THERMAL STRUCTURES IN THE LOWEST LAYERS OF THE ATMOSPHERE

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[*Manuscript received January* 22, 1958]

Summary

An analysis has been made of a number of records of simultaneous fluctuations of temperature at four heights. The results show that the correlation between temperatures at two heights is greatest when the records are displaced relatively to each other, so that earlier points in the upper record are considered together with later points in the lower, by an amount depending on the mean wind speed difference between the two heights. The correlation increases with height relatively to what would be expected in a locally isotropic turbulence.

This and other evidence points to the existence of organized thermal structures of considerable vertical extent which are superimposed on a background of random turbulent disturbances. It is probable that these structures represent convection plumes.

I. Introduction

During the summer and autumn of 1956 a number of simultaneous records of temperature at four different heights were made in order to investigate a phenomenon first noticed by the author in 1949 and briefly mentioned by Priestley (1952). It was found then that, when the correlation coefficient is calculated between simultaneous records of temperature at two heights, the maximum value is attained, not when the correlation is between temperatures at corresponding instants, but when earlier temperatures at the upper level are taken with slightly later temperatures at the lower. The general impression given is that temperature anomalies which are big enough to affect both recording points in general reach the higher levels first. A similar effect for velocity fluctuations in a wind-tunnel boundary layer has been reported by Favre, Gaviglio, and Dumas (1957).

The earlier observations mentioned were confined to two simultaneous temperature records (one thermometer fixed at either 1 or 2 m above the ground and the other at a variable height) and were not accompanied by detailed wind and temperature profile measurements. It was therefore decided to make a completely new set of observations with temperature fluctuations at four heights and vertical velocity fluctuations at one of them, in order to permit a qualitative comparison of the natures of the two types of record.

II. Recording and Analysis

Temperatures were measured using fine wire resistance thermometers of approximately 2000 Ω of 0·0005 in. diameter nickel wire included in suitable

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Wheatstone bridge networks provided with zero-shift controls and fixed resistors for rapid calibration-checking. The maximum dimension of each thermometer coil was less than 2 in. Since temperature fluctuations only were of interest, the thermometer bridges were calibrated for sensitivity but not for absolute value. The anemometer used for measuring the vertical velocity fluctuations was of a new design which has been described elsewhere (Taylor 1958). The records were made using the galvanometers and photographic arrangements incorporated in the atmospheric fine structure recorder described by McIlroy (1955). The thermometers were mounted at $1 \cdot 5$, 4, 16, and 30 m above the ground and the anemometer at $1 \cdot 5$ m. Response times of all the instruments were so small that the resolution obtained in the traces is determined by the recording galvanometers (natural period 2 sec) rather than by the sensing parts. All records were made over 10-min periods.

Simultaneously with the fluctuation recordings, measurements were made of mean wind speed at a number (eight or nine) of heights and of mean temperature difference over four height intervals.

The records were in the form of sheets of photographic paper about 45 cm by 200 m, each carrying traces of temperature at the four heights ($T_{1 \cdot 5}$ etc.) and of vertical component at $1 \cdot 5$ m (w). The analysis was carried out on the differential analyser described by Taylor and Webb (1955), the quantities calculated being :

(1) Root-mean-square fluctuations denoted by $\sigma_{T(1 \cdot 5)}$ etc.

(2) Correlation coefficients R between temperatures at two heights as a function of time-lag (τ) between the two traces. Special interest attaches to three values ; R at zero lag (R_0), the maximum correlation (R_m), and the lag τ_m when $R = R_m$. Values of τ are counted positive when earlier times at a higher level are coupled with later times at a lower.

(3) On four occasions, a graph of the progressive total of the covariance between temperatures at two heights was written by the analyser as a function of record length x. That is, the relationship of $\int_0^x T'_{1 \cdot 5} T'_4 \mathrm{d}x$ (and similar quantities) with x was displayed, where the primes indicate deviations from means. This permitted the location on the original record of those features contributing most strongly to the correlations.

Each record analysed (with certain exceptions) thus gave five values of σ and six sets of values of R at various τ. Because of the time-consuming nature of the calculations only 20 complete records (16 day-time observations and 4 from the evening) were analysed in this way. The results, however, are sufficiently consistent for valid conclusions to be drawn.

III. Results

In almost every case the values of R showed a clear-cut maximum at a moderate positive value of τ (mostly between 1 and 10 sec). Qualitative inspections of the day-time records clearly show this time lag at maximum correlation, and obvious " structures " affecting all heights not quite simultaneously are frequent. These structures appear on the records as asymmetrical triangular waves of temperature (gradual rise followed by sudden drop) and frequently attain several Centigrade degrees in magnitude with duration mostly about 10–20 sec. An example has been used by Priestley (1956) and the reader may be referred to his Figure 3 for illustration. An interesting feature of the temperature traces is that there frequently seem to be a fairly constant " base " temperature and temperature fluctuations which are almost exclusively positive relative to it. The effect is particularly well shown in a record obtained by I. C. McIlroy (unpublished data) in another connexion. Part of this record (which was made with $\frac{1}{5}$ sec galvanometers and refers to a height of 7 m above the ground) is reproduced in Figure 1. Although the asymmetrical, triangular nature of the temperature fluctuations is less evident here, the separation of temperature into quiet and disturbed periods is well marked, as is also the virtual absence of fluctuations negative with respect to the " quiet " temperature. Figure 1 also

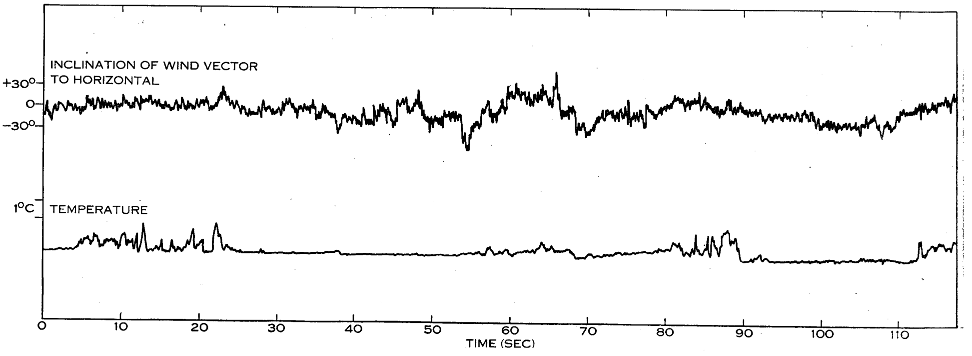

Fig. 1.—Record showing " quiet " and " disturbed " periods in temperature at 7 m.

shows the angle of inclination of the wind vector to the horizontal, and it is clear that the motion is predominantly upwards during the " disturbed " temperature periods although the inclination record is strongly influenced by random motion at all times. These features also appear in the w-traces of the present records.

The association between thermal structures and vertical velocity component is also very well shown in a record made at 23 m above the ground by E. L. Deacon (unpublished data), a part of which is reproduced here in Figure 2. Particularly striking is the virtual absence of negative contributions to the turbulent heat flux.

Of the 16 day-time observations (involving 96 (R, τ) graphs) only five negative τ_m were found and for three pairs of traces (all in the same record) it was impossible to locate a maximum R in any reasonable range of τ. The four evening runs analysed lacked a 4 m temperature record but showed positive τ_m in all but one case. In general, the evening runs differed from the day-time ones in the absence of structures such as those referred to above, in having less well-marked maxima, and in having an occasional very large τ_m. The last two points are illustrated by calculating, separately for day-time and evening observations, the ratio of the average of $(R_m - R_0)$ to the square of the average τ_m. The values are $0 \cdot 005$ sec^{-2} (day-time) and $0 \cdot 001$ sec^{-2} (evening). Table 1 shows values of R_0, R_m, τ_m, σ_T, and σ_w for those traces which have been analysed, together with the Richardson number at $1 \cdot 5$ m ($Ri_{1 \cdot 5}$).

An obvious explanation for the existence of a positive τ_m lies in the distorting effect of the mean wind shear on any atmospheric structure having sufficient vertical extent. If there is any process in the flow creating temperature disturbances over the height range of the observations, then the wind shear will

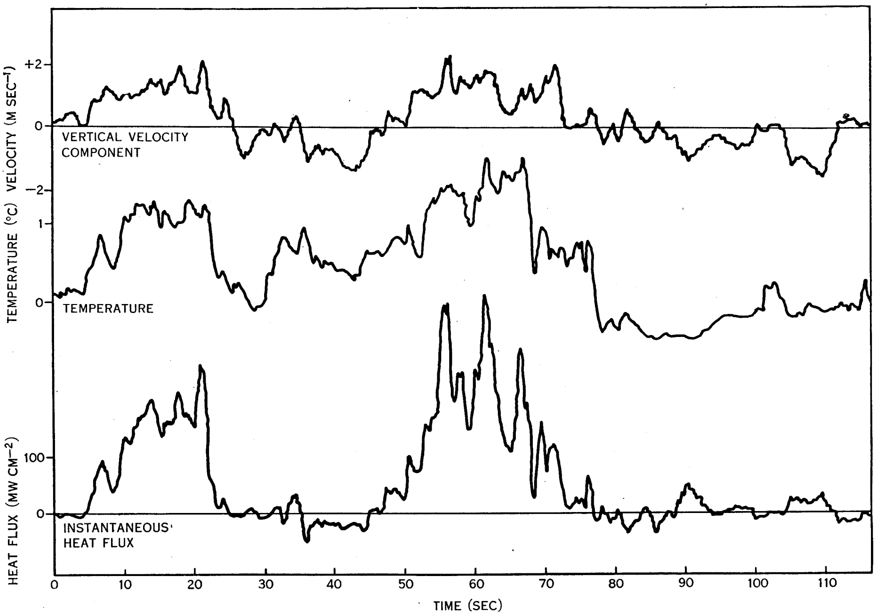

Fig. 2.—Association of temperature fluctuations with vertical velocity.

tend to give them a rotation in the observed sense. However, the narrowness of the range of τ_m observed makes it appear improbable that we are here dealing with the effects of wind shear on disturbances originally oriented at random in all possible directions.

The suggestion that wind shear is responsible for the observed displacement of maximum R is given weight by a detailed comparison of the profiles. The means of day-time observations of both τ_m and wind speed difference (Δu) show fairly smooth curves when divided by the height interval (Δz) concerned and plotted against the geometric mean of the extremities of that interval. Figure 3 shows these values of $\tau_m/\Delta z$ and $\Delta u/\Delta z$ expressed as fractions of the values over the whole height range $1 \cdot 5$–30 m. There is good agreement except in the layer closest to the ground where disturbing influences are generally likely to be greatest. The suggestion that the observed thermal structures are convection columns will be examined in more detail later; here it is sufficient to note that the general pattern of τ_m observed is consistent with the existence of convection

TABLE 1

CORRELATIONS BETWEEN TEMPERATURE RECORDS

Run No.	Time of Start E.S.T.	$Ri_{1·5}$	σ_T (°C) at				σ_W at 1·5 m (m sec^{-1})	Heights Correlated																	
								1·5 m and 4 m			1·5 m and 16 m			1·5 m and 30 m			4 m and 16 m			4 m and 30 m			16 m and 30 m		
			1·5 m	4 m	16 m	30 m		R_0	R_m	τ_m (sec)	R_0	R_m	τ_m (sec)	R_0	R_m	τ_m (sec)	R_0	R_m	τ_m (sec)	R_0	R_m	τ_m (sec)	R_0	R_m	τ_m (sec)
	17. i.56																								
1	1234	−0·03	0·56	0·49	0·38	0·36	0·30	0·78	0·82	0·9	0·56	0·65	4·5	0·47	0·60	7·3	0·64	0·72	4·2	0·49	0·60	3·8	0·69	0·73	1·6
2	1246	−0·05	0·54	0·35	0·32	0·29	0·22	0·70	0·82	1·4	0·45	0·53	4·4	0·44	0·52	6·4	0·56	0·62	2·4	0·51	0·59	4·2	0·75	0·76	0·8
3	1258	−0·03	0·49	0·41	0·30	0·28	0·33	0·76	0·82	1·4	0·46	0·54	5·4	0·27	0·41	10·7	0·50	0·56	1·5	0·31	0·38	2·9	0·65	0·73	1·8
4	1310	−0·04	0·42	0·37	0·30	0·26	0·20	0·62	0·68	1·1	0·10	0·31	8·6	0·03	0·32	15·0	0·30	0·43	5·8	0·18	0·45	6·2	0·50	0·57	2·4
5	1322	−0·02	0·51	0·43	0·30	0·33	0·26	0·72	0·85	1·5	0·52	0·55	1·8	0·54	0·54	0·0	0·59	0·59	0·6	0·50	0·51	−1·0	0·72	0·72	0·0
	1. ii.56																								
2	1342	−0·07	0·33	0·98	0·43	0·45	0·19	0·73	0·80	2·2	0·32	0·40	10·9	0·25	0·37	8·4	0·44	0·53	6·7	0·33	0·46	10·0	0·62	0·67	2·5
3	1358	−0·07	0·53	0·49	0·37	0·45	0·23	0·65	0·69	1·8	0·26	0·26	2·7	0·36	0·46	10·9	0·38	0·40	1·8	0·39	0·48	8·4	0·48	0·51	3·2
	24. ii.56																								
2	1145	−0·06	0·69	0·74	0·47	0·45	0·50	0·73	0·80	1·0	0·44	0·65	7·6	0·39	0·50	9·0	0·56	0·71	2·0	0·42	0·50	6·5	0·82	0·82	0·0
3	1158	−0·04	0·75	0·80	0·62	0·50	0·40	0·79	0·83	0·7	0·50	0·57	3·6	0·45	0·51	3·1	0·62	0·66	2·0	0·53	0·58	2·8	0·73	0·77	2·3
	19.iii.56																								
1	1203	−0·60	0·64	0·60	0·53	0·39	0·23	0·63	0·64	1·2	0·42	0·44	2·7	0·42			0·67	0·68	−2·8	0·55			0·71		
2	1218	−1·17	0·63	0·55	0·28	0·22	—	0·84	0·84	0·3	0·32	0·37	−2·8	0·20	0·21	4·6	0·34	0·36	1·5	0·24	0·24	5·4	0·69	0·80	9·6
3	1232	−0·33	0·71	0·64	0·48	0·32	0·29	0·49	0·62	2·0	0·25	0·29	6·0	0·32	0·32	1·6	0·49	0·50	0·1	0·40	0·45	−1·6	0·70	0·70	0·0
4	1245	−0·16	0·61	0·51	0·39	0·23	—	0·52	0·63	1·8	−0·09	0·01	3·6	−0·04	0·08	9·1	0·19	0·21	2·1	0·16	0·21	5·4	0·58	0·58	−1·0
5	1301	−0·31	0·84	0·66	0·36	0·31	0·31	0·66	0·70	1·8	0·27	0·40	4·5	0·28	0·45	7·2	0·40	0·50	7·2	0·37	0·49	5·8	0·57	0·58	1·9
6	1402	−0·10	0·64	0·61	0·42	0·34	0·27	0·60	0·71	1·7	0·36	0·44	3·0	0·19	0·34	4·8	0·61	0·61	0·0	0·45	0·48	2·8	0·72	0·74	0·9
7	1414	−0·17	0·65	0·66	0·33	0·30	0·26	0·65	0·75	1·8	0·25	0·34	2·7	0·12	0·26	9·5	0·35	0·42	3·9	0·21	0·27	9·9	0·52	0·53	1·4
	20.iii.56																								
1	1955	+0·05	0·06		0·08	0·08	0·17				0·28	0·31	7·4	0·27	0·31	−2·6							0·49	0·54	6·2
2	2011	+0·08	0·06		0·07	0·06	0·13				0·27	0·27	0·0	0·16	0·29	2·0							0·15	0·34	14·0
3	2026	+0·09	0·07		0·07	0·06	0·11				0·14	0·28	20·2	0·23	0·24	4·0							0·24	0·42	6·8
4	2040	+0·08	0·06		0·08	0·07	0·14				0·27	0·39	13·0	0·16	0·33	21·5							0·37	0·41	5·5
Mean of day-time observations		−0·203	0·596	0·581	0·392	0·342	0·285	0·679	0·750	1·41	0·336	0·422	4·32	0·293	0·392	7·17	0·478	0·531	2·44	0·378	0·446	4·76	0·654	0·681	1·83
Mean of evening observations		+0·075	0·066		0·075	0·068	0·138				0·240	0·312	10·1	0·205	0·292	6·22							0·312	0·428	8·12

columns travelling down wind at a speed less than the wind speed at any of the heights of observations.

The mean values of correlation coefficients at zero lag from Table 1 are repeated in Table 2 which also shows the standard errors of the means as derived from the observed scatter in R_0.

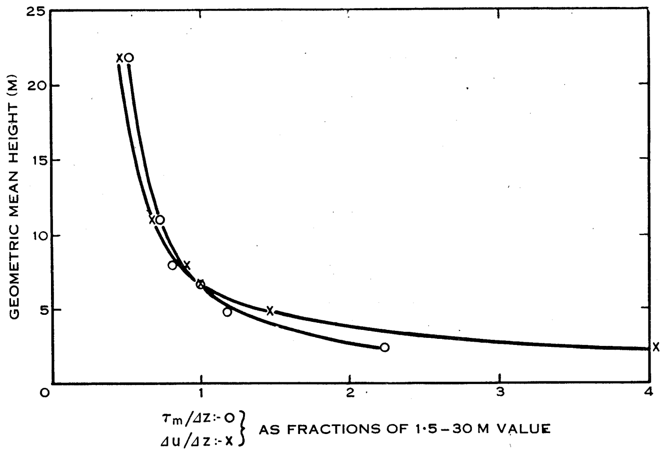

Fig. 3.—Profiles of τ_m and wind speed difference.

It will be noticed that R_0 is generally smaller by night than by day and, at least in the layer 16–30 m, there is no doubt that the difference is significant.

When considering the variations of R_0 with height, one must take account of the fact that the correlations are measured over unequal height intervals and some system of normalization must be adopted. The present author (Taylor 1955) has shown that, as far as the velocity field is concerned, the predictions of similarity theory apply up to eddy sizes which may be several

Table 2

MEANS AND STANDARD ERRORS OF CORRELATION COEFFICIENTS

Layer (m)	1·5–4	1·5–16	1·5–30	4–16	4–30	16–30
Day-time mean R_0 . .	0·68	0·34	0·29	0·48	0·38	0·65
Standard error of mean	0·02	0·04	0·04	0·04	0·03	0·02
Evening mean R_0 . .		0·24	0·20			0·31
Standard error of mean		0·03	0·03			0·08

times the height of observation. It is probably reasonable, therefore, to apply similar considerations to the analysis of the temperature field. Theoretical discussions of temperature fluctuations in locally isotropic turbulence have been made by Obukhov (1949) and Corrsin (1951). The former writes in terms of " structural functions "—the mean square temperature difference between two points—while the latter uses spectrum functions, but both agree in determining the temperature field over the intermediate range of wave numbers in terms of the distance involved (or wave number), the rate of dissipation of kinetic energy (ε), and a quantity N which describes the rate at which temperature differences are being destroyed by the action of molecular conduction. N has dimensions (temperature)$^2\times$(time)$^{-1}$ and is defined by

$$N=k\,\overline{(\text{grad } T)^2},$$

where k is the thermal diffusivity and T is temperature. Dimensional analysis then indicates that

$$\overline{(T_1-T_2)^2}=CN\varepsilon^{-\frac{1}{3}}r^{\frac{2}{3}},$$

where T_1 and T_2 are temperatures at two points separated by a distance r and C is a constant. Tatarsky (1956) discusses this expression, produces observations to demonstrate that $\overline{(T_1-T_2)^2}$ does indeed vary as the two-thirds power of r, and relates the constant C to the mean meteorological conditions. In locally isotropic turbulence, the mean square temperature difference can be written in the form

$$\overline{(T_1-T_2)^2}=2\overline{T'^2}(1-R),$$

where $\overline{T'^2}$ is the mean square temperature fluctuation and we therefore have

$$(1-R)\propto r^{\frac{2}{3}}.$$

This relationship has been taken as the basis of a scheme of normalization for R_0 to make allowance for the varying height interval Δz, and Table 3 shows the means and standard errors of the means of $y=(1-R_0)/\Delta z^{\frac{2}{3}}$.

TABLE 3

MEANS AND STANDARD ERRORS OF $y=(1-R_0)/\Delta z^{\frac{2}{3}}$

Layer (m)	1·5–4	1·5–16	1·5–30	4–16	4–30	16–30
Day-time mean y ($m^{-\frac{2}{3}}$)	0·174	0·112	0·076	0·100	0·071	0·060
Standard error of mean ($m^{-\frac{2}{3}}$)	0·013	0·007	0·004	0·007	0·004	0·004
Evening mean y ($m^{-\frac{2}{3}}$)		0·128	0·085			0·118
Standard error of mean ($m^{-\frac{2}{3}}$)		0·006	0·003			0·013

It is clear from these results that, by day, y does decrease significantly with increasing height in a systematic way and therefore that the correlations are relatively greater with height than would be expected in a locally isotropic turbulence. The presence of some sort of eddy, directionally influenced by the boundary, is thus indicated.

By night, the picture is less straightforward. There is some evidence for a significant difference between the layers 1·5–16 m and 1·5–30 m, but the layer 16–30 m provides no support for the trend thus suggested. The difference between day and night in the 16–30 m layer is very clear.

The suggestion that the directional influence of the boundary is greater by day than by night is consistent, of course, with the fact that the vertical turbulent fluxes of heat and momentum are larger in the former case.

An example of a graph of progressive total of covariance is shown in Figure 4, which gives $\int_0^x T'_{1\cdot5}T'_4 dx$ as a function of record length x for Run 1 of January 17, 1956 with $\tau=\tau_m$. Parts of the curve are obviously much steeper than the general trend and these parts are those which contribute particularly strongly to the

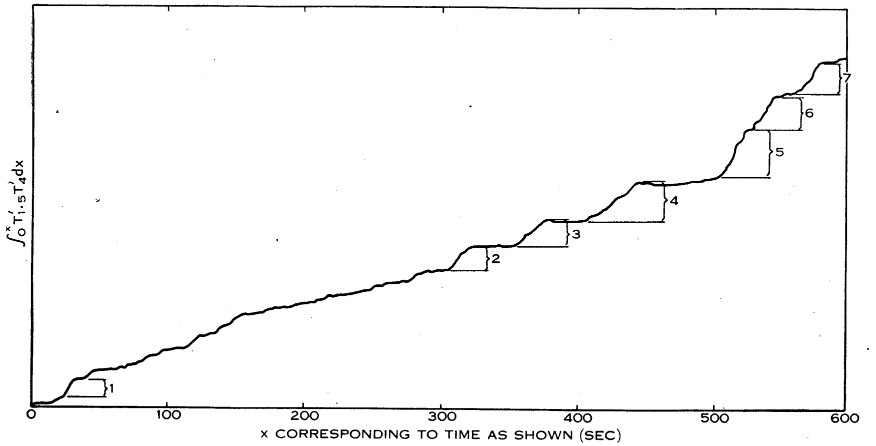

Fig. 4.—Events contributing most strongly to covariance.

covariance. There is clearly some subjectivity in defining them but seven "events" have been chosen (as indicated by braces and numbers in Figure 4) and, for this run, these events contribute 63 per cent. of the covariance in 24 per cent. of the total recording time. Table 4 summarizes the results from the four records so analysed.

TABLE 4

EVENTS CONTRIBUTING STRONGLY TO COVARIANCE

Date	Run No.	Height Interval (m)	Fraction of Covariance Contributed p	Fraction of Time Occupied q	$\frac{q}{p}$	No. of Events
17.i.56 ..	1	1·5–4	0·632	0·242	0·383	7
17.i.56 ..	2	1·5–4	0·652	0·223	0·342	9
17.i.56 ..	2	1·5–16	0·734	0·191	0·260	8
17.i.56 ..	2	16–30	0·364	0·089	0·244	4

An examination of the graph of cumulative covariance in conjunction with the original records discloses that almost all the special events listed in Table 4 can be identified with structures similar to those referred to above. The few cases where this is not so are associated with broader oscillations of temperature of rather smoother character. As far as they go, the results shown in Table 4 would indicate that these special events become rarer, but more intense, with increasing height.

IV. Discussion

The evidence provides a convincing picture of a turbulent flow of the usual random character, on which are superimposed organized structures of considerable vertical extent. Briefly recapitulating, the main points in this evidence are:

(i) the fact that temperature excursions affecting all four heights nearly simultaneously can be identified on the original records,

(ii) the presence on the graphs of cumulative covariance of special events corresponding, in most cases, to these excursions,

(iii) the increase with height of correlation coefficient relative to what would be expected in a locally isotropic turbulence,

(iv) the fact that the temperature excursions affect all heights at times which are consistent with their being continuous vertically but distorted by wind shear.

The observations, however, let us go further than this. The structures do not appear by night and when they do appear, by day, they are generally associated with upward vertical velocity component at all heights. Moreover, there exist occasions (similar to that illustrated in Figure 1) when these structures are almost the only temperature disturbances existing and then they clearly take the form of positive deviations from a nearly constant base temperature. These considerations make it extremely probable that they represent some sort of convection process. Priestley (1956) has discussed the various sorts of possible convection plume and the present observations are generally consistent with the models he there proposes.

V. Acknowledgments

The original observations were taken with the assistance of many members of the staff of the Division of Meteorological Physics and the very laborious computations were carried out under the direction of Mr. N. E. Bacon.

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