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The growth rate of finite depth wind-generated waves

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Abstract

Fetch limited wind wave experiments traditionally investigate the growth of wave energy with distance from shore. [Donelan, M., Skafel, M., Graber, H., Liu, P., Schwab, D., Venkatesh, S., 1992. On the growth rate of wind-generated waves, Atmos.-Ocean 30, 457–478], have, however, shown that for deep water conditions it is advantageous to investigate the differential growth between points located along the fetch. Based on the extensive data set collected by [Young, I.R., Verhagen, L.A., 1996a. The growth of fetch limited waves in water of finite depth, Part I: Total energy and peak frequency, Coastal Eng. 28, 47–78], this approach has been extended to finite depth conditions. The data clearly show that at short fetches the growth rate is comparable to deep water conditions. At longer fetches the finite depth influences increase and the growth rate decreases compared to deep water. Finally the waves approach a depth limited state where the growth rate becomes zero. Based on the observed differential growth between measurement stations, a relationship is developed which can be integrated to yield the development of the total energy with fetch. This relationship is significantly more flexible than previous finite depth growth relationships. Cases in which the water depth and/or wind speed vary with fetch can be investigated. In particular, it is shown that the development of the atmospheric boundary layer with fetch has a significant influence on the observed wave growth. By the inclusion of a realistic relationship for the boundary layer development it is shown that apparently anomalous features of the [Young, I.R., Verhagen, L.A., 1996a. The growth of fetch limited waves in water of finite depth, Part I: Total energy and peak frequency, Coastal Eng. 28, 47–78] data set can be explained.
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1. Introduction

The study of the development of waves under fetch limited conditions has a long history. The simplifications of one spatial dimension, invariance with time and a constant wind yield a problem sufficiently ideal to investigate many of the physical processes active in wind wave evolution. In addition, the idealized nature of the problem leads to relatively simple empirical relationships which can be used for preliminary engineering design.

Despite the apparent simplicity of the problem, the determination of universal fetch limited growth relations has been elusive. Significant differences have been observed between individual fetch limited growth experiments. Kahma and Calkoen (1992) have attempted to reconcile these differences, investigating processes such as variability in the atmospheric boundary layer and measurement uncertainty.

Donelan et al. (1992) approached the problem of fetch limited growth in an innovative manner by investigating the differential growth between individual measurement stations along the fetch. In this manner it was possible to develop a growth relationship as a function of fetch which could include variability of the wind speed along the fetch. Applying this approach, they were able to show that the development of the atmospheric boundary layer along the fetch has a significant influence on the short and moderate fetch development of waves. In addition, it was concluded that as the development of the boundary layer with fetch was a function of the magnitude of the wind speed, no single universal growth curve exists. This may well explain much of the observed variability in field measurements. The investigation of differential growth also has the advantage that it avoids the necessity of accurately defining the origin of the fetch. This is often a problem in field experiments as the land/water boundary seldom conforms to an idealized linear form perpendicular to the wind direction.

In finite depth water the situation is complicated by the additional variable of water depth. The ideal situation of fetch limited finite depth growth involves water of constant depth. Even in the most ideal of field basins such a situation never exists. Hence, an additional uncertainty exists in attempting to quantify fetch limited growth relationships in finite depth situations. In addition, the field data set is far less comprehensive than in deep water. Recently, however, Young and Verhagen (1996a) have presented results obtained from a comprehensive experiment conducted at Lake George, Australia. This data set covers a wide range of conditions recorded at a series of eight stations along the fetch.

The relatively large number of measurement stations located along the fetch makes the Lake George data set ideal for the investigation of the differential growth of finite depth fetch limited waves. This paper presents such an analysis, extending the results of Donelan et al. (1992) to finite depth conditions.

The arrangement of the paper is as follows. Section 2 presents a brief review of measurements of fetch limited growth with particular emphasis on finite depth situations. The finite depth Lake George experiment and the resulting data set is described in Section 3. The differential growth between individual measurement stations is investigated in Section 4 and the results of this analysis are applied to realistic finite depth fetch limited cases in Section 5. Finally, the conclusions of the study are presented in Section 6.

2. Fetch limited growth

2.1. Deep water

The idealized case of fetch limited growth provides a unique situation in which to investigate the physical processes responsible for wind wave evolution. In addition, it is a convenient test case for the evaluation of the performance of numerical wave prediction models. Hence it is a case which has received considerable investigation. The early stages of wave development with increasing fetch have been well documented in both the laboratory (Hidy and Plate, 1966; Sutherland, 1968; Mitsuyasu, 1968, 1969) and in the field (Burling, 1959; Hasselmann et al., 1973; Kahma, 1981; Donelan et al., 1985; Dobson et al., 1989; Perrie and Toulany, 1990). Following Kitaigorodskii (1962), the results of such experiments have generally been presented in terms of non-dimensional variables ($\chi = gx/u^2$, $\varepsilon = g^2E/u^4$, $\nu = f_p u/g$; where x is the fetch length, E is the variance (energy) of the surface elevation, f_p is the frequency of the spectral peak, g is gravitational acceleration and u is a representative wind speed). Considerable debate surrounds the appropriate choice of u. Commonly used values include the wind speed measured at the fixed reference height of 10 m, U_{10}, the friction velocity u_* (Kitaigorodskii, 1962; Janssen et al., 1987; Kahma and Calkoen, 1992) and the wind speed measured at a reference height equal to half the wave length of the energetic waves, $U_{\lambda/2}$ (Donelan and Pierson, 1987). Irrespective of the potential advantages of the use of u_* or $U_{\lambda/2}$, the quantity U_{10} is the wind speed parameter commonly measured during experiments, other wind speed parameters typically being indirectly evaluated. Hence, U_{10} has been the most common choice as a scaling wind speed.

The initial growth of ε with χ is approximately linear. At longer fetches the growth rate decreases, finally approaching a fetch independent fully developed level (Pierson and Moskowitz, 1964). The difficulty of ensuring homogeneous wind fields over the large fetches required to reach full development means that the transition to this state is not well defined (Pierson and Moskowitz, 1964; Bretschneider, 1973; Ewing and Laing, 1987).

Despite the relatively simple nature of fetch limited growth, there appear to be inconsistencies between the various data sets and scatter within individual data sets. The scatter is partly due to the statistical variability associated with the measured quantities. This, however, cannot explain the inconsistencies between the data sets. Explanations have focused on the form of the atmospheric boundary layer and the development of the boundary layer with fetch (Taylor and Lee, 1984; Dobson et al., 1989; Kahma and Calkoen, 1992).

2.2. Finite depth water

In contrast to the extensive deep water fetch limited data set, finite depth measurements are much more limited. The first study of shallow water wave growth was conducted by Thijsse (1949). This was followed by the field investigations staged in Lake Okeechobe, USA (U.S. Army Corps of Engineers, 1955; Bretschneider, 1958). This experiment was limited by available instrumentation of the time (paper tape recording) and was largely concentrated on determining the depth limited asymptotes to growth, rather than defining evolution with fetch. Ijima and Tang (1966) combined the results of the Lake Okeechobe measurements with available deep water fetch limited results and numerical modelling of the effects of bottom friction and percolation (Bretschneider and Reid, 1953) to develop a set of fetch limited finite depth growth curves for ε and ν. These results appeared in CERC (1977). They were further revised in CERC (1984) to be consistent with the JONSWAP (Hasselmann et al., 1973) deep water results.

These studies showed that the inclusion of finite depth in the problem required the introduction of an additional non-dimensional variable $\delta = gd/u^2$ where d is the water depth. Rather than a single relationship existing between ε and χ, as in deep water, a family of curves results, one for each value of δ.

Young and Verhagen (1996a) reported the results of a comprehensive finite depth fetch limited growth experiment conducted at Lake George, Australia. Data were recorded at eight locations with fetches ranging from 1.3 km to 15.3 km. The water depth was approximately 2 m. During the three year duration of the experiment the water depth varied between 1.5 m and 2.4 m. They were able to confirm that an asymptotic limit to growth existed which could be defined in terms of δ. In addition, they were able to redefine the family of growth curves previously proposed in CERC (1984). The redefined relationships were supported by recorded data rather than simply satisfying the asymptotic limits at short and long fetch as in CERC (1984).

As Young and Verhagen (1996a) had anemometers at a number of locations along the fetch they were able to confirm that the wind speed increased with increasing fetch as the boundary layer developed over the water surface. Following Dobson et al. (1989) they adopted U_{10} averaged over the down wind fetch as the appropriate scaling velocity. Although this approach achieved acceptable results, measurements at short non-dimensional fetch, χ still appeared anomalously low.

3. Lake George data set

A detailed description of the Lake George experimental site, instrumentation and available data has been presented by Young and Verhagen (1996a) and Young et al. (1997). A brief description appears below.

Lake George (see Fig. 1) is approximately 20 km long by 10 km wide and has a relatively uniform bathymetry with an approximately uniform water depth of 2 m. A series of 8 measurement stations were established along the long North–South axis of the lake as shown in Fig. 1. Each of these stations measured the water surface elevation. In addition, a number of stations also measured the wind speed and direction at a reference height of 10 m (see Young and Verhagen, 1996a for details).

The full data set collected during the measurement period consisted of approximately 65,000 30 min time series together with meteorological data. In order to investigate

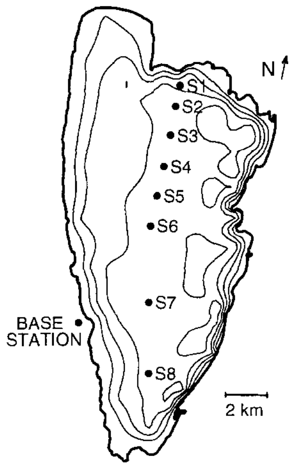


Fig. 1. Map of the Lake George experimental site. The measurement locations are labelled S1 to S8. Data were transmitted to the Base Station on the western shore of the lake where it was logged under computer control. The contour interval is 0.5 m, with the maximum contour value 2 m.

differential growth between the measurement stations, the wind direction must be closely aligned with the north/south instrument array. This reduced north/south data set is defined by wind directions which are within 20° of the alignment of the instrument array. In addition, only data for which the wind speed and direction were relatively constant during the 30 min sampling period have been retained. The criteria used for this selection were that the wind speed should not vary by more than 10% nor the wind direction by more than 10° during the 30 min sampling period. The resulting north/south data set consisted of approximately 1,000 observations.

4. Differential growth

Donelan et al. (1992) investigated the fractional energy increase per radian, $\Gamma = C_g/(\omega_p E)(\Delta E)/(\Delta x)$ as a function of the inverse wave age U_{10}/C_p where C_g and C_p are the group velocity and phase speed respectively of components at the spectral peak frequency $\omega_p = 2\pi f_p$. They found that their data could be adequately represented by the relationship

$$\Gamma = \frac{C_g}{\omega_p E}\frac{\Delta E}{\Delta x} = A\left(\frac{U_{10}}{C_p} - 0.83\right) \tag{1}$$

where A is a constant between 6.5×10^{-5} and 7.2×10^{-5}. This relationship indicates that the growth rate becomes zero at the point of full development ($U_{10}/C_p = 0.83$) determined by Pierson and Moskowitz (1964).

In order to integrate Eq. (1) and determine the fetch dependent growth $E(x)$, a

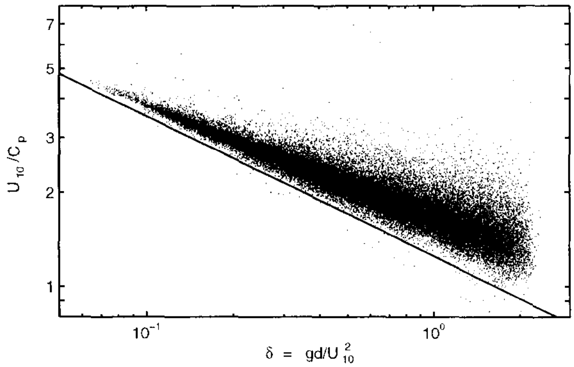


Fig. 2. Scatter plot of the inverse wave age, U_{10}/C_p as a function of the non-dimensional water depth δ for the full Lake George data set. The solid line (Eq. (5)) represents the depth limited envelope to the data.

relationship between E and U_{10}/C_p is required. Based on their Lake St. Clair data, Donelan et al. (1992) adopted the following relationship

$$\varepsilon = \frac{Eg^2}{U_{10}^4} = 0.0023\left(\frac{U_{10}}{C_p}\right)^{-3.2} \tag{2}$$

By integrating Eqs. (1) and (2), Donelan et al. (1992) were able to develop an analytical relationship for $E(x)$.

Eq. (1) is clearly not applicable to finite depth conditions since full development will be defined by δ rather than the value $U_{10}/C_p = 0.83$. Young and Verhagen (1996a) have shown that under finite depth conditions, the total energy E increases with fetch and the peak frequency, f_p decreases with fetch. With increasing fetch, however, an asymptotic limit is approached where continued spectral peak migration to lower frequencies and continued energy growth both cease. These asymptotic limits can be expressed in non-dimensional form as (Young and Verhagen, 1996a)

$$\varepsilon = 1.06 \times 10^{-3}\delta^{1.3} \tag{3}$$

$$\nu = 0.20\delta^{-0.375} \tag{4}$$

Because of the depth dependence of the dispersion relationship a direct conversion between ν and U_{10}/C_p is not possible for finite depth cases. Fig. 2, however, shows a scatter plot of U_{10}/C_p as a function of δ for the full Lake George data set. A clear limit to growth exists as a function of U_{10}/C_p. A relationship representing the envelop to the 'data cloud' and hence the fully depth limited state is

$$U_{10}/C_p = 1.25\delta^{-0.45} \tag{5}$$

which is shown in Fig. 2. As the wind speed occurs in both non-dimensional quantities plotted in Fig. 2 there is a potential for spurious correlation due to errors in the values of U_{10}. Young and Verhagen (1996a) have, however, investigated this possibility in the context of Eq. (4) and found such spurious correlations not to be significant.

The implication of Eq. (5) for the growth rate Γ of finite depth wave is as follows. At short fetch, C_p will be small (short period waves) and the ratio U_{10}/C_p will be large.

The waves will not be influenced by the finite water depth (i.e. deep water waves) and the growth rate will be as defined by the deep water relationship Eq. (1). As the fetch increases, C_p also increases and the longer waves begin to interact with the bottom. The influence of the bottom retards the development of the waves (Young and Verhagen, 1996a) and the growth rate, Γ falls below that predicted by Eq. (1). The inverse wave age, U_{10}/C_p continues to decrease and approaches the limit defined by Eq. (5), at this point the growth rate becomes zero (i.e. the fully depth limited state).

The variation in the growth rate with fetch, described above is supported by the present data set, as shown in Fig. 3. These figures show the growth rate, $\Gamma = C_g/(\omega_p E)(\Delta E)/(\Delta x)$ as a function of the inverse wave age U_{10}/C_p. As the non-dimensional water depth, δ is also assumed to govern the growth rate, the data have been partitioned into four different intervals, based on the value of δ ($\delta = 0.1$–0.2, 0.2–0.3, 0.3–0.4 and 0.4–0.5). For clarity, each data interval is shown in a separate panel of Fig. 3. In determining the values of Γ, ΔE and Δx have been taken as the difference in energy and fetch, respectively, between adjacent measurement stations. The values of E and ω_p have been taken as the arithmetic means of the values measured at station pairs. The group velocity, C_g and the phase speed, C_p have been evaluated from ω_p using linear wave theory and the average water depth between the tower pairs.

As indicated by Donelan et al. (1992), the differences in ΔE are relatively small, and hence statistical variability in the measured values of E result in significant scatter in calculated values of Γ. Despite this scatter, clear trends in the behavior of Γ can be seen in each of the panels of Fig. 3. At large values of U_{10}/C_p, Γ is consistent with the deep water relationship Eq. (1). As U_{10}/C_p decreases, the finite depth growth rate decreases relative to the corresponding deep water values. The growth rate finally approaches zero at a U_{10}/C_p limit defined by Eq. (5).

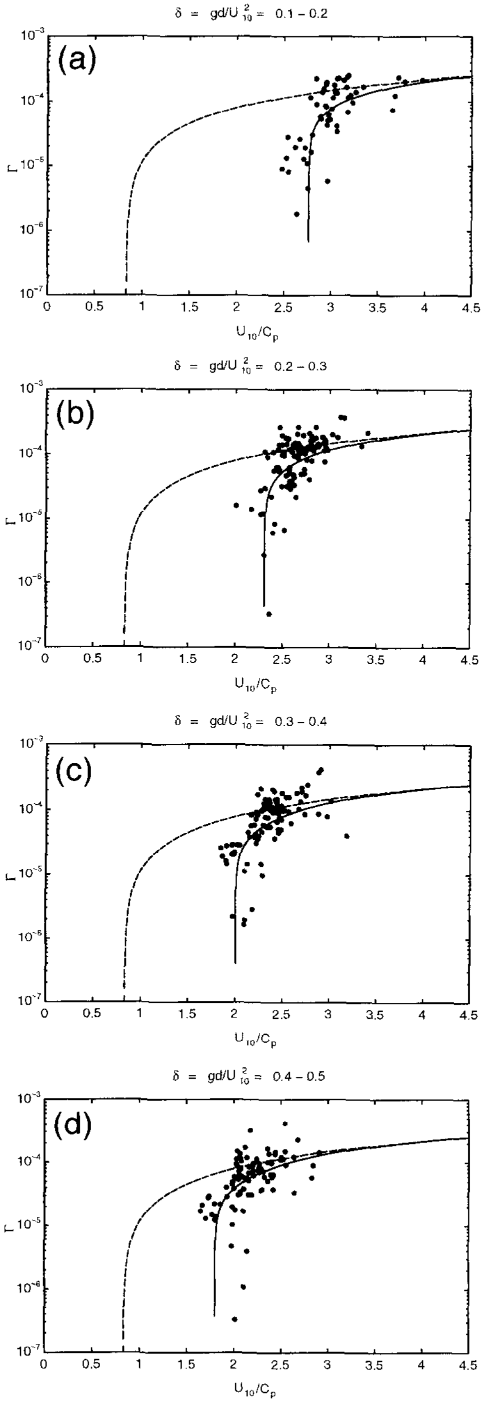
An empirical relationship which is consistent with the deep water form Eq. (1) and the data of Fig. 3 is

$$\Gamma = A\left(\frac{U_{10}}{C_p} - 0.83\right)\tanh^n\left(\frac{U_{10}}{C_p} - B\right) \tag{6}$$

where $A = 6.8 \times 10^{-5}$ (Donelan et al., 1992), $B = 1.25\delta^{-0.45}$ (the depth limit of Eq. (5)) and the exponent n controls the rate at which the relationship transitions to the depth limited state. For U_{10}/C_p large, the 'tanh' term approaches unity and Eq. (6) reverts to the deep water form Eq. (1). As U_{10}/C_p decreases, the 'tanh' term is less than unity and hence the resulting growth rates are smaller than in deep water. As U_{10}/C_p approaches the depth limited value specified by B, the 'tanh' term and hence the growth rate approach zero.

The value of n was determined from a least squares fit to the data of Fig. 3, yielding $n = 0.45$. Eq. (6), together with Eq. (1), is shown in Fig. 3. Despite the data scatter, Eq. (6) appears to be a good representation of the observed dependence of Γ on U_{10}/C_p and δ.

Following Donelan et al. (1992), integration of Eq. (6) to determine $E(x)$ requires a relationship between E and U_{10}/C_p. For the deep water data of Donelan et al. (1992), this relationship was provided by Eq. (2). To investigate whether similar scaling exists in finite depth water, the north/south data set is represented in this form (U_{10}/C_p verses


δ = gd/U 2 10 = 0.1 – 0.2
(a)
Γ
U10/Cp
δ = gd/U 2 10 = 0.2 – 0.3
(b)
Γ
U10/Cp
δ = gd/U 2 10 = 0.3 – 0.4
(c)
Γ
U10/Cp
δ = gd/U 2 10 = 0.4 – 0.5
(d)
Γ
U10/Cp

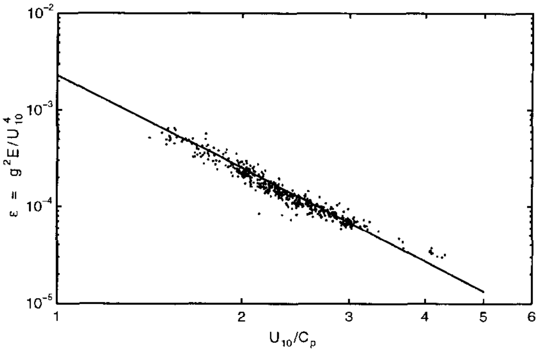


Fig. 4. The non-dimensional energy, ε as a function of the inverse wave age, U_{10}/C_p. Only data from the north/south data set are shown. The relationship developed by Donelan et al. (1992) for deep water (Eq. (2)) is shown by the solid line.

ε) in Fig. 4. Eq. (2) is also shown in Fig. 4 and represents a good approximation to the data.

It might initially appear unusual that the same relationship between ε and U_{10}/C_p exists for finite depth water as deep water. This is particularly so when it is considered that the growth rates of finite depth waves are smaller than their deep water counter parts. As shown by Young and Verhagen (1996a) the rates of development of both ε and ν (which is closely related to U_{10}/C_p) are retarded by the finite depth. The result, as shown in Fig. 4, is that the relationship between these two non-dimensional quantities is the same as in deep water. Such a result suggests that the shape of the finite depth spectrum is not greatly different to that for deep water (i.e. the relationship between E and f_p must be similar). Young and Verhagen (1996b) have shown that finite depth spectra are better represented by the TMA spectral form (Bouws et al., 1985) than the deep water forms of either JONSWAP (Hasselmann et al., 1973) or Donelan et al. (1985). The differences between TMA and the deep water forms are, however, largely confined to the shape of the high frequency tail of the spectrum. As this region contains little energy, the affect on the total energy E is small. Such differences would easily be contained within the data scatter observed in Fig. 4.

Substituting Eq. (2) into Eq. (6), using $\Delta E/\Delta x$ as an estimate of the derivative and introducing the non-dimensional variables ε and χ yields

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}\chi} = 0.0023A\frac{\omega_p U_{10}^2}{C_g g}\left(\frac{U_{10}}{C_p} - 0.83\right)\left(\frac{U_{10}}{C_p}\right)^{-3.2}\tanh^n\left(\frac{U_{10}}{C_p} - B\right) \tag{7}$$

The use of differential growth has avoided the necessity to use χ in the analysis, hence

Fig. 3. (a) The growth rate $\Gamma = C_g/(\omega_p E)(\Delta E)/(\Delta x)$ as a function of the inverse wave age U_{10}/C_p. Data within the interval $\delta = 0.1$–0.2 are shown. The dashed line represents the deep water relationship of Donelan et al. (1992) and the solid line Eq. (6). (b) As for (a) but for the interval $\delta = 0.2$–0.3. (c) As for (a) but for the interval $\delta = 0.3$–0.4. (d) As for (a) but for the interval $\delta = 0.4$–0.5.

it is not possible to directly integrate Eq. (7) with respect to χ. Eq. (7) can, however, be inverted to obtain

$$\frac{\mathrm{d}\chi}{\mathrm{d}\varepsilon}=a=\frac{C_g g}{0.0023A\,\omega_p U_{10}^2}\left(\frac{U_{10}}{C_p}-0.83\right)^{-1}\left(\frac{U_{10}}{C_p}\right)^{3.2}\tanh^{-n}\left(\frac{U_{10}}{C_p}-B\right) \tag{8}$$

Eq. (8) can be integrated in the form

$$\chi=\int a\,\mathrm{d}\varepsilon \tag{9}$$

As $a=a(C_p)$ it is convenient to integrate with respect to C_p rather than ε

$$\chi=\int a\frac{\mathrm{d}\varepsilon}{\mathrm{d}C_p}\,\mathrm{d}C_p \tag{10}$$

where, from Eq. (2)

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}C_p}=0.0073U_{10}^{-3.2}C_p^{2.2} \tag{11}$$

Substituting Eq. (11) into Eq. (10) and adopting $A=6.8\times10^{-5}$ and $n=0.45$ yields

$$\chi=46675g\int\frac{C_g}{\omega_p U_{10}^3}\left(\frac{U_{10}}{C_p}\right)\left(\frac{U_{10}}{C_p}-0.83\right)^{-1}\tanh^{-0.45}\left(\frac{U_{10}}{C_p}-B\right)\mathrm{d}C_p \tag{12}$$

For the case of constant wind speed, U_{10}, Donelan et al. (1992) were able to form an analytical solution to their simpler deep water counter part of Eq. (12). Both C_g and ω_p are functions of C_p (and d) and due to the transcendental nature of the finite depth dispersion relationship, an analytical solution could not be achieved for Eq. (12). Eq. (12) can, however, be integrated numerically to yield χ (C_p). When coupled with Eq. (2), $\varepsilon(\chi)$ can be determined.

5. Applications of results

The flexibility of Eq. (12) enables a number of wind wave generation cases to be investigated. These include constant wind speed along the fetch, a variable wind speed as well as constant water depth or water depth which varies with fetch.

5.1. Constant wind speed

The standard case of finite depth fetch limited growth assumes constant water depth, d and wind speed U_{10}. This is the case considered by Young and Verhagen (1996a), for which they developed growth curve relationships between ε and χ. This case was investigated for a number of constant water depths. Comparisons between the solution of

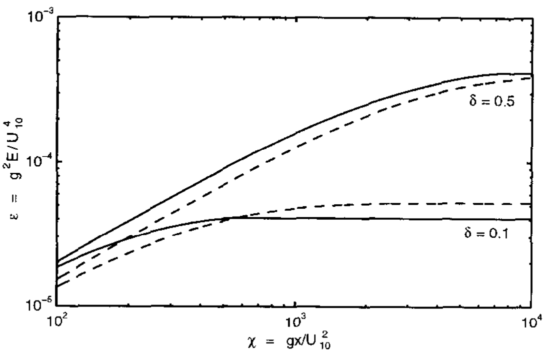


Fig. 5. Growth curves representing the development of the non-dimensional energy, ε as a function of the non-dimensional fetch, χ. Results are shown for a constant wind speed and two different non-dimensional water depths: $\delta = 0.1$ and $\delta = 0.5$. The results of Young and Verhagen (1996a) are shown by the dashed lines and the results achieved by the integration of Eq. (12) by the solid lines.

Eq. (12) and the curves of Young and Verhagen (1996a) are shown in Fig. 5 for non-dimensional depths $\delta = 0.1$ and 0.5. Eq. (12) yields the same qualitative trends as the relationships of Young and Verhagen (1996a). At short fetch the waves develop as for deep water. With increasing fetch the growth rate decreases and ε falls below that which could be expected for deep water. At longer fetch, a 'plateau' dependent on the value of δ is reached where further growth ceases.

Quantitatively, differences exist between the present results and those of Young and Verhagen (1996a). At short fetch Eq. (12) yields higher values than Young and Verhagen (1996a). This occurs since at short fetch Eq. (12) reverts to the deep water relationship of Donelan et al. (1992) whereas the results of Young and Verhagen (1996a) revert to that of JONSWAP (Hasselmann et al., 1973). As already shown by Donelan et al. (1992), their result is larger than that of JONSWAP, reflecting the variability of deep water data sets. At long fetch Eq. (12) asymptotes to a slightly different depth limited state than predicted by Young and Verhagen (1996a). For small δ, Eq. (12) yields lower values of ε than Young and Verhagen (1996a) and for large values of δ, Eq. (12) yields larger values. This occurs because Eq. (5), which represents the depth limited extreme for U_{10}/C_p is slightly different to the form represented in terms of ε proposed by Young and Verhagen (1996a). The results are, however, comparable, the differences being consistent with the scatter of the recorded data set.

5.2. Boundary layer development with fetch

At the shoreline there is a discontinuity in the surface roughness, from the aerodynamically 'rough' land surface to the relatively smooth water surface. As a result, an internal marine boundary layer begins to grow within the thicker terrestrial boundary layer. Hence, the wind speed measured at a constant reference height will gradually increase moving down the fetch. The development of such internal boundary layers has

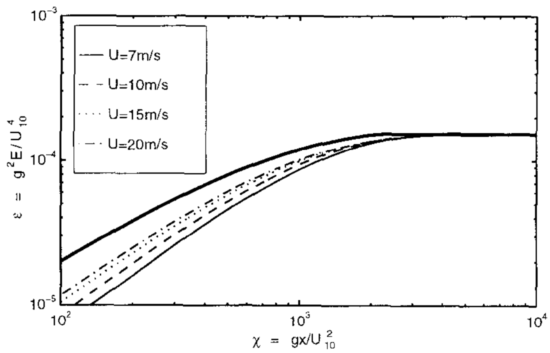


Fig. 6. Growth curves representing the development of the non-dimensional energy, ε as a function of the non-dimensional fetch, χ for a non-dimensional water depth, $\delta = 0.25$. The wind speed, U_{10} along the fetch has been assumed to vary according to the relationship of Taylor and Lee (1984). Results are presented for four different wind speeds at full development (see legend). The result for a constant wind speed along the fetch is shown by the thick solid line.

been previously investigated by Taylor and Lee (1984) and Smith and MacPherson (1987), and in the context of fetch limited growth by Dobson et al. (1989), Perrie and Toulany (1990) and Kahma and Calkoen (1992). Young and Verhagen (1996a) showed examples of this development as recorded by anemometers along the fetch. Following Dobson et al. (1989), Young and Verhagen (1996a) attempted to account for this variability in the reference wind speed by using the wind speed averaged over the down wind fetch as the scaling wind speed used in the non-dimensional variables. Despite these attempts, the short fetch data reported by Young and Verhagen (1996a) appeared anomalously low compared to JONSWAP (Hasselmann et al., 1973) to which the Young and Verhagen (1996a) curves approach at short fetch.

In order to investigate this influence, Eq. (12) was solved for a wind speed which varied with fetch according to the relationship of Taylor and Lee (1984) (see also Young and Verhagen, 1996a). The results are shown in Fig. 6 for a variety of wind speeds and a non-dimensional water depth, $\delta = 0.25$. The wind speed used to normalize each result was the value at full development. As shown by Donelan et al. (1992) for deep water, a single growth curve does not exist as the boundary layer development is itself a function of wind speed. At short to medium fetch the results fall below that obtained for a constant wind speed. The magnitude of this effect increases for lighter winds. At long fetch, all cases asymptote to the same depth limited state. As concluded by Donelan et al. (1992) for deep water, such a result casts doubt over the existence of a single universal growth relationship for fetch limited cases.

In order to investigate whether this influence could account for the anomalously low growth rates at short fetch reported by Young and Verhagen (1996a), Eq. (12) was solved for a wind speed at full development of $U_{10} = 7$ m/s and $\delta = 0.25$. The result is plotted in Fig. 7 together with the data of Young and Verhagen (1996a) for δ in the range 0.2–0.3. Also shown is the relationship proposed by Young and Verhagen (1996a) for $\delta = 0.25$. The value of $U_{10} = 7$ m/s was chosen as it was the mean value recorded

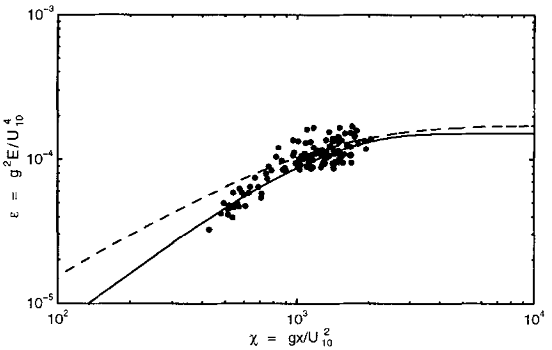


Fig. 7. The Lake George data of Young and Verhagen (1996a) showing ε as a function of χ. Data in the interval $\delta = 0.2$–0.3 are shown. The growth curve of Young and Verhagen (1996a) for $\delta = 0.25$ is shown by the dashed line. The result obtained by the integration of Eq. (12) with $\delta = 0.25$ and U_{10} varying along the fetch according to Taylor and Lee (1984), with a fully developed value of $U_{10} = 7$ m/s, is shown by the solid line.

for the data shown in Fig. 7. The solution of Eq. (12) is in good agreement with the data and provides a considerably better representation of the data than the Young and Verhagen (1996a) result.

6. Conclusions

Donelan et al. (1992) have argued that wind variability along the fetch, boundary layer stability and shoreline geometry have a significant influence on the observed development of deep water fetch limited waves. They have attempted to overcome these limitations by investigating the differential growth between adjacent stations along the fetch. This paper extends this result to finite depth situations. The Lake George experimental data set (Young and Verhagen, 1996a), with its multiple fetch measurements has been reanalyzed to investigate the growth rate between the measurement stations.

A relatively simple relationship has been developed Eq. (12), which can be integrated to yield $E(x)$. This result is significantly more flexible than previous growth law proposals as it can easily accommodate variations in both the wind speed and water depth with fetch. For practical applications, the assumption of constant water depth over the fetch is very restrictive. Hence, the present result has significant advantages in practical applications.

As shown by Donelan et al. (1992) for deep water applications, the development of the atmospheric boundary layer with fetch also has a significant influence on the observed growth rate. As a result, a single non-dimensional growth curve relationship does not exist. Rather, the relationship becomes dependent on the actual wind speed. This result has been used to explain the anomalously low growth rates observed at short fetch by Young and Verhagen (1996a).

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