Sea-Surface Roughness Length Fluctuating in Concert with Wind and Waves*

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Abstract: When the nondimensional aerodynamic roughness parameter for the sea surface \( \frac{g\zeta_0}{u_+^2} \), \( g \) being the acceleration of gravity, \( u_+ \) the air friction velocity, is plotted as a function of the wave age, the data points in the diagram are distributed mostly in a triangle area between the Charnock formula and the Toba-Koga formula; the nondimensional roughness parameter is not expressed as a unique function of the wave age, but rather there seem to be multiple regimes. In order to investigate the cause of the data point scattering, a reanalysis was made of the 4.5-hour time series of the wind profile and wind-wave statistics which were obtained at an oceanographic tower station under the conditions of a winter monsoon wind having slightly fluctuating speed and steadily growing wind waves.

It is concluded that the averaged variation of \( \zeta_0 \) is given by the Toba-Koga formula with a constant of value 0.015. However, as a result of the wind fluctuation on the time scales ranging from several minutes to an hour, data points show a conspicuous fluctuation on the nondimensional roughness parameter-wave age diagram in the direction transverse to the averaged variation. The variation in \( \zeta_0 \) directly reflects the degree of over- or under-saturation in the high-frequency range of the wind-wave spectra. Physical interpretation of these variations is also presented.

1. Introduction

In modeling ocean-atmosphere interactions, parameterization of the air-sea fluxes of momentum, heat, water vapour, and other gases is one of the essential tasks. There is much uncertainty in the proper value of the drag coefficient of \( C_D \), and many efforts have recently been made to elucidate the wave dependence of the sea-surface roughness parameter \( \zeta_0 \) which has one-to-one correspondence to \( C_D \) under near-neutral conditions.

Stewart (1974) considered that \( \zeta_0 \), when it is nondimensionalized by using the acceleration of gravity \( g \) and the friction velocity of air \( u_+ \), could be expressed generally as a function of the wave age \( C_p/u_+ \), or using the dispersion relation for small-amplitude water waves, of \((\sigma_p u_+ / g)^{-1}\) as

\[
g\zeta_0/u_+^2 = f(C_p/u_+) \quad (1)
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where \( C_p \) is the phase speed of wind waves at

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Fig. 1. The nondimensional roughness parameter $g_{z_0}/u_{*}^2$ versus inverse wave age $a_{p_{w}}/g$ diagram including the past composite data set.


Earlier, Kitagorodskii (1968) proposed a form of $z_0$ as an integration of roughness components which were expressed by a weighting function of the wave age. Geernaert et al. (1986) supported this expression. Volkov (1970), Donelan (1982), and Geernaert et al. (1987) presented data where $g_{z_0}/u_{*}^2$ becomes smaller with the wave age. A stress formula which Hsu (1974) proposed corresponds to,

$$C_p = 0.012 (C_p/u_{*})^{2/3},$$

(5)

or to $m=1/2$, when it is expressed in terms of the drag coefficient $C_D$, and converted to the form (1) and (2), by using the 3/2-power law of wind waves connecting the nondimensional significant wave height with wave period (Toba, 1972). More recently, Wu (1988) supported Eq. (3) rather than Eq. (4). Janssen (1989) presented a theory for surface-wave induced air-flow stress which led to a prediction of $m=1$ for a wave spectral model. Thus the proposed wave dependence of the sea-surface wind stress is apparently open to further examination.

A composite data set is seen in Fig. 1 of the $g_{z_0}/u_{*}^2$ vs. $a_{p_{w}}/g$ diagram, which is cited from TIKEJ augmented by Geernaert et al. (1987) data. The augmented data of Geernaert et al. (1987), were adopted after eliminating from their table such data that appeared to be affected by swells which prevailed. From Fig. 1, it is seen that data points are distributed approximately in the triangle area between Eq. (3) (we will call this tentatively the Charnock regime) and Eq. (4) (the steady wind, growing wind-wave regime). In other words, the nondimensional roughness parameter $g_{z_0}/u_{*}^2$ is not expressed as a unique function of the wave age, or there seem to be multiple regimes for the expression of Eq. (1), although an intermediate expression:

$$g_{z_0}/u_{*}^2 = a_{p_{w}}/g = 0.020 (a_{p_{w}}/g)^{-6.5},$$

(6)

may be regarded as a compromise formula for practical uses, which was one of the formulas proposed by TIKEJ.

The Charnock regime represents a lower limit in the $g_{z_0}/u_{*}^2$ vs. $a_{p_{w}}/g$ diagram as shown in Fig. 1. The value of $\beta$ of Eq. (3) has been proposed to be 0.0130 by Smith and Banke (1975), 0.0144 by Garratt (1977), and 0.0185 by Wu (1980). The lower limit value of $\beta$ will be, say, 0.008 from Fig. 1. When the wind is very strong, the condition of the water surface is aerodynamically smooth, and this regime may be treated separately.

Why are the data points in this diagram distributed in the triangular area between Eqs. (3) and (4)? The motivation of this paper is to
elucidate possible mechanisms for this distribution.

When pure wind waves are growing under a steady wind, the wind-driven breaking adjustment, as discussed by Toba (1988), is performed in order for the 3/2-power law (Toba, 1972) to be satisfied, and the momentum of the air flow is transferred to the water more effectively than over solid surfaces. Since the Reynolds number is sufficiently large, turbulence in the surface layer of the sea plays a large role in such a situation, the conditions being independent of the molecular viscosity \( \nu \). If we could assume that the effect of \( g \) does not appear, the functional form becomes Eq. (4), as discussed in TIKEJ. The form of Eq. (4) with, say, \( \gamma = 0.025 \) as the upper end of the triangular region seems to be supported by many fetch-limited laboratory data and lake data by Donelan (1979) and duration-limited Bass Strait data by TIKEJ.

In this expression, characteristic variables of the waves such as \( \sigma_s \) should be used solely for wind waves, and the values of swells should not be used.

However, the growing wind-wave regime does not seem to be applicable for various conditions where growing pure wind-wave conditions are contaminated. Possible such conditions are: (a) when the wind weakens. The extreme case is when the wind waves travel faster than the new 10-m wind speed. (b) when the wind waves are coexistent with significant swells mostly from different directions. This case may include various situations of changing wind fields. (c) when the wind waves shoal, and feel the bottom. In this case wave breaking other than the wind-driven breaking adjustment may become effective. (d) when the height of the ceiling of the wind-wave tunnel, or such an experimental artifact, affects the conditions. In such cases the conditions of the growing wind-wave regime are no longer valid and the situation seems to approach the Charnock regime via the triangle region between the two regimes.

Another important possibility for the scatter of data in Fig. 1 is the intrinsic fluctuation of data points even in the case of purely growing wind waves. In the present paper, the concept of fluctuating roughness is proposed by use of the detailed 4.5-hour time series of wind profiles and wind waves. The data were obtained at the Shirahama Oceanographic Tower Station of Kyoto University in November 1969 under the condition of the winter monsoon (Toba et al., 1971; Kawai et al., 1977, hereafter called KOT; Toba et al., 1988, hereafter called TOJ). In Section 2 the data source is described, while the detailed time series are investigated in Section 3. As a result, it is found that the \( z_0 \) fluctuation is caused by the variation in the wind speed of having the time scale ranging from several minutes to an

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Fig. 2. The location of the Shirahama Oceanographic Tower Station of Kyoto University. (Cited from Hayami et al., 1964)
hour, through the adjustment of the energy level of wind waves in the equilibrium range to the wind speed variation. In Section 4 some further discussions are given.

2. Data

The conditions of the observation were described in Toba et al. (1971) and KOT. The essential points will be given below. Since change in the wind direction with respect to the coastline configuration is essential in the later analysis, Fig. 2 shows the location map of the Tower Station. The tower was made of steel angles with a small instrumentation room in the middle level. A continuous record of the wind speed was made by using a small 3-cup anemometer with a photo-electric device, at each of the nominal heights of 13 m, 6 m, 3 m and 1.5 m; the tide gauge record was used to get the real heights of the anemometers every minute. The anemometers and the wave-gauge, which were specially calibrated for this experiment, were mounted on steel pipes and projected out about one meter to the west from the angle of the northwest corner of the tower in order to minimize the influence of the body of the tower.

The wind was the winter monsoon. Figure 3 shows the entire 6.5 hours time series of the
10-m wind speed $U_{10}$ and $u_*$. Both $U_{10}$ and $u_*$ were derived from two kinds of time series of wind profiles calculated respectively from the 3-min. moving average wind speeds and from the 15-min. moving average winds speeds at the four levels. A discussion of the wind profiles during this observation period was already given in KOT. The time series of $U_{10}$ and $u_*$ obtained from the 15-min. moving average wind data are naturally smoother than those obtained from the 3-min. moving average wind data. For the purpose of the present paper, the original wind data have been reanalyzed.

A small atmospheric front passed the site at 11:45, since the wind direction changed from WSW to WNW. In the direction of WSW from the tower, there were a small peninsula and islands at a distance of about 1 km (see Fig. 2), and so we are using hereafter only data after 11:45. This part is of 4.5 hours duration. It should be noted that for winds from WNW, the observation conditions were good with 60 km in fetch, but when the wind direction changed to NW and then to NNW, the wind was along the coast or from the land (Fig. 2).

There are two kinds of time series of wind-wave spectra as reported by TOJ. In series A of 6.5 hours length, wave spectra were calculated every 15 minutes by using 1024 wave-gauge data points collected at 10 Hz. In Series B, which is of 28 minutes length, wave spectra were calculated every minute from 1024 wave-gauge data points also at 10 Hz with a small moving overlap.

The air temperature at 6 m and sea surface temperature are shown in Fig. 4, together with the bulk Richardson number $Ri$ calculated from these values and the wind speed. The stratification was slightly unstable, with the minimum value of $Ri$ of $-0.04$. Consequently, all of the data of $u_*$ and $z_0$ were calculated by the following log-linear law:

$$U(z)/u_* = 1/k(\ln(z/z_0) + aRi),$$

where $k$ is the von Kármán constant 0.40 and $a = 3$.

3. Detailed investigation of the time series

Figure 5 shows the Series A data of $U_{10}$, $u_*$, the wind-wave peak frequency $f_p$, the degree of under-saturation of the equilibrium range of wind-wave spectra $\tilde{a}_s$, and $z_0$. The $\tilde{a}_s$ is defined by

$$\tilde{a}_s = 1 - \alpha_s/\alpha_0,$$  \hspace{1cm} (7)

where $\alpha_s$ is the average value of the coefficient of the energy level $\alpha_s$ of the equilibrium range of wind waves given by

$$\phi(\sigma) = \alpha_0 g u_* \sigma^{-4},$$  \hspace{1cm} (8)

where $\phi(\sigma)$ is the spectral density as a function of the angular frequency $\sigma$. The values of $\tilde{a}_s$ are the same as reported by TOJ, and $\tilde{a}_s$ is 0.062. The ranges of frequency to determine $\alpha_s$ were reported in KOT, and they were about 0.5 to 3 Hz.

The general trend of $U_{10}$ shows that after the passage of a front at 11:45, the wind decreased until 12:45 (marked by b in Figs. 3, 5, and others), then it increased. It seems that a kind of small front or some special structure of wind occurred at 12:45. At 14:00 (marked by d), the wind direction changed from WNW to NW.
but we have no evidence at present whether this change was continuous or somewhat abrupt. However, it should be assumed from Fig. 2 that toward this time the effect of land would have been to disturb, to some extent, the structure of the wind.

Corresponding to the characteristic points in $U_{10}$, such as b, c, and d, similar characteristic points are recognized in $u_*$ and $z_0$. It is noted that at b and d, where there were possible atmospheric fronts, the direction of changes are opposite in $z_0$ with respect to $U_{10}$.

The value of $f_p$ was determined from the wave spectral shape of TOJ, so it is independent of the wind data. As already reported in TOJ, there is a good correlation between the variation of $U_{10}$ (or $u_*$) and $f_p$ on the time scale of 15 minutes to an hour, since the adjustment occurs in the energy level of the high-frequency side with little change in the total wave energy for this time scale. This tendency is clearly seen in Fig. 5. There is a decreasing trend in $f_p$. This is due to the development of total wave energy, representing the growing wind-wave conditions.

Also, there is a very good correlation between $f_p$ and the degree of undersaturation $\tilde{\alpha}_s$ for the above time scale ranging from 15 minutes to an hour. The fluctuation in $\tilde{\alpha}_s$ is caused by the time delay for the adjustment of the energy level in the equilibrium range to the variation of wind, as already discussed in TOJ.
These observations lead us to the following physical interpretation. The variation of $U_{10}$ on the time scales of several minutes to one hour causes the variation of $f_p$ and $\tilde{a}_s$. The larger $\tilde{a}_s$ corresponds to the situation where the energy level of the wave equilibrium range is rapidly increasing. This condition is associated with larger $z_0$. Probably, the wave components of the very high-frequency part of the wave spectra outside the equilibrium range are steeper in this situation, and small-scale processes related to viscosity, surface tension, and breaking adjustment of wind waves, will be more important in the momentum flux.

We should recall that, while $\tilde{a}_s$ is changing, the shape of the spectra of the equilibrium range always has a slope very close to $\sigma^{-4}$, as reported by TOJ. In other words, it seems that there is a strong constraint for the spectra to be kept to the statistical $\sigma^{-4}$ slope, presumably caused by wave interactions, which may include the breaking adjustment. Consequently, the air momentum entering the waves due to the increased roughness at the very high-frequency part of the spectrum is quickly transferred to the entire equilibrium range. The delicate variation of the wave spectral shape near $f_p$ with $\tilde{a}_s$ was already reported in TOJ.

Figure 7 shows the time series of $\sigma_p u_{\infty}/g$ and $g z_0 / u_{\infty}^2$, calculated from the time series of $u_{\infty}$ and $z_0$ from the 3-minutes moving-average wind data. Interpolated values of $\sigma_p$ estimated from the values of $f_p$ as shown in Fig. 5, were used. The points of b and d in Fig. 5, corresponding to the possible small fronts, appear very clearly in $g z_0 / u_{\infty}^2$, but not so clearly in $\sigma_p u_{\infty}/g$. The points of c and e which are seen clearly in both $g z_0 / u_{\infty}^2$ and $\sigma_p u_{\infty}/g$, seem to correspond to characteristic points in the variations of the wave-field measures of $f_p$ and $\tilde{a}_s$.

Figure 8 is the $g z_0 / u_{\infty}^2 - \sigma_p u_{\infty}/g$ diagram (the nondimensional roughness-wave age diagram) plotted from the time series of Fig. 7. Figure 9 is the same as Fig. 8 except that the values were calculated from the 15-min. moving-average wind data. Characteristic points of a, b, c, d, and e are entered here also, corresponding to Figs. 3 and 5. These correspond to turning points in the trends of the data points.

As seen from Fig. 9, after the point d at 14:00, all data points form a low value cluster with
Fig. 7. Time series of $\sigma_p u_*/g$ and $gz_0/\kappa u_*^2$, calculated from the time series of $u_*$ and $z_0$ from the 3-min. moving average wind data.

Fig. 8. The nondimensional roughness-wave age diagram plotted from the time series of Fig. 7.
respect to $g z_0 / u^2_\infty$. After 14:00, the wind direction was NW to NNW, and the wind and wave fields were possibly affected by the land, as already noted.

As seen in Figs. 8 and 9, in the first half of the period when the wind felt no land effect, the averaged variation of this diagram is along the growing wind-wave regime, with, say, $\gamma = 0.015$. However, it is evident that there is a fluctuation of the data points which is transverse to the growing wind-wave regime, i.e. in the direction of positive $m$ in Eq. (2).

This transverse fluctuation corresponds to the in-phase fluctuation of $g z_0 / u^2_\infty$ and $\sigma^2_{\phi \nu_{\infty}} / g$, as seen clearly in Fig. 7 at shorter time scales, and this corresponds to the good correlation of $z_0$ and $f_\theta$ or $\tilde{\alpha}_4$ as seen in Figs. 5 and 6, for which we already gave a physical interpretation. At the same time, in Fig. 7, we can see an evident trend of inverse correlation of the values of $g z_0 / u^2_\infty$ and $\sigma^2_{\phi \nu_{\infty}} / g$, and this corresponds to the averaged variation of Figs. 8 and 9 with a slope of $m = -1$ parallel to the line of the growing wind-wave regime.

Since Figs. 8 and 9 are nondimensional representations with $u_\infty$ appearing in both the axes, the plots may include an effect of “spurious self-correlation” difficulty as discussed by Kenney (1982). However, the same characteristics that we have described are clearly recognized also in corresponding dimensional representations of Figs. 10 and 11. Thus the variation of $g z_0 / u^2_\infty$ is actually determined by the overwhelming variation of $z_0$.

The physical interpretation of the shorter period correlated fluctuations of $z_0$ and $f_\theta$ (or $\tilde{\alpha}_4$) was given several paragraphs ago. Now the physical interpretation of why the growing wind-wave regime has a negative value of $m$ is given as follows. For simplicity, we will consider the case of given wind speed, i.e., a constant $U_{10}$. This is not a constant $u_\infty$, but it would approximate the latter condition. The momentum entering the high frequency part of the wave spectrum is quickly transferred through the equilibrium range to the waves near $f_\theta$ to increase

Fig. 9. The same as Fig. 8 except that the values were calculated from the 15-min. moving average wind data.
Fig. 10. Dimensional presentation of Fig. 8.

Fig. 11. Dimensional presentation of Fig. 9.
the wave energy of these waves, as was already discussed with the same wave data in TOJ. Some energy may also enter directly from the air to the waves near \( f_p \). However, wave dissipation exists throughout the spectral range. Since the total dissipation is larger for developed-wave conditions, \textit{i.e.}, for the cases of smaller \( f_p \) which have naturally wider spectra, much more momentum is needed in order to compensate for this larger dissipation. This is the reason for higher values of \( z_0 \) for larger wave age, even though the wind speed is the same, and it will also be the reason why the actual observation for the growing wind-wave regime differs from theoretical deductions of the momentum transfer for the wave-induced air flow, such as studied by Janssen (1989), where the small scale processes and the quick transfer through frequency ranges were not considered. The above described situation of the fluctuation of \( z_0 \) in concert with \( U_{10}, f_p \), and \( \delta_e \) suggests that there are interactions of wind and wave waves much stronger than expected from treatments of weekly nonlinear interactions.

At this point we should recall the merits of the nondimensional analyses. The most conspicuous merit is that we can extract substantial physical relationships by eliminating dimensions and diminishing the number of variables. For differing winds, we can consider the effect of wind waves by adopting the nondimensional variables. This is done by using the form of Eq. (1) or (2). In fact, in the nondimensional representation of Fig. 9, the abscissa indicates the wave age (the left is older), but in Fig. 11 it is hard to see such a physical interpretation.

In order to make the matter simple, let us restrict ourselves at present to a condition where the wind direction remains almost the same (as our cases of Bass Strait data, and the Shirahama data for some periods), though the change in wind direction is another most important matter. Then, the wind fluctuations may be classified as (1) short period fluctuation, say, several minutes to one hour (this may also include directional fluctuation), where \( \sigma_p \) does not vary appreciably or varies in positive correlation with the wind; (2) variation of the time scale comparable to the wave growth, so that we can conceive a quasi-equilibrium wave field with the wind, \textit{i.e.}, the

![Fig. 12. Dimensional presentation of the Charnock formula, Eq. (3) with the same data set as Fig. 1.](image-url)
Fig. 13. Dimensional presentation of the Toba-Koga formula, Eq. (4) with the same data set as Fig. 1.

Fig. 14. Dimensional presentation of the TIKEJ formula, Eq. (6) with the same data set as Fig. 1.
wave spectral form had similarity, the nondimensional 3/2-power law holds, and $\sigma_p$ decreases gradually; (3) sudden large decrease of the wind speed, where waves near $\sigma_p$ become swells.

In the case of item (2), the physical situation should be expressed by the wave age $C/U_{10}$ or $\sigma_p u_0/v$, and according to the decrease or increase in the wind speed, the wave age becomes either larger or smaller. In this sense, Stewart’s (1974) original idea of Eq. (1) was correct. Our result predicts that in this situation $z_0$ is expressed by the Toba-Koga form, Eq. (4). Variation in the peak enhancement and other small deviations from the spectral similarity will become the question of a fine adjustment of the above situation.

In the case of item (1) of short time-scale fluctuation, the process of adjustment of the wind wave spectra to changing winds causes a large variation of $z_0$. This has been the main subject of the present paper, and it has been found that in the case of the item (1), the situation cannot be expressed by Eq. (1).

4. Discussion—Proposed practical formula

As a result of the considerations given above, the most appropriate formula for the averaged variation of the nondimensional sea-surface roughness parameter for steadily growing wind-wave conditions is given by Eq. (4) with, say, $\gamma = 0.015$. However, these pure wind-wave conditions are not frequent, and the wind fluctuations seem to cause fluctuations of data points within the triangle region of Fig. 1, between the growing wind-wave regime and the Charnock regime. Thus a more conservative overall formula, representing the triangle region of Fig. 1, is given by Eq. (6).

It should be worthwhile to express the three formulas Eqs. (3), (4), and (6) in dimensional diagrams: Figs. 12, 13, and 14. The data set is the same as that of Fig. 1. In Fig. 12, points of the high-speed wind-wave tank data set (crosses) by Kunishi and Inamasato (1966) and points of high wind and wave data set at Bass Strait (open circles) are separated in this expression, whereas in Fig. 13 they are continuously distributed. In Fig. 13, the Geernaert et al. (1987) data set (closed squares) deviates from the line of formula (4) just as in Fig. 1. Since the upper limit of the whole data set is close to the formula (4), our interpretation is that for pure wind waves (without large wind fluctuations) (4) holds, and that points deviated downwards occur by wind fluctuations or other causes. In Fig. 14, TIKEJ

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**Fig. 15.** $C_D$ values corresponding to the growing wind-wave regime, Eq. (4) with $\gamma = 0.015$. (Cited from Toba et al., 1990: TIKEJ.)
formula (6) is shown to fit the whole data set in a compromised way.

The value of the drag coefficient $C_D$ corresponding to Eq. (4) is shown in Fig. 15 cited from TIKEJ. The value of $C_D$ corresponding to Eq. (6) is shown in Fig. 16 again cited from TIKEJ. In Fig. 16 lines for parameters of $H_2$ and most of $C_D/U_{10}$ are abbreviated.

It might be expected that the values of momentum flux calculated from the 3-min. moving-average wind data are different from those from the 15-min. moving-average wind data, since $U_{10}$ and $C_D$ might have some kind of correlating variation. However, the actual calculation by the present data shows that the ratio is 1.03.

Also, there may be an appreciable difference between the estimates of integrated wind stress values by using longer time average $\overline{U_{10}}$ and $\overline{C_D}$ and by using fluctuating $U_{10}$ and $C_D$ of the time scales of 15 minutes to one hour. For the whole period from 11:45 to 16:08, $\overline{U_{10}}=8.31$ m sec$^{-1}$ with $\overline{C_D}=2.02 \times 10^{-3}$, and the ratio of $\overline{C_D}U_{10}^2/\overline{C_DU_{10}}^2$ is 1.04.

Now we will give some further discussion with respect to the overall situation of the past and present wind stress studies. First, why has Charnock's formula been so popular? One reason might be that, as far as observation conditions are concerned, many of these data were obtained over sea surfaces under moderate winds with light swells. In addition to the large frequency of occurrence of these moderate wind conditions, the condition for observation, say, on a tower in the sea is convenient in these cases and the quantity of data becomes naturally large, whereas data obtained under severe wind and wave conditions have been rare. Also, wind-wave tunnel data give stress values similar to those predicted by the Charnock formula, since the fetches are very small and wind waves are not much developed even though the wind is strong.

Some field data sets show that drag coefficient $C_D$ decreases with the wave age (e.g., Hsu 1974; Geernaert et al., 1987; Perrie and Toulany, 1990). On the diagram of Fig. 1, such data sets have been interpreted such that the value of $m$ of Eq. (2) is positive. Maat et al. (1991) have recently analyzed data from HEXMAX and reported a rather scattered distribution of points with a slope $m=1$ ending at the point $C_D/u_w=40$, $g z_0/u_w^2=0.0185$ in Fig. 1. If it is extrapolated to conditions of such small wave ages as are realized in wind wave tunnels, $C_D$ or $g z_0/u_w^2$ should become very large. However, such data were never obtained in experiments.

Donelan (1990) reported that laboratory data
had a trend different from field data. However, the basic physics should be continuous, unless there is a low ceiling or narrow side walls, or some other such experimental condition. In fact, the steepness of wind waves varies continuously as a function of wave age, from steeper laboratory wind waves to less steep field wind waves (Bailey et al., 1991). The fact that the data points exist within the triangle area of Fig. 1 between the lines of \( m = -1 \) and \( m = 0 \) is interpreted as indicating that the growing wind-wave regime with \( m = -1 \) exists as the upper limit condition.

Then, why do some data show positive values of \( m^2 \)? Since the wind over the oceans is mostly varying in both speed and direction, the large wave ages, or high values of \( g z_0/u_s^3 \) in the growing wind-wave regime are realized rather seldom. These conditions may be achieved when a unidirectional strong wind lasts for a long time, as for the data of TIKEJ, or in the east-Asian winter monsoon, or in the Southern Ocean. The upper limit of \( g z_0/u_s^3 \) of the growing wind-wave regime may be around the condition of \( C_p/U_{10} \approx 1 \), or \( C_p/u_s \) of 20 to 40. These conditions are indicated by two vertical dotted lines as indicating the transition between wind waves and swells in Fig. 1. When this regime is no longer applicable, say, because of a decrease of wind speed, the value of \( g z_0/u_s^3 \) will approach the value of the Charnock regime. When the wind direction is changing, the wave spectral form becomes complicated, and \( \sigma_p \) cannot represent the wave conditions for our growing wind-wave regime, though data points are often plotted using these \( \sigma_p \)'s. If we use \( \sigma_p \) only for the wind-wave component, and when the wind increases again, the points in the \( g z_0/u_s^3-\sigma_p u_s/g \) diagram jump to the right for young wind-sea conditions, and again climb up through the line of \( m = -1 \).

If a steady wind lasts only for a short period, the data points climb up the \( m = -1 \) line, stop and somehow come down to the Charnock regime. The longer the steady wind lasts, the further the data points climb to the upper left in Fig. 1 before coming down. Consequently, it is expected that as more data are plotted from different experiments, the triangle area of Fig. 1 will be more filled up with data points.

5. Conclusions

When the nondimensional aerodynamic roughness parameter for the sea surface \( (g z_0/u_s^3, g \) being the acceleration of gravity, \( u_s \) the air-friction velocity) is plotted as a function of the wave age, the data points in the diagram are distributed mostly in a triangle area between the Charnock formula and the Toba-Koga formula; the nondimensional roughness parameter is not expressed as a unique function of the wave age, but rather there are multiple regimes. A practical conservative overall formula representing the triangle area is given by Eq. (6) which was proposed by Toba et al. (1990, TIKEJ).

From a reanalysis of a 4.5-hour time series of the wind profile and wind-wave spectra under growing wind-wave conditions observed at the Shirahama Oceanographic Tower Station, the following conclusions have been given:

1. In the case of slightly fluctuating wind with no large change in the wind direction, the averaged variation of \( z_0 \) is given by the Toba-Koga formula, Eq. (4) with \( \gamma = 0.015 \), with a minus unity slope on the nondimensional roughness-wave age diagram or the \( g z_0/u_s^3-\sigma_p u_s/g \) diagram. The conditions where Eq. (4) holds will be the situation where wind waves are growing with a quasi-steady decrease in \( \sigma_p \) under a steady wind.

2. Shorter time-scale (several minutes to an hour) fluctuations of the wind speed \( U_{10} \) cause conspicuous fluctuations of \( z_0 \) in the direction transverse to the Toba-Koga formula in the above diagram.

3. The variation in \( z_0 \) directly reflects the degree of under-saturation of the wind wave spectra \( \tilde{a}_s \) in the equilibrium range, as defined by Eq. (7).

Some physical interpretations of these variations have also been given in the text. Cases of drastically changing winds should be future tasks to be investigated.

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References


風と波とに連動して変化する海面粗度長さ

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要旨：無次元の海面の空気力学的尺度パラメーター（$gza/\nu^2$, $z_a$ は波の高さ, $\nu$ は空気の粘性係数）を波の関数として表現すると、データ点は、Charnock の公式と、Toba-Koga の 1986 年の公式との間の三角形の領域に分布する。すなわち、無次元の尺度パラメーターは波の一定的な関数として表現されず、むしろ多重構造が存在するようにみえる。このデータ点の散布さびりの原因を研究するために、海洋観測で、少し風速変動があり、

風波が定常的に発達しつつある冬の寒風の下で得られた、風速分布と風波の統計量の 4.5 時間の時系列を再解析した。その結果次の結論が得られた。すなわち、$z_a$ の平均的な変化は定数値を 0.015 とした Toba-Koga の公式で与えられる。しかし、数分から 1 時間の時間スケールの風の変動の結果、データ点は無次元尺度パラメーター波長図上で、この平均的な変化を横切る方向に、顕著な変動を示す。この $z_a$ の変化は、風波のスペクトルの周波数領域のレベルの変動を直接反映している。この変動の物理的解釈も提出した。

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