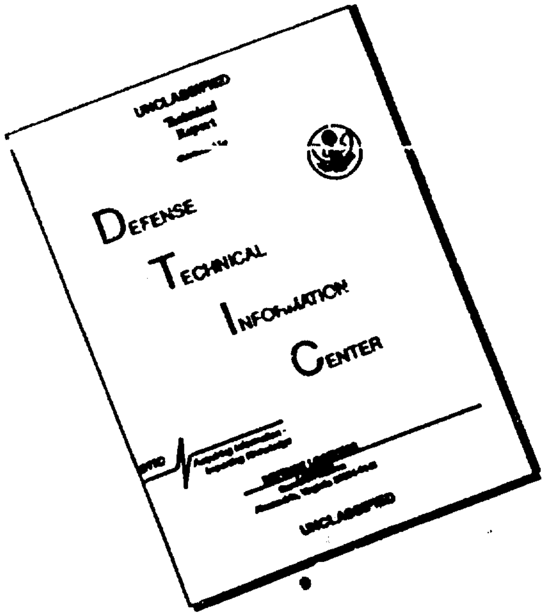
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

HYDRONAUTICS, incorporated
research in hydrodynamics

Research, consulting, and advanced engineering in the fields of NAVAL and INDUSTRIAL HYDRODYNAMICS. Offices and Laboratory in the Washington, D. C., area: Pindell School Road, Howard County, Laurel, Md.

57

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

HYDRONAUTICS, Incorporated

TECHNICAL REPORT 231-18

WIND STRESS AND SURFACE ROUGHNESS AT AIR-SEA INTERFACE

By

Jin Wu

December 1967

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Prepared Under

Office of Naval Research
Department of the Navy
Contract No. Nonr 3688(00)
NR 220-016

TABLE OF CONTENTS

	Page
ABSTRACT	1
INTRODUCTION	2
PREVIOUSLY PROPOSED CORRELATION	4
COMPILATION OF WIND-STRESS DATA	5
FLOW REGIMES AND SURFACE ROUGHNESSES UNDER DIFFERENT SEA CONDITIONS	7
REGIMES OF WIND-STRESS AT AIR-SEA INTERFACE	10
DISCONTINUITY OF WIND-STRESS COEFFICIENT — CRITICAL WIND VELOCITY	13
PROPOSED WIND-STRESS FORMULAE	16
CONCLUSION	19
REFERENCES	21

LIST OF FIGURES

Figure 1 - Summary of Wind Stress Measurements in Laboratories and in Field

Figure 2 - Oceanic Measurements of Wind-Stress Under Different Sea Conditions

Figure 3 - Surface Roughness and Flow Regimes Under Different Sea Conditions

Figure 4 - Surface Roughness and Mean Square Surface Slope Under Different Sea Conditions

Figure 5 - Determination of Charnock Constant

Figure 6 - Changing of Wind-Stress Regimes

NOTATION

$A_{\frac{1}{3}}$	$= \frac{H_{\frac{1}{3}}}{2}$, significant wave amplitude
a	Charnock proportionality constant
C	Wave phase velocity
C_y	$= \frac{\tau_o}{\rho U_y^2}$, wind-stress coefficient
F	$= \frac{U_y}{\sqrt{yg}}$, Froude number
L	Fetch
g	Gravitational acceleration
$H_{\frac{1}{3}}$	Significant wave height
η	Dynamic roughness
k	$= 30\ \eta$, surface roughness
u_*	$= \sqrt{\frac{\tau_o}{\rho}}$, shear velocity
U	Wind velocity
U_y	Wind velocity measured at distance y above mean water level
κ	= 0.42, Kärmän universal constant
λ	Wave length
ρ	Density of air
σ	Surface tension at air-water interface
τ_o	Wind stress

ABSTRACT

Based on the compiled data of thirty independent oceanic observations, this report systematically presents the wind-stress coefficient, the surface roughness and the boundary layer flow regime at the air-sea interface under various wind conditions. The air flow near the water surface is shown to be aerodynamically rough or in transition region except at very low wind velocity ($U_{10} < 3$ m/sec). Both the wind-stress coefficient and the surface roughness are found to increase with the wind velocity when U_{10} is less than 15 m/sec and reach a saturated value for U_{10} greater than 15 m/sec. Based on the oceanic wave observations, it shows that the presence of this discontinuity at U_{10} = 15 m/sec is due to an increase in the wind velocity (measured at the significant wave amplitude above the mean water level) beyond the average wave phase velocity. This finding provides a well-defined separation for the often quoted terms "light" and "strong" winds, and also explains the existence of the so-called "critical wind velocity" suggested by Munk. It also shows that the surface roughness is governed by the amplitude of the short gravity waves rather than the mean square surface slope. Charnock's relationship is shown to be applicable to most of the oceanic data,and Charnock's proportionality constant is determined,

$$\frac{\eta}{u_*^2 / g} = 0.0156.$$

Finally, two approximate formulae for the wind-stress coefficient

$$C_{10} = 0.5 \times U_{10}^{\frac{1}{2}} \times 10^{-3} \text{ for light wind}$$

and

$$C_{10} = 2.6 \times 10^{-3} \qquad \text{for strong wind}$$

are suggested for oceanic applications.

INTRODUCTION

The wind-stress acting at the air-sea interface locally is an important influence on the wind-wave interaction, including the generation of water surface set-up, drift current and surface waves, as well as on the transfer of heat and mass through the interface. For the global scale, therefore, it influences the geophysical state of the atmosphere. Numerous experimental investigations, analytical studies, and summarized reviews of this subject have appeared in various journals, showing the great effort that has been made in this area, and indicating the importance of the subject.

In considering the difficulties involved in field wind-stress determinations, discrepancies among their results are inevitable. However, the trend of the data, hidden by the discrepancies, may be uncovered if many sets of data are compiled, and if the compiled data are analyzed with the help of physical reasoning. Extending a previous laboratory study (Wu, 1967) about the physics of wind-stress and surface roughness at the air-water interface, and a subsequent work about the scaling of the wind-stress coefficient (Wu, 1968), the abundant field data are herein correlated in order to investigate the wind-wave interactions at the air-sea interface and to establish a reliable formula or formulae for oceanic applications.

The wind velocity near the air-sea interface was reported unanimously to follow the logarithmic distribtion, see Roll (1965). This distribution has also been verified by Wu (1967) in a laboratory channel. In the same study, an expression relating surface roughness and wind-stress, first suggested by Charnock (1955), has been established, provided that the surface roughness is governed by gravity waves. Characterizing the equilibrium condition between the wind and waves, this non-dimensional expression coordinates satisfactorily the laboratory and field determined wind-stress coefficients, despite the great differences in their fetches (Wu, 1968).

Based on the collected oceanic data and by accepting the logarithmic nature of the wind profile, we have studied the applicability of Charnock's expression and determined Charnock's proportionality constant. The present determined value (0.0156) is much smaller than the commonly accepted one (0.078) previously obtained by Hay (1954). (His measurement consists of six wind profiles and contributes six points to the present 3[illegible]5 data point collection). Moreover, this report systematically presents, for the first time, the wind-stress coefficient and the surface roughness at the air-sea interface under different wind conditions. Furthermore, we have shown and explained the existence of a discontinuity of the wind-stress coefficient at U_{10} = 15 m/sec, where U_{10} is the wind velocity measured at 10 m above the mean water level. We relate this discontinuity to the "critical wind velocity", which was first suggested by Munk (1947), and has been misinterpreted as being due to the transition of the boundary layer from laminar to turbulent. We suggest this wind velocity (U_{10} = 15 m/sec) as the separation for the often quoted but very confusing geophysical terms "light" and "strong" winds. Based on all of these findings and physical reasonings, two approximate formulae are suggested and they are shown to have much less deviation from the compiled wind-stress data than the formulae proposed by other investigators.

PREVIOUSLY PROPOSED CORRELATION

Since the validity of the logarithmic wind-velocity distribution with height is well established, the wind-stress coefficient, C_y, defined in terms of the wind velocity, U_y, measured at a certain height, y, can be written as

$$C_y = \frac{\tau_o}{\rho U^2_y} = \left[\frac{\varkappa}{\ln(y/\eta)}\right]^2 , \qquad [1]$$

where ρ is the air density, $\varkappa$ is the Kärmän constant, and η is the virtual origin of the logarithmic velocity profile (or the dynamic roughness).

It was found in laboratory experiments (Wu, 1967) that at high wind velocities when the wind-stress is supported by the form drag of the gravity waves, a nondimensional expression, first suggested by Charnock (1955), could be established

$$\frac{\eta}{u_*^2/g} = a = 0.0112 \ . \qquad [2]$$

By substituting [2] into [1], an equation for determining the wind-stress coefficient was obtained (Wu, 1968)

$$\frac{1}{\sqrt{C_y}} = \frac{1}{\kappa} \ \ln \left(\frac{1}{aC_y \mathbf{F}^2} \right) \ , \qquad [3]$$

in which **F** is defined as

$$\mathbf{F} = \frac{U_y}{\sqrt{gy}}$$

This equation suggests the Froude scaling law for wind-stress coefficients and has been shown by Wu (1967, 1968) to correlate satisfactorily the results obtained from measurements at all fetches.

COMPILATION OF WIND-STRESS DATA

The results of forty-two experimental investigations, twelve laboratory studies and thirty oceanic observations, have been collected. Most of the data were obtained from Francis (1951, 1954).

Hill (1962), Phillips (1966), Roll (1965), and Wilson (1960) instead of the original articles; no attempt is made here to examine the accuracy of the individual works and the various methods employed and equal weight has been assigned to each data point.

The compiled data (C_y vs U_y) are plotted in Figure 1, in which different symbols are used for the laboratory and the field results. For the latter, the wind velocity was measured at a unique height above the mean water level, y = 10 m. As for the former, six authors adopted y = 10 cm; the rest of the data were presented with the average wind velocity across the tunnel section. However, it is believed that for an ordinary wind wave channel these two wind velocities may not differ to a great extent and therefore are used interchangeably. This assumption will certainly limit the accurate evaluation of the laboratory data; however, the main purpose of this paper is to examine oceanic observations.

Much scattering of the laboratory results is shown in Figure 1, but, surprisingly enough, the oceanic data show considerable consistency among themselves. These two groups of data (laboratory measurements and oceanic observations) are distinctly separated from each other largely due to great difference in their fetches,and they can be correlated by means of [3] with the substitution of y = 10 cm for laboratory results and y = 10 m for oceanic measurements; two continuous lines are drawn in Figure 1 to show this correlation. For readers interested in scaling the wind-stress coefficient, a detailed discussion is offered by Wu (1968).

The oceanic data are further sorted into bands of 1 m/sec, having their upper and lower bounds at integral wind velocities. The data falling into each band are first averaged, and their standard deviations from the average value is subsequently determined. Along with the average value of each band, a short vertical line is drawn to indicate the standard deviation of the data from the average value for each band; see Figure 2. The average percentage of the standard deviation from the average value is only 22 percent. A discontinuity in the wind-stress coefficient is shown very clearly at U_{10} = 15 m/sec. For wind velocities below this discontinuity, the wind-stress coefficient is approximated very well by the proposed correlation curve, and above this discontinuity the wind-stress has a constant value. The mechanism responsible for this discontinuity will be explained in a latter section.

FLOW REGIMES AND SURFACE ROUGHNESSES UNDER DIFFERENT SEA CONDITIONS

According to Schlichting (1955), the surface roughness can be found from [1]

$$k = 30\,\eta = \frac{30y}{\exp(\kappa / C_y^{\frac{1}{2}})} \qquad [4]$$

It is obvious from the calculated surface roughnesses plotted in Figure 3a, that there are two different regions, namely, the region of roughness establishment in which surface roughness increases with wind velocity, and the region of established roughness in which surface roughness reaches a saturated value.

The roughness Reynolds numbers which characterize the boundary layer flow conditions can now be obtained from the calculated roughnesses and are plotted in Figure 3b. In the same figure, the limits for different flow regimes, (Schlichting, 1955) — aerodynamically smooth flow, $ku_*/\nu < 5$; transition, $5 < ku_*/\nu < 70$; aerodynamically rough flow, $ku_*/\nu > 70$ — are also marked, where ν is the kinematic viscosity of air. The boundary layer flow conditions, found from Figure 3b, are summarized below.

TABLE 1

Boundary-Layer Flow Conditions at Air-Sea Interface

Boundary Layer Flow Condition	Wind Velocity Range m/sec
Aerodynamically Smooth Flow	$U_{10} < 3$
Transition	$3 < U_{10} < 7$
Aerodynamically Rough Flow	$U_{10} > 7$

Since boundary layer conditions and surface roughnesses are the most frequently discussed subjects concerning the air-sea interface, it is surprising that only piecemeal information containing widely scattered values have been reported. The present result is believed to be the first systematic presentation of the oceanic-determined surface roughness and subsequently the boundary layer flow conditions.

The roughness at the air-sea interface is composed of a great variety of moving waves, differing in height, shape and phase velocity. Moreover, these waves are subjected to continuous and irregular changes. The instantaneous picture of the complicated sea-surface structure shows short waves superimposed upon longer waves of various sizes.

If we consider the maximum wave height-to-length ratio to be 0.14, then we find that the minimum wave lengths corresponding to the estimated surface roughnesses in the aerodynamically rough regime are between 2.1 and 58 cm, which fall within the gravity wave category. At low wind velocities (3 m/sec $< U_{10} <$ 7 m/sec), the minimum wave length corresponding to the respective surface roughness has a very small value. However, it is clear from Schlichting (1955) that the height of the actual roughness is usually greater (sometimes much greater) than that of the surface roughness calculated from the wind profile, depending on the density of the actual roughness. On the other hand, an indirect proof of relating the surface roughness to gravity waves at low wind velocities is provided by showing the applicability of Charnock's nondimensional expression to the wind-stress data compiled within this wind velocity range; see Figure 2 and discussions in later sections. The restriction of the applicability of the Charnock expression to the cases of gravity waves governing surface roughnesses has been established by Wu (1967).

More analytical studies along with detailed oceanic observations are necessary to understand the precise nature of the surface roughness and its variation with sea conditions, especially for the low wind velocity range, discussed above, and for the regime of established roughness. The results here seem to relate the surface roughness to the short gravity waves and demonstrate no direct correlation between the surface roughness and the mean square surface slope; see Figure 4. The latter correlation was suggested earlier by Munk (1955).

REGIMES OF WIND-STRESS AT AIR-SEA INTERFACE

We have shown the boundary layer flow conditions at the air-sea interface for various wind velocities. As shown in Figure 2, in which the scales of sea state as well as of Beaufort number are marked, the proposed correlation formula approximates the trend of the oceanic data at the frequently occurring light wind, (3 m/sec $< U_{10} <$ 15 m/sec, or sea state 1-4 corresponding to Beaufort number 1-6). For a wind velocity less than 3 m/sec or breeze, (sea state 0-1 and Beaufort number 0-1), the flow is aerodynamically smooth, and a higher wind-stress coefficient is shown. The wind-stress coefficient remains constant for strong wind, ($U_{10} >$ 15 m/sec, or sea state above 5 corresponding to Beaufort number above 7). A discussion of each case follows.

Wind-Stress for Breeze: The wind-stress coefficient for aerodynamically smooth flow can be shown as

$$C_y = \left[\frac{\kappa}{\ln\left(\frac{9.1\ yu_*}{\nu}\right)}\right]^2 \qquad [5]$$

and is plotted as a dotted line in Figure 2. As indicated by the compiled data, the flow is aerodynamically smooth for $U_{10} < 3$ m/sec as concluded in the previous section. The wind-stress coefficient in the transition region (3 m/sec $< U_{10} <$ 7 m/sec), however, is shown to be represented very well by the formula for aerodynamically rough flow rather than (the dotted line corresponding to) aerodynamically smooth flow.

Wind Stress for Light Wind: In Figure 2, the region of applicability of the Charnock relationship is shown clearly. The proportionality constant of the Charnock expression was determined by Wu (1967) in a laboratory channel as 0.0112 and has been shown in Figure 1 to fit the field wind-stress data fairly well. However, at this stage it may be worthwhile to determine a new constant based on the data compiled from thirty independent oceanic investigations.

This constant is determined indirectly by finding a value which, after substituting into [3], offers the best fit of the stress coefficient curve to the compiled data in the region of light wind. Equal weight has been assigned to each original data point; consequently, each averaged data point shown in

Figure 2 possesses a different weight proportional to the number of the original data points it contains. The root-mean-square deviation of the compiled data points from the curves with the substitution of various values for "a" are plotted in Figure 5a. The minimum point corresponds to a new Charnock proportionality constant determined directly from oceanic data

$$a = 0.0156 = \frac{\eta}{u_*^2/g} . \qquad [6]$$

The wind-stress coefficient for this most frequently encountered regime can now be written as

$$C_y = \left[\frac{\kappa}{\ln\left(\frac{yg}{0.0156\ C_y U_y^2} \right)} \right]^2 , \qquad [7]$$

and is drawn as a continuous curve in Figure 2; in which an excellent representation of the compiled data by this expression is shown.

The expression for the wind velocity distribution can then be obtained as

$$\frac{U_y}{u_*} = \frac{1}{\kappa} \ln \left(\frac{yg}{u_*^2} \right) + 10.4 \quad . \qquad [8]$$

Wind Stress for Strong Wind: Beyond sea state 5 $U_{10} > 15$ m/sec) the wind-stress coefficient shows a trend to remain constant, which is obvious from [1], suggesting the saturation of roughness, η. More studies, especially oceanic observations, are needed in order to thoroughly understand this mechanism. However, this trend does not conflict with expectation since the waves responsible for the surface roughness cannot grow with the wind velocity forever. As the wind blows harder, the transfer of more energy from the air merely provides energy to waves with large wave lengths, which by having very high phase velocities and relatively flat shapes, is hardly responsible for the surface roughness.

The wind-stress in this case is found to be

$$C_y = 2.6 \times 10^{-3} \qquad [9]$$

It may be worthwhile to note that this trend, C_y remaining constant at high wind velocities, is also shown in the Nikuradse experiments for rough pipe flow at very high Reynolds numbers. These experiments bear a close analogy with the present case.

DISCONTINUITY OF WIND-STRESS COEFFICIENT — CRITICAL WIND VELOCITY

As stated in previous sections, more oceanic observations of the microscopic structure of the air-sea interface are needed in order to understand the precise nature of the surface roughness which in turn governs the wind-stress. We are now attempting to employ oceanic information already available to explain the existence of the discontinuity of the wind-stress coefficient at U_{10} = 15 m/sec.

A well coordinated and frequently quoted presentation of oceanic data concerning the wave period, phase velocity, and significant wave height was presented by Wiegel (1962); its small scale reproduction is shown in Figure 6. Empirical formulae for the dimensionless phase velocity (C/U_{10}) and the significant wave height ($gH_{\frac{1}{3}}/U^2_{10}$) at various combinations of wind velocity and fetch (gF/U^2_{10}) are found to be

$$\frac{C}{U_{10}} = 0.050\left(\frac{gF}{U^2_{10}}\right)^{0.30} ; \qquad [10]$$

$$\frac{gH_{\frac{1}{3}}}{U^2_{10}} = 0.0031\left(\frac{gF}{U^2_{10}}\right)^{0.47} \qquad [11]$$

Data points for ($gH_{\frac{1}{3}}/U^2_{10}$) are seen to deviate from the drawn line at the left half of the plot; however, the oceanic observations,owing to their great fetches, occupy only the right half of the plot.

From these two empirical formulae, the average phase velocity and the significant wave height for various wind velocities, at any given fetch, can be obtained. On the other hand, based on the logarithmic velocity distribution and the compiled wind-stress coefficient data, the wind velocity at a height of the significant wave amplitude, $A_{\frac{1}{3}}$ (half the significant wave height), from the mean water level, can be determined from [8]. A sample plot of these two velocities, the average phase velocity, C, and the wind velocity at the height of the significant wave amplitude $(U_{10})_{A_{\frac{1}{3}}}$ for a fetch of 50 km is shown in Figure 6a. Notice that these two velocities intersect. Let us call U_I the wind velocity at which, for a particular fetch, the intersection occurs. Following the same procedure, the intersecting wind velocities U_I at various fetches are found and plotted in Figure 6b. Surprisingly enough, as the fetch increases, this wind velocity, U_I, approaches asymptotically to U_{10} = 15 m/sec. This is the very velocity where the discontinuity of the wind-stress coefficient occurs. These fetches (50 km or greater) where the intersecting velocity approaches 15 m/sec are very common for oceanic applications.

The implication of the intersection of these two velocities (wind velocity and phase velocity) is that the typical waves pull the air mass for U_{10} less than 15 m/sec and the air mass pushes the typical waves for U_{10} greater than 15 m/sec. A drastic change in the structure of the air flow and, consequently, in the wind-stress coefficient is thus inevitable. This finding provides the explanation for the existence of the discontinuity of the wind-stress coefficient. In addition, this finding offers encouragement to oceanographers by proving the consistency of the wind-stress data (this discontinuity was shown almost in every set of wind-stress data) and the consistency between the wind-stress data and other oceanic observations (by using wave measurement results to explain the trend of wind-stress data).

There are two commonly used, but very confusing, geophysical terms: light wind and strong wind. Various values of wind velocities, between 8 and 15 m/sec, are quoted as the separating velocity. The present finding thus proposes a natural division (U_{10} = 15 m/sec) for the light and strong winds. This finding may also be related to the so-called "critical wind velocity" first proposed by Munk (1947) but accorded erroneously to the transition of the boundary layer flow from laminar to turbulent.

PROPOSED WIND-STRESS FORMULAE

Many reviewers have proposed various wind-stress formulae. They generally contain only a few sets of data which may not be representative and, more importantly, make little attempt to provide some physical reasoning about the grouping of the data. Some investigators improperly compiled the laboratory data with the oceanic results by employing y = 10 cm for the former and y = 10 m for the latter. Other investigators neglected the obvious trend of the dependency of the wind-stress coefficient on wind velocity. The discontinuity of the wind-stress coefficient was not noted in most of the reviews. The present review has separated the oceanic observations from the laboratory results (see Figure 1) and preserved the dependency of the wind-stress coefficient on the wind velocity (see Figure 2). Moreover, the finding of the boundary layer flow conditions, aerodynamically smooth or rough (see Figure 3), and of the discontinuity of the wind-stress coefficient (see Figure 2) help very much in the proper handling of the wind-stress data. Some of the wind-stress formulae discussed in the previous section have not been expressed explicitly and simply for common applications. Consequently, the following approximations of the wind-stress formula are suggested for various cases and are compared with some available authoritative formulae at the end of this section.

Breeze: Following the frictional resistance formula for the turbulent boundary layer along a smooth plate, the wind-stress coefficient for this case can be approximated by

$$C_{10} = \frac{1.25}{U_{10}^{1/5}} \times 10^{-3} \quad \text{for} \quad U_{10} < 1 \text{ m/sec} \qquad [12]$$

Light Wind: In order to approximate the trend of the curve expressed in [7] and to select the simplest formula possible, the following is suggested

$$C_{10} = 0.5 \times U_{10}^{\frac{1}{2}} \times 10^{-3} \quad \text{for} \quad 1 \text{ m/sec} < U_{10} < 15 \text{ m/sec} \quad [13]$$

This curve, drawn in Figure 2, is seen to approximate very well the original wind-stress curve except at the lower wind velocity end. As shown in the last section, the boundary layer flow condition is in the transition region at this lower wind velocity end. The uncertainty of the data in the transition region makes this slight deviation even more discernable.

Strong Wind: The wind-stress coefficient is already in a very simple form as shown in [9]. This formula is applicable for a wind velocity greater than 15 m/sec.

The present and the previously proposed and often quoted formulae are tabulated in the following table. The root-mean-square errors of the wind-stress data from the proposed curves are also presented for the purpose of comparison. In the error calculation, equal weight once again has been assigned to every original data point.

TABLE 2

Comparison of Wind-Stress Formulae

Author	Year	Proposed Formula $C_{10} \times 10^3 =$	Range of Application m/sec	Root-Mean-Square Error
Wu	1967	$0.5 \times U_{10}^{\frac{1}{2}}$	$1 < U_{10} < 15$	0.103
		2.6	$U_{10} > 15$	0.130
Deacon & Webb	1962	$1.0 + 0.07 \times U_{10}$	$1 < U_{10} < 14$	0.246
Wilson	1960	1.49	$1 < U_{10} < 10$	0.369
		2.37	$U_{10} > 10$	0.403
Sheppard	1958	$0.8 + 0.114 \times U_{10}$	$1 < U_{10} < 20$	0.367
Francis	1951	$1.3 \times U_{10}$	$1 < U_{10} < 25$	0.379
Neumann	1948	$0.9 \times U_{10}^{-\frac{1}{2}}$	$1 < U_{10} < 30$	1.441

CONCLUSION

The wind-stress data are compiled from the following independent laboratory and field investigations

TABLE 3

Sources of Wind Stress Data

Laboratory Investigations		Field Investigations	
Author	Year	Author	Year
Francis	1951	Colding	1876
Francis	1951	Ekman	1905
Keulegan	1951	Johnson	1927
Johnson, et al	1952	Shoulejkin	1928
Hamada	1953	Montgomery	1936
Sibul	1955	Sutcliffe	1936
Hayami, et al	1959	Palmen, et al	1938
Fitzgerald	1963	Bruch	1940
Fitzgerald	1963	Schalkwijk	1947
Fitzgerald	1963	Hela	1948
Hidy, et al	1966	Roll	1948
Wu	1967	Corkan	1950
		Durst	195[illegible]
		Sheppard	1952
		Sheppard, et al	1952
		van Dorn	1952
		Hellstrom	1953
		Hellstrom	1953
		Keulegan	1953
		Hay	1955
		McIlroy	1955
		Charnock, et al	195[illegible]
		Deacon, et al	1956
		Takahashi	1958
		Brocks	1959
		Vinogradova	1959
		Bruce, et al	196[illegible]
		Brocks	196[illegible]
		Deacon	196[illegible]
		Deacon	196[illegible]

The results found in this report are summarized in Table [illegible].

TABLE 4

SUMMARY OF RESULTS

WIND-STRESS AND SURFACE ROUGHNESS AT AIR-SEA INTERFACE

DESCRIPTION OF WIND	BREEZE	LIGHT WIND	STRONG WIND
WIND VELOCITY U_{10}, m/sec	1 2 3	4 5 7 9 11 13 15	18 21 24 27 30
SEA STATE	0 1 2 3 4 5 6 7 8 9		
BEAUFORT NUMBER	0 1 2 3 4 5 6 7 8 9		11 12
BOUNDARY-LAYER FLOW CONDITIONS	AERODYNAMICALL SMOOTH FLOW	TRANSITION; AERODYNAMICALLY ROUGH FLOW	AERODYNAMICALLY ROUGH FLOW
REGION OF SURFACE ROUGHNESS		REGION OF ROUGHNESS ESTABLISHMENT	REGION OF ESTABLISHED ROUGHNESS
SURFACE ROUGHNESS cm		$0.03 < k < 0.3$; $0.3 < k < 1.5$	$k = 8$
WIND-STRESS FORMULA	[illegible]	[illegible]	$C_{10} = 2.6 \times 10^{-3}$
APPROXIMATE WIND-STRESS FORMULA	[illegible]	$C_{10} = 0.5 \times U_{10}^{1/2} \times 10^{-3}$	$C_{10} = 2.6 \times 10^{-3}$

Note on the table layout: the SEA STATE and BEAUFORT NUMBER cells are printed in the same ruled row as the wind-velocity scale. Sea state: 0 and 1 (up to about 2 m/sec), 2 (3), 3 (4–5), 4 (7–13), 5 (15–18), 6 (18–21), 7 (21–24), 8 (24–27), 9 (27–30). Beaufort number: 0, 1, 2, 3, 4, 5, 6, 7 (13–15), 8 (15–18), 9 (18–21), [blank] (21–24), 11 (24–27), 12 (27–30). In the surface roughness row, $0.03 < k < 0.3$ covers 3–7 m/sec and $0.3 < k < 1.5$ covers 7–15 m/sec. The transition band covers 3–7 m/sec.

[illegible]

REFERENCES

Brocks, K., "Measurements of Wind Profiles Over the Sea and the Drag at the Sea Surface," Proc. Intern. Oceanog. Congr. (Preprints), Am. Assoc. Advan. Sci., 742-744, 1959.

Brocks, K.,"Results of Wind Profiles Measurements Above the Sea," Proc. Symp. Math. Hydrodgn. Methods of Phys. Oceanog., Hamburg, 409-419, 1962.

Bruce, J. P., Anderson, D. V., and Rodgers, G. K., "Temperature, Humidity and Wind Profiles Over the Great Lakes,"Great Lakes Res. Div., Univ. of Michigan, Publ. No. 7.

Bruch, H., "Die vertikale Vertielung von Windgeschwidigkeit und Temperatur in den untersten Metern über der Wasseroberfläche,"Veröffentl. Inst. Meeresk. Univ. Berlin, A. 38, 5-51, 1940.

Charnock, H., "Wind Stress on a Water Surface," Quart. J. Roy. Meteorol. Soc. 81, 639, 1955.

Charnock, H., Francis, J.R.D., and Sheppard, P. A., "An Investigation of Wind Structure in the Trades," Phil. Trans. Roy. Soc. London, A, 249, 179-234, 1956.

Colding, A., "Results of Certain Investigations of the Current in the Sea Caused by the Force of the Wind," Danske Videnskabs, Shrifter, Naturvidenskab. Math. Afedl, 11, 3, 1876.

Corkan, R. H., Phil. Trans. A, 242, 1950.

Cox C., and Munk, W. H., "Slopes of Sea Surface Deduced from Photographs of Sun Glitter,"Bull. of Scripps Inst. of Oceanog., Univ. of Calif., Vol. 6, No. 9, 1956.

Deacon, E. L., Sheppard, P. A., and Webb, E. K., "Wind Profiles Over the Sea and the Drag at the Sea Surface," Australian J. Phys., 9, 511-541, 1956.

Deacon, E. L., "Aerodynamic Roughness of the Sea," J. Geophys. Res. 67, 31673/72, 1962.

Durst, C., "On Surface Friction and Turbulence in the Ocean," Monthly Notices Roy. Astron. Soc., Geophys. Suppl., 5, 369-373, 1950.

Ekman, V. W., "On the Influence of the Earth's Rotation on Ocean Currents," Arkiv Matematik Astron. Fysik 17, No. 26, 1905.

Fitzgerald, L. M., "Wind-Induced Stresses on Water Surfaces," Australian J. Phys. 16, 1963.

Francis, J.R.D., "The Aerodynamic Drag of a Free Water Surface," Proc. Roy. Soc. London, A, 206, 387-406, 1951.

Francis, J. R. D., "Wind Stress on a Water Surface," Quart. J. Roy. Meteorol. Soc., 80, 438-443, 1954.

Hamada, T., Mitsuyasu, H., and Hase, N., "Experimental Study of Wind Effects on Water Surface," Transport Tech. Res. Rep. Tokyo, No. 8.

Hay, J. S., "Some Observations of Air Flow Over the Sea," Quart. J. Roy. Meteorol. Soc., 81, 307-319, 1955.

Hayami, S., and Kunishi, H., "A Wind Flume Study on the Generation of Waves," Proc. Intern. Oceanog. Congr. (Preprints), Am. Assoc. Advan. Sci., 753-755, 1959.

Hela, I., "On the Stress of the Wind on the Water Surface," Eripainos Geophys., Helsinki, 3, 146-161, 1948.

Hellstrom, B., "Wind Effect on Ringköbing Fjord," Trans. Am. Geophys. Union, 34, 194-200, 1953.

Hidy, G. M., and Plate, E. J., "Wind Action on Water Standing in Laboratory Channel," J. Fluid Mech. 26, 651-687, 1966.

Hill, M. N., (editor), "The Sea," Interscience Publishers, New York, 1962.

Johnson, J. W., and Rice, E. K., "A Laboratory Investigation of Wind-Generated Waves," Trans. Am. Geophys. Union, 33, 845-854, 1952.

Johnson, N. K., "Some Meteorological Observations Made at Sea," Quart. J. Roy. Meteorol. Soc. 53, 59-63, 1927.

Keulegan, G., "Wind Tides in Small Closed Channels," Res. Paper 2207, Natl. Bur. Standards U.S., 1951.

Keulegan, G., "Hydrodynamic Effects of Gales on Lake Erie," J. Res. Natl. Bur. Standards U.S., 50, 99-110, 1953.

McIlroy, I.C., "The Atmospheric Fine Structure Recorder," C.S.I.R.O. Div. Meteorol. Phys. Tech. Paper No. 3, Melbourne, 1955.

Montgomery, R. B., "Measurements of Vertical Gradient of Wind Over Water," Papers in Phys. Oceanog. Meteorol., Mass. Inst. Technol. and Woods Hole Oceanog. Inst., 4 (3), 21, 1936.

Munk, W. H., "A Critical Wind Speed for Air Sea Boundary Process," J. Marine Res. 6, 203-218, 1947.

Munk, W. H., "High Frequency Spectrum of Ocean Waves," J. Mar. Res. 14, 1955.

Palmen, E. H., and Laurila, E., "Über die Einwirkung eines Sturmes auf den hydrographischen Zustand im nordlichen Ostseegebiet," Soc. Sci. Fennia, Commentationes Phys.-Math., 10, 1-53, 1938.

Phillips, O. M., "The Dynamics of Upper Ocean," Cambridge University Press, 1966.

Roll, H. U., "Das Windfeld über den Meereswellen," Naturwissenschaften, 35, 1948.

Roll, H. U., "Physics of the Marine Atmospheres," Intnal. Geophys. Ser. Vol. 7, Academic Press, New York, 1965.

Schalkwijk, W. F., "A Contribution to the Study of Storm Surges on the Dutch Coast," Koninkl. Ned. Meteorol. Inst., 125, 1947.

Schlichting, J., "Boundary Layer Theory," McGraw-Hill, New York 1955.

Sibul, O. J., "Water Surface Roughness and Wind Shear Stress in a Laboratory Wind-Wave Channel, " Tech. Mem. 74, Beach Erosion Board, Corps of Engrs., U. S. Army, 1955.

Sheppard, P. A., and Omar, M. H., "The Wind Stress Over the Ocean from Observations in the Trades," Quart. J. Roy. Meteorol. Soc. 78, 583-589, 1952.

Shoulejkin, W., "The Evaporation of Sea Water and the Thermal Inter-Cause Between the Sea and Atmosphere," Gerlands Beitr. Geophys., 20, 99, 1928.

Sutcliffe, R. C., "Surface Resistance in Atmosphere Flow," Quart. J. Roy. Meteorol Soc., 62, 1936.

Takahashi, T., "Micro-Meteorological Observations Over the Sea," Meteorol. Notes, Kyoto Univ., Meteorol. Res. Inst., Ser. 2, No. 12, 1958.

van Dorn, W. G., "Wind Stress on an Artificial Pond," J. Mar. Res., 12, 249-276, 1953.

Vinogradova, O. N., "The Tangential Stress of the Wind on a Disturbed Sea Surface," Bull. Acad. Sci. USSR Geophys. Ser. No. 11, 1646-1655, 1959.

Wiegel, R. L., "Wind Waves and Swell," Proc. 7th Conf. on Coastal Engr., 1962.

Wilson, B. W., "Note on Surface Wind Stress Over Water at Low and High Wind Speeds,"J. Geophys. Res. 65, 3377-3382, 1960.

Wu, J., "Laboratory Studies of Wind Wave Interactions," HYDRONAUTICS, Incorporated Technical Report 231-13, 1967. J. Fluid Mech. (to appear).

Wu, J., "Froude Number Scaling of Wind-Stress Coefficients," HYDRONAUTICS, Incorporated Technical Report 231-23, 1968.

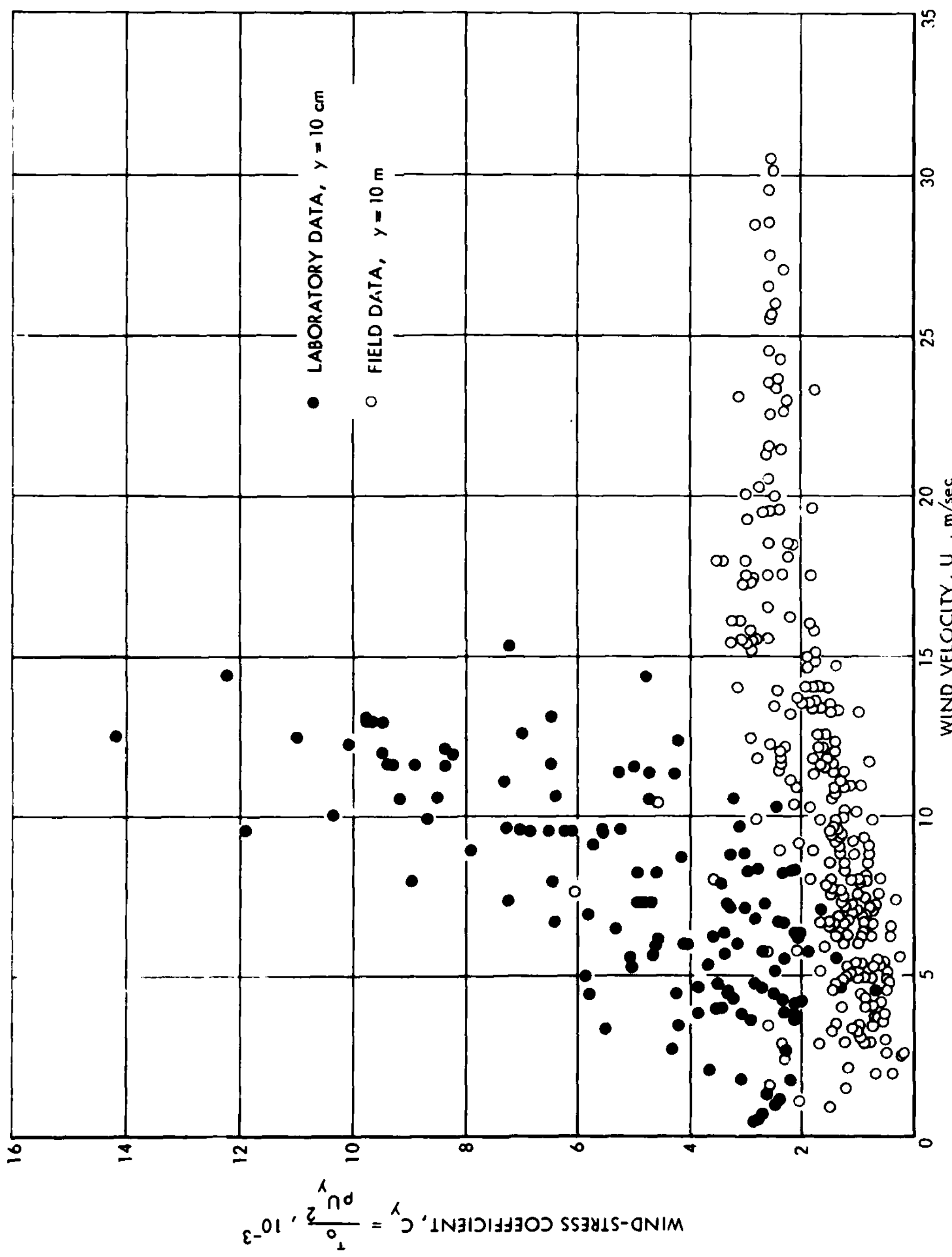


FIGURE 1 - SUMMARY OF WIND-STRESS MEASUREMENTS IN LABORATORIES AND IN FIELD

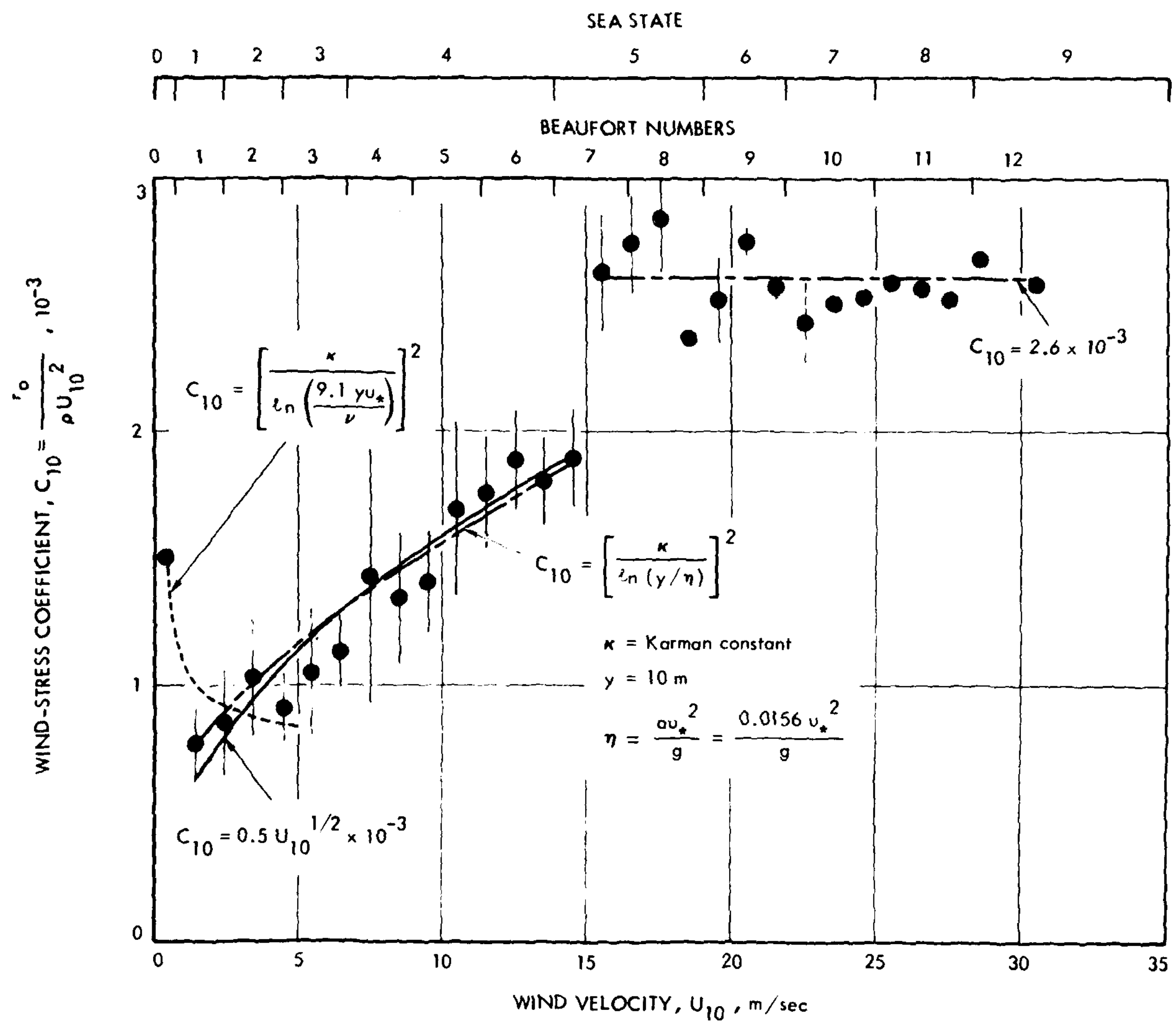
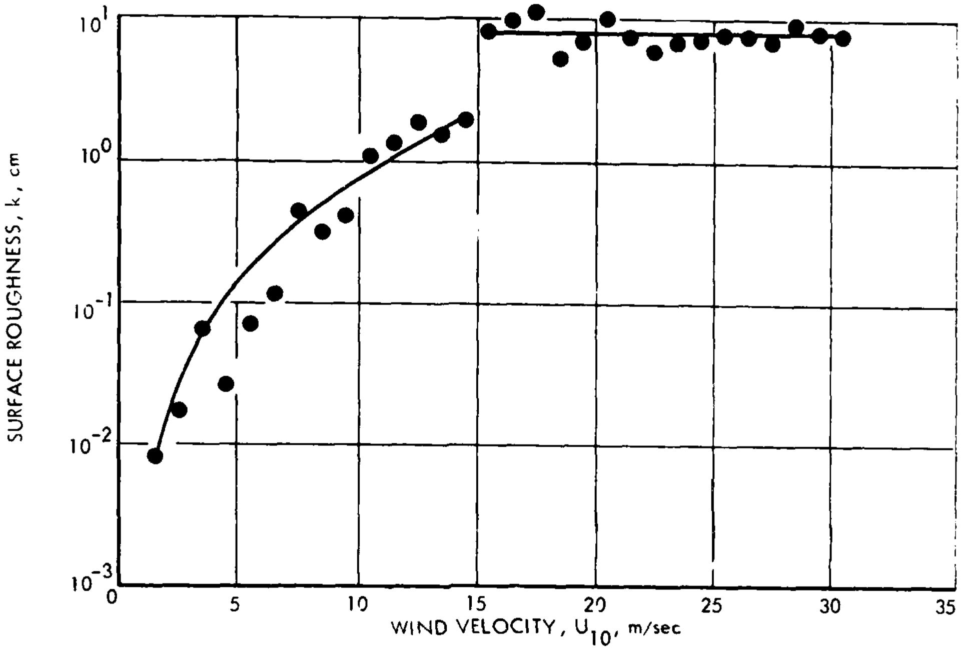
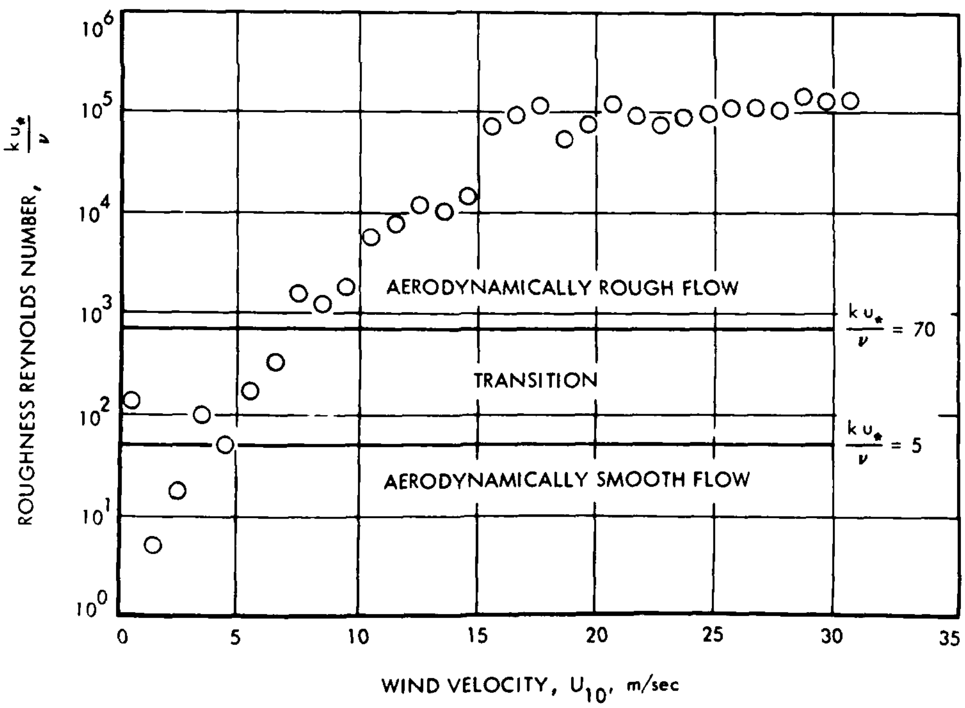


FIGURE 2 - OCEANIC MEASUREMENTS OF WIND-STRESS UNDER DIFFERENT SEA CONDITIONS



(a) SURFACE ROUGHNESS AT AIR-SEA INTERFACE



(b) BOUNDARY LAYER FLOW CONDITIONS

FIGURE 3 - SURFACE ROUGHNESS AND FLOW REGIMES UNDER DIFFERENT

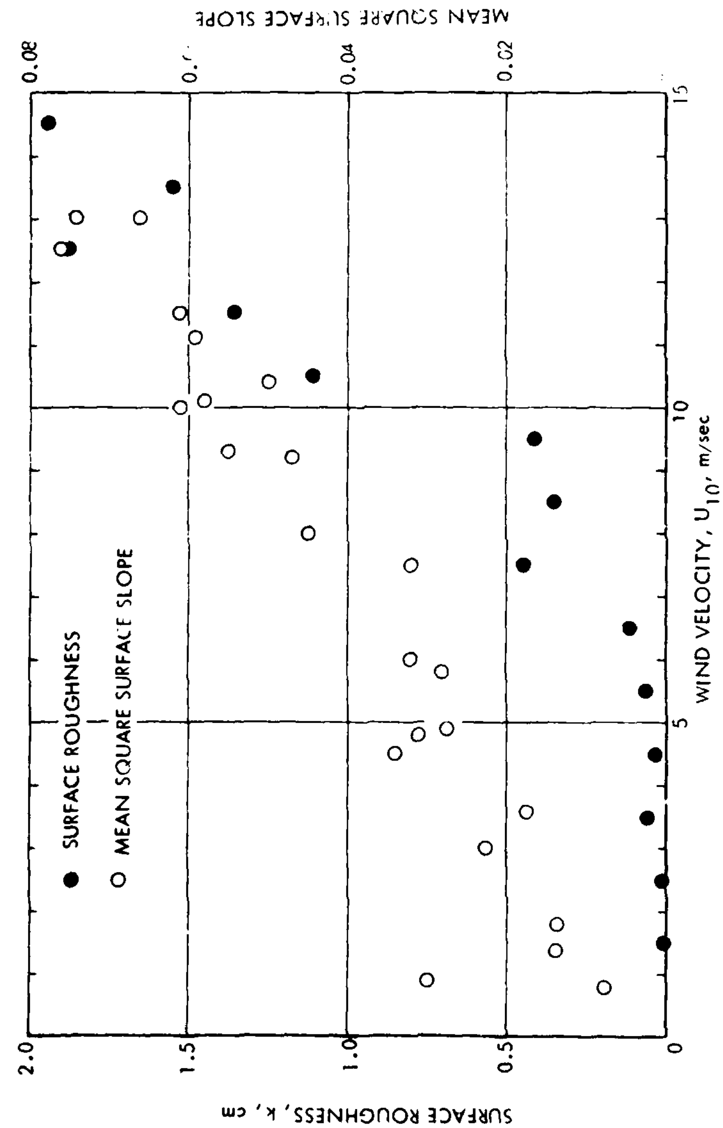


FIGURE 4 - SURFACE ROUGHNESS AND MEAN SQUARE SURFACE SLOPE UNDER DIFFERENT CONDITIONS (THE MEAN SQUARE SURFACE SLOPES ARE REPRODUCED FROM COX AND MUNK, 1956)

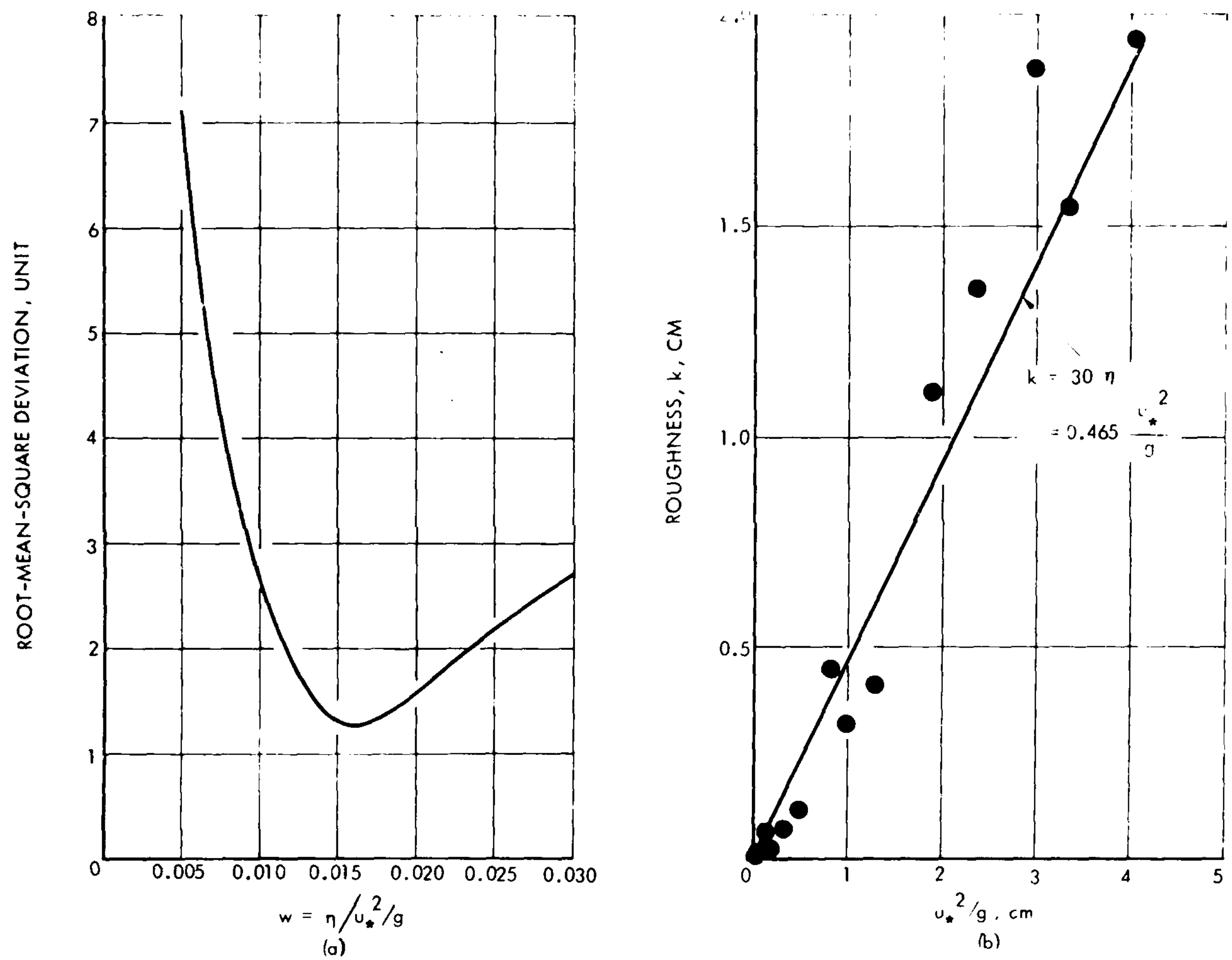


FIGURE 5 - DETERMINATION OF CHARNOCK CONSTANT

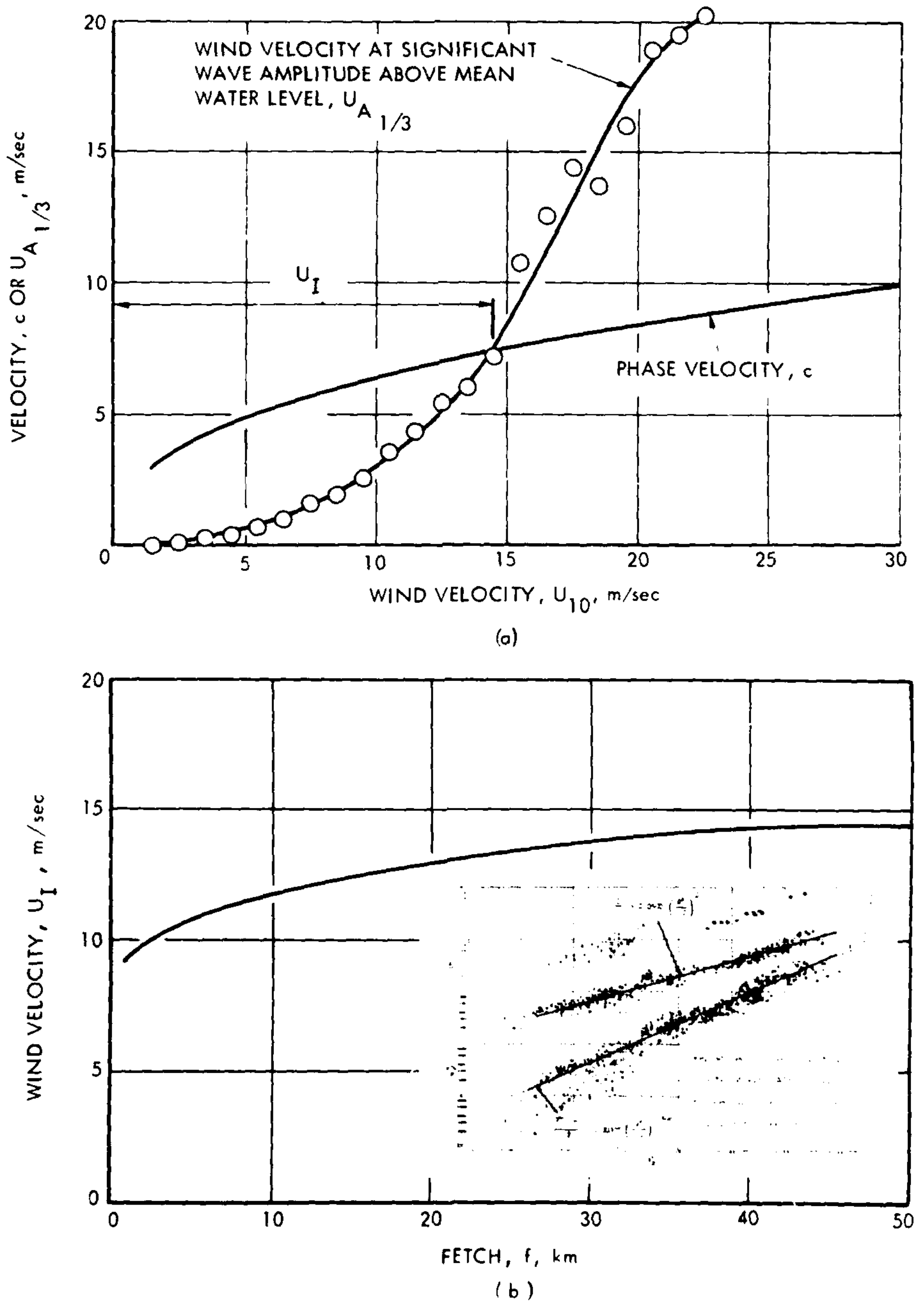


FIGURE 6 - CHANGING OF WIND-STRESS REGIMES

BLANK PAGE

Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) HYDRONAUTICS, Incorporated Pindell School Road, Laurel, Md.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Wind Stress and Surface Roughness at Air-Sea Interface

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Wu, Jin

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 1967	35	48

8a. CONTRACT OR GRANT NO. Nonr 3688(00) NR220-016 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report 231-18 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Office of Naval Research Department of the Navy

13. ABSTRACT Based on the compiled data of thirty independent observations, this report presents the wind-stress coefficient, the surface roughness and the boundary layer flow regime at the air-sea interface under various wind conditions. Both the wind-stress coefficient and the surface roughness are found to increase with the wind velocity when U_{10} is less than 15 m/sec and reach a saturated value for U_{10} greater than 15 m/sec. Based on the oceanic wave observations, it states that this discontinuity at U_{10} = 15 m/sec is due to an increase in the wind velocity (measured at the significant wave amplitude above the mean water level) beyond the average wave phase velocity. This finding provides a well-defined separation for the often quoted terms "light" and "strong" winds, and also explains the existence of the so-called "critical wind velocity." It also shows that the surface roughness is governed by the amplitude of the short gravity waves rather than the mean square surface slope. Charnock's relationship is shown to be applicable to most of the data and Charnock's proportionality constant is determined. Finally, two approximate formulae for the wind-stress coefficient, one for light wind and the other for strong wind are suggested.

DD FORM 1 JAN 64 1473

Unclassified

Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Wind Waves						
Wind Stress						
Surface Roughness						
Critical Wind Velocity						

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION. Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________ ."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________ ."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________ ."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS), (S), (C), or (U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.

DD FORM 1 JAN 64 1473 (BACK)

323551

Unclassified

Security Classification