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Breaking of Wind Waves and the Sea Surface Wind Stress*

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Abstract: In the conventional treatment of the coefficient of sea surface wind stress by plotting it against 10-m wind speed, there are inevitable discrepancies among results of various investigators. The reason is considered to lie primarily in the fact that the state of the sea surface or of waves is disregarded, which may have great influence on the sea surface wind stress.

Former concepts concerning the conditions which control the sea surface wind stress are discussed, and it is shown that a more universal expression may be obtained by plotting the coefficient against a kind of roughness Reynolds number: $Re_2{}^* = u_* H/\nu$, where u_* is the friction velocity of air, ν the kinematic viscosity of air, and H the characteristic wave height. H is used here to treat some data in wind-wave tunnels, as a tentative variable, one step towards a more rigorous approach to the problem.

This variable $Re_2{}^*$, or $Re_4{}^* = u_{*w}L/\nu_w = 2\pi g u_{*w}/\nu_w n_1$, where the subscript w represents values for water, L and n_1 the characteristic wave length and frequency, respectively, is also the condition describing the air entrainment or the breaking of wind waves. In this case, these Reynolds numbers are interpreted as the quantity describing the intensity of turbulence of the water surface itself. It is shown, using data from our wind-wave tunnel experiments, that the breaking commences as $Re_2{}^*$ reaches 1×10^3, or as $Re_4{}^*$ reaches 3×10^3. Simultaneously, the stress-coefficient begins to increase sharply at this value of $Re_2{}^*$. This phenomenon is understood as an increased momentum transfer from the air to the water through "boundary penetration of turbulence" caused by the breaking of wind waves. Further, it is suggested that there is a possibility that this excess momentum transfer does not increase wave momentum, but reinforces drift current.

1. Introduction

The friction coefficient concerning the sea surface wind stress, or the drag coefficient, $\gamma_{10}{}^2$ is defined by

$$\tau_0 = \rho\gamma_{10}{}^2 u_{10}{}^2, \qquad (1)$$

where τ_0 is the shear stress of wind exerted on the sea surface, ρ the density of air, and u_{10} average wind speed at the 10-m level. The determination of the value of $\gamma_{10}{}^2$ have been made by many investigators, and it is a well known fact that the value has a tendency to increase with increasing wind speed for $u_{10} > 1.5$ or $3\ \mathrm{m \cdot sec^{-1}}$, in a conventional treatment where $\gamma_{10}{}^2$ is plotted against u_{10} (DEACON and WEBB, 1962; ROLL, 1965; KRAUS, 1967; and WU, 1969).

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The value of $\gamma_{10}{}^2$, however, does not show a definite value as a function of u_{10}. It may be due, on the one had, to the difference in the method of observation or to the error of measurement as discussed by KRAUS (1968). On the other hand, however, it is possibly due to the great influence of the state of the sea surface or of surface waves on the value of $\gamma_{10}{}^2$, as was already discussed by KITAĬGORODSKIĬ and VOLKOV (1965) and by KITAĬGORODSKIĬ (1968). It has also been pointed out that the stability of the air may cause some difference in the value (*e.g.* DEACON and WEBB, 1962). The effect of the stability, however, is not discussed in this article, since it is a different kind of problem.

In the paper below, the former concepts are discussed to lead to a more rigorous approach, first as to what controls the sea surface wind stress, or the value of $\gamma_{10}{}^2$ in relation to the state of the sea surface, and secondly it will be shown that the sea surface wind stress increases substantially with the bubble entrainment, or the breaking of wind waves.

2. Conditions governing the sea surface wind stess——Discussion of former concepts

In 1953 VAN DORN measured the wind stress at an artificial pond, and found that the application of a detergent eliminates waves and that there the value of γ_{10}^2 was a constant of 1.1×10^{-3}. In the case of detergent free water surface γ_{10}^2 was somewhat higher, and he showed that the value deviated substantially from the above value for a wind speed stronger than about $6\,\mathrm{m\cdot sec^{-1}}$. This seems to show that the excess of the stress value was caused by surface waves.

Further, the fact that the stress values measured in wind-wave tunnels of short fetches (for example, γ_{10}^2 values by FRANCIS, 1954; and by HAYAMI and KUNISHI, 1959; or KUNISHI, 1963) had the same order of magnitude as those measured on the open sea is considered to indicate that the mechanism for sea surface wind stress is mainly controlled by slowly moving high-frequency waves which reach equilibrium in short fetches of several meters. This is a concept supporting the discussion of FRANCIS (1954) and MUNK (1955).

It seems established by many measurements that wind profiles, under the neutral stratification, at least at some distance above wind waves, are described by the well-known logarithmic law:

$$\frac{u}{u_*}=\frac{1}{k}\ln\frac{z}{z_0}, \qquad (2)$$

where u_* is the friction velocity defined by

$$u_*=\sqrt{\frac{\tau_0}{\rho}}, \qquad (3)$$

k von Kármán constant, and z_0 roughness parameter, an artificial length introduced by a condition: $u=0$ at $z=z_0$. From the equations (1), (2) and (3), it follows that

$$u_*=\gamma_{10}u_{10} \qquad (4)$$

and

$$\gamma_{10}=\left(\frac{1}{k}\ln\frac{z_{10}}{z_0}\right)^{-1}, \qquad (5)$$

where z_{10} indicates 10 m. As is clear from the equation (5), γ_{10}^2 and z_0 have a one-to-one correspondence in the neutral stratification. Consequently, the variation in γ_{10}^2 manifests itself as that in z_0, in the wind profile.

Thus, there have been some discussion on the condition controlling the value z_0. ROLL (1948) proposed dimensionally a relation

$$z_0=\frac{\nu}{2.1\,u_*}, \qquad (6)$$

where ν is the kinematic viscosity of air, from observations for $u_*\leqslant 30\,\mathrm{cm\cdot sec^{-1}}$. Comparing this with a well-established equation for velocity profile over a smooth surface of a solid wall:

$$\frac{u}{u_*}=\frac{1}{k}\ln\frac{z}{\beta z_*},\quad z_*=\frac{\nu}{u_*}, \qquad (7)$$

where $\beta=1/9.0$ after NIKURADSE (1932), it is seen that the flow regime expressed by the relation (6) is similar to that over a smooth solid wall, with only a different constant, 1/2.1, instead of β. It is considered natural that the above flow regime holds for smaller wind speeds where the water surface is smooth, but that it does not hold when the wind is strong enough for the sea surface to be rough.

On the other hand, CHARNOCK (1955) proposed dimensionally an another relation

$$z_0=\frac{u_*^2}{bg}, \qquad (8)$$

where b was considered a universal constant. Since then several values for b has been proposed, *e.g.*, 148 by CHARNOCK (1955), 58.8 by KUNISHI (1963a), 29 by KITAĬGORODSKIĬ and VOLKOV (1965), 89.3 by WU (1968), and 64.2 by WU (1969), the values being scattered considerably.

The scattering of the value is understood as follows. If equation (8) holds true, z_0 and u_* are uniquely correlated with each other, and from equations (8), (4) and (5) we obtain

$$(bgz_0)^{\frac{1}{2}}=u_{10}\left(\frac{1}{k}\ln\frac{z_{10}}{z_0}\right)^{-1} \qquad (9)$$

indicating that z_0, consequently γ_{10}^2, is uniquely determined for each value of u_{10}, if b is a universal constant. Consequently, a large scattering of the proposed value of b is substantially equivalent to the scattering of γ_{10}^2 plotted against

u_{10} in a conventional way. Further, the relation (8) presupposes that a Froude number constructed by u_* and z_0 is constant, assuming that the surface stress is governed by a phenomenon in which the gravitational force only is of primary importance. This is not easy to understand since high-frequency waves, which would have a primary bearing on the surface stress, are to a considerable extent exerted by surface tension.

In this connection, Froude number scaling of the friction coefficient by WU (1969a) should be mentioned here. He defined his friction coefficient, γ_z^2, by

$$\tau_0=\rho\gamma_z^2 u_z^2 \tag{10}$$

and plotted it against the following Froude number:

$$F_r=\frac{u_z}{(gz)^{\frac{1}{2}}} \tag{11}$$

and showed that values of γ_z^2 obtained from data in wind-wave tunnels and from field data lie together near one smooth curve. However, the Froude number defined by equation (11) has a different physical meaning from the ordinary Froude number which governs dynamical similarity, and his results may be ultimately understood as showing that wind wave tunnels are not models but the lowest part of the proto type; in other words, that the water surface wind stress is mainly determined by high-frequency waves which reach equilibrium in quite short fetches, as been described already in the second paragraph of this section.

KRAUS (1966) discussed the condition governing the sea surface wind stress from a different point of view. He presented an idea that when a mean wind speed in the viscous sublayer on the sea surface exceeds the minimum phase velocity of surface waves, boundary layer separation occurs, and it is the cause of the increase in the momentum transfer with increasing wind speed when $u_{10}\geqslant 6$ or $7\,\mathrm{m\cdot sec^{-1}}$. The quantitative derivatition, however, is not so rigid since the mean wind speed within the viscous sublayer does not seem to have such a special meaning. Moreover, from his reasoning, if we consider a limiting case of a solid wall with zero phase velocity, the boundary layer separation should occur for all non-zero wind speeds. However, apart from the quantitative derivation, his reasoning that wind stress is increased by the form drag must be correct.

3. A more rigorous approach to the condition governing the sea surface wind stress

It is considered that a more rigorous approach to the present problem may be found in the following line of reasoning. According to a well-established concept, the flow regime over a solid wall is governed by a roughness Reynolds number $R_e{}^*$ defined by

$$R_e{}^*=\frac{\varepsilon}{z_*}=\frac{u_*\varepsilon}{\nu}\ , \tag{12}$$

where ε is an average height of the surface irregularities, and z_*, which was defined in equation (7), is about 1/5 of the thickness of the laminar sublayer. The equation (7) for the wind profile over a smooth surface is said to hold for $R_e{}^*\lesssim 4$, and the equation (2) for the wind profile over a completely rough surface holds for $R_e{}^*\gtrsim 60$ (*e.g.* MONIN and YAGLOM, 1965). Transition of the flow regime over a smooth surface to that over a rough one manifests itself as a shift of the value βz_* in the equation (7) to another value z_0, and the degree of roughness appears as a change in z_0.

So, it will be natural to consider that the air flow regime over water surface also is governed by a similar roughness Reynolds number $R_{e_1}{}^*$ defined by

$$R_{e_1}{}^*=\frac{\varepsilon_1}{z_*}\ , \tag{13}$$

where ε_1 is a certain length determined by the state of surface waves, or something like the height of high frequency waves which reach an equilibrium at quite short fetches of several meters. Namely, transition from air flow over a smooth surface to that over a rough surface, in turn, the value of z_0 and γ_{10}^2, must be governed by $R_{e_1}{}^*$. Of course, the critical values of the transition may naturally differ from those for solid walls, since irregularities proceed as surface waves although water particles at the surface do not proceed quickly.

KITAĬGORODSKIĬ and VOLKOV (1965) and KITAĬGORODSKIĬ (1968) seem to have proposed an expression for such a kind of roughness Reynolds number:

$$R_{e_r}=\frac{u_*\sigma}{\nu}\exp\left(-\frac{kc_0}{u_*}\right), \qquad (14)$$

where σ denotes root mean squared wave height:

$$\sigma=\left[\int_0^\infty \phi(n)dn\right]^{\frac{1}{2}},$$

where $\phi(n)$ is the spectrum density of surface waves, k von Kármán constant, and c_0 the phase velocity of a wave corresponding to the maximum value of $\phi(n)$. The above-mentioned ε_1 has a shape of

$$\sigma\exp\left(-\frac{kc_0}{u_*}\right),$$

in equation (14). The theoretical background of the equation (14) does not seem so rigid, but it is understood that the shape was supported empirically by data presented in Fig. 2 of their 1965 article.

Since the value ε_1 is controlled by interactions among waves, it should ultimately be determined from the wave spectrum. The most appropriate expression is a subject for future study, but the height of characteristic waves H may be taken tentatively for data from a wind-wave tunnel, where there is no swell and waves are small. Namely, another roughness Reynolds number $R_{e_2}{}^*$ is defined as

$$R_{e_2}{}^*=\frac{H}{z_*}=\frac{u_*H}{\nu}. \qquad (15)$$

In Fig. 1 are plotted values of $\gamma_{10}{}^2$ against $R_{e_2}{}^*$ from experimental data in a wind-wave tunnel of 21.6 m length by TOBA (1961) and by KUNISHI (1963), and in another wind-wave tunnel of 40 m length by KUNISHI and IMASATO (1966). It is seen from Fig. 1 that values of $\gamma_{10}{}^2$ lie near one curve which does not depend

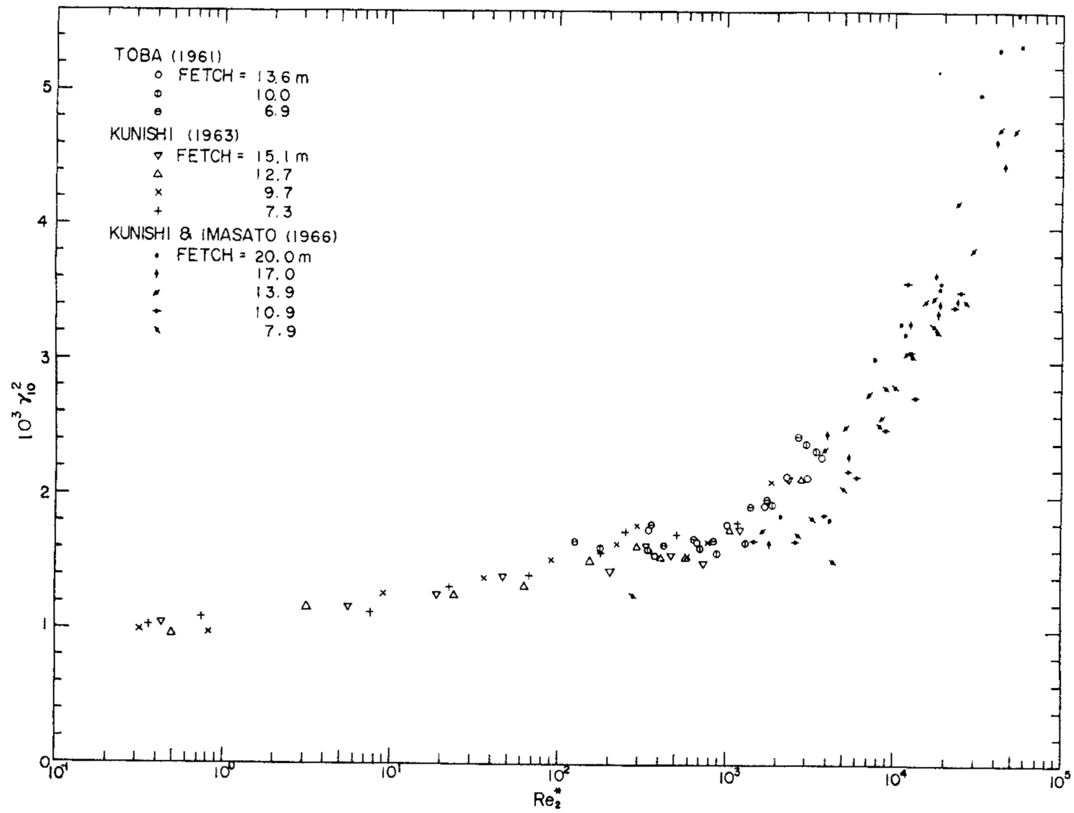

Fig. 1. Plotting of the drag coefficient $\gamma_{10}{}^2$ against the roughness Reynolds number $R_{e_2}{}^*$ defined by equation (15). Data were taken from wind-wave tunnel experiments by TOBA (1961), KUNISHI (1963), and KUNISHI and IMASATO (1966).

on fetches for fetches longer than 6 or 7 meters, demonstrating a more universal treatment of γ_{10}^2 plotting.

That the transition from the smooth water surface to the rough one occurred at a certain value of $R_{e_2}^*$, has already been found in the wind-wave tunnel by KUNISHI (1963). He reported that the water surface became fully rough at $R_{e_2}^*=2\times10^2$. Corresponding well, the value of γ_{10}^2 in Fig. 1 becomes flat at $R_{e_2}^*=2\times10^2$.

Further, the value of γ_{10}^2 increases clearly after $R_{e_2}^*$ exceeds 1×10^3. This corresponds to the commencement of the air entrainment or the breaking of wind waves, and a detailed description will be given in the next section.

4. Effect of the breaking of wind waves on the sea surface wind stress

In what follows, the data of wind-wave tunnel experiments by TOBA (1961) concerning bubble entrainment and drop production by wind waves, have been newly treated by the use of $R_{e_2}^*$.

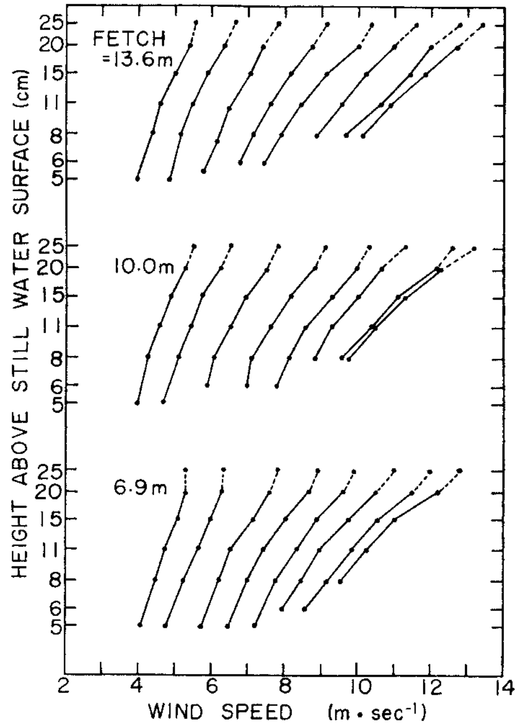

Fig. 2. Wind profiles at three fetches in the wind-wave tunnel, used in the present analysis.

The wind-wave tunnel used was 21.6 m in length, 75 cm in width, and 102 cm in height, containing water of 50 cm in depth, the same tunnel as that used by KUNISHI (1963). The items of measurement were wind profiles, waves, air entrainment or the breaking of wind waves, air bubbles and water droplets.

Wind profiles below 35 cm level were taken by use of a small cup anemometer at fetches of 4.5 m, 6.9 m, 10.0 m, and 13.6 m. Data at the fetch of 4.5 m are excluded in the following treatment since the local equilibrium seemed not to be established at this fetch, as KUNISHI has already pointed out. Wind profiles at the other three fetches are shown in Fig. 2.

Wind waves were recorded by an ink-writing oscillograph with a resistance type wave meter at the above-mentioned four fetches. The average wave length was smaller than 50 cm, and the average wave period smaller than 0.5 sec.

By the term "breaking of wind waves" one immediately recalls white-capping at the condition of sea state 3 or more. If one observes the sea surface with care, however, one will find quiet air entrainment by wind waves here and there at a wind speed of about 4 m·sec^{-1}. It seems started by small wavelets several cm in length, which override large gravity waves, which have a shape pointing downwards, and in which surface tension is exerted to a considerable degree. This was already pointed out by TOBA (1961) in Figs. 5 through 8 of his paper.

As the rate of occurrence of the breaking of wind waves the percentage, α, of the characteristic wave crests that were entraining air bubbles

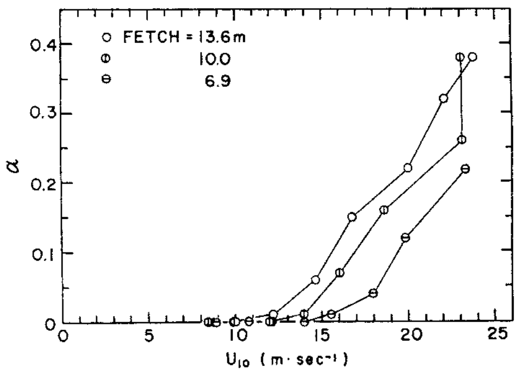

Fig. 3. Percentage of breaking wave crests, α, plotted against u_{10}.

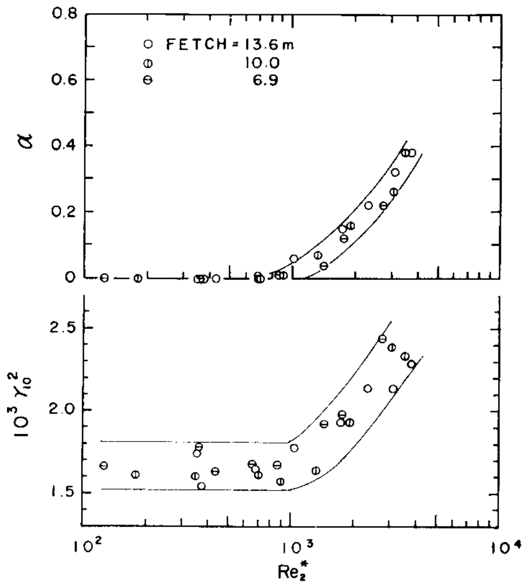

Fig. 4. Upper: Value of α (same with Fig. 3) plotted against Re_2^*.
Lower: Corresponding value of the drag coefficient γ_{10}^2 plotted against Re_2^*.

at some fixed fetches was measured. In Fig. 3 are plotted the values of α against u_{10} (extrapolated wind speed at 10-m level by use of the logarithmic law), with a parameter of the fetch. It is clear that the curves shift according to the fetches.

In the upper part of Fig. 4 are plotted the same values af α against $R_{e_2}{}^*$. The fetch dependence has almost disappeared, and the α begins to have its non-zero value when the $R_{e_2}{}^*$ reaches 1×10^3, and it increases with increasing $R_{e_2}{}^*$. In this treatment, the $R_{e_2}{}^*$ has been calculated from the value u_* which was determined from the lowest four points of Fig. 2, by the method of least squares.

In the lower part of Fig. 4, the values of γ_{10}^2 are plotted, which have been determined simultaneously with the values of u_*, against the same $R_{e_2}{}^*$. These are the same as the circles in the middle of Fig. 1. As is clearly seen from Fig. 4, the friction coefficient γ_{10}^2 simultaneously begins to increase as the breaking of wind waves commences.

A series of phenomena which includes the

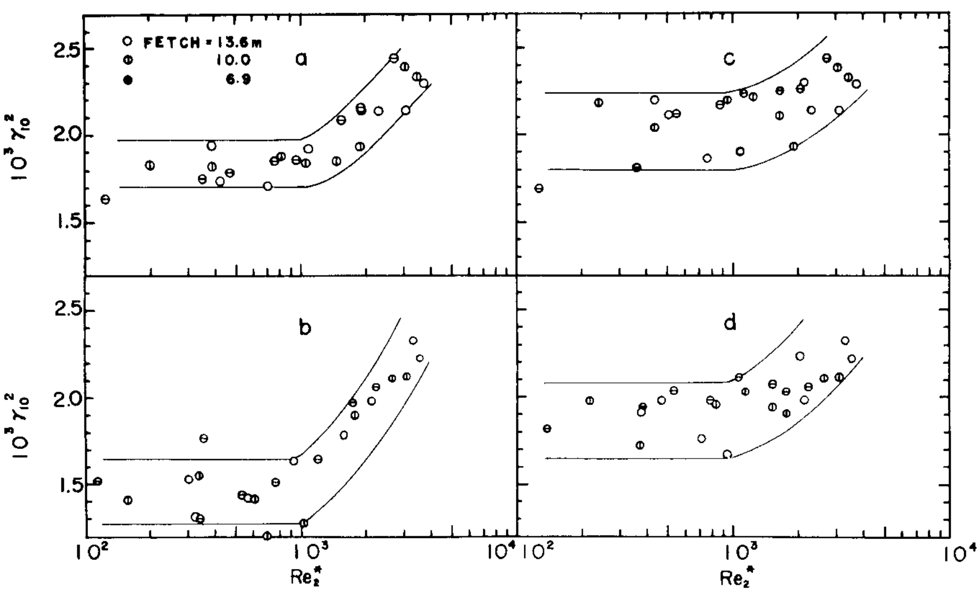

Fig. 5. Values of the drag coefficient γ_{10}^2 calculated by using different combinations of points in Fig. 2.

a: All points below 20 cm.
b: The lowest three points.
c: Four points from 8 cm to 20 cm.
d: Three points from 8 cm to 15 cm.

breaking of wind waves, bubble entrainment, and drop production indicates the breaking of the air-sea boundary. The horizontal momentum of the air is transferred to the water directly through turbulence, causing an increase in γ_{10}^2. It is here called "boundary penetration of turbulence".

As is seen from Fig. 2, the wind profile deviated a little from the logarithmic law, with a convex shape below 20 cm level. This may be a phenomenon of the increase of wind speed at the center of the wind tunnel, caused by the pressure gradient in the tunnel. Although u_* and γ_{10}^2 values determined from the lowest four points in Fig. 2 are used in Fig. 4, it is expected that the values may change if another combination of points in Fig. 2 is selected for the calculation. In order to check this point, four sets of calculations of u_* and γ_{10}^2 have been performed by using all the points below 20 cm (a), the lowest three points (b), four points from 8 cm to 20 cm (c), and three points from 8 cm to 15 cm (d), by the method of least squares. The results are shown in a, b, c, and d, respectively, in Fig. 5. Although the absolute values of γ_{10}^2 vary from one another, the fact that the values begin to increase at $R_{e_2}^* = 1\times10^3$ is common to all four cases. Consequently, it is considered that the above finding is accurate.

MONAHAN (1966) investigated excess momentum which is given to the water, when spray droplets produced by the breaking of waves fall back to the sea surface after being horizontally accelerated by wind, and he estimated it to be about 0.5 % of the usually accepted value of momentum transfer at about 9 m·sec^{-1} in wind speed. The present authors consider that the excess stress by the boundary penetration of turbulence is much more important than that caused by droplets, as the effect of breaking of wind waves. However, droplet production is directly correlated to the breaking of waves, and so it is expected that the effect of droplets may become significant in a condition where $R_{e_1}^*$ is large enough and many more droplets are produced.

5. What governs breaking of wind waves

In the previous section, it has been shown that a kind of roughness Reynolds number $R_{e_2}^*$, which may be used as a variable controlling the shift from the flow regime over a smooth surface to that over a rough surface, may be extended to a variable describing the phenomenon of the occurrence of the breaking of wind waves. This extention is not self-evident *a priori*. This problem will be discussed below.

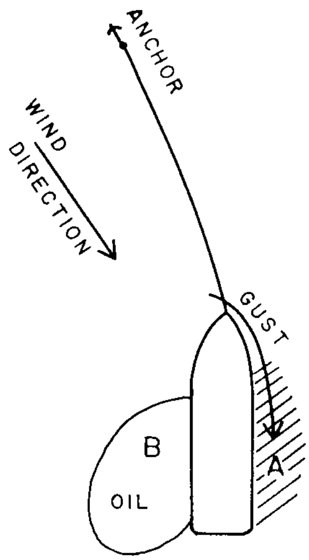

Fig. 6. Schematic picture of observation of wave breaking conditions from an anchored ship (see the context).

In an actual observation on board ship of the wave breaking phenomenon, one may notice the following facts. When a ship is anchored in the sea, and a strong gust of wind blows around the ship onto the water surface on the lee side, where larger waves have been diminished by the body of the ship (area A of Fig. 6), one may see that every crest of small wavelets is entraining air bubbles. Here, the wind stress itself (u_*) must play the principal role in the breaking of waves. On the other hand, on the windward side where the water surface is contaminated by some oil (area B of Fig. 6), there is little opportunity to see the breaking of waves, although there are many large breakings outside the oil area. It is clear that the small number of breaking in the oil area is caused only by the interaction of the waves, in other words, as a dynamical process attributed to the water waves themselves. The latter type of breaking is controlled primarily by a dynamical condition of the water waves themselves, such as $an^2=g/2$ as given by LONGUET-HIGGINS (1969), where a represents the wave amplitude, n the wave frequency, and g the acceleration of gravity.

On the ordinary sea surface where there are neither obstacles nor oil, it is considered that both factors co-operate: besides the large-scale breaking of crests of conspicuous waves, there is quiet air entrainment or breaking, which also occurs here and there at parts of larger waves other than their crests. Namely, both of the sea surface wind stress and the wave field must be concerned in the condition governing the breaking of wind waves. Consequently, the Reynolds number, which describes the intensity of turbulence of the water surface itself, must be constructed with the quantity representing the present situation of the wave field and the quantity representing the wind stress. As the latter quantity, u_{*w} seems most appropriate, where the subscript w represents values for water, and as the quantity representing the wave field, we may first use H. The Reynolds number in this case becomes $R_{e_3}{}^*=u_{*w}H/\nu_w$, and it is convertible with a constant factor to $R_{e_2}{}^*$ which was discussed as the Reynolds number describing the air flow regime above the water surface in the previous sections. Alternatively, the characteristic wave frequency, n_1 may be adopted as the representative of the wave field. In this case, using the relation:

$$L=\frac{gT^2}{2\pi}=\frac{2\pi g}{n_1{}^2},$$

where L is the characteristic wave length and T the characteristic wave period, the Reynolds number must have the following shape:

$$R_{e_4}{}^*=\frac{u_{*w}L}{\nu_w}=\frac{2\pi g\,u_{*w}}{\nu_w n_1{}^2}.$$

The values of α plotted against $R_{e_4}{}^*$ show a very similar picture as the upper part of Fig. 4, as shown in Fig. 7. If we plot smoothed values from Fig. 3, Fig. 7 will have an excellent curve shown by the dashed line. The critical value where the breaking of wind waves commences is in this case $R_{e_4}{}^*=3\times10^3$, corresponding to $R_{e_2}{}^*=1\times10^3$.

KUNISHI (1963) found a universal relationship between u_*H/ν and u_*L/ν in his wind-wave tunnels (Fig. 19 of his paper and Fig. 7 of KUNISHI and IMASATO, 1966). Although its physical meaning is not yet clear, since $R_{e_4}{}^*$ and u_*L/ν are interchangeable with a constant factor it is considered that either of $R_{e_4}{}^*$ and $R_{e_2}{}^*$ may be adopted as the Reynolds number describing the intensity of turbulence of the water surface itself, so long as waves in the wind-wave tunnels are concerned.

Surface tension, which exerts an effect on high-frequency waves which make form drag, must be concerned in the condition controlling the air flow regime. It is considered that surface tension implicitly enters u_* through form

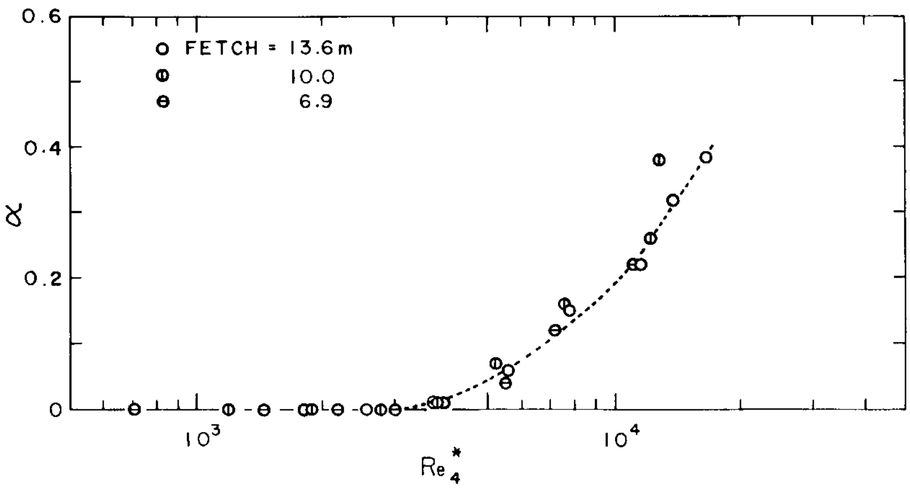

Fig. 7. Value of α (same with Fig. 3) plotted against $R_{e_4}{}^*$.

drag.

In the above-mentioned universal relationship of the initial wavelet found by KUNISHI (1963), the point of $R_{e_2}^*=1\times10^3$ has no perceptible singularity, although much horizontal momentum is transferred from the air to the water at $R_{e_2}^*>10^3$. Consequently, it is expected that the excess momentum does not increase the wave momentum, but does increase the current momentum since waves break there, and the drift current grows rapidly after $R_{e_2}^*$ reaches the critical value.

One thing should be mentioned here about our basic point of view. MILES (1967, etc.) and LIGHTHILL (1962) presented a theory of the increase of wave momentum through wave-induced Reynolds stress. The reasoning of the present article, originating from the point of view that momentum transfer is performed through high frequency waves, is incompatible with the MILES mechanism. By an observation of wind and waves on board ship, one may notice that only components of very long wave lengths can proceed with a phase velocity comparable to wind speed near the crest, and that shorter waves of several tens of cm or so which mainly break on very long waves, proceed with considerably smaller phase velocities, and are always overtaken by wind, where form drag seems much more important. It is considered that there is still a possibility that large waves do not derive appreciable momentum directly from the air, but receive their energy through a cascade-up from high frequency waves which take their momentum from the air.

STEWART (1961) estimated from the increase of wave momentum that at least 20% of the sea surface wind stress goes into waves through a wave generation mechanism. However, it would not be necessary to consider that wave momentum increases by taking the momentum directly through Reynolds stress induced by that wave.

Acknowledgments

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風波の崩れと風の海面応力

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要旨　風の海面摩擦係数は通例 10 m 高さの風速に対してプロットされるが，種々の測定の結果にはかなり大きなばらつきがある．その理由は多分に，風の海面応力に大きな影響をもつはずの海面状態，いいかえれば波の状態が，無視されていることによると考えられる．

風の海面応力を支配する条件についてのこれまでの考え方を議論した後，摩擦係数を一種の粗度レイノルズ数 $Re_2{}^*=u_*H/\nu$ に対してプロットすることによって，より普遍的な表現が得られることが示される．ここに u_* は空気の摩擦速度，ν は空気の動粘性係数，H は特性波の波高であり，ここで H は，より厳密な取扱いへの一段階として，仮にとられた変数である．

この変数 $Re_2{}^*$ または $Re_4{}^*=u_{*w}L/\nu_w=2\pi g\,u_{*w}/\nu_w n_1{}^2$（$w$ は水の値，L と n_1 はそれぞれ特性波の波長と周波数）は，風波の気泡捕捉，すなわち，崩れを記述する条件ともなっている．この場合，これらのレイノルズ数は，水の表面そのものの乱れの強さを記述する量であると解釈できる．すなわち，われわれの風洞水槽実験の資料を用いて，$Re_2{}^*$ が 1×10^3，または $Re_4{}^*$ が 3×10^3 に達すると崩れが起こり始めることが示される．同時に，$Re_2{}^*$ のこの値から，摩擦係数が急に増大し始める．この現象は，風波の崩れによって起こされる「乱れの境界面突破」によって，空気から水へのより大きな運動量輸送が起こることであると解釈される．さらに，この過剰の運動量輸送は，波の運動量を増加させないで，吹送流を増強させる可能性があることが示唆される．