Some Turbulence and Wind Variability Observations in the Lee of Mountain Ridges[1,2]

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ABSTRACT

A field of turbulence and space and time wind variability in the lee of a ridge line is observed with double theodolite wind data. It is shown that the most turbulent areas occur above the lee slope and are associated with the sharp transition zone between the wind shadow regime just above the slope and the prevailing flow. This transition zone is quite intermittent in time and variable in height and is usually characterized by sustained vertical gusts which may extend to 3 km downwind of the ridge line. The scale of turbulence in the transition zone is quite large. Examples of pure thermodynamic upslope winds are also given.

The effect of insolation and prevailing wind speed on the turbulent regime in the valley is discussed and it is shown that the zone of maximum turbulence and wind unrest tends to move to ridge line height under relatively stable temperature gradient conditions.

1. Introduction

The purpose of this paper is to summarize the results of a large number of double theodolite runs which were made in a number of valleys in Vermont during the summer of 1959. The primary objective of this phase of the investigation was to determine the three dimensional field of turbulence as a function of a) distance from the valley wall, b) direction of wind with respect to ridge line, and c) atmospheric stability.

2. Experimental methods and site description

The experimental methods varied in detail according to the terrain investigated. A common feature of all the methods employed was at least one double theodolite line extending in the cross-valley direction with one theodolite located on the slope of the valley side and the other located on the valley floor, approximately in mid-valley. The observational technique was then to release balloons alternately from the valley slope and mid-valley location. Each balloon was followed for about 8 min with angular observations made usually at 15-sec intervals, but sometimes at 10- or 20-sec intervals. The number of balloons released per hour varied but averaged about five.

The most ambitious of the experimental schemes employed two double theodolite lines which were manned simultaneously. The location of the mid-valley theodolite in each line was approximately the same, but the slope positions were at about $\frac{1}{3}$ and $\frac{2}{3}$ the height of the ridge line. For this configuration it was feasible to release two balloons simultaneously, and from these data it was possible to infer the scale of turbulence and short-time variations in wind speed and direction.

In order to get better height and "distance from the ridge line" definition, the ascent rates of the balloons were varied by tying predetermined weights to the balloon after the balloons were weighed off with standard free lifts. For the most part J-10 balloons were inflated to 45 gm of free lift. The average of a great many night observations indicated that the ascent rate of these balloons with 45 gm of free lift was 2.5 m sec^{-1} with very little internal variation in the rate of ascent for the first 8 minutes after release. For many observations this rate of ascent was slowed down to 2 m sec^{-1} or 1.5 m sec^{-1} by tying appropriate weights to the balloon. A few observations were made with standard J-30 balloons and for these balloons a nominal ascent rate of 3 m sec^{-1} was assumed.

The data relevant to the present paper were obtained in two valley locations which are crudely mapped in Fig. 1. A sketch of the terrain in the plane of the theodolite stations is shown in Fig. 2. The curves are drawn to scale and yield representative values of the slope of the terrain and the average ridge line height for each of the configurations. The A stations were manned under WNW flow conditions and the B stations under SW flow conditions.

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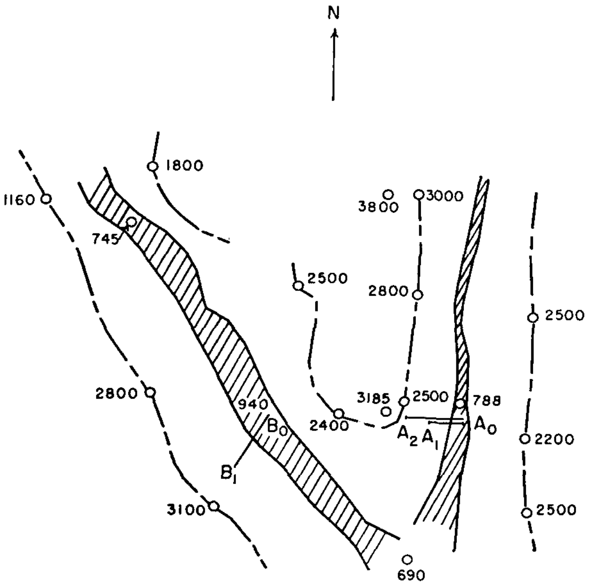

FIG. 1. General topography of experimental area near Manchester, Vt., showing ridge lines (dashed lines) valley floors (hatched areas) and station locations. Numerals indicate height (ft) above sea level.

3. Data reduction

The position of the balloon was projected on a vertical plane with the line connecting the theodolites as the base of the plane. The adjusted elevation angles were then used to triangulate for the height of the balloon above either theodolite. Once the height of the balloon was calculated, the horizontal distance out from each theodolite was computed, and velocities were obtained by differencing consecutive positions of the balloon. A double theodolite system is in general over-determined and wherever possible the additional information provided by *all* the readings was used to check the consistency of the data. The method of checking and editing the data is described in detail by Davidson (1960). On a number of occasions conventional azimuth angle triangulation was employed. On these occasions, it was required that the differences in the height of the balloon as determined from each theodolite should not exceed ±1.5 m.

It follows from this procedure that the nominal height resolution of the data was on the order of 37.5 m if the basic data met the error standards. Averaging consecutive velocities was necessary for about 30 per cent of the points so that the basic height resolution for $\frac{1}{3}$ of the data is on the order of 75 m. For some configurations, errors in velocity cannot be detected by any internal checks. For these observations a standard smoothing procedure was employed. All in all, it is felt that the data used in subsequent sections are as accurate as can be obtained from double theodolite observations made under field conditions and edited at leisure.

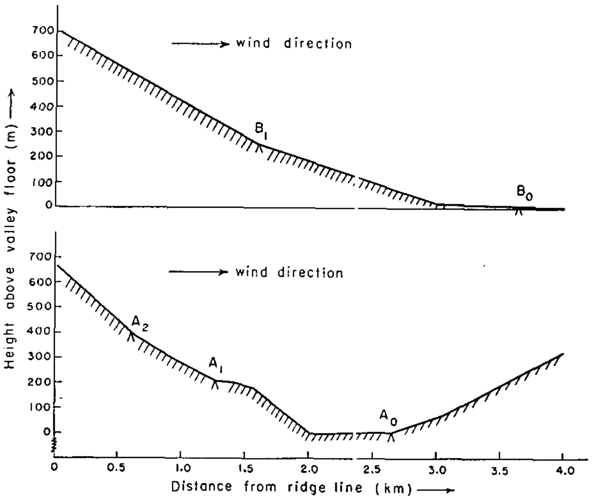

FIG. 2. Cross-sectioon in XZ plane showing terrain slopes and station locations.

4. Statistical procedures

Analysis of a velocity field where both the average and turbulent components are functions of x, y and z is a formidable statistical problem This is especially the case when 1) the level of turbulence is great, 2) the x, y, z position of the probes themselves are functions of the wind field, and 3) when the time interval between observations is relatively large.

The bias associated with item (2) above precluded any objective statistical analysis of the turbulence as a function of distance from the valley wall. As will be demonstrated subsequently, relatively large horizontal wind speeds are associated with negative vertical velocities which, at times, are of the same magnitude as the ascent rate of the balloon. Since the balloons were released from fixed points on the slope, it follows that balloons would enter certain fixed volumes of space if and only if extreme downward gusts carried them there. There is no way of removing this sort of bias from the data.

Balloon launchings are, of course, not the ideal way of studying wind field variability. Even under the best of circumstances, it was not possible to launch more than 6 balloons per hour. Considerable change in external conditions may occur in the period of an hour or two. The sampling rate is therefore grossly inadequate and one can never be sure just what atmospheric condition has been sampled. The data, nevertheless, yield systematic reproducible results in at least a semiquantitative sort of way. In keeping with the semiquantitative nature of the statistical data quantitative measures of dispersion, where appropriate, have been limited to statements concerning the observed range of individual velocity components. For comparative purposes, occasional values of gustiness, defined as:

$$G=(\sigma_{v_x}{}^2+\sigma_{v_y}{}^2)^{\frac{1}{2}}/\bar{U},$$

are quoted: values of σ^2 for this measure of variabliity were estimated from the range and the number of available observations according to a statistical technique suggested by Dixon and Massey (1957).

Further definitions follow:

dr/dt = rate of rise of balloon in still air;

v_x = velocity component normal to the ridge line, positive when directed from ridge line to mid-valley;

v_y = velocity component parallel to ridge line;

w = vertical velocity of air obtained by subtracting dr/dt from observed rate of rise of balloon.

The data to be discussed are restricted to those hours when the prevailing wind at one to one and a half times the ridge line height was within ±30° of the normal to ridge line. The speed of the wind at these heights ranged from about 2 m sec^{-1} to 15 m sec^{-1}; the temperature gradients ranged from unstable to an estimated isothermal. In all cases the slope stations are in the lee of the ridge line, that is, the average wind at ridge line height is always directed from the slope station to the mid-valley station. The data are presented in graphical form and in general have been arranged to exhibit first the wind field as observed from the slope station releases, and then the wind field as observed from the mid-valley releases.

5. Data discussion

a) Unstable conditions. To help organize the discussion, a schematic sketch of the wind regimes to be expected near the lee slopes of the valley is shown in Fig. 3. In general, two distinct wind regions may be defined. The phase 1 regime is confined to a ground-based layer of thickness Z_1. During this phase the wind speeds are relatively light and the wind direction may be quite variable. This region is in a wind shadow area; it is in the wake of the valley wall. Depending on the overhead wind speed and the amount of insolation being received on the slope, the winds in the phase 1 region may be directed upslope towards the ridge line (counter to the prevailing flow) for substantial periods of time. This is especially the case with light overhead winds and strong insolation. With stronger prevailing winds and good insolation conditions, the wind may be directed towards the ridge line as often as it is directed towards mid-valley. With still stronger overhead winds and cloudy conditions, the wind direction in the phase 1 region is mostly towards mid-valley; but the speeds are relatively light when compared with the speed measured in mid-valley at comparable height.

The phase 2 regime is essentially the connecting region between the wind shadow regime and the prevailing flow regime. In the phase 2 region, the wind speed increases very rapidly with height, or distance from the valley wall or time; it is impossible to say which from our data. These intense shears are usually, though not always, accompanied by downward vertical gusts of varying magnitude. The regions of most intense turbulence are found in the phase 2 region.

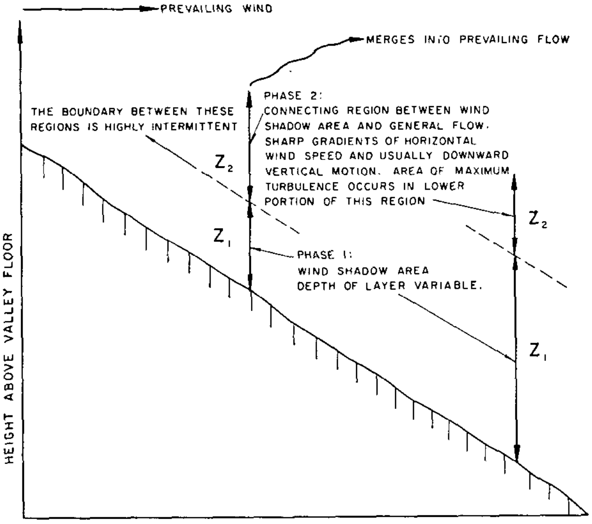

FIG. 3. Schematic sketch of characteristic wind regimes found over slopes under unstable conditions.

Unfortunately, the geometry of the two regions is highly variable. For example, the observed vertical thickness of the phase 1 region may vary from about 50 to 500 m. Considering the geometry of the valleys investigated, this means that the phase 1 region may, on occasion, extend up to and even above the ridge line. The intermittency of the location of the dividing line between the two phases is a very striking characteristic of the data.

We proceed now to discuss these points in greater detail. Fig. 4 illustrates a phase 1 regime. This set of observations were made on 18 August 1959 from 1515 to 1715 EDT, under moderate overhead wind speed conditions (6 m sec^{-1}). Since the cloudiness varied between 20 and 70 per cent, the temperature gradients were probably moderately unstable. The wind directions observed on the slope cover a full range of 360° while the range of wind directions observed in mid-valley is about 120°. The mean vector wind direction near the slope has a component directed up-slope; the magnitude of this vector is about 0.7 m sec^{-1}. The range of variation of the v_y component is about 4.5 m sec^{-1} while that of the v_x component is about 4 m sec^{-1}. The mid-valley releases indicate a range of about 5 m sec^{-1} for each component, but the magnitude of the vector mean wind has increased to about 3 m sec^{-1}. The gustiness, G, as calculated from the observed range is slightly greater than 2.0 in the areas above the slope and is about 0.8 for the mid-valley location.

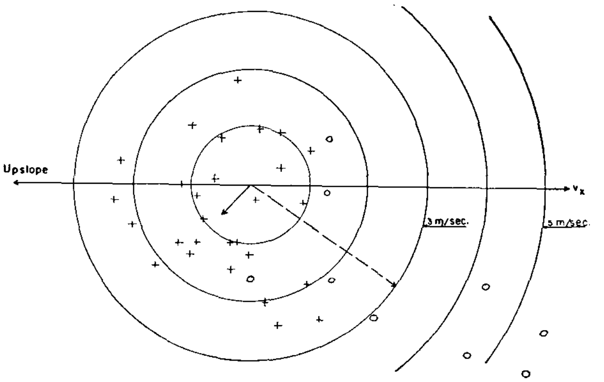

FIG. 4. End points of horizontal wind vector observed in the first 100 m above slope stations A_1 and A_2 (crosses). Open circles are end points of horizontal wind vector observed at mid-valley station, 250–350 m above valley floor. Data cover period 1515–1715, 18 August 1959.

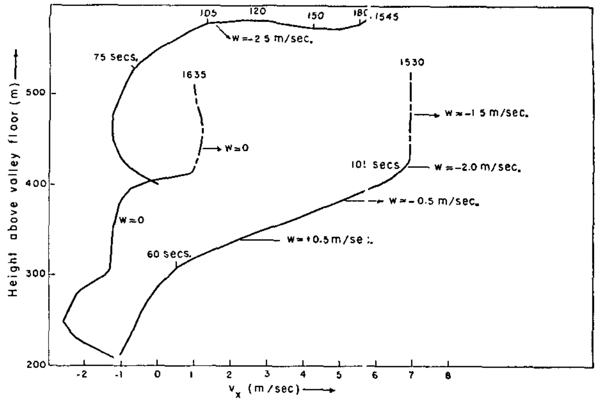

FIG. 5. Three profiles of v_x component of velocity observed from slope releases, 18 August 1959.

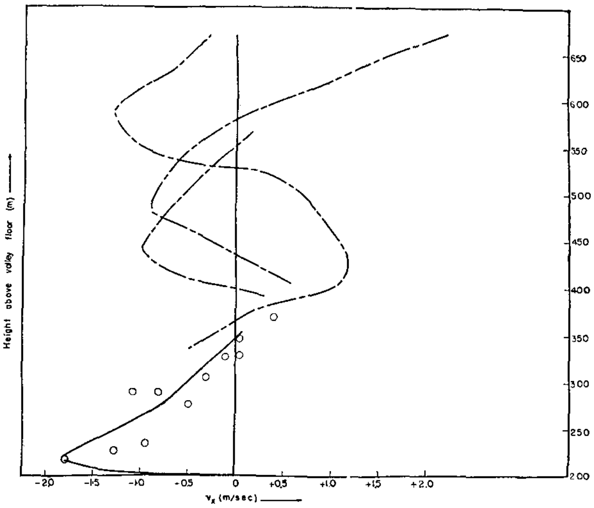

FIG. 6. Three v_x profiles demonstrating an almost pure up-slope wind system, 0840–1010, 14 August 1959.

Fig. 5 illustrates the velocity profiles observed during the first and second phases of the wind regime above the slopes. The data are from the same set of observations described in Fig. 4. The profile marked 1545 was observed by a balloon released from station A_2. Up-slope motion (negative v_x) persists in a layer adjacent to the slope whose thickness is on the order of 150 m. Coincident with the beginning of the downward gust between 75 and 105 seconds, the v_x component of velocity increases steadily with time (or distance from the valley wall) and reaches its maximum speed of close to 6 m sec^{-1} about 75 seconds after the downward gust is encountered.

The history of the 1530 balloon released from A_1 is somewhat similar except that the region of sharp gradient of v_x is not associated with downward vertical velocity; rather the maximum vertical velocity is reached at the top of the sharp shear zone. The depth of the phase 1 layer is on the order of 150 m for the 1545 balloon and about 110 m for the 1530 balloon although, as will be shown subsequently, there is considerable variability in this statistic.

The 1635 profile is shown to indicate the complete lack of strong v_x component even at 300 m above the launch point. Note that the vertical velocity of the air is close to zero for the upper part of this run. It should also be noted that the up-slope motion reaches a maximum of close to 2.5 m sec^{-1} at about 50 m above the slope. Despite the fact that at this time of day, the western slope of valley A_1, a north-south valley, is not receiving a great deal of insolation, it appears that the 1635 profile may be an example of a more or less pure form of thermodynamic up-slope wind.

Probably the purest form of up-slope wind was observed in valley A, from 0840 to 1010 EDT on 14 August 1959. This was a clear day; the overhead wind was about 2 m sec^{-1}, and a considerable amount of insolation was being received on the launch slopes during the observation period. The velocity points derived from the three best profiles for the first 150 m of each ascent are shown in Fig. 6. The dashed curves are individual profiles observed during the upper portion of each ascent.

The maximum observed velocity in the first 150 m occurs about 20 m above the release point and from the reports of the observers it is probable that the maximum is stronger and possibly lower than is indicated. The height of the first zero (150 m above the slope) is about the same for all three runs. Above the first zero the picture becomes a little confusing. Each of the runs, however, shows a definite return circulation (positive v_x) and then another zero followed by a second lobe of up-slope motion and then a third zero at which point the prevailing wind seems to take over. However, the heights of the second and third zeros are quite variable from run to run and it is possible that slight variations in the upper level flow are distorting the picture. It is interesting to note, however, that the profiles show (in crude

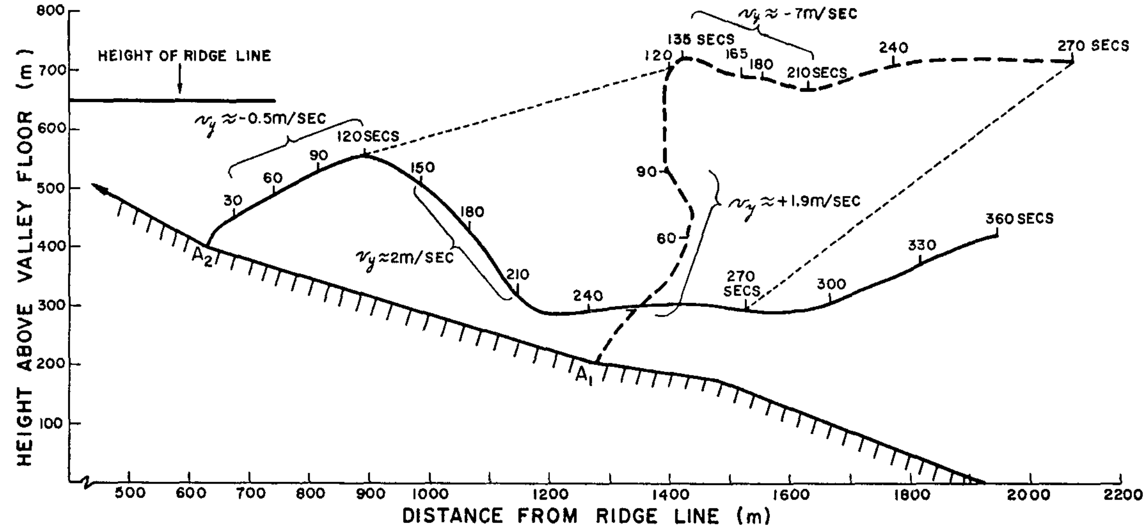

Fig. 7. Horizontal and vertical position in the XZ plane of two balloons released simultaneously from A_1 and A_2 at 1515, 25 August 1959.

outline) a kind of damped oscillation with height as is predicted in the theoretical work of Prandtl (1942) and Tang.[1]

On this day (14 August) balloons were released continuously almost throughout the day. During the period 0840–1010, consistent up-slope motion existed simultaneously at A_1 and A_2. After about 1030 the up-slope motion near the slope became sporadic; sometimes a profile like those shown in Figs. 5 and 6 was observed; at other times the up-slope motion was completely absent.

A clearer idea of the range of variation of the phase 1-phase 2 aspect of the lee slope releases may be gleaned from Fig. 7, where the horizontal and vertical position of two balloons released simultaneously from A_1 and A_2 at 1525 are shown as functions of time after release. These data were taken on 25 August 1959, a sunny day with 2 to 3/10 high cloud present. The velocity component normal to the ridge line and the vertical component of the balloon's velocity with respect to the air may be computed directly from the graph. To yield a three-dimensional picture of the wind field, average values of v_y for the bracketed time groups are also shown. The following features are worthy of note. Both balloons encounter sharp downward gusts at about the same time but the height at which this downward gust is encountered varies from 250 to 550 m above the slope. The magnitude of the average vertical velocity from 120 to 210 sec after release is about -3.3 m sec^{-1} and -5.5 m sec^{-1} for the A_1 and A_2 balloons, respectively. The maximum vertical velocity during this period is about -7 m sec^{-1}. Both balloons are immersed in the downward gust for at least 3 min. The maximum v_x component occurs 240 to 270 sec after release for each balloon at which time the separation distance is about 500 m in the x, 500 m in the z direction and at least 700 m in the y direction. It is apparent that the scale of turbulence here is quite large.

The variability of the height at which the balloons encounter descending air is demonstrated again in Fig. 8. The horizontal and vertical positions of two balloons, one released at 0810 and the other at 1000 from station A_1 on 11 August 1959 are plotted in this figure. The overhead wind here is about 7 m sec^{-1} normal to the ridge line; the sky is overcast. The 0810 balloon is caught in a down gust at 400 m above the valley floor,

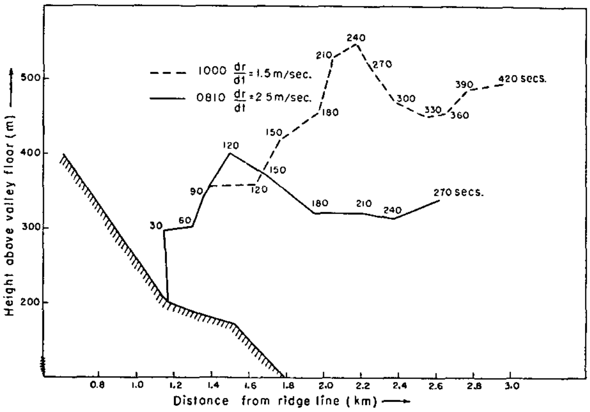

Fig. 8. Horizontal and vertical position in the XZ plane of two balloons released at station A_1 on 11 August 1959. Numerals indicate seconds after release.

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[1] Tang, W., 1960: The diurnal variation of temperature and wind over sloping terrain. Ph.D. thesis, New York University, Department of Meteorology and Oceanography, 63 pp.

about 300 m above the slope and about 1.5 km from the ridge line. The downward gust persists for two minutes during which time the balloon has travelled about 900 m and is now in mid-valley. The balloon released at 1000 encounters a downward gust at about 550 m above the valley floor when the balloon is substantially clear of the slope and about 2.2 km from the ridge line. Again the balloon remains in the down gust for about two minutes during which time it has travelled almost 550 m.

It is evident from Figs. 7 and 8 that once the balloon is caught in a down draft, the horizontal velocities become quite variable. Some idea of the fine structure of the turbulence is given in Fig. 9 where the three components of velocity are plotted at 10-second intervals in fixed 100 m layers. The velocities at ridge line height were on the order of 15 m $\sec^{-1}$ and the sky conditions were overcast. Only balloons which remained in the same 100 m layer for a substantial period of time were selected for analysis. This means that substantial negative vertical velocities must have been present. The three components of air velocity are plotted at 10-sec intervals. These data were thoroughly checked for consistency and the height triangulations check to within ±1 m. However, since these are low angle trajectories, a height error of 1 or 2 m may involve rather more substantial velocity errors, but probably the chief source of error for these data are timing errors for which there is no remedy.

Particularly worthy of note are 1) the rapidity with which the v_x component of velocity increases once the 350 m level is penetrated and 2) the duration of essentially negative vertical velocities. For example, the balloon launched at 0948 is in a down gust for about 4 minutes during which time the balloon has travelled about 1500 m and is approximately 3.0 km from the ridge line.

The extent of wind variability to be found in mid-valley and on the slopes during convective situations with a steady mean wind of about 5 m $\sec^{-1}$ is illustrated in Figs. 10 and 11. These observations are the set from which Fig. 7 was constructed. The maximum range of v_x occurs at 300 m above the valley floor and is of the order of 7 m $\sec^{-1}$, contrasted with the mean value of 4.3 m $\sec^{-1}$ at this height. The average value of the wind components parallel to the ridge line does not exceed 1.5 m $\sec^{-1}$ but it may be seen that the range of variation is again of the order of 7 m $\sec^{-1}$. The value of the gustiness, G, for the mid-valley releases is about 0.7 at 300 m and about 0.35 at ridge line height.

These gustiness ratios are high compared to the usual

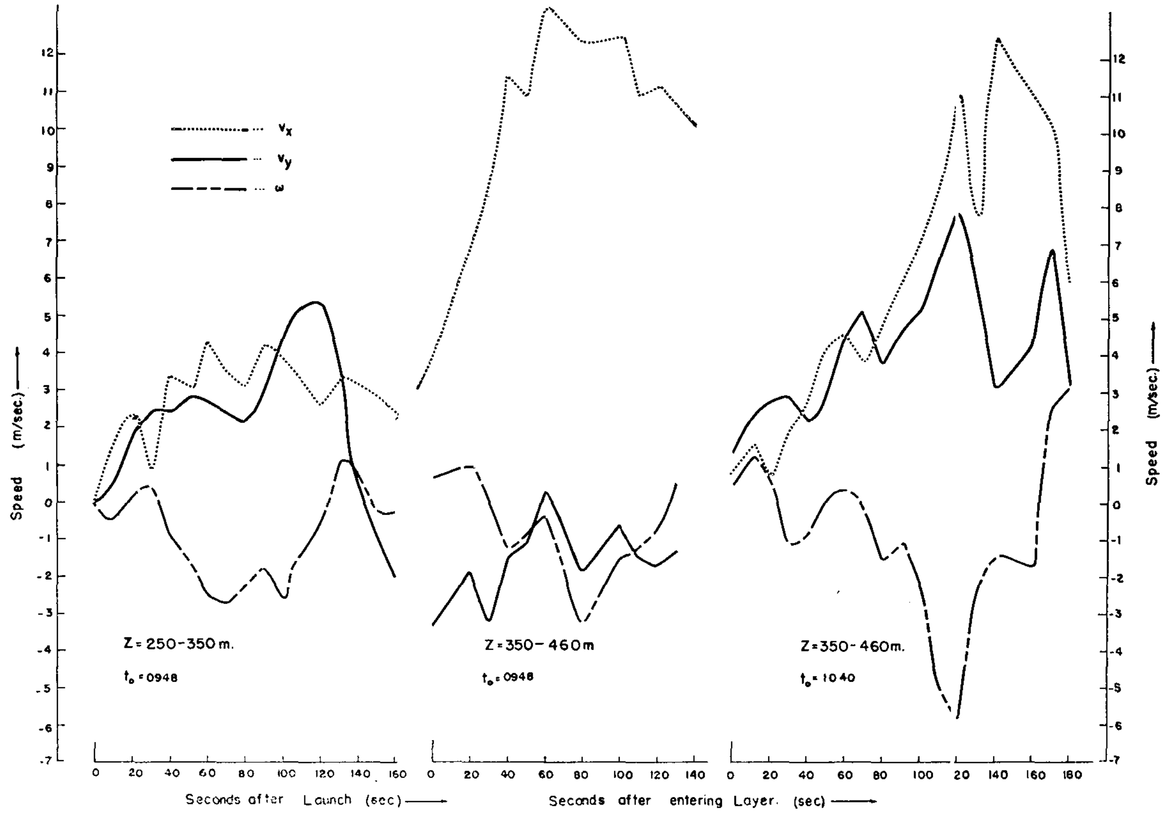

FIG. 9. Time history of three components of velocity at approximately 10-sec intervals as obtained from balloons released from B_1, 28 July 1959.

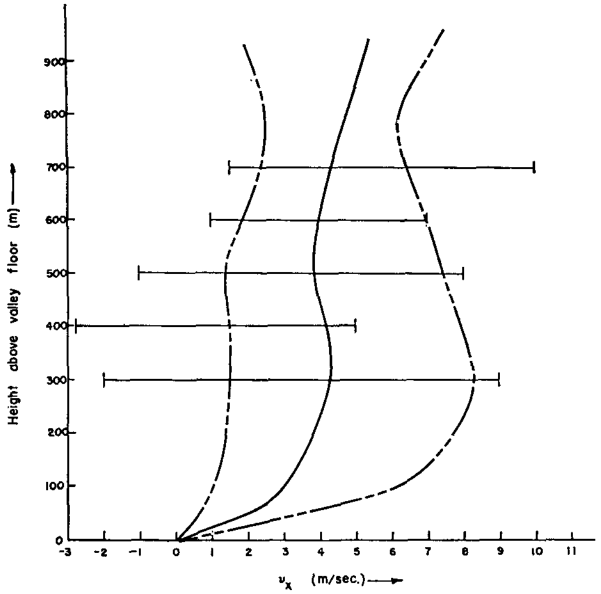

Fig. 10. v_x versus height; valley A, 25 August 1959, 1410–1600 hours. Solid curve is mean profile (12 balloons) observed from mid-valley releases; dashed lines are extreme values observed from mid-valley releases; solid horizontal curves are range of values observed from slope releases (6 balloons).

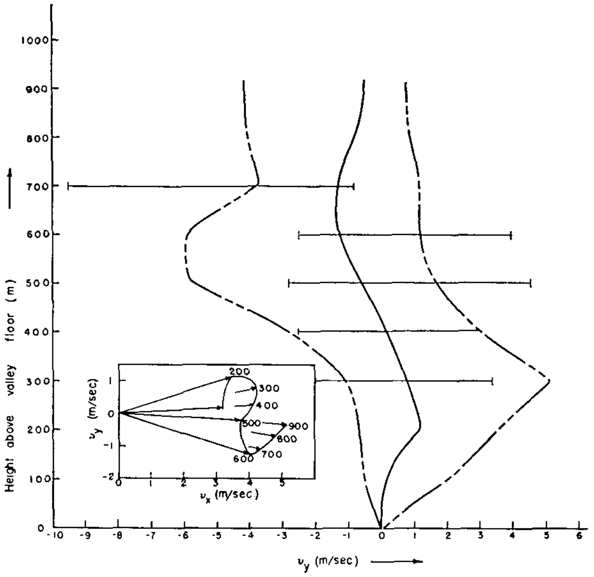

Fig. 11. v_y versus height; valley A, 25 August 1959, 1410–1600 hours. Solid curve is mean profile (12 balloons) observed from mid-valley releases; dashed curves are extreme values observed from mid-valley releases (6 balloons). Inset is average horizontal wind vector as function of height determined from mid-valley releases.

values of gustiness quoted in the literature especially when it is remembered that the heights above valley floor are substantial. But they do not tell the whole story. The extreme profiles shown for the v_x components in Fig. 10 represent, with minor exceptions, actually observed profiles. In other words, the average v_x components determined from the ground to the ridge line varied from about 1.5 m sec^{-1} to almost 7 m sec^{-1}. This is an extraordinarily large variation in vertically averaged winds over a layer almost 1 km thick and indicates that the entire layer of air within the valley may simultaneously experience velocities substantially above or below average. This is additional evidence that the scale of turbulence in these situations is very large.

The inset of Fig. 11 is a hodograph of the vector winds observed from the mid-valley releases and illustrates a rather neat oscillation of wind direction with height within the valley. The balloons released from the A_0 station reached the opposite slope of the valley approximately 2 or 3 minutes after release, so that some of the variability shown in Figs. 10 and 11 is appropriate to the case of air ascending a mountain slope (see Fig. 2). Since this is the only case where we succeeded in following balloons up a slope it is worth examining some of the details of this type of flow.

The characteristic features of the flow ascending the slope under the wind flow and stability conditions of this experiment are as follows: a) intense upward vertical motion of the air even before the balloons really begin to ascend the slope. This upward motion is of the order of 2 m sec^{-1}. b) increased upward motion of the air as the underlying slope steepens so that the vertical velocity of the air increases to 3–4 m sec^{-1}. Vertical velocities of this order of magnitude were found even 1000 m vertical distance above the slope. c) the angle of the vector wind in the *XZ* plane is generally greater than the angle of the slope over which the air is flowing. In other words the streamlines are not parallel to the sloping sides, but form an angle with the horizontal which is sometimes 2 or 3 times the slope of the terrain. d) occasional (one out of 12) sustained downward vertical velocities of the order of 2 m sec^{-1} occur over the ascending slope. These occurred with larger than usual v_x components and as far as 3 to 3.5 km from the upwind ridge line. e) despite the occasional downward gust found over the ascent slope, the flow is reasonably smooth and there is no evidence that the jagged kind of turbulence exhibited in Figs. 7, 8 and 9 is found over the ascent slope. For the moderate wind speeds and good insolation conditions of this experiment, the evidence is that a gigantic convective eddy is superimposed on the aerodynamic field of turbulence induced by the air flowing over the ridge line.

The extent of wind variability to be found under stronger wind speed conditions is illustrated in Fig. 12. The observations were made in valley B from 1724–1956 EDT. Sky conditions were cloudy and the wind speed at ridge line height was 10 m sec^{-1} directed at an angle of about 25° off the normal to the ridge line. In view of the wind speed, the cloudiness and the lateness of the hour there is little doubt that the temperature gradient

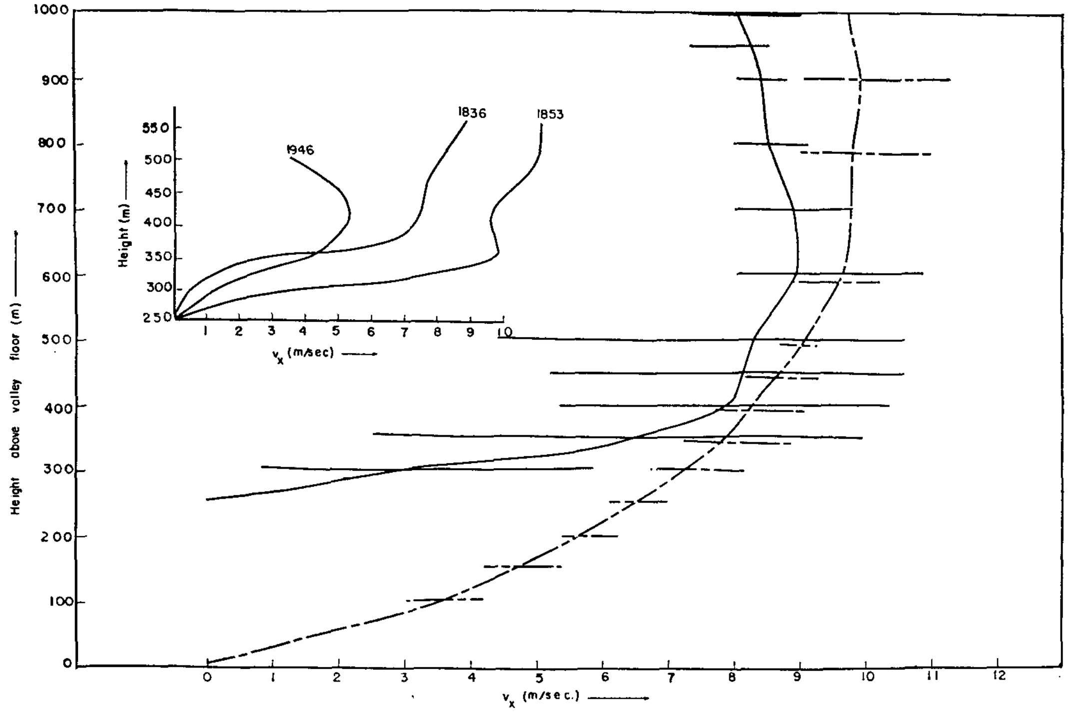

FIG. 12. v_x versus height; valley B 1724–1956. Solid curve is mean v_x component observed from slope station releases (12 balloons, 6 above 600 m). Solid horizontal lines give range of variation observed from slope releases. Inset shows three individual profiles. Dashed curve is mean v_x component observed from mid-valley (3 or 4 balloons); dashed horizontal line is range of variation in mid-valley releases.

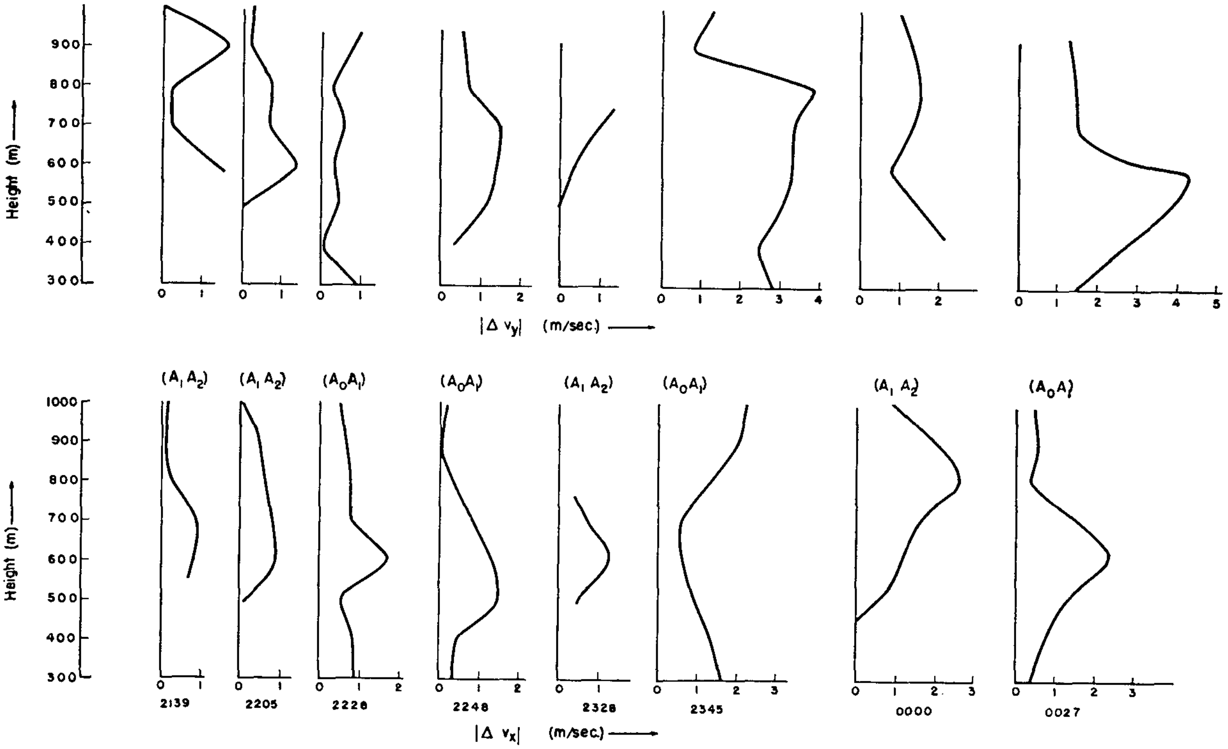

FIG. 13. Absolute value of wind differences observed during simultaneous releases from A_2, A_1 or A_1, A_0. Data taken from 2043–0027, 13–14 August 1959.

was very nearly adiabatic. The maximum range and the maximum gustiness occur 100 m above the slope or at about half the ridge line height. The maximum gustiness ratio here is about 0.4 as contrasted with a gustiness ratio of about 0.7 found at the same relative height for the mid-valley releases under convective conditions. A great deal of the observed variability may be accounted for by the three profiles shown in the inset of Fig. 12. The 1853 balloon encountered a downward gust of about 1 m sec^{-1} at 300 m elevation; the 1836 balloon encountered a downward gust of similar magnitude at about 350 m elevation, while the 1946 balloon encountered no vertical gust. Essentially, then the physical process contributing to the variability remains unchanged; the thermal component is absent due both to the temperature gradient and the greater wind speed. This explains the decreased level of variability. Since at best only four balloons are involved for the B_0 data there is little reliability in these observations. The curves, however, do show how soon after release the slope balloons begin to take on mid-valley values of wind speed under adiabatic, strong wind speed conditions.

b) *Isothermal to adiabatic conditions.* Problems associated with collection of turbulence data in ridge-valley country as the temperature gradient ranges from adiabatic to isothermal are considerable. Unless the wind speeds are very strong, or along the axis of the valley, a stable layer is bound to show up within the valley. The flow in the valley will then tend to be along the valley axis and the cross-valley flow will cease to penetrate into the valley. This was indeed the case on the night of 13–14 August when the only data relevant to the isothermal–adiabatic case were taken. Twenty balloons were released during the observational period, 2043–0027 EDT; these consisted of ten simultaneous pairs of balloons released either from A_1 and A_2 or A_0 and A_1. The data were analyzed to exhibit 1) cross-valley wind differences at fixed times, and 2) the total wind variability in the valley during the almost 4 hours of observations.

Differences in the v_x and v_y components of velocity as observed from eight balloon pairs are shown in Fig. 13 as a function of time and height above the valley floor. Since the pairs were released simultaneously, all long-term trends during the observation period are irrelevant. The A_1A_2 differences illustrate wind differences on a time scale of less than 2 minutes (the balloon released at A_1 reached a fixed height about one or two minutes after the A_2 balloon had sampled that height), and a space scale (near the valley wall) of about 500 m. The A_1A_0 pairs illustrate wind differences on the same time scale and on a space scale of about 1500 m measured from near the valley wall to mid-valley. For the period 2139–2328, the differences for both the v_x and v_y components rarely exceed 1 m sec^{-1}. The maximum differences occur somewhere near ridge line height. Beginning at 2345, however, very large v_y differences, on the order of 4 m sec^{-1}, are observed between the A_0A_1 pairs. These differences are systematic. The A_0 station shows a consistently larger v_y component than the A_1 station up to about 900 m above the valley floor. What has happened is that the wind direction at both stations has become very nearly parallel to the valley axis up to 500 or 600 m above the valley floor. The magnitude of the wind vector has remained about the same for the A_0 station but has decreased by about a factor of 3 at the A_1 station. The wind direction and wind speed at 1000 m has remained unchanged and it is therefore reasonable to assume that a stable layer has developed in the valley and the flow in mid-valley is consequently being channeled in the direction of the valley axis. It appears then that so long as the temperature gradient remains between neutral and isothermal, synoptic cross-valley differences under the wind speed conditions studied during this experiment are not excessive.

The mean v_y and v_x component of the horizontal velocity vector as well as the extremes observed during the entire experiment are shown in Fig. 14. The average v_x components observed at the A_0, A_1 and A_2 stations do not differ greatly from one another, especially if the first 100 m above each slope station is disregarded. The highest absolute range of v_x component occurs slightly above ridge line height. During unstable conditions (see Figs. 10–12, for example) the maximum absolute variability occurs at about half the ridge line height.

The average v_y values, on the other hand, exhibit a systematic cross-valley difference which is of the order of 1 m sec^{-1}. From our previous discussion, the reason for this is obvious and had we continued sampling the stable atmosphere there is little doubt that greater differences in the mean would have resulted. The range of variation of the v_y component of velocity within the valley is larger than was observed for the v_x component, again for the reasons discussed previously. The observed range of variation partly reflects a systematic change of wind with time due to the change of stability within the valley. This is clearly seen from the inner set of pips which represent the observed range of v_y for the height interval 400 to 800 m when the last three observations are omitted.

6. Conclusions

Under unstable conditions the wind regime above the lee slopes may be divided into two phases. The phase 1 regime is characterized by light variable winds under low to moderate overhead wind speed conditions. Under these conditions gustiness values may be close to two. However, in view of the generally light mean wind speeds, the maximum absolute value of turbulence is not encountered in the phase 1 region. The height of the phase 1 region is quite intermittent and may vary from 50 m above the slope to at least the height of the ridge line.

The phase 2 regime is characterized by downward

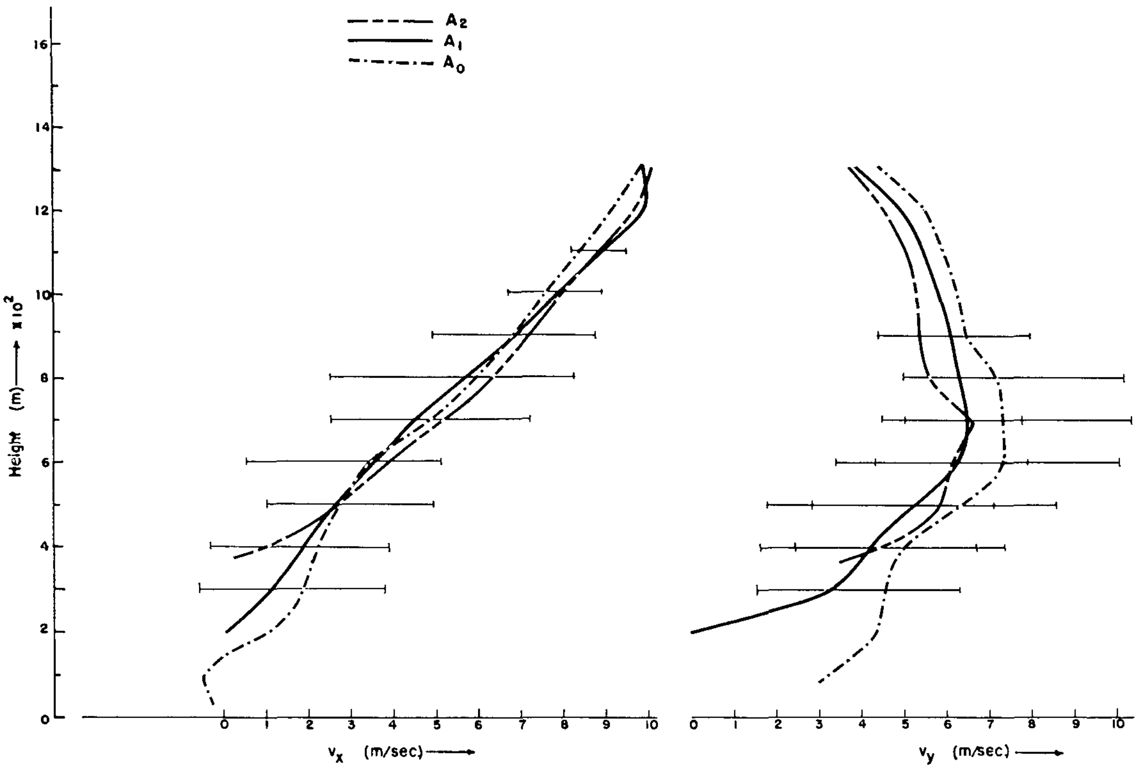

FIG. 14. Profiles of average v_x and v_y as observed at A_0, A_1 and A_2, 2043–0027, 13–14 August 1959. Range of variation for all releases is shown by solid horizontal lines.

vertical velocities, intense shear of horizontal velocity components and, in general, is the most turbulent (on an absolute scale) area to be found within the valley. The maximum value of turbulence in mid-valley is found, on the average, to be about 200–300 m above the valley floor, or, in view of the geometry of the valleys investigated, at about half the ridge line height. The scale of turbulence in the phase 2 regime is quite large, but there is reason to believe that the extreme turbulence damps out at most elevations at horizontal distance of 3 to 4 km from the ridge line.

Under near inversion conditions, the zone of maximum turbulence moves to slightly above the ridge line height and is considerably diminished in intensity.

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