ANALYSIS OF WIND DIRECTION FLUCTUATIONS

by

Don G. Friedman

B.A., University of California at Los Angeles, 1950

SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
(1951)

Signature Redacted
Signature of Author

Department of Meteorology, May 18, 1951

Signature Redacted
Certified by
Thesis Supervisor

Signature Redacted
Chairman, Department Committee on Graduate Students
Meteor
Thesis
1951
ABSTRACT

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Submitted for the degree of Master of Science in the Department of Meteorology on May 18, 1951.

The structure of turbulent air flow was studied with the aid of a new instrumental technique. Wind recording instruments were mounted at six logarithmically determined levels on a 44-meter tower located at the Round Hill Field Station in South Dartmouth, Massachusetts. The wind directions at the six levels were recorded instantaneously by photographing an instrumental panel every four seconds. A 1400-second run was made during the afternoon, sunset and evening periods of October 26, 1950.

Changes in the wind direction fluctuations were investigated in terms of changes in the three basic turbulent parameters set forth by H. Lettau. The study of the thermal stratification determined the effect of the thermodynamical parameter. Changes in the dynamic factor were determined by measuring the geostrophic wind as obtained from the surface pressure field in the vicinity of Round Hill. The geometric term was investigated by examining the character of the surface roughness upwind of the tower during each run.

The effect of the dynamic and geometric terms was found to be approximately constant during the observation period. Changes in the wind direction fluctuations were then studied in terms of changes in the thermal stratification and a direct relationship was determined between them.

The results of this investigation demonstrated the present and future value of the new instrumental technique in the study of turbulent air flow. Future investigation could be aided with a better observational location and with additional instruments for the measure of wind speed and temperature on the same basis as wind direction.
ACKNOWLEDGMENT

I wish to express my gratitude to Project No. AF28(099)-7 of the Geophysical Research Directorate under whose auspices the data for this study were obtained, to Dr. E. W. Hewson, Project Director, for his valuable assistance and advice, and to Mr. G. C. Gill for gathering the data.

I also wish to express my sincere appreciation to Dr. H. Lettau for his interest and many worthwhile suggestions.
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I. INTRODUCTION

Although the importance of the unsteadiness of the air flow in the lower atmosphere has long been recognized, only a small amount of appropriate data has thus far been compiled. The unsteadiness is evidenced by irregular changes in the speed and in the direction of the wind. This characteristic is a manifestation of turbulent fluctuation superimposed upon the basic air motion. There are many types of fluctuations depending upon the time scale and the interrelation of the determining factors. However, primary empirical knowledge of the turbulent fluctuations and its relation to the determining factors is not yet available.

Short term changes in the wind direction and wind speed are of equal importance in studying the small scale turbulent motions near the earth's surface. This is due to the fact that the turbulent element may be thought of as a vector which is added to the steady flow vector, the resultant of which is the observed wind. A wind vector has both a speed and direction component. Lulls and gusts in the observed wind speed occur when the eddy component adds to or subtracts from the mean air motion. However, the eddy vector usually subtends an angle with the basic flow vector and a change in the direction of the observed wind also occurs. In the past, fluctuations in the wind speed have been the primary tool used to investigate the turbulent structure of the surface layer air flow.

Instrumental limitations thus far have hindered investigation of individual eddies. The records of a recording anemometer and wind vane were in most cases investigated in terms of the mean
width of the trace over a period of an hour or more. This averaging process seriously hampers the study of the size and character of the individual fluctuations. The integrated effect of the entire eddy spectrum which is present is the result. Such averaging processes are usually involved in the computing of the gustiness factor and other turbulent indices which have been mentioned in the literature.

Another point which has not been properly stressed is the need to fix the basic parameters which theoretically are responsible for the type of turbulent fluctuation which is observed. This is necessary so that at least a partial reproducibility is approached.

This study will attempt to combine the above points which have not been fully utilized in the past. Wind direction fluctuations will be investigated as a possible turbulence index. The use of instantaneous vertical variations in the horizontal component of the wind direction is possible with the aid of a new instrumental arrangement. The three basic parameters which influence the turbulent character of the lower atmospheric layers will be discussed for each period of observation. Changes in these parameters will be investigated in terms of changes of the type of turbulence produced with wind direction fluctuations as the index.
II. HISTORICAL BACKGROUND

The scope of observational studies of turbulent motions of the lower atmosphere has, in the past, been limited by instrumental considerations. Hence, developments of new instrumental techniques will be used as criteria for tracing the gathering of empirical data in previous investigations. Prior to 1927 few, if any, direct observations of the turbulent fluctuations in the atmosphere had been attempted. During this period most of the practical knowledge of turbulence in the atmosphere was based upon its effect on the distributions of temperature and water vapor. In a few cases the effects of atmospheric turbulence acting on a small scale and involving individual eddies were investigated by measuring the dispersion of smoke clouds.

In 1927, G. I. Taylor (15) investigated the lateral and vertical fluctuations of the wind by observing the oscillations of a balloon tethered at about six meters above the ground. He observed the balloon at a distance downwind from its point of attachment and followed its trajectory with a pointer to which was attached a pencil. He drew conclusions from the type of curve which could be drawn to enclose the trace.

A study of turbulent fluctuations according to size was conducted by F. J. Scrase (14). To investigate fluctuations of a large scale, that is, where the mean values of the fluctuation velocity were taken over periods of an hour, he used an ordinary instrument for recording wind directions. The mean semi-width of the trace was used to obtain the lateral component of the
fluctuation in speed. In a somewhat similar manner, the along-wind fluctuation in speed was obtained from the record of a pressure tube anemometer. The ratio of these to the mean wind speed was taken as a measure of the turbulent motion. The observations were made at one level only and were made when the atmosphere was approximately isothermal near the earth's surface. To investigate turbulence where the mean values are computed for periods of a few hundred seconds, Scrase used a small bi-directional wind vane. It traced out on a fixed chart the actual movements of the vane for any desired time interval. In measuring the traces, the method adopted was to draw an oval around the mass of lines so that it included all the loops except a few of the extremes. The lateral and vertical diameters were taken to represent a measure of the components of a turbulence index.

The first observations of instantaneous wind directions were made by Scrase during the same general period. A kinemagraph camera took pictures from the end-on view of a small lightweight vane. From the pictures instantaneous angles of the vane from the mean wind direction were obtainable. Also included in the range of the camera was a small air meter for the mean wind speed, and a small swinging plate anemometer to give some information on the along-wind fluctuation of the wind speed. The instruments were fixed at a height of nineteen meters above the ground and exposures were taken at a rate of 16 pictures per second. However, due to the laborious task of extracting the data, the rate of exposure was slowed to about 1/5th of a second. As a result of plotting the two rates, Scrase showed that an interval of 1/5th of a second was
sufficiently short to include most of the small fluctuations.

The first attempt to record the variation of turbulent fluctuations with height was made using the above instrumental technique. The use of but one set of instruments made it necessary to first mount them at 1.5 meters and film the fluctuations for one minute. The instruments were then moved to a height of nineteen meters and the fluctuations at this height were similarly recorded. There was a half-hour time lapse between these observations. In order to compensate for changes in the mean wind speed over the half-hour period, a correction was applied to the fluctuation velocities at 19 meters on the assumption that the fluctuation speed is proportional to the wind speed. Only one such observation was made, but the results of this observation are widely quoted in the literature. In all of Scrase's studies, he attempted to account for the effect of the temperature gradient and the surface roughness.

A method of investigating the changes and characteristics of turbulent fluctuations was discussed by M. A. Giblett and others (6). In this study, three Dines anemometers with wind vanes were mounted on fifty-foot towers to form a 700-foot equilateral triangle. A fourth installation was located at the midpoint of one of the triangle legs. A nearby tower, 45 meters in height, supported another anemometer, wind vane and a platinum resistance thermometer which recorded the temperature every three minutes on a chart in a small recording room beside the tower. On the same chart, the temperature at 1.5 meters was also recorded. Unfortunately, the horizontal distance between the two thermometers was over a quarter
of a mile. An electrical timing devise enabled the wind speed and direction records from all the installations to be made comparable by marking the traces at fixed time intervals. Turbulent fluctuations as recorded continuously at the four towers were available for studying turbulence of the scale of hours, minutes, and tens of seconds by changing the speed of the charts. The results of the analysis of the charts from such observations were summed into a classification of fluctuation types based on the type of thermal stratification present.

The gustiness factor was used by Goldie (7) in 1935 as a turbulence index for observations taken at a single level atop a lighthouse off the coast of England. His method involved measuring and taking a line between the upper edge of the wind speed trace and the darkest part of the trace for periods of one hour. Wind direction fluctuations were analyzed in a similar manner in order to obtain average values of the angle between the fluctuations and the mean wind direction for the period. From this he obtained, as did Scrase, the average lateral component of the fluctuation vector. By comparing the summer observations with the winter observations, he took the thermal stratification into account in a very general manner.

In 1935, Best (1) investigated gustiness in the lateral and vertical directions at heights up to 5 meters above the ground. He also used small bi-directional wind vanes. The thermal stratification was measured by a temperature gradient apparatus which consisted of a Wheatstone bridge circuit employing two platinum
resistance thermometers. These thermometers were artificially aspirated. The wind speed was measured with small air meters of the vane type. Irregular wind direction traces were obtained by letting the bi-directional vane move freely in the wind for a certain time period. No provision was made for a time scale. An oval was drawn to include the trace and to give a measure of the type of turbulent motion present. The procedure was to mount one of the bi-directional vanes at 2 meters while the other was mounted at 25 cm., 49 cm., 1 m., or 5 m., respectively. The idea was to compare the effect of wind speed and temperature on the movements of the auxiliary vane and the movements of the vane mounted at two meters was to indicate the effect of height under the same conditions. Air meters were mounted on the direction vanes at 1 meter and 2 meters and also at the auxiliary height. The temperature gradient apparatus was located nearby. The galvanometer was read every 30 seconds during the run.

One of the first studies of turbulent fluctuations with the use of instruments mounted on a tower was presented by Flower in 1937 (4). A wind vane and a Robinson cup anemometer were mounted at the top of the tower and another anemometer was mounted about 15 meters above the ground on the 61-meter tower. Artificially aspirated platinum resistance thermometers were mounted at five levels above the surface. The short investigation involved the study of the lapse rate and the gustiness of the wind. The charts of the anemometer at the 15-meter level were used to obtain the gustiness factor. This has been defined as the ratio of the mean width of the
speed trace to the mean speed. It was found that the gustiness factor increased with increasing wind speed at the same rate for lapse rates varying from moderate lapse to moderate inversional conditions. This result implies that the thermal stratification is not of importance in determining the magnitude of the gustiness. However, Flower did not consider the influence of the thermal stratification on the speed profile.

A tubular wireless mast 94.5 meters in height was used by Johnson and Heywood (10). A Dines pressure tube anemometer was installed on the mast at 13 meters and a recording Robinson anemometer was installed at 94 meters. Resistance thermometers, each mounted in its own aspirated housing, were mounted at various levels on the tower. In most of these earlier studies the primary purpose of the instrumental arrangement on the tower was to study the variations of the temperature profile near the earth's surface and the studies concerning fluctuations in the wind were short incidental investigations. General statements concerning the type and behaviour of turbulence were based upon the variation of the coefficient of eddy diffusivity which was computed from the temperature profiles. This practice eliminates the vastly important shape of the speed profile. The actual wind speed is not the most appropriate parameter to use in such situations.

Meteorological investigations at the Guggenheim Institute (11) included observations of wind speed and wind direction plus temperature from the top of a 16.5-meter tower on the roof of a building which was 20 meters high. Any conclusions drawn from the
records of such an installation must be carefully considered due to the type of exposure involved.

Within the past five years, at least four tower installations have been equipped with instruments capable of further investigation of the structure of the turbulent structure of the atmosphere. At Manor, Texas, The Electrical Engineering Research Laboratory of the University of Texas has utilized a tower on which Bendix-Friez Aerovanes are mounted at about 4 meters, 15 meters, 30 meters, 60 meters, and 100 meters. Thermistors are mounted at sixteen levels between the surface and the top of the tower. At the present time, no information is available concerning any fluctuation observations that may have been taken at Manor. At Richland, Washington (2) a 400-foot tower has been equipped with instrument levels spaced at 50-foot intervals. At each instrument level is mounted a Gurley electronic anemometer and a thermohm. Wind vanes are mounted at the 100, 200, 300 and 400-foot levels. The records are continuous. No further information is available.

Recording wind vanes on the 400-foot tower at Brookhaven National Laboratory have recently been used to study fluctuation of the wind in the lower atmosphere (8). M. E. Smith has classified the fluctuations of the vane at 355 feet into four general groupings depending upon the type of fluctuations recorded over a rather long period of time.

The rather detailed survey of past instrumental techniques for studying the turbulent fluctuations has been presented so that a comparison may be made with the present instrumental technique at
Round Hill Field Station. Data from the Round Hill tower were the basis of this thesis. It should be noticed that the various results of the past investigations were not generally mentioned in this section. This was done purposely so that the instrumental technique could be stressed. Results of a comparable nature will be discussed in the conclusions to this study.
III. INSTRUMENTATION

Stationary Tower

The data for this present study were obtained from records of instruments mounted on a 44-meter tower. The tower is located on the grounds of the Round Hill Field Station near New Bedford, Massachusetts. It is an open framework steel structure (Fig. 1a) within 100 meters of Buzzard's Bay. Instrumental booms are mounted such that they may be moved outward from the tower to reduce the influence of the tower structure on the air flow past the instruments. The lowest instrument level is 1.4 meters and a logarithmic distribution of the levels is used. Instruments are mounted at 1.4 m, 2.7 m, 5.5 m, 11.0 m, 22.0 m, and 44.0 m. The booms may be drawn inward so that the instruments may be inspected. When in operating position the booms point toward the southwest. A northeast wind will blow through the tower before reaching the instruments.

The wind direction measurement is obtained at each of the above levels with the use of a standard Weather Bureau wind vane. The directions are transmitted electrically to an instrument panel located in a small building. This building is located about 50 feet eastnortheast of the instrument tower. The wind direction transmitters and dial indicators have an accuracy of approximately plus or minus two degrees. The wind direction is continuously indicated by six dials on the panel, each representative of a particular level.

The wind speed instruments have been specially constructed to obtain an added degree of accuracy at low wind speeds. The
FIGURE 1a VIEW OF TOWER INSTRUMENTATION FROM BELOW.

FIGURE 1b DETAILS OF TOWER INSTRUMENTATION AT 4.5 FEET SHOWING ASSEMBLY FOR ASPIRATING TEMPERATURE ELEMENT.
anemometers consist of standard commercial cups mounted on a sensitive Metron "precision switch actuated by rotation" which requires a very small torque to rotate the shaft and to open and close the electric circuit. A commercial electro-magnetic counter is used which is actuated by impulses from the transmitter. A counter for each instrument level is mounted beneath the appropriate wind direction dial on the instrument panel. The counter measures each 1/60th of a mile of air which passes the anemometer. This, in effect, integrates the wind speed over a finite period of time and hence an instantaneous wind speed is not obtainable. Each of the six wind speed indicators have been individually calibrated (9) and a single straight line calibrated for all six instruments is true to within $1\frac{1}{2}$ mph. The stopping speed is $1.0 \pm 0.3$ mph and the starting speed is probably about twice this value.

The temperature measuring equipment consists of six thermocouple junctions. Each copper-constant thermo-junction is mounted in the inner most of two concentric bakelite tubes through which a small blower draws air at a prescribed rate (Fig. 1b). This artificial ventilation is essential to the proper operation of the thermocouple. The concentric bakelite tubes are 5" and 4" long. Both the inner and outer tubes are covered with $23\frac{3}{4}$ carat gold leaf to reduce the effects of radiation, either solar or terrestrial. The bakelite is used in place of metal to reduce the effect of heat capacity. The thermoelectric E.M.F.'s are amplified in a Manning, Maxwell and Moore D.C. amplifier and then fed into a Weston Milliammeter. The Milliammeter is located in the center of the instrument panel. A reference junction of the thermocouples is immersed
in a constant temperature bath. By means of a stepping switch, each thermocouple in turn is switched into the circuit and a relative reading is observed on the milliammeter. After the six levels are, in turn, switched into the circuit, the reference bath temperature is indicated on the milliammeter. Three ranges of selectivity are used, i.e., a full-scale milliammeter deflection for temperature differences between the levels in question and the constant temperature bath of 30°C, 15°C, and 7.5°C. A small light for each level is activated when the milliammeter reading is indicating the temperature of that particular level. For example, if the timing switch is set for 4-second observations, each level temperature is recorded on each successive 7th observation or every 28 seconds. Although the accuracy of the thermocouples is 0.03°C, the accuracy of the temperature measuring devise is approximately accurate to within 0.1°C. Hence, the accuracy of the temperature may be expected to be in the neighborhood of ±0.1°C.

Since the ventilation is artificially controlled and the dimensions of the thermojunctions are known, the lag coefficient of these thermometers can be computed. The dimensions were selected so that the lag is between 60 and 90 seconds. Small scale fluctuations of the air-temperature are integrated into a mean indication and with the reading at each level made at 28-second intervals a representative value of the mean lapse rate of temperature can be obtained.

Also included on the instrument panel is a chronometer with a sweep second hand. The panel is photographed at fixed intervals. The time interval may be shortened to about ½ second, however, the standard interval is 4 seconds. Since the pointers of the six wind
direction dials are directly synchronized with the motion of the wind vanes, their respective instantaneous positions are always that of the instantaneous wind. The stepping switch of the temperature apparatus shifts to the next level during each successive four second period.

**Portable Tower**

The portable tower is a steel framework unit 11 meters in height mounted on three auto wheels. Instrument levels are at the same heights as on the stationary tower: 1.4 m., 2.7 m., 5.5 m., and 11.0 m. Wind direction measurements are made by four Electric Speed Indicator Company wind vanes equipped with 0-360 degree ohmmite potentiometers. These are switched one at a time into an Esterline-Angus recording voltmeter, on which the direction is recorded on a continuous scale. For wind speed measurements, four 3-cup indicators are fitted on Green 1/60 mile contact anemometers. These are connected with an Esterline-Angus 20-pen Operation Recorder which records the speeds simultaneously. The timing devise which trips the stationary tower camera was arranged so that the time interval is also marked upon the records of the portable tower.
IV. OBSERVATIONAL DATA

The basis of this study is the three periods of observation, each 24 minutes in length, which were taken in the afternoon (13:50-14:14 EST), at sunset (16:50-17:14 EST), and in the evening (21:06-21:30 EST) of the 26th of October 1950. These observation periods will hereafter be referred to as the afternoon, sunset, and evening runs. The time interval is 1 photo/4 seconds. The portable tower was set 66 meters upwind at a true angle of 327 degrees from the stationary tower. This position subsequently proved to be about 20 degrees to the left of the upwind direction. Wind directions for the 11 meter level were recorded as were wind speeds at the 1.4 m., 2.7 m., 5.5 m., and 11 m. levels. The timer automatically synchronized the portable tower data with that of the stationary tower.

October 26, 1950

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Afternoon run  Sunset run  Evening run

*Sunset 16:45

Three comparable periods of observations are also available with a 1/2-second photo time interval. Such an interval more closely approximates the instantaneous wind. Analysis of the 1/2-second observations has not been possible due to the limited time available. However, it is hoped that in the near future a more thorough investigation of the data may be continued on both the 1/2-second and the presently analyzed 4-second interval data. The four-second interval limits the
investigation to a scale of turbulence of a period greater than about 8 seconds.

The sky was clear during all three observation periods and the wind was from the northwest shifting more to the north during the evening run. This type of a synoptic situation was chosen to minimize as much as possible the effect of the proximity of the shoreline to the point of observation. The shoreline effect (figure 7) is of major importance in the interpretation of the tower data even when the winds are not blowing directly off the Bay.

Data are read from the motion picture film of the stationary tower panel with the aid of a Recordak. It is believed that the error of reading the film is within the accuracy of the instruments. The wind directions were read to the nearest degree, the wind speed to one-half of a counter reading, and the temperature to one-tenth of the milliammeter scale reading.

Wind Direction

The instantaneous height variations of the wind directions at the six levels were recorded for the three 24-minute runs and for the 11-meter level of the portable tower. One of the largest tasks of this study was the extraction of this data from the film. It is unfortunate that the true wind direction at each level is not obtainable for this analysis. It is very difficult to obtain a correct orientation of the wind vanes since they are mounted on the projecting booms. By computing the mean wind direction for each level and then plotting each observation as a deviation from the mean, there is a tendency to offset this handicap to a large extent.
Figures (14, 15, 16) are plots of the wind direction fluctuations about the 24-minute means of the afternoon, sunset, and evening runs. Immediately obvious are the marked changes in the size and character of the fluctuations from one run to the next. The tendency for large fluctuations to show up at all levels with a slow meandering of the wind in the afternoon is in sharp contrast to the rather uniform changes during the sunset run. During the evening run, the indicated fluctuations lose some of their significance since the wind during this period at the lower levels is at times equal or less than the starting and stopping speeds of the wind vanes. The change in the turbulence spectrum during the observational period will, as indicated in the next section, be linked with changes in the determining parameters. The fact that there are changes and these changes occur concurrently with time implies only that these changes in the turbulent motions are due to the diurnal changes in the determining factors and hence time is not a dependent variable. The 1400-second (approximately 24 minutes) runs include 350 values at each level for each run.

**Wind Speed**

The original idea for use of the wind speed was merely to read the counter at the beginning and end of each of the runs for each level and then compute the mean value over the respective 1400-second intervals. However, it was noticed that if the counter reading for each 4-second observation was plotted against time, figure (2), that the curves were not smooth, but that fluctuations in the speed of the order of one-half minute could be easily identified. It was also noticed that the counter rotates for each half unit (1/120th of a mile) which gives an accuracy of ±0.5 m.p.h. for a one minute
Wind Speed Fluctuations

Wind Speed Counter Reading (0.5 unit)

44.0 m.
22.0 m.
11.0 m.
5.5 m.
2.7 m.
1.4 m.

Time →
Sunset Run

0 sec → 200 sec

Figure 2
period of observation. This percentile inaccuracy decreases with increase in the wind speed. On the basis of these two facts, wind speeds for much shorter periods than 1400 seconds have been computed (Table VI) and will be discussed later in the report.

Wind speed to the closest one-half unit was recorded for all levels at each 4-second observation point. The 1400-second means of wind speed, figure (8), indicate that as with the directional fluctuations there is a marked decrease from the afternoon to the evening run.
V. THEORY

It is the purpose of this thesis to study the height variation of wind direction fluctuations as an index of turbulence. In order to make such an index universal, an investigation must be made of the causes of the turbulent fluctuations. This was first attempted by Scrase in making his observations when an isothermal atmosphere existed. In 1935, Best specified that the fluctuations of the wind were a function of the following factors and attempted to determine the individual influences:

1. The nature of the surface of the ground;
2. The height above the ground;
3. The wind velocity;
4. The thermal structure of the atmosphere near the ground;
5. The length of the period over which gustiness is measured;

Lettau (12) has theorized that there are three independent determiners of turbulence at any particular level in the lower atmosphere:

1. Dynamic,
2. Geometrical,
3. Thermodynamical.

This classification agrees in most respects to Best's classification. Two important exceptions exist:

1. Best's use of the observed wind velocity as an independent parameter is inconsistent with theory, since the observed wind velocity is a function of both the dynamical and the thermodynamical factors of Lettau's classification.
2. Lettau's grouping assumes independence of the parameters. This study will use Lettau's classification. The scale of turbulence to be investigated will be kept constant throughout the three observational periods.

The dynamic factor is given by a measure of the geostrophic wind. Changes in the geostrophic wind theoretically will result in changes in the turbulent fluctuations when the other factors are held constant. The best estimate of the geostrophic wind may be obtained from the pressure distribution on the surface weather chart. It is not advisable to use the gradient wind at, say, 4000 ft. as a measure of this term. Although the wind at this level is constant in direction and speed, the pressure gradient at the surface may have changed radically and the thermal wind may compensate for the change (Table I).

The geometrical factor may be characterized by a measure of the surface roughness. The greater the unevenness of the surface, the greater the mechanical turbulence produced. A measure of the roughness should not vary with changes in the wind speed. The integrated effect of a non-uniform surface must be considered at a relatively large distance upwind.

The thermodynamical effect is dependent upon the direction and magnitude of the vertical heat flux. It is characterized by the vertical profile of potential temperature and the observed wind velocity.

The wind direction fluctuations, in the same manner as wind speed fluctuations, will be assumed to give an indication of the integrated resultant of these three types of turbulent motion. It will be shown that to a first approximation the dynamic and geometrical effect
can be assumed constant during the three periods of observations, and that the changes in the observed turbulent attributes are due to changes primarily in the thermal stratification. In the following sections the dynamic, geometric, and thermodynamical factors will be discussed in detail.

**Dynamic**

The dynamic effect is manifested in the behaviour of the pressure at the surface of the earth. A measure of it is represented by the geostrophic wind which depends on the balance of the large-scale horizontal pressure distribution and the Coriolis parameter:

\[
- \frac{1}{\rho} \frac{\partial \rho}{\partial n} = 2 \lambda c \sin \varphi
\]

where

- \( c \) is the actual geostrophic wind velocity, having a magnitude \( \sqrt{u^2 + v^2} \) and a direction always specified as 90 degrees to the right of the pressure gradient in the Northern Hemisphere. The pressure gradient force is measured normal to the isobars.

The surface pattern of pressure is investigated since the thermal shear, if one exists, must equal zero at the surface. Consequently, using the observed wind at the geostrophic wind level may not be representative of the actual pressure pattern but may include also the result of thermal shears in the boundary layer. The boundary layer is defined here to include that part of the atmosphere bounded by the surface of the earth and the geostrophic wind level. The surface wind will change with changes in the thermal stratification, in spite of unchanged geostrophic wind velocity. Consequently, the actual
wind velocity should not be used as a basic parameter, but the theoretical geostrophic wind which corresponds to the surface pressure pattern should be used.

Figures (3, 4, 5) are based on the six-hour synoptic sequence and characterize changes in the pressure pattern during the overall observation period. Figure (3) is indicative of the afternoon pressure pattern (1330 EST). Each wind barb equals five miles per hour. The surface winds very closely parallel the isobars. There is a more or less even pattern of pressure throughout the Northeastern states. The geostrophic wind as computed from the isobar spacing one-half hour before the afternoon run was 16.4 meters per second from 333 degrees. Figure (4) is the 0030Z synoptic chart and is representative of pressure conditions about two hours after the sunset run. The shoreline effect is noticeable with a very distinct crowding of the isobars along the immediate coast. By taking an arbitrary length on either side of the New Bedford location, the author found the geostrophic wind to be 16.1 meters per second but from 344 degrees. Figure (5) represents the 0630Z synoptic conditions. The evening run (0230Z) is spaced about a third of the way in time between the conditions on figure (4) and figure (5).

The intense crowding of the isobars along the coastline probably has a pronounced effect on the dynamic factor involved in the operations at Round Hill Field Station; however, as a first approximation, the same length unit as used on the 0030Z chart was placed on either side of the tower location. The geostrophic wind was 19.8 meters per second from 347 degrees. Since the evening run was taken about a
Figure 3. Sea Level Pressure and Surface Wind Velocity. Each full barb equals 10 mph.
Figure 4. Sea Level Pressure and Surface Wind Velocity. Each full barb equals 10 mph.
Figure 5. Sea Level Pressure and Surface Wind Velocity. Each full barb equals 10 mph.
third (2 hours after the 0030Z) of the way to the 0630Z chart and if a continuous change in the isobaric pattern is assumed between 0030Z and 0630Z, the geostrophic wind at the time of the evening run would have been 16.1 mps plus 1.2 mps or 17.3 meters per second from 345 degrees.

Table I. Quantitative Measure of the Dynamic Component

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<thead>
<tr>
<th></th>
<th>Afternoon</th>
<th>Sunset</th>
<th>Evening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface geostrophic speed</td>
<td>16.4 mps</td>
<td>16.1 mps</td>
<td>17.3 mps</td>
</tr>
<tr>
<td>Direction</td>
<td>333°</td>
<td>339°</td>
<td>345°</td>
</tr>
<tr>
<td>Nantucket 4000' winds</td>
<td>10.9 mps</td>
<td>10.8 mps</td>
<td>10.8 mps</td>
</tr>
<tr>
<td></td>
<td>320°</td>
<td>320°</td>
<td>320°</td>
</tr>
</tbody>
</table>

Figure (6) is a hodograph of the wind at the various levels during each of the observation periods. The fact that a true orientation of wind directions is not available can be partially offset by computing the relative deviation of the sunset and evening mean wind directions from the means of the afternoon observation.

Table II. Changes in the Mean Wind Direction

<table>
<thead>
<tr>
<th>Height Stationary tower</th>
<th>Afternoon</th>
<th>Sunset</th>
<th>Evening</th>
<th>Afternoon</th>
<th>Sunset</th>
<th>Evening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.4 m</td>
<td>2.7</td>
<td>5.5</td>
<td>11.0</td>
<td>22.0</td>
<td>44.0</td>
</tr>
<tr>
<td>Indicated Directions</td>
<td>M</td>
<td>M+1</td>
<td>M+11</td>
<td>M+14</td>
<td>M+15</td>
<td>M+25</td>
</tr>
<tr>
<td>Relative Direction Changes</td>
<td>M+9 M+12</td>
<td>M+11 M+14</td>
<td>M+15 M+17</td>
<td>M+20 M+22</td>
<td>M+25 M+27</td>
<td>M+27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Height Portable tower</th>
<th>Afternoon</th>
<th>Sunset</th>
<th>Evening</th>
<th>Afternoon</th>
<th>Sunset</th>
<th>Evening</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>11.0</td>
<td>333</td>
<td>352</td>
<td>355</td>
<td>M</td>
<td>M+19</td>
</tr>
<tr>
<td>Relative Direction Changes</td>
<td>M+1</td>
<td>M+19</td>
<td>M+22</td>
<td>M+22</td>
<td>M+19</td>
<td>M+22</td>
</tr>
</tbody>
</table>
The approximate vertical wind shear for the afternoon run can be obtained from a comparison of the mean wind directions at the higher levels of the tower and the wind direction as recorded on the portable tower. The directions on the stationary tower are accurate to within ± 3 degrees. The direction as obtained from the portable tower should be accurate to within several degrees of the true direction. A comparison (Table II) of the 2.7 m., 11 m., 22 m., and 44 m. directions of the stationary tower implies that in the afternoon the wind backs with height about 3 degrees from the 1.4 meter level to the 44 meter level. In figure (6) a graphical representation of this assumed shear of the afternoon run and the subsequent deviations of the direction means of the sunset and evening runs is presented. If the assumed shear of the afternoon is correct, the wind veers proportionate amounts so that during the sunset run there is a zero shear. The shift during the interim between the sunset and evening run results in a rather distinct veering of the wind with height.

The clockwise shift of the wind from the afternoon to the sunset run and from the sunset run to the evening run is of a greater magnitude than the shift of the geostrophic wind for the comparable periods. This may be attributed to the shoreline effect in which there is a tendency for the air to flow offshore perpendicular to the coastline. The ocean is much warmer than the land. Since the isobars are at an angle to the coastline in the vicinity of Round Hill, there would result a veering of the wind of a greater magnitude than the geostrophic flow.

Changes in the dynamic effect are indicated only as a
Figure 6. Changes in the Wind Shear.
change in the wind direction during the three observation periods. The geostrophic wind speed is shown to be nearly constant and is the most important constituent of the dynamic effect. The geostrophic wind direction changes are of importance in influencing changes in the geometric parameter. In light of this discussion, changes in the dynamic effect will be assumed to be small during the three observation periods.

Geometrical

The geometrical parameter is a measure of the roughness and unevenness of the surface upwind from the point of observation. A measure of this surface characteristic is important in determining the drag upon the observed wind speed and upon the wind structure. Since this parameter is assumed independent of the thermodynamical and in part independent of the dynamic factor, its effect can be assumed to remain constant with varying values of wind speed when the direction of the wind is fixed. But with changes in wind direction, the effect of this roughness may be expected to change since the surface unevenness upwind is usually heterogeneous with direction from any given spot.

An empirical rule for obtaining a uniform ground character is given by Lettau to be fifty times the height of the highest observational level. In the present case, a uniform roughness would be required at least 2,200 meters upwind from the tower and over an arc which would include the effect of the longer term upwind meandering of the wind. This unfortunately is not the situation at Round Hill (figure 7). The surface near the tower is sandy and is
Figure 7. Surface Characteristics near the Towers at Round Hill Field Station.
covered with bushes averaging two feet in height. This type of surface extends uniformly for about 450 meters into the north and northwest quadrants from the stationary tower. Wooded areas border the flat sandy surface and a low hill begins about 500 meters to the northwest. Despite this lack of homogeneity it is desirable to obtain a quantitative estimate of the roughness effect over this terrain. The roughness parameter and effective height of the vegetation will be computed.

The effective height is a measure of the effective surface at which the logarithmic wind curve would theoretically originate. It is a measure of the average height of the upwind surface contour. The roughness parameter is a small increment of height which is added to the effective height of the instruments.

In determining estimates of the effective height and the roughness parameter over various types of vegetation, Thornthwaite and Holzman (16), found that the roughness parameter varied from hour to hour and seasonally. It also varied with wind speeds. This according to Lettau's theory is not possible since the geometric parameter is taken to be independent. The roughness should vary only with the physical characteristics of the surface. The varying values of the roughness parameter of Thornthwaite are due to the fact that he used the ratio (equation 6) on data in which the thermodynamical factor was not eliminated; that is, when a neutral stratification did not exist. In these cases the thermodynamical effect produced a wind profile which did not follow the logarithmic law and which, therefore, is not appropriate for use in computing these
quantities. The fact that the wind speed is dependent upon the thermal stratification also accounts for the dependence of the roughness parameter upon changes in the wind speed.

An estimate of the roughness parameter $z_0$ will be used to check the applicability of several relationships which will be used later in the analysis of the wind direction data. Values of the temperature, wind speed, and direction are available at only a finite number of points on the tower. The profiles of each quantity are dependent upon these points. Most of the earlier studies of temperature and wind profiles have related only portions of these profiles to one another by measuring the slope between two of these observation points. This, for example, is the method of computing Richardson's number (13). It is much more desirable to obtain from each profile a number which would in itself give a measure of the entire profile.

Dr. Heinz Lettau has suggested the use of the following relations which accomplish this aim:

$$\frac{(\Delta V)_m}{V_m} = \text{Profile Contour Number}$$ \hspace{1cm} (2)

where,

$(\Delta V)_m$ is the difference in wind speed between levels such that the successive top-half levels are subtracted from the successive bottom-half levels.

$V_m$ is the mean of the wind speeds at the various levels.

This equation yields a single number which is representative of the entire wind speed profile.
The thermodynamical profile is represented singularly by the following relations:

\[
\frac{(\Delta \theta)_m}{(V)_m^2} = \text{Stability factor} \frac{\text{deg} \cdot \text{sec}^2}{m^2}
\]  \hspace{1cm} (3)

where,

\((\Delta \theta)_m\) is the potential temperature difference of the successive top-half of the tower levels from the successive bottom-half-levels.

\( (V)_m^2 \) is the square of the mean wind speed taken over all levels.

From the logarithmic law of wind distribution in the surface layer for neutral thermal stratification:

\[
V_a = C \ln \frac{z + z_o + d}{z_o}
\]  \hspace{1cm} (4)

where,

\(V_a\) is the wind speed at the level of the anemometer \(z\).

\(z_o\) is the roughness parameter.

\(z\) is the geometrical height.

\(z + d\) is the effective height.

\(C\) is a constant equal to the adiabatic mixing velocity divided by Von Karman's constant (12).

The term \(z_o\) represents a virtual displacement of the zero height. This additional height results in

\[V_a = 0 \text{ at } z + d = 0.\]

Substituting the value of \(V_a\) into the expression for the profile contour number:
\[
\left( \frac{\Delta V}{V_m} \right)_a = \left[ \frac{\Delta \ln \left( \frac{z + D}{z_o} \right)}{\ln \left( \frac{z + D}{z_o} \right)} \right]_m = f \left( z_o, D \right) \tag{5}
\]

where,

\[ D = d + z_0 \]

\[ m \text{ is the mean value.} \]

Since none of the three observations were made under neutral thermal stratification, it is necessary to estimate the profile contour number by plotting its value for each of the three runs against the stability factor using the value of the profile contour number where a curve of best fit intersects the point where the stability factor using the value of the profile contour number is equal to zero. The profile contour number at neutral stratification is thus determined. It is a function of \( z_o \) and \( D \).

The next step is to determine the value of \( D \) so that it may be substituted into the above equation and the roughness parameter can then be obtained. This is accomplished by taking the ratio of the differences of the wind speeds at the lowest four levels:

\[
\text{Ratio} = \frac{V_4 - V_2}{V_3 - V_1} = \frac{\ln \left( \frac{z_4 + D}{z_2 + D} \right)}{\ln \left( \frac{z_3 + D}{z_1 + D} \right)} = f \left( D \right) \tag{6}
\]

The ratios are plotted versus the stability factor and the points are joined with the best fitting line. The value of the ratio under neutral stratification conditions is obtained as the point of intersection of the best fitting line and the line of zero stability factor.

\[ D \text{ is thus obtained and substituted into the adiabatic} \]
profile contour number; the roughness parameter is then determined by a numerical method.

This procedure for determining a roughness parameter is valid only if the wind has a constant direction during each of the three observation periods or if the roughness of the upwind surface were the same throughout the solid angle of deviation of the mean wind. The wind speed profiles (figure 8) when investigated indicate a pronounced s-shaped configuration about the 11 meter level. Since the instruments were calibrated just before the run, this effect seems to be real. As the determination of the roughness parameter is dependent upon a simple logarithmic wind distribution, only the first three levels were used to obtain the parameter. The fourth level was estimated by joining the third and fifth levels with a smooth curve.

Table III. Relationship of Wind Speed Profile to Thermal Stratification

<table>
<thead>
<tr>
<th>Run</th>
<th>Afternoon</th>
<th>Sunset</th>
<th>Evening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability Factor</td>
<td>-0.037</td>
<td>0.193</td>
<td>*</td>
</tr>
<tr>
<td>Profile Contour Number</td>
<td>0.137</td>
<td>0.202</td>
<td>*</td>
</tr>
<tr>
<td>Ratio</td>
<td>1.55</td>
<td>1.76</td>
<td>*</td>
</tr>
</tbody>
</table>

*Wind speeds too low to be reliable at lowest four levels

The height correction \( d \) was found to be 0.71 meters. This value is subtracted from the geometrical height of the observation levels because of the type of vegetation present in the vicinity of the tower and the unevenness of the ground. The roughness parameter
Figure 8
Wind Speed Profile

Height (Meters)

Evening
Sunset
Afternoon
was found to be 0.6 cm. This value is equivalent to that reported by Geiger (5) as being representative of a grassy surface.

The small shift of the wind direction in the lower levels and the more or less uniform character of the surface contour when integrated over distance implies that the geometrical effect may be assumed to change but little during the observational period.

Thermodynamical

The temperature data were extracted from the film as a meter reading. The temperature is recorded at each level each 28 seconds. A switching mechanism engages successively each of the six recording heights on consecutive four second observations. After the 144-foot reading is recorded, the next four second observation is a reference. The temperature measuring devices are artificially aspirated thermocouples with a lag coefficient of between 60 to 90 seconds. A lag of this magnitude smooths out the small-scale sudden fluctuations of air temperature and provides a representative value of the mean lapse rate from the measurements made at each level at 28-second intervals.

The initial idea for the use of the temperature was merely to obtain the mean lapse rate for the individual 24-minute runs. However, when the temperatures of each height are plotted with time it is found that the regular variations (figure 13) follow a definite pattern at all levels. This fact indicates that the variations of the mean lapse rate of thirty seconds or more may be treated as real occurrences in spite of the manner in which the
temperatures are recorded. Variations of 200-second temperature means from the overall 1400-second means are legitimate and are given in table VIII. Since the temperatures can be used in this manner, an estimate of the thermodynamic effect can be obtained by an investigation of the lapse rate of temperature. In order to convert the actual temperature to the potential temperature, the following approximation will be used:

$$\theta^\circ C = T^\circ C + 0.01 z$$  \hspace{1cm} (7)

where,

- $T$ is temperature in degrees $C$.
- $z$ is meters.

Figure (13) indicates the relative lapse rates on the afternoon, sunset and evening runs, respectively. The lapse conditions of the afternoon run are marked by periodic shifts in stratification. Similar characteristics are noted in the inversionsal stratifications of sunset and evening. Since it has been stated that turbulence is a function of the dynamic, geometric, and thermodynamic factors and the dynamic and geometric factors can be treated as approximate constants during any one run, any changes in the thermal stratification should also be indicated by a change in the magnitude and type of turbulence.

The negative trend of the temperature at all levels on the sunset run is attributed to the advection of colder air. This is immediately apparent from the surface isotherm charts, figures (9, 10, 11) for the appropriate periods. It should be noted that the $0.75^\circ C$ cooling can not be attributed to cooling of the surface
Figure 9. Surface Isotherm Configuration.
Figure 10. Surface Isotherm Configuration

0030 Z
27 October 1950

Tower Location
Figure 11. Surface Isotherm Configuration.
since there is more of a tendency for the entire lapse rate to shift as a unit instead of as a progressive cooling of the lower layers. The evening run indicates longer period shifts in the stratification although the overall mean shows a four degree difference between the 1.4 and 44-meter level.
VI. INTERPRETATION

In light of the assumption regarding the basic turbulence parameters, it has been shown that changes in the geometric and dynamic terms are small during the observation period. However, it should not be assumed that the effects of the geometric and dynamic parameters are small, but only that these effects are approximately constant during the period of observation. The object of this study is to investigate the turbulent fluctuations in light of changes of the thermodynamical parameter.

A. The Relationship of Changes in Thermal Stratification and Wind Direction fluctuations

1. 1400-second stratification means versus 4 second instantaneous values of wind direction

The relative stratification of the layer between 1.4 meters and 44 meters is illustrated graphically in figure (12). The height is plotted on a logarithmic scale as the ratio of each level to the lowest level. The temperature is the 1400-second mean of the 28-second readings and is plotted relative to the 1.4-meter level which is taken as the reference level. Since the potential temperature is used, the vertical lines are lines of equal potential temperature and represent a neutral stratification. A negative slope indicates superadiabatic conditions. A positive slope is indicative of inversional conditions. The greater the slope the greater the respective stratification.

During the afternoon run, it is noted that above the 5.5-meter level the layer is in neutral stratification. The evening run is strongly inversional. There are thus distinct changes in
Thermal Stratification: $\theta$-Profile Relative to 1.4 meter level.

- Afternoon
- Sunset
- Evening

Lapse  Inversion

Figure 12.
the thermodynamical term which is implied to have an effect upon
the character of the direction fluctuation present during the runs.
This difference is clearly shown in figures (14, 15, 16).

Figure (14) illustrates the great unsteadiness of the wind under conditions of unstable stratification. The vertical extent of the fluctuations can be clearly traced with the fluctuation reaching the higher levels first and at lower levels at progressively later times. This type appears to be of type "B" of the Brookhaven National Laboratory gustiness classification (8). Type "B" is defined to be a result of the combination of mechanical and thermal turbulence. In the Durst classification (3) this period would be indicative of a combination of "convectional" and "frictional" eddies and the addition of the "splashing" type near the surface where the fluctuations which appear at all levels are broken into an intensified frequency of smaller scale fluctuations.

Figure (15) is a representation of the fluctuations during the sunset run. Inversional conditions have become firmly established. The fluctuations are of a smaller magnitude, but there is less difference in the character of the curves with height. The fluctuations are much more uniform with time. Type "C" of the Brookhaven classification most closely depicts this state of fluctuation. Type "C" is defined to show the effect of mechanical turbulence alone. Durst's classification would class this case as resulting from "frictional eddies."

Figure (16) shows the wind direction fluctuations during the period of strong inversional stratification. The fluctuations
WIND DIRECTION FLUCTUATIONS

44.0 m

22.0 m

11.0 m

5.5 m

2.7 m

1.4 m

Time [10^2 seconds] →

Figure 14
Figure 15.

Wind direction fluctuations for different heights:
- 44.0m: Missing
- 22.0m
- 11.0m
- 5.5m: Time (10^4 seconds) →
- 2.7m
- 14m: WIND DIRECTION FLUCTUATIONS

SUNSET RUN
WIND DIRECTION FLUCTUATIONS

EVENING RUN

Figure 16.
at the lower levels are of questionable significance since the wind speed during this period approaches the stopping speed of the individual wind direction vanes. However, they can not be entirely disregarded in light of a significant wind speed of at least three miles per hour toward the end of the evening run at the lower levels which results in only a small amount of fluctuation. On the other hand, the 22-meter level wind speed of a comparable magnitude caused considerable fluctuation. The evening run may be typed "B" in the Brookhaven system and the Durst classification would include a combination of "wave eddies" and "frictional eddies."

2. 1400 second stratification means versus frequency of fluctuations about the mean

To best illustrate the effect of a changing heat flux upon the distribution of the lateral fluctuations, a series of frequency distributions have been constructed. Figures (17, 18, 19) show the four-second instantaneous wind direction fluctuations from the mean direction for each level during the respective runs. A five-degree class interval is used since smaller intervals gave much more irregular curves indicating a bias for certain numbers over neighboring numbers when the data were read from the film. Each distribution is composed of 350 observations. With the dynamic effect constant during the period, both the wind speed and wind direction fluctuations are dependent upon the heat flux change. It is unfortunate that the frequency distribution of the 44-meter level on the sunset run is not available, since the wind speed during this period was the same as during the evening run at the same level. The effect of wind speed could have been held constant and variations in the
Figure 17. Distribution of Wind Direction Fluctuations about the Mean Direction.
Figure 18. Distribution of Wind Direction Fluctuations about the Mean Direction.
Figure 19. Distribution of Wind Direction Fluctuations about the Mean Direction.
frequency distribution of the 44-meter level of the sunet and evening runs could have been attributed to changes in the thermal stratification alone.

As the change from lapse to inversional conditions occurs, there is a marked tendency for the distribution to become more peaked. This is especially noted at the higher levels. The trend of the 44-meter histogram from the afternoon to the evening best illustrates this point. At the lower levels there is less of a tendency for the distribution to change. As was mentioned previously, the validity of the distributions at the lowest four levels of the evening run may be questioned due to the frictional limitations of the wind vanes at low wind speeds. An examination of the traces, especially the trace at 5.5 meters, on figure (18), implies there is an abrupt shift of wind direction during the middle of the period. The fluctuations about the mean wind direction before and after this shift are within ±5 degrees of the mean. There is no such tendency in the 44-meter distribution.

3. Quantitative evaluation of the relationship between the temperature and fluctuation profiles

An estimate of the dependence of wind direction fluctuations upon the thermal stratification changes may be obtained with the use of the Stability Factor (eq. 3) and the standard deviation of the direction fluctuations at the particular levels.

Figure (20) is a plot of the standard deviation of the instantaneous wind directions taken every four seconds with respect
Figure 20. Standard Deviation Profile of Wind Direction Fluctuations.

Evening (one level only).

Sunset

Afternoon

Height Ratio $z/1.4m$
to height. In order to compute this statistical measure, it was required to make the assumption that the frequency distributions could be approximated by a normal distribution. This assumption seems to be satisfied, see figures (17, 18, 19), during the afternoon and sunset run, but is not satisfied by the histograms of the lower four levels of the evening run. The standard deviation for these levels was not computed. It should be noted from Table IV that the deviation at the 22-meter level reads about 0.9 degree too high during the afternoon and sunset run. This is inferred if a smooth curve is drawn through the lowest four levels and the highest level of the afternoon run. If the point were displaced about 0.9th of a degree lower, a smooth variation in the vertical would be the result. However, there is at present no reason to doubt the reliability of the wind vane at this level. Consequently, the original value will be retained.

The stability factor has been computed for the afternoon, evening and sunset runs. The significance of this parameter in relation to the profile contour number has been discussed in the section describing the geometric parameter. It is desirable now to derive a relationship which will, in a similar manner, yield a dimensionless index of the profile of wind direction fluctuations. Such a measure may be obtained with the use of the following relationship which divides the sum of the difference of successive standard deviations by the mean of the standard deviations of the wind direction fluctuations at the six levels of the tower;
\[ 2 \sum_{i=1}^{3} \left( s_i + r_i - s_i' \right) \sum_{i=1}^{6} s_i \quad \text{Fluctuation number} \quad (8) \]

where,

\[ s_i \] is the standard deviation of the 4 second wind directions from the overall mean at the \( i \)-th level.

The fluctuation number is equal to zero when the standard deviations of the direction fluctuations are constant with height. It is also small when there are large fluctuations about the mean, that is, when the standard deviation averaged over all levels is large. Conversely, when there is nearly laminar flow and a large variation of the standard deviation with height, a large negative value may be expected. One would then expect small values during the lapse conditions and large negative values during the inversionsal conditions.

Table IV. Standard Deviation of Wind Direction Fluctuations

| Standard deviation | Afternoon | Degrees Sunset | Evening | n=350 |
|-------------------|-----------|----------------|---------|
| \( s_{1.4 \text{ m}} \) | 19.9      | 12.3           | ---     | n=350 |
| \( s_{2.7 \text{ m}} \) | 17.1      | 12.1           | ---     | n=350 |
| \( s_{5.5 \text{ m}} \) | 14.6      | 11.1           | ---     | n=350 |
| \( s_{11 \text{ m}} \) | 14.0      | 8.9            | ---     | n=350 |
| \( s_{22 \text{ m}} \) | 14.5      | 9.4            | ---     | n=350 |
| \( s_{44 \text{ m}} \) | 12.6      | *              | 5.2     | n=350 |

Fluctuation number \(-0.227\) \quad \(-0.284\) \quad ---
The standard deviation of the fluctuations was computed only at the 44-meter level during the evening run for reasons which were mentioned previously. Since the standard deviation of the 44-meter level is equal to 5.2 degrees, a large vertical variation of the standard deviation would be required. This small value is probably indicative of some small finite value which the standard deviation must approach since laminar flow in the atmosphere probably never occurs.

Table V. Dependence of the Profile of Wind Direction Fluctuations and of Wind Speed upon the Thermal Stratification

<table>
<thead>
<tr>
<th></th>
<th>Afternoon</th>
<th>Sunset</th>
<th>Evening</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stability factor</td>
<td>-0.033</td>
<td>0.234</td>
<td>2.260 deg sec²/m²</td>
</tr>
<tr>
<td>Fluctuation number</td>
<td>-0.227</td>
<td>-0.294</td>
<td>---</td>
</tr>
<tr>
<td>Profile contour number</td>
<td>0.296</td>
<td>0.414</td>
<td>1.113</td>
</tr>
</tbody>
</table>

Figure (21) is a plot of the above quantities. A straight line may be drawn through the three points of the stability factor versus profile contour number. It is doubtful whether the third point of the fluctuation number would have allowed a linear relationship to be applied to this function. It should be noted that if a linear relationship exists between the stability factor and the fluctuation number, the point for the evening run would equal about -0.8. Large standard deviations would be necessary near the earth's surface. This is in fact the case, if the histograms of the evening run are examined. However, the instrumental limitations preclude a quantitative measurement of the standard
Thermodynamical Effect.

- Overall (1400 sec) value
- 200 sec values (when appropriate)

Profile Contour Number

A Afternoon Run
B Sunset Run
C Evening

Stability Factor (deg sec²/m²) →

-0.5 0.0 0.5 1.0 1.5 2.0 2.5

-0.2

-0.4

Fluctuation Number

D Afternoon Run
E Sunset Run

Figure 21.
deviations. There is also reason to believe that the relationship is not linear. Best (1) mentioned a curvilinear relation between the stratification and lateral gustiness. He used a different instrumental arrangement and analysis technique.

The practicability of using the wind direction fluctuations as an index of turbulence has been sketched. A more thorough investigation is in order before any statements can be made.

4. Dependence of 200 second mean values of wind direction and wind speed fluctuations upon 200 second mean stratification changes

In the preceding section, the overall average values of the wind speed and wind direction fluctuations for the afternoon, sunset and evening runs were related to changes in the stratification from one run to the next run.

Scrase (11) showed, as a result of his observations, that the components of eddy velocity increase in proportion to the wind speed. If this is true, one would expect to find larger wind direction fluctuations with periods of above average wind speeds. Scrase's observations were made during periods of neutral stratification. Best, on the other hand (1), took the heat flux term into account and found that lateral fluctuations are independent of velocity for lapses greater than -0.9 F, but for lapses less than this and for inversions, the lateral fluctuation increases with increasing velocity. He also found that for wind speeds above 6.0 m./sec. there was no variation of gustiness with changing temperature gradient. For speeds between 4 to 6 meters per second, the lateral fluctuations decrease when the stratification is changed
from lapse to inversional.

Another way in which to investigate this dependence is to utilize the two-hundred second means for the wind speed, wind direction and temperature. The deviations of the respective values from the 1400-second average have been computed and are tabulated in Tables (VI, VII, VIII). In figures (22, 23, 24) comparable 200-second averages of the temperature, wind speed, and direction are related according to height. The respective traces are deviations in degrees Centigrade, meters per second, and degrees.

In figure (22) the afternoon run is illustrated. The seven successive 200-second mean values of the temperature are joined by a curve for each level. There is a rather constant variation with height. Below average temperatures during the second and third 200-second periods give way to above average temperatures during the fifth and sixth periods. It should be noted that the above-average temperature of the sixth period at the lower levels is replaced by below-average values at the 22-meter and 44-meter levels. The wind direction deviations during the same period indicate a more or less concurrent fluctuation with that of the temperature. The variations are nearly constant with height. A fluctuation during the mid part of the 1400-second run builds to a maximum at the 2.7-meter level, and is not identifiable at the higher levels. Wind speed fluctuations show a definite increase with height. The fluctuations are, in general, 180 degrees out of phase with the temperature deviations and in phase with the wind direction deviations. There is not a comparable increase in the lateral fluctuation in the wind direction with increase in wind speed as has been suggested by Scrase.
## Table VI

**Mean Wind Speeds for the Afternoon, Sunset, and Evening Runs**

<table>
<thead>
<tr>
<th>Height</th>
<th>1.4 m</th>
<th>2.7 m</th>
<th>5.5 m</th>
<th>11.0 m</th>
<th>22.0 m</th>
<th>44.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afternoon</td>
<td>3.97</td>
<td>5.04</td>
<td>5.83</td>
<td>5.98</td>
<td>6.84</td>
<td>6.92</td>
</tr>
<tr>
<td>Sunset</td>
<td>1.70</td>
<td>2.36</td>
<td>2.86</td>
<td>3.04</td>
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### Difference of successive 200 second wind speed means from overall 1400 second mean wind speed (meters per second)

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<td>+0.02</td>
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*Uncertainty due to reading mechanical counter*
Table VII

Deviation of 200-second Wind Direction Averages from the 1400-second Mean Wind Direction

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*missing
Table VIII

Height Differences in Potential Temperature
1400 second Average
Reference Level: 1.4 meters

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<th>5.5m</th>
<th>11.0m</th>
<th>22.0m</th>
<th>44.0m</th>
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<td>0.50</td>
<td>0.73</td>
<td>0.90</td>
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Potential temperature differences between 200 second averages and 1400 second average

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<tr>
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<td>-0.13</td>
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<td>-0.00</td>
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<tr>
<td>400-600</td>
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</tr>
<tr>
<td>600-800</td>
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<td>-0.03</td>
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<table>
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<tr>
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<th>0.26</th>
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<th>0.73</th>
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<th>1.76</th>
<th>2.22</th>
<th>2.86</th>
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<tr>
<td>200-400</td>
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<td>-0.18</td>
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<td>+0.23</td>
<td>+0.05</td>
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*estimated

Actual temperature

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</tr>
</tbody>
</table>

Actual temperature after sunset is estimated.
Figure (23) represents the sunset run. The temperature traces indicate a definite cooling trend which amounts to about 0.3 degree at the 1.4-meter level and decreases with height to a cooling of 0.5°C at the 44-meter level. Small irregularities in the traces at the lower levels are replaced by a smooth decrease in temperature at the higher levels. The wind direction fluctuations exhibit a characteristic trace which is constant with height and the fluctuations decrease in magnitude with height. The wind speed deviations show an erratic variation with height during this run. An entirely different configuration is present at the 44-meter level. In general, there are three distinct patterns present. The lower three levels represent one type, the middle two another, and the top a third type. No relation is obvious between magnitude of the wind direction and the magnitude of the wind speed deviations.

Figure (24) shows an erratic temperature variation with height during the evening run. At the 1.4-meter level, during the first part of the period, there is an above average deviation of nearly one degree centigrade and then a very rapid cooling of one degree centigrade during the last half of the period. The last two values of the temperature deviations are estimated because the milliammeter needle went off scale. The 2.7-meter and 5.5-meter level experienced the same type of fluctuations. The hodograph, figure (6), indicates a distinct wind direction change between the 2.7-meter and the 5.5-meter levels. On the other hand, the temperature traces at the three higher levels are generally of the same type and exhibit a decrease in the magnitude of the temperature
200 Second Deviations from 1400 Second Mean.
(7 values)

Temperature
0 \rightarrow t
Time \rightarrow

Wind Direction

Level 1.4 m  2.7 m  5.5 m  11.0 m  22.0 m  44.0 m

Afternoon Run

Wind Speed

Figure 22.
200 Second Deviations from 1400 Second Mean. (7 values)

**Temperature**

-0.25°C to +0.25°C

**Wind Direction**

*Missing*

**Level**

14 m, 2.7 m, 5.5 m, 11.0 m, 22.0 m, 44.0 m

**Wind Speed**

0.5 mps to -0.5 mps

*Sunset Run*  
*Figure 23.*
200 Second Deviations from 1400 Second Mean
(7 values)

Temperature

Level 1.4 m 2.7 m 5.5 m 11.0 m 22.0 m 44.0 m

Wind Direction

Wind Speed

*wind speed sensitivity below instrument

Evening Run

Figure 24.
changes with height. The wind direction fluctuations at the lower levels can not be given too much significance, as indicated previously; however, it would seem from the rather consistent patterns of the upper four levels that perhaps these fluctuations are not too far from the actual deviations. There is a distinct decrease in the magnitude of the changes in wind direction at the 44-meter level. The wind speed fluctuations are of two types. A zero wind speed was recorded at the 1.4-meter level. At the three higher levels, the traces are similar to each other and the magnitudes do not change with height. The 22-meter and 44-meter traces exhibit a change to a different type. The minimum value of the below-average speed at these levels comes at an earlier time than at levels immediately below.

Conclusions regarding the relationship between temperature changes at a particular level with changes in the wind direction and wind speed at the same level are not immediately obvious. However, the vertical variation of these quantities is nicely shown. The use of 200-second means, integrates the effect of the fluctuations smaller than this value so that only the larger scale effect is given. The effect of the buoyancy force is obvious by a comparison with the afternoon and evening runs. During the afternoon run, the entire layer under investigation is affected by the larger scale fluctuations. During the evening run, there seems to be a tendency for stratified air flow.
Graphical interpretation of 200-second mean temperatures and wind directions versus time.

Individual wind direction fluctuations can be constructed from the instantaneous data which are available. However, since most of the discussion has been concerned with 200-second deviations, a plot of the afternoon and evening runs, using these deviations, as criteria, will be made. Although the method of interpolating between the mean points is not entirely correct, the plot will illustrate the differences between the larger scale fluctuations of the air flow during the afternoon and evening runs. Figures (25, 26) graphically exemplify the changes in the character and vertical variation of the wind direction fluctuations at times of lapse and inversional thermal stratifications in the lowest 44 meters of the atmosphere.

Horizontal variation of wind direction fluctuations

Variations in the direction of the 11 m. wind vane on the portable tower during each of the three observational periods are illustrated on figure (27). Since the collection of data was synchronized between the portable and stationary towers, it is possible to investigate the variation in the character of the direction fluctuations between these towers. Although Giblett (6) was unable to trace wind direction fluctuations with his instrumental arrangement, even though the smallest distance separating the 15.3 m towers was 107 meters, the fluctuations can be traced over a distance of about 61 meters using the Round Hill instrumental technique. This
Vertical Structure of Turbulent Deviations: Wind Direction and Temperature. Afternoon Run

Based on the seven 200-second Deviations at each level of the Stationary Tower. Figure 25.
Vertical Structure of Turbulent Deviations: Wind Direction and Temperature.

Evening Run

Based on the seven 200-second Deviations at each level of the Stationary Tower.

Figure 26.
fact is clearly illustrated in the afternoon run when the wind was nearly parallel to a line joining the two towers. The fluctuations appeared first at the portable tower (see Afternoon run, Figure (27)) and appeared eight to twelve seconds later at the stationary tower (see 11 m. trace, figure (14)). The variable air flow of about six meters per second accounts for the advection of the directional changes and hence the time lag. The larger directional variations exhibit very few changes while the shorter variations are more erratic and changeable. This fact may be the result of taking observations at fixed intervals of four seconds while the distance and rate of advection of the fluctuations between the two points of observation are such that the exact portion of the eddylike motion is not at the second observation point when the subsequent four-second observation is made. A northward shift of the mean wind in the interim between the afternoon and sunset periods positioned the portable tower about 10 degrees to the left of the mean wind direction relative to the stationary tower. The individual fluctuations are not traceable from the portable to the stationary tower, (see 11 m. trace, figure 15 and Sunset Run, figure 27). However, similar changes in the character of the two traces are evident. The wind speed during the evening run was near the stopping speed of the wind vanes so that the differences in the characteristics of the portable and stationary tower wind vanes were amplified. This point is stressed by comparing the evening traces of figure (27) and the 11 m. trace of figure (15). The portable tower was 20 degrees to the left of the mean wind direction relative to the
WIND DIRECTION FLUCTUATIONS
PORTABLE TOWER
Wind Vane Height: 11.0 meters
Figure 27.
stationary tower. On the basis of this brief investigation, it may be concluded that fluctuations in the wind direction of scale ranging from about 28 to 60 seconds (wind speed approximately 6 mps) can be traced over a finite distance without radical structural changes. This conclusion is true, at least, for a period of unstable thermal stratification.
VII. CONCLUSIONS

The study of the turbulent atmospheric structure is at present in the embryonic stage. There is as yet no prescribed line of approach to the problem. In this study several possible methods of describing pertinent data have been discussed. This investigation utilized data from only three 1400-second observational periods. A much larger sample is required before generalized statements can be expounded. However, on the basis of these three runs the following conclusions can be made:

1. There is a distinct difference between the vertical characteristic of wind direction fluctuations under varying conditions.

2. If the assumption of three independent turbulence parameters is applied, there is a direct relationship between the changes in the vertical characteristics of the horizontal wind direction fluctuations and changes in the thermal stratification of the layer, when the dynamic and geometric effects are relatively constant.

The ultimate aim of this study has been to demonstrate the possible value of the Round Hill instrumental technique in this type of investigation. The results have emphasized this value. Future investigations could be aided with the addition of appropriate instruments for the measurement of wind speed and temperature on the same basis as the wind direction.
BIBLIOGRAPHY


