# Preliminary Results Obtained with a Sonic Anemometer-Thermometer[1]

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## 1. Introduction

A continuous wave sonic anemometer-thermometer (abbreviated S. A. T.) for measuring fluctuations in the vertical wind component and temperature has been described by the authors in a preceding paper in this journal (1963). Results obtained with the instrument during two field tests will be discussed in this note.

The tests were conducted at the experiment site of the Atmospheric Physics Operation, Hanford Laboratories, in eastern Washington. The terrain is reasonably flat, with scattered sagebrush up to 1 m in height. Routine measurements of wind, temperature, and humidity are made from a 125-m tower at the site. For both the tests the acoustic array was mounted vertically on a smaller portable tower with its mid-point 3.5 m above the ground. This tower is located about 100 m away from the main tower and is equipped for measuring wind speed, wind direction, and temperature at heights of 0.75, 1.5, 3, 6, 12 and 24 m.

## 2. Field measurements

For the first field test an acoustic path length of 103 cm was used and recordings of $w$ and $T$ fluctuations were made on a two-pen Speedomax Recorder. Reproduced in Figs. 1–6 are some of the interesting situations encountered during two days of operation. Each sample represents a run of approximately 15 min. The time scale on the abscissa corresponds to one min per division; the exact times for the beginning and end of each run are marked near the top edge of the chart paper. The scales for the vertical wind component $w$ and the temperature $T$, as well as their directions, are indicated on the left. Error in the temperature measurement from humidity fluctuations was estimated to be less than one per cent for all the runs, so no corrections were applied to the temperature scales. The attenuator settings in the recording system were adjusted from time to time, depending on the magnitude of the fluctuations, and consequently, the scales are different for the different runs.

Mean horizontal wind and temperature (denoted by $\bar{u}$ and $\bar{T}$) profiles for each of the runs were computed from measurements made with the conventional instruments[3] on the portable tower, and these are shown in Fig. 7. In all cases except $d_1$ and $d_2$ the mean profile represents an average over the 15-min period. These profiles serve to illustrate quantitatively wind shear and lapse rate conditions for the different runs.

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[3] Modified Casella cup anemometers for $u$ and copper-constantin thermocouples for $T$ measurements.

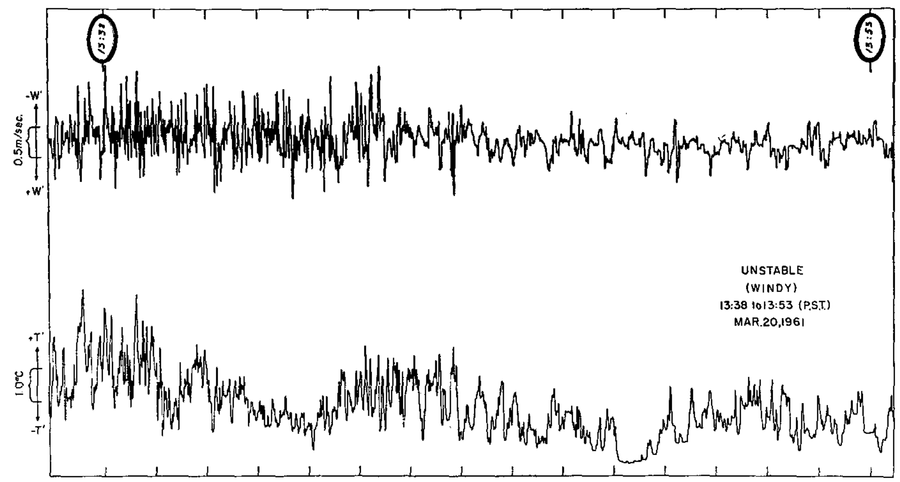

Fig. 1. $w$ and $T$ fluctuations for unstable lapse rate on a windy day; time scale: 1 div=1 min.

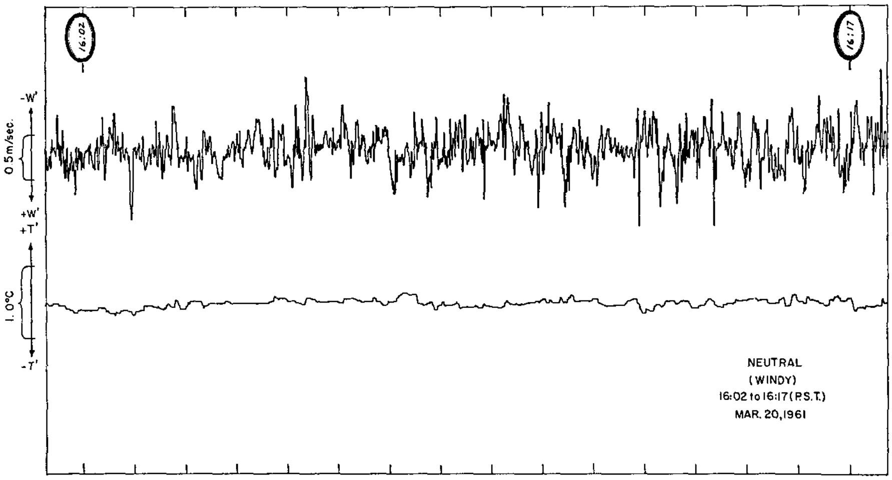

Fig. 2. $w$ and $T$ fluctuations for neutral lapse rate on a windy day; time scale: 1 div=1 min.

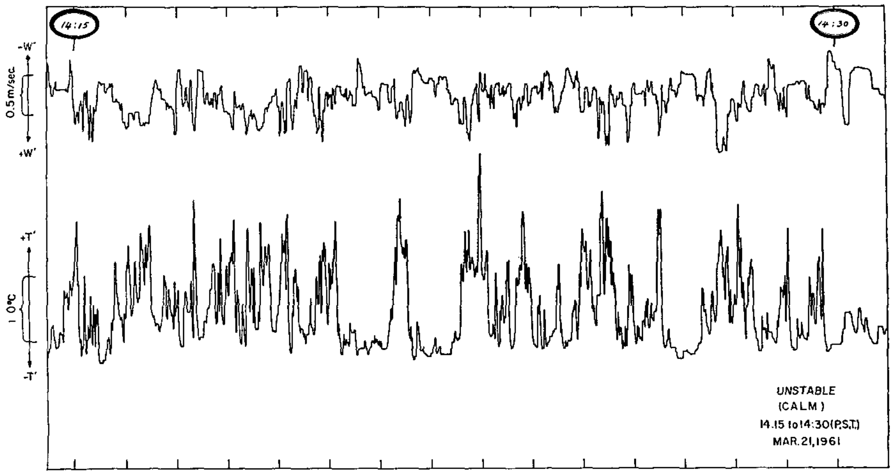

Fig. 3. $w$ and $T$ fluctuations for unstable lapse rate on a calm day; time scale: 1 div=1 min.

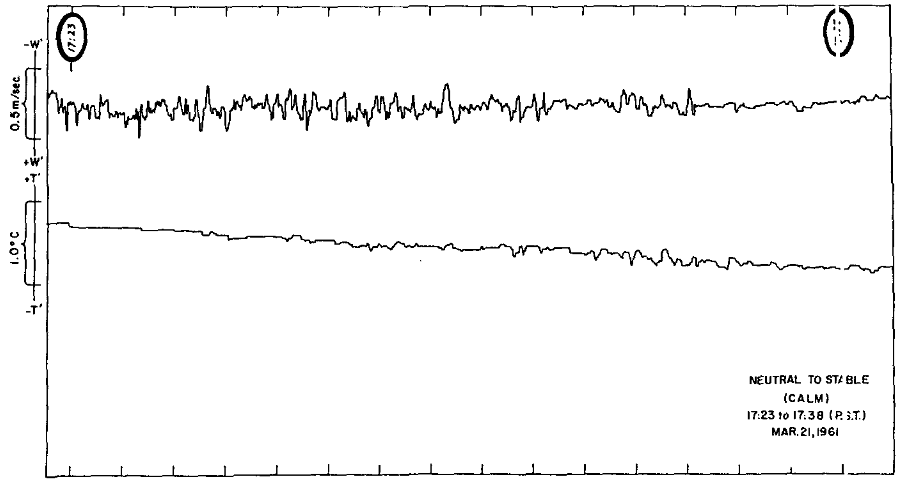

FIG. 4. $w$ and $T$ fluctuations during transition from neutral to stable lapse rate on a calm day; time scale: 1 div = 1 min.

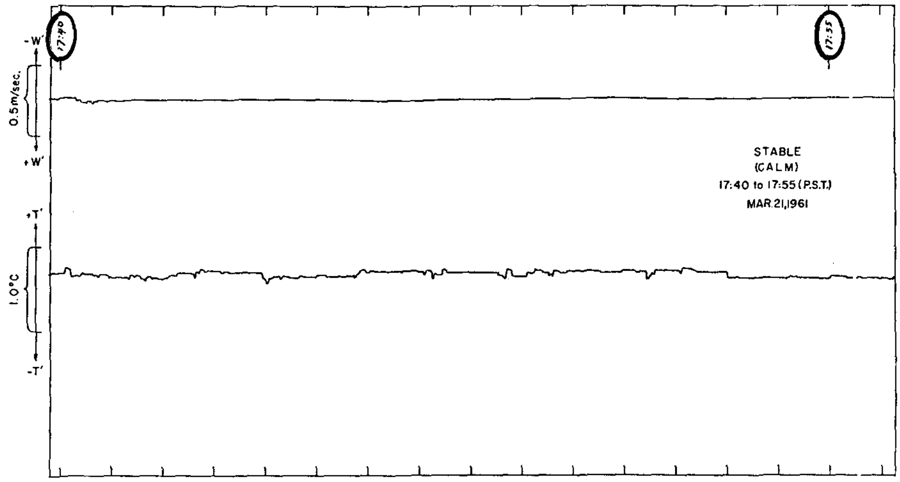

FIG. 5. $w$ and $T$ fluctuations for stable lapse rate with very low winds; time scale: 1 div = 1 min.

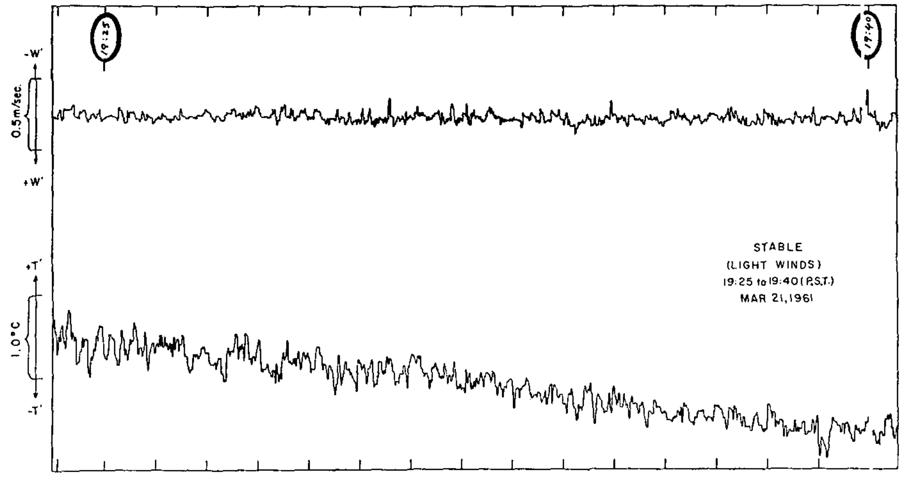

FIG. 6. $w$ and $T$ fluctuations for stable lapse rate with light winds; time scale: 1 div = 1 min.

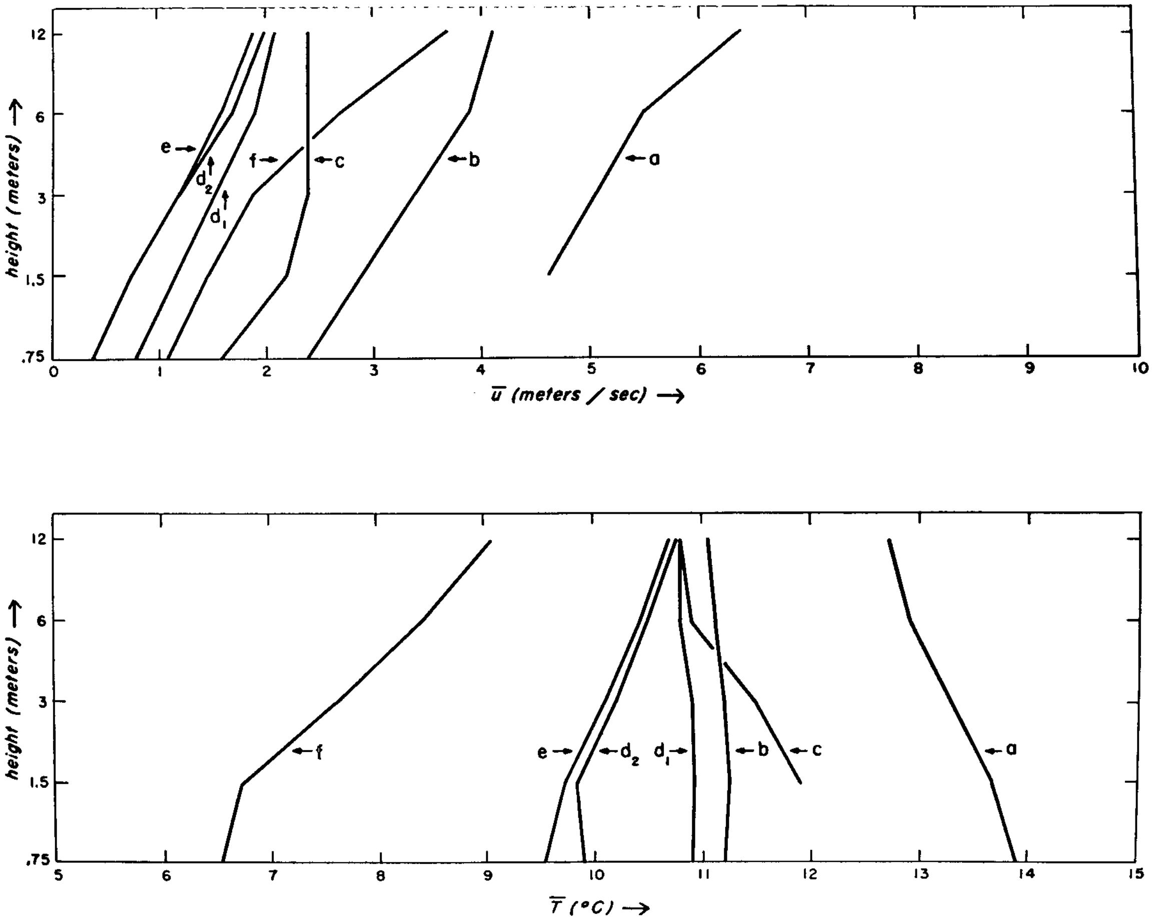

Fig. 7. Mean profiles of horizontal wind and temperature for the selected cases: *a* for Fig. 1, *b* for Fig. 2, *c* for Fig. 3, $d_1$ for beginning of Fig. 4, $d_2$ for end of Fig. 4, *e* for Fig. 5, and *f* for Fig. 6.

Figs. 1 and 2 are fairly typical of a windy day. Mechanical turbulence generated by wind shear is the dominant feature in Fig. 1 and the fluctuations in both $w$ and $T$ are rapid and of considerable magnitude. The latter part of this record represents a period of less turbulence ($\bar{u}_{3m}=3.5$ m sec$^{-1}$) and the fluctuations exhibit a decrease in amplitude as well as frequency. In Fig. 2 establishment of neutral lapse rate has brought about a virtual cessation of fluctuations in $T$, while the fluctuations in $w$ continue without restriction. Peak vertical velocities up to 0.75 m sec$^{-1}$ occur without causing any appreciable change in temperature. Here we have a dramatic illustration of the neutral case or the "adiabatic hour."

Figs. 3 and 4 are records obtained on a relatively calm day with moderate insolation. The $T$ fluctuations in Fig. 3 exhibit a bimodal structure with a most frequent temperature associated with negative $w$ and another frequent temperature with random scatter about it associated with positive $w$. This is characteristic of free convection, the bursts of higher temperatures accompanying upward motion being directly caused by the passage of convective elements. Temperature peaks associated with these disturbed periods are fairly constant in magnitude, about 2C higher than during the calm periods. Careful examination also reveals a marked asymmetry in the shape of each temperature burst. The ascent to the maximum is always gradual in contrast to the sharp descent on the other side. Fig. 4 shows the behavior of the fluctuations during transition from neutral to stable lapse rate. The transition seems to be characterized by opposing trends in $w$ and $T$. The $w$ fluctuations are slowly damped out while small fluctuations start appearing in $T$. The slight negative correlation between the two traces during this reappearance of the $T$ fluctuations clearly indicates that the lapse rate is no longer adiabatic. Towards the end of this record the $T$ fluctuations appear to diminish as the lapse rate becomes stable enough to inhibit further fluctuations in $w$.

Figs. 5 and 6 illustrate two different conditions that exist during stable lapse rates depending on wind shear. The record in Fig. 5 is contiguous with that of Fig. 4 and shows a state approaching laminar flow. Wind shear is small (see Fig. 7) and, although no discernible temperature change occurred at the 3-m level on the tower, the 1.5-m level indicated a cooling of 1C between the beginning and end of the record. The small, abrupt shifts in the S. A. T. temperature trace are attributed to inhomogeneities in the horizontal temperature field combined with some sluggishness of the recorder. Later in the evening, as the inversion deepened, the flow became turbulent again. $w$ and $T$ fluctuations recorded during this period (Fig. 6) display small and rather rapid irregular fluctuations typical of purely mechanical turbulence; the high degree of negative correlation that exists between the two furthermore indicates a downward directed heat flux associated with the stable stratification of the surface layer.

The second field test was made with an acoustic path of 50 cm and the S. A. T. outputs were recorded simultaneously on the Speedomax Recorder and a two-channel analog tape recorder. The tape recordings were made at 7 1/2 inches per sec and later played back into the Speedomax Recorder at 1 7/8 inches per sec. As expected, the smaller acoustic path length, together with the expanded time scale, revealed some of the finer details in the fluctuations. A small portion of the playback is shown in Fig. 8a.

## 3. Heat flux computations

The two quantities measured by the S. A. T. together provide a direct means for computing $H$, the eddy heat flux. Assuming steady state and horizontal homogeneity

$$H=c_p\bar{\rho}\,\overline{w'T'},$$

where $c_p$ represents the specific heat at constant pressure, and $\rho$ the density. The 15-min periods represented by Figs. 3 and 6 were selected for computation. The records were reduced manually by reading off values for every 1.36 sec. Adjustable working means used in the recording of these fluctuations appeared in all the readings. Thus, each wind reading was actually $(\alpha+\bar{w}+w')$ and each temperature reading $(\beta+\bar{T}+T')$, $\alpha$ and $\beta$ being working means for the two traces. $\overline{w'T'}$ was then obtained from the following relation:

$$\overline{w'T'}=\overline{(\alpha+\bar{w}+w')(\beta+\bar{T}+T')}$$

$$-\overline{(\alpha+\bar{w}+w')}\,.\,\overline{(\beta+\bar{T}+T')}.$$

The bars denote average over the 15-min period. Using the same data points $\overline{(w')^2}$, $\overline{(T')^2}$ and $r_{wT}$ were computed, respectively, from

$$\overline{(w')^2}=\overline{(\alpha+\bar{w}+w')^2}-[\overline{(\alpha+\bar{w}+w')}]^2$$

$$\overline{(T')^2}=\overline{(\beta+\bar{T}+T')^2}-[\overline{(\beta+\bar{T}+T')}]^2$$

$$r_{wT}=\frac{\overline{w'T'}}{[\overline{(w')^2}\,.\,\overline{(T')^2}]^{1/2}}.$$

The results are presented in Table 1.

TABLE 1. Computed values from the S.A.T. data.

| Lapse rate | $\overline{w'T'}$ [$C$ cm sec$^{-1}$] | $\overline{(w')^2}$ [cm$^2$ sec$^{-2}$] | $\overline{(T')^2}$ [C$^2$] | $H$ [cal cm$^{-2}$ min$^{-1}$] | $r_{wT}$ |
|---|---|---|---|---|---|
| Unstable | +15.85 | 1870 | 0.339 | +0.274 | +0.63 |
| Stable | −0.564 | 11.1 | 0.129 | −0.0097 | −0.47 |

The cases selected here represent rather extreme stability conditions and consequently any attempt to verify the above $H$ values with equations using eddy transfer coefficients is of little significance. A useful equation for eddy heat flux during free convection has been developed by Priestley (1959) from purely dimensional considerations:

$$H=c_p\rho h\left(\frac{g}{\bar{T}}\right)^{1/2}z^2\left|\frac{\partial\bar{T}}{\partial z}+\Gamma\right|^{3/2},$$

where $h$ represents a dimensionless constant; $g$, acceleration due to gravity; $z$, reference height; and $\Gamma$, adiabatic lapse rate. The constant $h$, which may be considered as a dimensionless eddy heat flux, has been found from both Swinbank's and Taylor's measurements to be 0.69. This value of $h$, substituted in the above equation with the mean values from the tower data, yields for the unstable case an eddy heat flux density of +0.279 cal cm$^{-2}$ min$^{-1}$ which is very close to the value obtained from the S. A. T. data.

Priestley suggests that 0.9 is probably a more accurate value for $h$. He attributes the decrease in the observed numerical value to a systematic underestimation that could arise from too long a response time in the recording instruments. If this is true, the eddy heat flux density computed from the S. A. T. data cannot be expected to produce more accurate results than those of Swinbank and Taylor since the Speedomax Recorder has lag comparable to that of the galvanometers used in the Edithvale experiments. Detailed analysis using the magnetic tape recordings made during the second Hanford field test may yield more information about the value of $h$.

No satisfactory theory has yet been developed for computing $H$ during extremely stable stratification, and

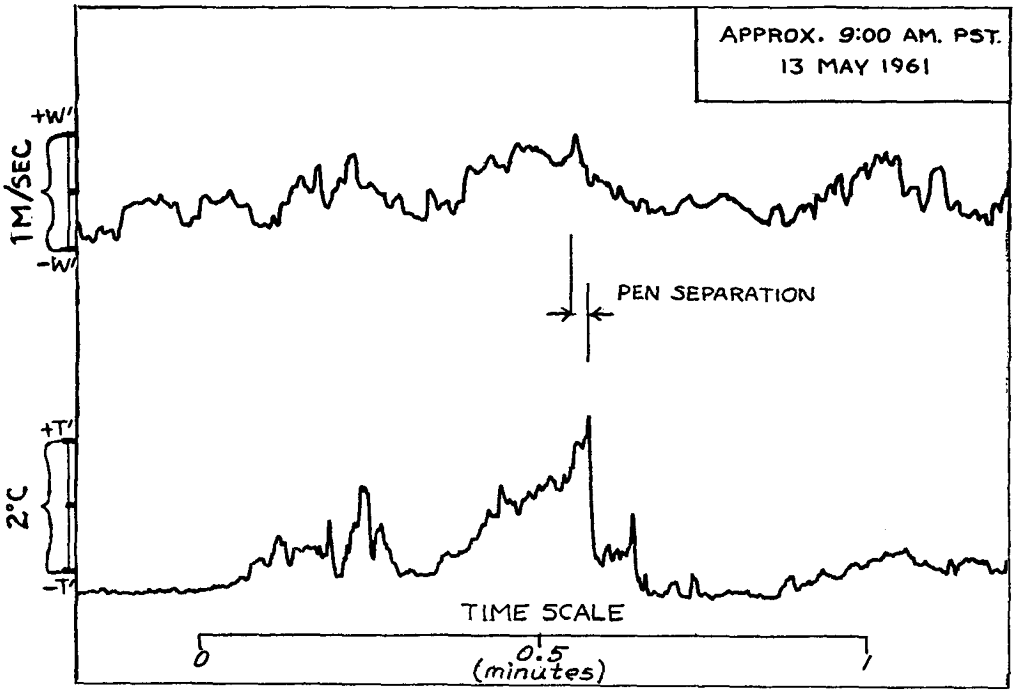

Fig. 8a. $w$ and $T$ fluctuations attributed to central traverse by a convective plume.

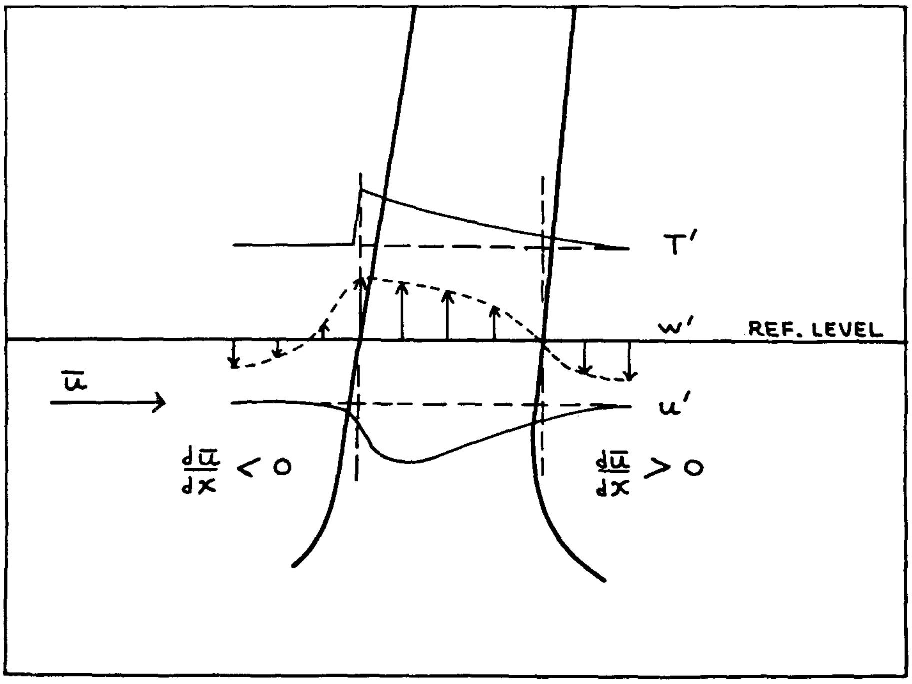

Fig. 8b. Simple model of convective plume.

so it is impossible to verify the S. A. T. flux determination for the second case.

## 4. Structure of free convection

Considerable effort has been directed in recent years towards determining the mechanism of free convection. Various modes of free convection seem to be possible, mainly depending on the stability of the surface layer. This is also suggested by the difference between Figs. 1 and 3. The sudden bursts in the temperature fluctuations of Fig. 3 indicate the existence of well organized convective elements. The S. A. T. may prove to be a useful tool for the detailed investigation of such convective elements, as is illustrated by the following example.

The second field test provided the opportunity to examine in greater detail the behavior of $w'$ and $T'$ during free convection. The winds were very low ($u_{3m} < 1$ m sec$^{-1}$) so that the effect of mechanical turbulence at the reference level could be considered minor compared to buoyancy. An interesting part of the record is reproduced in Fig. 8a. Good correlation exists between $w'$ and $T'$, but marked differences are also apparent in their structure. During periods of downward motion when the $w$ trace still shows fluctuations, the temperature stays remarkably constant, suggesting that the reference level is in an adiabatic layer. Upward motions, on the other hand, are associated with significant fluctuations in temperature. Furthermore, the gradual rise and the sudden drop in temperature which do not have their counterpart in the vertical wind are noteworthy.

These observations seem to be consistent with the concept of continuous plumes of rising air passing the instrument, as schematically indicated in Fig. 8b. Because the average horizontal wind speed increases with height, the rising air has, on the average, a lower horizontal wind speed than the surrounding descending air. Consequently, horizontal divergence develops in front of the plume which tends to spread out the transition from cold descending air to warm ascending air, and horizontal convergence develops in the rear of the plume which tends to sharpen the discontinuity in temperature. It is as if a micro-cold front is formed at the rear of each plume. It will be of interest to investigate in greater detail the structure of these convective elements with more comprehensive instrumentation.

### REFERENCES

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Priestley, C. H. B., 1959: Turbulent transfer in the lower atmosphere. Chicago, Univ. Chicago Press, 130 pp.