Comparison of the Vertical Motions of Paired Tetroon Flights

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ABSTRACT

Pairs of constant volume balloons (tetroons) released ~1 min apart from the same site at Haswell, Colo., and continuously tracked by two M-33 radars, are used to estimate the mutual consistency of tetroon vertical motions. In the strong well-organized vertical motion systems of midday and afternoon, it is possible unambiguously to relate the vertical oscillations of the two tetroons so long as the tetroon separation distance is less than about 3 km, implying that under these conditions the tetroons are indeed passing through the same systems (convection cells or thermals). At other times of day such a comparison becomes difficult, partly because of the smaller amplitude and period of oscillation. Where identification of the same vertical motion system is possible, the phase lag between vertical oscillations of adjacent tetroons is related in a meaningful way to the tetroon spacing and the relative position of the tetroon pair with respect to wind direction, and accordingly there is good evidence that tetroon vertical motions are basically consistent.

1. Introduction

A constant volume balloon (tetroon) does not follow the vertical air motion exactly (e.g., Hanna and Hoecker, 1971; Hoecker, 1975), and therefore the question arises as to the usefulness of tetroon height traces for the delineation of atmospheric vertical velocity fields. A requisite first step in any investigation of the utility of tetroons for this purpose involves determination of the similarity in vertical motion exhibited by two tetroons flying in close proximity through an organized vertical velocity system, since if the vertical motions of adjacent tetroons turned out to be appreciably different, one would immediately reject the use of tetroons for the study of atmospheric vertical velocity. On the other hand, similarity in tetroon vertical motion certainly does not imply that the tetroons are representative of the (vertical) air motion, only that the derived tetroon motions are coherent and mutually consistent, and accordingly that it may be worthwhile to examine more closely the relation between tetroon and atmospheric vertical velocity.

An Environmental Research Laboratories (NOAA) field experiment at Haswell, Colo., in the summer of 1972, during which pairs of tetroons were released from the same site and tracked by two different radars, seemed most suitable for such an investigation, both because of the fairly large and organized convective systems in this region during the day and because, unlike the Los Angeles Reactive Pollutant Program (Angell *et al.*, 1975), at Haswell each member of the tetroon pair was *continuously* positioned by a radar, facilitating the identification of corresponding vertical-velocity systems. In the following, as an integral part of the analysis, we shall consider the phase lag between tetroon vertical motions in relation to tetroon spacing and the relative orientation of the tetroons with respect to the wind direction, but there is no emphasis here on deducing details of the convective system from the tetroon vertical motions, as done for example by Levine *et al.* (1973).

2. Procedure

During the 1972 Haswell experiments (Little and Gossard, 1975), 36 pairs of tetroons, with transponders attached, were released from the same site, with the time interval between paired release ~1 min. Each tetroon was positioned continuously by a M-33 radar from the Air Resources Field Research Office, Idaho Falls. For the relatively short tracking ranges under discussion in this paper, the error in horizontal and vertical tetroon position should be considerably less than 100 m. Considered herein are the 12 tetroon pairs whose mean separation distance did not exceed 3 km.

The two M-33 radars were stationed just south of Haswell, Colo., in arid farm country about 200 km southeast of Denver. Fig. 1 shows the radars, and the usual tetroon launch site, in relation to the Haswell tower. A main purpose of the experiment was to fly the tetroons past the tower for a comparison of Lagrangian and Eulerian statistics. All the tetroon trajectories considered in this paper moved northward within the sector delineated by the dashed lines in Fig. 1, and the ground height (m) above sea level is indicated for this region. Note the slow rise in ground height beneath the tetroons as they moved northward out of the "bowl" in which the Haswell tower is located and, in particular, that the planned tetroon flight altitude of 150 m near the tower would correspond to a flight altitude of only about 50 m to the north of Haswell. As a consequence, the tetroons frequently grounded, limiting the number of flight pairs available for study.

The flights were made during the typical summer weather regime of southeastern Colorado, with scattered cumulus clouds of fair weather during the day and clear (but frequently windy) weather at night. The daytime tetroon height variations of about 1000 m and Lagrangian periods of oscillation of 20–40 min were intermediate to the values observed over the deserts of Nevada and the green fields and woods of Ohio, indicating convection of medium intensity. It will be shown later that the tetroon flights themselves suggest a daytime convection-cell spacing of order 5 km, in line with the apparent spacing of the cumulus clouds. While it is recognized that the slight rise in ground height as the tetroons moved northward past Haswell may have slightly enhanced the convective activity, it is unlikely that any sort of standing wave was introduced thereby; at least there was little evidence of same from the tetroon flights.

3. Analysis

The top diagram of Fig. 2 illustrates the two tetroon height traces for flight 15 near midday on 7 August. This flight was chosen first for analysis because the separation of the paired tetroons never exceeded 1 km, the smallest separation for an appreciable travel time. The smaller the separation distance, of course, the more assurance one has that the tetroons are passing through the same vertical motion systems, an implicit requirement for this analysis. The box at upper right shows the relative orientation and spacing of the two tetroons during the $2\frac{1}{2}$ h of tracking. Thus, at 1115 (all times Mountain Daylight) tetroon B was 300 m north of tetroon A, whereas at 1315 tetroon B was about 1 km west of tetroon A. Since the tetroons were moving toward the northeast, initially the tetroons were separated mainly in the lateral or cross-wind direction, whereas later the separation was mainly in the longitudinal or along-wind direction. The arrows in the main diagram illustrate how the vertical oscillations of tetroon A (solid arrows) tended to precede the vertical oscillations of tetroon B (dashed arrows). In general, the height traces are sufficiently similar that there is little difficulty in pinpointing the corresponding vertical velocity systems through which the tetroons are moving, although both at 1130 and 1245 tetroon B lingered longer at relatively high altitude than did tetroon A. It is uncertain whether this reflects a different tetroon response to the same vertical air motion, or a slightly different vertical air motion due to the subtle difference in tetroon location. Overall, however, flight 15 offers strong support for the mutual consistency of tetroon vertical motions.

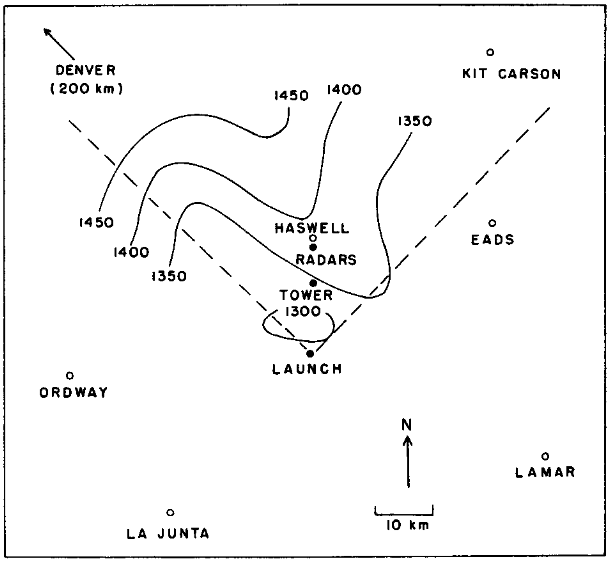

FIG. 1. Relation of the tetroon-tracking radars, and the usual tetroon launch site, to the Haswell tower and surrounding towns. The height above mean sea level is given in meters within the sector (dashed lines) traversed by the tetroons.

An interesting feature of flight 15 is that the vertical oscillations of tetroon A preceded those of tetroon B even when the tetroons were separated in the cross-wind direction. This implies that the tetroons were moving through a vertical motion system oriented more nearly north-south than cross-wind, perhaps reflecting a steering effect of the veered higher level winds on the direction of motion of the vertical motion system.

The bottom diagram of Fig. 2 indicates the two tetroom height traces for flight 21 near midday on 9 August. This flight was chosen for analysis because the tetroon separation was mainly in the along-wind direction. In this case the time delay in vertical motion reflects well the longitudinal separation of the tetroons, being small near 1130 and 1230 and somewhat larger near 1200. Note, however, the different magnitudes of the height oscillations near 1200, or when the tetroons were furthest separated. It is again uncertain whether this reflects a lack of consistency in the tetroon response to the vertical air motions, or implies an intensification of the vertical motion sys-

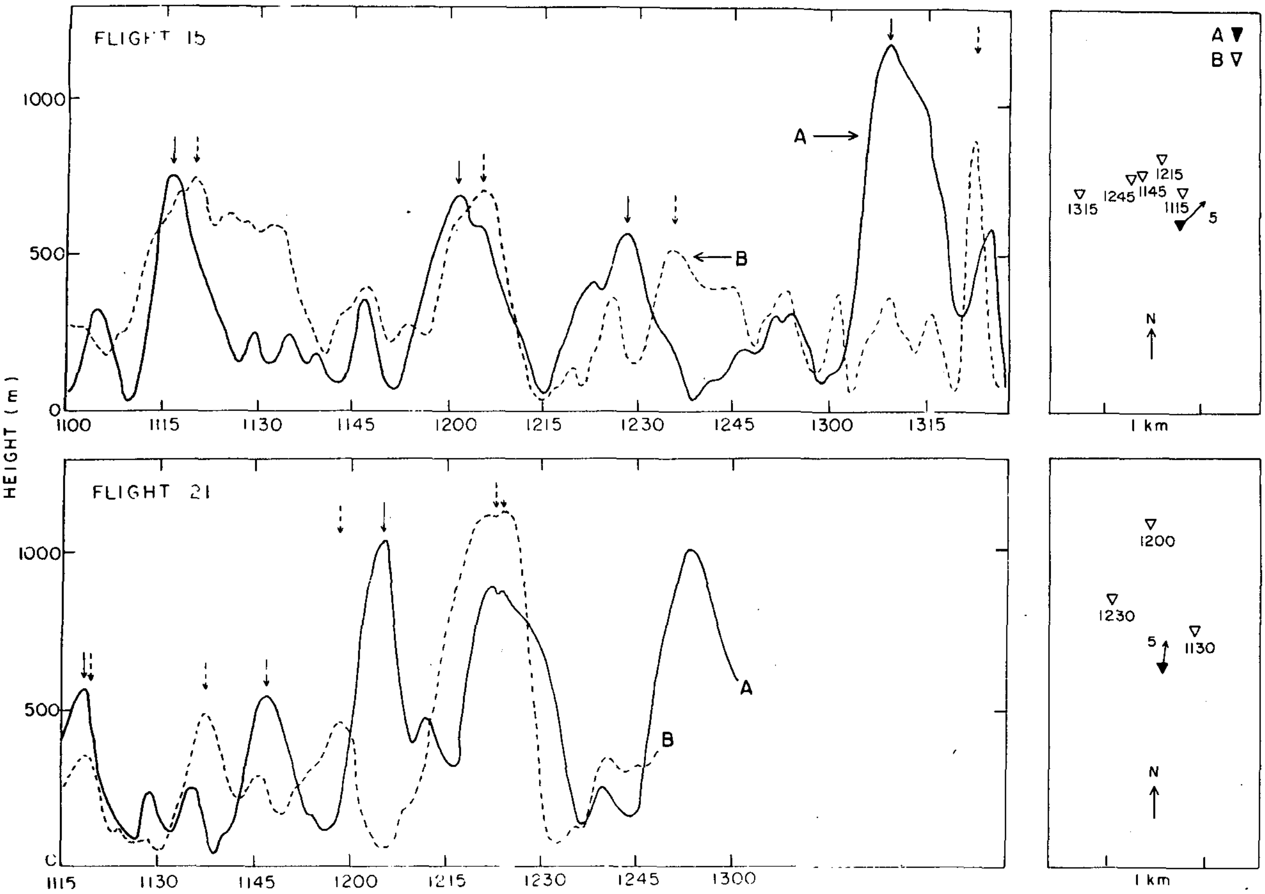

FIG. 2. Height above surface for paired tetroon flights 15 (7 August 1972) and 21 (9 August), with the solid trace representing tetroon A and dashed trace tetroon B. The vertical arrows indicate the time (local) of respective height maxima. The diagrams at right illustrate the location, in the horizontal, of tetroon B (open del) with respect to tetroon A (solid del) as a function of local time, with the mean tetroon direction and speed (m s^{-1}) shown by the arrows and adjacent number.

tem. In general, however, flight 21 also offers support for the inherent consistency of tetroon vertical motions.

Of interest on flight 15 is the observation that at 1200 the tetroon separation is about 1.5 km, and accordingly tetroon A, moving at a speed of 5 m s^{-1}, would be at the position of tetroon B in 5 min. Since the phase lag in vertical motion between the two tetroons is about 10 min at this time, the vertical motion system is indicated to be moving at about half the speed of the tetroons. It will be shown later that this seems to be a general result of this analysis, and that a certain spacing of the convective elements is implied thereby.

Fig. 3 illustrates the uncertainty that begins to arise in the analysis as the tetroon separation becomes larger. On flight 17 (8 August) the height variations are so different in amplitude and form that the identification of corresponding vertical motion features is somewhat uncertain. The assumed correspondence indicated by the vertical arrows agrees well with the relative position of the tetroons in the horizontal in that the vertical oscillations of tetroon B precede those of tetroon A except when tetroon B follows tetroon A in the horizontal (1200–1215). Flight 18 on the afternoon of the same day is tantalizing because the vertical oscillations of tetroon B clearly precede those of tetroon A during the period 1415–1515 MDT, when tetroon A is moving northward slightly ahead of tetroon B. Could the tetroons have been moving faster than the vertical motion system near midday, but slower than the system near midafternoon, even though the tetroon speed decreased by only 1 m s^{-1}? While possible, it does not seem likely, and this points up the inconsistencies and contradictions that may arise when dealing only with a well-separated two-point Lagrangian system.

Fig. 4 illustrates other cases in which, for various reasons, the consistency of tetroon vertical motions could not easily be gauged. Shown are tetroon height traces during stable nighttime conditions (bottom), the transition from stable nighttime flow to unstable daytime flow (middle), and during the development of the unstable daytime regime (top). In the latter case (flight 3 on 2 August) the tetroons were, un-

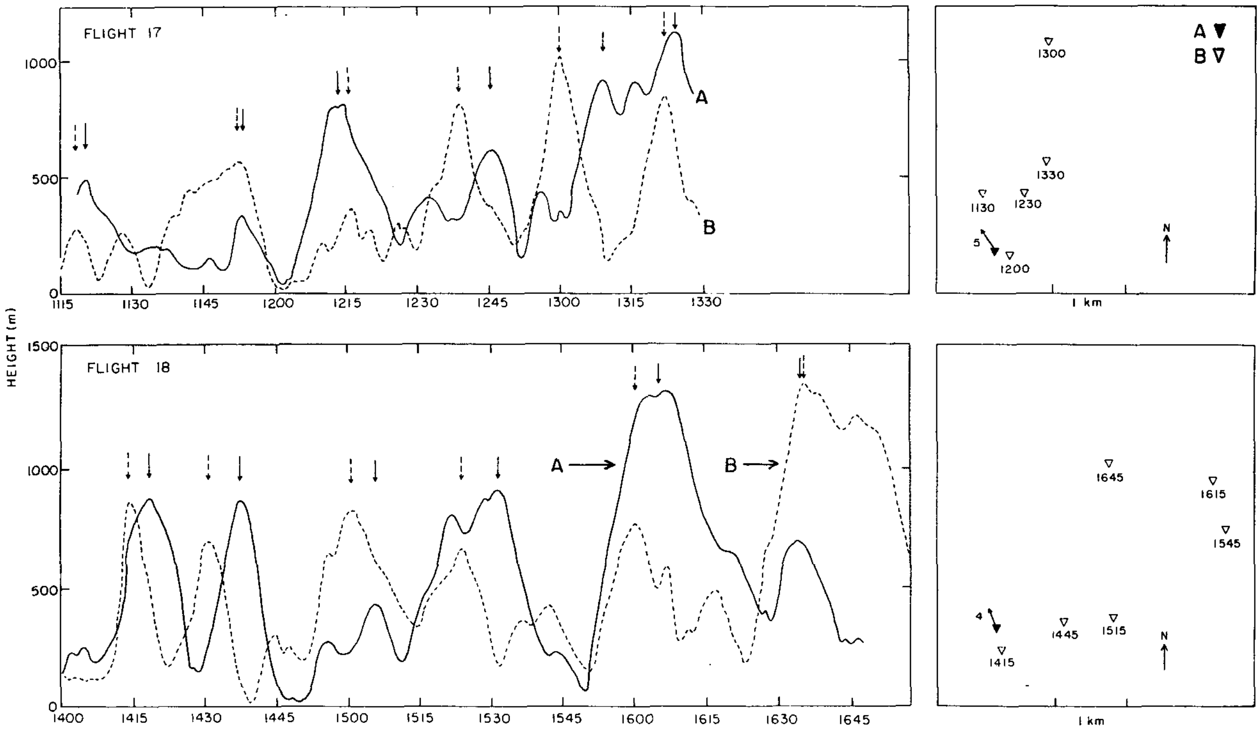

FIG. 3. As in Fig. 1, except for consecutive tetroon flights 17 and 18 on 8 August 1972.

fortunately, rather widely separated, complicating the determination of corresponding vertical motion systems (note the out-of-phase relation during much of the period), but it should be recognized that had the flights occurred later in the day when the period of vertical oscillation was larger, it presumably would

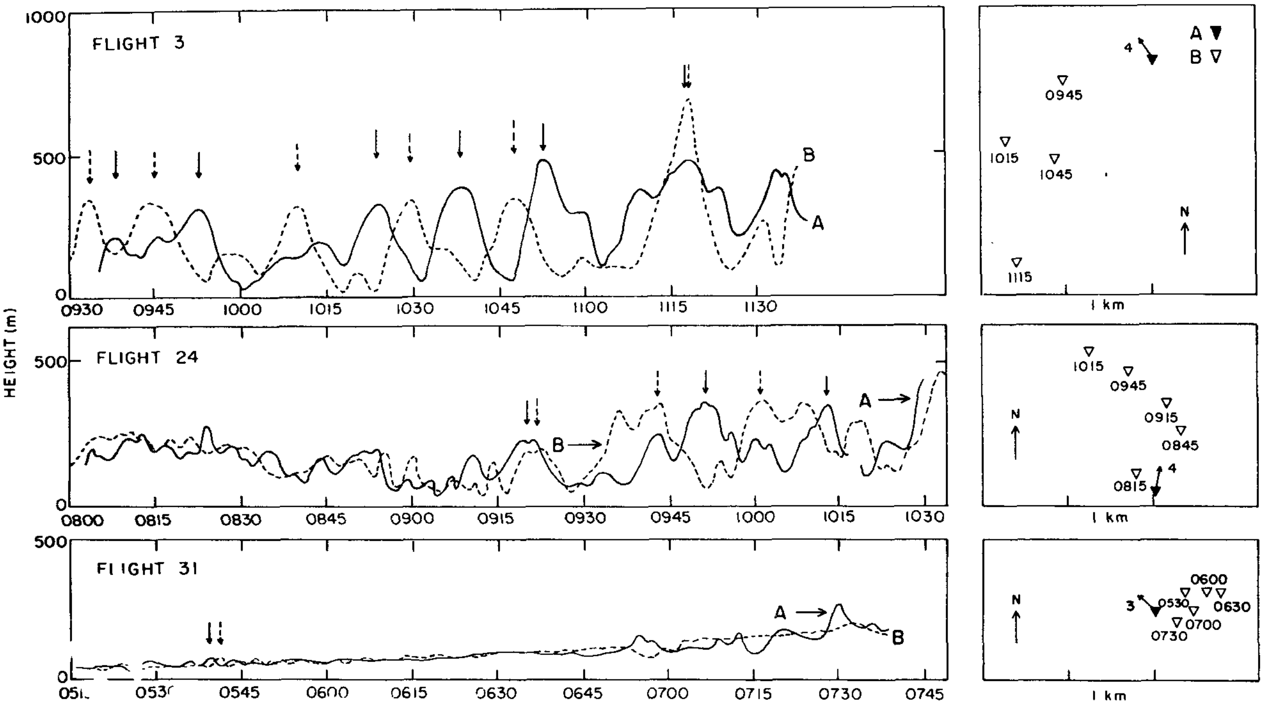

FIG. 4. As in Fig. 1 except for tetroon flights in the morning of 2 August (flight 3), 10 August (flight 24) and 12 August (flight 31).

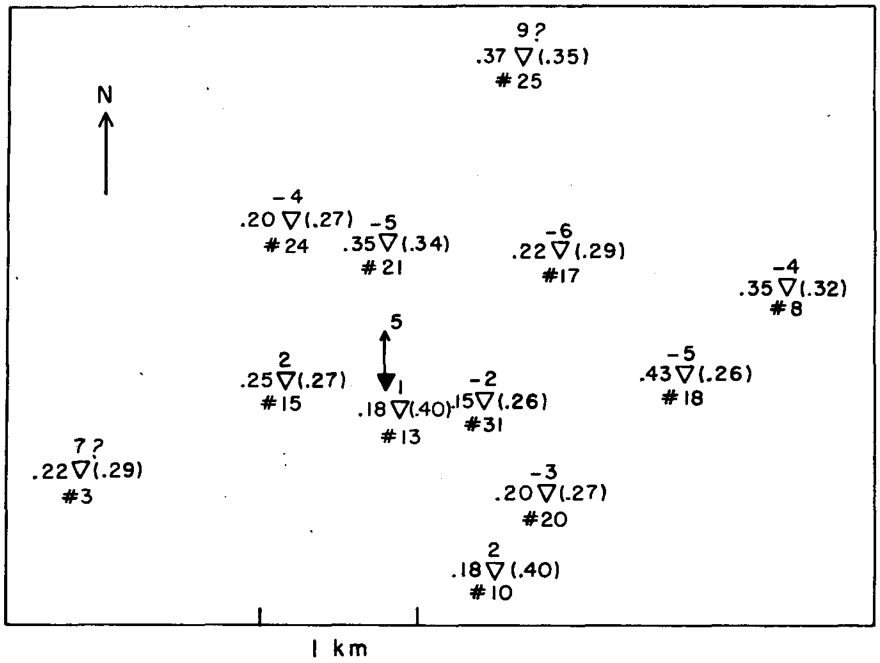

FIG. 5. Mean location of tetroon B (open del) with respect to tetroon A (solid del) for flights where the paired tetroons remained within 3 km of each other on the average. The data have been normalized by making all trajectory directions southerly and reorienting the relative positions of tetroons B and A (mean tetroon speed of 5 m s^{-1}). The flight number is indicated below the open del, the calculated time lag (min) between the paired vertical oscillations above the del (negative if the oscillation of tetroon B precedes that of A), the (maximum) correlation at this lag to the left of the del, and the correlation significant at about the 5% level in parentheses to the right of the del.

have been possible unambiguously to delineate these systems.

Along nighttime flight 31 (12 August) the vertical oscillations were indicated to be negligibly small except for a small "burst" of activity near 0545. Here the reliance upon electronic rather than visual tracking (by means of a light attached to the balloon) was probably a mistake since the height fluctuations could be obtained with much finer detail using the visual periscope on the M-33. The developing height oscillations along flight 24 (10 August) do not provide a consistent picture since the height variation of tetroon A slightly precedes that of tetroon B about 0915 MDT, but thereafter appears to follow it even though tetroon B leads tetroon A in the horizontal during the whole period. Of course, there is a question as to how organized and coherent the vertical motion systems are during their development phase in early morning, and perhaps for this reason one should not anticipate seeing corresponding vertical motion patterns at this time, at least not at separation distances exceeding 1 km.

We have quantified the results for the above seven flights, as well as five other flights for which the mean tetroon separation did not exceed 3 km, by averaging the tetroon vertical velocities over $2\frac{1}{2}$ min intervals, and determining the lag time of maximum correlation (based on the entire flight) for the tetroon pairs. Fig. 5 shows the lag time (min) of maximum cross correlation (plotted above the del and positive if the height variation of tetroon B follows that of tetroon A), the correlation at this lag (left of del), the correlation significant at about the 5% level (right of del) and the flight number. Note that the trajectories have been normalized by making all trajectory directions southerly and reorienting the relative positions of tetroons B and A, accordingly. The question marks after the lag times on flights 3 and 25 reflect the nearly out-of-phase height oscillations of these tetroon pairs, and the consequent uncertainty as to whether the lag time is positive or negative.

While the data sample is very small, there is the impression from Fig. 5 that the height oscillations do tend to occur first on the leading tetroon, and indeed, as indicated for flight 21 earlier, that the speed of the vertical motion system tends to be about half the tetroon speed. This is seen from the observation that the lag interval in vertical motion is about 5 min when the leading tetroon is ~750 m ahead of the following tetroon at the time when the mean tetroon speed is ~5 m s^{-1}. The Lagrangian period of vertical oscillation of 20 to 40 min along the daytime tetroon flights, together with the observation that the speed of the tetroons relative to the vertical motion system is about 2.5 m s^{-1}, implies a spacing of the vertical motion cells or elements of 3–6 km, in keeping with the apparent spacing of the scattered cumulus clouds.

The positive lags to the left of the solid del and negative lags to the right of the solid del suggest a tendency for a veered direction of movement of the vertical motion system relative to the tetroon direction of motion, probably not unexpected in view of the usual veering of the wind with height. However, confirmation of such a tendency in this area would require many more flights. Note that the (maximum) lagged correlations are relatively small, to be expected because the lag time is continuously changing during the flight in accord with the change in relative orientation and spacing of the two tetroons. As a result, the lagged correlations are, at best, only marginally significant.

4. Conclusion

In the case of individual daytime flights and in summary for the totality of daytime flights, there is good evidence that the tetroon vertical motions are basically consistent, in that the phase lag between the vertical oscillations of adjacent tetroons is related in a meaningful way to the spacing and relative position of the tetroon pairs. However, it is emphasized that while the demonstration of such a consistency is a necessary first step in relating tetroon vertical motion to atmospheric vertical motions, the more important problem of the quantitative difference between the latter motions has not been explicitly considered in this paper. Nevertheless, in the light of the results presented herein, the possibility should be considered that each tetroon reacts sufficiently the same to the vertical air motion that the *difference* between paired tetroon vertical motions is generally comparable to the *difference* between vertical air motions, even though in neither case is the tetroon reflecting the true air motion. While useful results might be obtained in this manner, it is apparent that any thorough experimental investigation would also have to make use of atmospheric vertical motions obtained by other means, such as aircraft or doppler radar.

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