The Wave-Driven Wind

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(Manuscript received 31 January 1966, in revised form 15 July 1966)

ABSTRACT

By photographing the movement of smoke plumes and recording the air movement at fixed points above the water in an indoor wave tank, it is shown that progressive waves in water may produce an airflow more than half a wavelength, or 14 wave amplitudes, above the water.

The significance of this finding is that it indicates that the mean wind speed should not vanish at the mean water surface as is commonly assumed, and that the vertical gradient of the horizontal wind near the surface of water covered by progressive waves should be less than the gradient near a land surface with other conditions nearly identical.

1. Introduction

In August 1964 the author discovered that the operation of a mechanical wave generator in an indoor laboratory wave tank led to an airflow immediately above the waves with a mean component in the direction of wave propagation. It seems likely that other experimenters would have observed this wave-driven component of the wind, but no mention of it has been found in the literature. This is a little surprising, for the mass transport of water by waves gives a similar phenomena on the water side of the air-sea boundary and has been known for more than a century (Stokes, 1847).

It appears intuitively that the energy of the mean airflow generated by surface waves could not be a significant part of the energy budget of either the air or water. This concept may explain the lack of attention to this phenomenon. However, the phenomenon may be important for quite different reasons. The mass transport by waves is concentrated in a shallow layer near the water surface. If the component of the wind due to the waves is likewise confined to a shallow layer, the existence of this component will affect the boundary condition of the flow at the interface between air and water whenever waves are present.

Roll (1965) presents an extensive review of the theoretical and empirical studies of the wind in the lowest few meters of the atmosphere above the sea. It is generally assumed in studying the wind at the lower boundary of the atmosphere that the wind speed and the turbulent mixing coefficient vanish near the boundary and that the mixing coefficient is a linear function of the distance from the boundary, at least for conditions of neutral stability. These assumptions lead to the well-known logarithmic wind profile law for steady state flow near the boundary in a homogeneous fluid. Sutton (1953, Chapter 7) reviews the theoretical and empirical evidence for this law above a land surface and concludes that it is well established for adiabatic conditions.

Roll finds considerable empirical evidence that, in general, the wind profile is not logarithmic over the sea even when a logarithmic profile would be expected over land. He also reviews several theoretical papers which imply that a logarithmic profile should not be expected above the sea surface during adiabatic conditions. He does not consider the wave-driven component of the wind. Roll also reviews the various theories proposed for a generalization of the logarithmic profile law for other than adiabatic lapse rates, but these need not concern us here.

A full explanation of the shape of the wind profile above progressive waves will require a combination of at least some of the mechanisms discussed by Roll, the wave-driven wind, and perhaps other mechanisms not yet identified.

Stokes found that each fluid particle affected by irrotational waves on a deep layer of an inviscid homogeneous fluid, otherwise at rest, would have a mean velocity in the direction of wave propagation given by

$$\bar{u}_p = cA^2k^2e^{2kz}, \tag{1}$$

where A is the amplitude of the wave, $\bar{u}_p$ the mean speed of the particle, c the phase speed of the waves, k the wave number $(2\pi/L)$, where L is the wavelength, and z is the distance from the mean water surface (positive upward). This may be rewritten in the form

$$\bar{u}_p = c\pi^2 s^2 e^{2kz}, \tag{2}$$

where $s = 2A/L$ is the wave steepness.

Russell and Osorio (1958) reported laboratory experiments which show good agreement between theory and observations for deep-water waves. The assumption of infinite depth is reasonably well satisfied if the depth exceeds half a wavelength.

The above theory can be generalized in a perfectly orderly way for fluids of finite depth. However, laboratory experiments by Bagnold (1947) and others show that there is little agreement between the generalized theory for finite depth and experimental data.

Longuet-Higgins (1953) has extended the theory to include the effects of viscosity and has shown that viscous friction between the wave motion and the bottom of the wave tank transforms wave energy to mean flow energy in such a way as to generate a steady flow in the direction of wave propagation near the bottom boundary. Russell and Osorio (1958) report experimental results which are in good agreement with the Longuet-Higgins theory for shallow water.

The theory of mass transport by waves in deep water may be taken as a first approximation to the theory for the mass transport by waves on the upperside of the air-sea boundary in the absence of a mean wind, if z in (1) is interpreted as $-|z|$. The analysis of experimental data from this point of view will furnish some guidance in the development of a hydrodynamic theory for the wave-driven wind.

2. Laboratory observations of the wave-driven wind

The simplest procedure for demonstrating conclusively the existence of a wave-generated component of the wind is to observe the flow of the air over mechanically generated waves in the absence of any other wind. Observations of this type have been made by the writer in the 72-ft long wave tank at the Coastal Engineering Research Center of the U. S. Army Corps of Engineers, described by Rayner (1964), in the 54-ft long wind-wave tank of the Bureau of Standards, described by Keulegan (1951), and in the 40- by 86-ft wave tank of the University of Michigan at Willow Run, Mich.

In each of the experiments, smoke was blown over the undisturbed water for a few moments and then the wave generator was turned on. In all cases, even with moderately steep waves, an individual puff of smoke could be followed for several wave periods before it became so diffused as to prevent identification. The smoke appeared to drift slowly in the direction of wave propagation over the troughs and then to take a quick jump up, backwards, and over the wave crests. This behavior is clearly evident in the moving pictures of the smoke but is difficult to see in the still photography reproduced here. The hot wire records discussed below showed a sharp drop in the forward motion of the air above each wave crest. This characteristic of the air motion can be predicted by considering the nonlinear aspects of the boundary condition in an inviscid theory.

In most experiments, the intensity of the turbulence, as displayed by the agitation of the smoke, and the speed of dissipation of the individual puffs appeared to be greater above mechanically generated waves than above calm water; and it appeared to decrease with distance above the water. The scale of turbulence, however, was always much smaller than the particle orbits resulting from wave motion. The intensity of turbulence seemed to depend more on wave steepness than wave heights.

In several cases in which the intensity of atmospheric turbulence was low at the beginning of a run, a pool of smoke collected above the water near the exit end of the supply tube with the mechanical wave generator not operating and moved away in the direction of wave propagation soon after the wave generator was turned on. In a few cases, the initial drift of the smoke was toward the wave generator before it was turned on. The direction of the airflow was reversed after a few full-sized waves had passed the smoke outlet. In some of the experiments, an initial flow existed in the direction of wave propagation. An increase in the speed of this flow appeared to take place when the wave generator was turned on.

In several of the experiments, small pieces of cardboard cut from punch cards by a card punch machine were sprinkled on the water surface to detect the mass transport in the water. Sometimes dye was used for the same purpose. The speed of mass transport of smoke, due to wave action, was greater than the speed of transport of particles in the water surface in each case in which a comparison was made.

Two hot wire anemometer probes were available for one series of tests at Willow Run. As some of the results from this set of tests will be discussed in detail, a sketch of the experimental setup is shown in Fig. 1. The test setup was near the middle of the tank. The hot wire probes were located above the top of the tank walls. Thus, horizontal circulations covering an area larger than the tank were possible. The roof of the building was 15–20 ft above the water surface.

The tank layout had been developed for testing the behavior of a barge in a confused sea, and meaningful results in this study could be obtained only for the period between the arrival of the first waves and the arrival of reflected waves in the test section.

Before running each test, it was necessary to let the

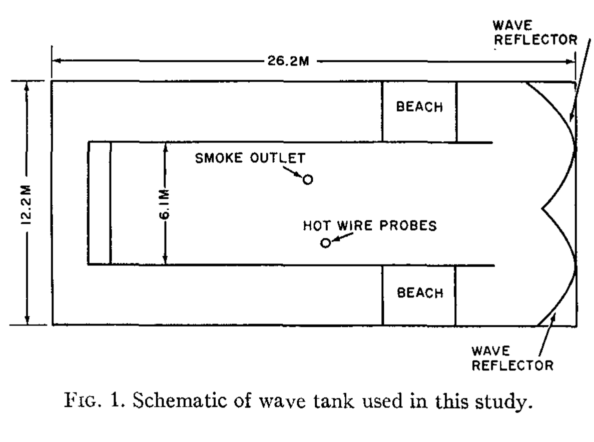

FIG. 1. Schematic of wave tank used in this study.

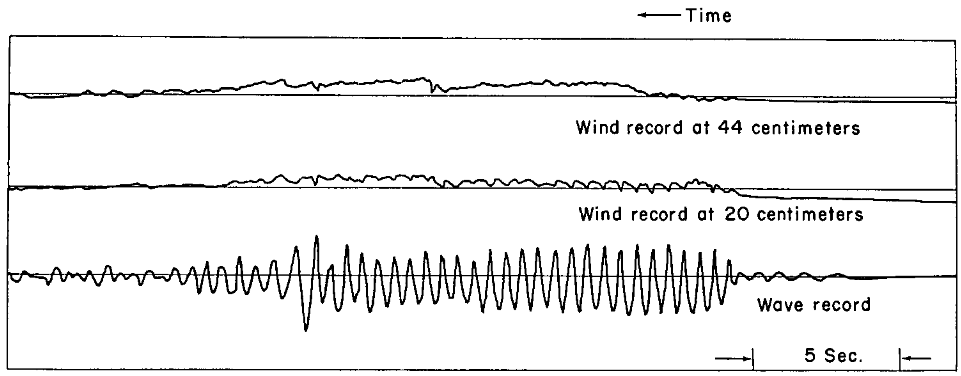

FIG. 2. Comparison of wave record and wind records at 20 cm and 44 cm, period 0.82 sec., height 10 cm.

turbulence levels in both water and air die down to acceptable values. A short section of record for quiescent conditions was taken at the beginning of each run. The generator was turned off as soon as the first fully developed wave reached the far end of the tank; thus, the duration of each test was something less than one minute.

The water depth during these tests was 1.0 m, and the wave period for the tests to be discussed in detail was 0.82 sec. No facilities were available for an actual measurement of the wave speed. However, the value of 127 cm sec^{-1}, obtained from classical theory, appears to be a good estimate. The wave amplitude was 5.1 cm, corresponding to a steepness of 0.097.

The lower hot wire probe was consistently located at 20 cm above the mean water level. The upper probe was located at 44 cm for the data shown in Fig. 2 and at 71 cm for the data shown in Fig. 3. The response of the hot wire was nearly linear for these observations, but its absolute value is uncertain by a factor of four. The lowest permissible calibration, not the mean value, has been used in reducing the data. Thus, the air velocities could have been larger than the values quoted below, but they are not likely to have been less.

A comparison of the observed and theoretical values of both the mean flow and the wave motion is given in Table 1. The theoretical speeds apply to a fluid particle whose equilibrium elevation corresponds to the indicated height. The theoretical value of the particle motion due to waves and all observed values apply at the indicated heights.

These records give clear evidence of organized air motion due to the waves that is detectable at an elevation seven times the wave height or 0.68 of the wavelength above the mean water surface. The speed associated with the mean air motion exceeded that of the oscillating component, so that the airflow did not reverse with the passage of each wave. This point was not clear in the qualitative observation of the smoke, in which one tends to view the air motion with respect to a point in the water surface. The minimum speeds did occur over the wave crests, where elementary theory would indicate a reversal of the flow direction. The record of air speed at 20 cm above the water shows a flat-top wave in each of the dozen or more tests. This is indicative of harmonics which are in phase above the wave crests (speed minima) and out of phase above the troughs. A series of photographs illustrating the smoke behavior is given in Fig. 4.

The light patch near the center of frame a. is a smoke cloud extending about 10–15 cm above the water. The thin vertical line to the left is the smoke

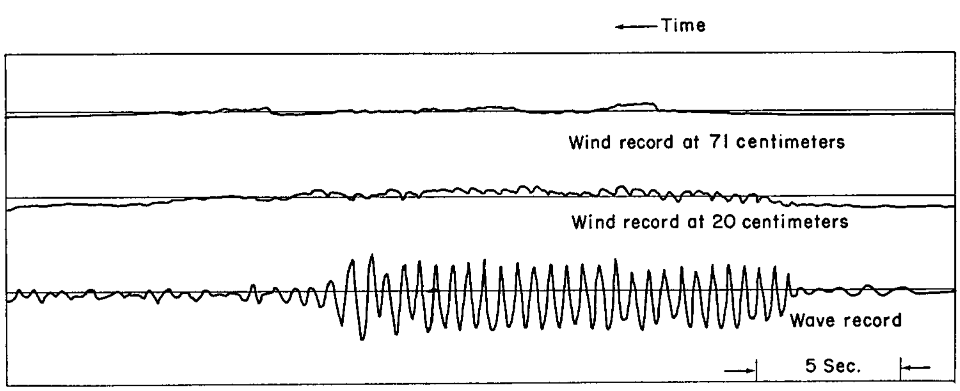

FIG. 3. Comparison of wave record and wind records at 20 cm and 71 cm, wave period 0.82 sec., height 10 cm.

Table 1. Comparison of the observed and theoretical values of the airflow above waves.

Height above mean water level (cm)	Maximum horizontal orbital speed		Mean horizontal speed	
	Observed (cm sec^{-1})	Theory* (cm sec^{-1})	Observed (cm sec^{-1})	Theory* (cm sec^{-1})
0	—	39	—	12
20	12	12	35	1.1
44	4.5	2.7	39	0.06
71	—	0.5	18	<0.01

* Theoretical speeds pertain to a particle whose equilibrium position is at the indicated elevation. Observed values pertain to a fixed elevation above the mean water level.

outlet. The smoke is released about 20 cm above the water. The first frame was taken before any waves reached the smoke outlet. The first waves that do pass are little more than ripples. Frame b. is taken after one of the first ripples. Frame d. was taken after the first full-sized wave had passed and frame e. after the third full-sized wave. At later times, the smoke was being carried to the right too fast to detect in still photography.

3. The effects of viscosity on the wave-driven wind

According to the theory of interface waves in an inviscid fluid, the horizontal component of the velocity

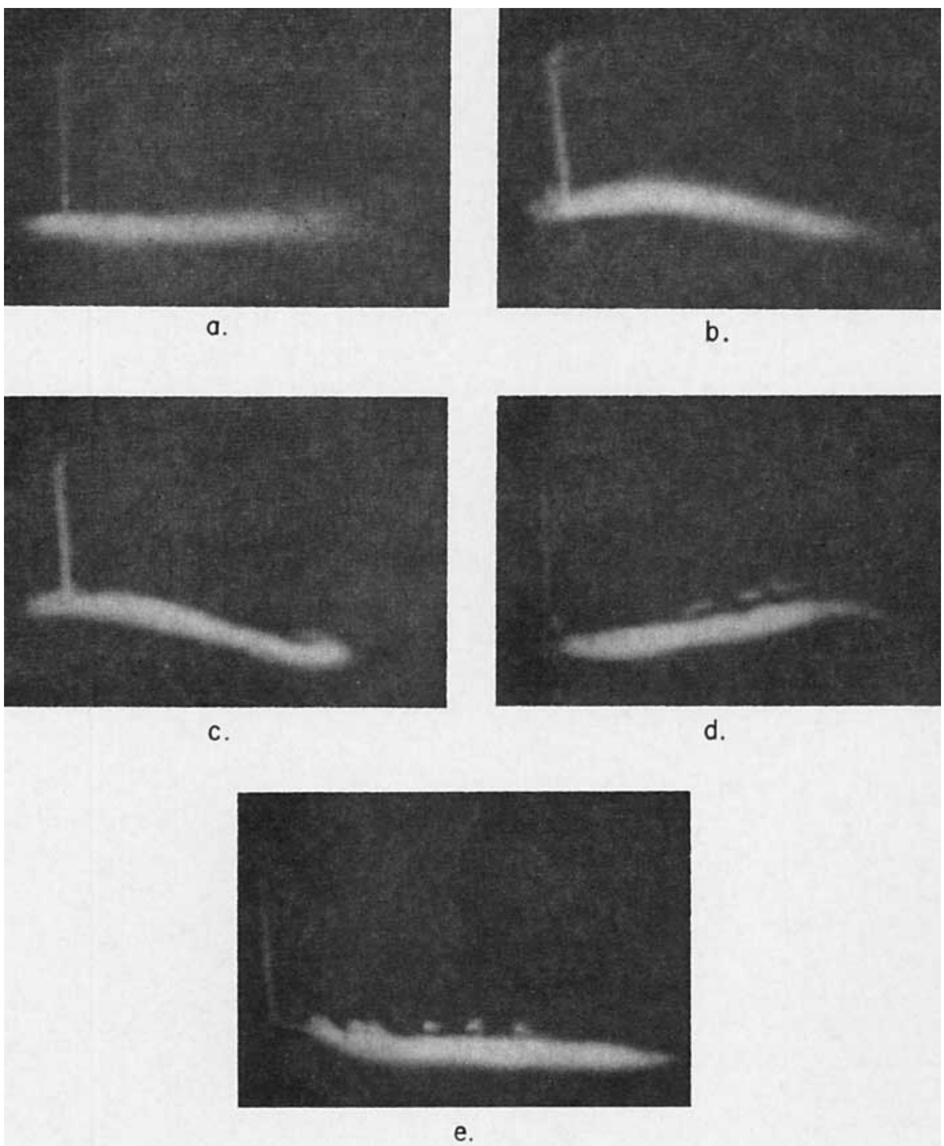

Fig. 4. Photographs of smoke plumes, waves moving to the right.

due to the waves must differ in phase by 180 deg on the two sides of the interface. This change of phase was observed in the smoke motion. Any viscous boundary layer in which the velocity was continuous was too thin for detection. The mean forward motion of the air, near the water, was greater than the mean forward motion of the water. Thus, it appears that the wave-driven wind is not the result of viscous drag, and that some understanding of the phenomena can be obtained without considering the molecular viscosity.

According to the inviscid theory, the interface is a layer of infinite shear and, therefore, a layer of infinite vorticity. As a matter of fact, this vorticity is diffused into the interior of the fluid by molecular diffusion and might have been more evident if the experiment had been continued for a longer time period. Any vortex which exists in the fluid will be alternatively stretched in the horizontal and vertical directions by the wave motion and would thereby extract energy from the wave motions. Thus, the existence of any vorticity near the interface would lead to the growth of turbulence in the presence of waves. In the absence of any other flow, turbulence produced in this way would be expected to decrease in intensity with distance from the interface because of the magnitude of the stretching by the wave motion decreases with distance from the interface. The observations of the smoke appeared to support the above reasoning, but it has not yet been possible to place either theory or observations on a satisfactory quantitative basis.

If there is a mean velocity shear between the free air and the water surface, as is normal with wind-generated waves, this shear will also produce turbulence. The resulting turbulent viscosity coefficient increases with distance above the water. It seems clear that a combination of these two turbulence generating mechanisms should produce a turbulent viscosity which does not vanish at the lower boundary of the atmosphere above waves as assumed in the Prandtl theory or its generalizations. The Prandtl theory was developed for a rigid boundary, but it has been widely applied in the analysis of wind profiles above water. It seems likely that the turbulent viscosity resulting from the superposition of these two turbulence generating mechanisms would actually decrease for a short distance above the water surface under some conditions.

4. Application to the study of wind profiles over the sea

It is customary, when studying the flow of a turbulent fluid near a boundary, to assume that the stress is constant in the boundary layer and that the stress is supported by a turbulent viscosity which vanishes at $z=0$ and increases linearly with z for $z>0$. When these assumptions are made, it is possible to show by several different methods that in a homogeneous (adiabatic) fluid

$$U(z)=(U_*/k)\ln(z/z_0), \tag{3}$$

where $U(z)$ is the mean wind speed at height z, $U_*=(\tau/\rho)^{\frac{1}{2}}$, τ is the surface stress, ρ the fluid density, and z_0 the effective height of the roughness elements in the surface.

Eq. (3) may be combined with observations to evaluate z_0 by assuming that $U=0$ at $z=z_0$. Nikuradse (1933) used (3) and observations made with pipes covered with uniform sand grains to determine that the actual height of the roughness elements was about 30 times z_0. Several writers have combined values of z_0 obtained by applying (3) to data observed above waves with Nikuradse's results to conclude that only the high frequency components of the wave spectrum form roughness elements for the flow of air above the sea. Roll (1965, pp. 135–140) summarizes the results of several writers who have found z_0 to be less than the thickness of the molecular viscous layer which he concludes must be at least 0.1 cm. Values of z_0 as low as 10^{-6} cm have been reported.

There must be a mean flow of water in the direction of wave propagation as described in Section 1. The analysis techniques which were used to derive (1) may be applied to the upper side of the interface to show that this is the minimum velocity to be expected in the air above waves. The experiments described above suggest that this minimum may be greatly exceeded outside the viscous boundary layer. Thus, it should be clear that the estimates of z_0 obtained by extrapolating (3) to a zero velocity are without physical meaning. Any tendency for turbulence to develop from the infinite vortex sheet at the water surface would also act to destroy the usually assumed meaning of z_0. Kitaĭgorodskiĭ and Volkov (1965) have suggested that z_0 should be a function of the propagation velocity of the high frequency components of the wave motion. They were not able to determine an entirely satisfactory expression for the roughness motion, but even a coarse allowance for the velocity near the interface greatly reduced the scatter in the observed values of z_0.

The value of the surface stress obtained by applying (3) to observed data may be correct if the assumptions stated at the head of this section are valid throughout the layer in which observations are obtained, regardless of the phenomena that occur in lower layers. If the observations extend downward into the region in which the wave-driven wind is significant, the derived value of U_* will be in error.

In the experiments reported in Section 2, the wind produced by the waves was greater than any other component of the wind for more than half a wavelength above the water. The more interesting case is that in which the waves are being generated by the wind. In this case the boundary layer wind produced by the downward transport of momentum from the free air must be dominant everywhere, excepting possibly in a very shallow layer near the water. Even so, it is possible that the wave-driven wind may produce a perturbation on the velocity profile by increasing the wind velocity in the direction of wave propagation at low elevations above the water. In the case of swell running into regions of natural calm, a phenomenon much like that observed in the laboratory may occur.

5. The mechanics of the wave-driven wind

The mechanics of the wave-generated wind may be visualized through a conceptual experiment. Suppose that mechanically generated waves are allowed to propagate through a rectangular tunnel, open at both ends. Let the top of the tunnel be even with the wave crests. As the crest of a wave moves into the tunnel opening, air is sucked in to fill the cavity between the water surface and the top of the channel. As successive waves move into the channel, the entrapped air is carried forward at the speed of wave propagation. The action results entirely from pressure forces.

If the top of the channel is lifted above the water, the pressure forces are still active and may extend above the crests of the waves. A new phenomenon, turbulent mixing, also comes into the picture.

Air from the space between successive wave crests is mixed with that at higher levels, thus reducing the peak forward velocity of the air near the water surface to something less than the wave velocity and giving forward momentum to the air at higher levels.

If there is no mean wind velocity, as in the laboratory experiment, a nonlinear perturbation method along the lines used by Longuet-Higgins (1953) can be used to show that there must be a mass transport by waves in the atmosphere as well as in the water. This explains the existance of a wind in the Lagrangian sense, and shows that the smoke should have moved in the direction of wave propagation as observed. It does not explain the existence of a wind in the Eulerian sense as shown by the hot wire records. Nor does it explain the magnitude of the observed wave-driven wind. Efforts to extend this theory to a normal wind profile which depends on the height above the water surface have failed because some of the integrals involved do not converge satisfactorily.

Acknowledgments. The author wishes to thank all who assisted him in this study. Particular appreciation is due to the staff of the U. S. Army Corps of Engineers, Coastal Engineering Research Center, for providing facilities and assistance, including instruction in the techniques of hydraulic experiments in January 1965; to Profs. Ernest F. Brater and Raymond A. Yagel for making facilities available at the University of Michigan Research Center at Willow Run, for many preliminary experiments as well as the final experiments reported here; and to Mr. W. Gale Biggs for making the crucial hot wire anemometer measurements.

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