A Lagrangian Study of Helical Circulations in the Planetary Boundary Layer

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ABSTRACT

During July 1966, nearly 100 tetroon flights were made at the National Reactor Testing Station (NRTS), Idaho Falls, with the primary purpose of verifying the existence of longitudinal roll-vortices, or helices, in the planetary boundary layer. The transponder-equipped constant volume balloons (tetroons) were ballasted to float 300 m above the ground and were tracked by two M-33 radars. One radar tracked two tetroons released simultaneously from sites 500 m apart (in a direction normal to the mean flow) and the other radar tracked two tetroons released simultaneously from the same sites about one-half hour later.

In the flat, desert-like region of NRTS, there is evidence that counter-rotating helices of about 2 km diameter frequently exist during the afternoon. Basically, the helical motion appears to be one of solid rotation, with an average absolute value for the vorticity in the transverse plane of 4×10^{-3} sec^{-1}, a magnitude similar to that derived from the vertical shear of the longitudinal wind. There is evidence that these helical structures move in a direction normal to the mean flow with a speed of about 1 m sec^{-1}. During the afternoon, the average value of the tetroon-derived horizontal stress is nearly 6 dyn cm^{-2}, and the average flux of kinetic energy from mean sheared flow to helix is nearly 6 cm^{2} sec^{-3}. There is considerable agreement between the tetroon-derived data and the theoretical and laboratory work of Faller and Lilly on helical circulations, even though the evidence from this atmospheric experiment suggests that, during the afternoon, the longitudinal vortices are driven both by buoyancy and the vertical shear of the mean flow.

1. Introduction

In July 1966 a superpressured, constant volume balloon (tetroon) experiment was carried out at the National Reactor Testing Station (NRTS) near Idaho Falls. The primary purpose of this experiment was to verify the existence of longitudinal roll-vortices, or helices, in the planetary boundary layer. The existence of such organized systems in the surface layers of the ocean has been inferred from the distribution of floating debris by Langmuir (1938), Faller (1964) and Faller and Woodcock (1964). The existence of similar mesoscale systems in the atmosphere has been inferred from observations of the soaring habits of seagulls by Woodcock (1940, 1942); from aircraft and TIROS cloud photographs by Kuettner (1959), Conover (1960), Plank (1960), Fritz (1963) and Rogers (1965); from bulk tracer experiments by Woodcock and Wyman (1947) and Hallanger *et al.* (1962); and from observations of free-floating balloons by Gifford (1953), Angell and Pack (1961, 1967) and Pack (1962). In addition, Faller (1965), Faller and Kaylor (1966) and Lilly (1966), based on the laboratory work of Brunt (1951), have suggested the existence of such circulations in the boundary layers of both atmosphere and ocean from a combination of theory and rotating tank experiments. Finally, no reference would be complete without acknowledging the pioneering work of Townsend (1956, Chap. 6) and Grant (1958) on the nature of "large eddies," and the more recent theoretical work undertaken by Kuettner (1967) along this line.

Observational results alone are presented in this paper, although Section 9 compares these results with some of the theoretical and laboratory findings of Faller and Lilly. Furthermore, emphasis is placed upon the relatively steady-state helical circulations delineated by tetroon flights in the afternoon. Analysis of the more complex interactions occurring during the development of the circulations in the morning is reserved for a subsequent paper.

2. Procedures

The tetroon-transponder system has been described by Pack (1962). The superpressured, constant volume, tetrahedral-shaped balloon used was made of 0.08-mm Mylar and possessed a volume of 1 m^3. The relatively high drag coefficient of the tetroon (about 0.8) enables it to respond well to mesoscale vertical air motions (Booker and Cooper, 1965), although the reader must bear in mind that the tetroon tends to float along an isopycnic surface and tends to return to that surface if displaced from it. For example, a tetroon displaced 1 km from its float surface will have a restoring velocity of about 1 m sec^{-1}. Nonetheless, because of the large vertical air motions at NRTS during the afternoon (see Fig. 4), the major conclusions of this paper regarding helical circulations are unlikely to be affected, though there is the interesting point that, because of the restoring velocity, the tetroon will tend to seek out, and move toward the center of, any helical vortex present.

One M-33 radar was used to track two tetroons released simultaneously from sites 500 m apart in a direction generally perpendicular to the mean flow. The second M-33 radar tracked two flights released from the same sites about one-half hour later. This time interval was larger than desired but was dictated by the time needed to inflate and weigh-off the second pair of tetroons. With the help of special receivers, preamplifiers and antennas, and with the capability of varying the magnetron power of the radars, those tetroons that did not ground prematurely could be quite accurately tracked to a distance of 105 km (the limit of the radar range-computer). The rms positioning error of the M-33 is estimated to be about one-thousandth of the range. The 100-gm transponder attached to the tetroon permitted radar tracking at extremely low elevation angles without the interference of ground clutter.

The radars could be operated manually or in the "auto-tracking" mode. The latter method was most frequently used for tetroon positioning, but, of course, the alternation of targets required extensive manual searching. Insofar as possible, the radar data (range, azimuth and elevation angle) were recorded at 1-min intervals for each tetroon (positions every 30 sec considering both tetroons). The raw radar data were processed by computer to yield, at 1-min intervals, 3-min average values of the velocity components in both standard (north-south, east-west) and natural (along and cross stream) coordinate systems as well as flight-mean values of the related Reynold's stresses.

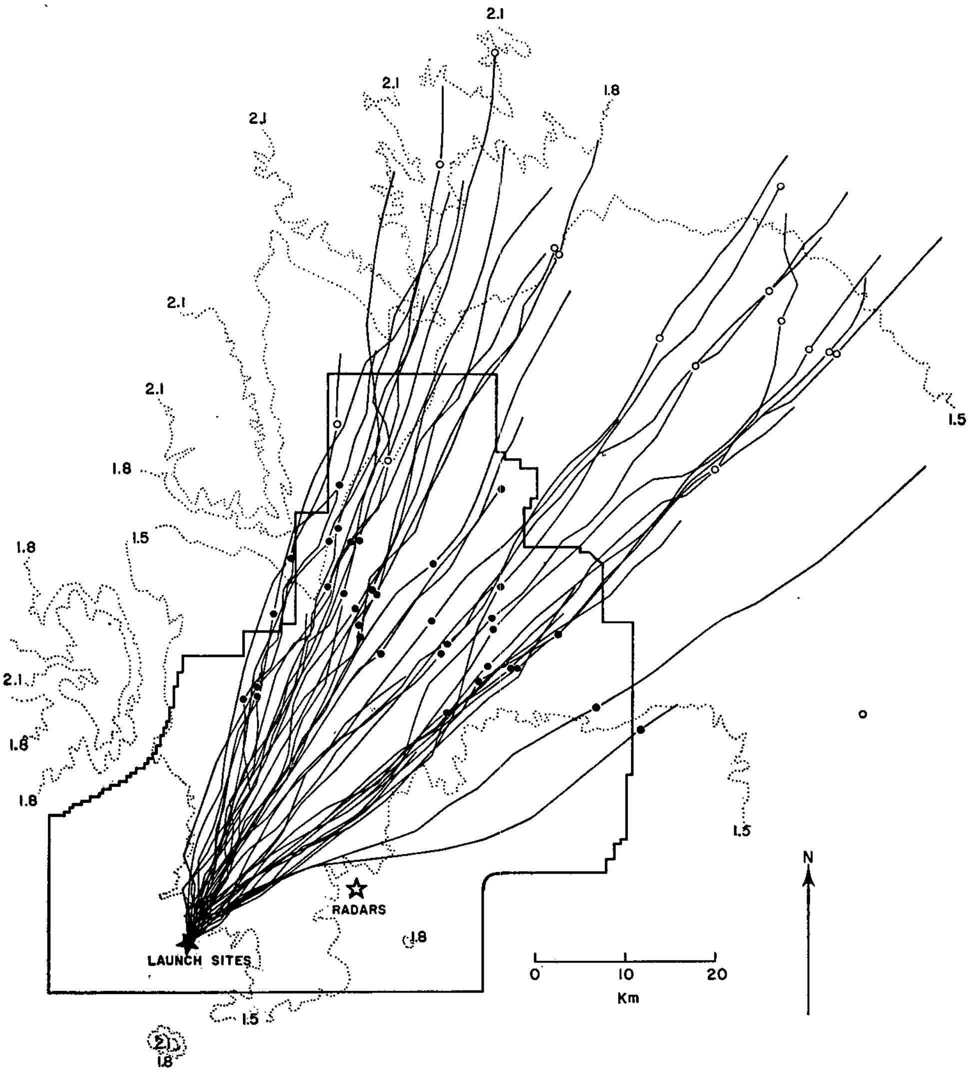

FIG. 1. Map of the National Reactor Testing Station (NRTS), Idaho Falls, showing the tetroon launch sites, the location of the tracking radars, and the afternoon tetroon trajectories during the period 5–16 July 1966. The dots represent tetroon positions 1 hr after release, the circles positions 2 hr after release. Terrain heights of 1.5, 1.8 and 2.1 km above sea level are indicated by dotted lines.

The computer data were fed directly to a curve plotter which furnished plots of the trajectories in the horizontal, vertical-lateral and vertical-longitudinal planes.

Fig. 1 shows the basic topography of the NRTS site, the location of the tracking radars (about 100 m above the tetroon launch sites), and the afternoon trajectories under consideration. The mountains to the west and north of NRTS actually extend as high as 3.7 km, but height contours above 2.1 km have been omitted to avoid clutter. Note the rather large butte (Big Southern Butte) about 10 km to the south of the tetroon launch sites. It would appear from the trajectories that the mountains produce some channeling of the low-level flow in the afternoon. The possible influence of Big Southern Butte on the air flow is unknown, but is worthy of future study. The desert-like terrain consists of lava flows interspersed with scrub vegatation. Because of these geographical features, some caution should be exercised in extrapolating the results obtained within the planetary boundary layer at NRTS to other areas.

Even though the tetroon trajectories are fairly straight during the afternoon, in order to obtain realistic estimates of the helical dimensions in the transverse (vertical-lateral) plane, a quadratic regression line was determined for the horizontal projection of each trajectory, and deviations from this regression line were used to represent the lateral displacement. Table 1 shows that the average rms lateral displacement so obtained (720 m) is similar to the average rms

Table 1. Flight parameters for afternoon tetroon flights at NRTS, Idaho Falls, during July 1966. Mean height is with respect to sea level.*

			Tracking			Standard deviation		
Flight	Date	Release time (local standard)	Duration (min)	Distance (km)	Mean height (m)	Height (m)	Lateral displacement (m)	Mean speed (m sec^{-1})
1A	5	1515	95	73	2750	930	880	12.8
1B	5	1515	54	43	2240	370	1210	13.4
2A	6	1505	51	35	2410	620	980	11.3
2B	6	1505	108	69	2690	980	500	10.6
5A	7	1415	118	75	2060	450	510	10.6
5B	7	1415	98	65	2150	360	330	11.1
7A	7	1516	124	82	2260	710	610	11.0
7B	7	1516	136	90	2570	650	400	11.0
10A	8	1431	139	86	2720	980	710	10.3
10B	8	1431	126	78	3110	980	660	10.3
11B	8	1503	115	68	2810	890	460	9.9
14B	9	1500	68	54	2370	500	600	13.2
19A	10	1434	68	42	1970	260	610	10.3
19B	10	1434	114	81	2350	510	410	11.9
20A	10	1500	139	101	2610	550	1620	12.1
20B	10	1500	57	44	2810	650	380	12.9
23A	11	1339	158	103	2500	730	630	10.8
23B	11	1339	158	101	2710	820	620	10.6
24A	11	1414	77	51	3190	720	400	11.0
24B	11	1414	113	67	2390	630	920	9.8
27A	12	1354	56	37	3300	1300	290	11.0
28A	12	1407	116	82	3240	1310	1540	11.8
28B	12	1407	119	85	3500	1000	450	11.9
31A	13	1253	125	50	2710	1040	620	6.7
31B	13	1253	139	64	2590	880	560	7.6
32A	13	1316	59	26	3140	790	380	7.2
32B	13	1316	183	82	2650	850	1090	7.5
37A	14	1409	109	65	3010	780	780	10.0
37B	14	1409	108	70	3370	930	450	10.8
41A	15	1430	132	94	3310	1080	1070	11.8
42A	15	1456	121	97	2770	750	470	13.3
42B	15	1456	119	91	2290	600	710	12.7
47A	16	1338	143	99	2560	880	370	11.5
47B	16	1338	147	103	2440	660	1100	11.7
48A	16	1400	131	96	2580	790	1160	12.2
48B	16	1400	124	102	2760	950	1540	13.7
Mean			112	74	2710	780	720	11.0

* Station elevation is 1500 m MSL.

variation in tetroon height (780 m). For the study of the relative motion of simultaneously released flight-pairs, a new axis was determined intermediate to the two axes given by quadratic regression techniques, and lateral deviations were measured from this new axis.

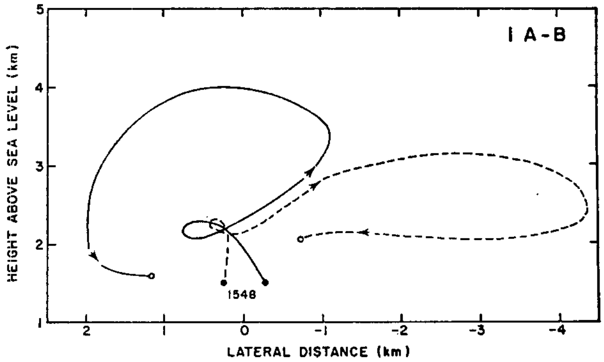

FIG. 2. Trajectories of simultaneously-released tetroon flights 1A-B (launched 5 July) in the transverse (vertical-lateral) plane looking downwind. The arrowheads are at one-half hour intervals in this and subsequent diagrams and the solid trajectory always represents the "A" flight. The release time (local standard) is plotted at the launch site.

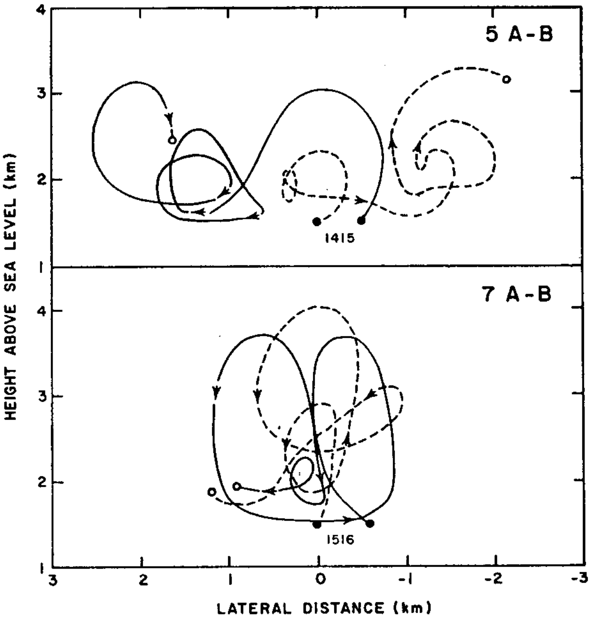

FIG. 3. Same as Fig. 2 but for flights 5A-B (top) and 7A-B (bottom). These pairs were launched on 7 July.

3. Examples of helical circulations

The tetroon launch sites were placed 0.5 km apart in a direction normal to the mean air flow with the hope that thereby the existence of adjacent, counter-rotating helical circulations could be verified. Actually, the 0.5-km separation was a compromise over a desired 1-km separation, and it is now apparent that, owing to the size of the helical circulations in the afternoon, it is unlikely (about one chance in four) that the tetroons would begin their flights in helices of opposite rotational sense with this initial launch spacing.

While the very first flights released (flights 1A-B, where the letters A and B denote simultaneous release at a separation distance of 0.5 km) provide some evidence of counter-rotating flow in the transverse plane (Fig. 2), more impressive visual evidence for such a phenomenon is provided by flights 5A-B, as shown in the top diagram of Fig. 3. Inasmuch as these latter flights quickly separated in the lateral direction, they could delineate the existence of adjacent circulations of opposite sense in the transverse plane. On the other hand, flights 7A-B, released 1 hr later (all other flights pairs were released about one-half hour apart), undergo no appreciable lateral separation, and consequently trace out similar (counterclockwise) trajectories in the transverse plane for most of the period of track. The latter was a common occurrence during the experiment. Throughout this paper we will view these transverse circulations as if looking in the downwind direction, with the arrow heads in the diagrams representing trajectory positions at one-half hour intervals.

4. Velocity statistics in the transverse plane

Fig. 4 shows the frequency with which tetroon-derived values of vertical and lateral velocity exceed a given magnitude during the afternoon, based on 704 observations each. Velocity isotropy in the transverse plane is implied by the near coincidence of the cumulative frequency curves for these two components. One-third of the time both velocity components exceed 1.9 m sec^{-1}, while one-tenth of the time they exceed 3.3 m sec^{-1}. These values represent, respectively, 17 and 30% of the mean horizontal speed of 11 m sec^{-1}. Inasmuch as the standard deviation of the longitudinal velocity averages 2.0 m sec^{-1}, the turbulence intensity is similar in all three dimensions.

Of more basic interest from our point of view are the derived values of angular velocity in the transverse plane. These have been estimated, at 15-min intervals, by finding the circle which passes through three successive 15-min positions of the tetroon in the transverse plane, and then determining (with the given radius of trajectory curvature) the angular displacement for the 30-min interval. Needless to say, through use of the 30-min interval, we have effectively filtered out the smaller scale circulations.

Histograms of the absolute values of radius of trajectory curvature and angular velocity so obtained are presented in Fig. 5, based on 284 evaluations each. The most frequent radius of trajectory curvature is 0.7 km, but the distribution is skewed toward larger values. The most frequent value of the transverse angular velocity is about 2×10^{-3} rad sec^{-1}. Although

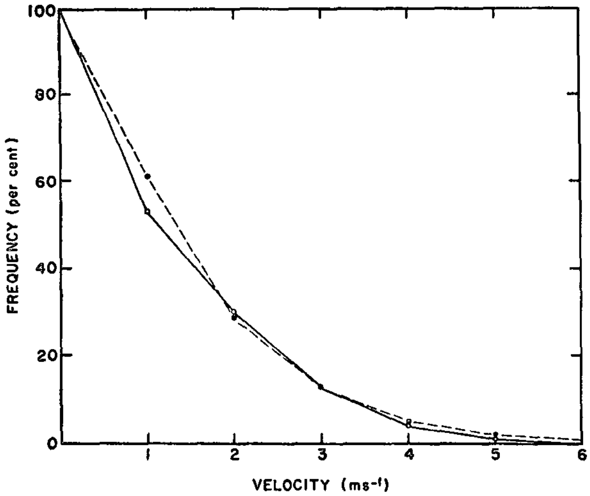

FIG. 4. Frequency with which 3-min average values of tetroon-derived vertical velocity (solid line) and lateral velocity (dashed line) exceed the abscissa value during the afternoon at NRTS.

some uncertainty is introduced by the fact that in many cases the trajectories in the transverse plane are not truly circular, it is unlikely that this seriously influences the overall statistics.

It is important to determine whether the observed (helical) flow in the transverse plane is one of solid rotation (V/R constant, where V is transverse speed and R is radius of trajectory curvature) or one of constant circulation (VR constant). Unfortunately, on any one flight, there are so few values of transverse angular velocity as a function of radius of curvature that it is difficult to generalize. Consequently, we have assumed that similar atmospheric conditions exist on different afternoons, and in Fig. 6 have plotted the absolute magnitude of the transverse angular velocity as a function of radius of trajectory curvature in the transverse plane based upon the 234 observations from all the flights. On the average, the angular velocity is essentially invariant for radii varying from 0.3–1.5 km. Since the radius of trajectory curvature in the transverse plane rarely exceeds 1.5 km (Fig. 5), in the great majority of cases the helical circulation appears to be one of solid rotation, but with some evidence (dashed line in Fig. 6) that circulation is conserved at the extremities of large helices. Consequently, in order to obtain representative values for the magnitude of the helical flow, regardless of where the tetroon is located within the helix, the angular velocity appears the appropriate parameter to use in the majority of cases.

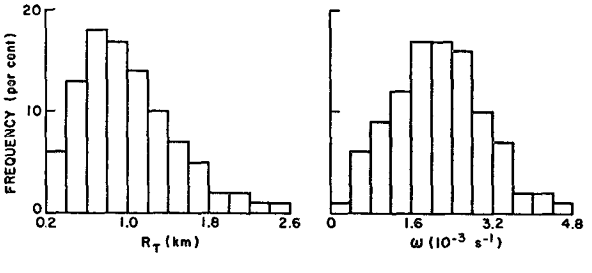

FIG. 5. Distribution of 30-min average values of radius of curvature of tetroon trajectory (left) and tetroon-derived angular velocity (right) in the transverse plane during the afternoon at NRTS.

Inasmuch as the vorticity has twice the value of the angular velocity when the motion is one of solid rotation, estimates of the distribution of vorticity can be obtained by doubling the values of angular velocity in Fig. 5. It is thereby seen that in the afternoon, at this locale, the vorticity about the longitudinal axis averages about 40 times the vorticity of the earth about the local vertical. Furthermore, it can be shown that the vorticity about the longitudinal axis is similar to the vorticity about the lateral axis as estimated from the shear of the longitudinal wind with height. It is apparent that longitudinal roll-vortices are an important part of the mesoscale circulation pattern during the afternoon at NRTS.

5. Statistical evidence for the existence of counter-rotating helices

Evidence for the existence of counter-rotating helices has been presented in Fig. 3. However, this evidence is very weak on occasion. In order to obtain a statistical assessment, the variation with lateral separation distance of the frequency with which vertical velocities and transverse angular velocities of different sense occur along all the simultaneously released flights has been tabulated. This tabulation, dependent on parameter comparisons at the same time, has been made regardless of the longitudinal separation of the simultaneously released flights, which on occasion exceeds 4 km. As an example, Fig. 7 shows that along flights 47A-B the transverse angular velocities were of different sense at lateral separation distances

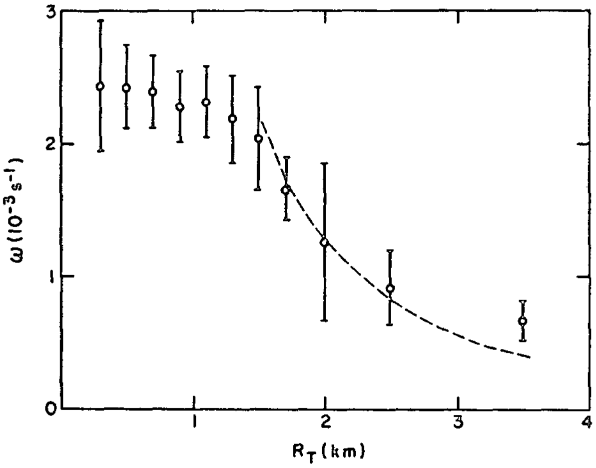

FIG. 6. Tetroon-derived absolute angular velocity as a function of radius of trajectory curvature in the transverse plane. The vertical bars extend two standard deviations of the mean above and below the mean values determined from all the afternoon flights. The dashed line shows the variation associated with a constant circulation.

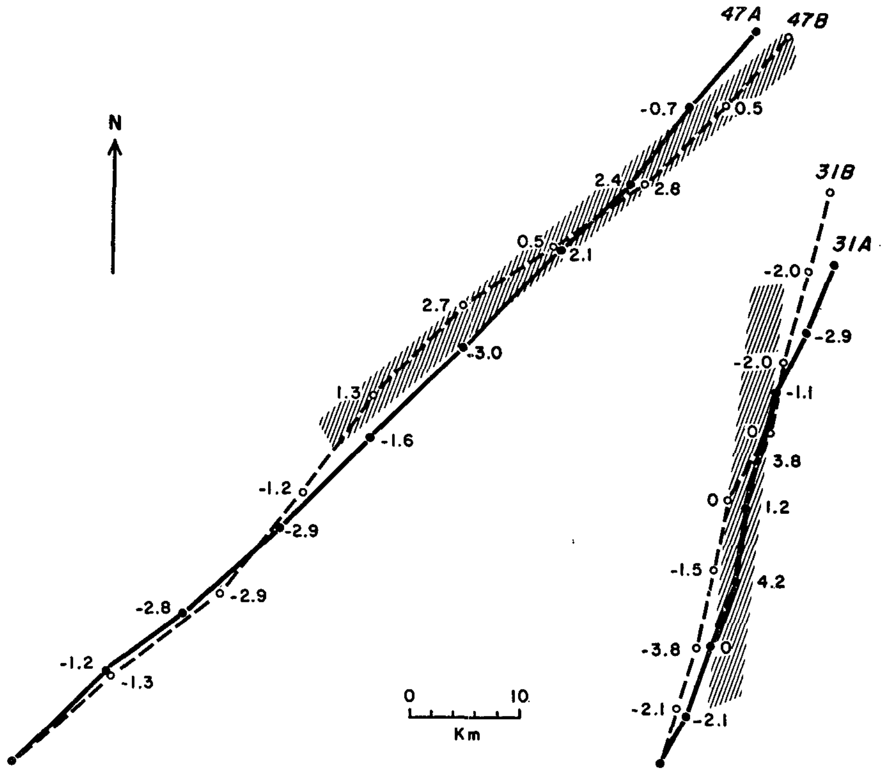

FIG. 7. Horizontal projections of trajectories of simultaneously released flights 31A-B and 47A-B. Angular velocities (10^{-3} sec^{-1}) in the transverse plane are indicated at 15-min intervals, with the hatching delineating areas of counterclockwise rotation in this plane (looking downwind).

of 2.1, 2.4, and 1.9 km, whereas for lateral separations <1 km the angular velocities were of the same sense. Flights 31A-B exhibit a similar tendency. Fig. 8, based on 351 vertical velocity comparisons and 117 transverse angular velocity comparisons, shows that at lateral separations of 2.0–2.5 km, both the vertical velocity and angular velocity are of different sense about half the time. For lateral separations of 3–4 km, however, a different sense prevails only about one-quarter of the time in the case of the angular velocity and about two-fifths of the time in the case of the vertical velocity. Thus, in the mean, there is evidence of an alternation in the sense of vertical velocity and transverse angular velocity with distance normal to the flow, although there is the possibility of some bias owing to the fixed, initial separation distance of the tetroons.

Because of the decrease in number of cases with increase in lateral separation distance, the maximum frequency at 2.0–2.5 km in Fig. 8 is more significant than the minimum in frequency at 3–4 km. Consequently, we estimate that at NRTS during the afternoon the diameter of the helical structures averages about 2 km. This is in reasonable agreement with the mean standard deviations of tetroon height and lateral displacement (780 and 720 m) presented in Table 1, and the modal value of radius of trajectory curvature (0.7 km) presented in Fig. 5. It is emphasized that if the vertical velocities associated with such counter-rotating mesoscale systems had produced clouds, the cloud rows would be spaced at intervals of about 4 km. Spacings of this magnitude are mentioned in some of the references in the Introduction dealing with cloud photographs.

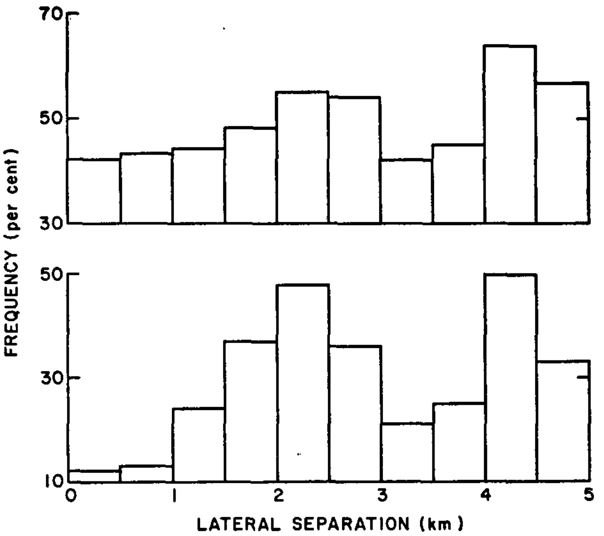

FIG. 8. Variation with lateral tetroon separation of the frequency of vertical velocities (top) and transverse angular velocities (bottom) of different sense based on simultaneous tetroon releases. The comparisons are made at the same time and the longitudinal tetroon separation has been disregarded.

6. Orientation and movement of helices

Figs. 3 and 7 show that the sense of transverse angular velocity may change along individual tetroon trajectories, although this is not the rule for trajectories of the given duration. In these cases a crude assessment puts the modal duration (half period) of transverse angular velocity of the same sense at about 70 min, but with wide variations (the modal period of transverse rotation is about three times the modal period of vertical and lateral velocity). At first, the authors believed that this change in sense of the transverse angular velocity implied either an angular difference between vortex and trajectory, a movement of the vortex in a direction normal to the trajectory, or both. However, it was pointed out to us by Faller that trajectories that rotate through more than 180° in the transverse plane would remain in the same vortex regardless of whether or not the vortex is moving. Thus, the occasional change in sense of transverse angular velocity indicates either an intermittent dissolving and reforming of helical structure, the presence of smaller scale turbulence, or (most unhappy to contemplate), a significant difference between air parcel trajectory and tetroon trajectory.

With the Lagrangian data available, it is difficult to determine either the orientation of the helices with respect to the mean flow or the lateral movement of the helices. Estimation of the former involves comparison of tetroon trajectories with the direction of the (surface) geostrophic wind. Unfortunately, due to the high mountains to the west of the site, the level at which geostropic flow is first attained is uncertain. We have assumed that geostrophic flow is first realized at 500 mb, although this may well be too high. The average angle between tetroon trajectory and 500-mb geostrophic wind was 19°, with the 500-mb wind veered from the tetroon-derived wind. Thus, with the assumption that the trajectories are oriented along the helical axes (which must be true if the helices are stationary), the mean angle between helix and mean flow is (at most) 19°, with the helices oriented counterclockwise from the mean flow. Note, however, that this angular difference may be partly the result of the orientation of the mountains to the west of NRTS (Fig. 1).

In an effort to distinguish helix movement in a direction normal to the mean flow, the average transverse angular velocity for the first half-hour of flight for the first pair of tetroon releases was compared to similar data for the second pair of releases. Thereby, the two pairs of flights yield some idea of the temporal variation of transverse angular velocity at a fixed point. In 6 out of 8 cases the sense of the "initial" transverse angular velocity changed between the pairs of flights released about one-half hour apart. While in most cases the first pair of tetroons released exhibited a clockwise rotation, followed by a counterclockwise rotation for the second pair, there was no evidence from the different flight release times on different days that the transverse angular velocity systematically becomes more counterclockwise as the afternoon progresses. We hypothesize, then, that the change in sense of transverse rotation at essentially a fixed point was due to helix movement in a direction normal to the tetroon trajectories. Based on this hypothesis, a helix velocity in the lateral direction of about 2 km per half-hour (1.1 m sec^{-1}), or some multiple thereof, is obtained. The smallest value is the more likely and would lead to velocity fluctuations of about 1-hr period at a fixed point. However, we have no way of knowing from these Lagrangian data alone whether the helices are moving toward high or lower pressure, although the latter seems more likely in view of the tendency for flow toward low pressure in the friction layer.

7. Comparison of helical circulations with sounding data

One of the fundamental questions involves the conditions under which longitudinal roll-vortices might be expected to occur. One school holds that the helices result from the organization of thermal convection into longitudinal cells by means of vertical wind shear [for example, see Kuo (1963)], while the other holds that they result from a type of shear-flow instability (Faller, 1963). Support for the former concept comes from the evidence for counter-rotating helices presented earlier, since in most cases (but not necessarily in the case of the "parallel instability" to be mentioned later), the shear (Ekman) instability should yield transverse circulations of the same sense; that is, clockwise looking downwind because of the usual wind direction shear in the friction layer.

In order to relate the magnitude of the angular velocities in the transverse plane to both wind shear and stability, an attempt was made to obtain wind (radar tracking) and temperature (sonde) data near noon, or shortly before the afternoon tetroon flights. Owing to various complications, however, adequate sounding data were obtained on only 7 or the 12 days, so that the data sample is small.

Fig. 9 shows the mean variation of temperature and wind with height based on data obtained near noon on these 7 days. Even in the mean, the lapse rate is slightly superadiabatic near the surface and, consequently, according to the parcel method, an air parcel initially at the surface, should experience an upward acceleration to a height at least 4 km above sea level (2.5 km above the ground). Over this same height interval, on the average, the wind veered by about 20° and doubled in speed. Despite this directional shear with height, the average (algebraic) value of the angular velocity in the transverse plane derived from the tetroons was very nearly zero. Fig. 10 shows some individual comparisons. In the case of flights 23A-B the pronounced clockwise rotation is in accord with a

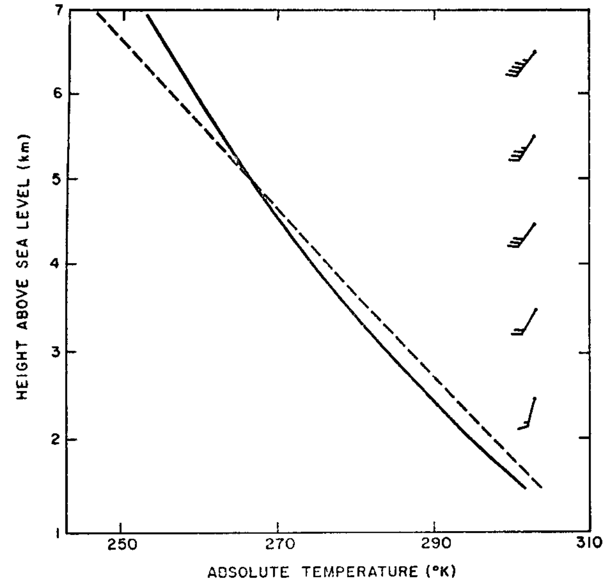

Fig. 9. Mean variation of temperature (solid line) and wind with height at NRTS based on soundings near noon during seven days of the experiment. The dashed line indicates the dry adiabatic lapse rate. Winds are plotted in conventional fashion (south wind pointing up, one full barb equalling 10 kt).

veering of the wind with height as determined from a wind sounding one-half earlier, whereas in the case of flights 48A-B, the pronounced counterclockwise rotation is in opposition to the veering of wind with height indicated by a wind sounding $1\frac{1}{2}$ hr earlier. Based on all available data, the correlation between transverse angular velocity derived from the tetroon and vertical wind shear perpendicular to the trajectory derived from the soundings was −0.01. Although the time interval between wind sounding and tetroon flight may be influencing the results, this lack of correlation supports the contention that counter-rotating helices are a frequent occurrence at NRTS.

The correlations between absolute magnitude of the tetroon-derived transverse angular velocity and absolute magnitude of the vertical wind shear along and normal to the trajectories are slightly negative. Thus, there is no evidence that the helices are driven by the shear of the mean flow. However, there is the problem that once the helices are established, the organized vertical velocities would tend to reduce the vertical wind shear within them.

There is a nearly significant correlation of −0.40 between absolute angular velocity in the transverse

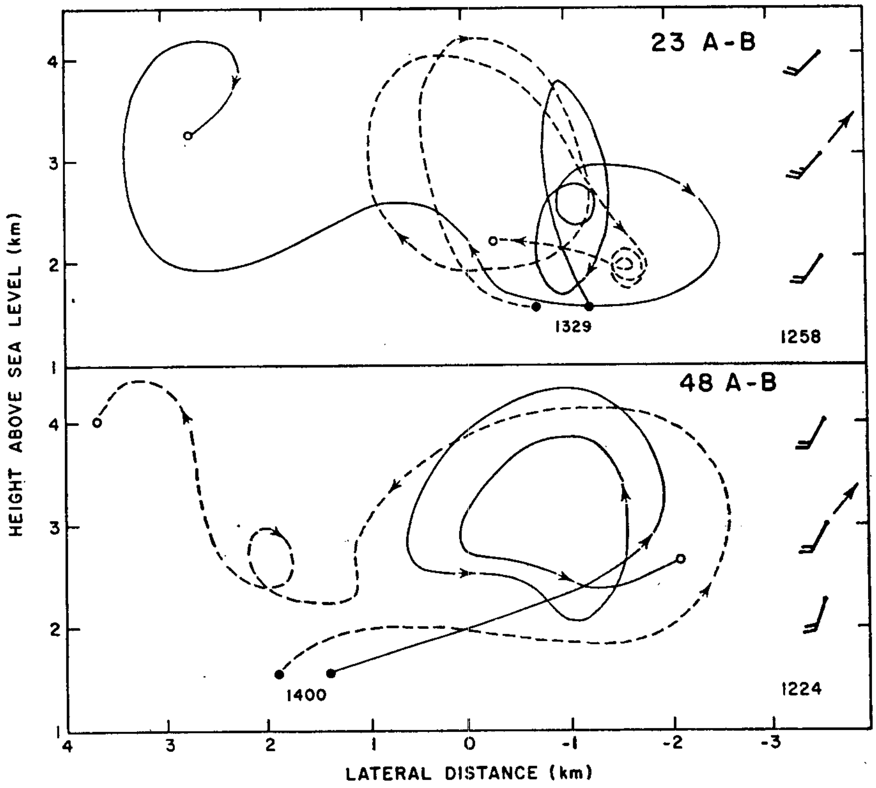

Fig. 10. Same as Fig. 2 but for flights 23A-B (top) and 48A-B (bottom). These flights were released, respectively, on 11 and 16 July. Wind soundings, obtained at the indicated times on these dates, are plotted as in Fig. 9, with the arrow at 3 km showing the mean direction of the tetroon trajectories.

plane and temperature lapse rate. Accordingly, there is the implication that the helical circulations are better developed in neutral or slightly stable conditions than in unstable conditions. In some ways this is an unexpected result, but might be explained by a tendency, in unstable conditions, for the helical structure to break down into conventional turbulence.

8. Stress and kinetic energy flux associated with helical circulations

At a fixed point the vertical flux of longitudinal momentum (or Reynolds stress τ_x) may be estimated from the expression

$$\tau_x = -\rho\overline{u'w'}, \tag{1}$$

where ρ is density and u' and w' are eddy values of the longitudinal and vertical velocities. Insofar as a tetroon follows the vertical air motion, it should yield comparable values of the vertical momentum flux, except that a space average as well as a time average now applies (perhaps a useful feature). However, direct comparison of fixed point and tetroon stress values is most desirable and such experiments will be made. In the case of the tetroon we assume density is a constant (of value 0.9×10^{-3} gm cm^{-3}) and let u' and w' represent deviations from flight-mean values of longitudinal and vertical velocity. In a similar fashion, the mean products of lateral and vertical velocity ($\overline{v'w'}$) and longitudinal and lateral velocity ($\overline{u'v'}$) are proportional to the vertical flux of lateral momentum, and the lateral flux of longitudinal momentum, respectively.

Table 2 shows the mean values of these stress parameters during the afternoon and, as a matter of interest, during the morning also. It is apparent that the vertical flux of longitudinal momentum dominates the vertical flux of lateral momentum, and that the total vertical momentum flux in the afternoon (5.7 dyn cm^{-2}) is about three times the flux in the morning. The question arises as to whether this relatively large vertical momentum flux is due to the existence of helical circulations, or whether a similar flux would exist if such organized structures were absent. There is no significant difference between the vertical momentum flux (or stress) when the flights are stratified according to the absolute magnitude of the transverse angular velocity. However, when one takes into account the size of the helices (by planimetering the area within the helices), is is found that the vertical momentum flux is half again as large when the helix area is above average than when it is below average, i.e., when there is little organized helical structure. This result, while not quite statistically significant, suggests that nature's way of ensuring a large downward flux of momentum may be through the formation of longitudinal roll-vortices, which have the capability of directly transporting horizontal momentum through large height intervals.

The flux of eddy kinetic energy (K_x, K_y) from mean sheared flow to turbulence is given by

$$K_x = -\overline{u'w'}\partial\bar{u}/\partial z, \quad K_y = -\overline{v'w'}\partial\bar{v}/\partial z, \tag{2}$$

where again u', v' and w' are eddy values of the longitudinal, lateral and vertical velocity, and $\partial\bar{u}/\partial z$ and $\partial\bar{v}/\partial z$ represent the vertical shear of the mean longitudinal and lateral wind. In the cases under investigation, the velocities associated with the large-scale eddies (helices) are dominant. Accordingly, with little approximation, the above expressions should represent the flux of kinetic energy from mean sheared flow to helix.

In principle, the vertical wind shear can be estimated from the tetroon data themselves. This has been accomplished by averaging the longitudinal and lateral speeds for those times when the tetroon was above and below the mean flight level, and dividing by the appropriate height interval. Table 2 indicates that in the afternoon the kinetic energy flux from mean sheared flow to helix is due to the directional shear of the mean wind, whereas in the morning it is due to the speed shear. One would like to know to what extent these fluxes maintain the helical circulations in the afternoon, and as one possible way to estimate this, Lilly has pointed out the dimensional relationship (Townsend, 1956, p. 95)

$$E \approx 0.8(L\epsilon)^{\frac{2}{3}}, \tag{3}$$

where E is the average intensity of the helical circulation (1.5×10^4 cm^2 sec^{-2} based on Fig. 4), L the length scale of the large eddies (2×10^5 cm based on Fig. 8) and ϵ the rate of dissipation. The implied value for the dissipation of about 13 cm^2 sec^{-3} could be balanced by buoyancy forces, by the working of the Reynolds stresses, or by divergence in the vertical flux of eddy kinetic energy. If we *assume* the latter term is negligible, which seems reasonable in view of the large vertical depth sampled by the tetroons, then Table 2 and the above calculation suggest that buoyancy forces and Reynolds stresses are about equally important in maintaining the helical circulations in the afternoon.

One word of caution should be appended here. Based on work at Cardington, England, Angell (1964) suggested that the tetroon may considerably underestimate the vertical wind shear, perhaps by as much as a factor of two. Such a result would not be unexpected because, presumably, the helical cells do not

TABLE 2. Tetroon-derived values of the Reynolds stress (dyn cm^{-2}), and flux of kinetic energy from mean sheared flow to helix (cm^2 sec^{-3}), during morning and afternoon at NRTS. Longitudinal, lateral and vertical velocities are given by u, v and w, respectively, with v positive to the left looking downwind.

	$-\rho\overline{u'w'}$	$-\rho\overline{v'w'}$	$\rho\overline{u'v'}$	$-\overline{u'w'}\partial\bar{u}/\partial z$	$-\overline{v'w'}\partial\bar{v}/\partial z$
Morning	2.3	−0.5	4.0	9.0	−1.4
Afternoon	4.5	1.2	0.8	0.1	5.4

tightly occupy all space, and where they are present, they are effective in transporting enough momentum to reduce the shear in their immediate vicinity. Consequently, the estimates of kinetic energy flux in Table 2 probably are conservative, and the buoyancy forces may not play as important a role as the above calculation would lead us to believe.

9. Comparison with theory and laboratory experiments

An interesting paper by Faller (1965) presents several expressions (obtained from a combination of theory and rotating tank experiments) which may be compared with the atmospheric data obtained at NRTS. For example, Faller states that if, in any adiabatic boundary layer, cloud bands are formed due to vertical shear instability, the lateral spacing of these bands should be given by $200U_g/\sin\phi$, where U_g is the geostrophic wind speed (m sec^{-1}) near the ground and ϕ is latitude. As mentioned previously, because of the high mountains to the west of NRTS, it is difficult to determine at what level geostrophic flow is realized. However, it seems certain that the geostrophic speed is greater than the mean tetroon speed of 11 m sec^{-1}, and less than the mean geostrophic speed of 15 m sec^{-1} at 500 mb on these days. Thus, at the latitude of NRTS (43.5N), according to Faller the lateral separation of cloud bands, or vertical velocities of the same sense, should be expected to lie between 3.2 and 4.4 km. On the basis of the tetroon flights, a lateral spacing of about 4 km is obtained (Fig. 8). Faller also states that the cloud spacing should be equal to eleven times the "boundary layer thickness," where the latter is approximately one-fourth the height through which appreciable vertical motion extends. With the assumption that "appreciable" vertical velocities extend through plus and minus one standard deviation of the tetroon height oscillations (Table 1), a cloud spacing of 4.3 km is obtained. On the other hand, it is found that the standard deviations of tetroon height and lateral displacement (Table 1) were essentially uncorrelated with 500-mb geostrophic speed, in spite of Faller's expression. Perhaps this is not surprising when one considers the large variations in these dimensions for flights on the same days. Presumably, the statistical sample is not large enough to overcome the dimensional variability due to chance location of the tetroon within the helix.

Faller's rotating-tank experiments yield a mean angle between helix and tangential (geostrophic) flow of 14°, with the helix oriented counterclockwise from the flow. It was indicated in Section 6 that the average angle between tetroon trajectories and geostrophic flow is nearly 19°, with the trajectories oriented counterclockwise from the geostrophic flow. It is worth noting that if the helices are indeed moving toward low pressure with a speed of about 1 m sec^{-1}, then with the given mean tetroon speed of 11 m sec^{-1}, an orientation of the trajectories 6° counterclockwise from the helices would be compatible with retention of the tetroons within individual helices. This would lead to an angle between helix and geostrophic wind of nearly 13°, or very close to the value obtained by Faller.

Faller's findings and the results from NRTS disagree to some extent on the strength of the flow in the transverse plane. Faller (1965) states that the vertical velocities might easily attain one-tenth the value of the geostrophic speed but Faller and Kaylor (1966) indicate a vertical velocity no larger than one-twentieth of the geostrophic speed. Even if one accepts a mean geostrophic speed as high as 15 m sec^{-1} at NRTS, Fig. 4 shows that 10% of the time the vertical velocity exceeds one-fifth of the geostrophic wind. On the other hand, Faller and Kaylor's suggested variation in longitudinal speed (up to 36% of the geostrophic wind) is not in disagreement with the tetroon-derived longitudinal standard deviation of 2 m sec^{-1}. Furthermore, their statement that the helices would move laterally with a speed not exceeding 10% of the geostrophic speed is in general agreement with the 7–10% value deducible from the data in Section 6.

Faller (1965) and Lilly (1966) also have presented evidence, both theoretical and experimental, for the existence of longitudinal vortices of somewhat larger wavelength, and with an orientation clockwise from that of the geostrophic flow (Lilly's parallel instability). These rapidly moving, unstable disturbances appear to originate at a lower value of the Reynolds number than the vortices considered previously. Lilly implied that the helical circulations shown by Pack's (1962) tetroon flights support the parallel instability concept. The simultaneous existence of both types of roll vortices is shown by a photograph in a recent review article by Hidy (1967), based on rotating tank experiments of Faller. It is apparent that if both types of "large eddies" exist simultaneously in the atmospheric boundary layer, the interpretation of the tetroon data becomes a difficult problem, unless additional simultaneous flights with a wider area coverage are available. Some of the uncertainties expressed in this paper may be due to complexities of this sort.

10. Conclusions

There is good evidence that longitudinal roll-vortices regularly exist in the planetary boundary layer during the afternoon at the National Reactor Testing Station, Idaho Falls. Adjacent counter-rotating vortices of about 2 km diameter are often present. These vortices probably exert an influence on the wind profile in the vertical, and the vertical fluxes of momentum, heat and moisture may be dependent upon location with respect to these vortices. Consequently, the representativeness of conventional fixed-point observations may sometimes be in question, particularly if the period of observation is fairly short.

The relative importance of sheared flow and thermal convection in the production and maintenance of helical circulations is not yet clear, though the tetroon data suggest that the former is most important in the morning and that both contribute in the afternoon. This problem might be resolved when temperature-measuring elements are placed on the transponders. Well-instrumented aircraft flights at the same time as the tetroon runs also would help enhance our knowledge of this important mesoscale phenomenon.

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REFERENCES

Angell, J. K., 1964: Use of tetroons to investigate the kinematics and dynamics of the planetary boundary layer. *Mon. Wea. Rev.*, **92**, 465–470.

——, and D. H. Pack, 1961: Estimation of vertical air motions in desert terrain from tetroon flights. *Mon. Wea. Rev.*, **89**, 273–283.

——, and ——, 1967: Helical circulations in the planetary boundary layer. *Boundary Layers and Turbulence, Physics of Fluid Supplement*, American Institute of Physics, 226–229.

Booker, D. R., and L. W. Cooper, 1965: Superpressure balloons for weather research. *J. Appl. Meteor.*, **95**, 122–129.

Brunt, D., 1951: Experimental cloud formations. *Compendium of Meteorology*, Boston, Amer. Meteor. Soc., 1255–1262.

Conover, J. H., 1960: Cirrus patterns and related air motions near the jet stream as derived by photography. *J. Meteor.*, **17**, 532–546.

Faller, A. J., 1963: An experimental study of the instability of the laminar Ekman boundary layer. *J. Fluid Mech.*, **15**, 560–576.

——, 1964: The angle of windrows in the ocean. *Tellus*, **16**, 363–370.

——, 1965: Large eddies in the atmospheric boundary layer and their possible role in the formation of cloud rows. *J. Atmos. Sci.*, **22**, 176–184.

——, and R. E. Kaylor, 1966: A numerical study of the instability of the laminar Ekman boundary layer. *J. Atmos. Sci.*, **23**, 466–480.

——, and A. H. Woodcock, 1964: The spacing of windrows of Sargassum in the ocean. *J. Marine Res.*, **22**, 22–29.

Fritz, S., 1963: Research with satellite cloud pictures. *Astronautics Aerospace Eng.*, **1**, 70–74.

Gifford, F. G., 1953: A study of low level air trajectories at Oak Ridge, Tenn. *Mon. Wea. Rev.*, **81**, 179–192.

Grant, H. L., 1958: The large eddies of turbulent motion. *J. Fluid Mech.*, **4**, 149–190.

Hallenger, N. L., G. R. Herd, G. Shortley and R. L. Stearman, 1962: Quasi-stationary waves observed in aerosol diffusion trials conducted in a coastal area. *J. Atmos. Sci.*, **19**, 99–106.

Hidy, G. M., 1967: Adventures in atmospheric simulation. *Bull. Amer. Meteor. Soc.*, **48**, 143–161.

Kuettner, J., 1959: The band structure of the atmosphere. *Tellus*, **11**, 267–276.

——, 1967: Cloudstreets. *Aero Revue*, **42**, 52–56.

Kuo, H. L., 1963: Perturbations of plane Couette flow in stratified fluid and origin of cloud streets. *Phys. Fluids*, **6**, 195–211.

Langmuir, I., 1938: Surface motion of water induced by wind. *Science*, **87**, 119–123.

Lilly, D. K., 1966: On the stability of Ekman boundary flow. *J. Atmos. Sci.*, **23**, 481–494.

Pack, D. H., 1962: Air trajectories and turbulence statistics from weather radar using tetroons and radar transponders. *Mon. Wea. Rev.*, **90**, 491–506.

Plank, V. G., 1960: Cumulus convection over Florida. *Cumulus Dynamics*, New York, Pergamon Press, 211 pp.

Rogers, W. C., 1965: A technique for estimating low-level wind velocity from satellite photographs of cellular convection. *J. Appl. Meteor.*, **4**, 387–393.

Townsend, A. A., 1956: *The Structure of Turbulent Shear Flow*. Cambridge University Press, 315 pp.

Woodcock, A. H., 1940: Convection and soaring over the open sea. *J. Marine Res.*, **3**, 248–253.

——, 1942: Soaring over the open sea. *Sci. Monthly*, **55**, 226–232.

——, and J. Wyman, 1947: Convective motion in air over the sea. *Ann. N. Y. Acad. Sci.*, **48**, 747–776.