THE DETECTION AND MEASUREMENT OF TURBULENT STRUCTURES IN THE ATMOSPHERIC SURFACE LAYER

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Abstract. Turbulence data from the planetary boundary layer (PBL) indicate the presence of deterministic turbulent structures. These structures often show up as asymmetric ramp patterns in measurements of the turbulent fluctuations of a scalar quantity in the atmospheric surface layer (ASL). The sign of the slope of the sharp upstream edge of such a triangular pattern depends on the thermal stability conditions of the ASL.

The turbulent structures in the ASL have been tracked by a detection method which searches for rapid and strong fluctuations in a signal – the VITA (variable interval time averaging) technique. This detection method has previously been employed in laboratory boundary layers. The VITA detection method performs well in the ASL and reveals the presence of vertically coherent turbulent structures, which look similar to those in laboratory shear flows. At the moment that a sharp temperature interface appears, the horizontal alongwind velocity shows a sharp increase, along with a sudden decrease of vertical velocity, independent of the thermal stability conditions of the ASL. The fluctuating static pressure reveals a maximum at that moment. The vertical turbulent transports show a twin-peak character around the time that the sharp jumps in the temperature and the velocity signals appear.

1. Introduction

Turbulence has long been described by its statistical properties only, for example its mean, variance, probability distribution, and power spectral density function. A few decades ago, laboratory experiments were performed in order to visualize turbulent flows. The results of these investigations indicated that a turbulent flow contained organized, spatially coherent motions, i.e., structures. These turbulent structures are central to understanding the mechanism of turbulence. They play an important role in the processes of production and transport of turbulence. The transport of mass, momentum and heat in a turbulent boundary layer does not occur continuously. Time intervals appear during which very intensive transport, contained in the structures, takes place, and other time intervals appear during which very little transfer occurs.

Laboratory visualization experiments demonstrated that turbulent structures, on the average, were regularly distributed in the flow field. However, the instantaneous distribution of the structures varied from one instant to another. The laboratory experiments were carried out under well controlled conditions in wind- or water-channels with either aerodynamically smooth or rough boundaries.

The question arises whether the cyclic structures observed in the laboratory also appear in the ASL. Turbulent kinetic energy is produced through the action of the shear stresses present in boundary-layer flows. Therefore, laboratory and atmospheric shear flows, the latter under neutral conditions, can be expected to show common characteristics. It is reasonable to suppose that the structures observed in laboratory shear flows also occur in a neutral ASL. In a non-neutral ASL, buoyancy can act as

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a source or sink of turbulent kinetic energy. In a daytime PBL, the thermally unstable stratification causes convective motions to develop. Thus, it may be expected that during the daytime when the atmosphere is unstable, both shear and buoyancy forces will cause turbulent structures.

In order to find out how turbulent structures behave, they have to be tracked and conditionally sampled. This means that one observes the values of the flow quantities inside the structures. In order to perform such conditional sampling properly, a detection scheme has to be used which unambiguously reveals the presence of turbulent structures. The major trouble with turbulence signals, in general, is that the flow patterns which are to be recovered are buried in background turbulence, which has roughly the same frequency of occurrence and amplitude distribution as these flow patterns.

In Section 2 a description is given of turbulent structures in the ASL, which have been tracked by visual inspection. The results of using the VITA technique to measure turbulent structures in the ASL are discussed in Section 3. In Section 4 some conclusions are finally drawn, and recommendations are made for future research.

Turbulent structures will be defined as spatially coherent, organized flow motions. 'Organized' means that characteristic patterns, observed at a point in space, occur almost simultaneously in more than one turbulence signal and are repeated periodically.

2. The Present Investigation

Turbulence data were gathered at two different sites. One set of data was provided by the Royal Netherlands Meteorological Institute (KNMI). These data were obtained at a meteorological tower of the KNMI, near the village of Cabauw, located in the central river delta of the Netherlands (see Driedonks *et al.*, 1978 for an extensive description). The data consist of turbulence measurements of wind velocities, air temperatures and humidity mixing ratios between heights of 20 and 200 m on August 26 and 27, 1976, and on May 30, 1978 (see Driedonks *et al.*, 1980 for a complete description of this data set).

The other set of data was collected during the spring of 1983 by the author, and members of the Department of Physics and Meteorology of the Agricultural University of Wageningen (LHW). The experiments were performed at the meteorological site of the Minderhoudhoeve near Swifterbant in the Oostelijk-Flevoland poder, which is located in the central part of The Netherlands. These turbulence data contain wind velocities, air temperatures and static pressure fluctuations, measured in the lowest 10 m of the surface layer on April 28, 1983. (A complete description of this measuring program is in preparation.)

Table I contains a general description of the data.

Figure 1a presents a graph of turbulent temperature fluctuations (T') which were measured simultaneously at five different heights during the afternoon of May 30, 1978 (KNMI site). Periods occur during which the fluctuations are vertically coherent as indicated by the horizontal bars. These large-scale patterns appear as above the mean fluctuations. Approaching the surface they become more like skewed ramplike patterns due to the increasing influence of the wind shear. The patterns at lower levels lag the

TABLE I

Description of the data

Run designation of the analyzed data. Values of sampling rate (f_s), the number of samples (N), the Obukhov length (L), lowest inversion height (z_i), measuring height (z), mean wind velocity ($\overline{U}_z$), azimuth angle ($\overline{\phi}_z$), and mean temperature ($\overline{T}_z$) are listed.

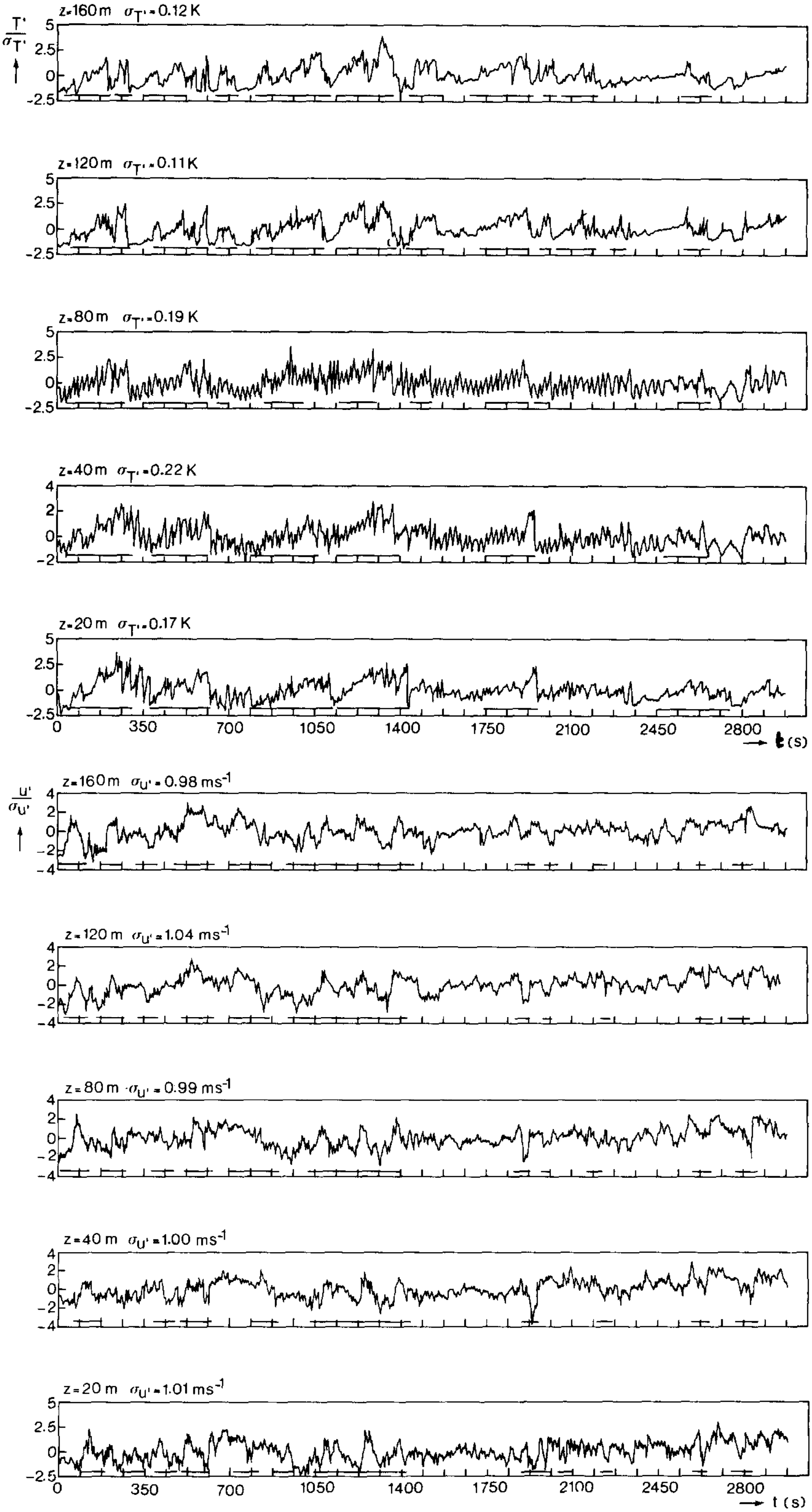
Run	Location	Date	Time (GMT)	f_s (s^{-1})	N	L (m)	z_i (m)	z (m)	$\overline{U}_z$ (m s^{-1})	$\overline{\phi}_z$ (deg)	$\overline{T}_z$ (°C)
KA 26	KNMI-site	8/26/76	1700–1800	2	7150	∞ [a]	1181 [b]	20	5.28	7.7	18.1
KA 27	KNMI-site	8/27/76	1300–1400	2	7150	−600	2238 [b]	20	9.65	16.3	20.6
KM 30	KNMI-site	5/30/78	1420–1510	5	14995	−59	750 [c]	20	3.89	71.3	25.3
								40	4.27	75.4	25.5
								80	4.57	76.6	25.0
								120	4.78	72.8	24.2
								160	5.05	80.5	24.0
								200	5.35	85.9	23.5
LA 28	LH-site	4/28/83	1509–1520	12.5	8275	−422	880 [b]	3.56	5.8	217	11.7
								9.56	6.7	217 [d]	11.4

[a] ∞ means $|L| > 5000$ m, where $L = \dfrac{-u_*^3}{kg\,\overline{W'T'}/\overline{T}}$.

[b] Estimated from $z_i \simeq 0.25\, u_*/1.1{*}10^{-4}$ (see Tennekes, 1970).

[c] Measured at 1115 GMT (see Driedonks, 1981).

[d] Estimated from value at other height.


z=160m σT'=0.12 K
z=120m σT'=0.11K
z=80m σT'=0.19 K
z=40m σT'=0.22 K
z=20m σT'=0.17 K
T'/σT'
u'/σu'
z=160m σu'=0.98 ms-1
z=120m σu'=1.04 ms-1
z=80m σu'=0.99 ms-1
z=40m σu'=1.00 ms-1
z=20m σu'=1.01 ms-1
0
350
700
1050
1400
1750
2100
2450
2800
t (s)

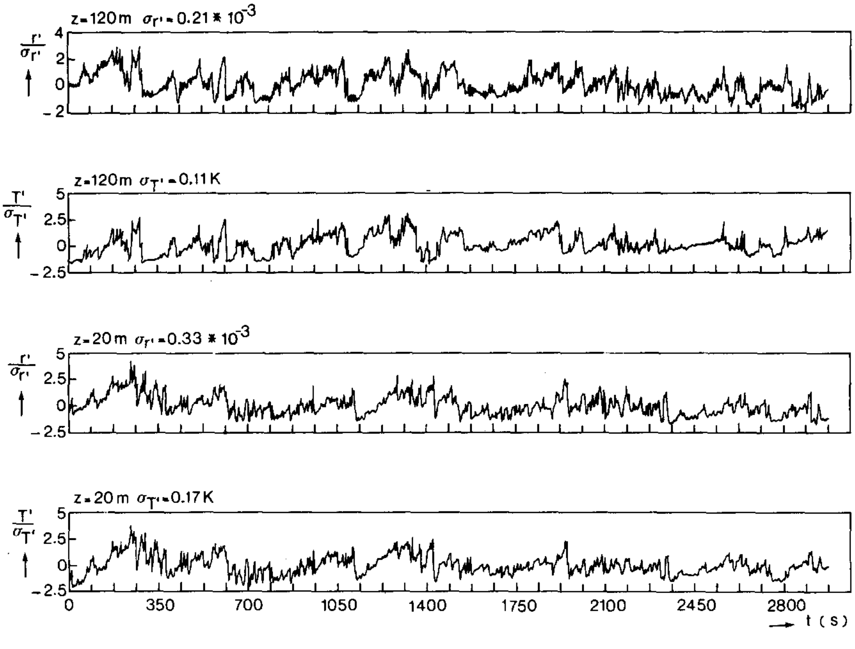


Fig. 1. Simultaneous measurements of turbulent temperature fluctuations (T'), fluctuations of horizontal velocity in the forward direction (u'), and variations of mixing ratio (r') at different heights. Data are normalized by their standard deviation (σ), and are from Run KM 30.

higher ones, indicating that the patterns are tilted in the direction of the mean wind.

The alongwind velocity fluctuations (u') presented in Figure 1b also show vertically coherent flow patterns. They are, however, less prominent than in the temperature records. The periods during which both velocity and temperature traces show vertical coherence roughly agree with each other. During these periods the flow contains turbulent structures, which modulate both velocity and temperature fluctuations.

Turbulent fluctuations of the mixing ratio (r') and temperature (T'), both being scalar quantities, behave identically as indicators of the large-scale structures. This is shown in Figure 1c.

Figure 2 shows another set of turbulence data, measured around noon on August 27 at 20 m height (KNMI site). The ramp patterns (indicated by horizontal bars) in the temperature trace appear on a variety of scales. They are often accompanied, at their upstream ends, by high values of vertical turbulent transport, which fluctuate intermittently throughout the entire length of the observation. A necessary condition, in order to infer that large-scale transport occur, is that the turbulent velocities and temperatures show large departures from their zero means simultaneously. Figure 2 shows that this also happens during intervals when no distinct asymmetric ramp pattern is visible in the temperature record, but when the temperature trace shows a 'top hat' shape (indicated by chained bars). Within these intervals, the transport is not concentrated at the upstream end, but is more evenly distributed along the time intervals. At one interval

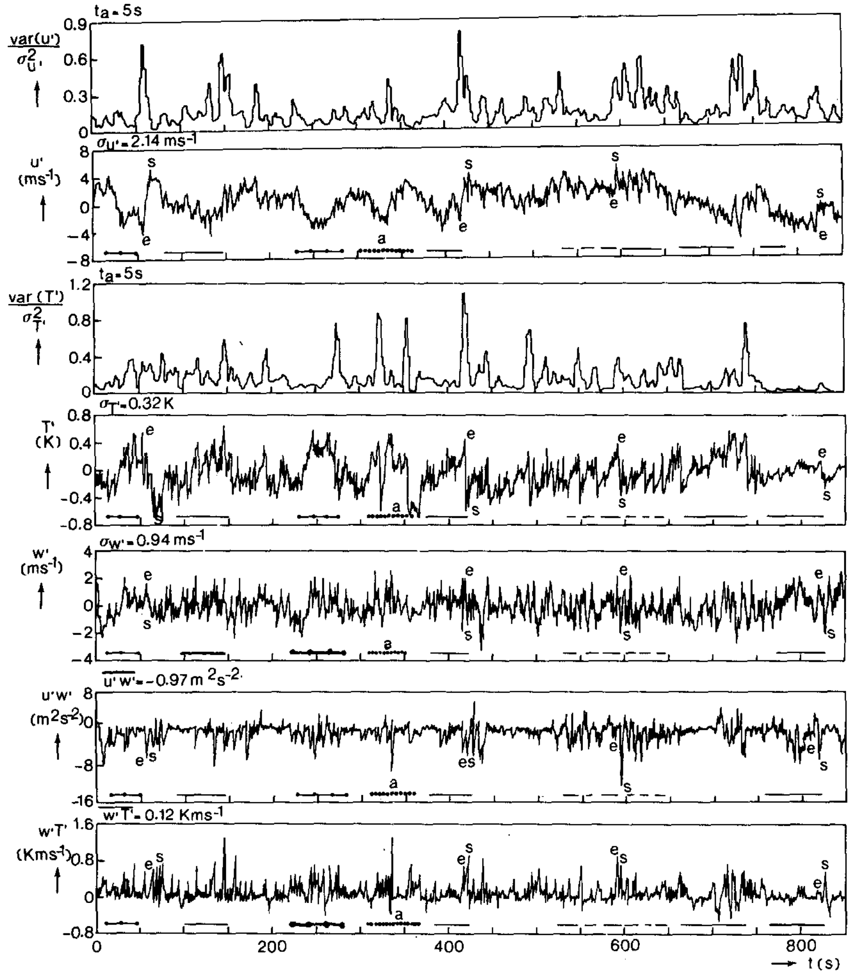


Fig. 2. Turbulent fluctuations of horizontal velocity in the forward direction (u'), vertical velocity (w'), and temperature (T'), and instantaneous turbulent kinematic vertical transports of horizontal windwise momentum ($u'w'$) and heat ($w'T'$). Long-time averages are denoted by a horizontal bar above a quantity. The normalized short-time variance signals of temperature and horizontal velocity in the forward direction are also presented (Run KA 27).

(indicated by a dotted line denoted with an '*a*'), a ramp pattern is captured inside a 'top hat' pattern.

The turbulent transport often shows a double peaked character (denoted by symbols '*e*' and '*s*') at the upstream interface of a temperature ramp. Such behavior of the $u'w'$-crossproduct has also been observed in the laboratory (Blackwelder and Kaplan, 1976, p. 107; Subramanian *et al.*, 1982, p. 354), and is called a 'burst event'. It has been explained as a sweep ('*s*') following an ejection ('*e*') inside a turbulent structure. A laboratory turbulent structure consists of four phases. First, fluid near the wall boundary is retarded and lifted, and a layer of low speed fluid (streak) builds up. Second, oncoming fluid from upstream, having a higher speed, causes a shear layer between itself and the low speed wall fluid. Third, increasing shear causes a sudden break-up of the wall streak during which violent ejection of the wall fluid takes place (bursting). Finally, the wall streak is quickly replaced by high-speed fluid (sweep) from the outer region of the boundary layer. The whole cycle then repeats.

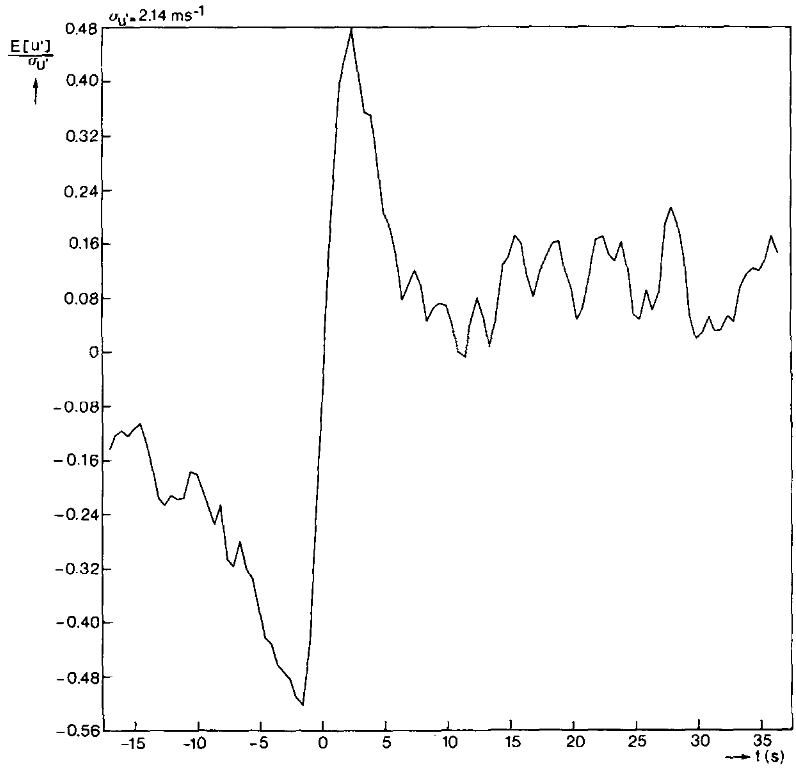
From the foregoing results, it may be deduced that the PBL contains turbulent structures which penetrate into the ASL where they modulate both velocity and temperature traces and show characteristics which are common to turbulent structures in the laboratory shear layer. The asymmetric ramp patterns in the temperature signals tracked by visual inspection in the ASL correspond to those observed by several other investigators (Taylor, 1958; Kaimal and Businger, 1970; Antonia *et al.*, 1979; Phong-Anant *et al.*, 1980). They have also been observed in laboratory shear flows (Chen and Blackwelder, 1978).

3. Results of the Use of the VITA Detection Technique to Measure Turbulent Structures in the Atmospheric Surface Layer

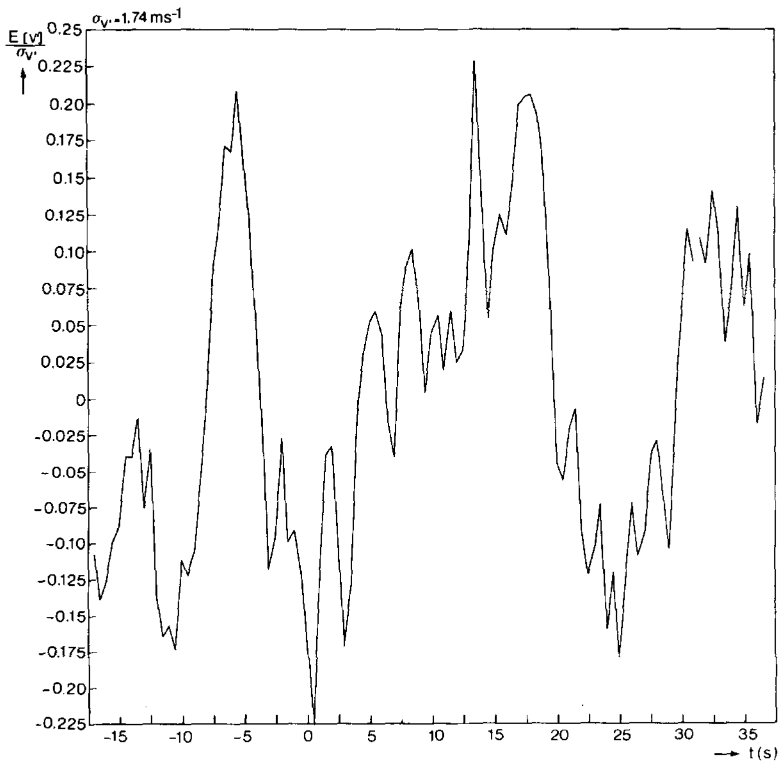
To track the turbulent structures in the ASL in an objective way, one has to look for one or more features characteristic of a turbulent structure which uniquely reveals its presence in the background turbulence. In Section 2 it was shown that most of the turbulent intensity is contained inside turbulent structures, which often manifest as asymmetric triangular shapes with a sharp upstream interface in the temperature records in the ASL. It seems straightforward, therefore, to check for rapid and strong fluctuations in a single turbulence signal. When this is done, using the VITA detection technique with the present data, the results reveal the features that are generally accepted for the description of the turbulent structures.

The VITA technique is based on a very simple flow concept and thus is easily applied. Subramanian *et al.* (1982) have shown that of various one-point detection schemes, the VITA method correlates best with a visual detection technique for coherent structures, based on examination of simultaneous temperature traces from a rake of cold wires inside a laboratory boundary layer. The VITA detection technique was first introduced by Kaplan and Laufer (1968) in order to study the structure associated with the motion of the turbulent/non-turbulent interface in the outer part of a laboratory boundary layer. The VITA method has been used here with minor modifications (cf. Chen and Blackwelder, 1978). The detection scheme computes a short-time variance signal, normalized by the long-time variance. When the normalized short-time variance exceeds some specified threshold level (k), and the slope of the short-time averaged fluctuations satisfies an additional criterion, an 'event' is said to occur. The normalized short-time variance signal, as also presented in Figure 2, is defined as

$$\frac{\mathrm{var}(d')}{\sigma_{d'}^2} = \frac{1}{\sigma_{d'}^2}\left\{\frac{1}{t_a}\int_{t-\frac{1}{2}ta}^{t+\frac{1}{2}ta} d'^2\,\mathrm{d}s - \left(\frac{1}{t_a}\int_{t-\frac{1}{2}ta}^{t+\frac{1}{2}ta} d'\,\mathrm{d}s\right)^2\right\}.$$



$\sigma_{u'} = 2.14\ ms^{-1}$
$\frac{E[u']}{\sigma_{u'}}$
0.48
0.40
0.32
0.24
0.16
0.08
0
-0.08
-0.16
-0.24
-0.32
-0.40
-0.48
-0.56
-15 -10 -5 0 5 10 15 20 25 30 35
t (s)



$\sigma_{v'} = 1.74\ ms^{-1}$
$\frac{E[v']}{\sigma_{v'}}$
0.25
0.225
0.20
0.175
0.15
0.125
0.10
0.075
0.05
0.025
0
-0.025
-0.05
-0.075
-0.10
-0.125
-0.15
-0.175
-0.20
-0.225
-15 -10 -5 0 5 10 15 20 25 30 35
t (s)

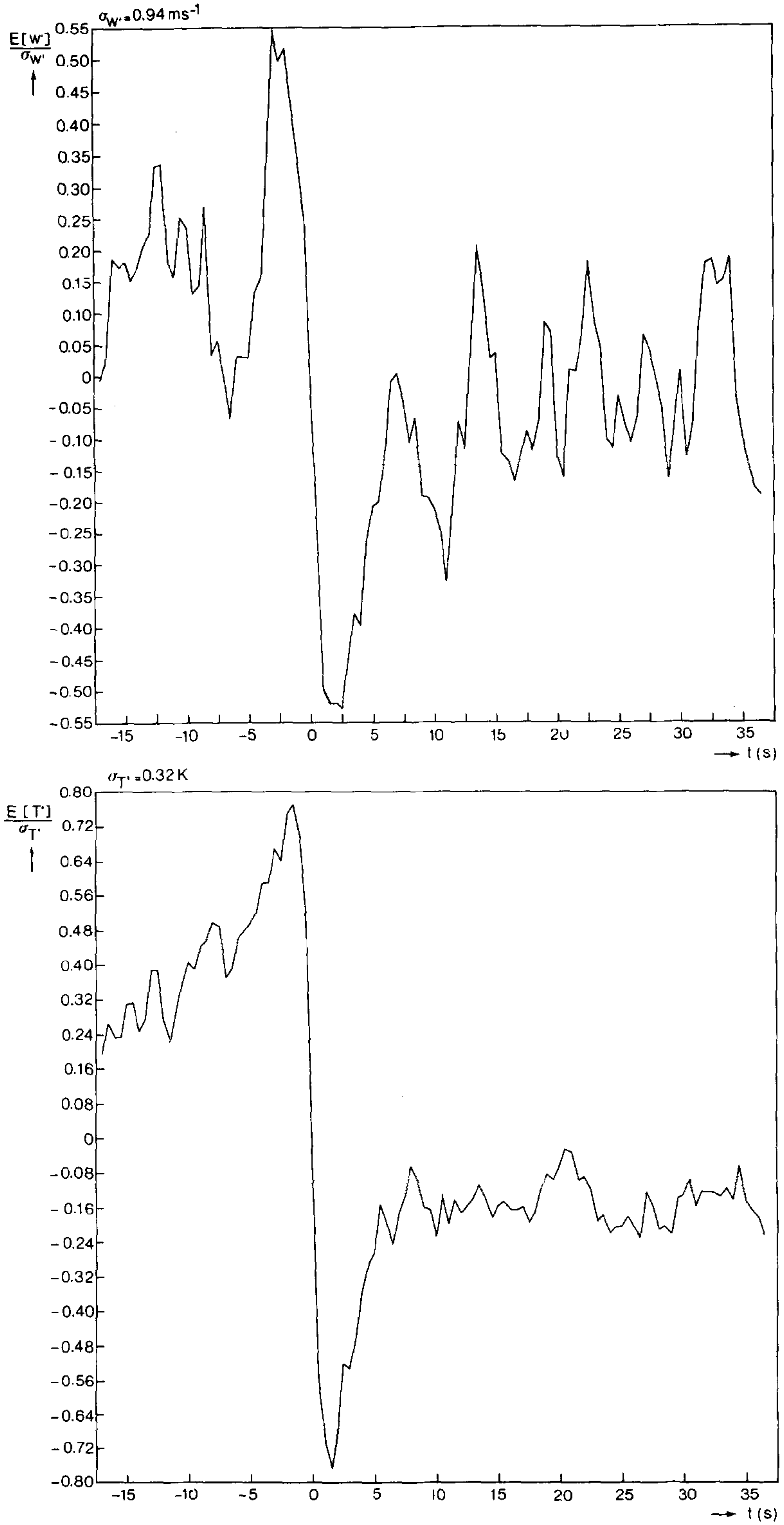


Fig. 3. Conditional averages of u', v', w', and T' turbulent signals from Run KA 27. The temperature has been used as detection signal, while the slope criterion is negative $t_a = 5$ s, $k = 0.4$, $n = 56$.

The averaging procedure acts roughly as a low-pass filter, accepting frequencies below $1/t_a$, where t_a denotes the length of the short averaging time. d' stands for the fluctuating turbulent detection signal and $\sigma^2_{d'}$ denotes its long-time variance.

A significant property of the VITA method is that it acts as a bandpass filter which passes time scales of the order of t_a. Johansson and Alfredsson (1982), found that the VITA method picks out those 'events' with a time scale of about $1.3t_a$, where the time scale of an 'event' is taken as twice the width of the sharp fluctuation which has been detected.

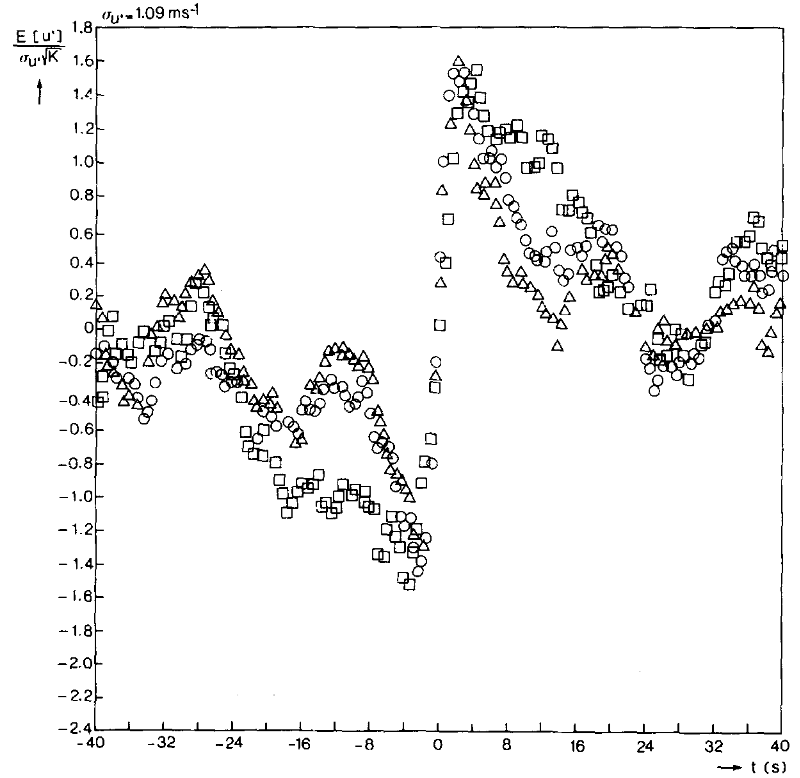
In an unstably stratified ASL (such as the KNMI data presented thus far), the temperature is used as a detection signal, since its signal-to-noise ratio is larger than that of the velocity signal, viz., the ramp patterns possess a markedly higher temperature than outside. The slope criterion is chosen negative with respect to time, since the ramps are marked by an abrupt decrease in temperature at their upstream end.

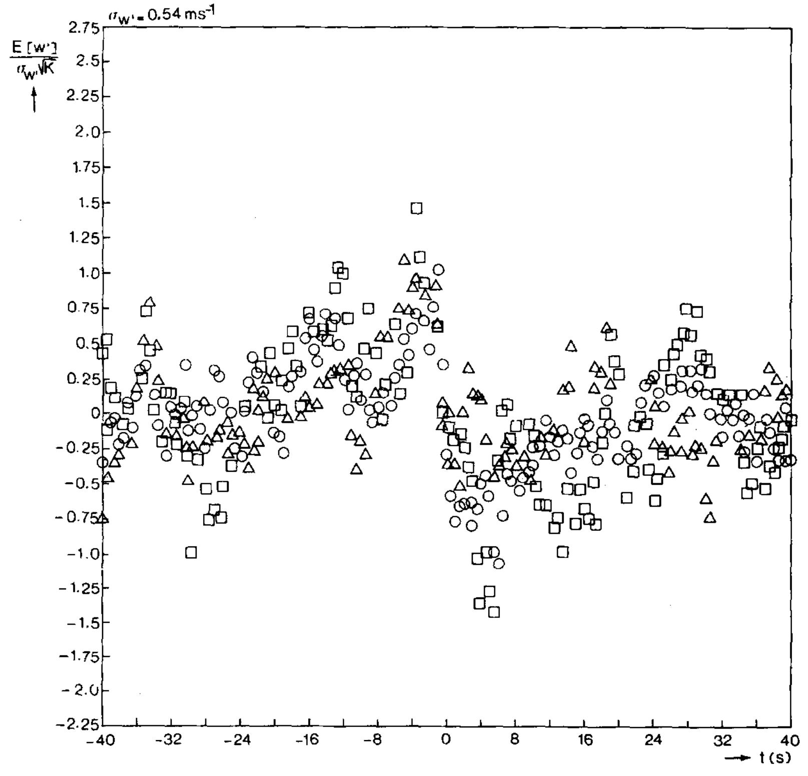
Figure 3 presents some conditional averages ($E[f']$), which are basically ensemble-averaged turbulence signals (f') around the time that a detection occurs. In Figure 4, ensemble averages are shown of turbulence data which were measured in a slightly stable ASL (during the evening of August 26 on the KNMI site). This is indicated by the inverted ramp patterns in the conditionally averaged temperature signal (cf. Figure 4c). The detection signal was defined as the horizontal alongwind velocity fluctuation, and not the temperature, because the signal-to-noise ratio for the velocity signal was higher than for the temperature signal. The slope criterion was chosen positive with respect to time, since the 'events' appeared to be marked by a sharp acceleration of the u' velocity. Van Maanen and Fortuin (1983) used a similar detection criterion in a turbulent pipe flow.

From the definition of the short-time variance and the threshold level, it can be inferred that the mean amplitude of the detected 'events' is proportional to the square root of the threshold level. The ensemble averages in Figure 4, which are normalized by $\sigma_{f'}\sqrt{k}$ confirm this suggestion. The virtual collapse of the ensemble-averaged data into a single curve indicates that the variation of the threshold level only affects the magnitude and not the character of the detected 'events'. Such a picture was also found in the laboratory (Blackwelder and Kaplan, 1976, p. 111; Johansson and Alfredsson, 1982, pp. 307 and 309).

During an average 'event', the horizontal velocity in the forward direction (u') shows a rapid increase, after a slow decrease. The vertical velocity (w') shows a fast decrease, after an increase. The general shapes of both patterns, as shown in Figure 3 and 4, are independent of the thermal stability conditions in the ASL. The conditionally averaged horizontal crosswind velocity fluctuations (v') show no particular pattern during an 'event' (cf. Figure 3b).

Around the so-called reference time ($t = 0$), i.e., the time that the sharp jumps in the various turbulent signals occur, the ensemble averaged $u'w'$ cross product ($E[u'w']$) displays a twin-peak character, as illustrated in Figure 5a. The conditionally averaged turbulent vertical kinematic heat flux ($E[w'T']$) shows a double peaked character around $t = 0$ as well (cf. Figure 5b). However, for the slightly stable ASL data, this


$\sigma_{u'} = 1.09\ ms^{-1}$
$\frac{E[u']}{\sigma_{u'}\sqrt{K}}$
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-1.4
-1.6
-1.8
-2.0
-2.2
-2.4
-40
-32
-24
-16
-8
0
8
16
24
32
40
t (s)


$\sigma_{w'} = 0.54\ ms^{-1}$
$\frac{E[w']}{\sigma_{w'}\sqrt{K}}$
2.75
2.5
2.25
2.0
1.75
1.5
1.25
1.0
0.75
0.5
0.25
0
-0.25
-0.5
-0.75
-1.0
-1.25
-1.5
-1.75
-2.0
-2.25
-40
-32
-24
-16
-8
0
8
16
24
32
40
t (s)

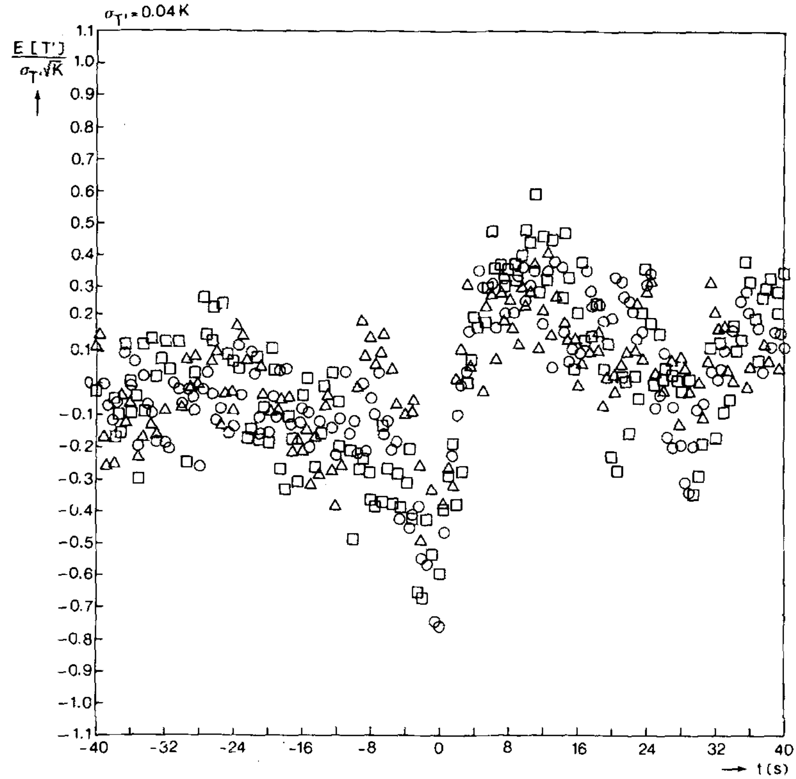


Fig. 4. Conditional averages of u', w', and T' turbulent signals, normalized by the square root of the threshold level (k). The short averaging time t_a is taken as 5 s. The horizontal alongwind velocity signal is taken as detection signal, while the slope criterion is taken to be positive (Run KA 26). (□) $k = 0.1, n = 61$; (△) $k = 0.3, n = 47$; (○) $k = 0.5, n = 22$.

behavior is less apparent. This may be due to the near neutral character of the ASL, in which the average turbulent heat flux has a very small negative magnitude, and is mainly determined by small-scale fluctuations.

In Figure 6 a series of turbulent signals, measured late in the afternoon of April 28, 1983 (LHW site) is presented. The graphs show turbulent velocities, temperatures and static pressure fluctuations (p') measured at 3.56 and 9.56 m heights. The static pressure fluctuations were measured with a probe designed by Elliott (1972) and built by members of the Department of Physics and Meteorology of the LHW. (A complete description of the pressure probe is in preparation.) The VITA technique has been applied to these unstable ASL data. The resulting conditional averages are shown in Figure 7. These ensemble averages reflect the properties that are accepted for the recognition of turbulent structures: the coherent temperature ramp patterns at the two levels, and the presence of characteristic patterns in the alongwind horizontal velocity fluctuations and the vertical turbulent velocity. The phase shift between the temperature interfaces at the two height levels (cf. Figure 7a and b) indicates that the ensemble-averaged turbulent structure is inclined to the surface.

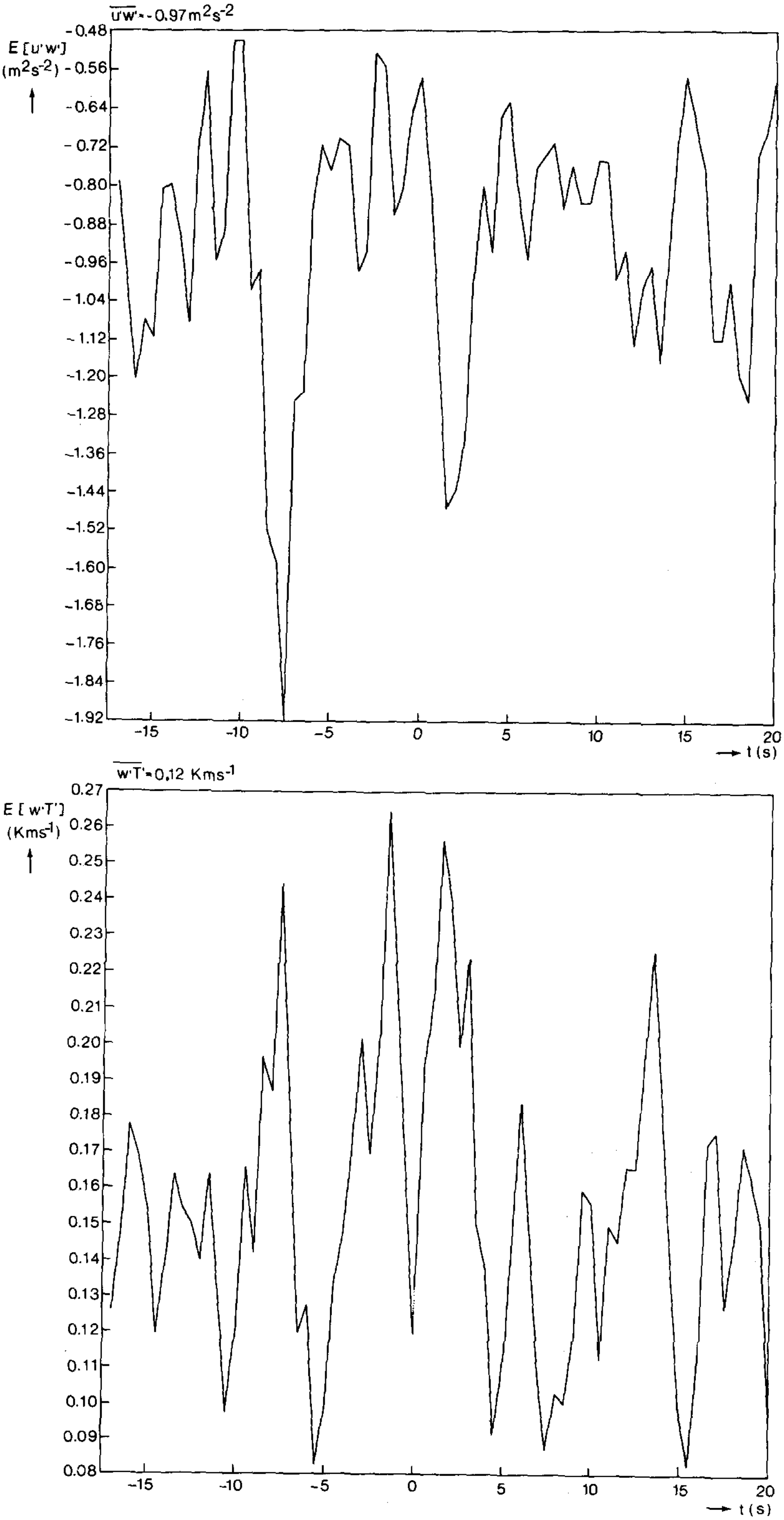


Fig. 5. Conditional averages of the turbulent kinematic vertical transports $u'w'$ and $w'T'$ for the data from Run KA 27. $t_a = 5$ s, $k = 0.4$, $n = 56$.

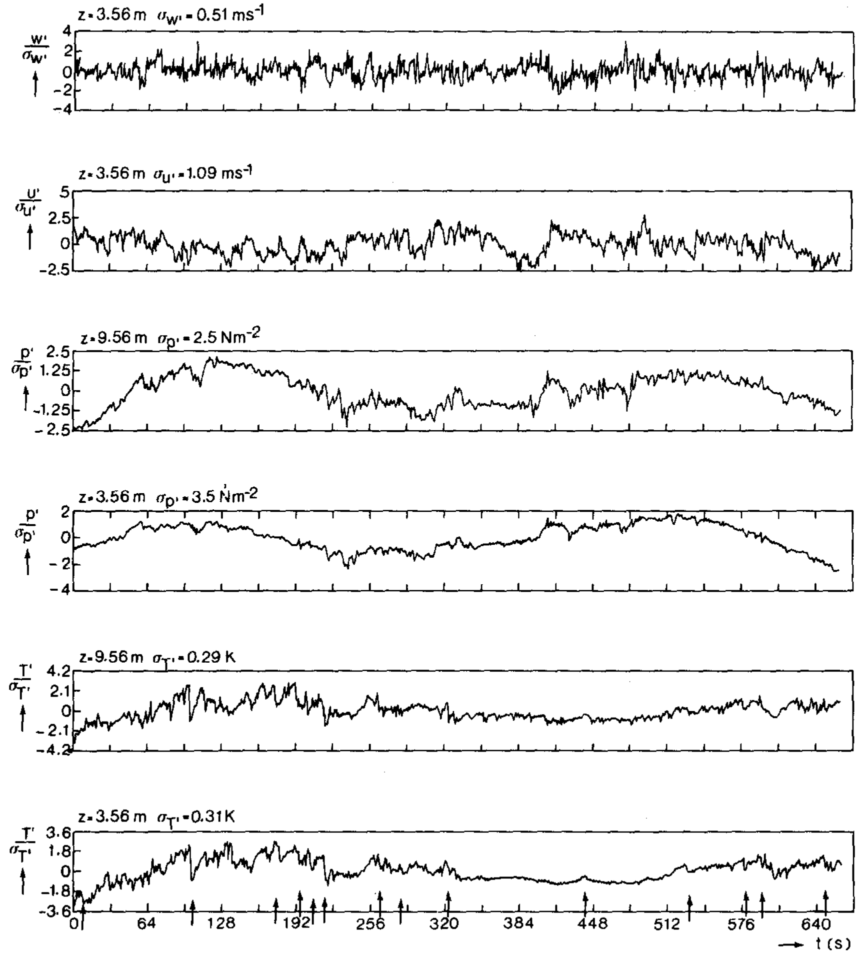
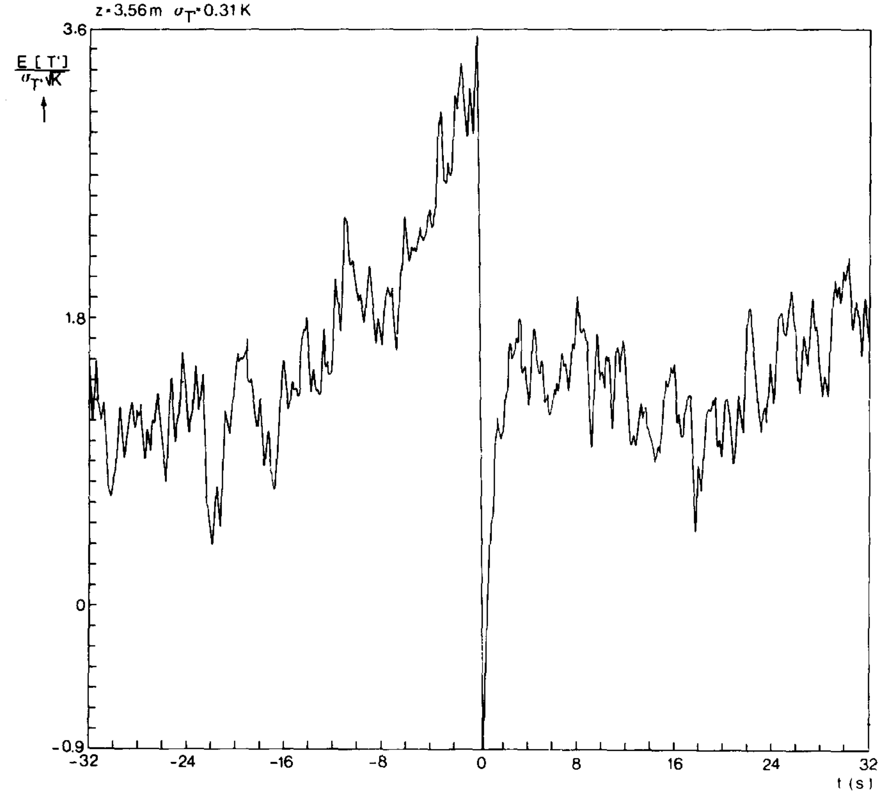
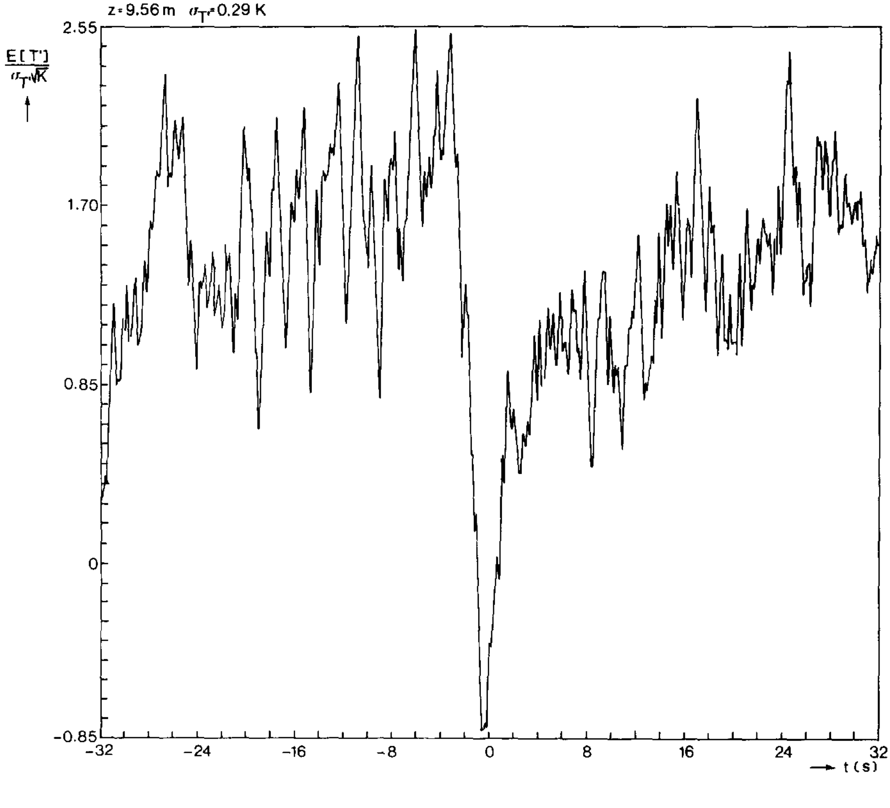


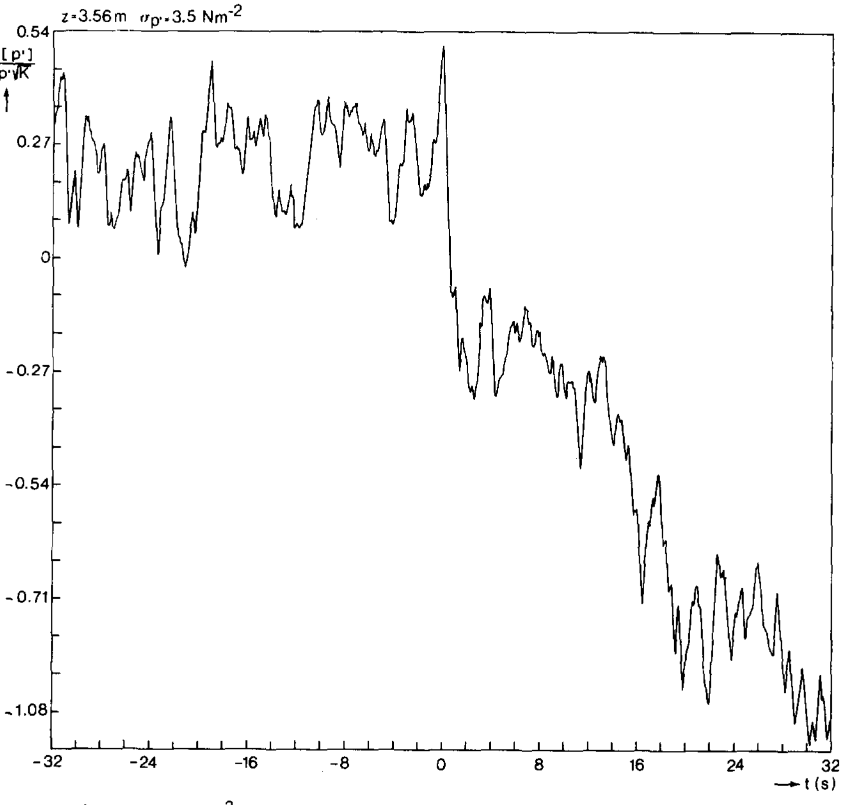
Fig. 6. Simultaneous records of turbulent fluctuating signals measured on the LHW site (Run LA 28) at heights (z) of 3.56 and 9.56 m. The data have been smoothed by a moving average over 11 points.

The patterns in the static pressure fluctuations around $t = 0$ (cf. Figures 7c and d) resemble those described by Thomas and Bull (1983), who measured wall pressure variations in a laboratory boundary layer. The vertically coherent pressure patterns are maximum at the sharp interface of the turbulent structure, which may be identified with the 'burst event' in a laboratory shear layer.

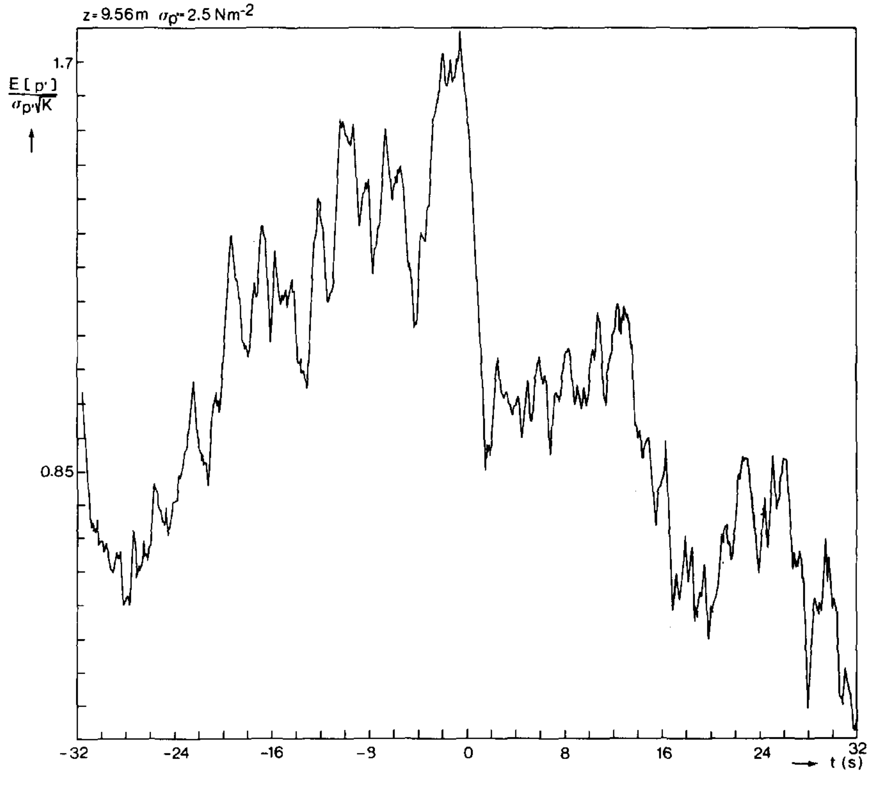
The conditionally averaged quantity $u'w'$ (cf. Figure 7g) is higher than average around $t = 0$. Near $t = 0$ it is close to zero, but it does not show a twin-peak behavior as pronounced as in the KNMI data. On the one hand, this may be due to the phase-shift error caused by the spatial separation of the sonic anemometer sensors, used to measure the velocity components. On the other hand, these data show many high-frequency fluctuations, which disturb the large-scale patterns characteristic of turbulent structures. The turbulent vertical kinematic heat flux is also poorly determined because of its small magnitude.


z = 3.56 m σ_T = 0.31 K
$\frac{E[T']}{\sigma_T \cdot \sqrt{K}}$
3.6
1.8
0
-0.9
-32
-24
-16
-8
0
8
16
24
32
t (s)

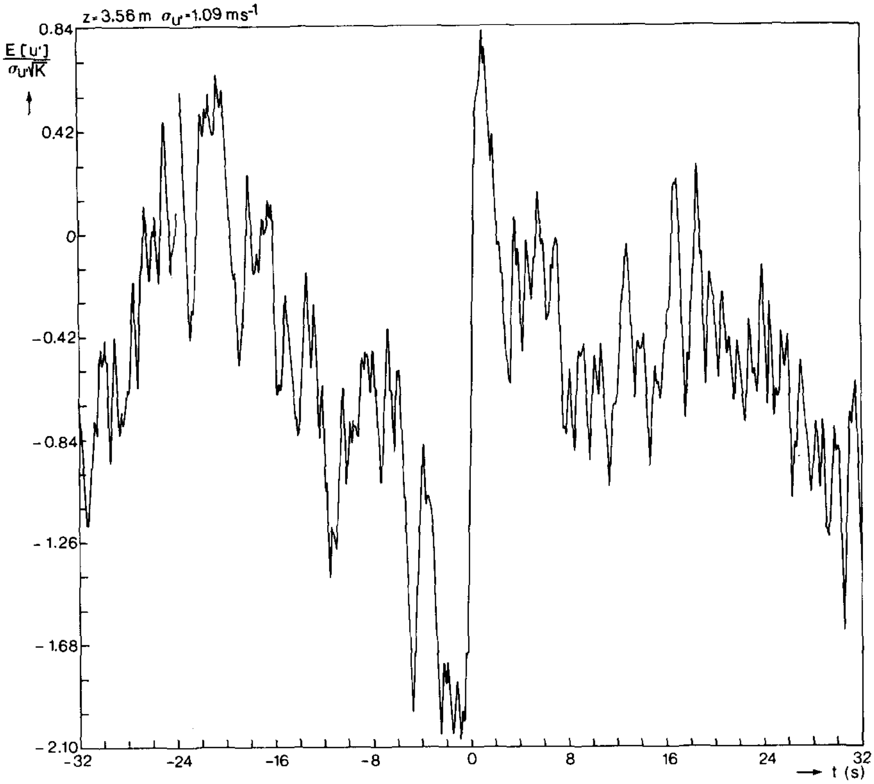

z = 9.56 m σ_T = 0.29 K
$\frac{E[T']}{\sigma_T \cdot \sqrt{K}}$
2.55
1.70
0.85
0
-0.85
-32
-24
-16
-8
0
8
16
24
32
t (s)

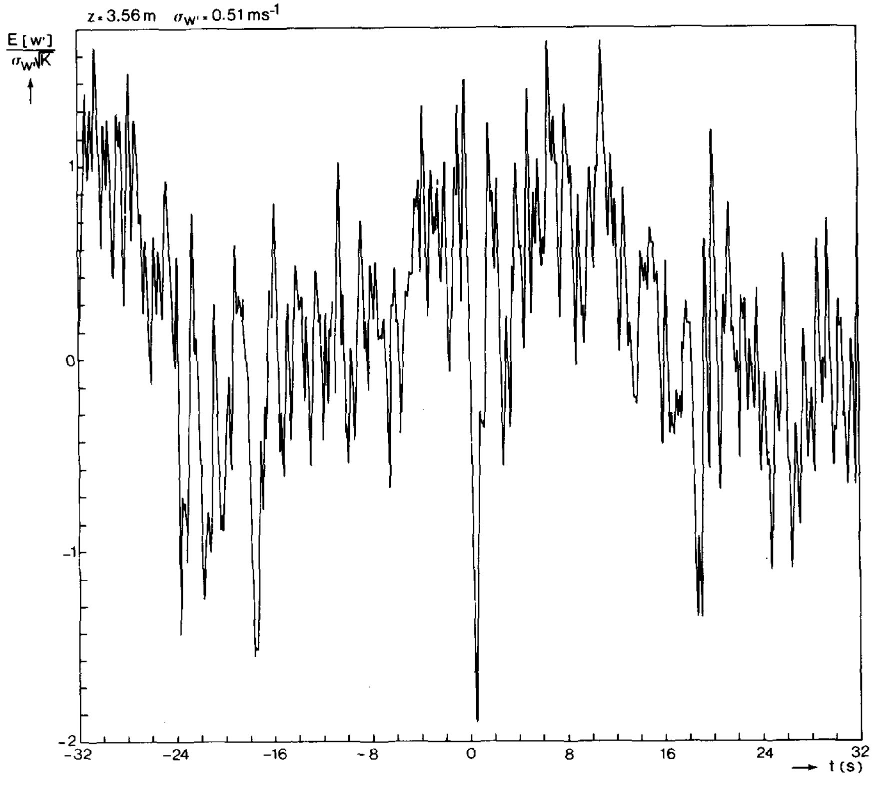


z = 3.56 m $\sigma_{p'}$ = 3.5 Nm^{-2}
0.54
$\frac{E[p']}{\sigma_{p'}\sqrt{K}}$
0.27
0
-0.27
-0.54
-0.71
-1.08
-32
-24
-16
-8
0
8
16
24
32
t (s)



z = 9.56 m $\sigma_{p'}$ = 2.5 Nm^{-2}
1.7
$\frac{E[p']}{\sigma_{p'}\sqrt{K}}$
0.85
-32
-24
-16
-3
0
8
16
24
32
t (s)


z = 3.56 m σu' = 1.09 ms⁻¹
E [u'] / σu' √K
0.84
0.42
0
-0.42
-0.84
-1.26
-1.68
-2.10
-32
-24
-16
-8
0
8
16
24
32
t (s)


z = 3.56 m σw' = 0.51 ms⁻¹
E [w'] / σw' √K
1
0
-1
-2
-32
-24
-16
-8
0
8
16
24
32
t (s)

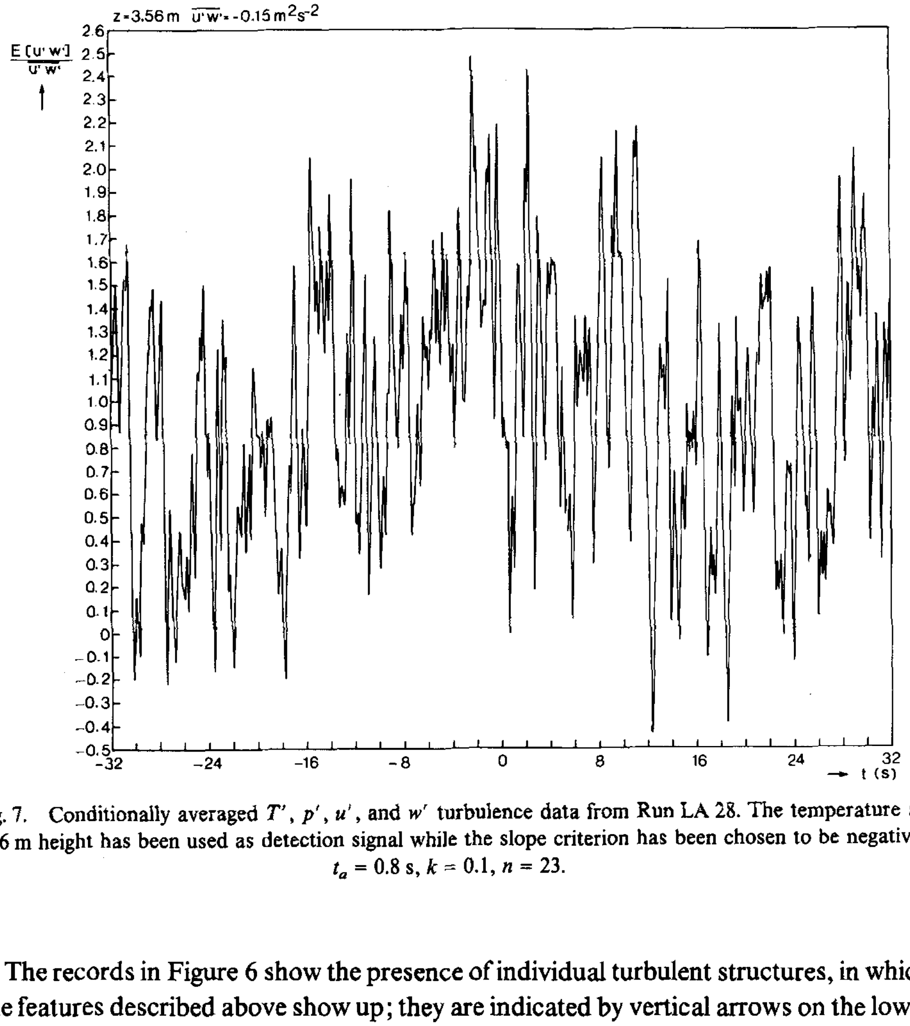


Fig. 7. Conditionally averaged T', p', u', and w' turbulence data from Run LA 28. The temperature at 3.56 m height has been used as detection signal while the slope criterion has been chosen to be negative. $t_a = 0.8$ s, $k = 0.1$, $n = 23$.

The records in Figure 6 show the presence of individual turbulent structures, in which the features described above show up; they are indicated by vertical arrows on the lower axis.

The performance of the VITA detection technique is satisfactory, when applied to ASL turbulence data. The qualitative behavior of the conditional averages, using this method, is not sensitive to the selection of the detection parameters, i.e., threshold level and short averaging time.

4. Conclusions

Results of conditional averaging of turbulence data from the atmospheric surface layer (ASL) clearly indicate a deterministic flow behavior in which turbulent structures are present. In the time traces of a scalar quantity, such as the temperature or mixing ratio, these structures are manifest often as asymmetric triangular shapes with a sharp upstream edge. The sign of the slope of that interface depends on the thermal stability conditions of the atmospheric boundary layer.

The turbulent structures are objectively detected by means of the VITA detection technique, which looks for rapid and strong fluctuations in a single turbulent signal at one point in space. The detected 'events' show, at the moment that the sharp temperature interface occurs, a sudden increase of the horizontal velocity in the forward direction, along with a sudden decrease of the vertical velocity, independent of the thermal stability conditions of the ASL. This is indicative of the presence of a so-called internal shear layer, as has already been observed at the upstream edge of turbulent structures in laboratory shear flows (cf. Chen and Blackwelder, 1978). Furthermore, this dynamic flow behavior has already been observed in the ASL by Phong-Anant *et al.* (1980) who selected the turbulent structures by visual inspection.

At the moment – the reference time – that the sharp temperature interface appears, the fluctuating static pressure shows a maximum. This organization is also tracked in the conditionally averaged turbulent shear stress, which shows a twin-peak character around the reference time. Such a double-peaked character has already been observed in laboratory flows, and has been explained as a sweep following an ejection inside a turbulent structure. The ensemble-averaged $w'T'$ signal shows a similar behavior, also being relatively small at reference time and relatively large just before and just after it. The turbulent structures contain much of the turbulent intensity. The Kansas experiments of 1968 (Haugen *et al.*, 1971) showed that the largest contributions to the turbulent transports in the ASL were governed by vertically coherent turbulent structures.

The present turbulence data set are being used to study the relationship of turbulent structures to their environment, such as translation velocity, inclination angle to the surface, spatial distribution and temporal behavior. The results, together with quantitative data on the contribution of turbulent structures to the turbulent transport processes, will be presented in a forthcoming paper. An interesting aspect to be studied is to find, if possible, some links between the scaling of turbulent structures in the laboratory and in the ASL. The exact role of static pressure fluctuations inside the turbulent structures in the ASL has to be resolved in order to understand the mechanism of the origin and development of structures.

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