NWRI CONTRIBUTION 88-77

ENERGY DISSIPATION JUST BENEATH THE AIR WATER INTERFACE AND CONSEQUENCES FOR GAS TRANSFER

by

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November 1988

MANAGEMENT PERSPECTIVE

In establishing the mass balance of toxics in lakes, the transfer rates of volatile toxics through the air water interface have to be adequately described. These rates are controlled by the turbulent mixing processes at the interface. This paper presents the results of exploratory measurements of the turbulence structure beneath small breaking waves (in contrast to large scale breaking, or whitecaps). Enhanced dissipation and penetration of the turbulence into the water column is observed under these waves: the consequences of these results are just beginning to be explored theoretically. More thorough experiments covering a broad range of wind and wave conditions will be forthcoming.

Dr. J. Lawrence
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PERSPECTIVE DE GESTION

Pour établir le bilan massique des toxiques dans un lac, les taux de transfert des toxiques volatils par l'interface air-eau doivent être établis avec précision. Ces taux sont régis par les processus de mélange turbulent à l'interface. Ce rapport présente les résultats de mesures exploratoires de la structure de turbulence sous de petites vagues déferlantes (par contraste aux grosses vagues déferlantes ou aux moutons). On observe sous ces vagues une dissémination et une pénétration accrue de la turbulence dans la colonne d'eau : les conséquences de ces résultats viennent tout juste de commencer à être analysées du point de vue théorique. Des expériences plus poussées couvrant une gamme plus vaste de conditions de vent et de vague doivent être effectuées.

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ABSTRACT

The effect of the breaking of short gravity and capillary waves on the sub-interfacial energy dissipation was explored in a wind-water tunnel. It is believed that the release of turbulent energy by these small breakers is an important element in easing the passage of dissolved gases across the air-water interface - a process of some significance in understanding the fate of pollutants released into the atmosphere or surface waters. A quasi-direct (assuming isotropy at high wavenumbers) method of estimating the dissipation rate was estimated via the local instantaneous derivative of the streamwise velocity. In order to compare the dissipation rate with and without breaking waves, a soluble surfactant was introduced in sufficient concentration to inhibit the growth of waves. Experiments with tap water resulted in a considerably higher dissipation rate compared with experiments using surfactant. An energy flux velocity, V, that is associated with the surface stress in doing work on the underlying fluid, is defined; it is estimated to vary between the surface drift velocity and the wave celerity. It is inferred that the kinetic energy flux from atmosphere to ocean may be several times larger than that obtained from equating V with the surface drift, as is customary.

RÉSUMÉ

L'effet du déferlement des petites vagues gravitaires et capillaires sur la dissémination de l'énergie sous-interfaciale a été étudiée dans un tunnel vent-eau. On croit que la libération de l'énergie turbulente par ces petits brisants est un élément important dans le passage des gaz dissous à travers l'interface air-eau, processus relativement important dans la compréhension de l'évolution des polluants libérés dans l'atmosphère ou dans les eaux de surface. Une méthode quasi-directe (reposant sur l'hypothèse de l'isotropie lorsque le nombre des vagues est élevé) pour évaluer le taux de dissémination a été évaluée au moyen de la dérivée instantanée locale de la vitesse du courant. Pour comparer ce taux établi en présence ou non de vagues déferlantes, un surfactant soluble a été introduit en concentration suffisante pour inhiber la croissance des vagues. Des expériences effectuées avec de l'eau de robinet ont donné un taux de dissémination considérablement supérieur comparativement aux expériences effectuées avec le surfactant. Une vitesse de flux énergétique, V, associée au stress superficiel pendant le travail sur le fluide sous-jacent, est definie; on estime que cette vitesse varie entre la vitesse de dérive de surface et la vitesse des vagues. On infère que le flux énergétique cinétique entre l'atmosphère et l'océan pourrait être plusieurs fois supérieur à celui obtenu avec l'équation de V avec la dérive de surface, comme cela est courant.

1.0 INTRODUCTION

The breaking of waves on natural water surfaces is among the most commonly observed step changes in entropy. A highly ordered flow becomes unstable and loses energy to turbulence in an often spectacular way. There can be no doubt that the mixing engendered by deep water breakers that produce white caps (large visible foam patches accompanying the breaking of surface gravity waves of lengths exceeding a metre) has an important local effect on the mixing of surface waters. This is most clearly revealed in the changes in submerged bubble concentrations in wind driven seas (Thorpe, 1986). Such large white caps are generally rather sparsely distributed and occur in association with the passage of groups (Donelan et al. 1972). At any instant only a small fraction of the surface of the ocean is thus disturbed (Monahan and O'Muircheartaigh, 1980).

Much less spectacular, but possibly equally important, is the breaking of short gravity and gravity-capillary waves having wavelengths from about 1 cm to a few tens of centimetres. This "micro breaking" is observed to occur at very moderate wind speeds (5m/s and above) and is much more uniformly distributed. These small breakers, with overturning crests only a few millimetres high, are sufficient to disturb the thin diffusive sublayer just beneath the interface (thickness $\delta_D \approx 10\nu u_*^{-1} Pr^{-1}$; ν is the kinematic viscosity; u_*, the friction velocity; $Pr = \nu/D$ is the Prandtl number; and D is the molecular diffusivity of the gas in water). For typical values of u_* and Pr, δ_D is of the order of a millimetre. Consequently the role of these small breakers in enhancing air-water gas transfer rates has been the subject of much recent research (c.f. Broecker and Hasse, 1980). This micro-breaking may be all that is necessary to "ventilate" the oceanic sub-layer. Kerman (1984) has estimated that the area covered by these small breakers is 6.4 times that disturbed by whitecaps.

A key ingredient in modelling gas transfer through the air water interface is therefore an appropriate parameterization of the effect of micro-breaking on mixing the surface diffusive sublayer. In this regard, perhaps the most useful turbulence characteristic is the turbulent kinetic energy dissipation rate, ϵ, (Hunt, 1984; Kitaigorodskii and Donelan, 1984). Various attempts have been made to explore the structure of ϵ very close to the interface (c.f. Brumley, 1984; and Dickey et al., 1984) using submerged oscillating grids to produce the interfacial disturbance. In view of the increasingly widely recognized role of ocean-atmosphere gas exchange in climatic trends and in the fate of anthropogenic pollutants (an almost tautological phrase), we resolved to attempt to explore the turbulent energy dissipation under a water surface excited by the wind. Previous attempts to estimate ϵ under water waves have relied on the existence of an inertial subrange and the attendant assumptions concerning the relative sizes of terms in the kinetic energy budget (Terray and Bliven, 1985; Jones, 1985). In our laboratory experiments we estimated ϵ from the local instantaneous velocity derivative - an almost direct estimate. To our knowledge these are the first such measurements. We have also made similar measurements in a wave following mode under natural wind waves in a large lake. We will report these measurements at a later date.

2.0 THEORETICAL CONSIDERATIONS

Under steady and longitudinally uniform wind conditions, the wind stress applied at the surface, τ_0, can be expressed at

$$\tau_0 = \tau_a + \tau_s \qquad (1)$$

where τ_a is the advected stress by the wave field, E is the variance of surface elevation and $\tau_s = \rho u^2_{*w}$ is the shear in the water.

The energy budget for the system is:

$$\tau_o V = \int_0^\infty \rho \, \varepsilon_m(z) \, dz + \tau_a C_g \qquad (2)$$

where $\varepsilon_m(z)$ is the measured dissipation rate of turbulent energy, C_g is the group velocity of the dominant waves and V is a velocity that is associated with the surface stress in doing work on (imparting energy to) the underlying fluid.

In an aerodynamically smooth flow the wind stress is communicated to the water via viscous forces so that ultimately the surface skin of the water is pulled along by direct contact with the air molecules. For such flows the energy flux from air to water is simply the product of the surface stress and the surface drift velocity, u_d which, according to Wu (1975) is roughly one-half the friction velocity in the air $u_* = (\tau o/\rho a)^{1/2}$, where ρ_a is the air density. This is the basis for the common practice among oceanographers of taking the kinetic energy flux into the ocean F to be proportional to u_*^3

$$F = 1/2 \; \rho_a \, u_*^3 \qquad (3)$$

On the other hand, for an aerodynamically fully rough flow, wherein the wind stress is communicated to the water via pressure differences across the roughness elements, the appropriate energy flux velocity is the propagation speed of the form of the roughness elements or their phase speeds (insofar as the roughnesses are waves) plus any underlying additive current. Since oceanic waves may travel at speeds approaching the wind speed, in aerodynamically rough flow the energy flux could exceed the corresponding smooth flow value (for the same wind) by 2 $C_D^{-1/2} \approx 50$, C_D is the aerodynamic drag coefficient, defined to be $(u_*/U_{10})^2$. Such extremes do not occur because the long wind waves, with phase speeds C approaching that of the wind, seldom support much of the stress, leaving the role of roughness elements to be played by much shorter waves. Phillips (1977) assigns this task to waves for which $C/u_* < 5$ or $k > g/25u_*^2$; where k is the wave number. The drag in fully rough flow is proportional to the steepness of the roughness elements and the square of the velocity difference. The latter is essentially constant in the range $C/u_* < 5$ so that an equivalent propagation speed of the roughness elements may be estimated from the slope-weighted theoretical speed of waves in the wave number range $g/25u_*^2 < k < k_{min}$. Where k_{min}[1] is the wavenumber corresponding to the waves of minimum phase speed, 3.7 cm^{-1}. For simplicity, we take the short wavenumber part of the spectrum to be proportional to k^{-4}, i.e., fully saturated. Thus the slope averaged phase speed in the range of wavenumbers $g/25u_*^2 < k < k_{min}$ is given by:

$$C = \frac{C_{min}(5u_*/C_{min} - 1)}{\ln\,(5u_*/C_{min})} \;;\quad \frac{5u_*}{C_{min}} > 1 \qquad (4)$$

which for typical values of u_*, of 20 cm/s and 40 cm/s, is 53 cm/s and 82 cm/s. Thus the speed of the roughness elements might be expected to exceed the drift velocity by a factor of 4 or 5 in the limiting case of waves approaching full development where the drag is probably supported by the short waves $C/u_* < 5$. In younger,

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[1] It is assumed that waves shorter than this do not contribute significantly to the drag. There is no general agreement on this point, but restricting k_{min} to waves of the minimum phase speed provides a lower bound on the estimate of the speed of the roughness elements. Further, the wind drift current adds to the speed of the roughness elements.

(undeveloped) wave systems the energy flux velocity would be somewhat higher so that in general $V \geq u_d$,[2] and specifically for fully rough flow we expect that

$$4\ u_d < V < 50\ u_d$$

Consequently, the oceanic estimate of the kinetic energy flux, F, is probably less than 25% of the actual value. The underestimate may be considerably worse than this in intense storms wherein the waves tend to be very underdeveloped. In such storms ε is very high being dependent on wind speed to the third or higher power.

With suitable measurements, equation (2) allows us to deduce V. The dissipation rate, under isotropic conditions can be written as:

$$\varepsilon = 15\ \nu(du/dx)^2 \qquad (5)$$

Equation (5) can be written, by making use of the Taylor's hypothesis, u t = x, in the following form:

$$\varepsilon = 15\ (\nu/\bar{u}^2)\ (du/dt)^2 \qquad (6)$$

where u is the water velocity.

The energy flux velocity in equation (2) can be expressed as

$$V = (\int_0^\infty \rho\varepsilon_m\ (z)\ dz + \tau_a C_g)/\tau_o \qquad (7)$$

In this study, experiments have been conducted with ordinary tap water and with a commercial surfactant dissolved in tap water. Note that,

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2 The equality applies only to aerodynamically smooth flow, which normally occurs only at low wind speeds, $U_{10} < 2.8$ m/s.

in the case in which the experiment was performed with the surfactant, surface waves were surpressed and equations (1) and (2) become

$$\tau_0 = \tau_s \tag{8}$$

$$\tau_0 u_d = \int_0^\infty \rho\varepsilon_m (z)\, dz \tag{9}$$

So that the energy flux velocity, V, may be determined from the dissipation profile alone and should be equal to the surface drift velocity, u_d. Furthermore, with an interface undisturbed by waves the drift velocity profile should follow the logarithmic law of the wall and, consequently, the dissipation rate may be computed from the friction velocity[3]:

$$\varepsilon_1 = \frac{u_{*w}^3}{\kappa z} \tag{10}$$

3.0 EXPERIMENT

The experiments were conducted in a 10 m long, 0.30 m wide, 0.60 m high, wind wave flume at the Canada Centre for Inland Waters; the water depth was 0.40 m. Tests were performed at fetch, F = 5.45 m with two different wind speeds, U = 7 m/s and U = 4.5 m/s. Measurements were made with tap water and with a surfactant dissolved in tap water to suppress the wind waves (Mitsuyasu and Honda, 1986).

The free stream wind speed, U, was measured with a Pitot-static tube. Surface waves were sensed with a capacitance wave gauge (diameter of the wire was 0.2 mm). Wave slope measurements were

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3 The boundary layer is unstratified and it is assumed that the production of turbulent kinetic energy is just consumed by dissipation.

made with a wave slope gauge (Kahma and Donelan, 1988). Water velocity was measured with a conical hotfilm (thermal current meter) and an acoustic current meter having an acoustic path of 4 cm. The hotfilm provided turbulence data, whereas the acoustic current meter provided mean data. Differentiated water velocity measurements were obtained by means of a differentiator with a cutoff frequency of 900 Hz. Data were sampled at 40 Hz and each data channel was low-pass filtered at 20 Hz (except wind speed).

The differentiated water velocity signal contained some noise. In order to determine this noise, additional tests were performed in a tow-tank where there was no apparent motion. Assuming that there is no dissipation in the tank, the signals from the hotfilm were recorded directly at the same time as those from the differentiator. Noise in the differentiator channel was determined as a function of the water velocity signal and subsequently used to correct the data.

4.0 RESULTS

We first report the measurements made with a smooth surface, i.e., with waves suppressed by the dissolved surfactant. As an example, we examine the lower wind speed case (U = 4.5 m/s).

Figure 1 shows the velocity profile in the upper 20 cm measured with the acoustic current meter. The top 7.5 cm (19%) is occupied with flow in the wind direction (wind drift) and in this region the velocity profile is closely logarithmic and intersects the viscous sublayer ($\delta_D = 11.5\ \nu/u_*$) at about 10 cm/s. The corresponding root-mean-square streamwise velocity component (Figure 2) is roughly constant in the upper wind driven layer, in agreement with boundary layer similarity theory (Monin and Obukhov, 1954).

In Figure 3 we compare the measured dissipation rates with those deduced from equation (10). Near the surface the agreement is good, but when the theoretical dissipation values fall below 3 cm^2/sec^3 the measured values are high. One possible cause of this is the deficiencies in the noise removal procedure, which are most likely to distort the results at these very low values of dissipation rates. Another cause is the export of turbulent energy from the return flow - a contribution not considered in the theoretical calculation. Thus, with waves suppressed, the wind driven surface layer appears to behave much like a solid wall with respect to the structure of the flow beneath and the rate of kinetic energy dissipation.

The surfactant trials provide a control for comparison with similar tests using tap water. In the latter case, waves are generated, eventually achieving a peak frequency of 4.3 Hz and a significant height of 0.71 cm (Figure 4).

The drift velocity profile in tap water, but otherwise identical conditions to those of Figure 1, is shown in Figure 5. The presence of waves on the surface restricted the uppermost measurement to 1 cm beneath the mean surface. Again the profile in the upper (wind driven) layer is closely logarithmic except the upper centimeter or so where the velocity profile approaches constancy. This is the region that is directly mixed by the breaking waves (Donelan, 1977; Melville and Rapp, 1985) and one might expect the eddy viscosity to be much higher than $u_{*}\kappa z$, given by analogy to a solid wall.

The root-mean-square streamwise velocity component, plotted in Figure 6 on a logarithmic scale versus linear depth, shows a straight portion (exponential decay) near the surface due largely to the wave orbital velocities. These have decayed to 10% of their surface value by 3 cm depth and immediately below this the profile is again constant. Between 3 and 4 cm the essentially turbulent root-mean-square velocity is almost twice the value for the control (surfacant) case of Figure 2. Evidently the surface breaking is sufficiently energetic to alter the kinetic energy of the turbulence at depths several times the wave height.

Finally, we consider the changes in the dissipation rate in the upper layers when the surface is disturbed by breaking waves. For comparison with the measured dissipation rates the solid wall values (equation 10) are computed, using the profile-derived friction velocity, and displayed (solid line) in Figure 7. Near the surface the measured values exceed the calculated values by a factor of 3 or 4. There can be little doubt that wave breaking is the source of the enhanced dissipation rates. Not only do the small scale breaking waves effectively destroy the diffusion barrier imposed by the diffusive sublayer, but they also considerably enhance the dissipation rates to depths of 1/4 to 1/2 wavelength.

The integrated dissipation plus the advected wave energy flux ($\tau_a C_g$ computed from the fetch gradient of surface elevation variance) provide a means of estimating the energy flux velocity, V, via the surface stress as in equation (7). $\tau_a = (3/8)\rho g(dE/dx)$ is the advected stress by the wave field (the factor 3/8 follows from the assumption of a cosine squared spreading function for the waves). These calculations are summarized in Table 1 for two cases with different wind speeds. The surface stress τ_o was estimated from equation (1) using the measured profile in water (τ_s) and the observed fetch-limited wave growth (τ_a). The advected wave momentum is less than 4% of the total surface stress. The integrated dissipation is roughly three times that given by the "solid wall analogy" and the energy flux velocity exceeds the drift velocity, in the lower wind speed case, by a factor of two. In fact, the energy flux velocity is 85% of the peak wave celerity, C, in the lower wind speed case and 65% in the other.

5.0 CONCLUSIONS

We have made some exploratory measurements of the structure of turbulence beneath small breaking waves in a laboratory tank, with particular emphasis on the turbulent kinetic energy dissipation rate.

We find that the solid wall analogy is appropriate when the surface waves are suppressed by the action of a dissolved surfactant. On the other hand, striking increases of the dissipation rate above this control were observed when tap water was used and the enhanced dissipation appears to penetrate to depths in excess of one quarter wavelength. The consequences of this in gas transfer across the ocean-atmosphere boundary are beginning to be explored theoretically and we expect that experiments such as this will provide much needed grist for the theoretical mills.

The flux of kinetic energy from atmosphere to ocean is one of the key components in the dynamic and thermo-dynamic modelling of the oceans. We have indicated that the drift velocity is the appropriate energy flux velocity only when the flow is aerodynamically smooth. Under other conditions, the energy flux velocity will exceed the drift velocity and tend, in the limit of very young (strongly forced) waves, to the phase velocity of the wave spectral peak. Our results show that this is indeed the case, although the effect is not as dramatic as it could be on the open ocean in rapidly increasing winds because our laboratory waves, though strongly forced, are rather short and slow (phase speed only a factor of three greater than the surface drift).

We emphasize that these results are only a starting point from which we will embark on a much more thorough study of turbulence near the air-water interface for various wave and wind conditions.

ACKNOWLEDGEMENTS

N. Merzi was a visiting fellow at the National Water Research Institute and the recipient of an NSERC of Canada fellowship during the course of this work. He wishes to thank both these organizations for their hospitality and generosity. E.A. Terray gratefully acknowledges support by the Office of Naval Research (contract N00014-87-K-007 NR 083-004) and by the National Science Foundation (on grant no. OCE 84-18711). We are indebted to D. Beesley and G. Voros for assistance in preparing experimental apparatus.

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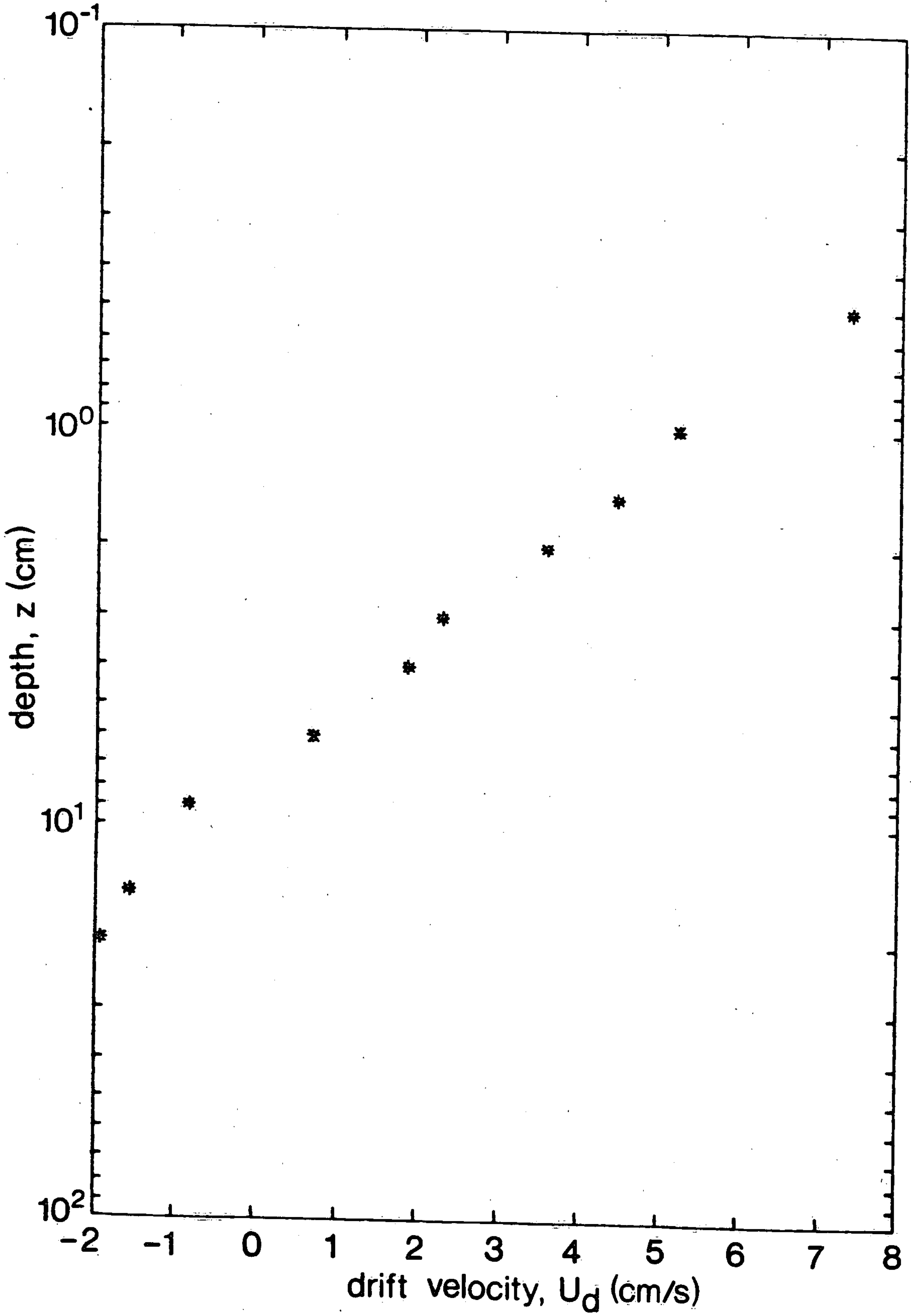


Figure 2.

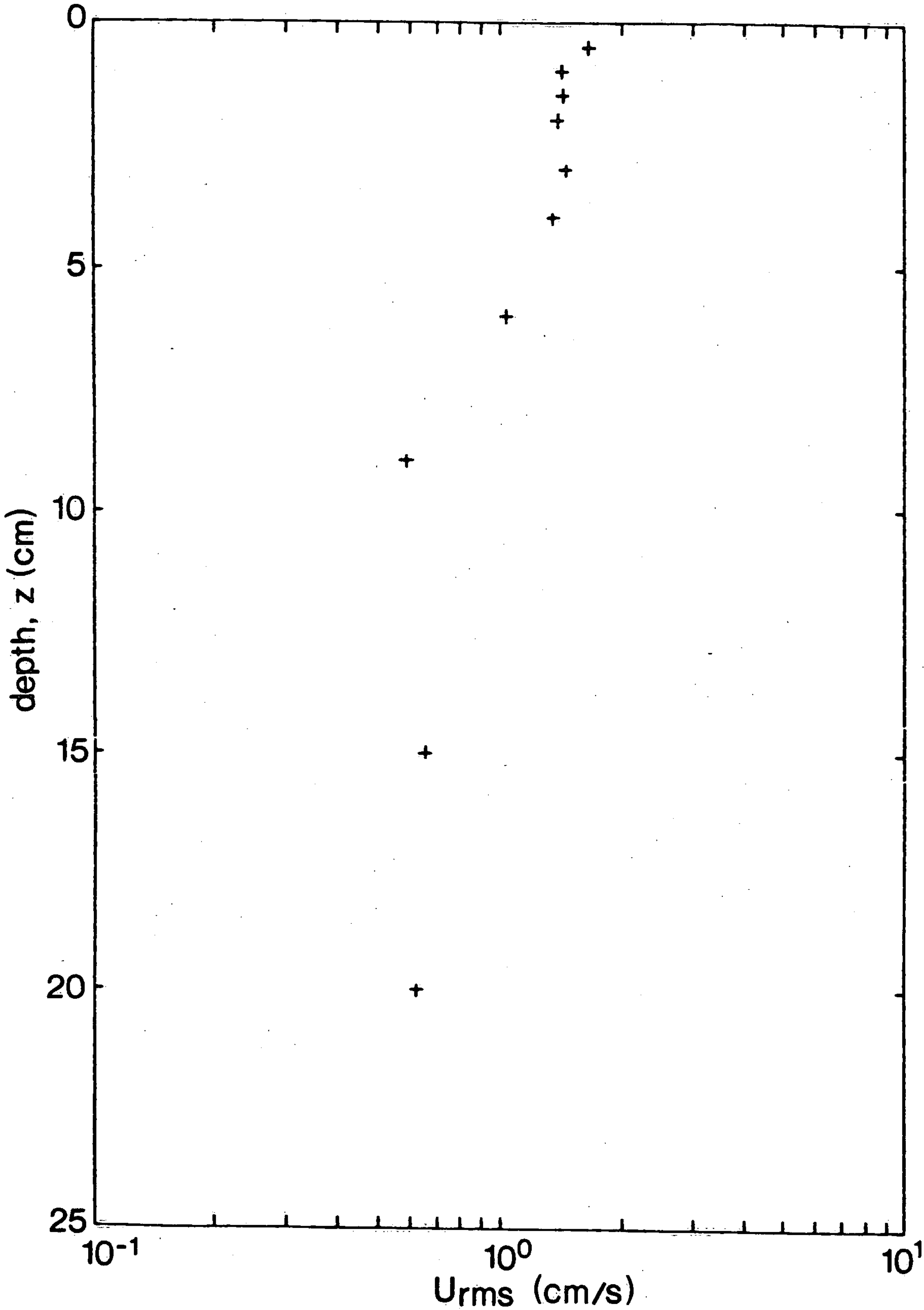
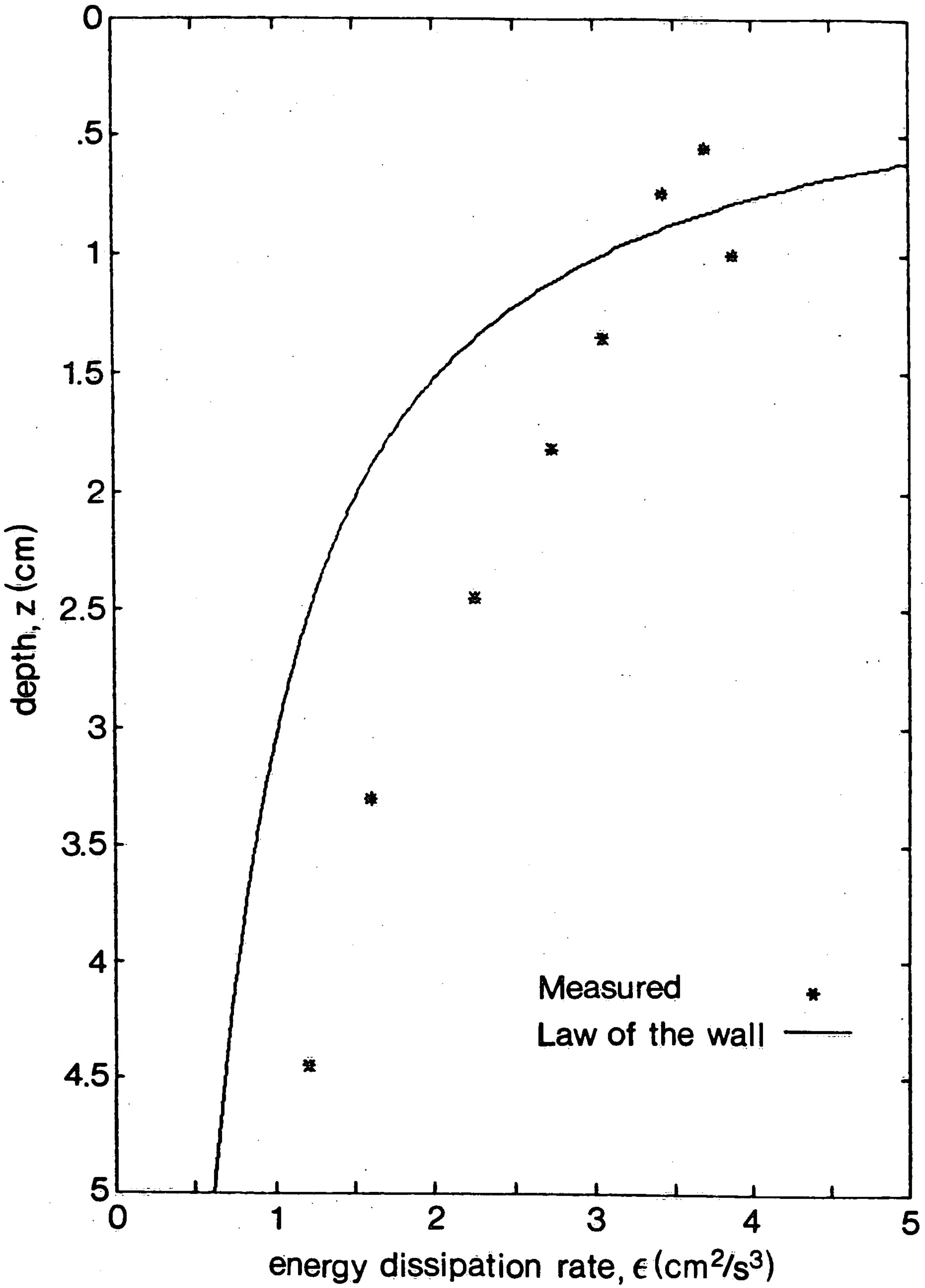
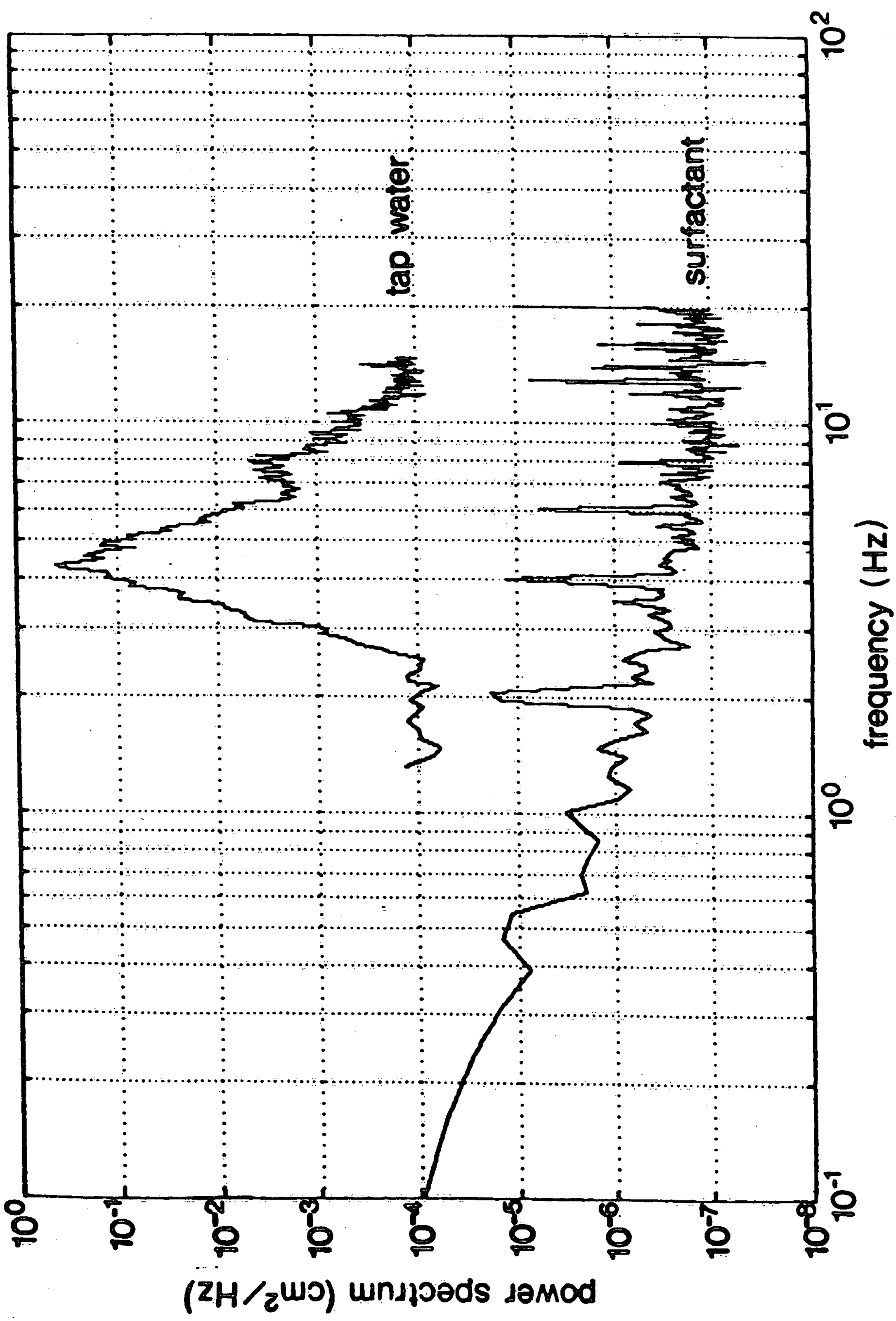


Figure 3.



0
.5
1
1.5
2
2.5
3
3.5
4
4.5
5
depth, z (cm)
0
1
2
3
4
5
energy dissipation rate, ϵ (cm²/s³)
Measured
Law of the wall

Figure 4.



tap water
surfactant
frequency (Hz)
power spectrum (cm²/Hz)
10⁻¹
10⁰
10¹
10²
10⁰
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸

Figure 5.

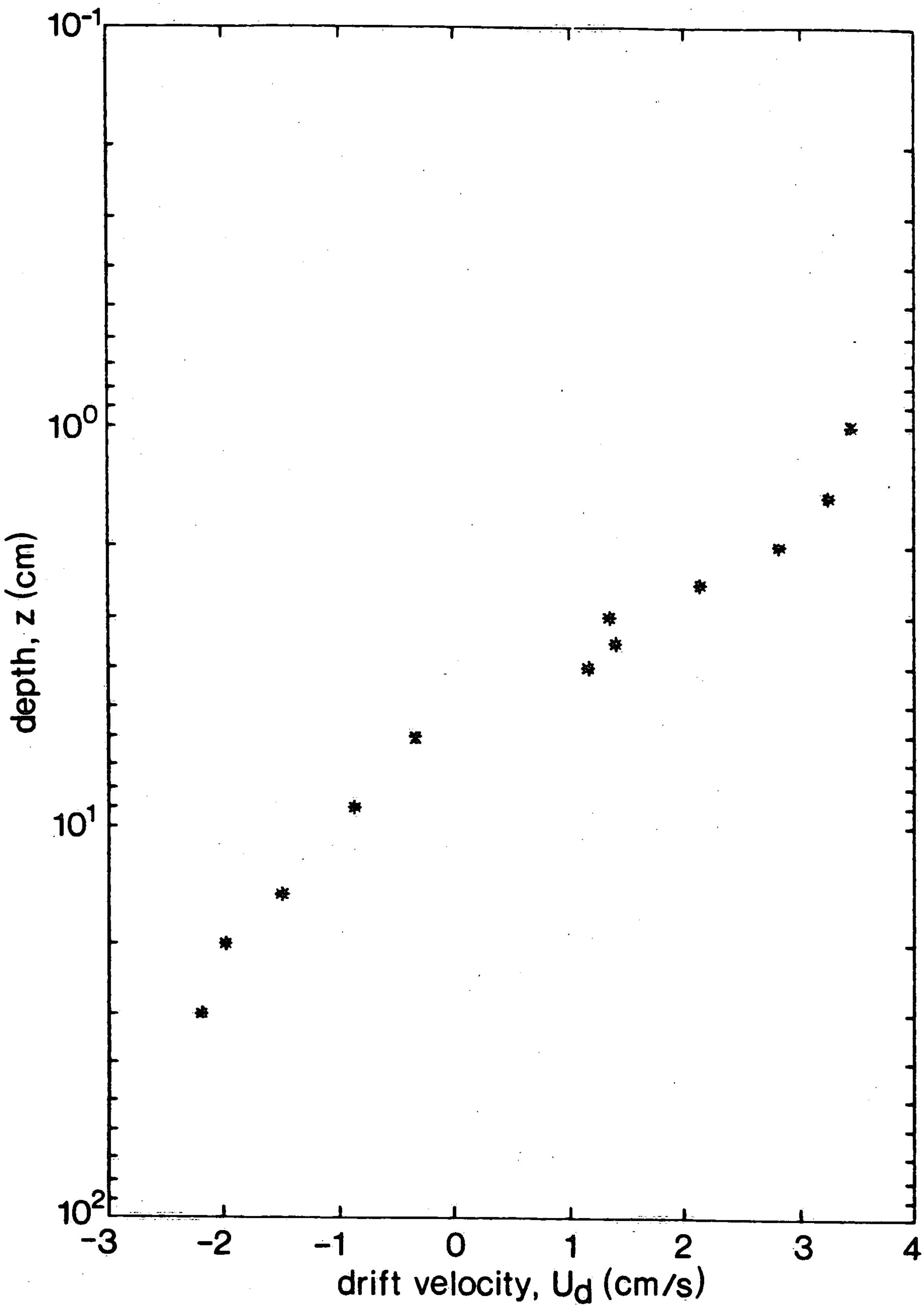


Figure 6.

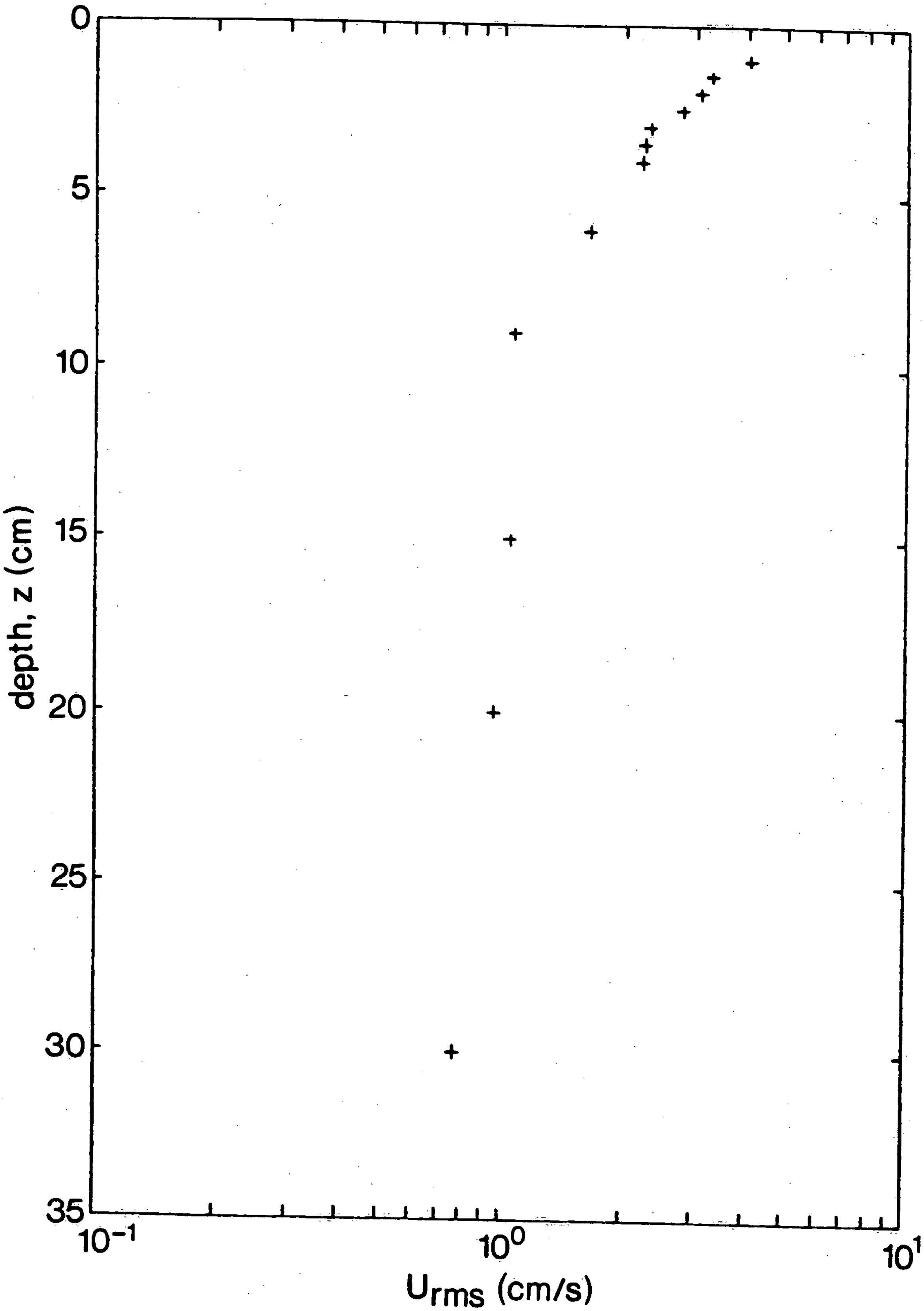
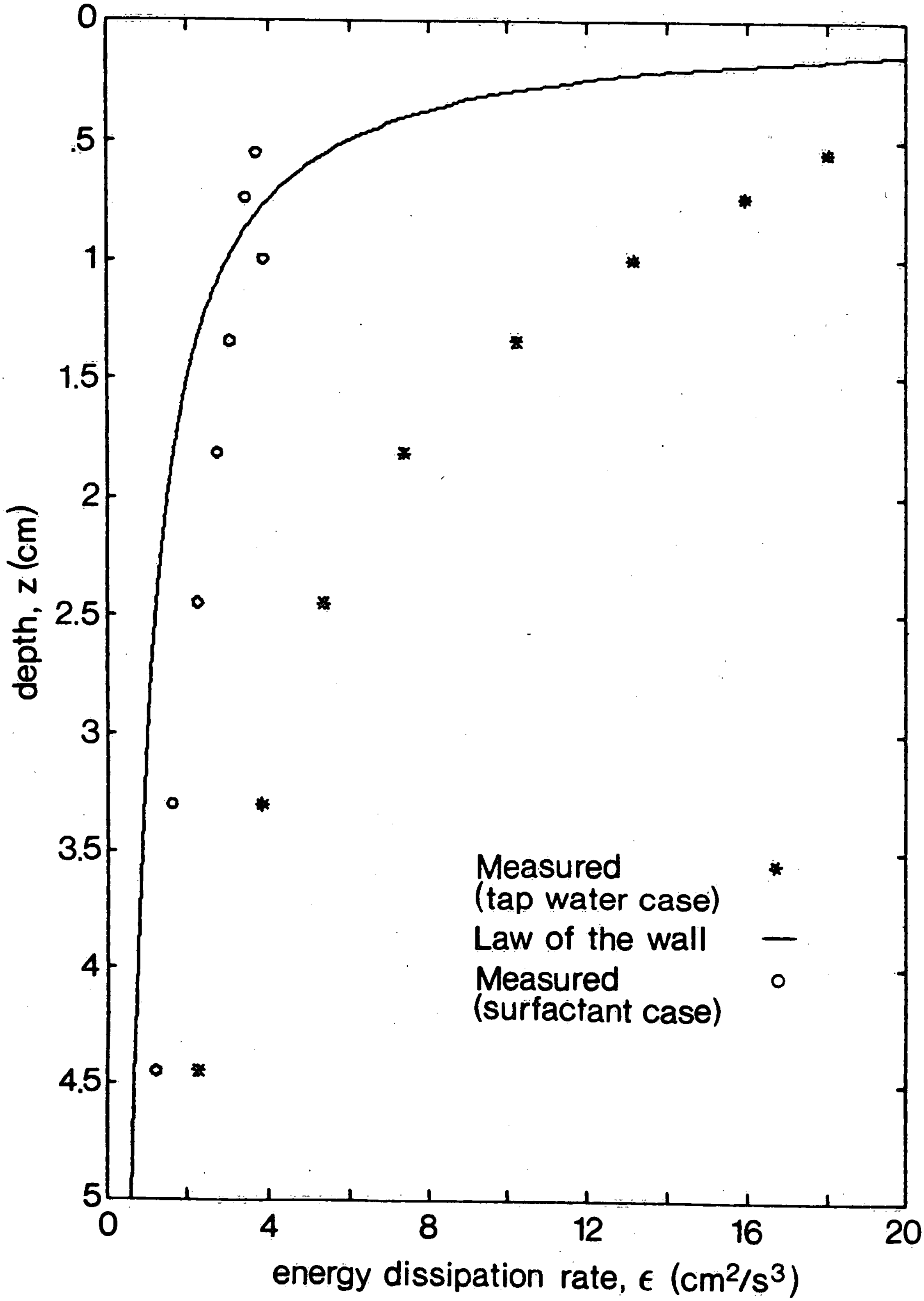


Figure 7.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.5
1
1.5
2
2.5
3
3.5
4
4.5
5
depth, z (cm)
0
4
8
12
16
20
energy dissipation rate, ϵ (cm2/s3)
Measured
(tap water case)
Law of the wall
Measured
(surfactant case)

TABLE 1a

Experimental Conditions and Results Concerning "Surfactant Case"

Wind Speed U (m/s)	Surface Drift u_d (cm/s)	Friction Velocity u_{*w} (cm/s)	Energy Dis. Law of the wall $u_{*w}^2 u_d$ (W/m^2)
4.5	13.5	1.07	0.0155
7.0	21.0	1.54	0.0498

TABLE 1b

Wave Parameters Concerning "Tap Water Case"

Wind Speed U (m/s)	Wave Celerity C (cm/s)	Group Velocity C_g (cm/s)	Peak Frequency f_p (Hz)	Sign. Wave Height H_s (cm)
4.5	37.03	18.52	4.30	0.71
7.0	43.87	21.94	3.59	1.46

TABLE 1c

Experimental Conditions and Results Concerning "Tap Water Case"

Wind Speed U (m/s)	Friction Velocity u_{*w} (cm/s)	Shear Stress τ_s (N/m^2)	Advected Stress τ_a (N/m^2)	Total Stress τ_o (N/m^2)	Wave En. Flux $\tau_a C_g$ (W/m^2)	Energy Dis. (measured) $\int \rho \epsilon_m dz$ (W/m^2)	Energy Flux Vel. V (cm/s)
4.5	1.06	0.1124	0.0048	0.1172	0.00089	0.03607	31.5
7.0	1.68	0.2822	0.0144	0.2966	0.00315	0.08149	28.5