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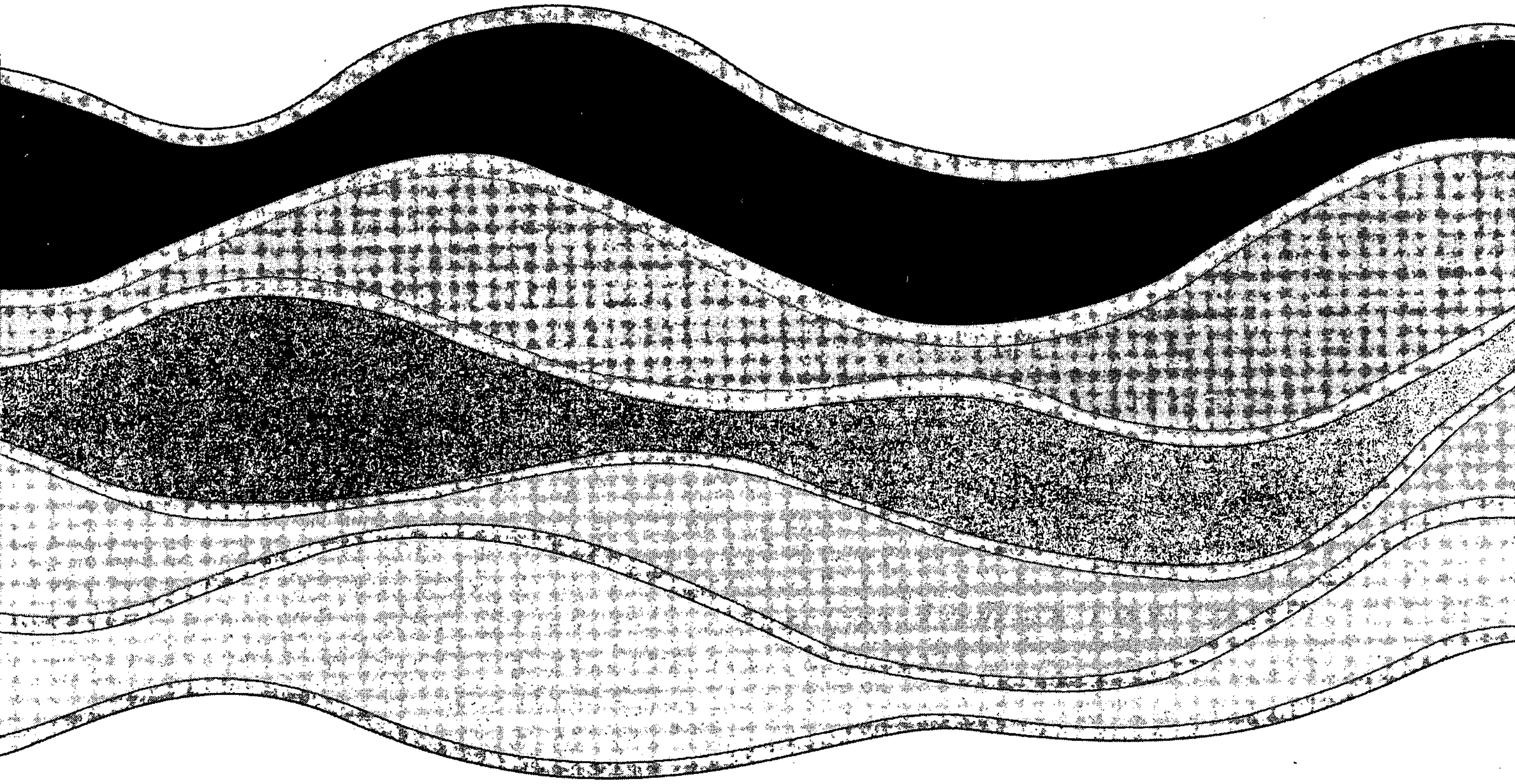

NEW EVIDENCE FOR HIGH KINETIC ENERGY DISSIPATION BENEATH SURFACE WAVES

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NWRI Contribution No. 92-04

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MANAGEMENT PERSPECTIVE

The mixing of surface waters has important consequences in many processes of interest to Environment Canada. Among these are enhancement of gas transfer, dispersal of pollutants and development of lake circulation. The rate of dissipation of turbulent kinetic energy provides a sensitive indicator of surface mixing.

This paper reports on very high dissipation rates beneath breaking wind waves as observed in Lake Ontario in 1985 – 1987, and reveals the strong intermittency of the process. Similar high values were observed from an earlier experiment at the same site. Many other studies from other sites report much lower rates, leading to a heated controversy in the scientific literature. Here, we indicate the statistical unreliability of short term measurements in such highly intermittent flows and resolve the controversy. The general conclusion is that strong winds and active breaking lead to enormous increases in the dissipation rates (factors of 10 to 100) above the conventional estimates.

SOMMAIRE À L'INTENTION DE LA DIRECTION

Le mélange des eaux superficielles a des effets importants dans de nombreux procédés d'intérêt pour Environnement Canada, entre autres, intensifier les échanges gazeux, la dispersion des polluants et le développement de la circulation lacustre. Le taux de dissipation de l'énergie cinétique turbulente est un indicateur sensible du processus de mélange dans les eaux superficielles.

Le présent article porte sur des taux de dissipation très élevés sous le déferlement des vagues produites par le vent comme on a pu l'observer dans le lac Ontario, entre 1985 et 1987, et montre la nature fortement intermittente du processus. Des valeurs élevées similaires ont été enregistrées lors d'une expérience antérieure, effectuée au même endroit. De nombreuses autres études, réalisées ailleurs, signalent des taux beaucoup plus faibles, ce qui est à l'origine d'un vif débat dans la littérature scientifique. Ici, nous indiquons le manque de fiabilité statistique des mesures à court terme dans ces écoulements très intermittents et ainsi nous pensons avoir fait avancer le débat. On conclut, en général, que des vents forts et un déferlement actif augmentent considérablement les taux de dissipation (facteurs de 10 à 100) au-delà des estimations classiques.

ABSTRACT

Physical processes in the near surface layer of lakes and oceans play critical rôles in the coupling between atmosphere and hydrosphere and in the circulation and mixing of water bodies. Unlike the atmospheric boundary layer, the velocity structure is dominated by motions induced by wind-driven waves. However, these wave motions are largely irrotational and it is the rotational or turbulent motions that are central to the key questions of the diffusion of mass, momentum and energy. This paper examines one important aspect of turbulence – the kinetic energy dissipation in the surface layers. We present new observations supporting a much enhanced dissipation rate close to the air-water interface, and discuss the controversy regarding the treatment of the near-surface layer in analogy to wall-bounded shear flows. Our data suggest that the highly intermittent process of wave breaking may greatly increase dissipation rates above wall-layer estimates and invalidate short term measurements.

RÉSUMÉ

Les processus physiques dans la couche proche de la surface des lacs et des océans jouent des rôles critiques au niveau du couplage atmosphère-hydrosphère et au niveau de la circulation et du mélange des masses d'eau. À la différence de la couche atmosphérique limitrophe, la vélocité est dominée par des mouvements induits par des vagues produites par le vent. Toutefois, ces mouvements des vagues sont en grande partie non-rotatifs, et ce sont les mouvements rotatifs ou turbulents qui sont au centre des questions-clés de la diffusion de masse, de la quantité d'énergie et de l'énergie. Le présent article étudie un aspect important de la turbulence, soit la dissipation de l'énergie cinétique dans les couche superficielles. On présente de nouvelles observations à l'appui d'un taux de dissipation grandement accru proche de l'interface air-eau, et on aborde le débat au sujet du traitement de la couche proche de la surface par analogie à des écoulements de cisaillement limités par une paroi.

D'après nos données, le processus hautement intermittent du déferlement des vagues peut accroître considérablement les taux de dissipation au-delà des estimations obtenues à partir de la théorie classique de l'écoulement près d'une paroi et invalider les mesures à court terme.

1. INTRODUCTION

The breaking of ocean surface waves is an essential mechanism of air-sea interaction, and affects a variety of processes at and near the interface. Examples are the exchange of momentum, energy and heat between the atmosphere and ocean, gas transfer and the generation of aerosols. Parameterization of these important air-sea exchange processes thus depends on the accuracy of estimation of the turbulent kinetic energy expended in the near surface waters. As it stands today, even the order of magnitude of the turbulent energy dissipation rate in the top few meters of the ocean will not find general consensus among the practitioners of the art of its estimation. Why is there so much uncertainty and what can be done to reduce it?

The motions responsible for turbulent mixing below the surface derive their energy in part directly from wave breaking, and in part from the shear current in the water. The latter is set up through a combination of wave breaking and the direct action of viscous stresses on the water surface. Wave breaking thus provides a mechanism for additional turbulence production which does not exist in flows over fixed boundaries - such as the surface boundary layer of the atmosphere over land - with the result that the vertical structure of water-side turbulence close to the air-sea interface may differ substantially from the analogous case of a wall-bounded shear flow. Stewart et al. (1962) suggested the existence of such a region near the surface based on a discrepancy between the energy input from the wind and their measurements of turbulent dissipation.

Since the pioneering hot-film observations of Stewart et al., several groups have attempted a more detailed study of near-surface dissipation using a variety of sensors. The results of these studies to date have presented an apparently contradictory picture: Kitaigorodskii et al.(1983) found very high dissipation rates in the top few meters, which they attributed to the effects of wave breaking; while Jones and Kenney (1977), and more recently Jones (1985), have argued that the water-side marine boundary layer is essentially similar to a wall-bounded shear flow. This point of view was supported by Soloviev (1986) using a freely-rising profiler. Soloviev et al. (1988) later compiled many data sets of kinetic energy dissipation rates, most of which were in general agreement with the vertical distribution expected of wall layers.

Our purpose in this paper is to re-examine these issues in light of new field observations obtained from a tower in Lake Ontario. The new data are derived from three types of velocimeters, different in principle of operation. The results consistently support dissipation rates well in excess of wall-layer values. An explanation is offered reconciling the two controversial views, suggesting that the intermittent nature of breaking may have caused profiling instruments to miss the dissipating events. Some statistics of observed dissipation are presented and used to illustrate the point.

2. FIELD EXPERIMENT

The data presented here were acquired during 1985-1987 as part of the WAVES (Water-Air Vertical Exchange Study) program in Lake Ontario, which was carried out as a collaboration among scientists of the National Water Research Institute (NWRI), the Woods Hole Oceanographic Institution, the Finnish Institute of Marine Research, the Johns Hopkins University and the U.S. Naval Research Laboratory. Observations were collected from a research tower operated by NWRI. The tower stands in 12m of water, 1.1 km east of the western shore of the lake. It was designed with great attention paid to minimizing flow disturbances. From 6m beneath the water surface to 3m above, only 4 tower legs of 41cm diameter obstruct the passage of wind and waves over a 10m horizontal separation. In addition to the velocimeters, the tower was equipped with wave gauges, a water surface thermometer and meteorological sensors (wind speed and direction, temperature and humidity) located 12m above the water surface. Westerly winds produce fetch limited waves at the tower of order of 30cm significant height. In contrast, the 300km easterly fetch can produce waves of several meters in significant height. The data presented in this paper are from westerly, strong wind (greater than 8 m/s) cases only.

Water velocity components in the near surface layer were measured with three different types of fast response velocimeters mounted at different locations on the tower. The velocimeters were: an array of acoustic current meters (BASS), three drag sphere velocimeters and a laser Doppler velocimeter (LDV). These sensors cover a range of space-time scales: BASS measured velocities with a spatial resolution of 15cm, the drag sphere and the LDV observed high frequency flows with resolutions of 4mm and 0.1mm respectively. Wave heights were measured with capacitance wave gauges at all three velocimeters.

The BASS array consisted of 12 acoustic travel time sensors (Williams, 1985), which were arranged in a vertical string at roughly 0.5m separation - the uppermost being at 0.3m depth. The array was attached to a mast of ellipsoidal cross-section (30cm by 19cm) placed midway between the tower legs on the western side of the tower. A BASS sensor uses 4 intersecting acoustic paths, each of which samples a tube of 15cm length and 1.5cm diameter. Each path was sampled at 25 Hz, averaged and recorded at 5 Hz. The cylindrical (10cm x 10cm) sampling volume of each sensor was 1m from the mast and a capacitance wave gauge was installed 0.5m inboard from the sensor.

The drag sphere velocimeter (Donelan and Motycka, 1978) senses velocity components from the forces on a 4mm diameter sphere on the end of a cylindrical stalk. Three drag sphere sensors were mounted on the same mast as the BASS array.

The drag sphere sensor in each case was positioned 1.5m from the mast, on the opposite side from the BASS array. A capacitance wave gauge was placed between the mast and the sensor heads. The sampling rate for this combination of velocimeter and wave gauge was 20 Hz. Extensive comparisons of the characteristics of these sensors with the BASS sensors in oscillating flows reveal excellent agreement (Terray et.al. 1992). The mast carrying the BASS array and the drag spheres could be rotated remotely to orient the velocimeters into the dominant wave direction.

The 2-axis LDV used forward scattering optical geometry (Agrawal and Belting, 1988). Two vertical columns (diameter 10cm) of the LDV structure penetrated the water surface, and were separated by a clear opening 95cm wide. These columns widened to 17cm dia. at 30cm above the lowest point. Three laser beams emerged from one of the submerged columns and the scattered light was received in the second column. The instrument measured the vertical and east-west horizontal velocity components. Each component was sampled at 128 Hz. The LDV was mounted on a vertical screw-driven profiler so that measurements were taken at a sequence of depths. Record lengths for these sequences were typically 256 seconds. A complete vertical profile of four levels separated by 10cm could be carried out in 26 minutes including time for profiler travel.

The velocity field in the near surface layer is dominated by wave-induced motions. Whereas this greatly increases the difficulty of measuring turbulence, it provides, through linear wave theory, a convenient check on the calibration of the sensors and recording systems. The BASS and LDV sensors, whose calibrations depend on the speed of sound and light, respectively, yielded agreement (within 5%) with rms vertical velocity deduced from the surface elevation record via linear theory. The drag sphere sensor, on the other hand, is subject to calibration variations primarily due to accretion of algae during long term submergence. During 1985 the maximum exposure of any drag sphere was 18 days and agreement with linear theory (within 7%) was shown (Drennan et al., 1992). In 1987 the drag spheres were deployed for 61 days and fouling of the spheres was noticed on recovery. Fortunately, the algal growth appeared to produce a uniform increase of sphere diameter and a simple increase in the sensitivity secured agreement with linear theory. The 1985 drag sphere is uncorrected, and the 1987 data has been recalibrated so that measured and calculated (linear theory) vertical velocities agree in the vicinity of the wave spectral peak.

3. RESULTS

The dissipation results included in this paper are derived from vertical velocity spectra, using only the high frequency part of the spectrum well beyond the wave peak. They are obtained from the -5/3rd slope inertial range of the velocity spectra (Figure 1, between 2 and 6 Hz). Cross comparison of the drag-sphere, BASS and LDV spectra of vertical velocity (w) from approximately the same depths indicate strong consistency. As these instruments are completely different in geometry and principle of measurement and were placed a few meters apart, such agreement should dispel doubts arising from possible flow disturbances. The conversion of frequency spectra to wave-number space was carried out using the rms orbital velocity (Lumley and Terray, 1983). By restricting our attention to the part of the spectrum above the influence of the wave orbital velocities (Figure 1), we avoid the need to separate wave-related and turbulent velocities.

In Figure 2, we show our dissipation estimates from all three instruments combined with Jones (1985) and previous data compiled by Soloviev et al. (1988). For comparison, we present these data with the dissipation normalized using wall-layer scaling, as employed by Soloviev et al., although the question of the appropriateness of this scaling is open and will be addressed in a subsequent publication (Donelan et al., 1992). In these data the dissipation rate is scaled with $u_*^3/\kappa z$, which is the expected dependence in a wall-layer, and the depth with u_*^2/g. κ, von Karman's constant, is taken to be 0.4. It is clear that the present data from the three velocimeters show substantially higher ranges of dissipation rates than those in Soloviev's compilation. The various data sets reported by Soloviev et al. (1988) were scaled with friction velocity estimates derived from the measured wind, using drag coefficient values between 0.001 and 0.0015. In each particular data set the drag coefficient was taken to be constant. For consistency we have recomputed the scaled variables using the wind dependent drag coefficient formula of Large and Pond (1981). A more complete formulation of the drag coefficient includes the wave age, but, regretably, most of the data sets cited by Soloviev et al. do not include the relevant information for making this adjustment.

We suggest that the discrepancy between the data sets of Figure 2 is due to the intermittent injection of intense turbulence due to occasional wave breaking (Drennan et al., 1991, Donelan et al., 1992). This additional energy flux can be expected to decay rapidly with depth as the result of both transport and dissipation. Consequently, fixed current meters are unlikely to be located close enough to the surface to see much enhancement under conditions in which large-amplitude swell is present. Similarly, the residence time of profilers is typically too short to sample adequately the intermittent production of turbulence via breaking. In the following we explore the intermittency of the observed dissipation, ϵ, computed from the spectral level of the inertial sub-range in the drag sphere data observed at 1m depth. Similar intermittency was observed by the BASS and LDV velocimeters.

The time history of dissipation estimates for 13 second averaging time is shown in Figure 3 for a case of strong winds (12 m/s) from the west (1.1 km fetch). The left hand ordinate shows the observed dissipation in wall coordinates ($\epsilon\kappa z/u_*^3$), while the right hand ordinate indicates the ratio of ϵ to its mean over the entire record. The probability distribution of dissipation rates over the 80 minute record is shown in Figure 4, in which there are 375 estimates, covering a range of three orders of magnitude. The smooth distribution shown in Figure 4 is lognormal with the parameters selected so that the mean and standard deviation of the corresponding normal distribution are the same as those of $\log(\epsilon)$. We emphasize that we are discussing the variability of 13 second averages of dissipation estimated from spectral levels and not the instantaneous dissipation that is associated with a lognormal distribution in the classical Kolmogorov theory of turbulence. It is immediately apparent that the dissipation estimates are highly intermittent with 14 values in excess of 5 times the mean, and one value of 18 times the mean. The mode of the distribution corresponds to an estimate of 1/5 the mean, and is approximately the expected wall-layer value. We note here that the LDV sampling time was 5 minutes and that of the BASS and drag spheres at least 80 minutes, whereas typical profilers rise rapidly through the upper layers. The profilers spend at most a second or two in the wave zone and thus yield essentially random instantaneous samples from a distribution with far greater kurtosis than that of Figure 3. An objective observer, tossing profilers through the wave zone, would, in this case, recover a value for the dissipation in general agreement (a factor of 3) with the wall-layer estimate 5 times out of 10 tosses. The occasional tosses that yield very high values might suggest a spurious measurement and be discarded.

4. SUMMARY

Many estimates of kinetic energy dissipation in the upper oceanic layers are in general agreement with wall-layer scaling. Others, notably Kitaigorodskii et al., (1983) indicate considerably higher dissipation rates. We believe that the differences are due to the highly intermittent process of wave breaking, which is very poorly sampled by profiling devices. We argue that convergent mean values require sampling times of the order of half an hour or more, encompassing several breaking events. The general character of the time-dependent dissipation estimates (Figure 3) suggests that dissipation in the upper layers is fed by energy production from two processes. The background level of dissipation is close to the wall-layer estimates and presumably arises from the micro-breaking of small waves, whose phase velocity is close to the friction velocity in the air, U_*, or, in the case of light winds, the breakdown of the shear layer at the surface driven by the wind stress (ρu_*^2) at speeds comparable to U_* (Wu, 1975). The intense intermittent events presumably are due to the breaking of larger waves, i.e., white-capping. The high dissipation rates observed in strong winds with active wave breaking require a much higher energy flux from the wind than the wall-layer estimate of $\rho u_*^2 U_d$, where U_d is the surface drift velocity. This is supported by energy flux estimates based on the delivery of energy to steep waves, at frequencies above the peak of the spectrum, which yield results consistent with our observations of enhanced kinetic energy dissipation near the surface. At greater depths or in conditions of negligible wave breaking we expect the intermittency of the dissipation to abate, with mean values approaching wall-layer estimates.

ACKNOWLEDGEMENTS

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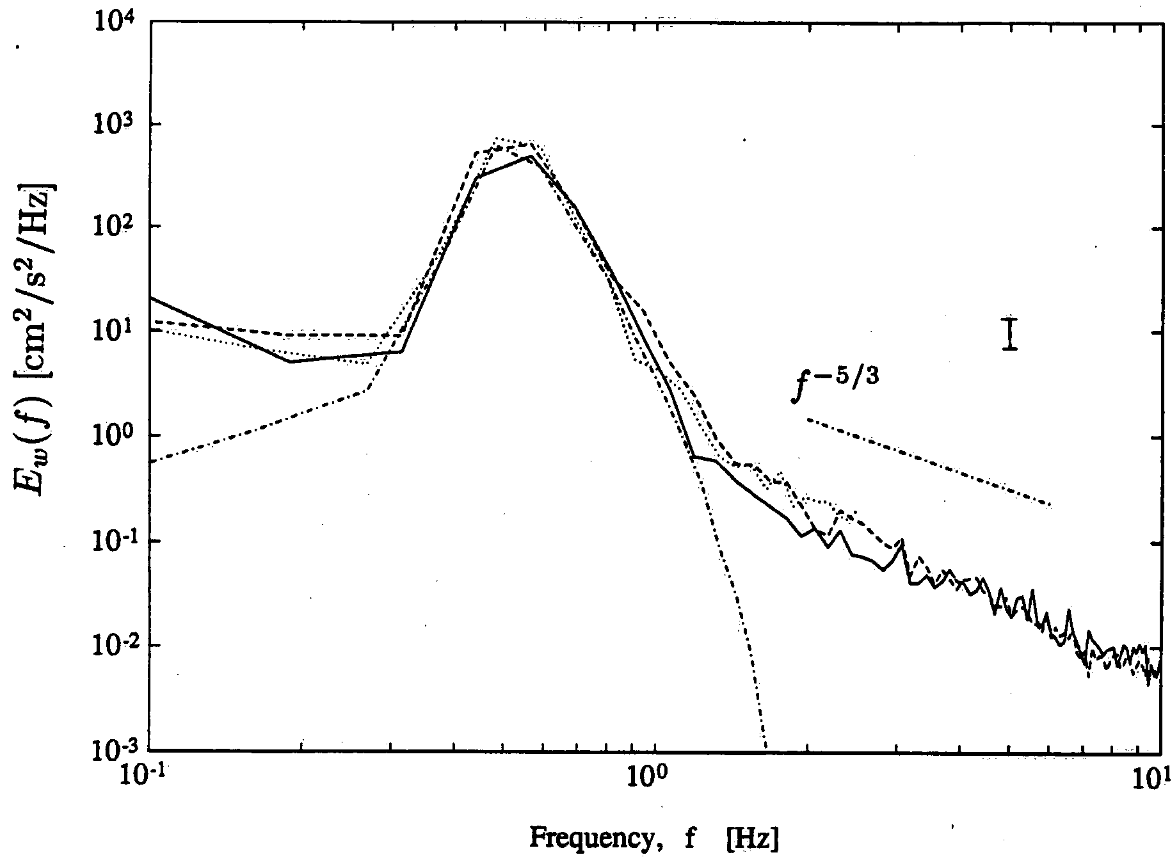
FIGURE CAPTIONS

Figure 1: Concurrent vertical velocity spectra E_w from LDV at 50cm (—), Drag sphere at 50cm (- -) and BASS at 56 cm (···), with linear theory (50 cm) (·-·-·). The vertical band shows the 90% confidence interval.

Figure 2: Dissipation in 'wall layer' coordinates $\epsilon\kappa z/u_*^3$ versus zg/u_*^2. The 'law of the wall' appears as the vertical line. Data are : WAVES (Drag sphere (o), BASS (∗), LDV (•)), Jones (1985), tower (■), Soloviev et al. (1988), profilers (+), Stewart and Grant (1962), towed hot film (▼), Oakey and Elliott (1982), profilers (▲), Dillon et al. (1981), profilers (♦), Arsenyev et al. (1974), tower (△), Kitaigorodskii et al. (1983), tower (x), all using a drag coefficent according to Large and Pond (1981).

Figure 3: Time dependent dissipation estimates, $\epsilon\kappa z/u_*^3$ (or $\epsilon/\bar{\epsilon}$).

Figure 4: Observed probability distribution of $\epsilon/\bar{\epsilon}$, with log normal fit. An additional 7 points lie in the range $7 < \epsilon/\bar{\epsilon} < 18$.



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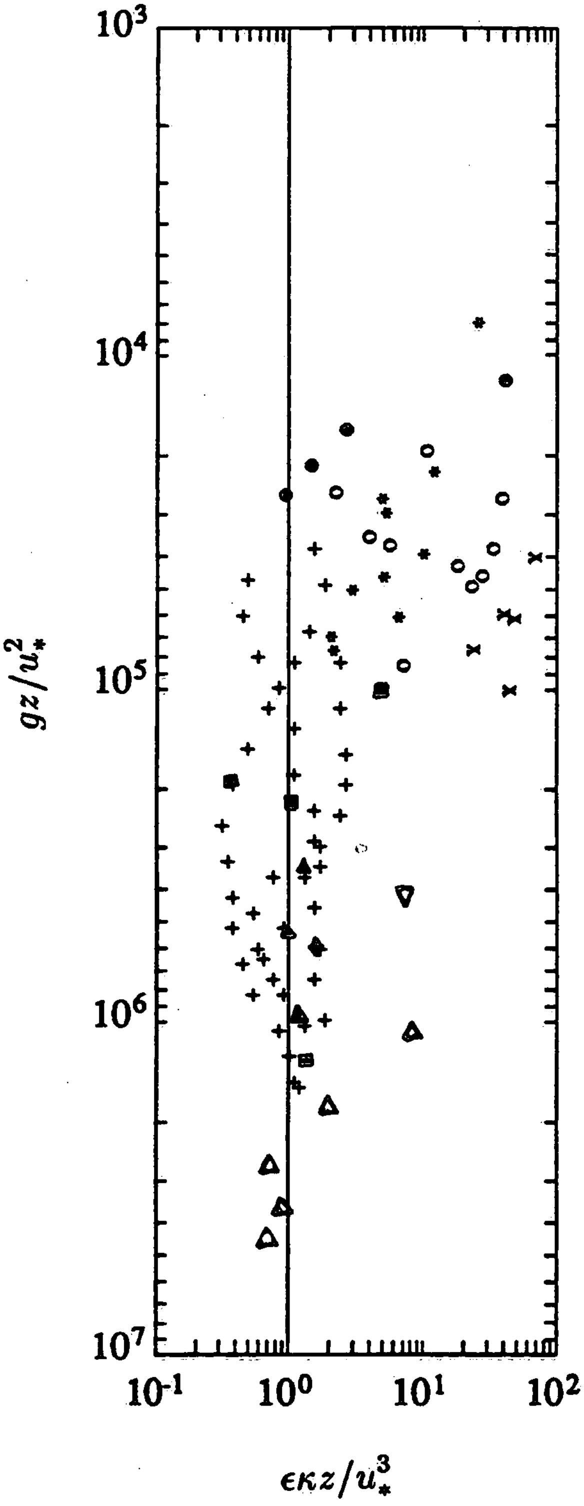

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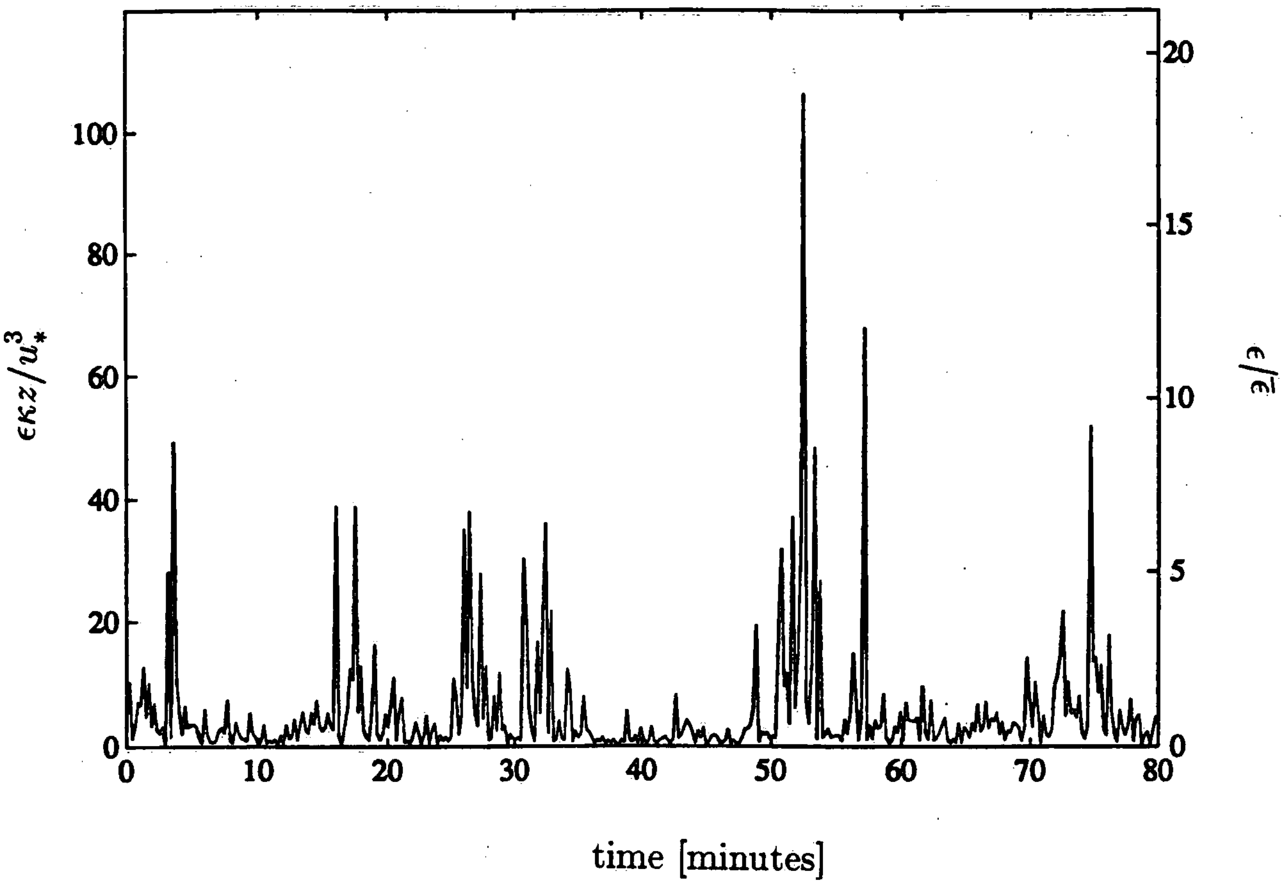

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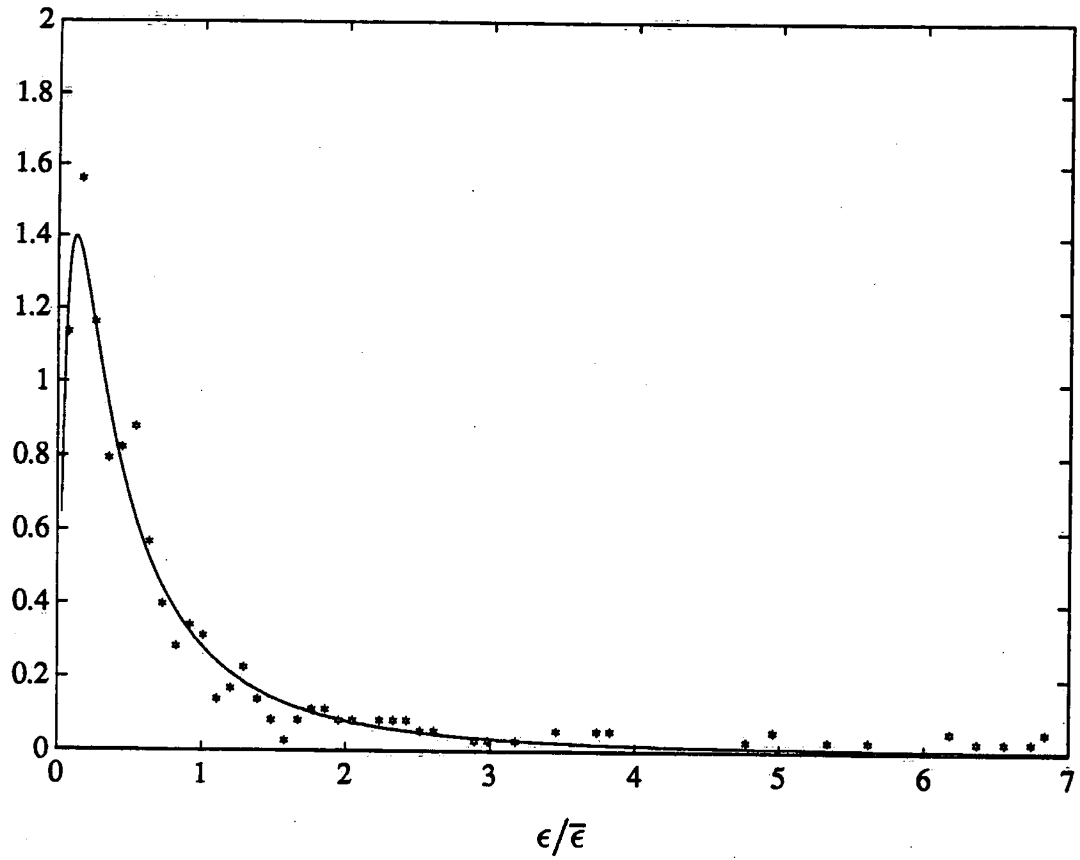

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