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A review of the sea state generated by hurricanes

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Abstract

Data from four studies of waves generated by hurricanes are reviewed and compared. The combined dataset presents a consistent picture of the wave field within a hurricane. The wave field is more asymmetric than the corresponding wind field, mainly due to the "extended fetch" which exists to the right of a translating hurricane. This concept leads to the specification of an equivalent fetch for a hurricane which enables the use of fetch limited growth relations for the prediction of the significant wave height within a hurricane. Examination of spectra recorded within hurricanes indicates that they are remarkably similar to fetch limited forms. Relationships for the parameters defining fetch limited spectra are found to also be valid for hurricane conditions. The reason for the similarity of hurricane and fetch limited spectra is attributed to the shape stabilizing effect of non-linear wave–wave interactions, which continually reshape the spectrum to conform to the standard JONSWAP-like form. Although the wind speeds within hurricanes are very high, the spectra generated are mature, with values of non-dimensional peak frequency typical of fully-developed seas. The analysis develops a set of standard relationships which can be used to define the wave field and spectral form for use in design of offshore fixed and floating structures.

Keywords: Hurricane; Tropical cyclone; Typhoon; Hurricane waves; Hurricane wave field

1. Introduction

Hurricanes, tropical cyclones or typhoons represent powerful meteorological events which are capable of generating extreme sea states. In tropical and semi-tropical regions they often represent the limiting design conditions for coastal and offshore structures, as well as shipping. Because of the extreme meteorological

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conditions associated with hurricanes, their relatively infrequent occurrence and their often unpredictable paths, obtaining a sufficiently large database of ocean wave measurements has been a challenging problem. As a result of a combination of buoy programs, satellite observations and numerical hindcasts using spectral models, conducted over a period of more than 30 years, detailed data now exists. This data set, coupled with our increasing understanding of the physics of wind wave generation and evolution make a quantitative description of the hurricane wave field possible. Recent high profile events, such as the legal enquiry in the UK into the sinking of the M.V. Derbyshire during Typhoon Orchid in 1980 have clearly demonstrated the need for accurate design information for hurricane conditions. This paper provides a review of our present understanding of the hurricane wave field, combines a number of existing data sets, and provides an easily applied method for determining design wave conditions for both fixed and floating structures.

The arrangement of the paper is as follows. Section 2 presents a description of the forcing wind field. Section 3 presents data and a full description of the distribution of significant wave height and peak wave frequency. This is followed by a description of the one-dimensional spectrum in Section 4. A description of the physical processes believed responsible for the observed spectral shape is presented in Section 5. Detailed design considerations are discussed in Section 6, together with limitations of the proposed method. Finally, conclusions are drawn in Section 7.

2. The hurricane wind field

The structure of the hurricane wind field has been the subject of considerable research [1–8]. The structure of the well formed vortex of the hurricane lends itself to relatively simple parametric formulations for the wind field. A number of such formulations have been proposed. A typical example is that of Holland [8]. Following Holland [8], the gradient wind can be expressed as

$$U_g = \left[\frac{AB(p_n - p_0)\exp(-A/r^B)}{\rho_a r^B} + \frac{r^2 f_c^2}{4}\right]^{1/2} - \frac{r f_c}{2}, \tag{1}$$

where U_g is the gradient wind at radius r from the centre of the storm, f_c is the Coriolis parameter, ρ_a the air density, p_0 the central pressure, and p_n the ambient atmospheric pressure far from the storm. The parameters A and B can be expressed in terms of the radius to maximum winds, R, as

$$R = A^{1/B}. \tag{2}$$

The dimensionless parameter B defines the shape of the wind field with increasing distance from the centre of the hurricane. Increasing B concentrates more of the pressure drop near R. Holland [8] has shown that B can be related to the central pressure p_0. A linear fit to his data yields

$$B = 1.5 + (980 - p_0)/120, \tag{3}$$

where p_0 is expressed in hectopascals (or millibars).

Following Shea and Gray [9], the radial winds can be assumed to spiral in toward the centre of the storm with a constant inflow angle of 25°. Also, a first-order asymmetry can be applied to the wind field by adding the cyclone forward speed V_{fm} to the symmetric flow and rotating the maximum to an angle of 70° to the direction of the cyclone forward motion (to the left in the southern hemisphere and to the right in the northern hemisphere). These modifications are consistent with the results of Shea and Gray [9] and Shapiro [10]. The gradient wind velocity U_g can be reduced to U_{10} (1-min average) by the application of a factor of 0.8 [11].

The maximum wind speed within the storm occurs at $r = R$ in (1). At this radius, the Coriolis force is small and the maximum wind speed can be estimated from (1) as

$$V_{max} = 0.8\left(\frac{B(p_n - p_0)}{\rho_a e}\right)^{1/2} + \frac{V_{fm}}{2}. \tag{4}$$

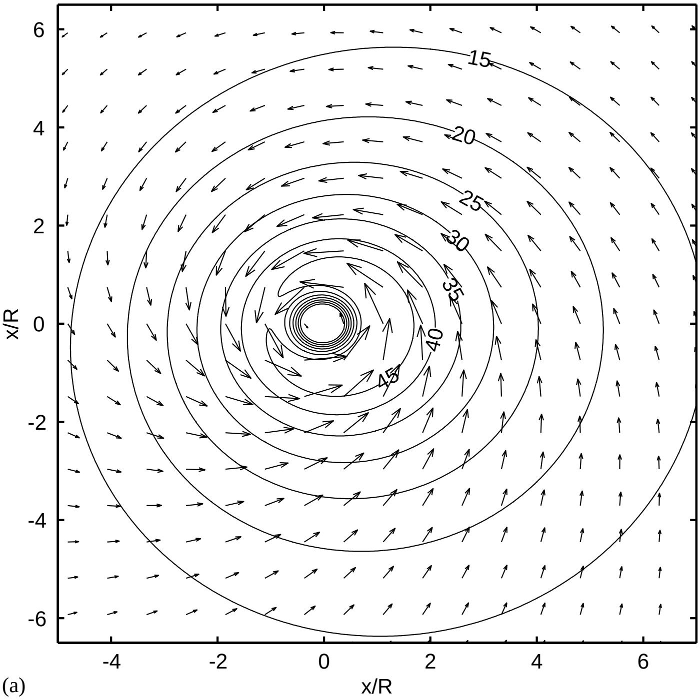
Therefore, the full hurricane wind field can be described by the specification of the three parameters V_{fm}, R and V_{max} (or $p_n - p_0$). Fig. 1a shows a typical example of the two-dimensional wind field generated by this model. The case shown has the parameters $V_{fm} = 5$ m/s, $R = 30$ km and $p_0 = 950$ HPa ($V_{max} \approx 50$ m/s). The characteristic calm eye of the storm and the crescent shaped region of intense winds to the "right" of the storm are clearly evident.

3. The distribution of significant wave height and peak wave frequency

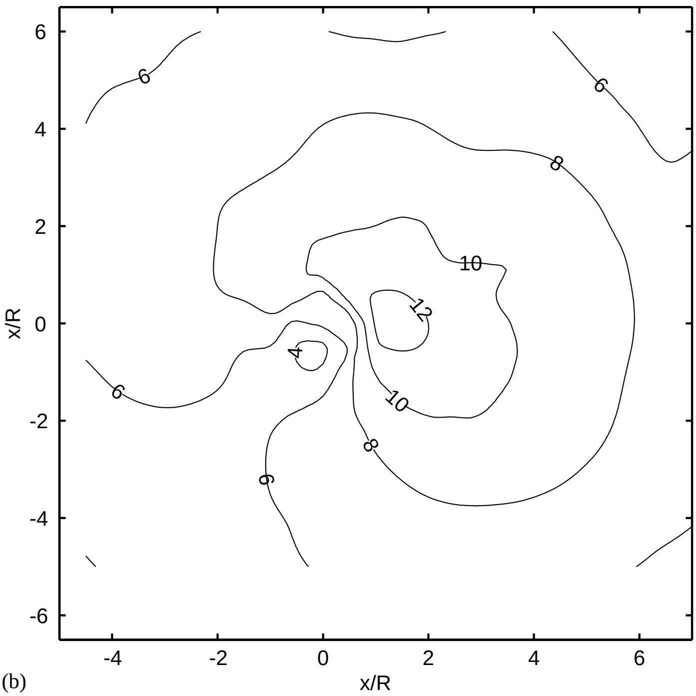
3.1. Observational evidence

An understanding of the spatial distribution of significant wave height, H_s and peak spectral frequency, f_p has been obtained from a number of sources. In situ buoy measurements during the passage of hurricanes have been presented by numerous authors including [12–17]. These data provide valuable measurements of both H_s and f_p, but only at a relatively small number of points in the two-dimensional spatial wave field. Observations over a larger area became available with the advent of satellite remote sensing data [18–24]. Much of these data have, however, been from synthetic aperture radar (SAR) instruments, and although providing valuable directional information, has not yielded reliable values of H_s. Additional information has also been provided from numerical wave prediction models [25–29].

From this composite data set, a consistent picture of the hurricane wave field emerges. A key advance in understanding was made by King and Shemdin [19], who introduced the concept of "extended fetch". Examination of Fig. 1a shows that in the region to the right of the eye of the hurricane, the wind vectors are approximately aligned with the direction of propagation of the hurricane. As a result, waves generated in this area will tend to move forward with the storm and hence remain in the intense wind regions for an extended period of time (extended fetch). Conversely, to the left of the storm centre, the waves move in the opposite direction to the hurricane propagation direction, and rapidly propagate out of the intense wind areas. As a result, the spatial distribution of the wave field does not exactly mirror



(a)



(b)

the wind field. The degree of asymmetry is greater in the wave field than in the corresponding wind field. Critical parameters in determining the degree of asymmetry are the values of $V_{\max}$ and V_{fm}. From fetch limited studies [30], it is known that the wind speed not only has a bearing on the wave height, but also the wave period (frequency), which also determines the group velocity, C_g at which the waves propagate. Assuming a constant fetch, the greater the wind speed, the higher the value of C_g. It can be assumed that the maximum wave height in the hurricane will occur when C_g is approximately equal to V_{fm}. In such a situation, waves will propagate at the same velocity as the storm, remain in the intense wind regions for an extended period and receive maximum energy input from the wind. For a given value of $V_{\max}$, if V_{fm} is relatively low, the waves generated in the intense wind region will "out run" the storm and propagate ahead of the storm. Conversely, if V_{fm} is relatively high, the storm will "out run" the waves, and they will be left behind in regions of lighter winds. These considerations demonstrate that the magnitude of the waves generated by hurricanes is not simply a function of wind speed.

SAR data from numerous studies, together with the numerical model results of Young [28] also provided information on the spatial distribution of the wave field. The wind generates a spectrum of waves with differing values of C_g. For all but the fastest moving storms, spectral components with the higher values of C_g are capable of out running the hurricane and appearing ahead of the hurricane as swell. This swell radiates out from the intense wind generation area to the right of the storm centre. The arrival of swell ahead of an approaching hurricane has been noted by many mariners. This qualitative description of the hurricane wave field is shown in Fig. 2. This figure shows that ahead of the storm, the swell radiating out from the centre of the storm will be crossed by locally generated seas, often at an angle of almost 90°. This leads to confused sea conditions. Reports of "pyramidal" waves in hurricanes, resulting from crossing wave trains are common [31]. These certainly occur ahead of the storm, and possibly also in the right rear quadrant where the swell would radiate out from the less intense wind region to the left of the storm centre.

3.2. Determination of H_s and f_p

A number of semi-empirical approaches have been proposed for the prediction of H_s and f_p under hurricane conditions. Many of these have been based on the general concepts developed for fetch-limited conditions. The simpler of these approaches have not considered the concept of "extended fetch" outlined above and assumed that H_s can be determine from the wind speed, U_{10} alone. Examples of this type of approach have been presented by Bretschneider [32,33] and Ochi [16]. Effectively,

Fig. 1. (a) An example of the wind field generated by the Holland (1980) hurricane wind field model. The contours are of U_{10} in units of m/s. The vectors indicate the wind direction. The hurricane shown has the following wind field parameters: $p_0 = 950$ HPa ($V_{\max} \approx 50$ m/s), $V_{\mathrm{fm}} = 5$ m/s and $R = 30$ km. The storm is propagating up the page with its centre at co-ordinates (0,0). (b) The wave field (Young, 1987) corresponding to the wind field shown in (a). The contours are of significant wave height. Note the significantly different spatial distributions for wind and waves.

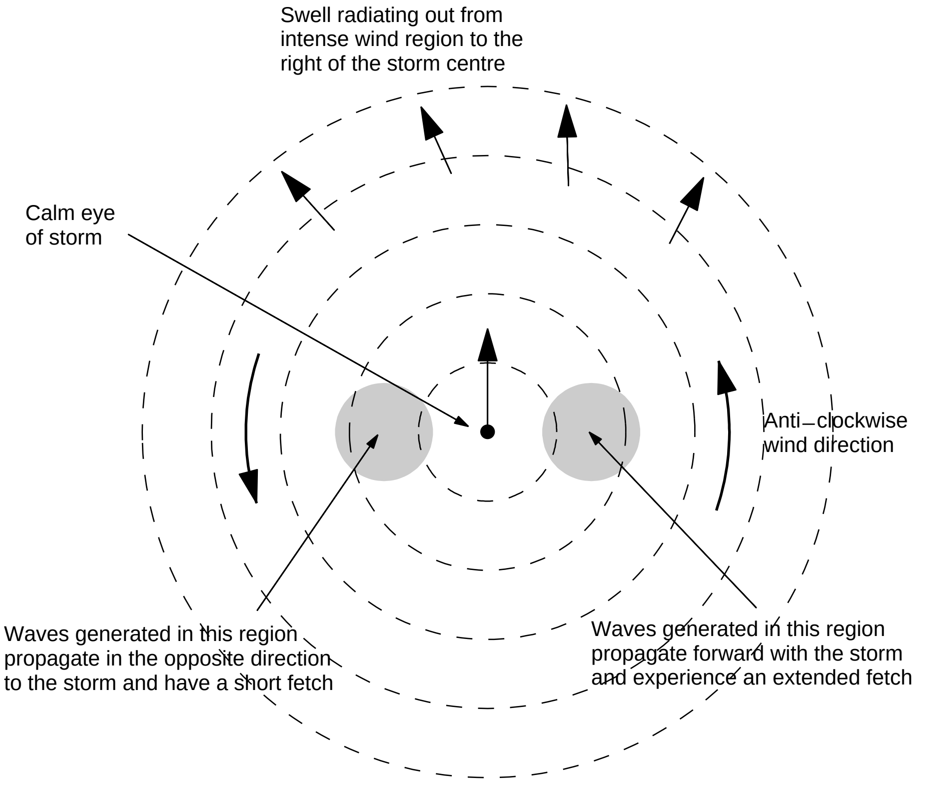


Fig. 2. Schematic diagram showing the generation of waves within a translating hurricane. The hurricane shown is translating "up the page" as shown by the arrow at the centre of the storm. The wave field is characterized by (a) swell ahead of the storm, radiating out from the intense wind region to the right of the storm centre and (b) significant asymmetry caused by the higher winds and extended translating fetch to the right of the storm centre.

these approaches assume that the equivalent fetch for a hurricane is a constant value. Ross [34] extended this approach by assuming that the equivalent fetch should be related to the curvature of the wind field vectors, and hence can be represented by r, the distance from the point of interest to the centre of the hurricane.

An attempt to incorporate the concept of an equivalent hurricane fetch was developed by Young [28]. Young [28] assumed that the JONSWAP [30] relationships, developed for fetch limited growth could be applied to hurricane conditions, with the specification of an appropriate equivalent fetch. A synthetic database was generated using the numerical model of Young [27]. The equivalent fetch, x was defined in terms of the hurricane parameters V_{fm}, V_{max} and R as

$$\frac{x}{R'} = \psi[aV_{max}^2 + bV_{max}V_{fm} + cV_{fm}^2 + dV_{max} + eV_{fm} + f], \tag{5}$$

where $a = -2.175 \times 10^{-3}$, $b = 1.506 \times 10^{-2}$, $c = -1.223 \times 10^{-1}$, $d = 2.190 \times 10^{-1}$, $e = 6.737 \times 10^{-1}$, $f = 7.980 \times 10^{-1}$ and R' is a spatial scale parameter, defined below. The term ψ is a scaling factor which in the representation of Young [28] was taken as 1. In a subsequent study, Young and Burchell [24] augmented the synthetic database with satellite altimeter observations of more than 100 hurricanes. Based on these data they defined ψ as

$$\psi = -0.015 V_{\max} + 0.0431 V_{\mathrm{fm}} + 1.30. \tag{6}$$

The resulting distribution of equivalent fetch x/R' obtained from (5) and (6) is shown in Fig. 3.

Young [28] determined that the effect of the spatial scale of the storm was related to R, through a non-linear relationship, expressed by R'

$$R' = 22.5 \times 10^3 \log R - 70.8 \times 10^3. \tag{7}$$

In (5)–(7) $V_{\max}$ and V_{fm} have units of (m/s) and R and R' have units of (m).

With the equivalent fetch defined, the maximum significant wave height within the hurricane, $H_s^{\max}$ can then be determined using the JONSWAP growth

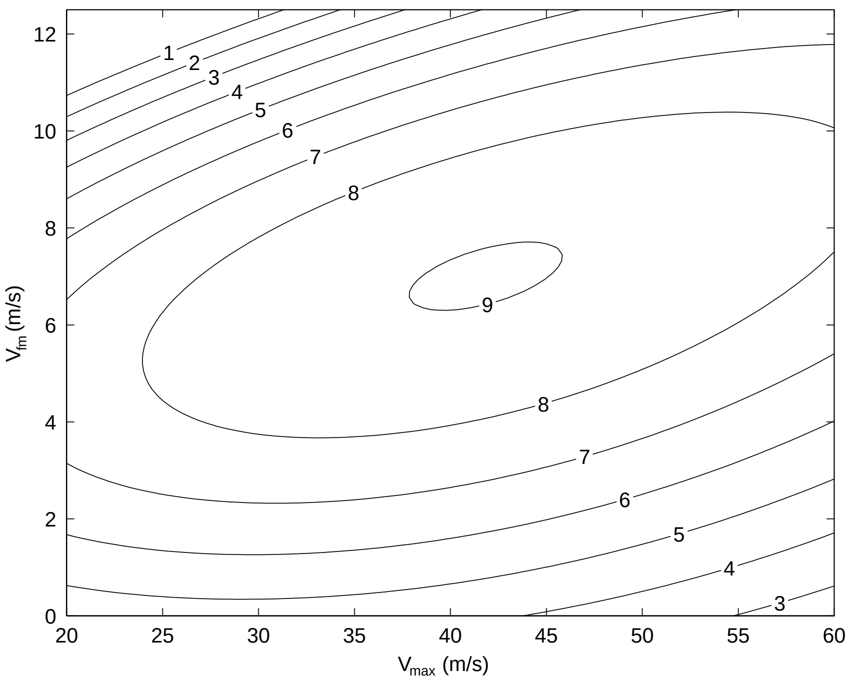


Fig. 3. Contours of the equivalent fetch within a hurricane as proposed by Young and Burchell (1996). The contours are of normalized equivalent fetch, x/R'. The figure was generated from (5) and (6). The surface takes the form of a ridge tilted towards the top right of the figure. Therefore, as storms become more intense (increase in $V_{\max}$) they must move increasing more rapidly (larger values of V_{fm}) to generate the maximum possible waves for that intensity storm. Note that the relationships developed by Young and Burchell (1996) are not applicable outside the parameter range shown in this figure.

relationship [30]

$$\frac{gH_s^{max}}{V_{max}^2} = 0.0016\left(\frac{gx}{V_{max}^2}\right)^{0.5}. \tag{8}$$

In order to determine values of H_s at other points in the hurricane, Young [28] presented a series of non-dimensional spatial distribution diagrams, scaled in terms of H_s^{max} for different values of V_{fm} and V_{max}. A typical example is shown in Fig. 1b. The differences between the wind and wave fields is clear in Fig. 1. As noted earlier, the wave field is more asymmetric. In the case shown, the maximum waves are located slightly ahead (and to the right) of the storm centre. As the velocity of forward movement increases, this region gradually moves to a point behind (and to the right) of the storm centre.

Although the JONSWAP fetch limited relationship is widely used for engineering design, it is only one of many such relationships which has been proposed. A number of studies [35,36] have also pointed out inconsistencies in the JONSWAP relationship. Therefore, some doubt may exist over the suitability of (8). In the present context, the equivalent fetch, as represented by (5) has been determined by fitting the JONSWAP form (8) to the available data. Hence, the use of this form should be valid within the parameter range covered by this data set.

In order to determine the peak wave frequency, Young [28] assumed that the JONSWAP [30] relationship for fetch limited growth could also be applied, and then checked this assumption against the synthetic database used to determine the equivalent fetch. This comparison confirmed the validity of this assumption. Although not explicitly stated by Young [28], this result indicated that, to first order, the spectra under consideration must approximate typical fetch limited forms. A significant limitation of the approach used by Young [28] was that the database used was generated by a model, and hence is limited by the accuracy of the model. The values of H_s produced by the analysis were later corrected by Young and Burchell [24] using altimeter data from actual hurricanes. As the altimeter does not measure f_p, a similar confirmation/correction could not be made for this parameter. In a subsequent study, Young [17] considered a database from in situ buoy data taken from 28 hurricanes in the Australian region. This data set will be considered further in Section 4. Young [17] used this data set to investigate the detailed shape of the spectrum, rather than the relationship between H_s and f_p. The data set can, however, be used for this purpose.

The JONSWAP [30] study proposed a relationship between non-dimensional energy and non-dimensional peak frequency of the form

$$\varepsilon = 7.13 \times 10^{-6} \nu^{-3.03}, \tag{9}$$

where the non-dimensional variables are

$$\nu = \frac{f_p U_{10}}{g}, \quad \varepsilon = \frac{g^2 E}{U_{10}^4} \tag{10}$$

and the total energy can be related to the significant wave height by $H_s = 4\sqrt{E}$. As indicated above, a number of alternative fetch limited relationships have been

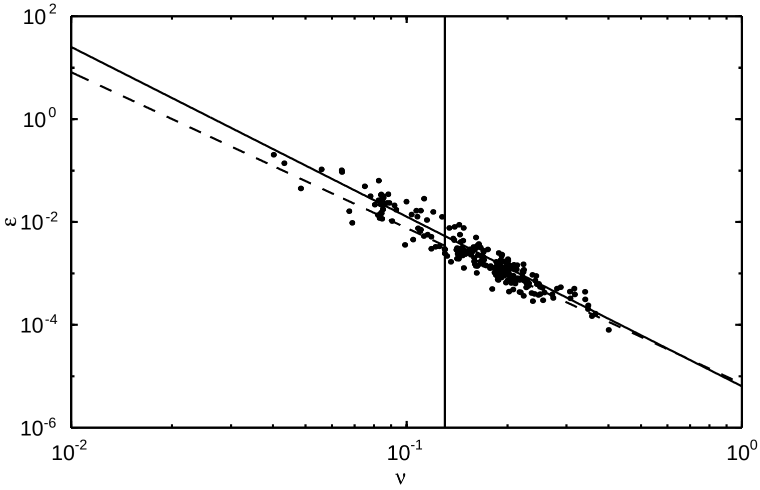


Fig. 4. Non-dimensional energy, ε as a function of non-dimensional peak frequency, ν. The data shown are from the hurricane database of Young (1998). The Donelan et al. (1985) expression (11) is shown by the solid line and the JONSWAP (Hasselmann et al., 1973) expression (9) by the dashed line. The vertical line drawn at $\nu = 0.13$ marks the commonly adopted demarcation between swell and wind-sea.

proposed as a result of more extensive data sets collected since the original JONSWAP experiment. One of the most comprehensive of these studies is that of Donelan et al. [37], who have proposed the alternative form

$$\varepsilon = 6.365 \times 10^{-6} \nu^{-3.3}. \tag{11}$$

Fig. 4 shows the data of Young [36] compared with both (9) and (11). Both results agree remarkably well with the recorded data. With the data scatter present, it is not possible to determine if one formulation is superior to the other. Both are in excellent agreement with the data. The data in Fig. 4 are taken from a large number of hurricanes covering a range of values of $V_{\max}$, V_{fm} and R. Also, the data are taken from a range of different positions, relative to the centre of the storms. In all cases, the data appears to be in quite remarkable agreement with results taken from fetch limited growth.

Ochi [16] has presented an alternative formulation for the prediction of H_s, in terms of the local wind speed, alone

$$H_s = 0.235 U_{10}, \tag{12}$$

where H_s has units of (m) and U_{10} has units of (m/s). Eq. (12) equates to (8) for a fetch $x = 210$ km. Examination of Fig. 3 shows that for a large percentage of the $V_{\max} - V_{\mathrm{fm}}$ parameter space the equivalent fetch is between $8R$ and $9R$. Assuming a typical value of $R = 25$ km, this yields an equivalent fetch very close to the constant value of $x = 210$ km implicit in the Ochi [16] formulation. Hence, the Ochi [16] result is likely to be a reasonable approximation for a reasonable region of the parameter space. Implicit in (12) is the assumption that the wind and wave fields have the same relative spatial distributions. This is clearly not the case in Fig. 1 (note that for this case $x \approx 8.5R$), indicating that (12) may be less reliable in regions distant from the maximum wind areas of the storm. Also, examination of the diagrams presented by Young [28] indicates the spatial distribution of wave height varies considerably as the relative values of $V_{\max}$ and V_{fm} vary.

4. Spectral shape

Both Ochi [16] and Young [17] have presented data on the detailed shape of hurricane wave spectra. Both studies showed that, for spectra recorded relatively close to the storm centre ($8R$ in the case of Young [17]), the spectra were uni-modal and appeared similar to typical fetch-limited data. As a result, these data were fitted to the commonly used JONSWAP [30] form

$$F(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp\left[-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right] \gamma^{\exp\left[\frac{-(f-f_p)^2}{2\sigma^2 f_p^2}\right]}, \tag{13}$$

where the shape parameters α, γ and σ were determined from the fitting process. The JONSWAP spectral form has been widely used in engineering design. A host of studies have, however, shown that this basic form, with a high frequency face proportional to f^{-5}, is not a particularly good representation for the wind-wave spectrum [37–43]. These studies showed that both the observational database and theoretical considerations favour a high frequency face proportional to f^{-4}. Based on this evidence, Donelan et al. [37] proposed the alternative form

$$F(f) = \beta g^2 (2\pi)^{-4} f_p^{-1} f^{-4} \exp\left[-\left(\frac{f}{f_p}\right)^{-4}\right] \gamma_d^{\exp\left[\frac{-(f-f_p)^2}{2\sigma^2 f_p^2}\right]}. \tag{14}$$

Note that the notation, β and γ_d has been used to distinguish these parameters from their JONSWAP counterparts, α and γ. In the present context, it is appropriate to investigate both of these spectral formulations.

Young [17] investigated the value of the parameter n in the formulation $F(f) \propto f^n$ for the high frequency spectral face of his hurricane spectral database. The resulting values are presented as a function of the non-dimensional peak frequency, ν in Fig. 5. The results are inconclusive, with a wide scatter in the data with values ranging between -3 and -6. The mean value of the data set is $n = -4.56$, almost mid-way between the values of -5 and -4 proposed for (13) and (14), respectively.

Fig. 6 shows the values of α and γ reported by Young [17] as a function ν. It should be noted that as the parameter σ has very little influence on the spectral shape, Young [17] held this value constant at $\sigma = 0.1$. Also shown in Figs. 6a and b are the JONSWAP [30] relationships

$$\alpha = 0.033\nu^{0.67}, \tag{15}$$

$$\gamma = 3.3. \tag{16}$$

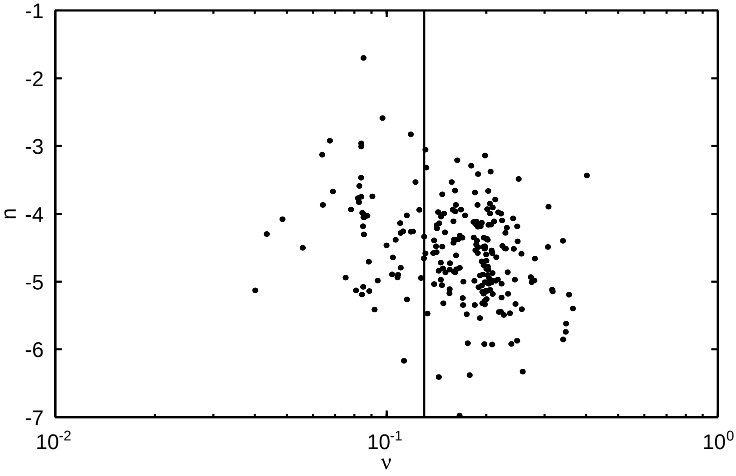


Fig. 5. Values of the exponent n in the relationship $F(f) \propto f^n$ plotted as a function of the non-dimensional peak frequency, ν for the hurricane data of Young (1997). The vertical line drawn at $\nu = 0.13$ marks the commonly adopted demarcation between swell and wind-sea.

It should be noted that Hasselmann et al. [30] could find not systematic trend in their data for γ, the constant value of $\gamma = 3.3$ in (16) being the mean of their data.

The values of α are in reasonable agreement with (15) showing the same general trend. It is interesting to note the values of ν shown in Fig. 6. The vertical line drawn at $\nu = 0.13$ marks the conventional limit for full development of the wave spectrum. For values of $\nu < 0.13$, waves at the spectral peak frequency are propagating significantly faster than the local wind speed and hence are not receiving direct input from the wind. Waves with $\nu < 0.13$ are traditionally classed as swell, rather than wind-waves. A significant proportion of the hurricane database has values in this range. Despite this, the same data trend exits in this region. That is, even for $\nu < 0.13$, the values of α and also the relationship for the energy (ε or H_s shown in Fig. 4) follow trends recorded for fetch limited wind seas. The values of ν also indicate that hurricane waves, although subjected to high winds, are quite mature. Although not explicitly reported in this form, the data of Ochi [16] appears to show the same features.

The values of γ shown in Fig. 6b show no consistent trend as a function ν as also reported in JONSWAP [30]. This is not surprising since, as reported by a number of authors, values of γ are extremely difficult to accurately determine from spectra defined at a limited number of frequency values. Hence, the sampling variability for γ is large. It is clear however from Fig. 6b that the values of γ recorded in hurricane conditions are significantly smaller than the mean JONSWAP value. As it is generally assumed that $\gamma = 1$ at $\nu = 0.13$, the Pierson–Moskowitz values [44], small values of γ are consistent with the recorded values of ν. The mean value of the Young [17] hurricane database is $\gamma = 1.9$.

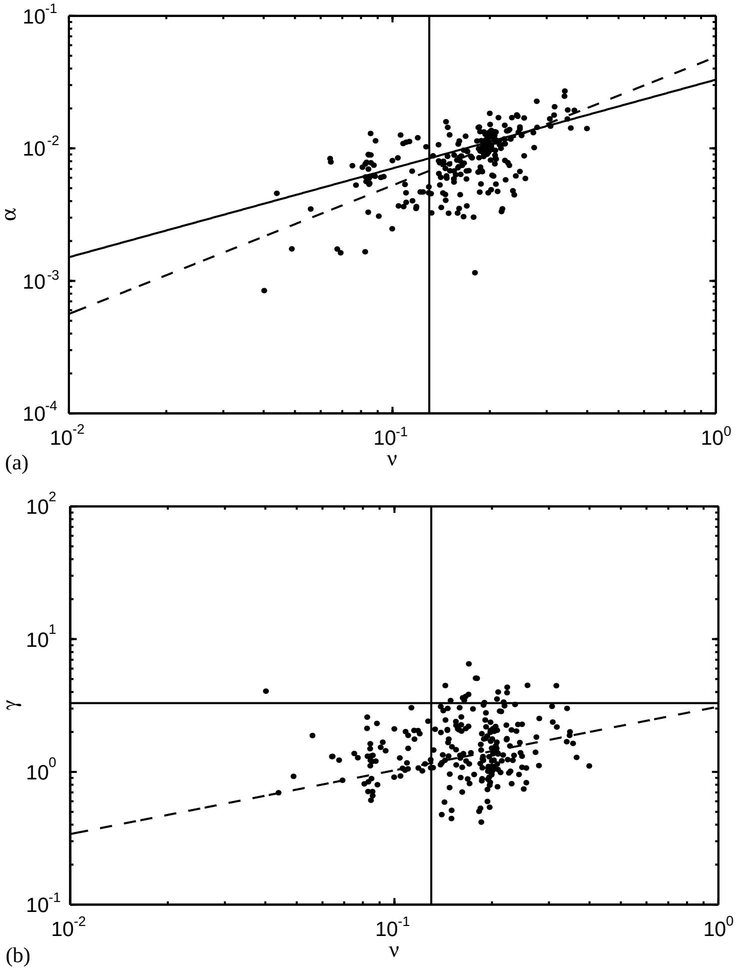


Fig. 6. (a) Values of the parameter α [Eq. (13)] as a function of the non-dimensional peak frequency, ν for the hurricane data of Young (1997). The JONSWAP (Hasselmann et al., 1973) expression (15) is shown by the solid line and the Ochi (1993) expression (18) by the dashed line. The vertical line drawn at $\nu = 0.13$ marks the commonly adopted demarcation between swell and wind-sea. (b) Values of the parameter γ [Eq. (13)] as a function of the non-dimensional peak frequency, ν for the hurricane data of Young (1997). The JONSWAP (Hasselmann et al., 1973) mean value (16) is shown by the solid line and the Ochi (1993) expression (21) by the dashed line. The vertical line drawn at $\nu = 0.13$ marks the commonly adopted demarcation between swell and wind-sea.

Ochi [16] also fitted the JONSWAP spectral form to his hurricane data, and represented α in the form

$$\alpha = 4.5 H_s^2 f_p^4, \tag{17}$$

where the constant is dimensional, having units of $[\mathrm{m}^{-2}\mathrm{s}^4]$. Introducing non-dimensional variables, and substituting the JONSWAP relationship (9), (17) becomes

$$\alpha = 0.049\nu^{0.97}. \tag{18}$$

Eq. (18) is shown in Fig. 6a and appears to be a better approximation to the Young [17] data than the JONSWAP form (15). This is hardly surprising, since it was developed explicitly from hurricane data. It does, however, demonstrate that the Ochi [16] and Young [17] data sets are consistent.

Ochi [16] also presented a relationship for γ of the form

$$\gamma = 9.5H_s^{0.34}f_p. \tag{19}$$

Again the constant is dimensional, both H_s and f_p being expressed in standard SI units (H_s – [m]; f_p – [s^{-1}, Hz]). Reformulating in non-dimensional variables and introducing (9), as for (18), yields

$$\gamma = 9.1U_{10}^{-0.32}\nu^{0.48}. \tag{20}$$

Eq. (20) is not expressed in non-dimensional terms, having a weak dependence on the wind speed. A comparison with the data of Fig. 6 requires the nomination of a representative wind speed. As the dependence on U_{10} is weak, the selection of this value is not too critical. If a value of $U_{10} = 30$ m/s is selected (typical for hurricane conditions) (20) becomes

$$\gamma \approx 3.1\nu^{0.48}. \tag{21}$$

Eq. (21) is shown in Fig. 6 and is clearly consistent with the data of Young [17].

One of the deficiencies of the original JONSWAP relationships is that they do not represent an internally self-consistent set of equations. For instance, for a given value of ε, ν can be defined from (9). The spectrum can then be defined in terms of the parameters of (15) and (16). If this resulting spectrum is integrated to determine the total energy, the result is not consistent with (9). The same deficiency exists for the Ochi [16] relationships (18) and (21). Lewis and Allos [35] have attempted to reformulate the JONSWAP relationships to develop a self-consistent set of equations.

Donelan et al. [37] developed a set of fetch limited relationships for (14) which are self-consistent. Together with (11), these equations take the form:

$$\beta = 0.0165\nu^{0.55}, \tag{22}$$

$$\gamma_d = \begin{cases} 6.489 + 6\log\nu, & \nu \geqslant 0.159 \\ 1.7, & \nu < 0.159 \end{cases}, \tag{23}$$

$$\sigma = 0.08 + 1.29 \times 10^{-3}\nu^{-3}. \tag{24}$$

Fig. 7 shows the values of β and γ_d obtained by Young [17], together with (22) and (23). Both relationships are consistent with the hurricane data. Indeed, the data scatter is slightly less than the corresponding JONSWAP parameters of Fig. 6. Both formulations are, however, consistent with the data.

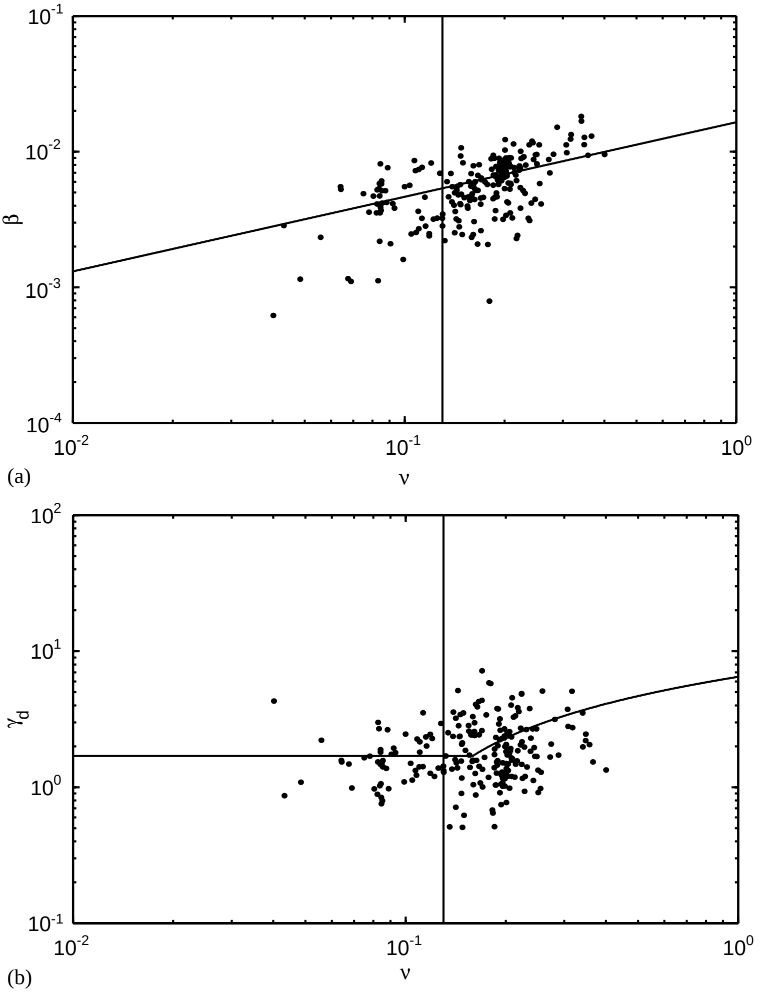


Fig. 7. (a) Values of the parameter β [Eq. (14)] as a function of the non-dimensional peak frequency, ν for the hurricane data of Young (1997). The Donelan et al. (1985) expression (22) is shown by the solid line. The vertical line drawn at $\nu = 0.13$ marks the commonly adopted demarcation between swell and wind-sea. (b) Values of the parameter γ_d [Eq. (14)] as a function of the non-dimensional peak frequency, ν for the hurricane data of Young (1997). The Donelan et al. (1985) expression (23) is shown by the solid line. The vertical line drawn at $\nu = 0.13$ marks the commonly adopted demarcation between swell and wind-sea.

5. The physics of spectral evolution

The results shown in Figs. 3, 6 and 7 show that the spectra generated by hurricanes are remarkably similar to fetch limited conditions. Provided the point under consideration is relatively close to the storm centre (less than $8R$ from the centre), the spectra are uni-modal and conform to the shapes defined by either (13) or (14). For a spatially inhomogeneous wind field, with the wind direction varying on a relatively short time scale, to produce the same spectra as observed in uni-directional, constant speed, fetch limited condition is perhaps rather surprising. An examination of the physical processes active in wind wave generation provides a clear explanation for this result.

In deep water, wind generated waves evolve as a result of the interaction of three process: atmospheric input from the wind, dissipation due to wave breaking and non-linear interactions within the spectrum [29]. Other processes may also be active, but they are considered second order. The non-linear source term is conservative, transferring energy between spectral components, rather than either adding or subtracting energy from the spectrum. This energy transfer has a very important role in shaping the spectrum. Young and van Vledder [45] have termed this process "shape stabilization". The non-linear source term always attempts to force the spectrum to confirm to a spectral shape very close to (13) or (14). A sudden change in wind speed or direction will cause a resulting change in the spectrum, but the non-linear terms rapidly force the spectrum back to this preferred shape. Clearly, if the rate of change is too great, then the non-linear terms cannot respond with sufficient speed and directionally skewed spectra or spectra with abnormally high or low energy in the tail may result. The present results indicate that even in the vortex of a hurricane, the rate of change in the wind speed is not sufficiently large to result in spectra which do not conform to this standard shape.

The rapidly changing wind directions within the vortex of the translating hurricane means that energy at a particular point is not all locally generated. Much of the energy will have propagated to the site from other areas. The "shape stabilizing" role of the non-linear terms also plays a role in this situation. Masson [46] has shown that the non-linear terms play a key role in determining how swell and wind-sea interact. Again, the non-linear terms shape the directional spectrum to conform to a unimodal form with a symmetrical directional distribution. Should the swell and wind-sea be separated by a large amount in either direction or frequency space, the magnitude of the non-linear coupling decreases and the two systems can co-exist [36]. This is what occurs at distances greater than $8R$ from the centre of the storm. A good example is ahead of the storm where swell radiating out from the centre of the storm co-exits with locally generated wind-sea (Fig. 2).

6. Design considerations

The results presented above bring together hurricane data from a number of independent studies (Ochi [16]—North America; Young [17]—Australia, Young and Burchell [24]—Global satellite data). These data sets provide a consistent composite data set, enabling preliminary design under such conditions. The steps in the determination of the wave field and resulting spectra can be summarized as follows.

1. Given design wind field parameters of V_{fm}, V_{max} and R.

2. Eqs. (5)–(8) yield the maximum significant wave height, H_s^{max} within the hurricane.
3. Values of significant wave height, H_s at other points within the hurricane can be determined from the non-dimensional charts presented by Young [28] or in digitized form from the author.
4. The non-dimension peak frequency, v and hence f_p can be determined from (9) (JONSWAP form) or (11) (Donelan form).
5. If a JONSWAP spectral formulation is to be used [Eq. (13)] then the spectral parameters can be determined from: (18)—α; (21)—γ and assuming $\sigma \approx 0.1$ (constant). If a Donelan et al. [37] spectral formulation is to be used [Eq. (14)] then the spectral parameters can be determined from: (22)—β; (23)—γ_d and (24)—σ.

The obvious question to arise in this process is which spectral form should be adopted (13) or (14)? Comparison with the data in Figs. 4, 6 and 7 indicates that there is very little between the different forms. They are both consistent with the hurricane data sets. The Donelan et al. [37] formulation, with a high frequency spectral face proportional to f^{-4} is, however, more widely supported in other situations and has a sounder theoretical basis. Also, the Donelan et al. [37] relationships represent an internally self-consistent set of relationships. For these reasons, it is believed that the Donelan et al. [37] formulation has a sounder basis.

The proposed approach has a number of limitations. The equivalent fetch concept has been developed under the assumption that the wind field parameters V_{fm}, V_{max} and R are approximately constant. The approach is likely to give unpredictable results in cases where these parameters are changing rapidly. Such cases may include a rapidly deepening or weakening hurricane or cases where the direction or speed of propagation changes rapidly. The data used to construct the model have been acquired in deep water and finite depth effects are not included. As indicated earlier, at distances greater than $8R$ from the centre of the hurricane, spectra may become bi-modal. Hence, the present model is limited to locations within $8R$ of the storm centre.

7. Conclusions

This study has reviewed four previous studies of hurricane generated waves [16,17,24,28]. By combining the data and analysis techniques from these studies a consistent picture of the wave field within a hurricane emerges. Hurricane spectra are typically unimodal (single peak) and consistent with forms reported for fetch limited growth. Also, the spectra of hurricane generated waves are typically mature with relatively small value of both non-dimensional frequency, v and peak enhancement factor, γ. The resulting wave field is described in terms of the concept of an extended translating fetch, which makes possible the determination of an equivalent fetch for a hurricane. This equivalent fetch is a function of both the velocity of forward movement, V_{fm} and maximum wind velocity, V_{max} of the hurricane.

Based on this model, and the similarity to fetch limited cases a set of relationships are provided which define H_s and f_p, as well as the parameters defining the spectrum.

One limitation of the present study is that it provides no information on the directional spreading of the waves within a hurricane. A comprehensive database of directional properties is yet to be presented.

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