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Recognition of Convection Currents

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Turbulent Heat Exchange Computer

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3.13. RECOGNITION OF THE PRESENCE OF CONVECTIVE CURRENTS WITHIN A NONSATURATED TURBULENT LAYER OF THE ATMOSPHERE[1]

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ABSTRACT

The presence of convective currents in the ground layer of the atmosphere is detected by the magnitude of the correlation coefficient existing between simultaneous values of the air temperature and the roughness of the air. These quantities are measured by a psychrograph and a vertical water-column accelerometer mounted on an airplane flying through the turbulent air. Values of the correlation coefficient are found to depend on the intensity of convection and associated conditions such as stability, cloud cover, height, the interval over which the values are averaged, and the roughness of the air. It is observed that convection in the slightly turbulent air of the "cloud layer" leads to a correlation coefficient approaching unity. In a turbulent stream of air with neutral stability, the coefficient attains only small values (0.0 to 0.2), while in an air mass heated from below higher values (0.4 to 0.8) are found. In extremely turbulent air the coefficient may be low (0.2) in spite of the presence of active convection in the "cloud layer" above the ground layer. These low values are interpreted to mean that convection cannot exist in an unstable ground layer if the turbulence is sufficiently great. The sensitivity of the correlation coefficient to the interval over which the observations are averaged makes it a valuable means of determining the sizes of convecting parcels or cells.

Massachusetts Institute of Technology, Geophysics Research Directorate
AIR FORCE CAMBRIDGE RESEARCH CENTER
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[1] Contribution No. 572 from the Woods Hole Oceanographic Institution. Research sponsored by the Office of Naval Research under Contract No. N6onr-277, Task Order No. II, NR-082-081.

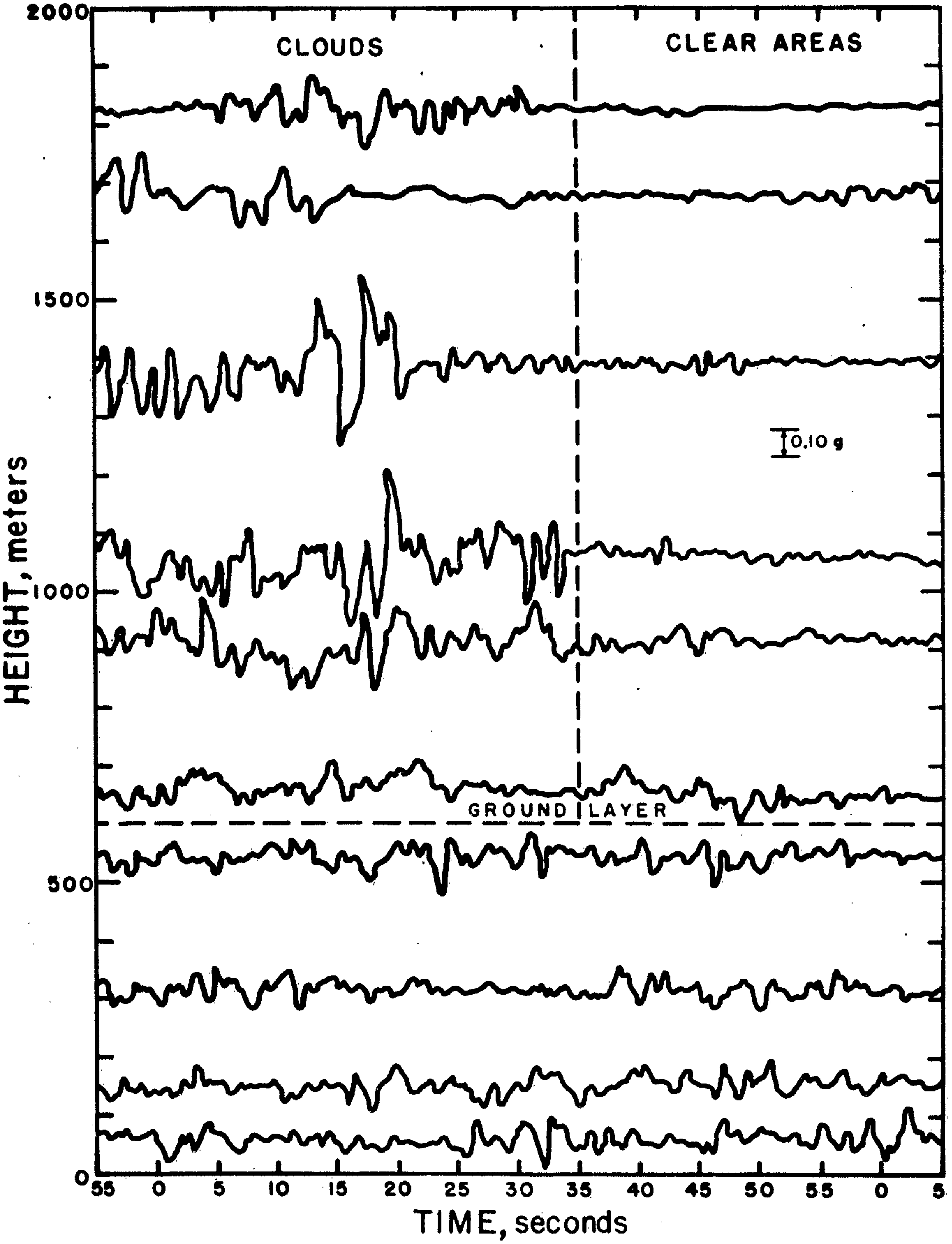

Fig. 3.13.1. Distribution of vertical accelerations imparted to an aircraft in the ground layer and cloud layer of the atmosphere.

The first case considered is a purely turbulent stream of heterogeneous fluid with no mean gradient of turbulence or temperature. In such a fluid, regions with any given degree of turbulence have equal probabilities of being either warmer or cooler than the mean. A correlation computed from pairs of values measured in this fluid will approximate zero.

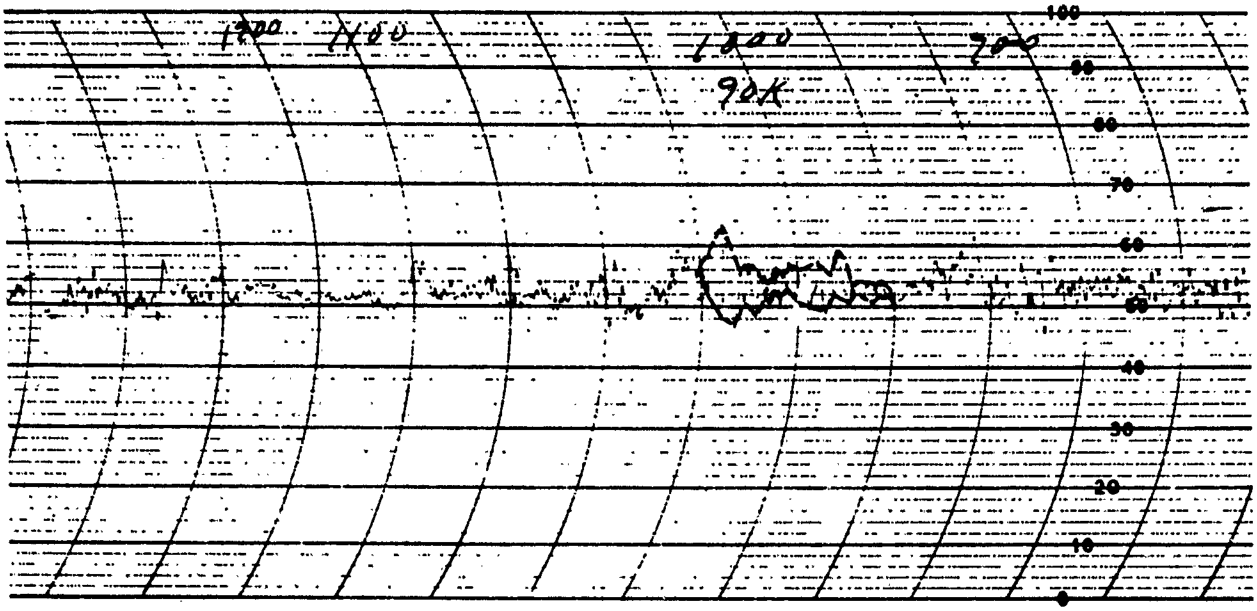

Fig. 3.13.2. Accelerometer trace with drafted line defining *turbulence index*.

One case of convection-free turbulence frequently encountered in nature is found in a ground layer composed of a heterogeneous fluid with vertical gradients of both the turbulence and potential temperature. An airplane flying through this medium will receive innumerable individual accelerations and temperature variations. These variations are the elements effective in the transport of properties and a correlation would be found to exist between them, if sufficiently fast recording elements were available. However, when a correlation is computed between averages of the roughness and the temperature variations, the coefficient will be zero if the averages are made over distances long relative to the gust sizes.

The effect of initiating autoconvective motions to the stream by applying heat to the lower surface is to add a longer enduring interval of increased turbulence to the existing random sequence of turbulent gusts. The rising parcels of air will have temperatures higher than their environment, and if averages are taken over time intervals nearly equal to the time of passage of the plane through a convective bubble or cell then the correlation coefficient approaches unity. The averaging interval used will affect the value of the correlation yielded since increasingly longer intervals lessen the effect of the shorter enduring turbulent and convective motions.

The following demonstration is given to show the sensitivity of the temperature-turbulence index correlation coefficient to intensity of convection and its relative insensitivity to frequency of occurrence of convective cells. From the definition of the correlation coefficient,

$$r = \sqrt{1 - (S_y/\sigma_y)^2} \tag{1}$$

CASE 1: Gulf of Maine, 3 February 1950

The 130-km offshore sounding of this set of data showed such a strong relation between turbulence index and mixing ratio that it was noted by inspection. Since convection was made evident by the formation of 3/10 coverage of small cumulus clouds at the top of the ground layer, it was thought that the relation must be associated with the convective activity and might act as a means of recognizing convection when cumulus clouds do not form.

Computations of the correlation coefficients have been carried out for three sets of data: turbulence index and temperature over Portland, Maine; and turbulence index and temperature, and turbulence index and mixing ratio at 42° 35′N, 69° 30′ W over the relatively warm waters of the Gulf of Maine. Since the plane was continually ascending in a helix and gradients existed in the temperature, the mixing ratio, and the turbulence index, changes of these properties with height had to be eliminated before the correlation computation could be performed.

The results of the computations are presented in Table 3.13.1.

Table 3.13.1. Correlation coefficients, 3 February 1950.

Portland, Maine		Gulf of Maine (42°35′N, 69°30′W)			
Height (m)	Temp. Turb. index	Height (m)	Temp. Turb. index	Height (m)	Mixing ratio Turb. index
120– 610	+0.6	210– 610	0.0	150– 300	0.1
640–1220	+0.3	640–1220	+0.7	300– 600	0.3
1250–1520	−0.2	1250–1610	−0.5	600– 900	0.6
1580–1830	−0.3			900–1200	0.5
				1200–1500	0.4

On this day a cold air mass was moving from the northwest over the warmer waters of the Gulf of Maine. No cumulus clouds were present over Portland but up to 3/10 were developing in the second sounding area 130 km downwind from Portland. The turbulence over the land was unusually great, frequently imparting vertical accelerations of 300 cm/sec^2 to the two-engined airplane. The general turbulence moderated considerably over the water, although a few accelerations still attained 300 cm/sec^2. These strong accelerations were less frequent and longer enduring than those encountered over land.

The Gulf sounding shows large values of the correlation and a variation with height which is interpreted as the effect of convection. The zero correlation is interpreted to mean that any convective motion present at the lowest level was too weak and underdeveloped to be detected by the present method, but autoconvective currents were well developed at the higher level. The negative coefficient indicates that the air parcels were decelerating (cooler) as they penetrated the inversion at the top of the ground layer. The mixing ratio correlation does not, of course, change sign at the inversion as high values of the mixing ratio are still associated with the rougher air.

Since the Portland sounding yields but a single high value at the lowest level and no trace of cumulus clouds existed in the area, it is concluded that free convection was absent or very weak. The high value (0.6) found in the first 600 m is thought to be evidence of forced convection discussed in the previous section.

CASE 2: Nantucket Island, 5 September 1950

On this day a cold air mass swept out from land over the warm waters of Nantucket Sound, over the solar-heated island of Nantucket and out over the cooler sea. Over Nantucket Sound 1/10 (measured) cumulus clouds had formed, over the island 3/10, while immediately to leeward 6/10 cumulus were forming. Four long horizontal runs were made upwind and downwind over the island at different altitudes. Several short runs were made in selected regions. The correlations computed from these flights are presented on a cross section. Fig. 3.13.3, of the atmosphere over Nantucket. Values of the correlation are plotted at the appropriate height with double headed arrows used to indicate the distance over which the data were collected for the computation.

The great increase in the value of the coefficient as the air is modified and heated by the island is coincident with the increase in the activity of convection. This is interpreted as confirmation of the proposition that the presence of convection in a turbulent stream can be detected by means of the correlation coefficient.

One short run was made above the ground layer through a cloud and the air immediately surrounding it. The correlation coefficient was found to be +0.9 in this case of unquestioned convection. Several short runs made between clouds yielded coefficients of 0.0. The existence of a correlation of 0.9 in the "cloud layer" immediately above a layer in which correlations of only ±0.2 existed emphasizes the role of condensation in accelerating convection. The increase in temperature due to the condensation of water vapor combined with its accompanying increase in buoyant force greatly increases the value of the correlation coefficient. In contrast, convection motions in the turbulent ground layer have as their source of energy only the relatively small temperature differences resulting from contact with a heated surface. The mixing of the turbulent air rapidly diminishes the temperature difference between a parcel of air originally near the heated surface and the surrounding air. Thus the difference grows smaller as the parcel moves through the air. In the "cloud layer," however, the temperature difference between the cloud and the surrounding air continually increases until a stable layer is reached which halts the cloud's ascent.

Over the island and downwind at the higher levels the value of the coefficient rises to the significant values 0.6 to 0.8. It is in this region that convection occurs and the cumulus clouds above the level of the airplane attain 6/10 coverage. The drop from a value of 0.4 to −0.2 at low levels leeward of the island coincides with the change from a heat source to a heat sink at the surface.

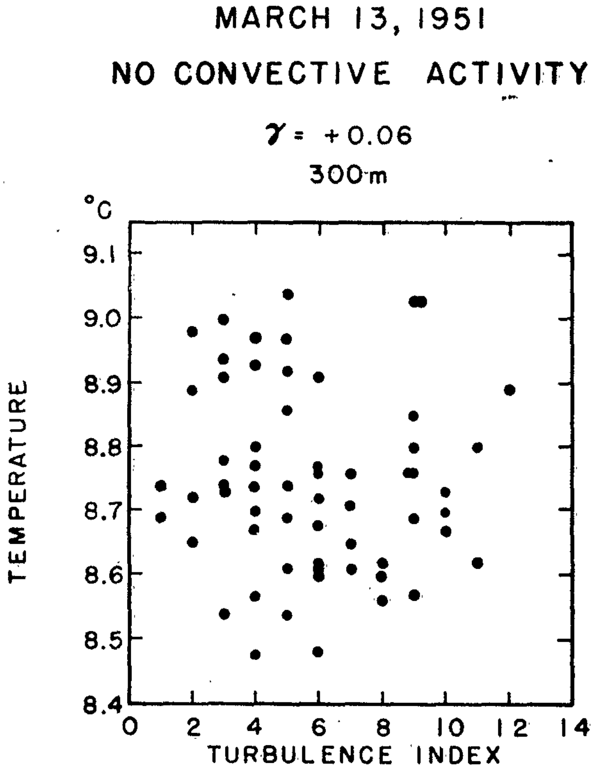

Fig. 3.13.4. Plot of temperatures and turbulence indices observed at 300 m, 13 March 1951, a day with little or no convective activity. Correlation coefficient equals 0.06.

CASE 3: Middleboro-Fall River, Massachusetts, 13 March 1951

Observations were made on this day as convection was considered to be weak or absent. A 10/10 coverage of stratus with 600 m base existed, cutting off the solar radiation from the ground. The following table gives the computed values of the correlation coefficients. Sixty to eighty pairs of values were used in the computation. The probable error of a correlation coefficient determination is thus about ±0.1. Correlations were obtained at various altitudes with different averaging intervals. The averaging interval is expressed in both time and distance traveled by the airplane.

Table 3.13.2. Correlation coefficients between temperature and turbulence index. Middleboro-Fall River, Mass., 13 March 1951

Altitude (m)	Averaging interval			
	300 10	600 20	1200 40	2400 (m) 80 (sec)
150	0.22	0.39	0.44	0.47
300	0.06	−0.10	−0.13	−0.14
550	0.24	0.33	0.48	0.34

The low values entered in the 10-sec column agree with the expectation that low values would be associated with the absence of convection. The higher values found for the longer intervals may be associated with weak large-scale convection. A plot of the values of temperature and turbulence index, Fig. 3.13.4, shows the random distribution characteristic of turbulence without convection.

CASE 4: Cape Cod, Massachusetts, 15 March 1951

The one short run presented here was made under one of the lines of cumulus clouds called "cloud streets" by the glider pilots who travel many miles with the lift from their updrafts. This particular line of cumulus originated during the passage of the air over the Elizabeth Islands which form a chain lying roughly parallel to the wind direction. The combination of slight turbulence, instability, heating, and frictional drag by the islands was suitable to produce an enduring convection pattern. The "cloud street" extended for more than 20 km. The horizontal run was made at 600 m perpendicularly under the line of clouds. Figure 3.13.5 presents the unreduced records of the psychrograph and accelerometer. The increase in turbulence under the clouds was phenomenal. Accelerations in the clear air ranged around 50 cm/sec² while under the "street," accelerations greater than 200 cm/sec² were recorded.

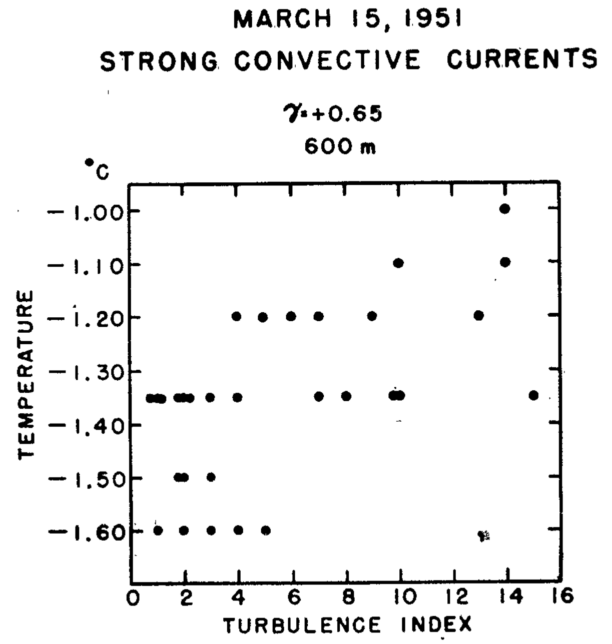

Fig. 3.13.6. Plot of temperatures and turbulence indices observed at 600 m, 15 March 1951.

The correlation coefficient computed from the twenty pairs of values obtained during the 6-km run was found to be +0.65. From this case, the only one in which it can be stated positively that a convection pattern existed in the ground layer, it is demonstrated again that the correlation coefficient is capable of detecting the presence of convection in a turbulent stream.

Figure 3.15.6 shows how the random distribution of points characteristic of turbulence (Fig. 3.13.4) changes when convection is present in the stream.

CASE 5: Duxbury-Middleboro, Massachusetts, 4 April 1951

Heating of the land in this region initiated cumulus cloud formation a few hours after sunrise. The amount increased rapidly until at noon, the approximate time of the flights, a general overcast of stratocumulus had formed. Not all of this cloud cover can be attributed to convective activity as strong convergence was operative in the atmosphere in connection with a closed low aloft. In the overcast there were large broken areas with 6/10 to 9/10 coverage of cumulus clouds. The lowest 150 m of air had a strongly superadiabatic lapse rate, while the next 1000 m was slightly stable (+1°C increase in potential temperature in 1200 m). As a result of this combination of instability and stability, the turbulence was very intense in the lowest level but died off rapidly with height in the stable region.

Correlations have been determined primarily from the data obtained in the broken areas as the temperature deviations under the thick overcast were small. Table 3.13.3 has been prepared to present the correlations obtained at the various altitudes with different averaging intervals.

Table 3.13.3. Correlation coefficients between temperature and turbulence index. Duxbury-Middleboro, Mass., 4 April 1951

Altitude (m)	Averaging interval					
	150 5	300 10	600 20	1200 40	2400 80	3600 (m) 120 (sec)
150	0.53	0.20	0.22	0.29	0.39	....
300	....	0.47	0.47	0.51	0.44	....
800	....	0.44	0.49	0.41	0.66	....
1350	....	−0.22	−0.30	−0.40	−0.80	−0.95

The routine of data reduction was changed to make 5-sec averages from the 150-m level records. This was done as it was obvious from inspection that a short-period relation existed that was completely lost by the usual computation of 10-sec averages. No other level showed evidence of a 5-sec relation. The high coefficient value of 0.53 is associated with the proximity of the heated surface. It is considered another example of forced convection produced by the roughness of the underlying surface.

The coefficients determined for the other heights show that higher values are obtained from the longer averaging intervals. The 10-sec interval and the 120-sec interval values of the temperature and the turbulence index for the 1350-m level have been plotted in Fig. 3.13.7 to show the transformation from the nearly random distribution to a linear relation with very little scatter of the observed points.

A steady shift occurs with height of the maximum coefficient value to longer intervals, until, at the 1350-m level and 3600-m interval, the large value of −0.95 is attained. This height-interval relation suggests a structure of convective parcels or cells that is small near the ground and expands with height so that

that whenever the turbulence exceeds a certain value the warmer parcels of air are diffused throughout the air mass before their buoyancy forces can accelerate them and thus produce free convection. The turbulence alone is not the controlling factor, as the intensity of the heat source also has a measure of control. However, with extreme turbulence the transport of heat is great and a large density difference between the top and bottom of the air column cannot develop, thus eliminating one of the requirements for initiation of convection.

From the success of the correlation coefficient in detecting convection in the preceding cases, it is concluded that little or no convection was occurring in the ground layer on this day. Further it is concluded that the vigorous convection showers occurring in the "cloud layer" were possible because the lower degrees of turbulence in this layer could not transport the huge amount of heat arriving from below and allowed the development of the necessary density differences.

3.13.3. SUMMARY

It is concluded that the correlation coefficient existing between temperature and turbulence index is capable of detecting the presence of free convection in a turbulent stream. This conclusion is based on the high values obtained in ground layers in which convection was known to exist, such as occurred on 5 September 1950, 15 March 1951, and 4 April 1951. Conversely, small values occurred on 13 March 1951, a day with little or no convection activity. The observations bear out the demonstration that the coefficient is dependent primarily on the intensity of convection.

The correlation coefficient should not be used alone as a test for convection, but should be used in conjunction with other means of analysis. Analysis of the processes operating in an air mass and their relative importance may be aided greatly by the computation of the temperature-turbulence index correlation coefficient.

Applying the correlation test to a highly turbulent air stream it is found that the flow does not break down into convective motions even though the air mass is in unstable thermal equilibrium and convection is active in the overlying layer.

The sensitivity of the correlation coefficient to the interval over which the values are averaged makes it a valuable tool for the study of the structure of convective parcels or cells.

3.13.4. ACKNOWLEDGMENTS

The major part of the airplane observing necessary for the completion of this paper was done by Kenneth McCasland. Joanne S. Malkus obtained the observations over Nantucket Island on 5 September 1950.

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4.4. A RECORDING COMPUTER FOR THE DIRECT MEASUREMENT OF THE TURBULENT HEAT EXCHANGE IN THE ATMOSPHERE

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ABSTRACT

An instrument has been developed at the Woods Hole Oceanographic Institution which measures the instantaneous sensible heat exchange through a horizontal surface by the turbulent motions of the atmosphere. The instrument multiplies electronically the simultaneous signals from a bead thermistor, a hot-bead anemometer, and a horizontal-axis vane attached to a microtorque potentiometer. Heat flow values are summed over any given length of record with a ball-disc integrator. Values obtained are presented and compared with determinations from airplane temperature measurements. Confirmation of the validity on Priestley and Swinbank's objection to the basic assumptions used in the development of the classical diffusion equation is noted by plotting simultaneous values of the temperature against vertical velocity.

Massachusetts Institute of Technology, Geophysics Research Directorate
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[1] Contribution No. 558 from The Woods Hole Oceanographic Institution.

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4.4.1. INTRODUCTION

The concept of the turbulent transport of properties by the atmosphere has been developed by summing the amounts of material or properties passing up or down through a horizontal surface.

The exchange is expressed by the following equation,

$$S = \frac{1}{Ft}\left[\sum m\uparrow s\uparrow \; - \sum m\downarrow s\downarrow\right] \tag{1}$$

in which m is the mass of a parcel, s the concentration of a property, F and t are the area and time interval. The small arrows indicate the direction of motion. Since in the past these small, individual mass and property exchanges were unobservable, Eq. (1) was developed further by Taylor [4] and Schmidt [3] to express the exchange in the more usable terms of the geometric distribution of a property. The differential diffusion equation,

$$S = -A\partial s/\partial z \tag{2}$$

introduces A, the coefficient of turbulent mass exchange. The value and variation of the coefficient with height, locale, and stability has been the object of numerous studies. The difficulty of determining a value of the exchange, S, which properly describes a given area has retarded the increase of our knowledge of the coefficient and its range of variation. The turbulent heat exchange computer described in this paper is an attempt to construct an instrument capable of detecting and recording the elements entering into the heat flow through a surface.

The basic notion of an instrument which could multiply the air temperature by the wind speed and the sine of the inclination of the wind thus yielding the heat flow was first suggested to the authors by Jeffries Wyman. Such an instrument observes the very elements that produce the heat flow and are the fundamental quantities used in the development of the diffusion equation.

One difficulty in the construction and use of the instrument is determining a size of vane and a lag of sensing elements and multiplying circuits that can respond to the variations causing the flow. The instrument constructed can only approximate the extremes of variation that the passing air presents, so the heat flow values determined cannot be exact. Further, it cannot be stated which range of eddy sizes or frequencies are instrumental in producing the bulk of the heat flow. The only certain way of determining whether the instrument can detect and compute the contribution to the heat flow of eddies within the critical range of sizes is to operate the computer in a region where the heat flow is known. Such an opportunity to test the equipment occurred in the summer of 1950, when airplane soundings were made by Joanne Malkus and Kenneth McCasland over Nantucket Island in connection with studies of convection, diffusion, and air flow over a heated island. From these temperature soundings which were made upwind, downwind, and over the island, the sensible heat flow into the atmosphere has been computed.

The diffusion equation (Eq. (2)) is based on the assumption that a parcel travels a distance l before mixing with its surroundings and that it possessed the concentrations s equal to the mean of s at the level at which it was last at rest. This assumption has been criticized by Priestley and Swinbank [2] on the grounds that mixing is a continuous process and that air parcels at rest have concentrations differing considerably from the mean. In the case of the property of temperature, they deduce that buoyancy forces will produce a component of the heat flow that is always upward. If this term is predominant, the flow will be upwards regardless of the sign of the temperature gradient. Since the instrument records both the temperatures and the vertical velocities of parcels, the data can be used to determine whether the parcels at rest vertically have individual temperatures equal to the mean or have temperatures distributed over several degrees either side of the mean.

4.4.2. DESCRIPTION OF THE TURBULENT HEAT EXCHANGE COMPUTER

4.4.2.1. *Detecting Elements*

The detecting elements of the instrument are a temperature element, an anemometer, and a small horizontal-axis vane. The temperature device is a ceramic bead thermistor whose electrical resistance is controlled by the temperature (Hales, [1]). The time constant of this resistor is 1.5 sec. The element is connected in a self-balancing bridge circuit (Fig. 4.4.1). To bring the variations on scale, the "Temp Zero" potentiometer is provided. In the present circuit, current through the thermistor element is kept at a low value, thus preventing any electrical heating which might affect the indicated temperature. Ganged with the bridge slide wire is a second potentiometer whose function will be explained later.

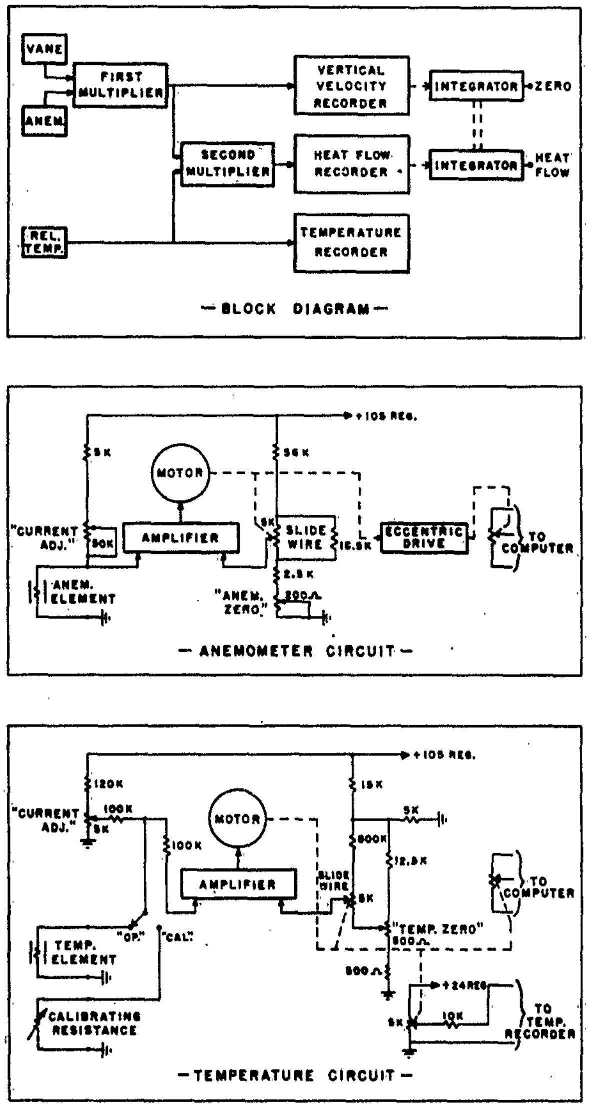

Fig. 4.4.1. Block diagram of computer with detail of anemometer and temperature circuits.

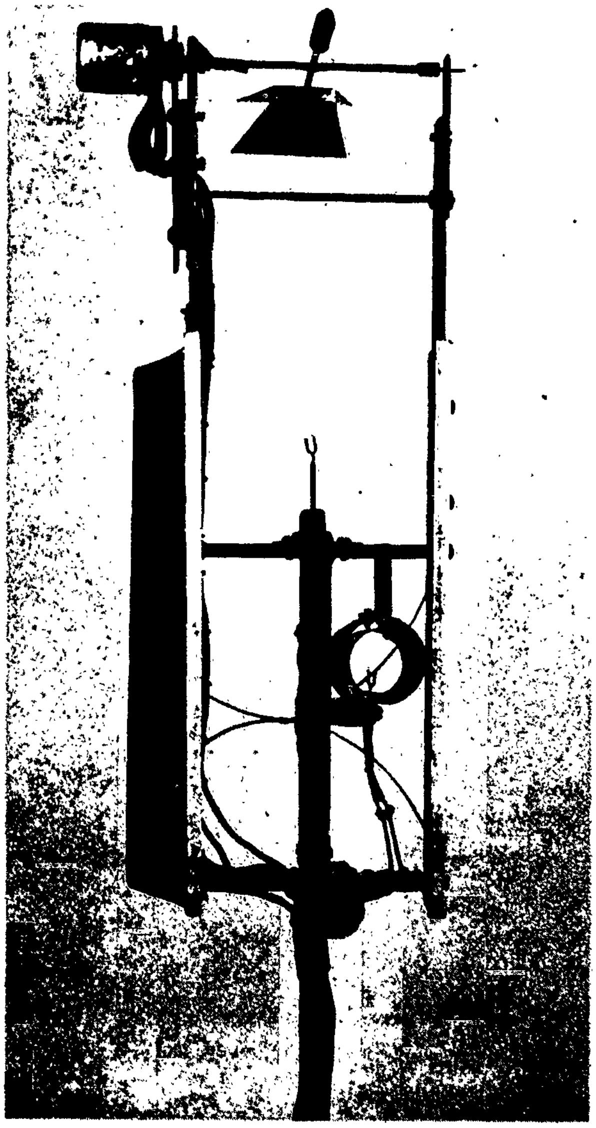

Fig. 4.4.2. Photograph of sensing unit showing horizontal-axis vane, shielded temperature element, and bead anemometer.

circuit multiplies the signals of the velocities by the temperature variations to give the heat flow which is then recorded. The signals are multiplied by connecting to the power stage (Fig. 4.4.3) a potentiometer driven by the temperature bridge-balancing motor. The output of this potentiometer is proportional to the product of the temperature by the vertical velocities and hence gives the instantaneous heat flow. This completes the description of the computer. Integration of the heat flow is carried out from the records of the vertical velocities and the heat flows.

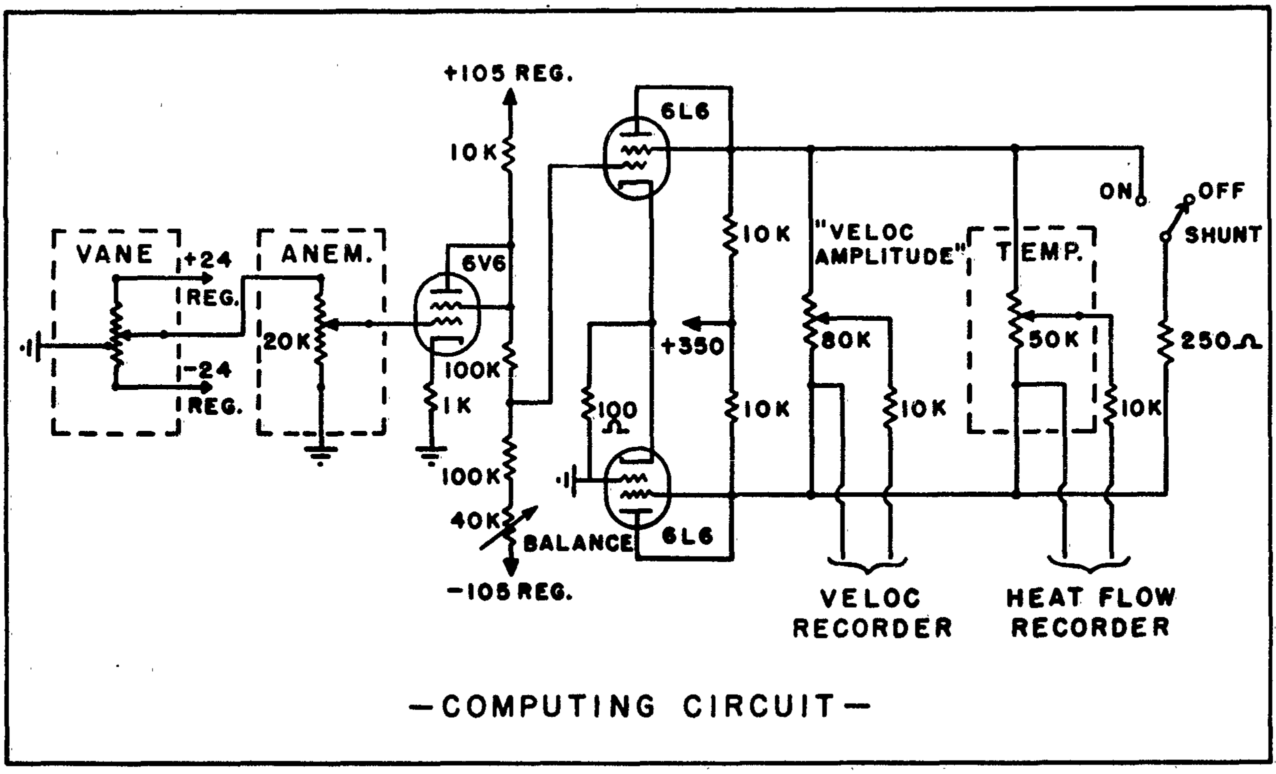

Fig. 4.4.3. Detail of computing circuit.

4.4.2.3. *Integration and Operation of the Instrument*

Instantaneous values recorded on the charts are summed with a ball-disc integrator. The integrator is in effect a variable speed device whose output is proportional to the speed of the disc and to the position of the balls. If the disc is caused to rotate at a rate proportional to the chart time, and if the balls are positioned by the chart trace, then the total registered by the output counter will be a measure of the area included under the chart trace.

It is immediately apparent that the proper evaluation of the heat flow record depends upon the summation of the mass transport being equal to zero. In practice a sum equal to zero can rarely be attained, since many hours would be consumed trying to adjust the tilt of the detecting vane so that the velocities would add up to zero. Accordingly, the instrument has been designed without concern for the absolute vertical, that is, the vertical component is not measured in absolute terms with respect to the direction of gravity. Rather it is more convenient, and also more significant, to assume that the summation of the vertical components must equal zero over a given time, and to adjust, with an additive term, all the individual recorded values so that this does occur. In this way the surface through which the transport is being measured is oriented parallel to the plane of flow of the air. The process is more clearly expressed by the following equations. The assumption is made that

$$\bar{\rho}\,\bar{w} = \bar{\rho}\sum w'/n = 0 \tag{4}$$

for a sufficient number of measurements of w'. Whenever the instrument is not set up vertically or an up or downslope wind is being measured

$$\bar{\rho}\sum w'/n = \bar{w}_{\text{obs}}\,\bar{\rho} \neq 0. \tag{5}$$

By subtracting $\bar{w}_{\text{obs}}$ from the individual values

$$\bar{\rho}\sum(w_1' - \bar{w}_{\text{obs}}), \quad (w_2' - \bar{w}_{\text{obs}}), \quad \ldots (w_n' - \bar{w}_{\text{obs}})/n = 0 \tag{6}$$

the reference surface for diffusion is made parallel to the plane of flow. By orienting the surface in this manner, advective contributions to the heat flow are eliminated. A mechanical means of subtracting $\bar{w}_{\text{obs}}$ will be described later.

The computer produces a record of the instantaneous values of $c_p\bar{\rho}(\bar{w} + w')(T')$, where T' is the deviation from an arbitrary zero temperature, usually 1° or 2°C below the lowest value of T'. It is necessary to eliminate the $\bar{w}T'$ term from the product to obtain the turbulent heat transport. The method of accomplishing this elimination can now be demonstrated. The operation of the instrument in the field is as follows. After the vane is set up in the wind so that $\bar{w}$ is small, the temperature zero is adjusted so that T' is always positive. The instrument is run for about 5 min, obtaining values of $\bar{w} + w'$, T', and $\bar{w}T' + w'T'$. After this run, another is made with the temperature "fixed" at the average temperature, T', by substituting a constant resistance for the variable resistance of the thermistor. The resulting traces when integrated later are used to correct any inequalities in the recorders and to subtract the $\bar{w}T'$ term from the heat flow record.

The application of the ball-disc integrator to the four records can now be described with the aid of Fig. 4.4.4. The chart is moved past a stylus at a rate which can be adjusted to suit the operator. The chart drive is coupled directly to the integrator disc thus causing the disc speed to be a function of time. By moving the handle, the operator positions the stylus on the trace, following it as the chart moves. Since the chart is recorded with a curved "Y" coordinate, the stylus arm length is made exactly equal to that of the recording pen.

The "displacement linkage" is shown schematically in Fig. 4.4.4. Basically, it consists of four concentric elements inserted between the stylus arm and the rack and pinion drive to the integrator balls. Each element takes the form of a wafer, each of whose center hole encompasses the shaft which connects to the integrator balls and operating handle, the whole assembly moving with the handle. The angular position of the "stylus wafer" relative to that of the "displacement wafer" is controlled by the "zero adjustment" and associated spring. Thus, with other elements undisturbed, the position of the trace is in effect varied by the "zero adjustment."

The "displacement wafer" is linked to the "output wafer" through the spring loaded equalizer stop screw or the fixed stop screw, depending on the position of the shift lever. If the lever is switched to "Heat Flow" the equalization adjustment becomes active, and operates similarly to the "zero adjustment."

Thus we have in effect a control over the average value of the heat flow trace relative to that of the velocities trace, and an over-all control which varies both by the same amount. The two adjustments are arranged so that their effects are cumulative.

The following operation of equalization serves to eliminate systematic errors in the two channels, and allows the subtraction of $\overline{\overline{w}T'}$ from the record of $\overline{w}T' + w'T'$.

(a) The vertical velocity record for the first run is placed on the integrator and measured. The "zero adjustment" dial is turned so that subsequent measurements of the trace yield zero.

(b) The vertical velocity record for the second run is placed on the integrator and measured until a point is reached near the end of the run at which the summation of the vertical velocities equals zero.

(c) The corresponding point on the heat flow record obtained with the fixed temperature is located. This length is integrated and set equal to zero by turning the "equalizer" dial. The displacement of the linkage now represents $-(\overline{\overline{w}T'}$ + systematic errors).

(d) The heat flow record obtained with the variable temperature is placed on the integrator and measured. The final result on the counter at the end of the run represents the desired $\overline{w'T'}$ free of systematic errors. If later calculation shows that $T_{\text{fixed}} \neq \overline{T'}$, then a correction term $\overline{w}(\overline{T'} - T_{\text{fixed}})$ must be added.

4.4.2.4. *Accuracy Specifications*

No attempt to define the accuracy of this instrument has been made from an analysis of its component parts. The dynamic response and damping of the detecting vane is undetermined and it was deemed inadvisable to expend the time and effort to determine it either theoretically or experimentally. The same holds true for the various electrical and mechanical units involved. The two servomechanisms used in the anemometer and temperature circuits introduce time lags which further complicate the analysis of errors, as does also the movement of the recorders.

Instead of carrying out a detailed analysis and synthesis of errors and time lags, it was decided to compare the results from this instrument with those yielded by a completely different system of measurement. A discussion of this work and the results obtained is presented below.

4.4.3. HEAT FLOW MEASUREMENTS

The computer has been used to measure heat flows on several days when simultaneous observations of the temperature made from an airplane were available. The sounding airplane, equipped with a recording psychrograph, made four ascents in the vicinity of Nantucket Island. One helical ascent was made 2 km upwind from the island, another over the center of the island, another about 2 km leeward of the island, and the last 8–10 km leeward. Heat flows have been computed from the accumulation of heat in the atmosphere as the water-cooled air blew over the warmer island. Flows measured in this manner were compared with the computer results. The good agreement between the two determinations indicates that the size and damping characteristics of the vane, the lags of the thermal elements, and the lag of the multiplying circuit introduce no serious error into the heat flow calculation.

Table 4.4.1 has been prepared to present the measured values. The first column, after the date of the observation, gives the heat flow value determined by the computer expressed in cal/cm^2 sec. Three values of the flow determined from the airplane soundings are presented next. The first column under the heading gives the average heat flow over the first 2 or 3 km of heated land. The second column represents the average over 3–5 km of land plus 1–2 km of cooler water. The last is the average over 4–8 km of cooler water.

Table 4.4.1. Heat flow computations.
(cal/cm² sec)

Date	Heat exchange computer	Airplane observations 1–2	2–3	3–4
9 Aug. 1950	$+3.5 \times 10^{-3}$	$+10 \times 10^{-3}$	$+6.3 \times 10^{-3}$	-16×10^{-3}
14 Aug. 1950	$+7.8 \times 10^{-3}$	$+14 \times 10^{-3}$	$+1.9 \times 10^{-3}$	-1.2×10^{-3}
28 Aug. 1950	$+6.5 \times 10^{-3}$	$+4.7 \times 10^{-3}$	$+9.1 \times 10^{-3}$	$+0.7 \times 10^{-3}$
5 Sept. 1950	$+22 \times 10^{-3}$	$+8.8 \times 10^{-3}$	$+4.8 \times 10^{-3}$	-0.2×10^{-3}
Average	$+10.0 \times 10^{-3}$	$+9.4 \times 10^{-3}$	$+5.5 \times 10^{-3}$	-4.2×10^{-3}

Since the computer was operated at the North Nantucket Airport about 3–4 km from the windward shore (in most cases), it is to be expected the computer values would agree best with the first column of the airplane observations as, indeed, they do.

A scatter diagram, Fig. 4.4.5, of individual vertical velocities of the turbulent air plotted against simultaneous temperature readings shows the validity of Priestley and Swinbank's objection to the assumption

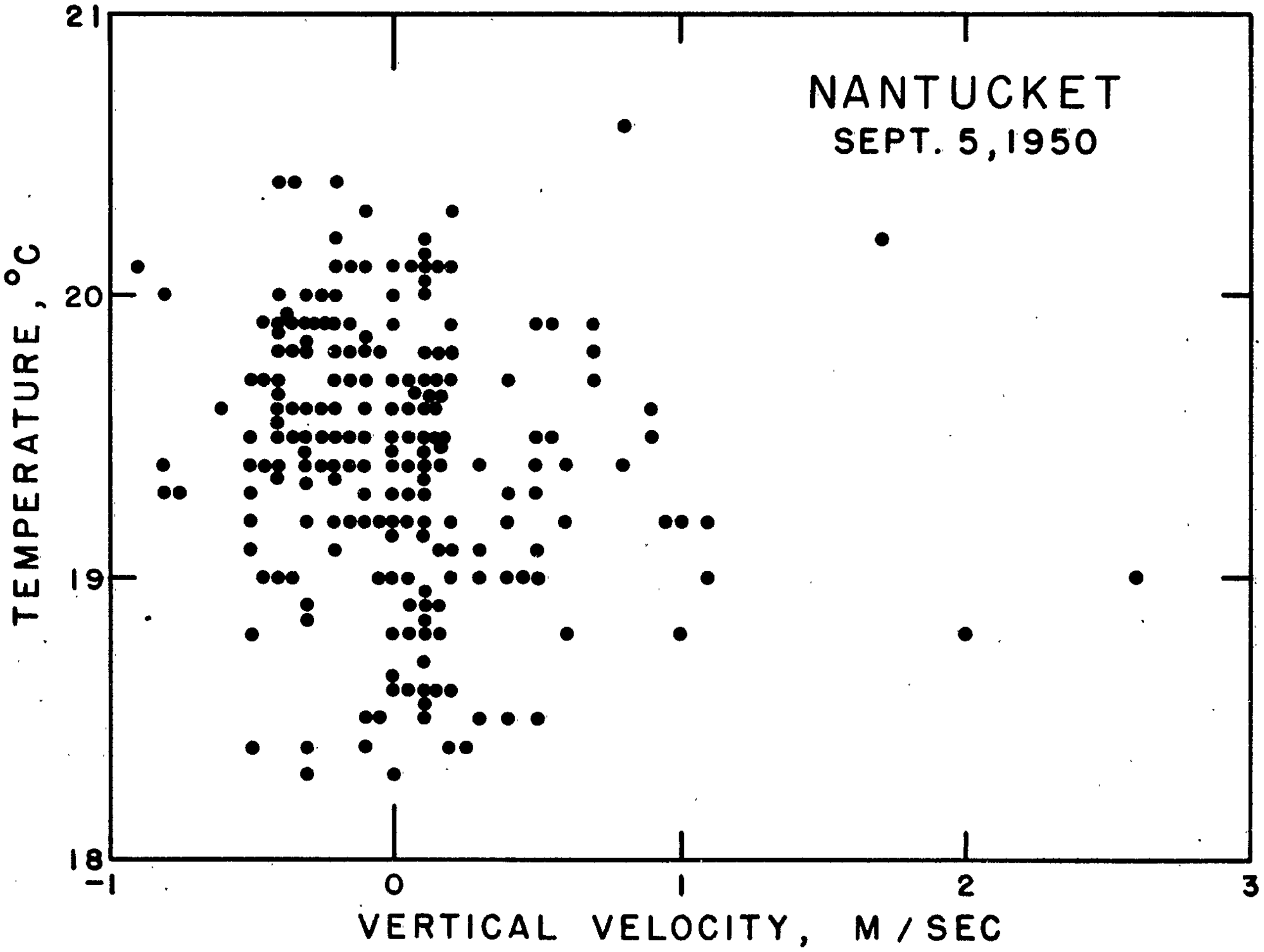

Fig. 4.4.5. Vertical velocity-temperature diagram.

As far as the instrumental errors are concerned, the errors are very low — probably a tenth of a degree centigrade. We should have taken more soundings, but there wasn't time for it, so there is an appreciable probable error although I haven't determined it.

MR. W. C. SWINBANK: I would like to raise a point on this question of errors. It was not clear from what Mr. Bunker said whether the possible source of error that I referred to earlier this morning does not occur in his analysis. As I understand it, he transfers his mean from one integrator to another and, unless this is done with extreme accuracy, a large error must thereby be introduced.

MR. A. F. BUNKER: We used the same integrator all the time, and we put the different traces on that one integrator. We made sure the two recorders and different channels were identical in that way.

(Note added later by authors): Modifications to the computer are being made as a result of the discussions both in and outside the meetings and of the recent paper by E. R. Sanford (*J. Meteor.*, 8, 182–190, 1951) on thermistor anemometry.

A sine function potentiometer is being built into the circuit to eliminate the previously mentioned approximation in the vertical velocity computation. Also, a temperature compensator is being added to the anemometer circuit to eliminate the effect of variations of the ambient air temperature.