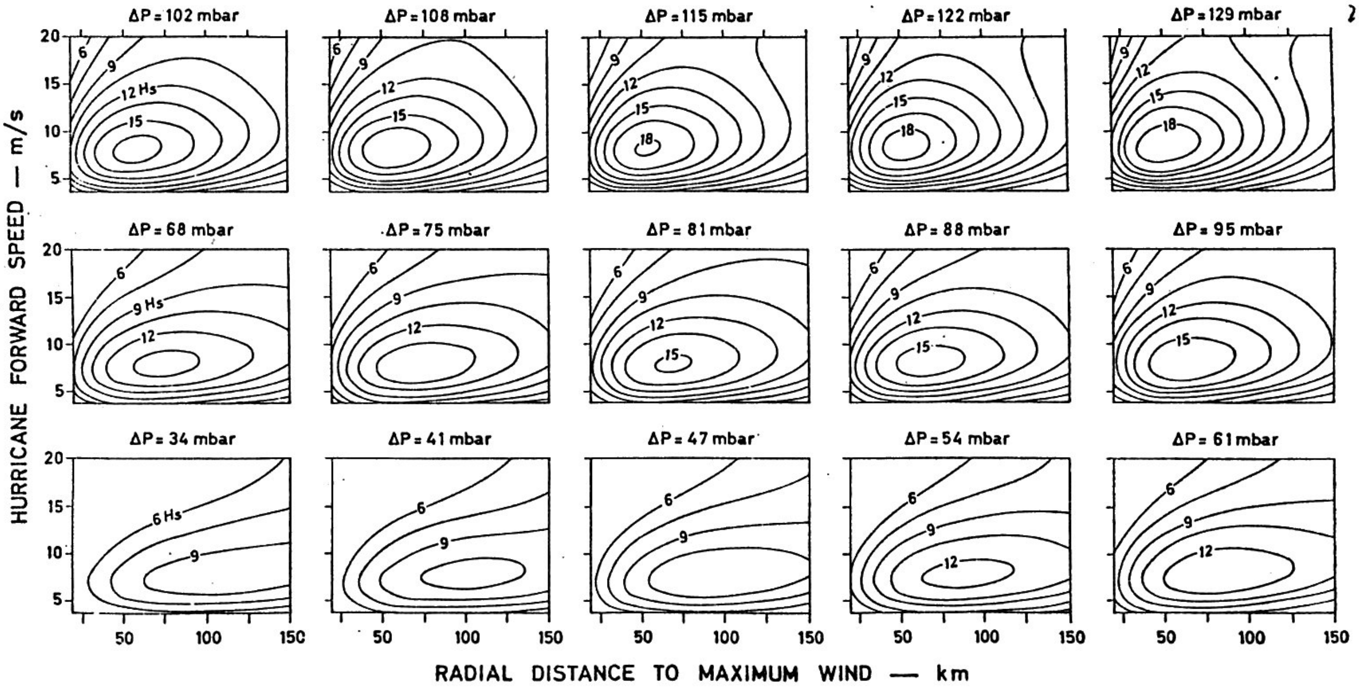


Fig. 14.21. Heights of deep water maximum significant waves Hs in metres for fully developed tropical cyclones (After Bea 1974)

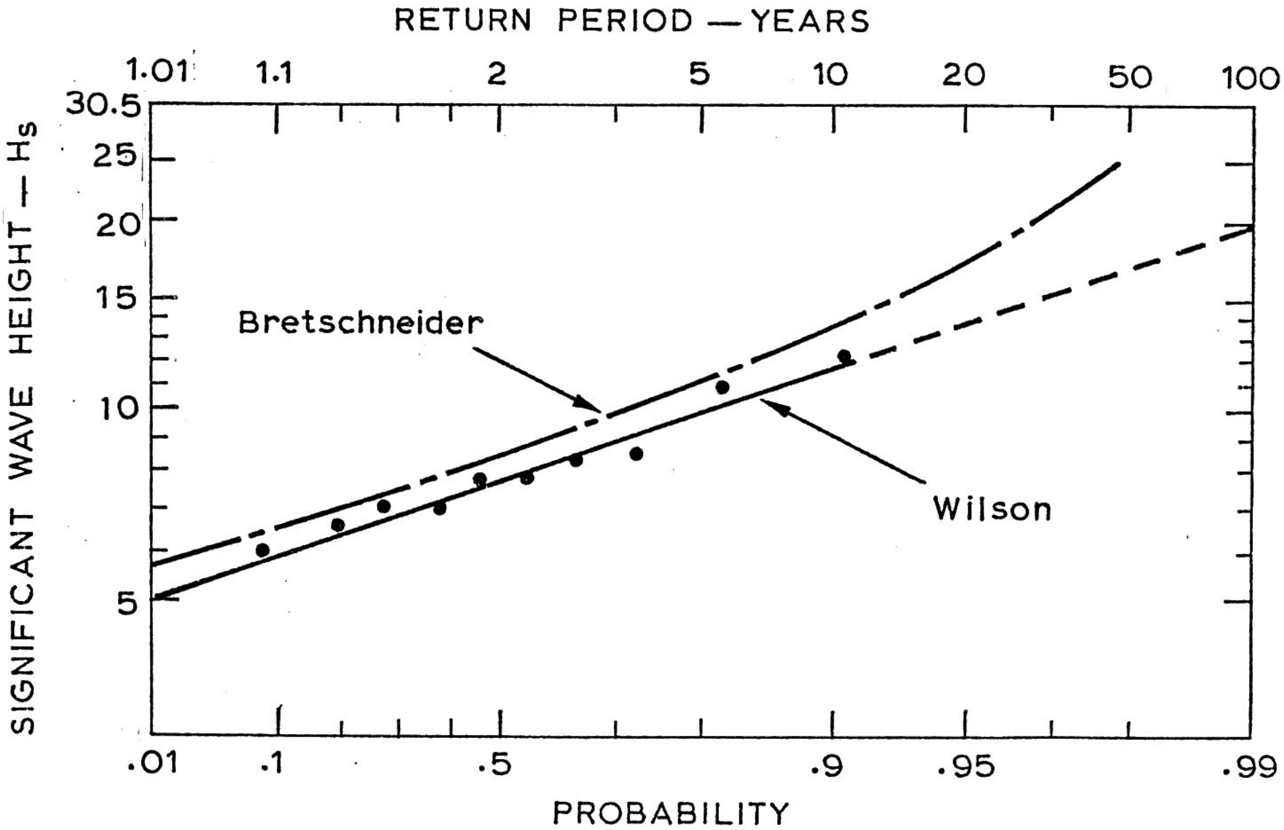


Fig. 14.22. Probability of deep water significant wave heights off Hong Kong (After Ackers et al 1972)

14-5-2 Parametric methods

Hasselmann et al (1976) noted that measurements of fetch-limited spectra could be normalised in such a way as to be approximately constant in shape with varying fetch. They proposed that the shape was stablised by non-linear interactions between waves which cause a short decay time for swell travelling through a local sea containing significant energy at a frequency close to the swell. This effect causes a migration of the spectral peak to lower frequencies. They showed further that the invariance of the shape of the normalised spectrum was not limited to uniform-wind, fetch limited situations but applied generally for a growing wind sea. Ross (1976) measured wave spectra in three hurricanes from an aircraft using a laser altimeter. He determined that they had a remarkably steep slope on the low frequency side and agreed well with the shape of the normalised spectra found by Hasselmann et al (1976). The invariance has also been demonstrated in [illegible] in Camille [illegible].

Kitagorodskii (1961) also proposed the similarity theory of waves and made the assumption that the dominant part of the power spectrum of a wind-generated sea is a function of only four variables, i.e. frequency, gravity, wind speed and fetch. All wave variables, when non-dimensionalized in terms of gravity, g, and the friction speed, v_*, should be functions only of the single non-dimensional fetch,

$$\hat{F} = (gF)/v_*^2$$

where F is the fetch length. In the Joint North Sea Wave Project (Hasselmann et al, 1973) the friction speed, v_*, is replaced by the wind speed at the 10 m level, v_{10}, the non-dimensional peak frequency, $\hat{f}_m$, was found to be:

$$\hat{f}_m = 2.84\,\hat{F}^{-0.3} \qquad (14.21)$$

where $\hat{f}_m$ is defined as

$$\hat{f}_m = (v_{10} f_m)/g$$

and f_m is the peak frequency.

Similarly, the non-dimensional total energy, $\hat{E}$, showed a linear fetch dependence:

$$\hat{E} = 1.6\,\hat{F}\,10^{-7} \qquad (14.22)$$

where $\hat{E}$ is defined as:

$$\hat{E} = (Eg^2)/v_{10}^4$$

and E is the area under the curve of a wave spectrum and is proportional to the total wave energy per unit sea area.

Eqn (14.21) and (14.22) constitute the basis of Fig. 14.1.

Ross (1976) proposed that the generation of waves in a tropical cyclone was of a local nature and was determined largely by the radius of curvature and speed ($\geq$ 20 m/s) of the local wind. From hurricane measurements he was able to derive equations for several parameters of the normalized spectrum in terms of r, the radial distance from the eye and v_{10}, the 15-minute average wind at 10 m. In his model, the fetch F is replaced by ~~the radial distance from the eye,~~ r, which represents a parameterization of fetch or duration. The non-dimensional peak freauency, $\hat{f}_m$, is given by

$$\hat{f}_m = 0.93\ \hat{r}^{-0.19} \qquad (14.23)$$

and the nondimensional total energy, $\hat{E}$, is given by

$$\hat{E} = 1.3\ \hat{r}^{0.56}\ 10^{-5} \qquad (14.24)$$

where

$$\hat{r} = (gr)/v_{10}^2$$

is the non-dimensional radial distance from the eye, ~~and v_{10} is the 15-minute average wind at 10 m~~. The validity of these equations for fast-moving storms (> 7 m/s) has not been established. Given a specified tropical cyclone wind field on an arbitrary set of grid points and the location of the storm centre, then $\hat{r}$, $\hat{E}$ and $\hat{f}_m$ can be quickly computed and E or $H_s = 4\sqrt{E}$ can be easily displayed.

Ross parametrical hurricane wave model can be represented by two curves as shown in Fig. 14.23, where the non-dimensional significant wave height, $\hat{H}_s$, is defined as

$$\hat{H}_s = \frac{H_s g}{v_{10}^2}$$

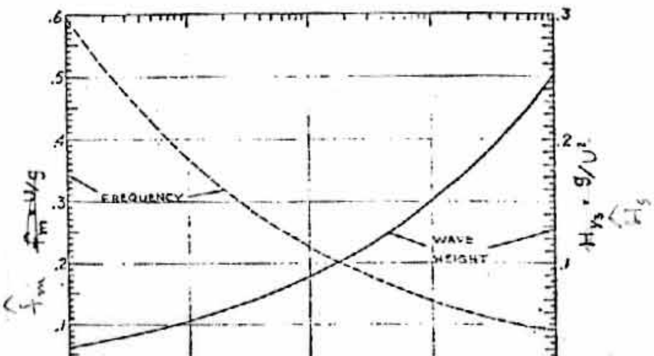
Chen (1979) analysed the data recorded in Hong Kong during the passage of nine typhoons in the South China Sea between 1971 and 1977 and obtained the following relations:

$$\hat{E} = 1.9\ \hat{r}^{0.58}\ 10^{-5} \qquad (14.25)$$

$$\hat{f}_m = 1.5\ \hat{r}^{-0.27} \qquad (14.26)$$

$$\hat{H}_s = 1.2\ \hat{r}^{0.33}\ 10^{-2} \qquad (14.27)$$

where the non-dimensional terms, $\hat{E}$, $\hat{H}_s$ and $\hat{f}_m$, have the same definitions as those proposed by Ross, using winds recorded at Waglan Island (74.7 m) reduced by 0.2 power law to the 10 m level. Using the same set of data, Chen also obtained an empirical relation of $H_s = 3.84\sqrt{E}$, which is very close to the theoretical relation of $H_s = 4\sqrt{E}$.



14.23

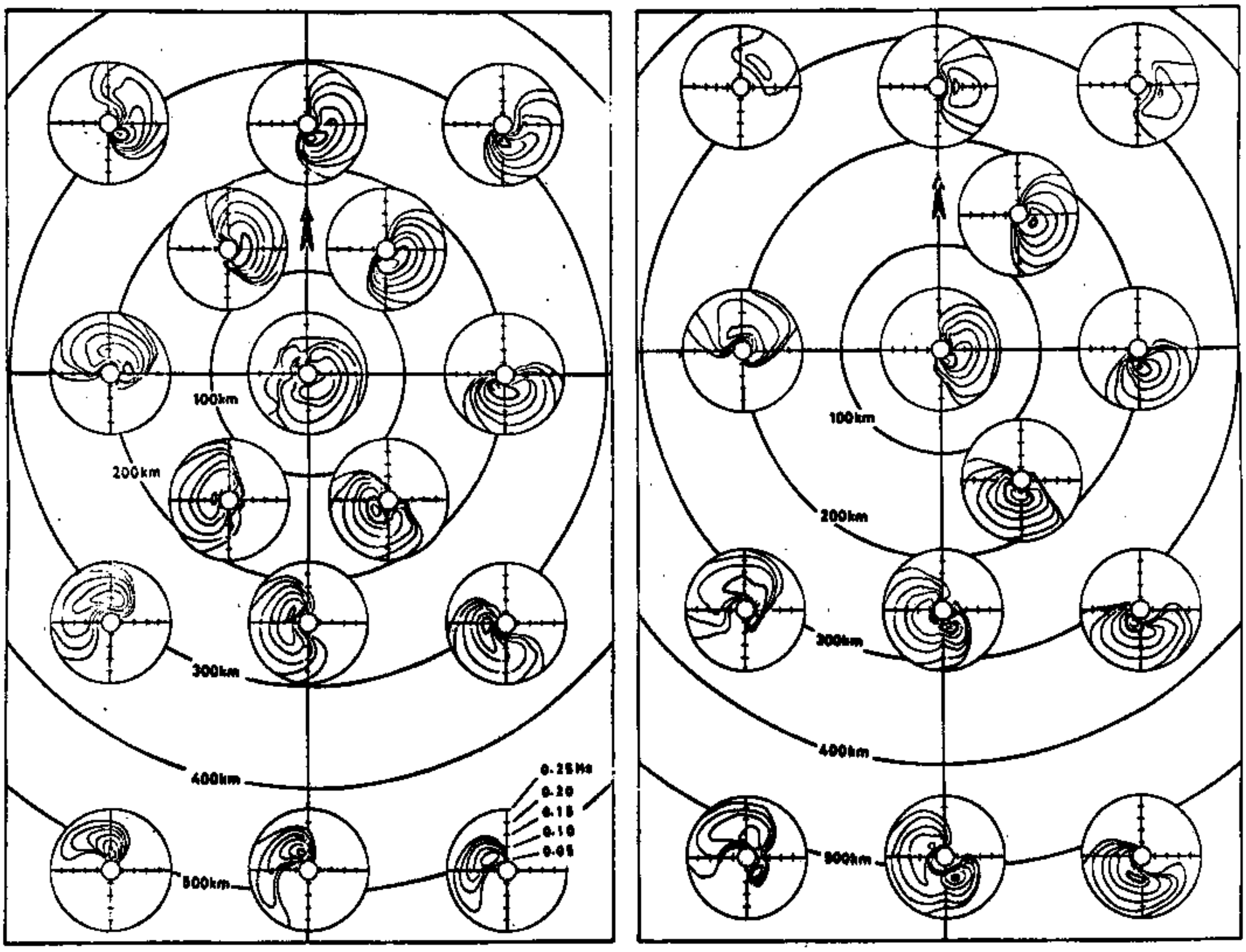
Figure 13.--Ross parametrical hurricane wave model (f_m = frequency spectrum maximum, R = local distance from hurricane eye, U = local windspeed, and the acceleration of gravity $g = 9.8 m/s^2$ in metric units. Plotting $H_{1/3}$ and f_m against R in these dimensionless forms collapses the entire model into these two curves. This graph may be used to estimate the hurricane wave height and frequency for any location where forecast winds and distance from the storm center are known.

14.5.3 Numerical spectral methods

The hindcasting methods described in the previous section have now been superseded, for many purposes, by the use of electronic computers and numerical models. The models are based on the integration of the wave energy-balance equation in which the rate of change of wave energy at a point is equated to the energy being advected to and from the point plus the local transfer of energy between the sea and the atmosphere. It is necessary to consider the transfer of energy from the wind to sea for growth, wave breaking, frictional dissipation and the effects of opposing winds. Wave propagation is corrected for dispersion and angular spreading. These calculations are carried out separately for waves of different frequencies and direction so that two dimensional spectra - which show the energy in waves of different frequency and direction - can be determined for each point. For example, Uji (1975) used a square grid of spacing 40 km and at each point he considered 22 wave frequencies and 16 directions. There were therefore 352 (16 x 22) numbers at each point of the grid for each step in the integration. Spectra at selected points in a fast and a slow moving typhoon are shown in Fig.14.24. However, the wind field is all important in determining the waves and this is seldom known in sufficient detail. This deficiency controls the accuracy attainable from numerical models. Several methods are used to approximate the wind field but most are based on the variables Δp, R_m and V.

Uji used his model to investigate the effects of typhoon speed V on the waves and found that the highest waves occurred at a speed of 12 m/s. He chose a model typhoon based on typhoon Vera (1959) which had Δp = 75 mbar and a central pressure of 935 mbar. In this model typhoon the highest wave was calculated to be 13 m when the storm was stationary and 16 m when moving at 12 m/s - an increase of 23%. The height fell again for faster movement to 15 m at 17 m/s. Fast moving typhoons had no significant seas 400 km ahead of the centre and the area of highest waves was found in the right rear of the storms.

Cardone et al (1976) used a 37 km grid and a fundamental wind-field model based on the interaction between the general atmospheric pressure field and the axially symmetric field in a hurricane, to hindcast waves in Gulf of Mexico hurricanes. They claimed significant advantages for their method of specifying the wind field in that it differentiated between the fields in small intense hurricanes with small radius to maximum winds (e.g. Camille 1969)



3 m/s 17 m/s

Fig. 14.24 Two dimensional wave spectra (see text) in typhoons moving along a straight path in the direction of the arrow at 3 and 17 m/s. The first (outer) contour represents a spectral density of 0.03 $m^2 s/(2\pi/16)$ others are drawn at 0.1, 0.3, 1, 3, 10 and 30 with the 10 $m^2 s/(2\pi/16)$ contour thickened. The direction of the waves is towards the origin. (After Uji 1975).

? No figure is shown here.

and those with a large eye and extensive area of gale or hurricane force winds (e.g. Carla 1961) and thereby improved the accuracy of wave hindcasts. Fig. 14.33 shows maximum spectra hindcast for hurricanes Camille and Carla and an observed spectra from an extra tropical cyclone in the eastern North Atlantic during December 1959. Although the maximum average (30 min.) wind speed in the extra tropical cyclone is only half of that in hurricane Camille the effects of the longer fetch and duration are able to generate sea states with a lower characteristic frequency.

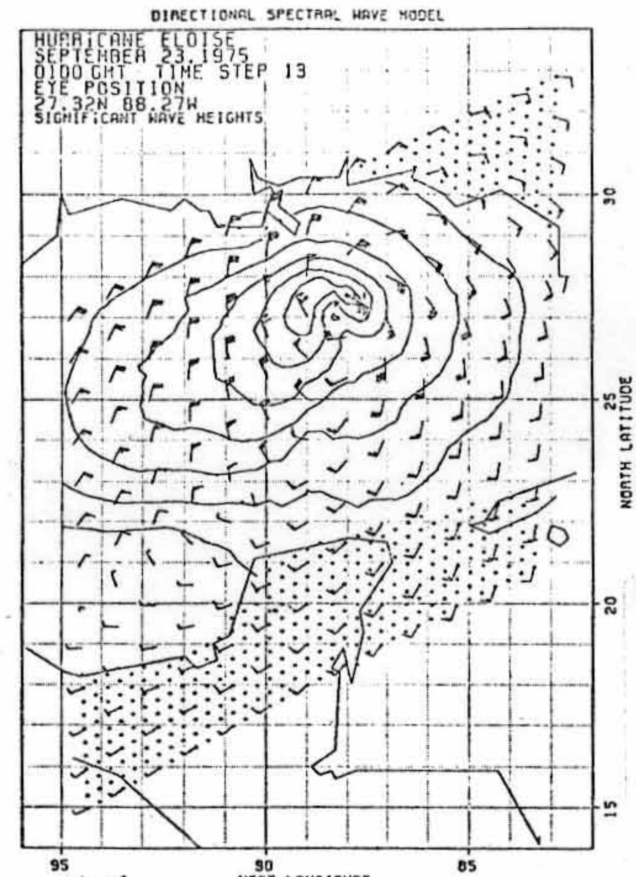
Brand et al (1976) used a coarse grid (74 km) model to determine the sea states associated with large and small typhoons, fast moving and slow typhoons and rapid and slowly intensifying typhoons. The results of their computations showed good agreement with the observational data.

In September 1975, hurricane Elloise passed 29 km southwest of a NOAA data buoy in the Gulf of Mexico, where the highest sea state with a significant wave height of 8.1 m was recorded. Fig. 14.25 shows model contours of significant wave heights and forecast winds at the grid points for the entire Gulf of Mexico as predicted by the full scale computer using directional spectral wave model (Cardone et al, 1976) in the SAIL (the Sea-Air Interaction Laboratory of NOAA's Atlantic Oceanographic and Meteorological Laboratory in Miani).

Experiments in forecasting hurricane-generated waves were made in real time for Hurricane Belle in 1976 over the east coast of the U.S. and for Hurricane Anita in 1977 in the central and western Gulf of mexico, using the numerical spectral model of Cardone et al (1976) and the parametric model of Ross (1976). Cardone et al (1977) analysed the experimental data and demonstrated the feasibility of obtaining useful forecasts of sea states in hurricanes with the existing model capabilities. It also indicates that the accuracy in the forecast of wave conditions is criticcally dependent on accurate forecasts of storm track, intensity and size.

Ross and Cardone (1978) made a comparison of parametric and spectral methods for the prediction of hurricane waves and the results indicated that given a proper specification of the wind field within tropical cyclones, accurage prediction of the generated wave field can be produced by both the spectral and parametric methods. Nevertheless, significant differences do occur for the unusual cases of very slow and very fast moving storms.

7



14.25

Figure M.--Contours of significant wave height in the Gulf of Mexico as predicted by the full-scale computer wave model for hurricane Eloise when the highest sea state was observed at the NOAA data buoy. Wind barbs indicate wind direction and speed (kn) computed with the SAIL hurricane wind model. The interval between contours is 1 m. Significant wave height at the buoy (+) was 8.1 m; the location of the eye of the storm is shown by "*". The stipling in the upper right and lower regions are points on the standard grid which were inactivated for this run.

14.6. Marine Navigation

14.6.1 Ships approaching typhoons

.1 The sea state around a tropical cyclone is of the utmost importance to a ship's captain since it can affect his navigation long before the gale force winds are experienced. Swells from a typhoon usually cover an area much greater than that effected by gales. A heavy swell can rise quickly and may so effect the speed of a vessel as to make it impossible to evade a destructive rendezvous with the central regions of a tropical cyclone. Many hair-raising accounts of near total disaster from this cause have been told. An illustrative account, from recent times, was given by Commander Taylor (Taylor 1971) after his destroyer, the U.S.S. Agerholm (2 500 tonnes) was caught by the swells from the moderate typhoon (952 mbar) Joan on the 15th October 1970 when the ship was en route from the Gulf of Tonkin to Hong Kong (Fig. 14.26). Extracts from his story follow :-

"At about 0500 on the 15th October some effects of weather were felt as the ship rounded the southern portion of Hainan Island. As we continued on a NE track during the forenoon the weather became increasingly rough, with wind and moderate seas from 020°, and an occasional large swell from about 060°. This combination of sea and swell made it impossible to select a "good" course. Several swells crested on a height even with the bridge. One particularly large swell took the UHF can-type antenna off the top of Mount 51 and threatened to break out the pilot house windows.

Consequently, we reversed course along our original track (Fig. 14.10) ...... Our intent was to run back along Hainan Island until the unfavourable weather improved and then proceed again to Hong Kong. We did not, at this time, associate the heavy swells with Typhoon Joan, reported to be 350 miles (650 km) to the southeast.

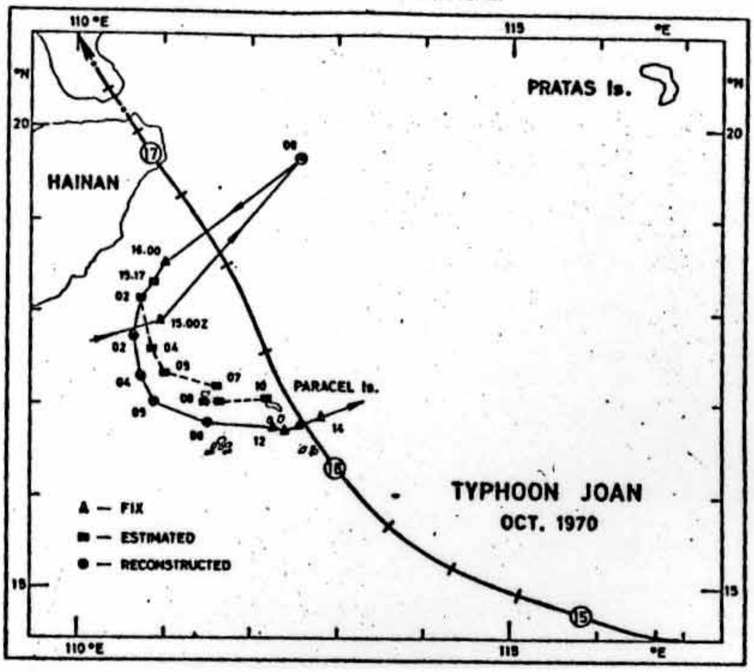


Fig. 14.26 The track of typhoon Joan and the U.S.S. Agerholm

At about 0130 (local time) on 16 October the ship was running southwest at 12 knots..... Rather than proceed south and closer to the possible path of the storm, the decision was made to turn about and lie to. I had some qualms about making the turn with the heavy sea state, but word was passed to stand by for heavy rolls and the turn was made without difficulty. Turns for seven knots were indicated and the ship rode fairly well, with a great deal of pitching. Radar held several peaks on Hainan Island and bearings on these showed the ship to be making no speed over the ground. At about this time we first associated the heavy ground swell with Typhoon Joan.

.... At the sunrise we were greeted by an endless procession of huge seas sweeping by, most of them with foaming tops from the high wind. Shortly after sunrise the steering alarm sounded and the bridge lost steering control. While we desperately attempted to maintain our heading by engines, the after steering room reported a fire in the electrical junction box and a complete loss of power to after steering. Very fortunately the rudder was nearly amidships and the bridge was able to maintain heading by using the engines until manual steering could be set up. .... The loss of power was determined to have been caused by water dripping through the vent to the main deck. ....

By 0700 on the 16th we were pitching heavily and winds were gusting to 55 knots (28 m/s). Shortly thereafter the latest report on Joan indicated that the storm had turned and was proceeding northwest, directly toward us, at a distance of about 180 miles (330 km). There was no longer any doubt as to the source of our troubles.

The answer to our wondering which direction we should evade in was readily arrived at, since we could make no headway in any direction except downwind. Even this might put us across the path of the storm.

The decision to turn the ship downwind was a distressing one to make because I felt she might roll over in the 40-foot seas (12.1 m), even though fully loaded with fuel. Visibility was extremely restricted because of flying spray and mist and it was impossible to pick an optimum time for the turn.

Shortly after 0800 on the 16th I directed the OOD to bring the ship about. I stood on the wing of the bridge trying to pick an optimum time. Wind and flying spray made it difficult to see and hear. The officer of the deck immediately put his rudder over and ordered full speed on the outboard screw and a standard bell on the inboard to provide good rudder control. Agerholm was caught by a 30-foot (9.1 m) swell on the beam as she came smartly around. This large swell simply lifted the ship up and dropped her again, with little rolling motion. I was fully convinced by now that if several large steep swells caught her broadside during the turn she might roll over. Succeeding experience proved this lack of confidence in my "Fram I" to be unjustified.

As we steadied on a downwind course of about 220°, there was a very noticeable air of relief on the bridge. The relative wind intensity dropped to about 35 knots (18 m/s) with a corresponding drop in noise, and the ship appeared to be proceeding easily down the face of the large swells. Steering control was somewhat difficult and speed was increased to 15 knots. Immediately thereafter, Agerholm had her stern picked up by a large swell and she careened wildly off to the right to broach to in the trough of the swell, heeling over to port at an extreme angle which I estimated to be in excess of 50 degrees. One could have stepped out of the port pilot house door directly into the sea. I had a premonition of the end, but surprisingly enough she righted hereself to an angle of about 30 degrees, where she was held by an estimated 60-knot (31 m/s) wind. Somehow we were able to regain control; as I remember, it was through an initial burst of speed on both engines followed by a backing bell on the inboard (port) engine that we were able to preclude the same incident from occurring again.

At this point I was thoroughly surprised at still having a ship, and my confidence had vastly increased. This confidence made my next 12 hours a little easier.

We quickly learned that with winds of 50 knots (26 m/s) or more aft of the beam, the ship was extremely difficult to hold downwind. Each time the ship broached on a sea, or tried to, the wind would push the stern downwind, down the slope of the swell, and force the bow around to windward. The only effective means of preventing this was to use speed to provide rudder control. But here again, excessive speed could easily lead to "surfboarding" down a swell with a high probability of broaching. Through a nerve-racking trial and error period, we discovered that with the starboard engine ahead standard and the port engine ahead one-third we could easily maintain good helm control. .... We were attempting to keep the seas on the starboard quarter in order to open from the storm's center.

As each large swell passed the ship she would settle into the following trough and appear to be making no way through the water. The succeeding swell would lift the stern and at the same time the bow would bury itself in the trough, with only the jackstaff pedestal remaining visible forward of Mount 51.

As the ship moved higher on the face of the approaching sea she would slowly pick up forward motion, her progress being marked by the jackstaff proceeding through the white water like a submarine periscope, until finally the bow would surface and the ship would drop over the crest into another trough. During each of these cycles Agerholm's speed would appear to increase from zero to an estimated 15 knots (8 m/s).

It became increasingly apparent that we were now slaves of the storm, being committee to run downwind in an attempt to open the storm center......

The seas were very large, steep and confused, indicating that we were quite close to the storm center. Large swells routinely came cresting by at a level above the pilot house. Occasionally seas on opposing courses would come together, ejecting gysers 60 feet (18 m) or more into the air. A look in any direction gave the appearance of a maelstrom in which no ship could survive, and we were in the middle.

Since reversing course at 0800 we had had no means of navigation and an accurate DR track was almost impossible to plot. .... Of immediate concern was the fact that the wind was slowly backing, thus Agerholm's course was continually shifting to the south and east. We knew that the Paracel Islands were some 60 miles (111 km) to the southeast. Avoiding these became one of my primary concerns. .... Radar was useless and visibility at all times was less than one mile. At about 1430, somewhat sooner than I had anticipated, the fathometer gave an indication of shoaling water which I correctly assumed to be the Paracel Group. .... Visibility was extremely restricted and every large swell periodically broke into a giant surfline. I conned the ship past this first reef by fathometer information with a distinctly sick feeling in the pit of my stomach, straining to see anything that might be surf, with the intention of immediately bringing the ship about in the event I could identify anything, or if the fathometer indicated rapidly shoaling water. The fact that I could probably make no headway, even if I should successfully make the turn, remained in my mind.

.... our heading was changed to 070° which placed the wind and seas about 30 degrees on the port quarter, at a point where almost full right rudder was required to prevent broaching. On this heading the wind heeled the ship over to a constant 20-30 degrees, which increased each time a following sea passed.

By dark, Agerholm was riding well, having crossed behind the storm center at a range estimated to have been 60 miles (110 km). We were able to open the storm on a course of 090°, although seas were still mountainous and the true wind remained between 65-80 knots (33-41 m/s).

Reconstruction based upon these final sightings indicated that we had been making a fairly steady 17 knots, running with the seas on the standard/one-third combination. This was double what we believed our speed to be.

Maneuvering was still restricted in that we could not turn more than 30 degrees off the downwind course. The wind, however, dropped occasionally to 55 knots (28 m/s) and for the first time the barometer increased, having dropped some 0.80 of an inch (27 mbar) over the last day and a half to a low of 28.80 (975 mbar). By 2 100 on the 16th the ship was riding easily, relatively wind was between 35 and 45 knots (18-23 m/s), with the seas more stable. We were thus able to maintain our desired 090° heading. I felt the bridge for the first time in almost 24 hours.

As I look back, the wind was the predominant factor with which we had to contend. Seas were generally mountainous but when the true wind speed remained between 50-60 knots (26-31 m/s) it was not too difficult running downwind. Periodically, however, the wind would increase to 70-80 knots (36-41 m/s). During these periods the seas would quickly increase in height and appear to run in several directions, cresting white foam continuously. Visibility decreased radically and noise intensity increased. Maintaining a downwind heading became increasingly difficult, and the ship would be boarded by successive seas. One could hear and feel each swell as it rumbled from aft along the ship. We were surrounded by white water and flying spray. The total effect was frightening and the question foremost in everyone's mind was "When will this end?" or "How much longer can we take it?" By comparison, when the wind dropped to 40-50 knots (21-26 m/s) it was almost like a Sunday afternoon at the park.

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2. In Fig. 14. 27 are shown two sets of curves which give the estimated resultant speed-of-advance of a ship in waves of different heights and from different directions relative to the ship's heading. The curves (A) is for a ship capable of 15 kn in good conditions and those in (B) are for a ship capable of 20 kn. They show, for example that a ship capable of 20 kn (curve (B)) when meeting seas of height 8.5 m from a direction 060° from the ship's heading will be slowed to about 8 kn. These are average figures and will vary from ship to ship as well as with wind conditions. Curves for individual merchant ships can be derived from a study of the ship's log. Fig. 14.28 shows typical curves for a vessel with an economical cruising speed of 11 kn. The effect of wind speed alone on a vessel's speed is given in Fig. 14. 29 for various ship types assumed to be in normal loading conditions.

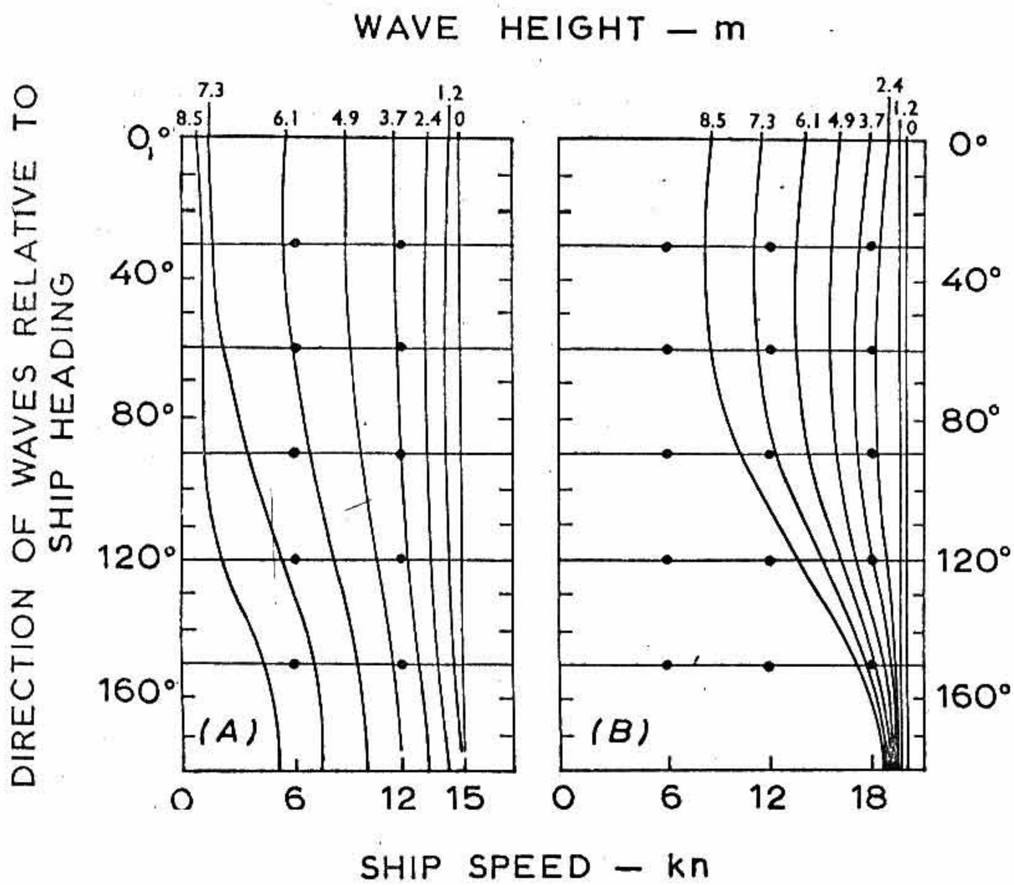


Fig. 14. ~~21~~ 27 . Expected ship speed as a function of wave height and wave direction relative to ship's heading for power settings equivalent to calm water ship speeds of (A) 15 kn and (B) 20 kn (Redrawn after J~~ames 1957~~). BRAND AND BLELLOCH 1976)

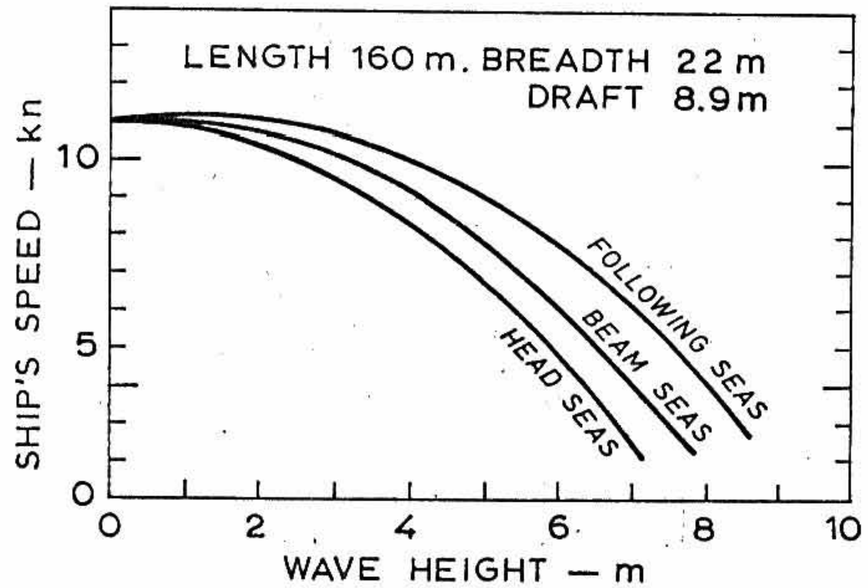
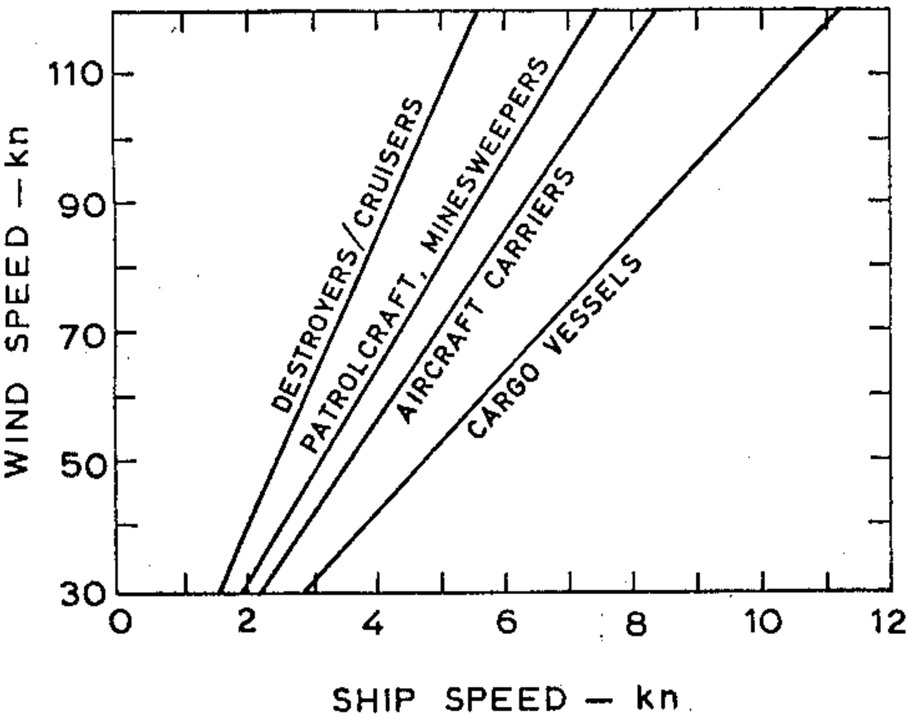


Fig. 14.~~29~~ 28 Typical curves showing the effect of waves on the speed of a conventional cargo liner of about 20 000 tonnes displacement and having a normal economical speed of 11 kn.



The curves shown were developed using the basic formula:

$$\text{WIND LOAD} = R_W A V^2$$

where R_W is equal to wind friction factor, (R_W is generally taken as 0.004.)

V is equal to wind velocity in knots

A is equal to projected area above the waterline in sq ft.

Fig. 14.23 Engine power, shown in equivalent ship speed, required to offset the force of the wind for different vessels and normal loading conditions. (Redrawn from Cranshaw 1965).

14.6.2 Ships near a typhoon centre

.1 Over the years the huge waves and violent winds near the centre of deep typhoons have brought disaster to many ships. Just two typhoons during World War II caused more damage to ships of the U.S. Navy than occurred in direct confrontation with the Japanese (Somervell and Jarrell 1969). The loss of the bows of two Japanese destroyers in the September 1935 typhoon (960 mbar) was mentioned in sect. 14.4.2.2. but, it was a component of the U.S. Pacific Fleet which meet with the most tragic typhoon disaster ever to be recounted. It occurred on the 18th December 1944 when the Fleet was caught near the centre of an intense typhoon while operating in support of the invasion of the Philippines in an area about 500 km east of Luzon. Three destroyers capsized and went down with practically all hands. Serious damage was sustained by a light cruiser, three small carriers, three escort carriers and three destroyers. In his report the then commander in Chief, Pacific Fleet, Admiral Nimitz wrote: "Lesser damage was sustained by at least 19 other vessels from C.A.s (heavy cruisers) down to D.E.s (escort vessels). Fires occurred on three carriers when planes were smashed in their hangers; and some 146 planes on various ships were lost or damaged beyond economical repair by the fires, by being smashed up, or by being swept overboard. About 790 officers and men were lost or killed and 80 injured. Several surviving destroyers reported rolling 70° or more; and we can only surmise how close this was to capsizing completely for some of them. The following conditions were typical during the typhoon:-

(a) Visibility zero to a thousand yards.

(b) Ships not merely rolling, but heeled far over continually by the force of the wind, thus leaving them very little margin for further rolling to leeward.

(c) Water being taken in quantity through ventilators, blower intakes, and every topside opening.

(d) Switchboards and electrical machinery of all kinds shorted and drowned out, with fires from short circuits. Main distribution board in engine room shorted by steam moisture when all topside openings were closed to keep out water.

(e) Free water up to two or three feet over engines or fireroom floor plates, and in many other compartments. It apparently all came in from above: there is no evidence of ships' seams parting.

(f) Loss of steering control, failure of power and lighting, and stoppage of main propulsion plant. Loss of radar and of all ability to communicate.

(g) Planes on carriers going adrift, crashing into each other, and starting fires. 3e+ ?

(h) Wind velocities and seas that carried away masts, stacks, boats, davits, and deck structures generally, and made it impossible for men to secure gear that had gone adrift, or to jettison or strike below topside weights when the necessity had become apparent. Men could not even stay up where they would have a chance of getting clear of the ship......

(k) Testimony that the ships lost took a long roll to leeward, varying from 50 to 80°, hung there a little while, and then went completely over, floating a short time before going down."

.2 In most years some cargo vessels are lost in typhoons and the questior arises as to how modern ships should be handled in the central regions of a typhoon. The matter is controversial and is discussed in some detail - with hai raising accounts - in the "Heavy Weather Guide" (Harding and Kotsch 1965) to whi the interested reader is referred. In essence there is disagreement between thc who believe in Captain Elmer Malanot's "Typhoon Doctrine" in which he recommends that the engines are stopped when winds of 60 knots (30 m/s) are encountered and those who consider that the minimum of steerage way should be maintained to keep the vessel headed more or less into the biggest waves with the wind on the starboard bow if at all possible, so as to "open with the storm" that is, to move away from the centre.

.3 Malanot's Typhoon Doctrine calls for a master to get 30 miles (56 km) of sea room before the effects of the typhoon are felt and then, when the wind attains 60 knots (30 m/s) or more and the sea becomes confused the engines should be stopped and the ship allowed to drift until the dangerous area has passed. Of the many examples which Captain Malanot gives to illustrate the success of his technique of not fighting the waves, perhaps the most impressive is that of his passage through typhoon Ruth which passed Okinawa in October 1951. He was then in command of a vessel of 4 500 tonnes displacement, with a draft of 12'2" (3.71 m) forward and 17' 3" (5.26 m) aft and metacentric height (G.H.) about 4.84' (1.48 m). The intense typhoon Ruth passed 25 miles (46 km) east of the vessel on which a minimum pressure of 948.9 mbar was recorded. His ship drifted easily broadside to the wind at speeds up to 5 knots (2.5 m/s) but the direction of the largest and most destructive waves was always from a direction different from that of the wind. Visibility was from zero to 300 m and the vessel pitched heavily with rolls of 35° and occasionally 43° "in general the vessel adapted itself easily to the heavy confused sea. It did not ship any water except for a very few times in the heaviest rolls when a few inches of water above the gunwhale were scooped off the crest of wave". Malanot is fully convinced that a seaworthy ship of any size or draft, with an adequate metacentric height, will be safer with engines stopped rather than using them to "hurl their vessels against the gigantic power of nature and succeed only in their own destruction..... For a ship dead in the water the onrushing crest of a wave will not hit the ship but only lift it". Malanot says that the ship will drift more or less broadside to the wind "which in a typhoon is always from a direction different from that of the biggest and most destructive waves". The part of the foregoing sentence in quotation marks is not, of course, true; the wind and the most damaging waves are quite often from approximately the same direction.

.4 In the same reference (i.e. Harding & Kotsch 1965) letters to the United States Naval Institute Proceedings on the "Typhoon Doctrine" were reprinted. Extracts from some of these letters follow to illustrate the problem areas. Cmdr. C.R. Calhoun U.S.N. was in charge of the destroyer "Dewey" in the December 1944 typhoon and the ship survived an astounding roll of 75°. Three other destroyers the "Hull", "Monaghan" and "Spence" sunk after taking a long roll to leeward, ~~veering from 30° to 80°, hung there a little while and then went completely ove~~r. The burden of Calhoun's letter was that these three destroyers were not lost because their commanders pounded them against the seas with engine power but because of their inherently low margin of stability. He beleived that the "Hull" and possibly "Monaghan" capsized after their engine rooms had been flooded and power lost. The "Dewey" could not be moved more than 10° either way of a position in the trough with the wind on the port beam. It was found that this vessel rode best with one third power on the port engine and 20° of right rudder to keep the wind one point abaft the beam.

.5 Lt. Cdr. Graham U.S.N.R. (Ret.) had one experience of a breakdown in violent weather and experienced the conditions described by Malanot. However, he considered that the excessive rolling which results could be dangerous especially in the case of a cargoship loaded with bulk ore. The cargo could shift and the vessel founder. He wrote:

" When heaving to, head to sea, the recommendation usually found in seamanship books is to keep the sea from two to four points on the bow. The purpose of this is to give the bow a chance to rise to the oncoming sea instead of poking her nose right into it. I disagree with this recommendation, however. I have found it best to head directly into the sea. With a gale force wind on the weather bow, you have to keep way on her to prevent her from falling off into the trough, and the stronger the wind the more way you require. By heading directly into the weather you can cut speed to a bare minimum, which means fewer - and much less forceful - seas coming aboard. Another advantage is that it reduces rolling materially. I have followed this practice for years and am convinced of its superiority.

In Hurricane Carol we made good 1½ miles in 5 hours (by accurate Loran fixes) which is as close to stopped - the ultimate ideal - as one could wish."

" The above is applicable only when wind and sea are from the same direction, of course, but that is the normal situation. In or near the eye of a storm, however, with dangerous seas coming from different directions, it is impossible to avoid heavy rolling. Under such circumstances, I can appreciate the wisdom of stopping and drifting, as is recommended in "Typhoon Doctrine"".

.6 Captain John F. Wilson of the S.S. Pioneer Lake U.S. Lines ".... concluded that no rules can cover all vessels. All depends on the vessel's size, her cargo, how it is stowed, and her handling qualities which only her master can know.

" In a loaded C-2 I fear rolling more than pitching or pounding. Experience has taught me just about how much work my vessel can stand. As long as possible, I "weather a gale," by maintaining steerage-way on 40 RPM, with a man at the phone and a throttle watch, to increase should she go off." He also described his experience in the T.E.S. Virginia (32 500 tonnes displacement) in the Caribbean hurricane of September 1933. He was caught in the centre of the hurricane and his barometer, corrected, fell to 927.8 mbar "the wind force was more than 125 mph (56 m/s) proved by the fact that the anemometer on Swan Island, near us, broke down at this force. The ship went out of control; the rain, driven by the wind, cleaned the paint off steel stanchions, as though they had been sandblasted. Rain water ran over the thresholds and under the outside doors, spilling into the main lobbies and cascading down the main stair cases. Our heads rang as though we had taken quinine tablets. To breath more easily, men in the fireroom had to remain near the floor plates. The hurricane bridge rails were folded back to the deck by the wind. Lifeboats were torn from their chocks and smashed against the boat deck house. I attempted to go down the outside ladder, and my 140 lbs. was virtually supported by the wind;

I had to haul myself down. Fantastic and freakish damage was sustained".

.7 In a discussion of the difficulties encountered by ships in typhoons Piddington (1845) wrote that "Hatches are not usually made strong enough". Doberck (1886 and 1898) expressed the same opinion but, 130 years after Piddington, it still happens that ships are lost in typhoons because hatches are broken and holds flooded. A cubic metre of water weighs one tonne and the stresses on decks and hatch covers from water falling from breaking waves must be great indeed.

14.6.3 Ships in port

.1 Very few ports in the Western Pacific area can be described as generally safe for large ships in typhoon conditions although some ports may give good shelter in particular circumstances. Brand and Blelloch (1976) in their excellent "Typhoon Havens Handbook" rate only Yokosuka and Kure as good typhoon havens. Among the many factors to be considered in assessing a port are its exposure to wind and sea, the adequacy of moorings and seabed conditions for anchoring, congestion, currents, storm surge effects and the influence of nearby hills and mountains on the wind flow. The change in direction of the wind which accompanies the close passage of a typhoon centre accentuates these problems because an anchorage that may be sheltered for one wind direction may suddenly become extremely hazardous if the wind direction reverses. A frequent cause of disaster to a well secured and prepared vessel is an impact with a drifting ship that has either broken from it moorings or is dragging its anchors. For these reasons it is usual for all ocean-going vessels larger than about 1,500 tonnes to put to sea early enough to obtain adequate sea room before a storm arrives - this aspect of evasion is discussed in section 14.5.5.

.2 The chains used to secure vessels to anchors or to mooring buoys frequently break under typhoon conditions. For example, when the centre of a typhoon passes sufficiently close to Hong Kong harbour to cause gusts there of 50 m/s or more then about 30 ocean-going cargo vessels can be expected to run aground or sink. When the centre of the small typhoon Rose 1971 (963 mbar) passed just to the west of Hong Kong harbour there were 40 ocean-going vessels riding at buoys. Twelve or 30% of these ships broke their cables and there were 38 vessels (not all at buoys) in trouble. In the stronger typhoon Ruby (955 mbar) 1964, 44% of the cables broke. In view of the large number of casualties and the great financial losses arising from this cause the problem of cable breakages, and mooring in typhoons generally, will be discussed further, in the Hong Kong context, although experience there will be typical of that in many other ports of the region.

.3 When a vessel breaks away from its mooring buoy in Hong Kong harbour it is, of course, the ship's cable or securing shackle that parts. The typhoon moorings remain intact; they are of two types, "A" class for vessels not exceeding

183 m in length and "B" class for vessels up to 113 m in length and they are spaced at intervals of 427 m and 305 m respectively. The A (B) class buoys are fixed to a 90 (50) tonne concrete blocks by 33 m of 89 (77) mm stud link steel cable tested to 251 (207) tonnes tension. Ships make fast to these buoys with their own cable which has to be of a size not less than that required by Lloyd's rules for the class of ship. By these rules a number is calculated from the formula:

$$L_s(B + d_s) + 0.85\,L_s(D - d_s) + 0.85(l + h) \qquad (14.18)$$

where L_s = ship's length, B = greatest breadth, D = depth at mid length from top of keel to the deck, d_s = the summer draft, l = overall length of superstructure and h is its height above deck. This number is then entered into a table (appropriate to the units used) to obtain the mimimum size of cable and anchor. For a 74 m cargo vessel of 3 m draft the rules would, typically, specify an anchor exceeding 1.7 tonnes and a 44 mm diameter mild steel chain which would have a breaking strain of about 92 tonnes. From an analysis of 102 cable breakages in the period 1960-1973 George (1974) concluded that about 65% could be attributed to cable fractures and 35% to joining shackle failures.

.4 Cables (or shackles) usually start to break when the gusts (2 second average) begin to exceed 25 m/s. As a rough working rule about 4% of vessels break loose with 25 m/s gusts rising to 35% for typhoons in which the gusts attain 60 m/s.[+] From long experience the Marine Department issue recommendations on typhoon mooring in a booklet entitled "Shipmaster's Guide". Although the professional mariner will wish to consult this guide the engineer, meteorologist or amateur sailor may be interested in the following selected recommendations for an average ocean-going cargo liner. Make fast the ship's cable to the mooring buoy with a shackle of approved type and adequate dimensions, run the ship's cable through the anchor cable hawse (damage to a cable can result in only moderate winds if led over a sharp edge). Two shackles (55 m) of chain should run from the ship, the second bower anchor should be dropped under foot and veered out as necessary, all ballast tanks should be completely filled to reduce windage and yawing (and to facilitate salvage should the vessel go aground), have towing lines ready for use fore and aft and a spare bower anchor suspended over the ship's foredeck ready to assist the second bower anchor if necessary. Finally,

+ Percentage vessels breaking = 0.96 V_g − 15 where V_g = maximum gust in m/s.

the ship's propulsion machinery should be used to ease the strain on the anchor cable. However, in the poor visibility in the violent rain extreme care should be taken not to overrun the buoy between squalls or to accentuate a yaw. I can add that ships which have broken from their moorings and have been trying to hold position with anchors and engine have been known to run aground against the wind in the poor visibility.

.5 George (1974) considers a simplified example of a breakage caused by a sudden shift in wind direction - the usual cause. In his illustration a 38 m/s head wind causes a ship resistance of 25 tonnes this is added to the 12 tonnes resistance due to a 2.5 m/s head current giving a total resistance of 37 tonnes. If the wind suddenly veers through 90^{o} to blow the ship to an equilibrium position against the current the total ship resistance rises to 185 tonnes sufficient to break the specified cable for the ship considered. In addition to the stresses caused by veering of the wind in squalls in a harbour formed by hills, there are stresses due to the snatching caused by waves when the cable is fully extended in squalls. Two cables should be used if their combined strength does not exceed that of the buoy cable. George (1974) suggests that a central hawse pipe and cable would obviate bad leads and permit the use of both bower anchors in an emergency.

.6 Ships at anchor and those at buoys should have out sufficient cable to allow for the increase in the depth of the water which results from the storm surge. In Hong Kong rises of more than 2 m in the main harbour and 3.5 m in Tolo Harbour are rare but greater rises are possible elsewhere (see sect. 14.)

.7 The s.s. "Queen Elizabeth", 84 323 tonnes, when commanded by Captain William Hsuan in August 1971, successfully rode out typhoon Rose while anchored in Hong Kong harbour. The vessel was anchored in 14.6 m of water in the western harbour to the southwest of Tsing Yi Island and was exposed to the full force of the typhoon. Sustained winds of 40 m/s with gusts to 62 m/s were typical for that area. The wind force on the vessel must have been enormous because its windage area is in excess of 1-2 hectares. In normal weather the ship rode to only the port anchor but Captain Hsuan augmented this by the middle anchor some 12 hours ahead of the typhoon passage and, in addition, dropped the starboard anchor six hours ahead of the typhoon. This sequence was adopted to prevent the cables fouling as the wind veered. Each anchor weighed approximately 16 tonnes and the length of chain out varied from 165 m to 247 m for the different anchors; the corresponding weights of the cables being 42 and 62 tonnes respectively. Captain Hsuan tells me that he did not use the ship's engines and that he had no troubles during the typhoon but he afterwards discovered that the anchors had dragged 1.85 km towards the west.

14.6.4 Drifting ships

In most years one or more cargo ships have to be abandoned on the outer fringes of a typhoon and are left to drift. The problem then arises of locating the drifting vessel after the storm has passed. The meteorologist is usually called in to help in this task given the last position and time at which each vessel was left to drift. Good results are attainable by relatively crude methods.

The procedure that I have used for finding drifting cargo vessels is to move them from their last known position at 8% of the wind velocity as determined from 3-hourly weather charts. The factor 0.08 applied to the wind velocity to get the drift speed, or leeway, was determined from experience. In this way a 10 m/s wind would generate a 0.8 m/s drift and a 40 m/s wind a 3.2 m/s drift. These are approximate average speeds for medium sized cargo vessels. Of course, the exact speed will vary with the type of vessel and, in particular, a nearly submerged ship will travel more slowly than a similar vessel with normal draught. The graph in Fig. 14. 29 gives an indication of the spread to be expected although the curves shown refer to the head-on wind resistance and speed.

The "Yoneyama Maru" a 6 900 tonne vessel carrying 9 900 tonnes of iron ore was abandoned in a typhoon and forms an interesting case study. She was caught in typhoon Emma to the southeast of Taiwan on the 13th November 1959 and her steering quadrant was smashed and the rudder jammed to port so as to give starboard helm. She drifted to the southwest under the influence of a strong northeast winds dodging the islands in the Balingtang Channel, Fig. 14. 30 . On the 17th November the vessel entered the circulation of typhoon Freda which eventually passed about 75 km (40 n. miles) west of the ship on the 18th November. The master of the tug "Tai Koo", from Hong Kong, located the drifting ship on 21st November but high seas prevented his securing the tow until the 23rd November. A strong surge of the north-east monsoon caused the tow to be dropped on the 26th November but it was picked up again on 2nd December and the vessel was safely towed to Hong Kong.

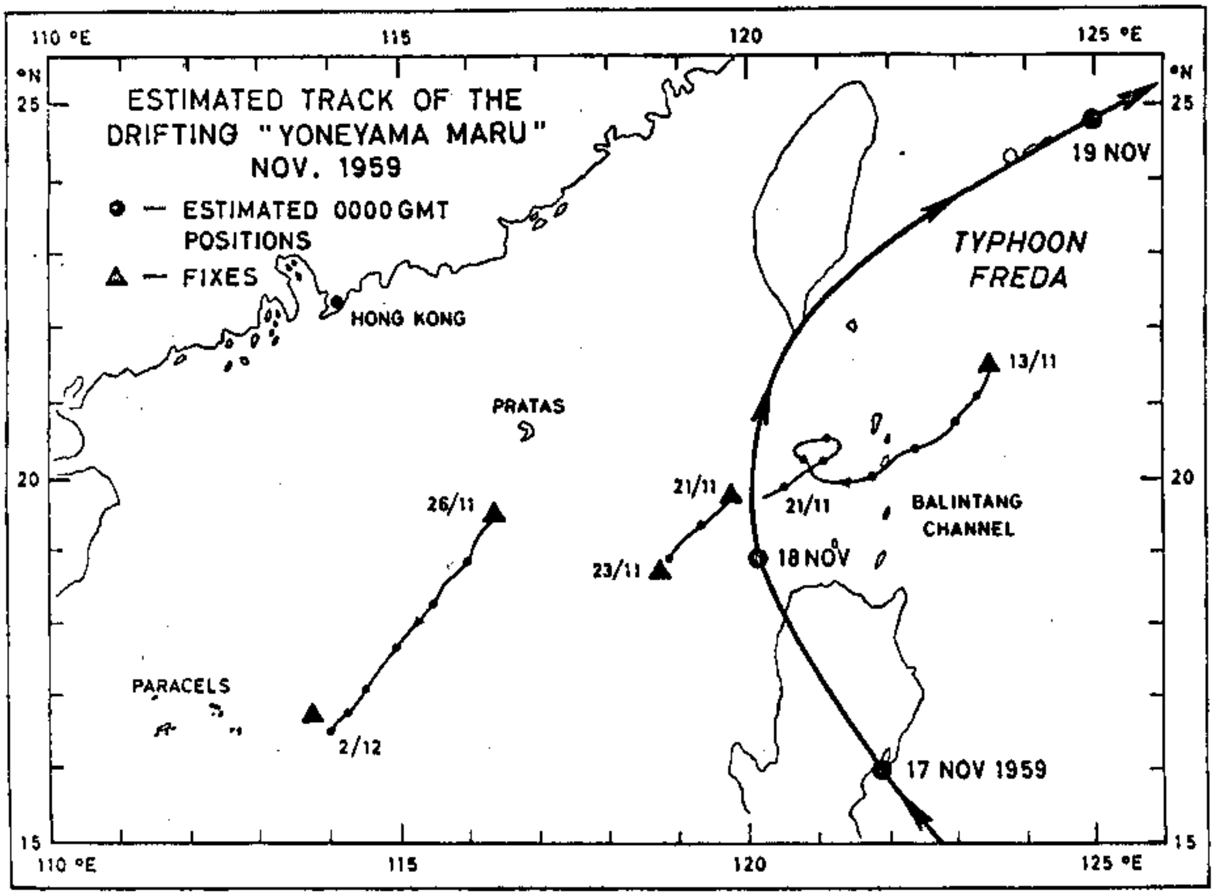


Fig. 14.30 . The track of the "Yoneyama Maru" after being damaged by typhoon Emma and drifting through typhoon Freda. The track starting on 26th November was a period of drifting in a strong northeast monsoon.

During the 16 days during which the "Yoneyama Maru" was adrift she covered about 1163 km averaging 73 km/d or 0.84 m/s (1.68 kn). At the end of each of the three legs its estimated position was within 40 km (22 n. mile) of the position fixed by the tug. No allowance for ~~wind induced counter~~ currents was made. Normal surface currents in the area at that time of the year are about 0.25 m/s but normal currents are probably perturbed by the passage of typhoons.

When tracking rubber dinghies and small lifeboats it is usual to make allowance for wind induced surface currents and their deflection by the earth's rotation and to obtain leeway from specially prepared tables. However, it is unlikely that either type of vessel would survive typhoon conditions. The U.S. Navy Fleet Numerical Weather Central at Monterey has a sophisticated computer programme for determining the drift of a floating object (Bone 1976). Twice each day, the wind field is analysed and the resulting wind-induced currents calculated. Sea currents are calculated from the sea surface temperature and that at 183 m depth. The leeway of the object in terms of a percentage of wind speed is obtained from experience and allowance can be made for objects which drift at an angle to the wind. However, the calculations are based on a grid of size 370 km which is too course to be of much use in tropical cyclone situations.

In the old days, sailing vessels had no choice but to drift with the wind once they were caught in a typhoon and as they passed close to the centre of the storm the winds would change markedly in direction. For this reason it sometimes happened that when the storm had passed sailing vessels found themselves not far from the place at which they first encountered the gales (see Section 2.1.1).

14.6.5 Typhoon evasion

The masters of ships operating in the Western Pacific are frequently faced with the problem of evading typhoons. On average there are about 150 days on which warnings are issued for one or more typhoons and 50 days on which warnings are issued for two typhoons; they are some four to five times as numerous as Atlantic hurricanes and occur throughout the year. The problems of evasion are therefore encountered more frequently in the Western Pacific than elsewhere and they are often more complex as is strikingly illustrated in Figs. 14.31 and 14.32. In the course of a year the delays and costs resulting from evasive action can add up to disturbingly large figures. Nevertheless, for the great majority of vessels, typhoon evasion is the foremost precautionary measure and the most prudent and cost-effective procedure whether the ship be in port or at sea.

In its simplest terms , typhoon evasion consists of navigating a vessel so as to keep it at all times at a safe distance from the centre of mature typhoons. When, for some reason, this cannot be attained the aim should be to ensure that the vessel is in the navigable semicircle of the storm at the time of its closest approach. All this implies that the vessel can move at a speed comparable to that of the storm. The slower the vessel the more complicated becomes the evasion problem and the earlier must action be initiated. Sometimes as much as 3 to 5 days lead time on the closest approach of the storm is required to permit a vulnerable vessel to obtain a safe position.

The most common evasion technique is called by Somervell and Jarrell (1969) "crossing the T" and involves running downwind and sea ahead of an approaching typhoon so as to cross the storm's track and reach a latitude south of the storm's centre. Of course, this should only be attempted if the track can be cleared well ahead of the gale force winds otherwise, the rising seas will progressively slow the vessel and ensure a rendezvous with the storm centre as occurred in the incident recounted in section 14.5.1. A latitude south of the centre should always be achieved, if possible, as this is safe from storms which start to recurve but subsequently resume a westerly track (sect.).

Recurvature is a problem both for the meteorolgist and the mariner. As explained in section a meteorologist can sometimes feel quite confident that a storm will or will not recurve only to have the

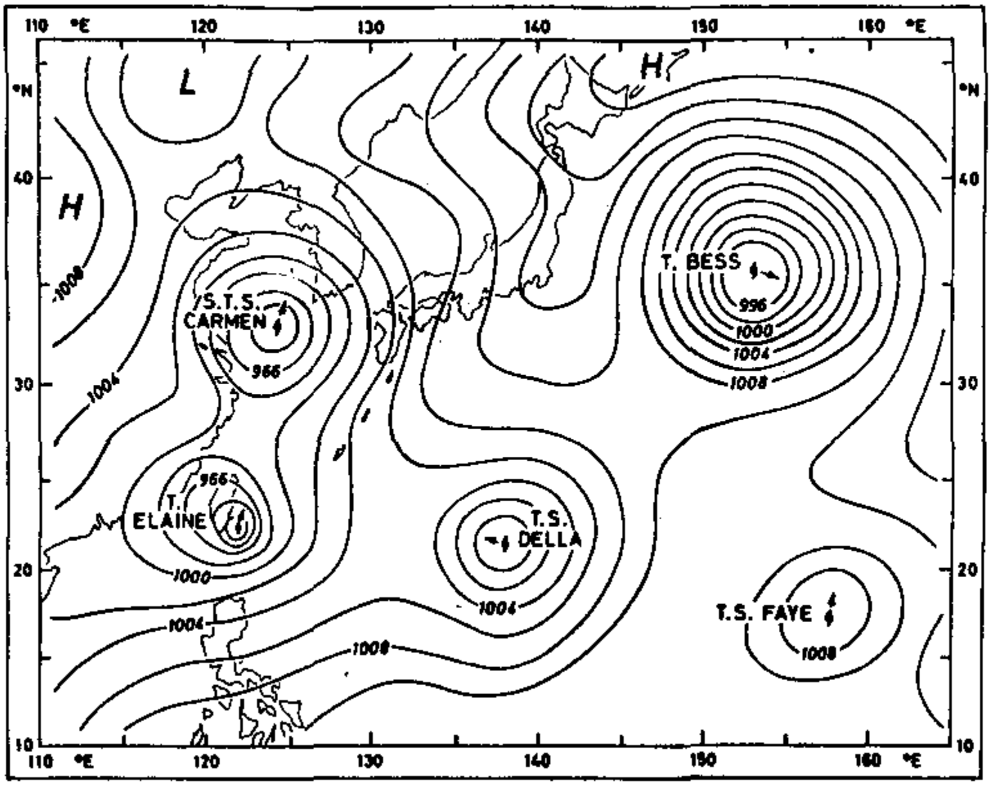


Fig. 14.25 The weather map at 1200 G.M.T. on the 22 August 1960 showing five tropical cyclones.

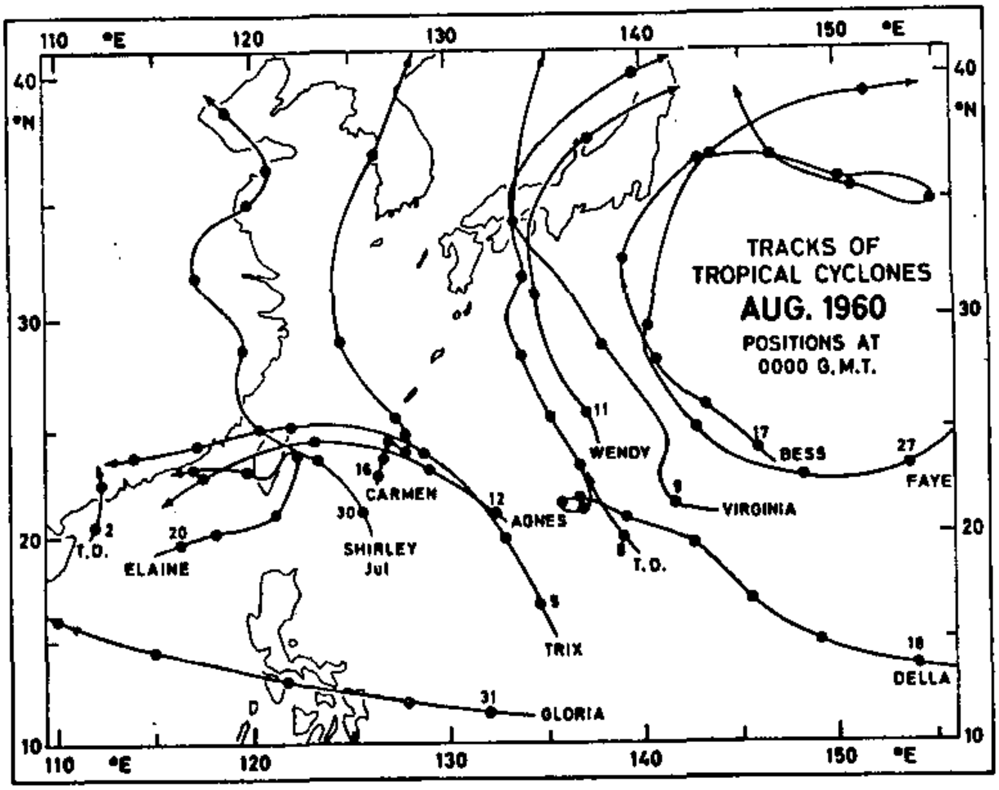


Fig. 14.26 The tracks of thirteen tropical cyclones during the one month of August 1960, as published by the Royal Observatory, Hong Kong.

situation change completely in a matter of twenty-four hours or so. A vulnerable vessel at a latitude north of a typhoon which has not recurved and is within about 1 000 km distance is not in a secure position until its bearing from the storm centre is 045° or more. Fortunately, during recurvature, typhoons tend to move more slowly (but not always) and give time for manoeuvring. However, once the storms are caught up by the polar westerlies they rapidly accelerate reaching speeds up to 15 m/s in summer and 25 to 30 m/s by mid-autumn. Under these circumstances, although the storm may begin to weaken the radius of the gales often increases and it then becomes almost impossible for a ship to escape the dangerous regions of the typhoon. The reference to a typhoon's slower movement during recurvature applies only to true recurvature that is, when the direction of the storm's movement passes through north to take on a significant easterly component; it does not usually apply when the storm swings from a westerly to a more northerly course.

Forecast positions given in warning messages should be used in an advisory role. They are of the nature of best current estimates and should not be taken as exact predictions; this applies particularly to forecasts for extended periods of more than 24 hours. It is unfortunate that current warning formats do not allow for some statement of confidence in the given forecast movement bacause, in some circumstances, the meteorologist can be very confident of his prediction for 48 hours or more but, on other occasions e.g. as a storm moves close to a recurvature situation, the probability of recurvature may be about 50%, leading to widely disparate forecasts of near equal probability yet only one is issued. The mariner should, therefore, always be on guard against the possibility of an unexpected recurvature or the failure of a predicted recurvature. The climatological charts of section are of some assistance in indicating the probability of recurvature in different areas. The foregoing remarks apply to changes in movement but, changes in intensity can sometimes have equal operational significance. A vessel which could safely traverse a tropical depression or tropical storm could be in difficulties in a typhoon. It is indicated in section how rapidly these storms can intensify. Estimates of current intensity should not be significantly in error in these days of satellite observations but, for planning purposes, it is advisable to allow for some deepening with time unless there are strong indications to the contrary.

Recognising the errors currently inherent in forecast of tropical cyclone positions Somervell and Jarrell (1969) recommended the plotting of ellipses to delineate the danger areas associated with each forecast position. The ellipses, centred on the forecast position, have their minor axes perpendicular to the forecast track and of length equal to twice the average error appropriate to the forecast period. The major axes are 1.5 times the minor axes and lie along the track to recognise that errors in forecasts of speed tend to be greater than those of direction. The ellipse is then expanded outward by a distance corresponding to the radius of the 15 m/s winds as given in the warnings. Brand and Belloch (1976) recommend delineating the area covered by 15 m/s winds around a forecast position and then expanding this outwards by the error appropriate to the forecast period. In 1975, average forecast errors were running at 200, 500 and 800 km for 24, 48 and 72 hour forecasts (JTWC 1975) so that the dangerous areas as delineated by these methods are very large and, in the face of the situation depicted in Fig. 14.29 would cover much of the Western Pacific. Although the great majority of forecasts will verify well within the area delineated by the described methods allowance should still be made for the occasional large error as a storm moves up to a latitude where recurvature is possible.

When in port, evasive action must be taken early because sea conditions in the port approaches can severely restrict navigation many hours ahead of the arrival of a typhoon centre and so prevent a vessel from obtaining safe sea room. For example, in 1949 a Royal Navy Fleet was late in leaving Hong Kong harbour ahead of an approaching typhoon. It attained the open sea near Waglan Island but could make no further headway. Hair-raising accounts were subsequently told of the struggles to keep the ships off the rocks as the typhoon passed by. Fortunately, no vessels were lost but much damage was caused and the flight deck of the aircraft carrier HMS Triumph was buckled. Fig. 14.9 shows that high seas can be experienced at Hong Kong when typhoons are still centred far away. Even the small typhoon Rose 1971 produced waves at Hong Kong of over 10 m in height (Fig. 14.4) when still centred more than 185 km or 14 hours away.

Somervell and Jarrell (1969) caution against relying on the ship's radar to assist in evading the most severe parts of a typhoon. They remark that air-reconnaissance crews find that "aside from super typhoons its the exception when you find the classical depiction" (sect. 10.7.1). In addition the wind has been known to stop the radar aerials from rotating - or even to drive them backwards - and there are limitations arising from heavy rainfall, flooding, loss of electric power and violent ship movements. Most of the vessels in the R.N. fleet mentioned in the previous paragraph lost the use of their radars as did the U.S. Navy vessels in the 1944 typhoon.

Some of the difficulties of achieving successful evasion are well illustrated by the case of the U.S.S. Agerholm and its encounter with typhoon Joan 1971 (sect. 14.5.1). The track of the typhoon with 6 hourly positions is shown in Fig. 14.33 (incidentally, note the ~~cycloidal~~ trochoidal track determined by aircraft fixes, just west of Luzon) Sect. 12.2.3. The larger full circles show the forecast positions for 24, 48 and 72 hours after the time of issue of the 112300Z warning (JTWC 1975). Circles of radii 200, 500, and 800 km have been drawn around the forecast positions to correspond with the appropriate average forecast errors (JTWC 1975). These circles have not been expanded to take account of the diameter of the 15 m/s winds but even so the danger area for the 72 hour forecast position, as determined by this technique, already covers most of the South China Sea. A ship unable to leave the shelter of Hainan until 141600Z would clearly be ill advised to try to cross the "T" to achieve a safe position south of the typhoon centre, especially as Joan was at that time still tracking due west. A run towards Hong Kong was therefore attempted but, as stated earlier, a position north of a typhoon puts a ship ~~ship would then be~~ at risk should the situation change and the typhoon curve to the north. By 150500Z the sea state prevented further progress although Joan was still 600 km to the southwest (cf. average 3.7 m sea at 580 km in Table 14.3). The typhoon position and forecast positions issued at 132300Z (solid triangles) and subsequently, were excellent and a big improvement on the earlier forecasts; this illustrates the need to keep up-to-date with both warnings and forecast positions. However, after 150800Z, good as they were, these warnings were of no relevance to the Agerholm which had lost all options and was by then at the mercy of the typhoon.

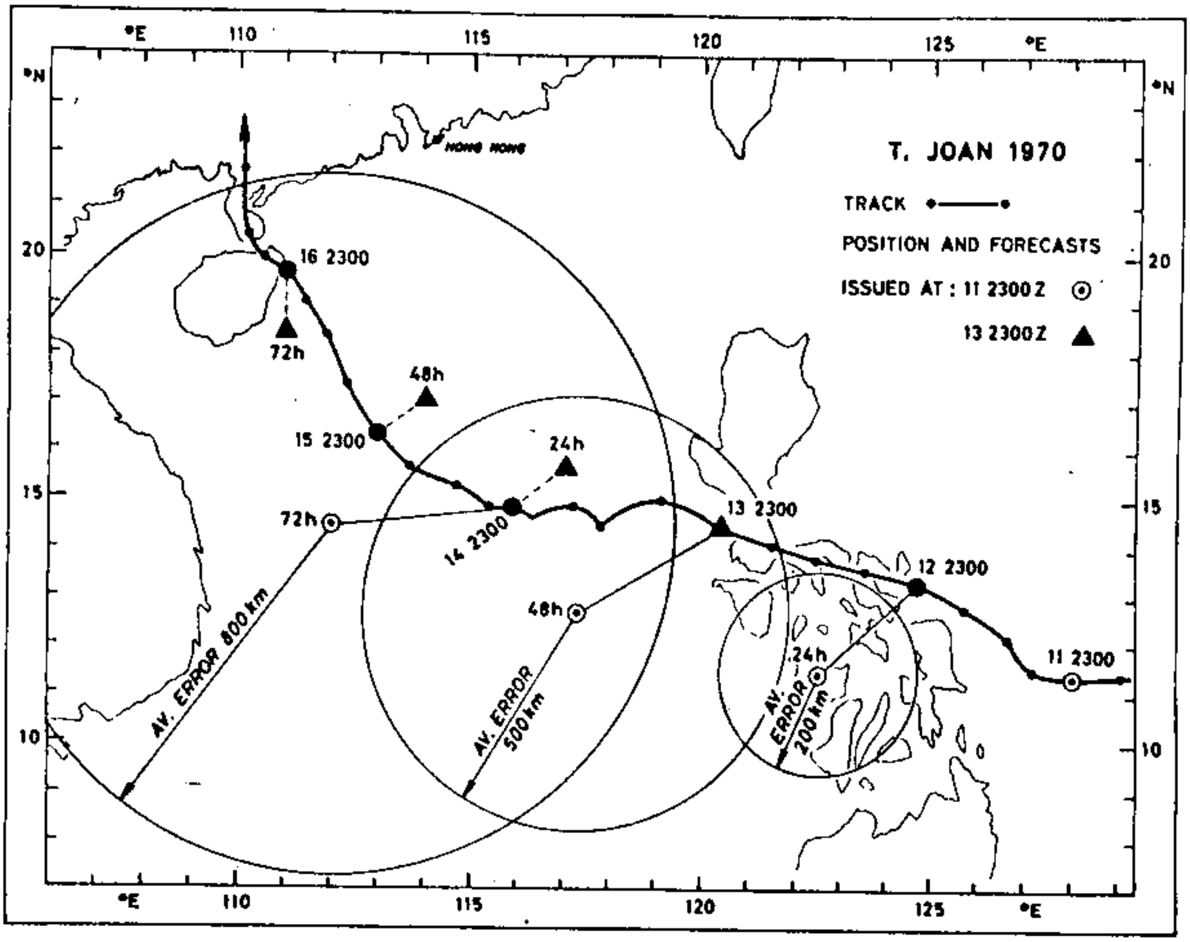


Fig. 14. The track of typhoon Joan with 24, 48 and 72 hour forecast positions issued by JTWC Guam (1970) at 112300 Z and 132300 Z. Average forecast error circles (JTWC 1975) are shown.

The first step in making a safe evasion is to recognise a threat based upon current warnings and a knowledge of the tracks taken by earlier storms at different times of year. A master next has many things to consider, the characteristic of his vessel, the type of cargo, the urgency of his operation and he has to balance the cost of fuel and time involved in a diversion against the risk of damage to ship or cargo in an encounter with the storm. The science of tracking and forecasting typhoons has now reached a level such that a ship routing service in the Western Pacific - like that used on the longer trans-Atlantic and trans-Pacific routes - would greatly reduce the very large financial losses that are now caused annually by typhoons to ship operators.

Finally, meteorologists preparing a typhoon forecast and mariners attempting to evade a typhoon have two things in common. Firstly, their decisions are made after considering very many factors and assessing their effects in the light of experience and judgement. Secondly, after the event, it is crystal clear to every armchair critic as to where they went wrong!

14.6 Buoys

14.6. Capsizing

Four NOAA ~~dot~~ discus type data buoys capsized in the nineteen seventies. In 1977 two 10m buoys capsized in the Gulf of Alaska while moored. A 5m discus buoy capsized ~~whilst~~ in the Atlantic Ocean in early 1978 while drifting after a mooring failure. and a 100 tonne 12m buoy capsized in the mid-Atlantic in early 1979 after drifting – with 10m of broken nylon mooring line – from its station off Cape Hatteras. The latter buoy broke free from its ~~statio~~ moorings at 35°N 75°W in January and drifted about 1000 km to 34.6°N 64.4°W where it capsized on 1st February. On 24 April the buoy was located at 26.6°N 54°W and was retrieved

A study of the environmental conditions associated with these capsizings were found to be very similar. In general, strong westerly winds south of deep cyclones occurred for a sufficient length of time to move maximum wave energy to ~~the~~ relatively long periods. Cold troughs with ~~intense~~ convective cells and thunderstorms locally increased the already strong wind and created high-energy short-period waves. These ~~short waves~~ high-energy short waves superimposed on the large long waves increased their height by superposition, and caused breaking ~~on the upper~~ at their crests. The breaking of the large long waves ~~then~~ caused the capsizing of the buoys.

Mariners Log Nov 79

14.6 Buoys

While travelling towards the north-west in the Gulf of Mexico on the 11-12 September 1979 hurricane Frederic moved directly over buoy 42003 at 26°N 86°W. The recordings of pressure, sustained wind speed and significant wave height are shown in Fig. 14.— The lowest pressure recorded by the buoy was 959.3 mb at 0200 GMT. The highest sustained wind of 34 m/s and the highest significant wave height of 10.4 m both occurred two hours earlier at 0000 GMT. These last two values fit well on the curve of Fig. 14.— relating local wind speed to local wave height in C—C—S.

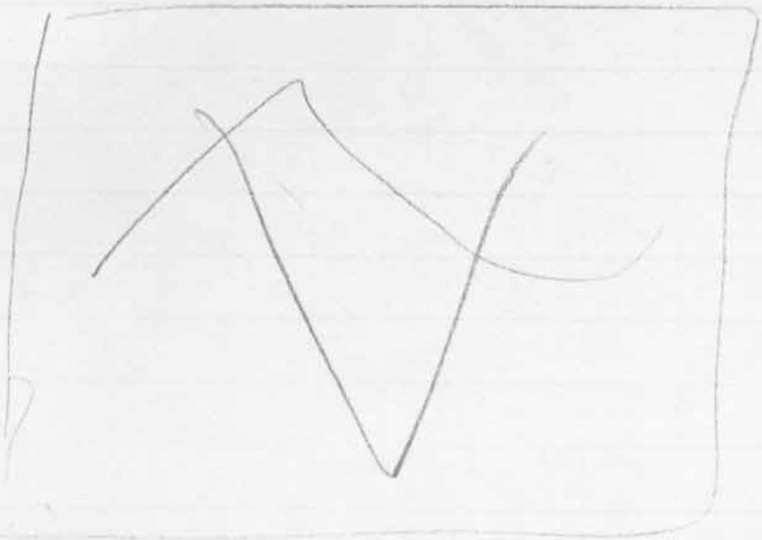


Fig 14.— Wind, wave and pressure traces, as hurricane Frederic passed over buoy 42003 in the Gulf of Mexico on 11-12 September 1979

(Redrawn from NOAA's publication Mariner's Weather Log 1979)

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List of Symbols used in ~~Chapter~~ Sections 14.4, ~~and~~ 14.5 and 14.6

a	Wave amplitude
A	Projected area above the water line
B	Greatest breadth
C	Wave celerity or phase speed
C_o	Deep water wave speed
d	Water depth
d_s	Summer draft
D	Depth at mid length from top of keel to the deck
E	Area under the spectrum having a vertical height expressed in $\frac{1}{2}a^2$ which is proportional to total wave energy per unit sea area
E_H	Area under the spectrum having a vertical height expressed in H^2
$\hat{E}$	Non-dimensional wave energy
f	Coriolis acceleration
f_m	Frequency of the peak spectral density
$\hat{f}_m$	Non-dimensional peak frequency
F	Fetch length
$\hat{F}$	Non-dimensinnal fetch length
g	Acceleration of gravity
h	Height above deck
H	Wave height
H_b	Breaker height
H_c	Characteristic wave height
H_m	Maximum wave height
H_o	Deep water wave height
H_{rms}	Root-mean-square wave height
H_s	Significant wave height
$H_{s\ max}$	Maximum significant wave height
H_7	Geopotential height of the 700 mbar ridge line
$\bar{H}$	Average wave height
$\bar{H}_{\frac{1}{3}}$	Average wave height of the one-third highest waves
l	Overall length of superstructure
L	Wave length
L_o	Deep water wave length
L_s	Ship's length

N	Number of waves
P_c	Central barometric pressure
ΔP	Central pressure deficit
r	Radial distance from the eye
r_m	Radius of maximum wind
R_w	Wind friction factor
$\hat{r}$	Non-dimensional radial distance from the eye
S	Spectral density
S_m	Peak spectral density
T	Wave period
T_c	Characteristic wave period
T_e	Wave period with maximum energy
T_m	Period of wave with maximum wave height
T_s	Significant wave period
T_z	Zero-crossing wave period
$\bar{T}$	Average wave period
$\bar{T}_{1/3}$	Average period of the one-third highest waves
v	Wind speed
v_{10}	Wind speed at 10 m level
v_m	Maximum wind speed at R_m
v_*	Friction speed
V	Forward speed of the storm
α	A coefficient for estimating $H_{s\,max}$
ε	Total wave energy per unit sea area or energy density
ε'	Total wave energy in one wave length per unit crest width
ρ	Density of the water
σ	Standard deviation