Conditional Sampling of Turbulence in the Atmospheric Surface Layer

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ABSTRACT

Conditional sampling and averaging techniques are used to obtain statistics of convectively-driven quasi-ordered structures at a height of 4 m within the atmospheric surface layer. The fraction of time γ occupied by these structures, and their frequency of occurrence f can depend on detection criteria parameters, such as the threshold and hold time. The effect of these parameters on γ and f is investigated for two conditional sampling techniques. Both techniques indicate that γ decreases continuously with increasing threshold, whereas there is a region in which f is independent of both parameters. When the parameters are suitably selected, reasonable agreement for both γ and f can be obtained between the techniques. This agreement does not depend on whether the velocity or the temperature fluctuation is used as the basis of detection for one of the techniques.

1. Introduction

The conditional sampling and averaging technique has been used effectively (e.g., Antonia, 1981) in a number of laboratory turbulent shear flows during the past decade to obtain information on interesting regions of these flows. These regions can fall into various categories, some of which are given below:

1) Turbulent flow regions in flows which exhibit a turbulent/non-turbulent interface.

2) Regions which are characterized by large turbulent energy dissipation. The focus here is on the intermittency of the fine structure.

3) Flow regions which are associated with coherent structures. In a laboratory boundary layer, these structures include both the large-scale quasi-organized motion in the outer region and events such as ejections and sweeps associated with the bursting phenomenon near the wall.

The application of the conditional sampling technique to the study of the atmospheric surface layer should, in principle, yield useful information on flow regions falling into categories 2) and 3). The success of a conditional sampling technique is dependent on a reliable method to detect a flow feature. For laboratory flows, different detection procedures may be tested (e.g., Subramanian *et al.*, 1982), and important properties (such as frequency of events) compared to the results available in the literature. Calibration of detection systems are more difficult for atmospheric flows because of problems like non-stationarity and lack of control over flow conditions. Frisch and Businger (1973) obtained measurements, within plume-like structures, of the vertical velocity using temperature as the indicator of these structures. Lenschow and Stephens (1980) found humidity to be a better indicator of thermals than temperature in the upper part of the convective layer. Manton (1977) analyzed temperature and vertical velocity data obtained from an aircraft flying ~100 m above the ground. His analysis used conditional sampling methods and yielded information about the intermittent structure of convection which is consistent with the results of Frisch and Businger. Khalsa and Businger (1977) and Khalsa (1980) used a conditional sampling technique based on the high-frequency variance of the longitudinal velocity u to obtain statistics associated with convectively driven quasi-ordered structures in the atmospheric surface layer.

Before statistics associated with the flow feature of interest can be obtained, an intermittency function $I(t)$ is required. Usually $I(t)$ is set to unity ("on" state) in the region of interest and is set to zero ("off" state) elsewhere. The generation of $I(t)$ suffers from the inevitable arbitrariness associated with the detection of flow regions of interest. For laboratory flows, difficulties associated with generating $I(t)$ for category 1) have been described by Bradshaw and Murlis (1974). In the context of category 3), Offen and Kline (see Willmarth, 1975) evaluated the performance of different conditional techniques used to detect ejections and sweeps near the wall of a boundary layer by comparing these techniques with flow visualization indications of these events. These authors found that none of the conditional techniques detected events which were in good correspondence with those detected using flow visualization.

The generation of $I(t)$ generally requires the selection of a threshold k and a hold or averaging time

τ. The purpose of the present paper is to investigate the effect of both these parameters on $I(t)$ obtained using two conditional techniques. One of the techniques was applied to both velocity and temperature in the atmospheric surface layer; the other only to temperature fluctuations. Of specific interest is the influence of k and τ on two statistics of $I(t)$: its average value or intermittency factor γ, and its average frequency f.

2. Description of techniques

Two conditional techniques are used. The first of these is somewhat similar to that used by Khalsa and Businger (1977) and is referred to in this paper as BPF, since the velocity or temperature signal is first band-pass filtered. The second method is referred to as LPF since the temperature signal is first low-pass filtered.

a. BPF

Signals proportional to u and the temperature fluctuation θ are first band-pass filtered, using two identical Krohn-Hite filters, prior to squaring. The filters were operated in a four pole Butterworth mode which allows the filter output to be virtually flat until the −3 dB cut-off frequency and has an attenuation rate of 24 dB per octave, at frequencies above approximately twice the cut-off frequency. The filter settings used were 10 and 100 Hz, the frequency range used by Khalsa and Businger (1977) to determine the "high frequency" variance[1] of the wind speed. After squaring, the signals were low-pass filtered at 10 Hz and digitized on a PDP 11/34 computer at a sampling frequency of 20 Hz.

Lump smoothing was implemented by using the computer to obtain

$$\tilde{a}_f(t, \tau) = \frac{1}{\tau}\int_{t-\tau/2}^{t+\tau/2} a_f(t_1)dt_1, \tag{1}$$

where $\tilde{a}_f$ is the smoothed signal, τ is the hold time and the subscript f denotes that the signal a (in this case θ or u) has been band-pass filtered and squared.

The intermittency function I was derived from $\tilde{a}_f$ using the conditions

$$I(t) = \begin{cases} 1 & \tilde{a}_f - \langle\tilde{a}_f\rangle \geq k\langle a^2\rangle^{1/2} \\ 0 & \text{otherwise,} \end{cases} \tag{2}$$

where the angular brackets denote averaging over the total record duration. Further smoothing was applied to I to avoid "patches" of short (less than 1 s duration) "on"–"off" excursions of $I(t)$ by combining these excursions into a single "on" period of larger duration. The smoothed intermittency function $I^*(t)$ was set such that

$$I^*(t, \tau_1) = \begin{cases} 1 & \text{when } \dfrac{1}{\tau_1}\displaystyle\int_{t-\tau_1/2}^{t+\tau_1/2} I(t_1)dt_1 \geq 0.04 \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

Only one value of τ_1 (≡0.55 s) is considered in this paper since I^* was found to be insensitive to τ_1. The low switching criterion of 0.04 was chosen experimentally by trying a range of levels and comparing I and I^*.

b. LPF

In this technique lump smoothing was applied to the digital time series corresponding to θ. The intermittency function was set up using (1) and (2) with the variable "a_f," now representing θ instead of the band pass filtered and squared signals used in BPF. For this technique, further smoothing of I was not required.

The above techniques have been applied to velocity and temperature fluctuations measured at the C.S.I.R.O. Division of Environmental Mechanics field site at Bungendore, New South Wales, during the period 20–26 August 1979. A description of the site, instrumentation and experimental procedures is given in Bradley *et al.* (1981a). Fluctuations u and θ were obtained with a pair of vertical wires (90% platinum, 10% rhodium) set 1 mm apart located at a height z of 4 m. The hot wire was 2.5 μm in diameter, the cold wire 0.63 μm in diameter and both were 0.8 mm long. The hot wire was operated with a DISA 55M10 constant temperature anemometer. The cold wire was operated with a constant current bridge at a current of 0.1 mA. The frequency response of the velocity and temperature systems was better than 1 kHz. Experimental conditions for 25 runs of 15 min duration are given in Table 1 of Bradley *et al.* (1981b). Two particular runs (nos. 19, 28) were considered for the present study. The values of $-z/L$ (L is the Monin–Obukhov length) for these runs are 0.42 and 0.25, respectively. Since the results obtained for these runs were in reasonably qualitative agreement and we are concerned here with testing different single point detection schemes, only detailed results for run 28 are presented in the following section. For this run, the mean wind velocity U is 3.1 m s^{-1}, the friction velocity is 0.26 m s^{-1} and the friction temperature is 0.32°C.

3. Results

The temperature trace shown in Fig. 1 exhibits features already noted in the literature. Taylor (1958) observed the fairly constant temperature base and

[1] The "high frequency" variance of the wind speed was postulated by Khalsa and Businger to be proportional to the dissipation rate of turbulent kinetic energy, because this range of filter setting is expected to be in the inertial subrange of the energy spectrum.

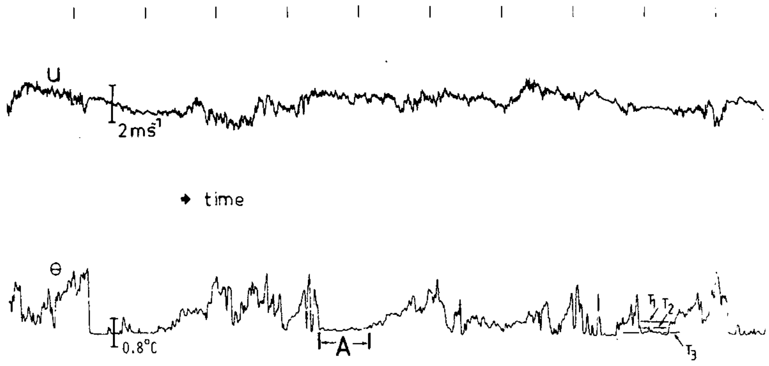

FIG. 1. Temperature and longitudinal velocity traces at $z = 4$ m ($-z/L = 0.42$). The duration between vertical bars is 12.8 s. Threshold level $T = \langle\theta\rangle + k\langle\theta^2\rangle^{1/2}$; $T1$: $k = -0.7$; $T2$: $k = -1.0$; $T3$: $k = -1.2$. Period A is a quiet θ period in which peak variation in $u = 0.2U$.

described the separation of temperature into quiet and disturbed periods as well marked. He also noted (see also Priestley, 1959) that the motion is predominantly upwards during the disturbed periods. Traces of u and θ in Fig. 1 indicate that the quiet temperature periods are usually accompanied by fluctuations in u. For example, for the period of little θ activity marked A in Fig. 1, the peak velocity fluctuation is $\sim 0.2U$. It is common, when examining traces of velocity and temperature measured in the surface layer, to observe periods of quite active velocity (especially vertical velocity) where there is little or no temperature activity. It follows that an intermittency factor, say γ_1, which denotes the fraction for which the temperature exceeds a threshold, cannot be identified with the more conventional intermittency factor which describes the fraction of time for which the flow is turbulent. It is also clear that γ_1 cannot necessarily be identified with the fraction of time occupied by quasi-organized structures in the flow, as a number of short duration events not associated with the organized structure will be included (e.g., Phonganant *et al.*, 1980, Fig. 2).

An attempt to estimate γ_1 was made to enable comparison with the intermittency factor associated with the quasi-organized structures. Several methods are used to determine the intermittency factor of the turbulence in laboratory shear flows which have been passively marked with temperature. Perhaps the more common method involves the formation of an intermittency function by comparison of θ with a visually selected threshold (e.g., Antonia *et al.*, 1975). Using unfiltered θ [$k = 1$, Eq. (1)] an estimate of $\gamma_1 = \langle I\rangle$ and f_1, the frequency of active θ periods, may be obtained from I generated using Eq. (2). Three thresholds, $T1$, $T2$, $T3$ (with $Ti = k\langle\theta^2\rangle^{1/2}$ and k equal to -0.7, -1.0 and -1.2, respectively) are indicated on the θ distribution in Fig. 1 and gave γ_1 equal to 0.70, 0.85 and 0.92 respectively. The threshold $T1$ visually appears to be set high, and active θ periods are missed. $T3$ is a more reasonable choice, but due to the unsteady temperature base line some quiet θ periods are included as active. For the three thresholds $T1$, $T2$ and $T3$ shown in Fig. 1, U/f_1z is equal to 1.45, 2.08 and 3.33, respectively.

Another, more objective, method to select the threshold (Bilger *et al.*, 1976) is based on examining the probability density function of θ. Fig. 2a shows a smoothed probability density function $p(X)$, where $X = \theta/\langle\theta^2\rangle^{1/2}$. The probability density function is constructed by allocating interval $X_i < X < X_i + dX$ to elements in an array and adding to the appropriate element the number of times X falls into the element range. Smoothing is provided by combining n neighboring elements in the array and adjusting the values in the resulting smoothed array so that the area between $p(X)$ and the X axis, $p(X) = 0$, is equal to 1.0. In Fig. 2a, smoothed with $n = 36$, $p(X)$ appears to be bimodal with primary and secondary peaks at $X = -0.9$ and -1.3, respectively. The region $-1.5 < X < -0.6$ in the neighborhood of the peaks is expanded in Fig. 2b where $n = 4$. In the vicinity of $X = -1.3$ the contribution to $p(X)$ is expected to come from quiet periods, for $X > -1.0$, the $p(X)$ contribution is from active θ periods. The quiet θ probability density function which is a convolution of instrument noise with base temperature density functions, deviates from a Gaussian distribution in the vicinity of $X = -1.3$. This is contrary to Bilger *et al.* (1976) result, as the base temperature varies and its probability density function cannot be approximated by a Dirac delta function or normal distribution with a very small variance. There is an overlap region in Fig. 2b, $-1.25 < X < -1.00$, in which quiet and active θ periods are important in determining $p(X)$. An estimate of γ_1 can be obtained by choosing as a threshold X_m, the position of minimum $p(X)$ between the twin peaks in $p(X)$. The area, in Fig. 2, to the right of X_m and bounded by $p(X)$ and X axis is equal to γ_1. For $X_m = -1.12$, $\gamma_1 = 0.89$ and $U/f_1z = 2.94$.

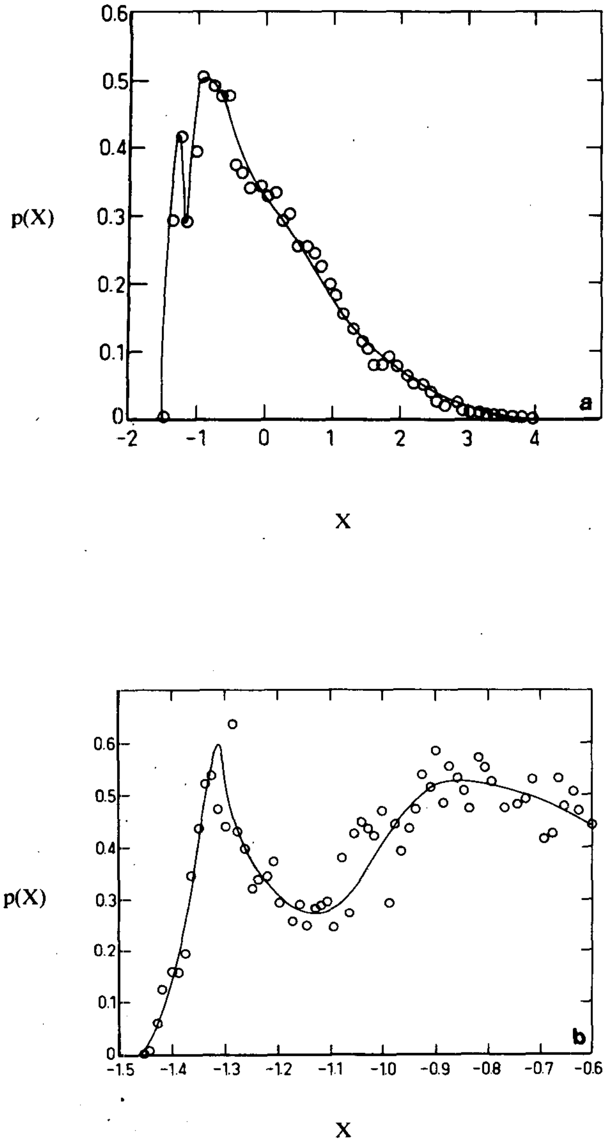

FIG. 2. Probability density function of θ, (a) with smoothing $n = 36$, (b) expanded in region of peak, smoothing $n = 4$. (Solid lines fitted by eye.)

Although there is some ambiguity in determining γ_1, the above estimates of γ_1 are significantly larger than the intermittency factor γ (≈ 0.44)[2] of the surface layer plumes. A summary of γ values obtained by various authors for the surface layer and mixed layer is given by Khalsa (1980). Also the frequency of occurrence of active θ periods is much larger than the frequency, $U/fz = 20$, of ramp like events observed in the θ traces in Fig. 1. These ramp events (Phong-anant *et al.*, 1980) may be associated with the quasi-organized structure in the flow.

[2] Khalsa found that γ is essentially independent of $-z/L$ for $-z/L > 0.3$.

The effect of k [Eq. (2)] on the intermittency factor γ obtained using BPF is shown in Figs. 3 and 4. Although the intermittency function I^* [Eq. (3)] was used to obtain these results ($\gamma = \langle I^* \rangle$ with $\tau_1 U/z = 0.43$), it was found that $\langle I \rangle$ was very nearly equal to $\langle I^* \rangle$ over the range of k values considered in these figures. The variation of γ is essentially insensitive to the parameter τ (three values of τ are considered). However, the effect of k is significant, both figures indicating no region where the intermittency factor is independent of k. As k increases, γ first decreases in an almost linear fashion and appears to depart from this trend at $k \approx 0$. This behavior is similar to that reported by Chen and Blackwelder (1978). For $k = 0$, both Figs. 3 and 4 indicate a value of γ of ~ 0.4, in reasonable agreement with the value reported by Khalsa (1980). The agreement is not unexpected since the latter investigator used essentially a threshold $k = 0$, I being set equal to unity when ϵ, an approximation to the instantaneous turbulent energy dissipation, exceeded its mean value. Khalsa justified this selection of k as that which maximized the ratio between the average energy dissipated in excess of the mean in the structure, and the average energy dissipated during a run, $\gamma(\langle \epsilon_{on} \rangle - \langle \epsilon \rangle)/\langle \epsilon \rangle$. It is interesting to note that a value of $k = 0$, corresponding to a threshold equal to $\langle \Theta \rangle$, where Θ is the absolute temperature, applied to the unfiltered θ would yield a value of γ_1 of 0.43. In a manner analogous to that of Khalsa, the justification for $k = 0$ would be that such a threshold would maximize the parameter $\gamma(\langle \Theta_{on} \rangle - \langle \Theta \rangle)/\langle \Theta \rangle$ where $\langle \Theta \rangle$ is greater than zero.

It is expected that there exists a "plateau region" in which the intermittency function frequency is independent of k and τ. As τ is increased, short duration high frequency events will be smoothed and result in a decrease in f. As k is increased, f first increases from zero and later returns to zero. It is postulated that if a "plateau region" occurs, then I or I^* is independent of k and τ in this region and correctly defines a large scale quasi-organized motion in the flow.

Figs. 5 and 6 exhibit a region where the frequency f of I^* is essentially independent of k. This region falls in the range $-0.3 \leqslant k \leqslant 0.3$. As $\tau U/z$ increases, the frequency decreases, but the results for both velocity (Fig. 5) and temperature (Fig. 6), shown for four values of τ, suggest that, for each value of τ, there is a range of k for which f is essentially independent of k. The sensitivity of frequency to τ can be ascertained more precisely in Fig. 7 where k is constant (≈ -0.25). This k value corresponds approximately with the beginning of the plateau in Figs. 5 and 6. Fig. 7 shows that the plateau for u is more distinct than for θ but both plateaus yield a common value of U/fz (≈ 22). For the present experimental conditions, this frequency corresponds to an average

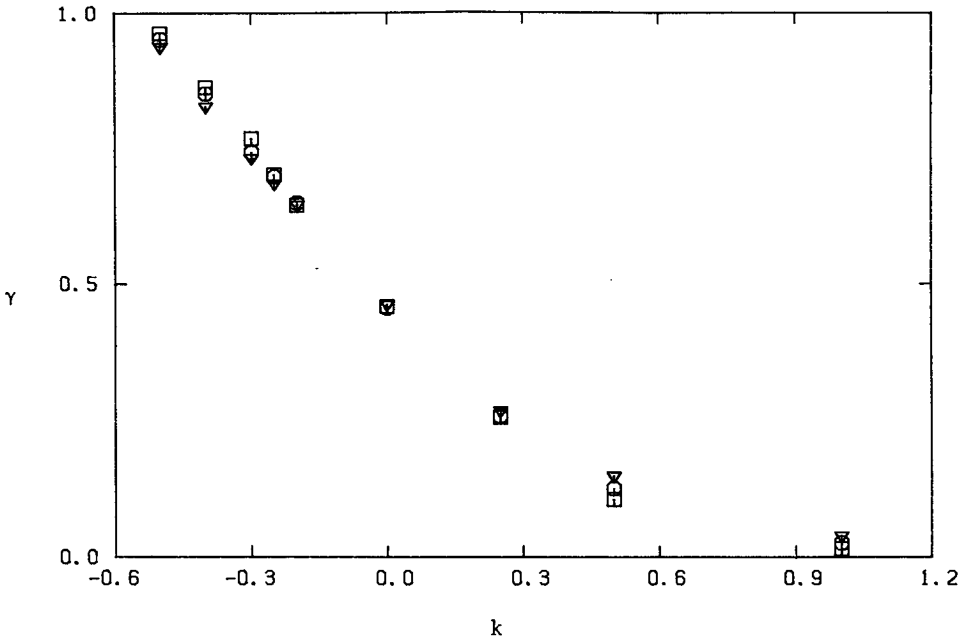

FIG. 3. Effect of threshold on intermittency factor using BPF applied to the velocity fluctuation u: Rectangles, $\tau U/z$ = 1.98; circles, 3.14; triangles, 4.30.

distance between structures of 88 m, if the translational velocity of the structure is assumed equal to the local wind velocity. This assumption is supported by the measurements of Phong-anant *et al.* (1980). It is interesting to note that a value of U/fz equal to $\sim$15 was estimated by counting ramps on temperature signals recorded simultaneously at heights of 2 and 4 m over a period corresponding to Run 28. From the data of Khalsa (1980), we infer values of U/fz equal to $\sim$26 and 30 when $-z/L$ are equal to 0.47 and 0.23, respectively.

It is evident from Fig. 1 that the u trace, contrary to the θ trace, does not have a constant velocity base which separates periods of quiet and active velocity,

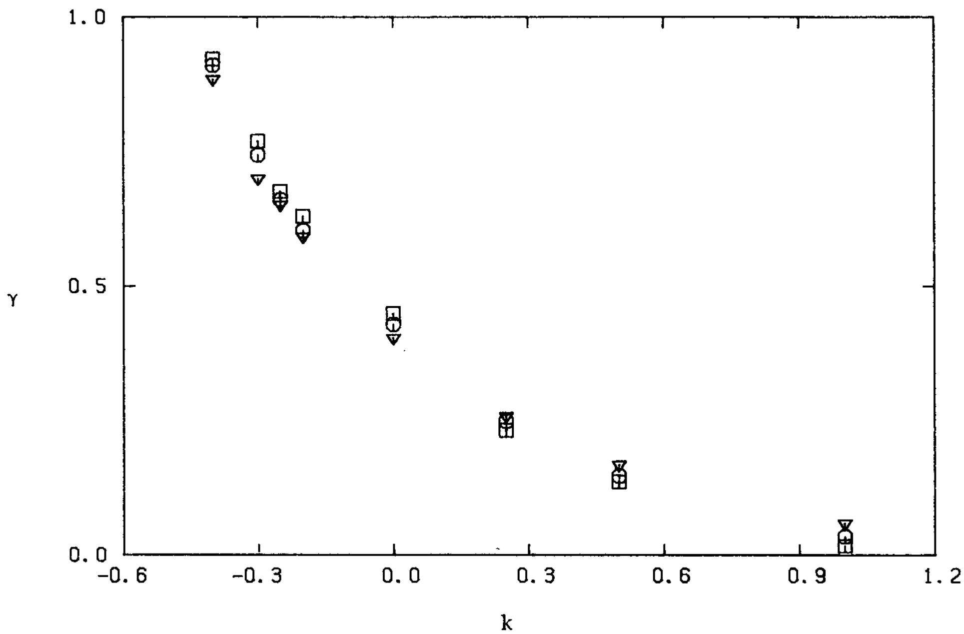

FIG. 4. As in Fig. 3, but for temperature fluctuation θ.

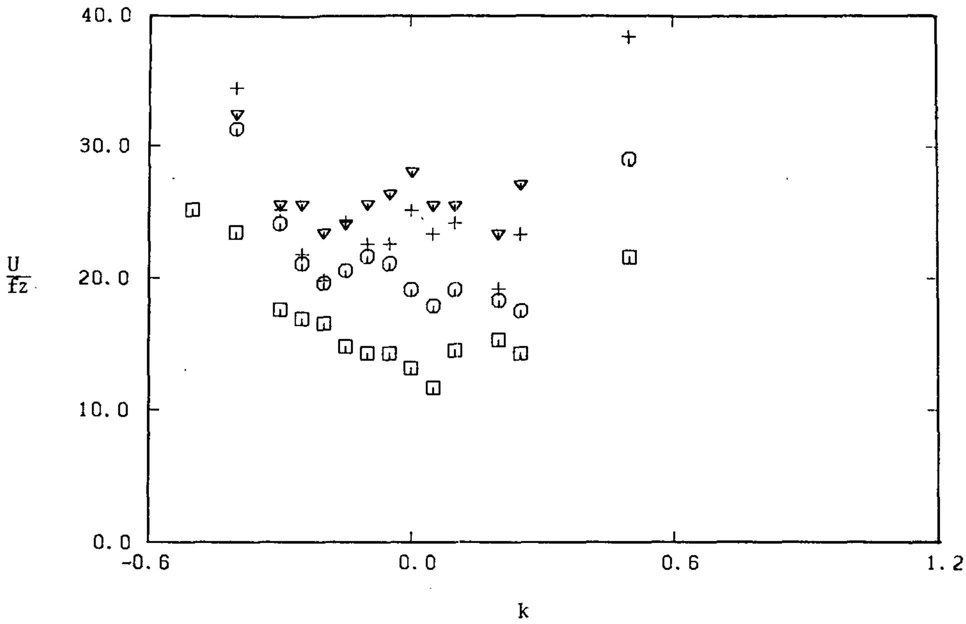

FIG. 5. Effect of threshold on frequency using BPF and u: Rectangles, $\tau U/z$ = 1.98; circles, 3.14; triangles, 4.3; crosses, 5.46.

hence the LPF technique was not applied to u. For LPF, the effect of k on γ and f is shown in Figs. 8 and 9, respectively, for a particular value (=4.3) of $\tau U/z$. Fig. 8, like Fig. 3, reveals a monotonic decrease in γ as k increases. The departure from a linear dependence in Fig. 8 occurs when $k \approx 0.4$, which corresponds to a value of γ of ~0.4. Fig. 9 indicates approximate independence of f on k in the range $-0.5 < k < 0.4$. Fig. 10 shows, for $k = 0$, that f is independent of τ in the range $3 < \tau U/z < 6$. The plateau frequency $U/fz = 21$, obtained by LPF, is very nearly equal to that inferred from Fig. 7.

While agreement can be obtained between BPF and LPF for γ and f by appropriate selection of detection parameters, Fig. 11 indicates that exact correspondence of intermittency functions is not

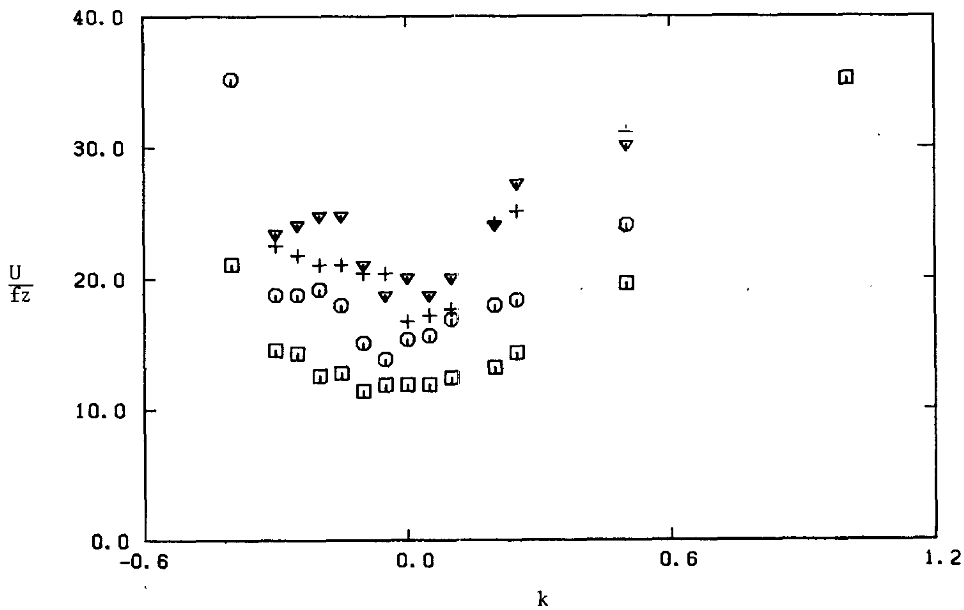

FIG. 6. As in Fig. 5, but for BPF and θ.

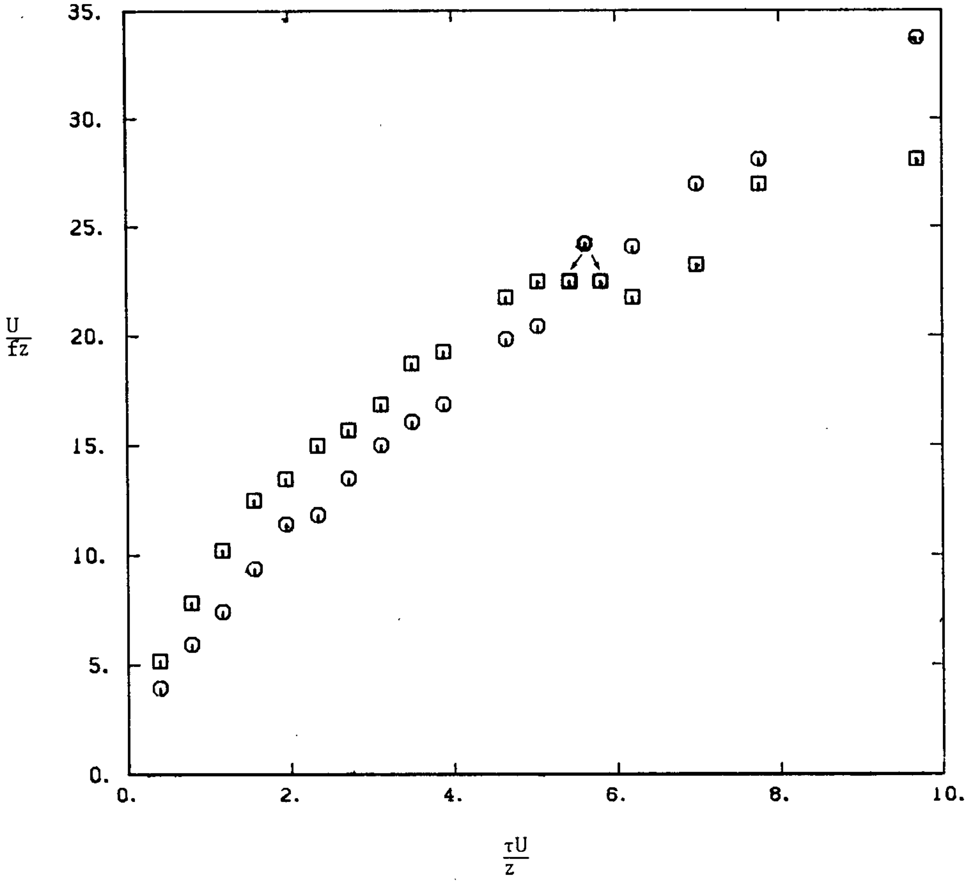

FIG. 7. Effect of smoothing time on frequency for $k = -0.25$ using BPF and either u or θ: Rectangles, u; circles, θ.

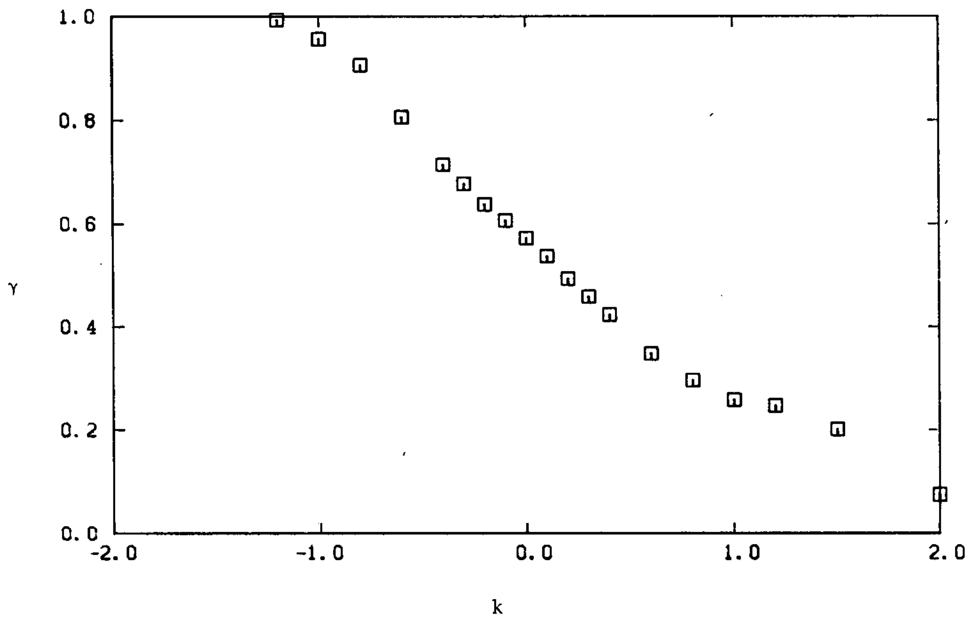

FIG. 8. Effect of threshold on intermittency factor using LPF and θ with $\tau U/z = 4.3$.

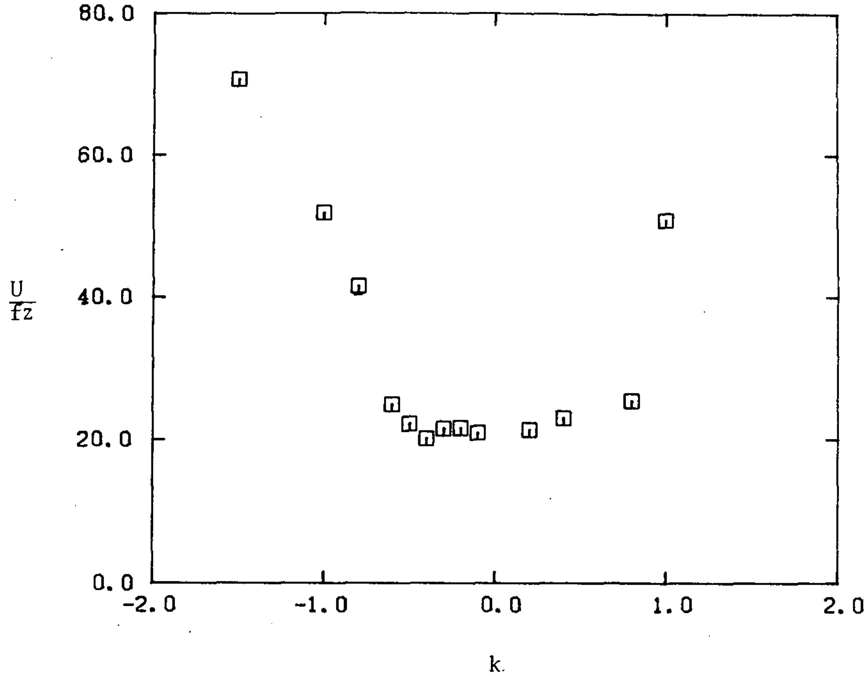

FIG. 9. Effect of threshold on frequency derived from LPF and θ with $\tau U/z = 4.3$.

achieved. The θ trace in Fig. 11 suggests the presence of several structures marked by a relatively well defined sudden decrease in θ at the upstream interface, down to the undisturbed temperature of the surrounding air. Intermittency functions obtained by BPF(u) and LPF(θ) indicate almost identical arrival times for this interface, but LPF(θ) detects a shorter duration structure, marked 1 in Fig. 11, immediately following the larger structure, whereas structure 2 detected by LPF(θ) is undetected by BPF(u). It is clear that the ambiguity in forming the intermittency function needs to be reduced if subsequent use of this function is to be made for determining conditional statistics within and outside the structure.

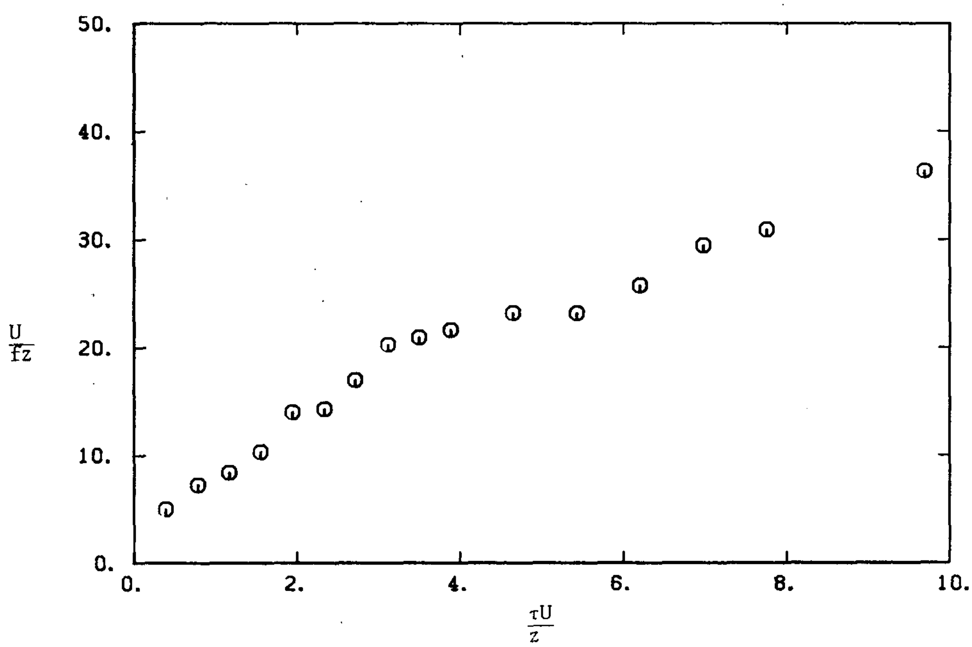

FIG. 10. Effect of filter time constant on frequency using LPF and θ with $k = 0$.

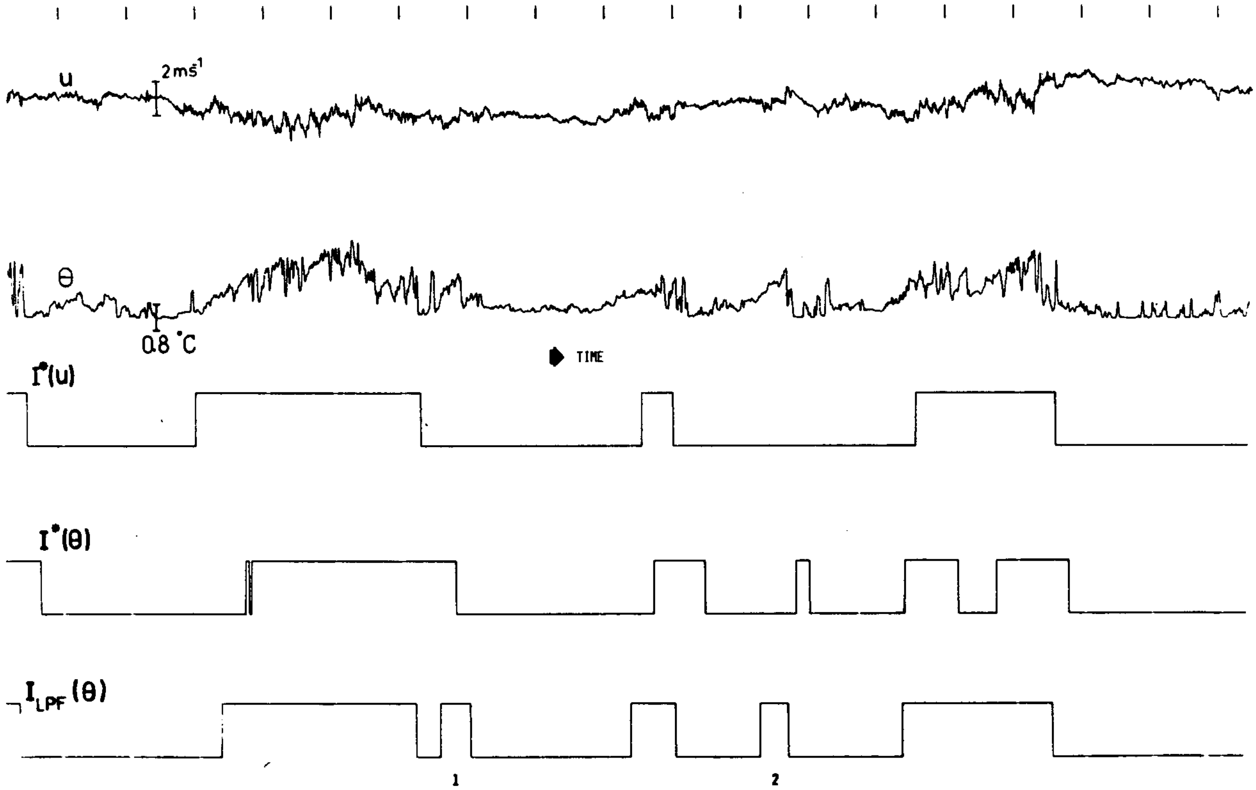

FIG. 11. Comparison between intermittency functions obtained with BPF and LPF. The duration between vertical bars is 12.8 s (time increases left to right). The lines from top to bottom are: u; θ; $I^*(t)$ using BPF and u ($\gamma = 0.45$; $U/fz \approx 25$); $I^*(t)$ using BPF and θ ($\gamma = 0.45$; $U/fz \approx 17$); $I(t)$ using LPF and θ ($\gamma = 0.43$; $U/fz = 21$). $\tau = 4.3$; $k = 0$.

4. Concluding discussion

The results presented in the previous section have indicated that two comparatively different conditional techniques can yield essentially identical values for the intermittency factor γ and the frequency of occurrence f of surface layer structures when the parameters used to form the intermittency function are suitably chosen. Since the intermittency factor is a monotonically decreasing function of the threshold, an obvious choice of threshold does not appear possible on the basis of this information. A useful indication of the appropriate ranges for the threshold k and hold time τ is provided by the frequency f which exhibits a plateau, with respect to both k and τ. The precise selection of the parameters k and τ remains uncertain. A possible basis for selection would be to choose k so that $d\gamma/dk$ begins to exhibit a departure from a nearly constant value. This choice of k yields, for both conditional techniques used, a value of γ in agreement with that found by Khalsa (1980) and other investigators for surface layer convective plumes. While this value of γ is relatively insensitive to τ, this latter parameter can be selected to fall within a range for which f is insensitive to τ. It should be noted that the plateau of frequency with respect to k has been observed in laboratory investigations of the turbulent/non-turbulent interface (e.g., Jenkins, 1974, for a plane jet; Antonia *et al.*, 1975, for a circular jet with a co-flowing stream; Chen and Blackwelder, 1978, for a boundary layer).

The present study has indicated that temperature can be as effective as velocity for the determination of γ and f. For laboratory shear flows, the use of temperature as a marker of the turbulent/non-turbulent interface, is often preferred to velocity. In his study of surface layer intermittency, Khalsa (1980) noted the desirability of using the "high frequency" variance of wind speed in preference to the temperature signal, since periods of large variance in temperature are not always associated with periods of large velocity variance. This recommendation is not supported by the present study which indicates that a temperature scheme can yield values of γ and f in good agreement with those obtained with a velocity scheme. The LPF results also suggest that a temperature-based scheme may be more easily implemented than a scheme such as BPF which focuses on the "high frequency" variance of velocity or temperature fluctuations.

It should be emphasized that an objective choice of the parameters k and τ seems unlikely unless an independent method of recognizing the structure can be found. This difficulty is analogous to that associated with the recognition of quasi-coherent structures in a laboratory boundary layer. The present conditional techniques clearly suffer from the limitation of making decisions about the structure on the basis of information obtained at only one point in space. A more appropriate experimental strategy would be to use information simultaneously obtained at several points in space. The spatial coherence of the ramp-like temperature structure has been well established (e.g., Taylor, 1958; Kaimal and Businger, 1970; Antonia *et al.*, 1979). A vertical array of temperature sensors or preferably a combination of vertical and horizontal arrays (such as used by Wilczak and Tillman, 1980, to study the three-dimensional structure of plumes) should provide a more reliable detection of the structures than is possible with one-point techniques.

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