On the Wave Dependence of Sea-Surface Wind Stress
—A Study by Using Data from an Ocean Data Buoy Station—

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Abstract: Analysis is made of wind and wave data, which were obtained during the passage of Typhoon 8013 at an Ocean Data Buoy Station south of Honshu operated by the Japan Meteorological Agency, in order to investigate the wave dependence of sea-surface roughness parameter in the situation where wind waves are dominant with less significant swells. The data fit better the wave-dependent expression of the wind stress, \( z_0 \sigma_p / u^* = \gamma \), than to Charnock’s formula, \( g z_0 / u^* \beta \), where \( z_0 \) is the roughness length, \( u^* \) the friction velocity of air, \( \sigma_p \) the angular frequency of the spectral peak of wind waves, \( u^* \) the friction velocity of air, \( g \) the acceleration of gravity, \( \gamma \) and \( \beta \) are non-dimensional constants. The results are very similar to those of our previous study using data from an oil producing platform in the Bass Strait, Australia, although the type of observation system and the synoptic situation of the winds and wind waves were totally different.

1. Introduction

In order to estimate wind stress on the sea surface, Charnock’s (1955) well-known formula,
\[ g z_0 / u^* \beta, \]
(1)
has widely been accepted, where \( z_0 \) is the roughness length, \( u^* \) the friction velocity of air, and \( g \) the acceleration of gravity, with \( \beta \) as a numerical constant.

Wu (1980), by reviewing many experimental results, proposed \( \beta = 0.0185 \). This relation corresponds approximately to the expression for the drag coefficient by Wu,
\[ C_D = (0.80 + 0.065 U_{10}) \times 10^{-3}, \]
(2)
with \( U_{10} \) in m sec\(^{-1}\), by using a logarithmic law of the wind profile for neutral stratification,
\[ U(z) / u^* = (1/\kappa) \ln (z / z_0), \]
(3)
where \( U(z) \) is the wind speed at a height of \( z \) and \( \kappa (= 0.40) \) is the von Kármán constant.

Recently, Toba et al. (1990, abbreviated as TIKEJ) have questioned the traditional concept of expressing the drag coefficient only as a function of the wind at 10-m height, and demonstrated that the drag coefficient depends also on parameters of the wind waves. They have analyzed wind and wave data which were obtained under storm conditions at an oil producing platform in the Bass Strait, Australia, together with previous experimental data. It has been shown that the wind and waves in local equilibrium satisfy the expression proposed by Toba (1979), and Toba and Koga (1986),
\[ z_0 \sigma_p / u^* = \gamma, \]
(4)
where \( \gamma \) is a constant and \( \sigma_p \) is the angular frequency of wind-wave spectral peak. The \( \gamma \) was originally proposed as 0.025. TIKEJ have proposed 0.015–0.025.

In Eq. (4), the wave dependence of wind stress, which is included implicitly in Eq. (1) as a restricted form, is explicitly parameterized by \( \sigma_p \). The formula of Eq. (4) requires that \( z_0 \) depends strongly on the characteristics of the wind waves. If this is converted to the drag coefficient by using the logarithmic law (3), for a wind speed of 20 m sec\(^{-1}\) and a significant wave period of 10 sec, it gives a value of air-sea momentum transfer three times larger than that estimated by Eq. (2). Wu (1988) suggested that the parameterization of Eq. (1) describes the primary growth of roughness length with wind while Eq. (4) describes the secondary effects due to waves.

TIKEJ have used the logarithmic law and the 3/2-power law between the non-dimensional...
significant wave height and period for the wind and wind waves in local equilibrium proposed by Toba (1972) as,

\[ H^* = BT^{3/2}, \quad B = 0.062, \quad (5) \]

or

\[ H_s = B(gu)^{1/2} T_s^{5/2}, \quad B = 0.062, \quad (5a) \]

where \( H_s \) and \( T_s \) are the significant wave height and period, respectively, and

\[ H^* = gH_s/\nu, \]
\[ T^* = gT_s/\nu. \]

Because of the difficulty in the flux measurements under conditions of strong winds and large waves, available data for these conditions are very few. TIKEJ analyzed data of only two storms observed at an oil producing platform, and encouraged further studies focused on the wave dependence of the sea surface wind stress.

The purpose of the present study is to examine the relation (4) using data taken by a different observation system under wind conditions different from TIKEJ. We have analyzed data obtained at an Ocean Data Buoy Station located south of Honshu of the Japan Meteorological Agency (JMA) during the period of Typhoon 8013 when strong winds and large waves were observed. The period of strong winds and large waves was short and the synoptic situation was changing fast compared with the storms analyzed by TIKEJ.

2. Data from Ocean Data Buoy Station

The JMA has been operating Ocean Data Buys since 1972 in the ocean and seas near Japan. The buoys are 10 m in diameter and 48 tons in weight. They measure eleven variables every 3 hr. The data from the buoys are published every year as “Data from Ocean Data Buoy Stations”, in which detailed explanations about the buoys and stations are also given.

In this study four of the variables, which are the wind speed, the wind direction, the average wave height, and the average wave period, are used. The wind speed and direction are measured as the 10-min average values by a three-cup anemometer and a wind vane, which are located on the top of the mast at 7.5 m above the sea surface. The wave height and period are measured as averages for 20 waves by using the zero-up-crossing method from the time series of the surface displacement. The displacement is obtained by twice integrating the acceleration observed by the sensor installed within the hull at the mean water level. The accuracy of the wave height and period are 0.1 m and 1 sec, respectively. According to Hatori (1983), the average wave height and period measured by the buoy and those measured by a shipborne wave recorder agreed well with each other for waves with period longer than 4 sec.

Here we have selected data observed by the Buoy No. 21003 (25°40'N, 135°55'E) during the passage of Typhoon 8013, which was from 6 to 13 September 1980. The location of the buoy and the track of the typhoon are shown in Fig. 1. The data of this typhoon was also used in comparison studies of wave models by Uji (1984) and Toba et al. (1985).

3. The wave dependence of sea-surface wind stress during the period of Typhoon 8013

The data is analyzed in the same way as TIKEJ. The average wave height \( \bar{H} \) and period \( \bar{T} \) observed by the buoy are converted to the significant wave height \( H_s \), period \( T_s \), and the angular frequency of wind-wave spectral peak \( \sigma_p \), by using

\[ H_s = 1.60 \bar{H}, \quad (7) \]
\[ T_s = 1.13 \bar{T}, \quad (8) \]
and

$$\sigma_p = 2 \pi/1.05 \, T_s \ . \quad (9)$$

The relation (7) is widely accepted and is supported by a statistical model (Horikawa, 1973). The factor 1.13 in Eq. (8) is determined from data obtained at the Bass Strait (TIKE). However, by using time series of crests and troughs obtained by the same type of buoy operated at a point off Nojimazaki (32°N, 147°E) from 18 October 1983 to 22 June 1984, it has been confirmed that the factor is 1.10±0.14, which is essentially the same as the value of Eq. (8). Equation (9) is a relation supported by observations (Mitsuyasu, 1968; Toba 1973).

Figure 2 shows the time series of the wind direction, the wind speed, and the significant wave height and period. In this period, Typhoon 8013 passed near Buoy No. 21003 as seen in Fig. 1, and strong winds and large waves were observed.

Next the friction velocity $u_*$ and the roughness length $z_0$ are calculated from $T_s$ and $U_{1.5}$ by using the relation of Eq. (4) and the logarithmic law expressed by Eq. (3) to examine whether the data satisfy the 3/2-power law expressed by Eq. (5). Figure 3 shows $T^*$ and $H^*$ calculated from $H_s$, $T_s$ and the $u_*$ obtained above. Except for the data on 11 and 12 September, the line of Eq. (5) is supported well by the data.

On 11 and 12 September, it can be seen in Fig. 2 that the typhoon had passed and the wind speed decreased rapidly. In such a situation, wind and waves cannot be in local equilibrium. If the wind decreases rapidly and the waves remain unchanged (i.e., $u_*$ decreases with constant $H_s$ and $T_s$), then both of $H^*$ and $T^*$ increase but $H^*$ changes proportional to $T^{*2}$ (instead of $T^{*3/2}$), because of the form of the normalization of $H^*$ and $T^*$ (Eq. (6)). The data in Fig. 3 show that the slope of the points is slightly
Fig. 4. Same data as Fig. 3 except in a dimensional form. The solid line is $B=0.062$ and the broken lines show the range of $B=0.062 \pm 20\%$.

smaller than 2, or about 1.8, because $H_s$ and $T_s$ are in the course of adjustment to the local equilibrium. This deviation from Eq. (5) was already reported by Jones and Toba (1985) for a similar situation of wind and waves in the Bass Strait. This is a kind of "spurious" effect as a result of the non-dimensional representation of data (Kenney, 1982), as also noted in TIKEJ. Swells propagating from the typhoon, which had gone from the buoy at that time, may also be a cause of the deviation from the local equilibrium.

Figure 4 presents the same data in a dimensional form, corresponding to Eq. (5a). The solid line corresponds to $B=0.062$, and the broken lines express a range of $B=0.062 \pm 20\%$, which was adopted as a criterion for selection of wind and waves which are in local equilibrium by TIKEJ. Except for the data on 11 and 12 September, most of the data are within or slightly lower than the range of $B=0.062 \pm 20\%$. The data on 11 and 12 September have much smaller values of $(g\nu_*)^{1/2}$ than the data on 9 and 10 September, though the values of $H_s/T_s^{3/2}$ are almost the same or slightly smaller. This means that the wind speeds decreased rapidly but the waves had not yet adjusted themselves to the decrease of the wind on those days.

Using Eq. (5), significant wave height can be estimated from the significant wave period $T_s$ and the friction velocity $\nu_*$ estimated above. The estimated significant wave height $H_{se}$ is superimposed on the time series of the observed significant wave height $H_s$ in the bottom panel of Fig. 2. The curves of $H_s$ and $H_{se}$ agree well with each other except for the period of decreasing wind on 11 and 12 September.

For the data from 12 hr on 8 September to 21 hr on 10 September, when the wind and waves were supposed to be in local equilibrium, the friction velocity $\nu_*$ and the roughness length $z_0$ are calculated again by using the logarithmic law Eq. (3) and the 3/2-power law Eq. (5a) to examine Eqs. (1) and (4). The data for the period of Typhoon 8013 are plotted in Fig. 5(a) so that the exponent $\varepsilon$ of the form

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(z_0/\nu_*^2 \propto (g_3 H_*/g)^2),
$$

as used by Masuda and Kusaba (1987), could be examined. Equations (1) and (4) correspond to $\varepsilon = 0$ and $\varepsilon = -1$, respectively. Data obtained by the same buoy during the period of another Typhoon, 8017, are processed in the same way including the reduction of data which are not in local equilibrium, and are also plotted in the figure.
Fig. 5(a). Relation between $g z_0 / u_*^2$ and $\sigma_p u_*/g$, calculated for the periods of Typhoon 8013 (●) and 8017 (○).

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Fig. 5(b). Relation between $g z_0 / u_*^2$ and $\sigma_p u_*/g$, cited from Toba et al. (1990).
The data support the line of $\varepsilon = -1$ of Eq. (4) rather than $\varepsilon = 0$ of Eq. (1), though the scatter of the points is large.

Figure 3(b) is cited from TIKEJ for comparison. In this figure data obtained at an oil producing platform in the Bass Strait, Australia under the condition of strong winds and large waves, are plotted together with data from laboratories (Hamada, 1963; Kunishi, 1963; Kunishi and Imasato, 1966; Toba, 1961, 1972; Hsu et al., 1982; Masuda and Kusaba, 1987), and data at platforms in a coastal region or a lake (Kawai et al., 1977; Donelan, 1979; Merzi and Graf, 1985). In these data, $u_u$ was measured independently of the wave data, except for the Bass Strait data. It is encouraging that Fig. 5(a) and Fig. 5(b) present results very similar to each other, despite the fact that the data acquisition systems and the synoptic situation of winds and waves are completely different.

The value of $\gamma$ was originally proposed as 0.025 (Toba, 1979; Toba and Koga, 1986). TIKEJ have proposed 0.015–0.025. From the results of this study, we cannot propose a final value of $\gamma$, because the accuracy of the measurements is not good enough and the parameters $u_u$ and $z_0$ are not measured directly. However, the result of this study supports the value 0.015–0.025 proposed by TIKEJ, as seen in Fig. 5(a). As for the large scatter of data points in Fig. 5(a) and (b), a further discussion is given elsewhere (Toba and Ebuchi, 1990).

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References

風の海面応力の風波依存性について
—気象庁海洋気象パイロット観測資料の解析から—

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要旨: 風波がうねりよりも支配的な状況における風の海面応力の風波依存性を調べるため, 台風 (8013) 通過時の気象庁海洋気象パイロット観測資料の解析を行った. その結果, データは Charnock の公式 \( g z_b / u^* = \beta \) よりも, 風波依存性を含んだ式 \( a_p z_b / u^* = \gamma \) によく一致

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