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13. ABSTRACT *(Maximum 200 words)*
Atmospheric turbulence immediately above and within vegetation has features that distinguish it from that observed over smooth terrain. A variety of statistical properties demonstrate these differences, which are believed to be reflections of organized motions. The study involved the analysis of four data sets: a deciduous forest, an almond orchard, a maize crop, and an English walnut orchard. Statistics included skewness, spectra, correlation coefficients, lagged correlations, and quadrant analysis. Overall, normalized statistics were remarkably similar for all four stands when vertically scaled by the height of the top of the vegetation, despite the large differences in the dimensions and vegetative structures of the stands.

Objective schemes were used to detect ramp patterns in data from each site. Applied to the forest data, the multilevel scheme showed that a consistent number of ramps was detected in the humidity traces during each run, despite the fact that thermal stability changed during the observation period. Comparing the four canopies, the frequency of occurrence of ramps increased as stand height decreased. A consistent relationship was found when the frequency was plotted against a measure of the wind shear. It is demonstrated that the wavelet technique accurately detects scalar ramps.

14. SUBJECT TERMS
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Atmospheric turbulence structure
at three vegetated sites

Final report

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A. STATEMENT OF PROBLEM

Predictions of rates and extent of diffusion by atmospheric turbulence near the ground surface have been attempted with both Eulerian and Lagrangian dispersion models but the success of such models will depend on how accurately they mimic natural air flow patterns. When the land surface is covered with tall vegetation, the air flow within the canopy and immediately above takes on unique characteristics. These characteristics are initially revealed by the presence of repeated patterns in time series of scalars such as temperature or humidity, in which the scalar slowly increases over a period of a few tens of seconds and then abruptly returns to an earlier level. These patterns are usually referred to as ramps and are similar in appearance but not in physical mechanism to the temperature patterns observed during the passage of convective plumes higher in the atmospheric boundary layer (Kaimal and Businger, 1970; Wilczak, 1984).

Examination of the three-dimensional velocity field in conjunction with individual ramp patterns reveals a consistent and spatially coherent flow structure composed of an ejection/sweep combination, in which the rapid temperature or humidity drop is nearly coincident with the change in direction of the vertical velocity from updraft to downdraft (Gao et al., 1989). It has been shown that, for forests, coherent structures contribute greatly to the total vertical fluxes of heat, water vapor, and momentum between the vegetation and the atmosphere. The appearance of humidity ramps in near-neutral conditions, and of inverted temperature ramps when the air is statically stable makes it very likely that the structures are formed by the high wind shear in the region near the canopy top, and that they are not only a consequence of thermal convection.

For some time it has been noted that the structure of atmospheric turbulence immediately above and within vegetation canopies has features that distinguish it from the flow observed over smooth terrain. A variety of statistical properties demonstrate these differences, which we believe are reflections of the organized motions discussed above. Spectra and cospectra have shapes that are more sharply peaked than those over smooth terrain; longitudinal and vertical velocity perturbations are more strongly correlated; quadrant analyses show a dominance of sweeps over ejections, and that turbulence is highly intermittent; and longitudinal and vertical velocities are strongly skewed, positively in the former and negatively in the latter case.

Extensive data sets are available to the author from turbulence studies in three distinctly different stand types: a deciduous forest from full summer foliage to fully defoliated (Shaw et al., 1988), an agricultural field crop of maize, and two orchards. One of the orchards was the almond orchard at Chico, California in which part of Project WIND was staged. Temperature and humidity ramps had been observed in all of the data sets.

Knowing that there is a large difference in the statistical properties of turbulence between smooth and rough land surfaces, the question arises whether vegetation of different heights produce fundamental differences in the character of the turbulence, or similar characteristics but possibly scaled according to the physical dimensions of the system. Differences that might exist could appear in both the statistical descriptions of the flow and in the degree of organization of the flow structures. The objectives of the study were to inspect turbulence data from distinctly different stands of vegetation, to compare them in terms of statistical properties of flow and scalar fields, and to develop a technique for examining organized motions and to survey and compare the data sets.

B. SUMMARY OF RESULTS

The study involved the analysis of four existing data sets. Three of these data sets were described in the research proposal; namely a deciduous forest experiment held in Ontario, Canada 1986/87 in which the author was a participant; a study of turbulence in an almond orchard near Chico, California in 1987, performed as part of Project WIND; and measurements in a maize crop near the University campus, Davis in 1988. The fourth data set arose from a study held in an English walnut orchard near Winters, California in 1989 (Zhang et al., 1991). The results are presented in two sections, the first dealing with statistical properties of the observed turbulence fields, and the second dealing with conditional sampling of coherent structures and the appearance and detection of scalar ramps. All data sets were broken into 30-minute blocks at the time of data logging, and statistical analyses are 30-minute averages.

Statistical properties

It has been known for some time that the probability distribution of wind velocity inside and immediately above plant canopies is much more strongly skewed than the air flow through the remainder of the atmospheric surface layer, or over smooth surfaces (Maitani, 1978; Raupach, 1981; Shaw and Seginer, 1987). Skewness is a measure of the asymmetry of a distribution. It is generally found that longitudinal velocity is positively skewed and vertical velocity is negatively skewed within the air spaces of a rough surface, meaning that large downdrafts with large streamwise velocity are much more likely than strong updrafts of low momentum fluid. The skewnesses decrease to small values at about twice the height of the vegetation.

Figure 1 compares skewness of longitudinal and vertical velocity calculated from data for each of the four locations, taken during weakly unstable conditions ($-0.15<h/L<0$, except for the almond orchard, for which $-0.5<h/L<0$, where h is stand height and L is the Monin-Obukhov length). Skewness is a non-dimensional quantity (the third moment divided by the cube of the standard deviation) and the vertical axis is also normalized according to the height of each of the canopies. The four results are quite similar in form and magnitude. At about twice canopy height, all skewnesses are small. Vertical velocity skewness becomes increasingly negative to values of about -1 in the middle and lower part of the canopy, while streamwise velocity skewness attains rather constant, positive values of about 0.7 in the orchard and maize canopies. The forest is slightly different in that maximum longitudinal velocity skewness is found near treetop height and skewness diminishes steadily with depth in the forest. Otherwise, there is quite remarkable similarity between the different sites when the vertical dimension is normalized by the height of each individual canopy.

While high positive u-skewness and negative w-skewness imply that strong downbursts of high momentum fluid intermittently penetrate the canopy, the statistic does not establish that longitudinal and vertical velocities are, in fact, related to each other. It is demonstrated in Figure 2, however, that u and w are quite strongly correlated in the upper part of each of the canopies. The figure shows vertical profiles (plotted against normalized height) of the correlation coefficients between longitudinal and vertical velocity (r_{uw}), and between vertical velocity and temperature (r_{wT}) for each of the four sites. It is apparent that the highest correlation coefficients are found in the upper layers of the canopies but the largest height variations occur in the forest, where a distinct peak is seen at the first observation level below treetop height. It is possible that lack of resolution in the instrument arrays prevented such a phenomenon from being observed in the shorter stands. In any case, the correlation coefficients are considerably higher than those reported over smooth terrain. For example, Haugen et al. (1971) reported r_{uw} equal to about -0.3 and r_{wT} equal to about 0.35, for the same stability range as our study, in measurements over wheat stubble in Kansas. Here, we find correlation coefficients of about -0.5 and 0.5, respectively. These large degrees of correlation, especially those between the velocity components, are indicative of a significant amount of organization in the turbulent flow.

The statistical technique of quadrant analysis (Willmarth and Lu, 1974; Finnigan, 1979; Raupach, 1981; Shaw et al., 1983), was applied to conditionally sample turbulent longitudinal and vertical velocities into quadrants according to the combination of signs of the two signals and their contributions to the Reynolds stress (sweep: $u'>0$, $w'<0$; ejection: $u'<0$, $w'>0$; outward interaction: $u'>0$, $w'>0$; inward interaction: $u'<0$, $w'<0$). Sweeps and ejections both contribute to the downward flux of momentum, while the interaction terms act in the opposite sense. We found only minor differences between the stands. All showed the previously reported pattern in which sweeps exceed ejections in terms of their contributions to the momentum flux in the upper levels of the canopies, and with the interaction terms being small by comparison. While canopy density appears to have little influence on velocity skewnesses, stress fractions obtained using quadrant analyses show that the relative contributions by sweeps and ejections decrease with depth in the forest most quickly when the forest is fully leafed.

Attempts to compare power spectra of velocities observed in the different stands, and to compare spectra with those reported elsewhere (e.g., Baldocchi and Meyers, 1988) have not been very successful because of differences and difficulties in normalizing spectra. It is normal to want to eliminate the effects of observation height and wind speed from calculated spectra. The most common method to accomplish this is to form a normalized, and non-dimensional frequency f=nz/U, where n is the natural frequency, z is the measurement level, and U is the mean wind speed at height z. Division by the local wind speed implies an acceptance of Taylor's hypothesis such that the physical dimension of eddies can be obtained from a time trace of fluctuations by assuming that eddies translate along at a speed proportional to the mean wind at that level. If canopy turbulence is strongly influenced by coherent structures, which translate as entities with the same velocity at all levels, the normalization described above would be inappropriate. In such a situation, division by the structure translation velocity, or by wind speed at a fixed level, would be better. In at least one case, we have seen that spectra at different levels within the canopy are best normalized by a single wind speed and by a single height, because the natural frequencies of the peaks of the spectra match at all observation levels. It is apparent, however, that if contributions to turbulence arise from both vertically coherent eddies and from local processes, there is no consistent method for matching spectra from different heights.

Overall, our analyses show that normalized statistics are remarkably similar for all four of the stands when vertically scaled by the height of the top of the vegetation. This similarity exists despite the large differences in the dimensions and vegetative structures of the stands.

Conditional sampling analyses

The primary objective of this part of the study was to optimize a scheme for detecting scalar ramp patterns observed in traces of temperature or humidity, and to survey the four data sets for coherent structures so identified. Included in this plan were the goals to find a way to scale the frequency of appearance of coherent structures and to characterize, in some quantitative manner, ramp patterns in the different data sets in terms of their duration and degree of organization. We have not yet completed this task. We have performed surveys of the data sets, as we report below, but show only early results of our attempts to apply wavelet transforms to the data.

Figures 3a-d show examples of traces of temperature from each of the four studies. It is apparent that the most clearly defined patterns are from the tallest canopy, and we have devoted more time to their examination than to the other data sets. An algorithm (Shaw et al., 1989) to detect the rapid scalar change at the termination of each ramp by (i) moving through the data to seek a relatively large change in the scalar occurring over a short interval of time (of the order of 3s for the forest data), and (ii) immediately examining the scalar at a series of lower observation levels for a continuation of the change, proved to be successful. Applied to the forest data, this multilevel scheme showed that a reasonably consistent number of ramps (of the order of 1 per 100s) were detected in the humidity traces during each half hour run (Figure 4), despite the fact that conditions changed during the observation period from unstable to stable. On the other hand, temperature ramps during the same period matched the number of humidity ramps at the start and end of the period but, when conditions were close to thermally neutral, few temperature ramps were detected. We believe that stability effects on the appearance of coherent structures are secondary but that, in order for scalar ramps to appear, it is necessary that there be a vertical distribution of the scalar. During near-neutral stability, it is likely that (potential) temperature is uniformly distributed with height, leaving none of the characteristic traces that remain on the humidity traces during a continuing transpiration process.

The same objective analysis scheme was used to identify ramp patterns in time traces of temperature from all four data sets. It became apparent that the frequency of occurrence of ramps increased as canopy height decreased but that, when frequency of occurrence was normalized with canopy height and wind speed (fh/U), ramp frequency was greatest for the forest and least for the much shorter agricultural crop. The normalized frequency decreased with increasing wind speed in all cases.

Clearly, the normalization described above is inadequate because it does not collapse the data onto a single curve. A much better relationship was found when the frequency of occurrence was plotted against a measure of the wind shear, such as the ratio of the friction velocity to the canopy height (u_*/h). Figure 5 shows data from all four canopies and demonstrates a much tighter relationship when presented in this fashion. Notice that frequency and wind shear have the same dimensions, suggesting that such a relationship is to be expected. However, data from the three canopy types: forest, orchard, and field crop, barely overlap, and data from the forest alone appear to have a steeper slope than those from the other canopies. The arguments presented here are weaker than they would have been had the data from the different sites interspersed on the graph.

It is evident that the scalar signals are somewhat "noisier" in the shorter canopies (Fig. 3), making ramp identification more uncertain. It is possible that the slope of the curve in Fig. 5 decreases with increasing values of u_*/h because, in the shorter canopies, the signal-to-noise ratio is smaller. This might also be the reason that the curve does not appear to extrapolate to the origin of the graph. We found it necessary to develop an objective scheme for evaluating scalar traces to reveal not only ramp frequency but also to provide measures of the duration of coherent structures and of the signal-to-noise ratio. To this end, we are examining the wavelet transform technique but, as stated earlier, this part of our study is not yet complete.

In the wavelet transform method (Daubechies, 1990; Gamage and Mahrt, 1990; Liandrat and Moret-Bailly, 1990), a short term correlation is formed between the scalar signal and a basis function, such as the Haar function (for $-T/2<t<0$, the function equals +1; for $0>t>T/2$, the function equals -1). The correlation between the signal and the basis function is obtained as a function of time progressing through the data record. An example of a temperature trace and the corresponding correlation function is shown in Fig. 6. Peaks in the correlation align themselves with the termination of the ramps.

The Haar function proved to be successful in detecting scalar ramps but, since its shape does not include the rising portion of a ramp pattern, it is not sensitive to ramp size nor can it be used to evaluate the contribution of ramps to the total signal variance. We have chosen to examine functions that are not true wavelets but which match more closely the patterns seen in scalar traces. An example of such a false wavelet is a function that consists of a slow, steady rise followed by rapid decrease to the initial value. We have applied this transform to artificially created data with prescribed durations of ramps and prescribed intervals between ramps, and to which random noise has been added.

The technique has proven to be successful in retrieving the duration and interval between ramps.

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C. LIST OF TECHNICAL REPORTS

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D. LIST OF SUPPORTED SCIENTIFIC PERSONNEL

Jie Qiu Research Assistant, Ph.D. student (expected graduation September, 1993).

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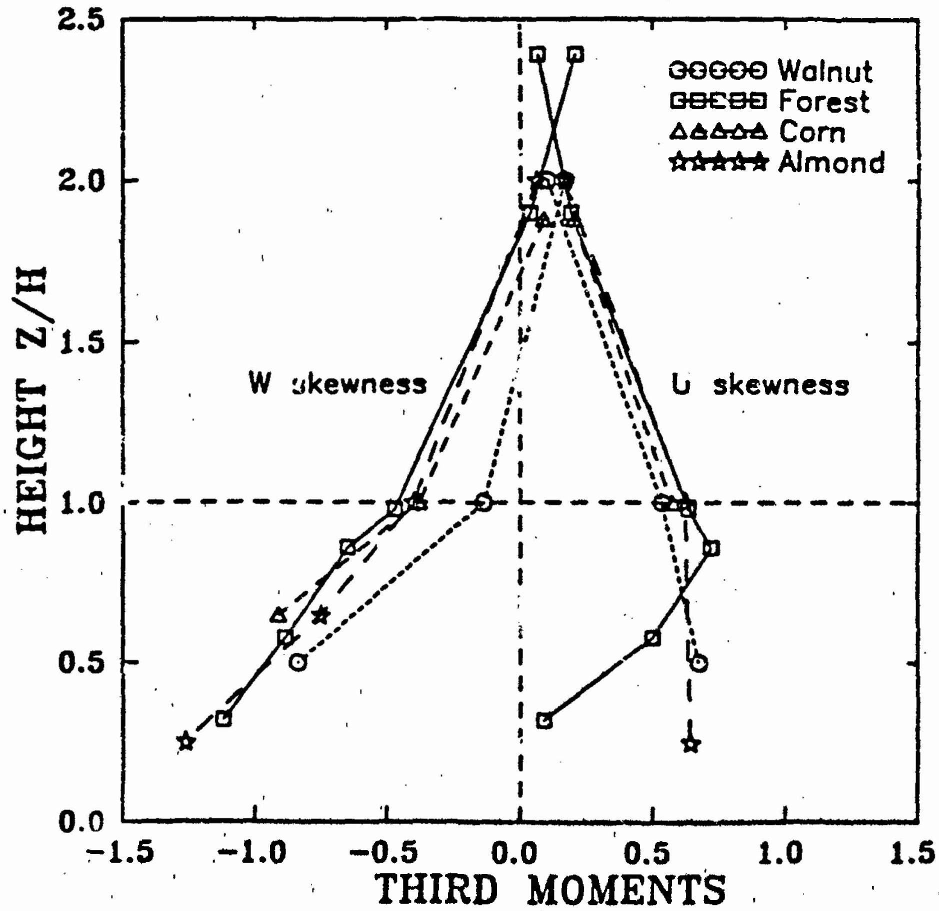

Figure 1. Skewness of longitudinal and vertical velocities within and above four different stands of vegetation.

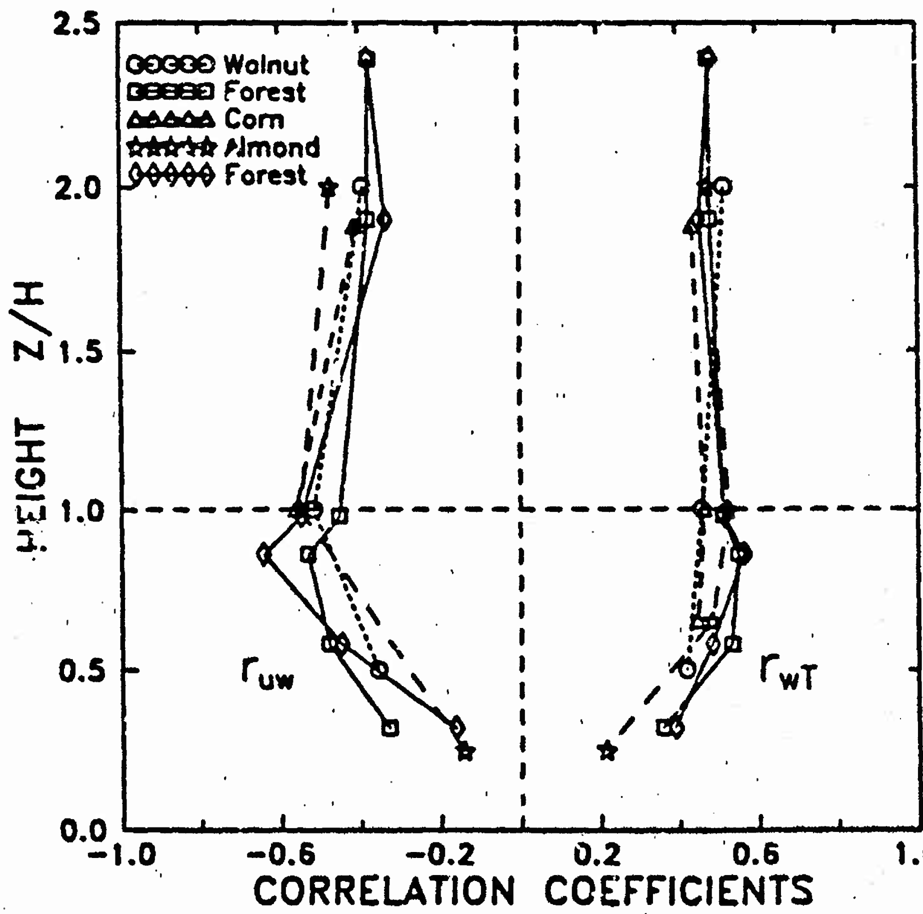

Figure 2. Correlation coefficients for u,w and w,T within and above four different stands of vegetation. The forest data are from two periods with LAI=1.6 (diamonds) and LAI=0.3 (squares).

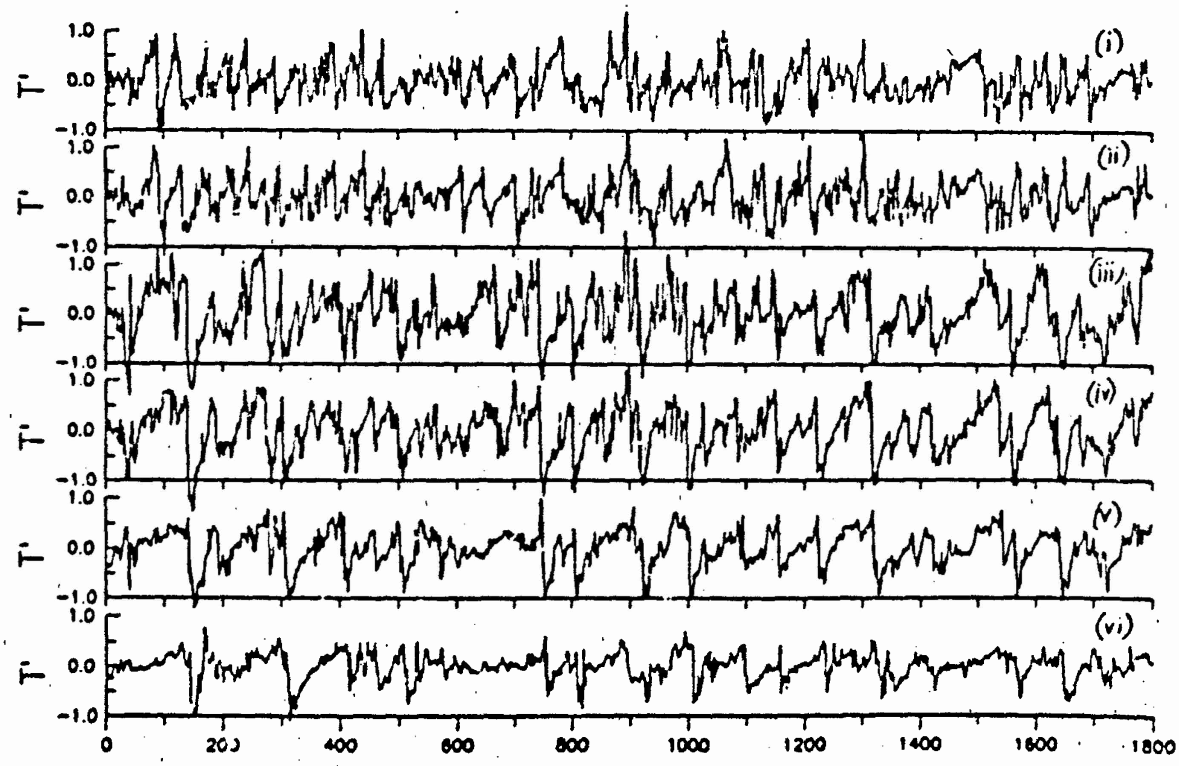

Figure 3a. Traces of temperature fluctuation (°C) from six levels of observation within and above an 18 m tall deciduous forest; (i) z=43 m; (ii) z=34 m; (iii) z=18 m; (iv) z=15 m; (v) z=11 m; (vi) z=6 m.

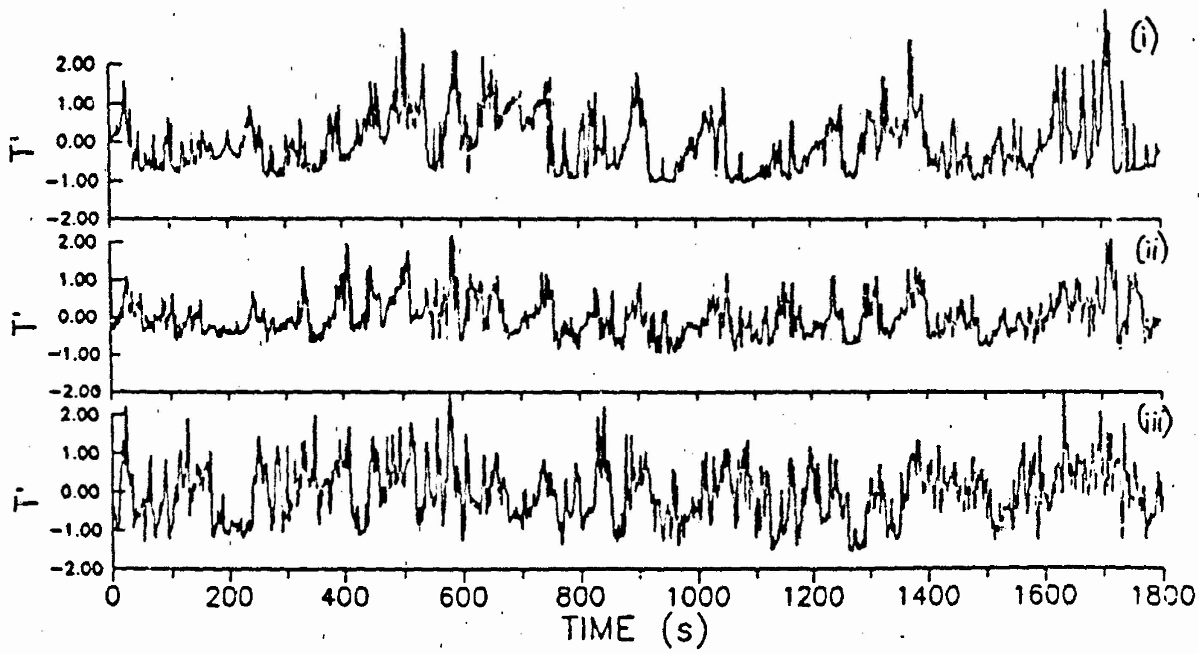

Figure 3b. Traces of temperature fluctuation (°C) from three levels within and above a 6 m tall walnut orchard: (i) z=12 m; (ii) z=6 m; (iii) z=3 m.

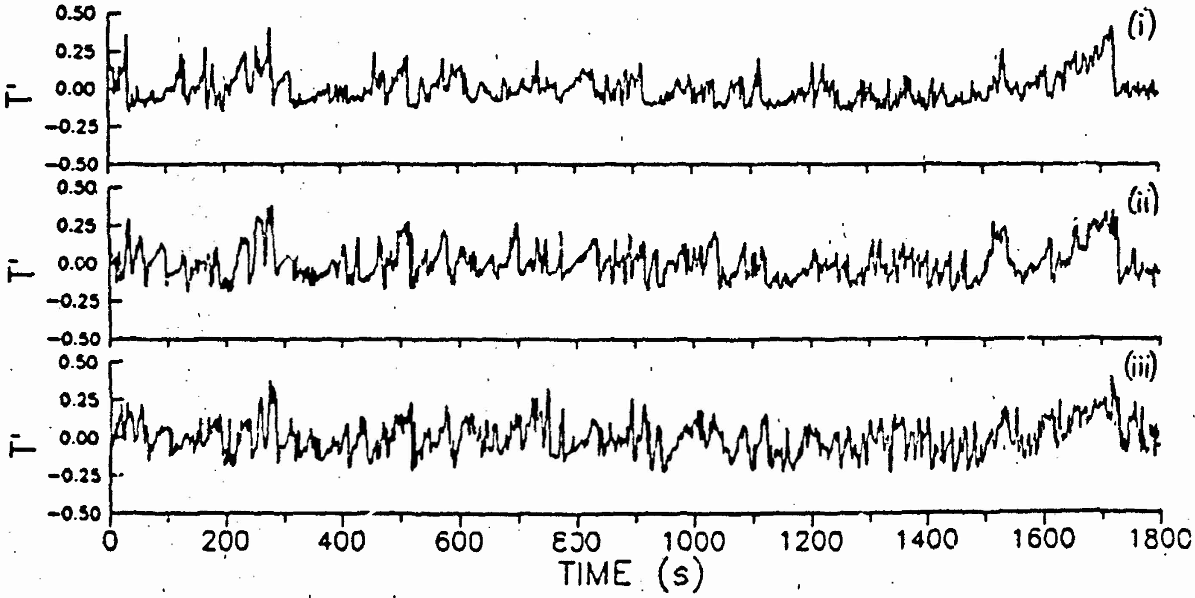

Figure 3c. Traces of temperature fluctuation (°C) from three levels within and above an 8 m tall almond orchard: (i) z=16 m; (ii) z=3 m; (iii) z=2 m.

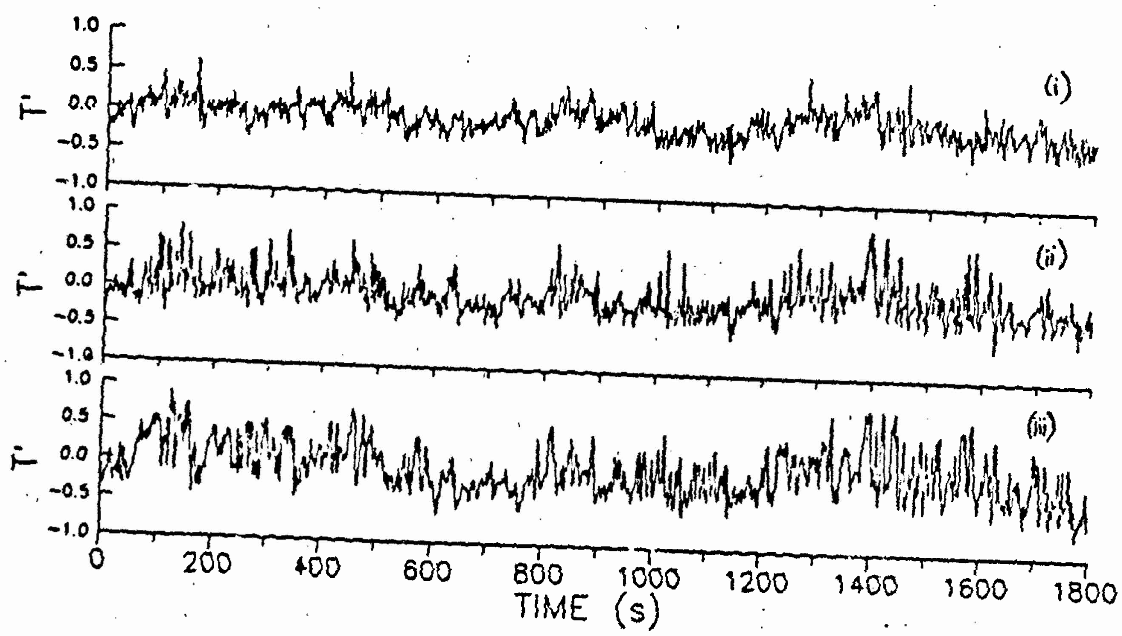

Figure 3d. Traces of temperature fluctuation (°C) from three levels within and above a 2.6 m tall field of maize (i) z=4.9 m; (ii) z=2.6 m; (iii) z=1.7 m.

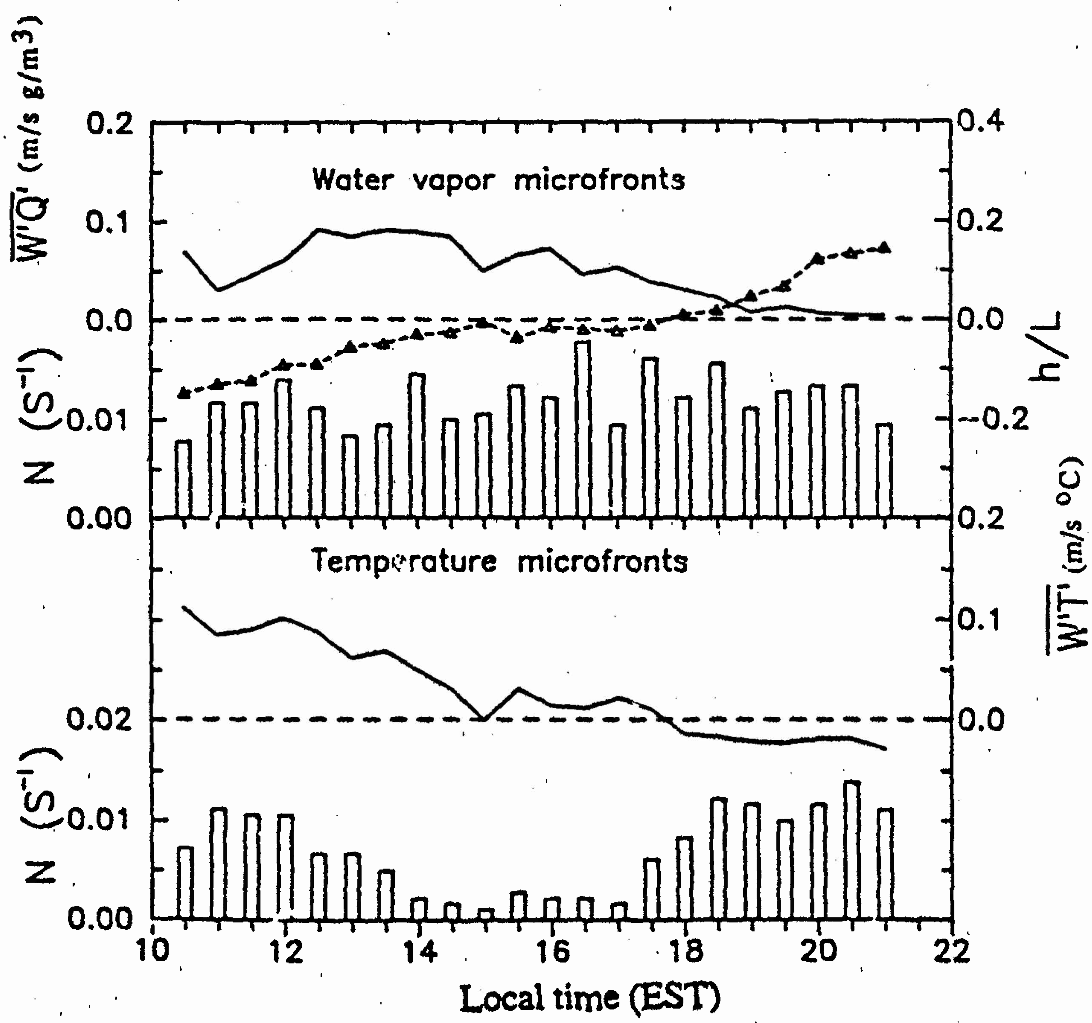

Figure 4. Number of temperature (lower panel) and water vapor (upper panel) microfronts per second in a series of 30-minute runs, using an objective detection scheme. Heat and vapor flux measurements (positive upwards) are shown by the solid lines. The stability parameter h/L is indicated by the dashed line.

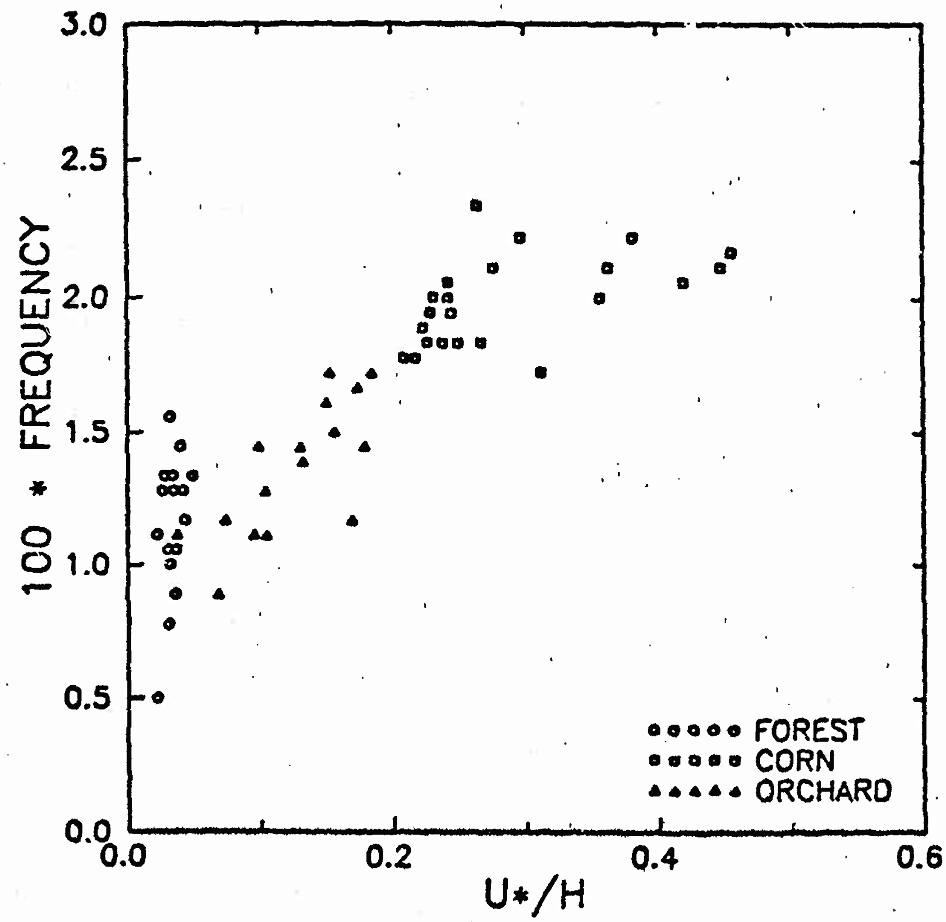

Figure 5. Frequency of ramp occurrence plotted against the ratio of the friction velocity u_* to the canopy height h.

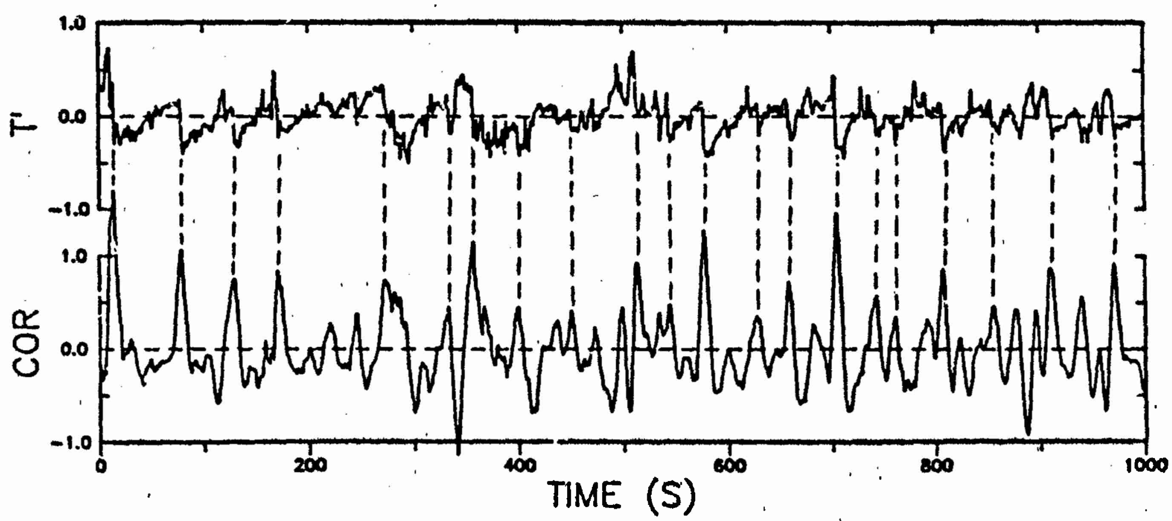

Figure 6. Example of temperature trace from the forest study and the corresponding correlation function.