Measurements of Wind-Driven Flow Profiles in the Top Millimeter of Water

WILLIAM MCLEISH AND GERALD E. PUTLAND

Atlantic Oceanographic and Meteorological Laboratories, NOAA, Miami, Fla. 33149

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ABSTRACT

Shapes of mean water velocity profiles measured with microscopic bubble tracers in developing laminar flows are recognizably different from those in a turbulent flow. A previously deduced viscous sublayer occurs at the surface, although it is thinner than an analogous sublayer computed for a solid boundary. The differing thickness leads in part to decreased surface temperatures at slicks.

1. Sublayers at a water surface

A cold surface layer is often found at the ocean surface, almost always so at night. McAlister (1964) suggested that within this boundary layer there must be a conductive sublayer with a nearly linear temperature profile. His measurements with a specialized infrared radiometer at low wind speed indicated a conductive heat flow from the sea in approximate agreement with the total heat flow estimated from measurements in the air. Later, Timofeev (1966) asserted that the boundary layer exists only when the water surface is relatively smooth and disappears at higher wind speeds. However, further radiometric measurements by McAlister and McLeish (1969) demonstrated the existence of a conductive sublayer in laboratory experiments at moderate air speeds, and McAlister *et al.* (1971) measured the total heat flow from the ocean by this technique. Since the turbulent water motions advecting heat also transport momentum, the existence of a conductive sublayer also implies a viscous sublayer. The viscous sublayer in water should be about twice as thick as the conductive sublayer (Wu, 1971). Information on the thickness of these sublayers at a water surface is necessary to measure ocean temperature and heat flow radiometrically and to predict exchanges of various materials between the atmosphere and the ocean.

Measurements showing boundary layer thickness at a water surface have not been found among previous studies. The radiometric measurements in a conductive sublayer indicate only a minimum thickness, not its total thickness. Velocity profile measurements at 0.1 cm depth intervals by McAlister and McLeish (1969) had insufficient resolution to show a linear surface region. Laboratory velocity profiles by Wu (1968) appeared linear but fitted calculated logarithmic profiles satisfying the experimental conditions and so do not indicate viscous sublayers.

Accepting the general assumption that boundary layers over a solid surface and the air-sea interface are similar, Wu (1971) calculated the thicknesses of conductive and viscous sublayers as a function of wind velocity. Katsaros and Businger (1973) made further calculations concerning the determination of heat flow from the ocean using radiometric measurements. In both papers, the authors emphasized the need for measurements to determine the flow structure near the surface. The present study furnished mean water velocity profiles very near the surface in both laminar and turbulent laboratory flows. The viscous sublayer at a free surface is considerably thinner than at a solid boundary.

2. Velocity profiles in the upper water

Profiles of velocity in the top millimeter of water in a wind-water tunnel have been measured from cine photographs of clouds of microscopic hydrogen bubble tracers. Experimental methods were described by McLeish and Putland (1975). The buoyant rise of the bubbles was small, and the bubbles were photographed shortly after release. By using neutrally buoyant markers, the bias errors of floating tracers in an irregular flow described by McLeish (1968) were avoided. Laminar and turbulent regions of the water surface could be distinguished with the bubble patterns, by the mixing of dye streaks, and, it has been found, through the shapes of the waves. The present depth interval of 0.005 cm between measurements provides several velocity readings within the depth region in which a linear viscous sublayer might be expected.

Fig. 1 shows downwind U and crosswind V mean water velocity profiles in the upstream region beneath

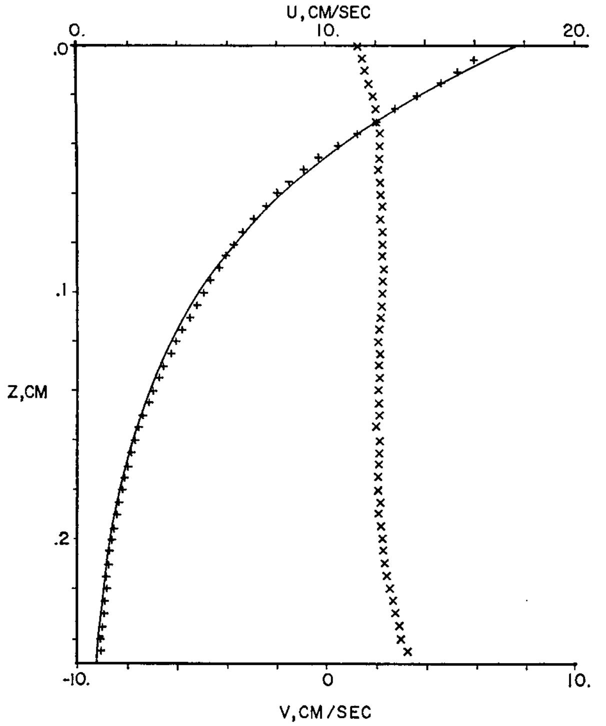

Fig. 1. Water velocity profile in an essentially laminar flow, + downwind and × crosswind. The fitted line is an exponential curve.

an air flow with a midstream velocity of 900 cm s^{-1}. The water flow there was essentially laminar but beginning a transition to turbulent flow. An exponential curve fitted the U readings well, although such a curve is not necessarily characteristic of a developing laminar boundary layer. In fact, Kunishi (1963) reported transient laminar velocity profiles with a different exponential shape. Instead, the fitted curve illustrates the precision of the individual measurements. In particular, an apparently erroneous mean velocity defect is seen in the upper 2–3 readings that might have been caused by air flow interference of equipment mounted asymmetrically in the air above the measurement area. The fitted curve indicates a surface shear from which a stress of 2.0 dyn cm^{-2} was calculated. Calculations based on estimated wave parameters indicated that the wave drift current was small. The crosswind velocity profile, although offset, shows generally little variation with depth.

The velocity fluctuations in Fig. 1 were rapid, and the rms value at a depth was roughly 15% of the mean value there. The depth-averaged variance, reduced by the number of photographs, was similar to the variance of the differences between the mean values and the fitted curve. These departures, then, could be random fluctuations. The correlation between fluctuations at a depth and at the surface

$$\overline{U'(z)U'(0)}/\{\overline{[U'(z)]^2}\,\overline{[U'(0)]^2}\}^{\frac{1}{2}}$$

decreased to a value of 0.5 at a depth of only 0.035 cm and remained near 0.3–0.4 below. Since the vertical correlation of wave motions should remain unity, the rapid decrease in correlation with depth suggests that wave orbital motions were largely removed by the $\frac{1}{16}$ s averaging between photographs. Furthermore, the kurtosis of the frequency distribution of surface velocity fluctuations was −0.2, as compared with zero with a normal distribution (turbulence) and −1.2 for a uniform distribution (approximately, waves). Rough estimates indicate that turbulent fluctuations in the air flow could cause the very shallow water velocity fluctuations.

The velocity profiles in Fig. 2 represent fully laminar flow with an air speed of 550 cm s^{-1}. The shape of the profiles were similar to those in Fig. 1, although the surface shear indicated a stress of only 1.0 dyn cm^{-2}.

Fig. 3 was obtained at the same air speed as Fig. 2 but downstream where the water flow was fully turbulent. The overall shear in the turbulent boundary layer was considerably less, and the shear zone was thinner than in the laminar flow case. Although the water surface was much rougher than upstream, the indicated stress was less, 0.7 dyn cm^{-2}. The linear portion of the profile at the surface represents a viscous sublayer. This was thinner than the computed profile at a solid boundary with the same stress, as represented in Fig. 3 by a straight line and a departing curved line. The curved line was derived from nondimensional

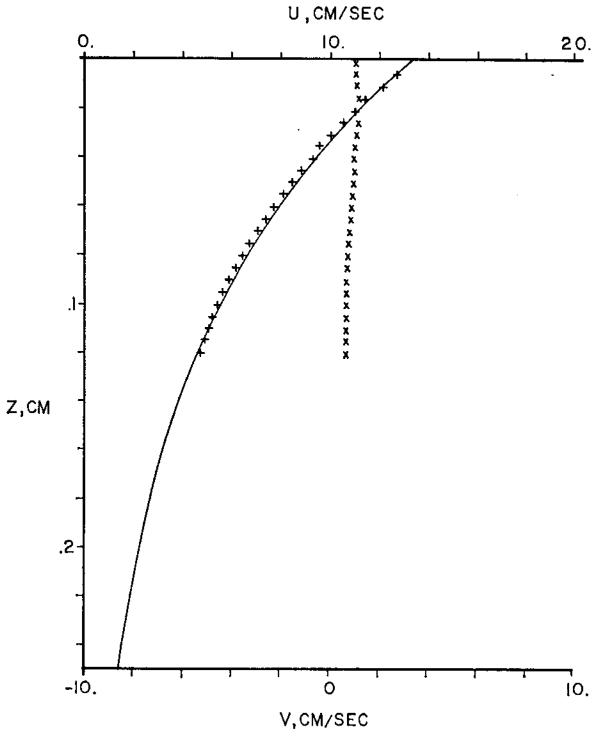

Fig. 2. Water velocity profile in a fully laminar flow, + downwind and × crosswind. The fitted line is an exponential curve.

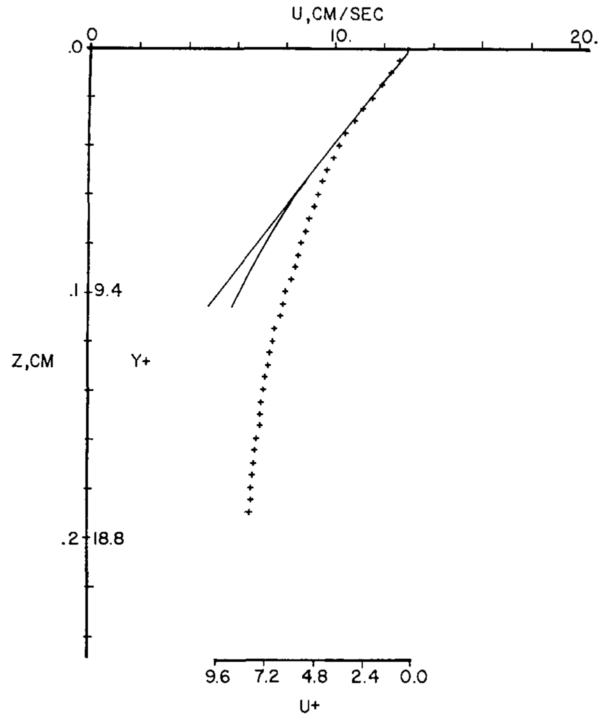

FIG. 3. Water velocity profile in a turbulent flow. The straight line fits the surface slope, and the curved departing line follows the mean profile at a solid boundary.

values by Kline *et al.* (1967) and by Mellor and Herring (1969, see Fig. 3a).

3. Discussion

The linear surface segment in Fig. 3 is believed to represent the first direct measurement of a viscous sublayer at a water surface. Although thinner than at a solid boundary, the viscous sublayer supports the previous evidence for a conductive sublayer sufficiently thick for radiometric heat flow measurements with moderate wind speeds.

Ocean slicks commonly are cooler than the adjacent water surface and, at certain scales and times, represent the dominant surface temperature fluctuations at sea (McLeish, 1970). This effect can be attributed in part to the horizontal rigidity of a slick. A slick acts on the water turbulence below much as does a solid boundary. The conductive sublayer beneath a slick, then, is thicker than elsewhere and, in hindering the normal loss of heat from the sea, gives an increased surface temperature depression. Reduced air stress on the smooth surface at a slick also gives increased sublayer thickness.

The thickness of the viscous sublayer at a free surface is determined in part by the horizontal water motions occurring there and can differ from that at a solid boundary. The present observations indicate that previous estimates of sublayer thickness based on an analogy to a layer at a solid boundary are of the correct order of magnitude but could be improved substantially through direct profile measurements.

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REFERENCES

Katsaros, K. B., and J. A. Businger, 1973: Comments on the determination of the total heat flux from the sea with a two-wavelength radiometer system as developed by McAlister. *J. Geophys. Res.*, **78**, 1964–1970.

Kline, S. J., W. C. Reynolds, F. A. Schraub and W. C. Runstadler, 1967: The structure of turbulent boundary layers. *J. Fluid Mech.*, **30**, 741–773.

Kunishi, H., 1963: An experimental study on the generation and growth of wind waves. *Disaster Prev. Res. Inst. Kyoto Univ. Bull.*, No. 61.

McAlister, E. D., 1964: Infrared optical techniques applied to oceanography, 1, Measurement of total heat flow from the sea surface. *Appl. Opt.*, **3**, 609–612.

——, and W. McLeish, 1969: Heat transfer in the top millimeter of the ocean. *J. Geophys. Res.*, **74**, 3408–3414.

——, ——, and E. A. Corduan, 1971: Airborne measurements of the total heat flux from the sea during BOMEX. *J. Geophys. Res.*, **76**, 4172–4180.

McLeish, W., 1968: On the mechanisms of wind-slick generation. *Deep Sea Res.*, **15**, 461–469.

——, 1970: Spatial spectra of ocean surface temperature. *J. Geophys. Res.*, **75**, 6872–6877.

——, and G. E. Putland, 1975: The initial water circulation and waves induced by an air flow. NOAA Tech. Rept. ERL 316-AOML 16. [Available from Superintendent of Documents, Washington, D. C.]

Mellor, G. L., and H. J. Herring, 1969: Two methods of calculating turbulent boundary layer behavior based on numerical solutions of the equations of motion. *Proc. Computation of Turbulent Boundary Layers—1968 AFOSR-IFP Stanford Conference*, S. J. Kline, M. V. Morkovin, G. Sovran and D. J. Cockrell, Eds., Thermosci. Div., Dept. Mech. Eng., Stanford University, 331–345.

Timofeev, Yu. M., 1966: Thermal sounding of surface water layers by means of thermal radiation. *Izv. Atmos. Oceanic Phys.*, **2**, 772–774.

Wu, J., 1968: Laboratory studies of wind-wave interactions. *J. Fluid Mech.*, **34**, 91–112.

——, 1971: An estimation of oceanic thermal-sublayer thickness. *J. Phys. Oceanogr.*, **1**, 284–286.