

Vertical and Horizontal Spatial Coherence of Temperature Fluctuations in the Atmospheric Surface Layer

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SUMMARY The temperature signature of the organised large scale motion in the atmospheric surface layer remains coherent and of approximately constant duration with height. Correlation and coherence statistics of temperature fluctuations associated with this motion were investigated. Estimates of the spatial extent of this organised motion in both horizontal and vertical directions are obtained.

1 INTRODUCTION

In the atmospheric surface layer as well as in the laboratory boundary layer, a ramp-like feature, referred to as a ramp event in this paper, is exhibited by the temperature signal. This feature has been interpreted to be the signature of an organised large structure (e.g. Antonia et al, 1979). It has often been suggested that this structure contributes a significant portion of the mean Reynolds shear stress and heat flux and therefore plays an important role in the momentum and heat transfer processes.

Taylor (1958) first observed the distinct and spatially coherent fluctuating temperatures and discussed them in the context of a convective plume that is inclined in the downwind direction and has a streamwise extent in the range 50-100 m. Antonia et al interpreted the coherent temperature signal as signatures of an organised motion with a vertical extent proportional to the Monin-Obukhov length, L , and with a streamwise extent one order of magnitude larger than L . Phong-anant et al (1980) found the convection velocity of the back (where the sudden decrease in temperature occurs) of the structure to be approximately equal to the local mean wind velocity \bar{U} . The average inclination of this back increases from about 20° to 50° as the height z increases from about 1 to 6 m.

The concept of geometric similarity for the coherence Coh , between the horizontal wind speed at two heights was first formulated by Davenport (1961). Since then the concept has been generalised to include horizontal separations and other signals such as vertical velocity and temperature θ , etc. For this paper geometric similarity for the Coh at a frequency f , between two signals separated by a distance Δx_i ($x_i \equiv$ longitudinal x , lateral y , vertical z , distance) is represented by

$$Coh = \exp(-a_i \Delta F)$$

where $\Delta F (\equiv f \Delta x_i / \bar{U}_\Delta)$ is f normalised by the separation length and a mean velocity \bar{U}_Δ at which the scales advect. If Taylor's hypothesis applies or if the advection velocity of the different scales is constant over the frequency range of the coherence similarity, then ΔF is the ratio of Δx_i to the wave number in the x -direction which implies an invariance in the shape of the eddies causing coherence. For this study \bar{U}_Δ is the velocity at the geometric mean height $\sqrt{z_1 z_2}$ of the two signals which is consistent with Taylor's hypothesis and the advective velocity of the back of the ramp-like structures. The Coh is

defined as $(Co^2 + Q^2)/G_1 G_2$ where G_1 and G_2 are spectral densities of the signals and Co and Q are the co-spectrum and quadrature spectrum respectively. The slope ' a_i ' ($\equiv a_x, a_y$ or a_z) may be interpreted as a decay parameter and has been obtained by several investigations for various velocity components and horizontal separations (Panofsky & Singer, 1965; Shiotani, 1969; Pielke & Panofsky, 1970; Ropelowski et al, 1973; Berman & Stearns, 1976). Davison (1976) extended Davenport's concept to θ in an unstable atmospheric surface layer. He found that a_i was frequency dependent and that the decay rate for the range of frequencies related to the ramp events was roughly half that for larger scales.

In this paper, cross-correlations and the associated coherence temperature fluctuations, simultaneously obtained at different points in space, are used to estimate the spatial extent of the large scale motion in the atmospheric surface layer.

2 DATA AND INSTRUMENTATION

The present results were obtained at the experimental site of the CSIRO near Bungendore (NSW) in December 1977. The site was freshly ploughed with a fetch of about 300 m in the prevailing wind direction (Northwest to West). Details of the site, wind velocity profile and surface flux measurements have been described by Phong-anant et al (1980).

The temperature was measured with thermistors (frequency response DC - 3 Hz), operated with 12 volt d.c. constant-current bridges ($I = 0.12$ mA). For vertical separations (runs B.1, B.2, B.3 and B.4), single thermistors were mounted on a mast at height $z = 1, 2$ and 8 m. At $z = 4$ m, two thermistors were placed 2 m apart at each end of a slender tube mounted on a directional wind vane.

For cross-wind separations (runs B.5 and B.6) the probes were mounted at $z = 4$ m on four masts aligned approximately perpendicular to the prevailing wind direction, with nominal separations of 6, 9 and 13 m. The actual lateral separations, Δy , were determined from the positions of sensors relative to the masts and the mean wind direction. The standard deviation in the wind direction was about $\pm 10^\circ$. For run B.6, a cold wire probe was used to provide another measuring point for θ ($z = 4$ m). The cold wire was a $0.6 \mu\text{m}$ dia. and 1 mm long Pt-Rh Wollaston wire, operated on a d.c. constant-current bridge ($I = 0.1$ mA). All signals were digitized and processed on PDP 11/45 and 11/20 computers. The sampling frequency, f_s , for thermistor signals was 6.25 Hz (real time)

TABLE 1
EXPERIMENTAL CHARACTERISTICS AND DETAILS OF RAMP EVENTS

Run No.	Date	Starting Time	Record Duration (min)	z (m)	U_{4m} (ms^{-1})	U_* ($(UW)^{1/2}$) (ms^{-1})	T_* ($(W\theta/U_*)$) ($^{\circ}C$)	L (m)	N	T (s)	T_2 (s)
B.1	16/12/77	1132	29	1,2,4,8	10.9	0.31	-0.42	-21	11	33	156
B.2	16/12/77	1508	29	1,4,8	10.2	0.37	-0.36	-33	14	--	123
B.3	16/12/77	1611	29	1,2,4,8	11.4	0.45	-0.44	-40	13	36	132
B.4	16/12/77	1640	29	1,2,4,8	11.7	0.42	-0.42	-36	15	26	115
B.5	14/12/77	1017	29	4	4.6	----	----	-9	13	--	132
B.6	14/12/77	1146	25	4	8.0	----	----	-11	11	--	134
40	27/10/76	1700	34	1.7,4.0	6.0	0.40	-0.09	-64	18	10	114
40A	27/10/76	1730	14	1.7,4.0	6.0	0.34	-0.04	-1430	12	6	70

with a cut-off frequency $f_{cf} = 3.13$ Hz. The digital record durations and other relevant experimental information are given in Table 1.

3 ENSEMBLE-AVERAGED TEMPERATURE SIGNATURES

Computer plotted traces of temperature signals for runs B.1, B.2, B.3 and B.4 were visually examined to identify the ramp events. To enable easier identification of these events the digital records of θ were further low-pass filtered using a lump-smoothing technique with a cut-off frequency of 0.24 Hz. The number of ramp events, N , was noted (Table 1) and the selected θ signals ensemble-averaged. All ramp events that were clearly distinguishable on all 4 thermistors with duration greater than 5 s were chosen to be ensemble-averaged. The location of the peak temperature value in each selected event at all heights was taken as a zero time reference for the ensemble-averaging process. Ensemble averages of θ were obtained for each height using the selected events for 32 s downwind of the peak (zero time) to 16 s upwind of the peak. This range was sufficient to capture all of the selected signatures.

Ensemble-averaged shapes of θ (normalised by characteristic temperature, T_*) for $z = 1, 2, 4$ and 8 m are shown in Fig. 1 for runs B.1 and B.3 (runs B.2 and B.4 were similar to B.3) with the time scale normalised by the mean time interval between ramps, $T_2 \approx 2$ min (Table 1). For the record duration of about 30 min, only relatively few events were obtained ($N \approx 11-15$) but this seems unavoidable as longer records may undermine stationarity. The decrease of θ on the upwind side, Fig. 1, is slightly retarded due to smoothing by the low-pass filter. The θ distributions are similar at each of the four heights for all runs. The average duration of the signature, T , (measured from the minimum point downwind where the gradual rise of temperature starts to the first minimum point upwind of the peak) was found to be about 32 s (Table 1) and is approximately constant with height for all runs.

4 CROSS-CORRELATION OF TEMPERATURE

The cross-correlation, $R_{ij} = [\theta_i(t)\theta_j(t-\tau)] / [\theta_i^2\theta_j^2]^{1/2}$ at time delay τ , was inferred from the cross-spectrum via an inverse fast Fourier transform. The maximum value of R_{ij} is denoted here by R_{max} and occurs at a maximum time delay, τ_{max} . A typical plot of R_{ij} vs τ/T_2 is shown in Fig. 2. As Δz varies from 1 to 7 m, R_{max} decreases from 0.8 to about 0.5. With $\Delta x = 2$ m, R_{max} is about 0.9 and for $\Delta y = 7$ to 19 m, R_{max} ranges from 0.4 to 0.1. The results for all separations are

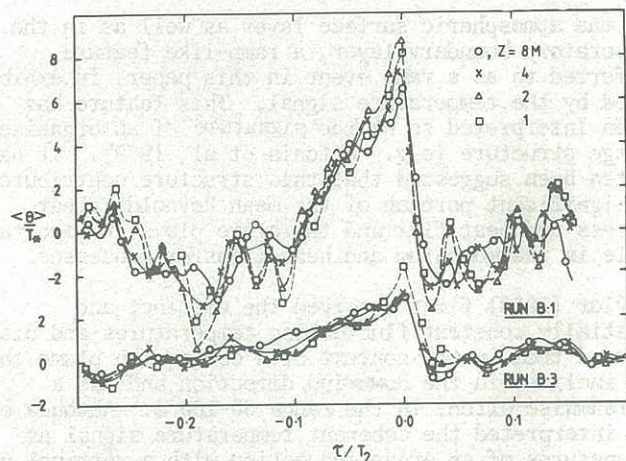


Figure 1 Ensembled averaged shapes of θ distribution

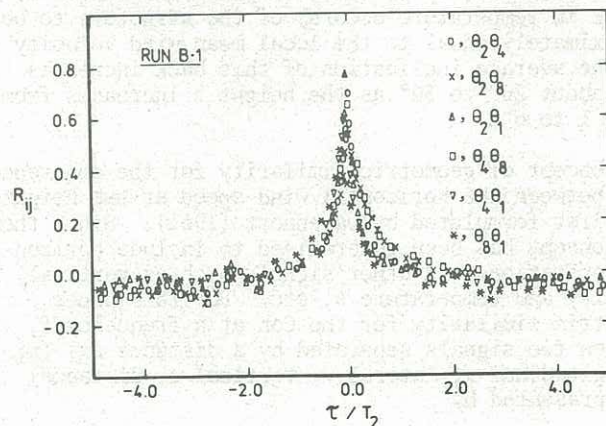


Figure 2 The cross-correlation of θ

shown together in Fig. 3 with the autocorrelation R_{xx} of θ (solid line) where $\Delta x \equiv U\tau$ (Taylor's hypothesis). R_{max} decreases rapidly as the separation Δx increases.

Approximate estimates of the integral scales of the turbulence were obtained by first fitting an exponential function of the form

$$R_{max} = \exp(-b_i \Delta x_i)$$

to the data in Fig. 3. It is assumed that for x

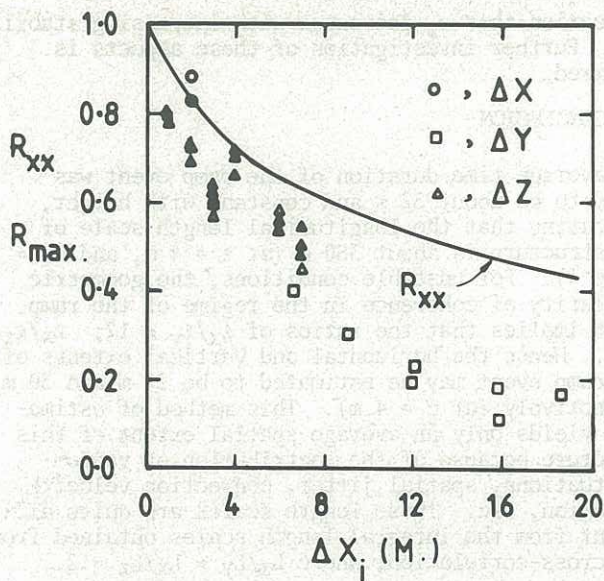


Figure 3 Variation of R_{\max} with separation Δx_i

separations, $R_{\max} \equiv R_{xx}$. The agreement between the data and exponential fit (not shown) was reasonable to $\Delta x_i = 16$; for larger separations in either x, y directions, R_{\max} was underestimated. The respective length scales are approximated by b_i^{-1} and are $L_x = 17.9$ m, $L_y = 8.1$ m and $L_z = 8.8$ m. The ratios of these scales are $L_x/L_y = 2.2$ and $L_x/L_z = 2.0$. Shiotani & Iwatani (1976) obtained $L_x/L_z = 2.4$ at $z = 40$ m from u correlation in high $x-y$ winds ($\bar{U} \approx 15$ m/s) over land.

5 COHERENCE OF TEMPERATURE

5.1 Vertical Coherences

To within the experimental scatter (larger as Δz increases) the vertical coherence decreases exponentially with increasing ΔF (Fig. 4). The Coh distributions appear to have two distinct regions with different decay constants (first observed by Davison 1976). At the lower frequencies geometric similarity appears reasonable (solid lines Fig. 4) but the decay parameter $a_z = 18 (\pm 5)$ fluctuates randomly for different Δz . For the higher frequencies the Coh levels are consistently higher than would be predicted by the decay constant fitted to the region of low ΔF . For the range of frequencies associated with the ramp event, $\Delta F > 2\Delta z/TU_\Delta$ where $T \approx 32$ s (Table 1), $a_z = 11 (\pm 2)$, dashed line Fig. 4. The rate of change of the phase angle between the θ signals with ΔF (not shown) for the ramp event frequency range is constant, (except for $\Delta z = 7$ m in which the phase angle does not change with increasing ΔF) which is consistent with a downwind tilt of the ramp event. Thus the change in slope of Coh vs ΔF appears to be real and is not due to random scatter about zero of Co and Q.

The average value of a_z for all runs is $19 (\pm 5)$ and $12 (\pm 2)$ respectively for the two regions. Davison obtained a_z of about 13 and 5 for wave-length ranges larger and smaller than 100 m. His data and the present results suggest, not surprisingly, that the ramp events exhibit a more constant and longer-lasting structure than can be expected from even larger scale (very low frequency) eddies.

5.2 Horizontal Coherences

The variation of \bar{U} in the lateral direction is expected to be small as the agreement in \bar{U} measured

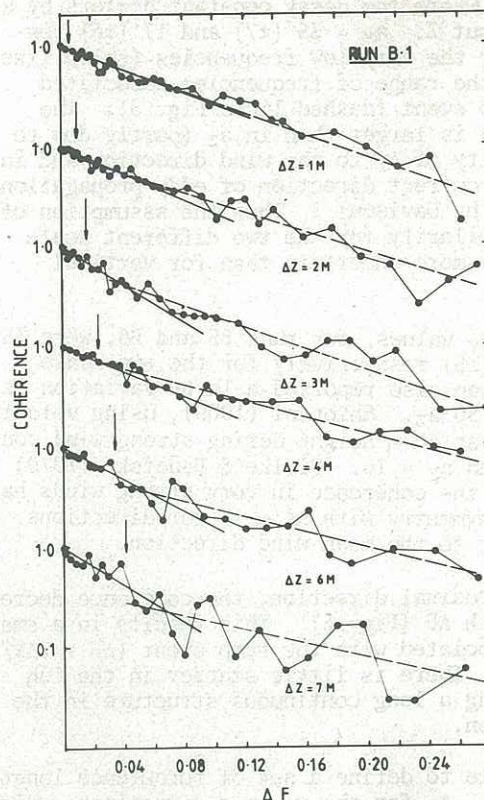


Figure 4 Temperature coherence for different Δz + $2\Delta z/TU_\Delta$ (lines fitted by eye).

at $z = 4$ m by two cup anemometers ($\Delta y = 6$ m) was better than 5% for all runs. Geometric similarity of Coh for lateral separations is possible for small ΔF and moderate Δy (Fig. 5). When $\Delta y > 16$ m, the hypothesis does not seem to work due to the very large scatter in the Coh distribution.

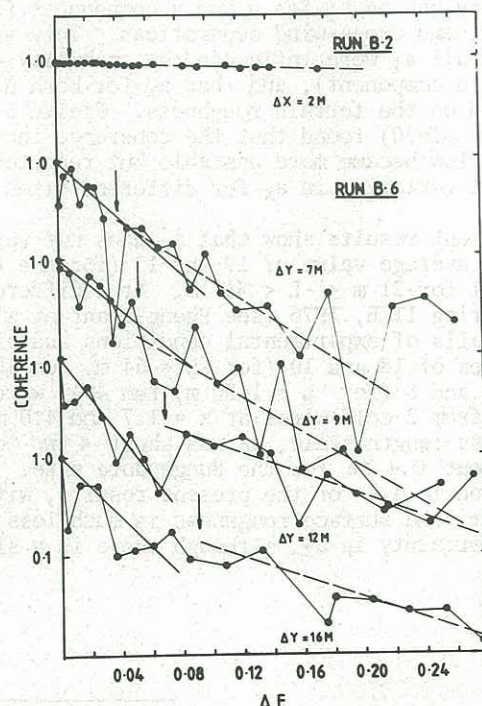


Figure 5 Temperature coherences for different horizontal separations. + $2\Delta y/TU_\Delta$ (lines fitted by eye)
As observed for vertical separations there appears to be at least two scale-size regimes of the Coh

distribution where the decay constant differs by a factor of about 2. $a_y \approx 35 (\pm 7)$ and $17 (\pm 6)$ respectively for the very low frequencies (solid line Fig. 5) and the range of frequencies associated with the ramp event (dashed lines Fig. 5). The scatter in a_y is larger than in a_z (partly due to the sensitivity of Δy to the wind direction and in choosing the correct direction of eddy propagation, as discussed by Davison). Thus the assumption of geometric similarity for the two different scale sizes is even more uncertain than for vertical separations.

The average a_y values, for runs B5 and B6, were 35 (± 5) and 17 (± 5) respectively for the two scale sizes. Davison also reported a large variation in a_y with $a_y \approx 50 a_z$. Shiotani (1969), using velocity measurements at 40 m height during strong wind conditions, found $a_y \approx 16$. Pielke & Panofsky (1970) assumed that the coherence in very strong winds has cylindrical symmetry with $a_i \approx 17$ for directions perpendicular to the mean wind direction.

In the longitudinal direction, the coherence decreases slowly with ΔF (Fig. 5). This results in a small $a_x (\approx 1)$ associated with the ramp event ($\Delta F = 2\Delta x / TU_\Delta = 0.01$). There is little scatter in the Coh data, implying a long continuous structure in the wind direction.

It is possible to define a set of turbulence length scales l_x, l_y, l_z for the x, y, z directions, which are associated with the decay in Coh, with increasing separation, for a particular frequency. These length scales are defined in a similar manner to the integral length scales obtained from the correlation functions. The assumption of geometric similarity for a particular range of frequencies of Coh yields $l_i = a_i^{-1}$. For the range of scales associated with the ramp event we obtain $l_x/l_y \approx 17$ and $l_x/l_z \approx 12$.

Ropelowski et al (1973) examined the dependence that stability has on a_i for u and v components for longitudinal and cross-wind separations. They suggested that all a_i were influenced by stability except a_x (for u component), and that a_x for both u and v depended on the terrain roughness. Pielke & Panofsky (1970) found that the coherence increased as the flow became more unstable but reported insignificant variation in a_x for different sites.

The present results show that a_z does not vary much from an average value of 19 and 12 (for the two regimes) for $21 \text{ m} < -L < 40 \text{ m}$. At a different site during ITCE, 1976 (see Phong-anant et al, 1980 for details of experimental conditions and site), a_z values of 18 and 10 (for $-L = 64 \text{ m}$, run 40) and $a_z = 15$ and 8 (for $-L = 1430 \text{ m}$, run 40A) were obtained from 2 cold wires at $z = 1.7$ and 4.0 m . The roughness length scale, z_0 was about 4 mm compared with about 0.4 mm for the Bungendore site. The variation in a_z , for the present results, with stability and surface roughness is much less than the uncertainty in a_z , although there is a slight

indication that a_z decreases with increasing stability. Further investigation of these aspects is required.

6 CONCLUSION

The average time duration of the ramp event was found to be about 32 s and constant with height, indicating that the longitudinal length scale of the structure is about 350 m (at $z = 4 \text{ m}$, and $U_h \approx 11 \text{ ms}^{-1}$). For unstable conditions, the geometric similarity of coherence in the regime of the ramp event implies that the ratios of $l_x/l_y \approx 17$; $l_x/l_z \approx 12$. Hence the horizontal and vertical extents of the ramp event may be estimated to be 20 m and 30 m respectively (at $z = 4 \text{ m}$). This method of estimation yields only an average spatial extent of this structure because of the contribution of random fluctuations, spatial jitter, convection velocity variation, etc. These length scales are quite different from the integral length scales obtained from the cross-correlation, where $L_x/L_y \approx L_x/L_z \approx 2$.

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