Relative Diffusion within the Los Angeles Basin as Estimated from Tetroon Triads[1]

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ABSTRACT

The Los Angeles Reactive Pollutant Project (LARPP) in the autumn of 1973 involved helicopter sampling of a volume of air "tagged" by means of three constant volume balloons (tetroons) released simultaneously from a point on the ground. Based on radar tracking of 35 tetroon triads at a mean height of 350 m above sea level, this paper considers the estimates of relative diffusion obtained from the rate of separation of the tetroons making up the triad. In the average, the median lateral standard deviation of tetroon position varies from 90 m after a travel time of 15 min to 800 m after 2 h, and from 140 m at a travel distance of 2 km to 1000 m at 20 km. The relative diffusion is indicated to be nearly twice as large in "neutral" as in "stable" conditions. Comparison with the results obtained by other investigators in other locations shows that the relative diffusion within the Los Angeles Basin is frequently unusually small, particularly with respect to travel time.

1. Introduction

The Los Angeles Reactive Pollutant Project (LARPP) was carried out in September, October and November of 1973. The main purpose of the experiment was to measure the change in pollutant concentration following a given volume of air (Lagrangian approach) rather than at a fixed point (Eulerian approach), as done previously. Toward this end, triads of constant volume balloons (tetroons) were released simultaneously from the same point on the ground in order to "tag" a particular volume of air. The tetroons, flying at a mean height of about 350 m MSL, were followed by helicopters which did the air sampling.

This paper considers only the tetroon aspect of the experiment, and in particular, the estimate of relative diffusion (the relative separation of the particles or elements of a diffusing cloud) obtained from the rate of separation of the three tetroons making up each triad. The diffusion is compared with that obtained from bulk tracer experiments in other locations, and is also evaluated as a function of atmospheric stability. So far as we know, this experiment represents the first *direct* estimate of relative diffusion within the Los Angeles Basin over relatively *large* space and time intervals.

2. Procedures

The tetroons, with transponders attached, were tracked by an M-33 radar from the Air Resources Laboratories Field Research Office, National Reactor Testing Station (NRTS), Idaho Falls. A second M-33 radar from NRTS was used to track and vector the helicopters engaged in air sampling. The transponder frequencies for each tetroon triad were set at approximately 403 MHz but with enough frequency separation to permit positive balloon identification. Tetroon positions were obtained every minute, i.e., an individual tetroon was positioned every 3 min. A computer in the radar served to translate (in real time) the range and azimuth and elevation angles of the tetroons into east-west and north-south grid coordinates, as well as height, for the purpose of vectoring the helicopters.

The two M-33 radars were positioned on Flint Peak (elevation 580 m) 3 km west of the Pasadena Rose Bowl. From this elevated site the radar could track tetroons from Santa Monica in the west to San Bernardino in the east, the latter city being nearly as far as the radar could position because of the pulse repetition rate (limiting tracking range 100 km). Frequently, however, the tetroons were lost to radar view in the region of the Puente Hills, and only occasionally was a tetroon triad successfully tracked over these Hills into the San Gabriel Valley to the east.

Some compromise was required with respect to the choice of tetroon float level. It was desirable that the tetroons be as close to the ground as possible without snagging power lines, etc., and if the flights had been confined to the Los Angeles area itself, a mean float

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TABLE 1. Experiment listing for tetroon triads tracked for at least 1 h during the autumn of 1973. "Downtown" refers to downtown Los Angeles.

Experiment	Date	Launch site	Launch time (local)	Tracking duration (h)	Wind speed (m s^{-1})	Tetroon MSL heights (m)
1	9–4	Redondo	1200	2½	4.0	480, 470, 440
5	9–18	Downtown	1030	2	1.4	390, 370, 390
8	9–24	Downey	0900	4½	1.9	480, 450, 460
9	9–25	Long Beach	1000	4	2.1	560, 440. 410
10	9–27	Downtown	0900	2½	2.5	170, 260, 250
11	9–28	Downtown	0830	4	2.8	250, 250, 240
12	10–1	Downey	0830	4½	1.5	370, 410, 490
13	10–2	Pomona	1400	1½	3.2	720, 850, 790
14	10–4	Downtown	1930	2½	1.1	300, 310, 340
15	10–5	Downey	1200	2	2.6	350, 300, 280
16	10–10	Downey	0830	1	1.7	280, 250, 260
17	10–11	Downtown	0800	4½	2.3	420, 290, 390
18	10–12	Downtown	0930	3½	2.4	510, 390, 420
19	10–15	Downey	0930	3½	1.4	390, 350, 380
20A	10–16	Downtown	0930	2	3.2	440, 460, 450
20B	10–16	Downtown	1300	1	1.9	420, 280, 290
21	10–17	Downtown	0930	4½	2.6	390, 360, 360
22A	10–18	Downey	0900	2½	2.9	320, 260, 360
22B	10–18	Downey	1130	2	2.0	290, 280, 340
23	10–24	Downey	0900	2½	0.8	360, 260, 290
24	10–25	Downtown	0830	4	1.4	370, 300, 280
25	10–26	Downtown	1000	6	1.9	340, 390, 320
26	10–27	Downtown	0900	3	2.7	360, 360, 370
27	10–28	Downey	1100	2½	2.8	550, 380. 400
28	10–29	Downey	0830	2	2.1	190, 220, 230
29	10–30	Downey	0830	2½	1.5	250, 250, 260
30	10–31	Downtown	0830	1½	3.1	310, 350, 350
31A	11–1	Downtown	0730	2½	2.8	270, 270, 280
31B	11–1	Downtown	1130	1½	3.0	400, 390, 530
32	11–2	Downey	1200	1½	5.1	360, 360, 350
33	11–5	Downey	0700	6	1.0	310, 340, 310
34A	11–6	Downtown	0730	3	1.9	280, 280, 270
34B	11–6	Downtown	1100	2	2.1	390, 450, 410
35	11–7	Downtown	0830	2½	1.2	280, 290, 330

level near 200 m MSL would have been satisfactory. However, since an important aspect of LARPP was the question of the source of air reaching the Riverside-San Bernardino area (height ~300 m MSL) during the afternoon, the tetroons were set to float about 350 m above sea level. The results from this aspect of the Project will be discussed in a subsequent paper.

Table 1 gives the date and time of the tetroon experiments under consideration as well as the mean MSL height of the three tetroons making up each triad. The wind speed is also an average based on the speeds derived from the three tetroons of the triad.

3. Trajectories of tetroon triads

Fig. 1 shows the trajectories of tetroon triads for those cases when the transition from land to sea breeze resulted in a quite abrupt trajectory turning toward the north. In this and subsequent diagrams, the triangle vertices indicate the locations of the three tetroons at ½ h intervals, while the numbers along the trajectories indicate the time after release in hours. The dashed line represents a subjective estimate of the mean path of the triad. The "downtown" launch site was located at 7th and Alameda, or just east of the high-rise section of downtown Los Angeles.

It can be seen from Fig. 1 that the tetroon dispersion was increased by encounter with the sea breeze from the west, generally by a factor of about 2. In experiment 11 the increase was noted mainly in the lateral (cross-stream) direction whereas in experiment 24 it was noted mainly in the longitudinal (along-stream) direction. In experiments 12 and 18 both components exhibited a considerable increase. Note the evidence in experiment 17, and to a lesser extent in experiment 11, for a decrease in triad size before the sea breeze reversal, implying the existence of horizontal convergence. In experiment 34A the tetroons were again located near the downtown launch site 7 h after release, but a continuous track was not possible because of new tetroon launches.

The top diagram of Fig. 2 shows that in experiment 11 the tetroon height doubled due to the ascending

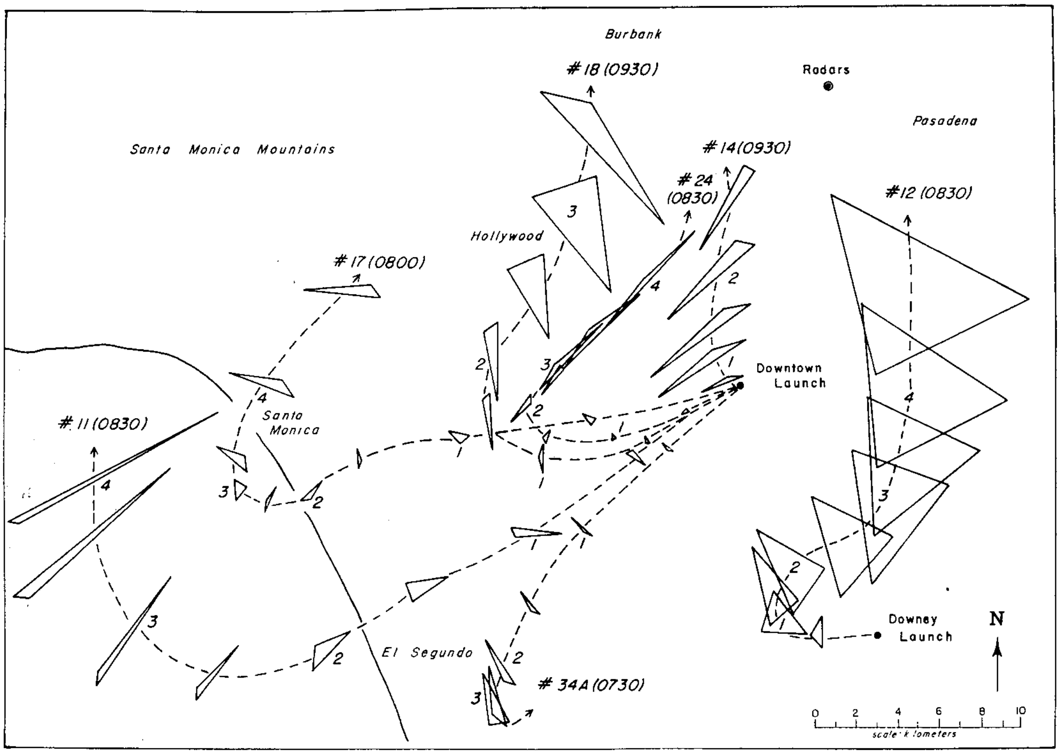

FIG. 1. Tetroon dispersion within the Los Angeles Basin in cases of trajectory turnings toward the north associated with the transition from land breeze to sea breeze. The triangle vertices indicate the location of the three simultaneously released tetroons at $\frac{1}{2}$ h intervals, while the numbers along the trajectory signify the hours since release. The experiment number and local time of release (parenthesis) are plotted at the end of the dashed line representing the triad path. "Downtown" refers to downtown Los Angeles.

motion associated with the sea breeze convergence zone. At this time and in this general area there was a temperature inversion between the surface and a height of 500 m. A similar tetroon height change (not shown) was noted in experiment 17. The second diagram from the top in Fig. 2 shows the pronounced vertical tetroon oscillations associated with the large dispersion in experiment 12, a time of nearly dry adiabatic lapse rate between the surface and 500 m.

Fig. 3 presents examples of tetroon triads in cases of trajectory turnings toward the east. The increase in tetroon dispersion at the time of these sea breeze reversals is not nearly so pronounced as in Fig. 1, presumably because most of the reversals occurred further to the east where the sea breeze is not so strong. In this connection, the middle diagram of Fig. 2 shows that there was no appreciable change in tetroon height, i.e., no appreciable vertical air motion, at the time (2 h after release) of trajectory turning toward the east in experiment 21. Experiment 22A is of interest in suggesting that in the Long Beach area one cannot always speak of a northward advancing sea breeze "front," but rather the heating of the south-facing San Gabriel Mountains north of Pasadena induces air further and further to the south to move northeastward as the day progresses.

Fig. 4 illustrates the tetroon dispersion under conditions of relatively straight flow. The morning releases often move northward due to the heating of the south-facing mountain slopes, and it is this northward transport of polluted air that brings about the severe smog in places such as Pasadena and Glendale. By afternoon, the westerly sea breeze generally becomes dominant, as shown by the eastward movement of the tetroons in experiment 1. Note the increased tetroon dispersion in the latter case, reflecting the greater diffusion in the sea breeze flow.

In 12 other experiments the flow was essentially straight, and the tetroon dispersion very small, in fact so small that on the map scale used, many of the tetroon triads appear as hardly more than a dot. In order to keep this paper of reasonable length, these experiments are not illustrated or discussed here.

The preceeding diagrams have shown that in the great majority of cases the simultaneously released tetroons remain relatively close together, i.e., any one of the tetroon trajectories would have sufficed to give a good estimate of the actual air trajectory. For two experiments, however, there *was* considerable difference in triad trajectory. In experiment 25 one of the tetroons launched from downtown Los Angeles did not turn to the northeast as quickly as the other two, and the triad

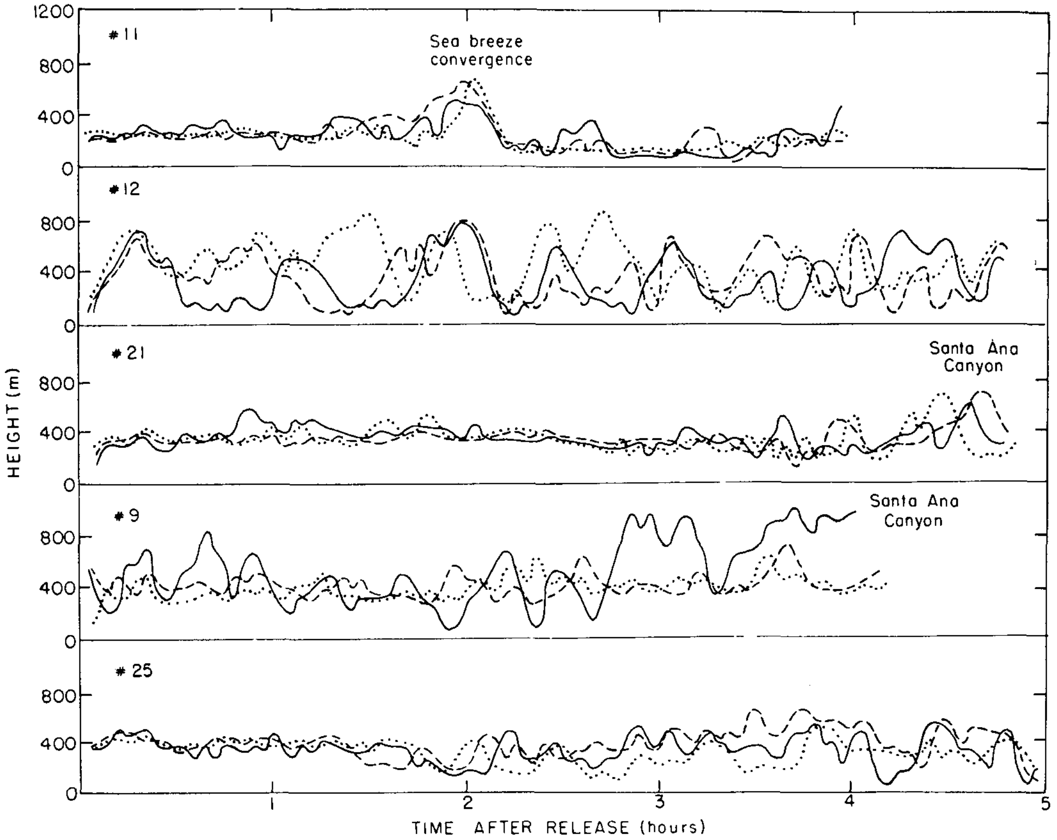

FIG. 2. Time variation of tetroon height (m MSL) for several experiments for each member of the tetroon triad. The experiment number is indicated at left.

approached the Puente Hills on a 20 km front. The trajectory difference was more spectacular in experiment 9, where two of the tetroons moved southeastward along the coast from Long Beach while the other tetroon moved eastward into Santa Ana Canyon, resulting in a tetroon separation of 30 km after 4 h.

The two bottom diagrams of Fig. 2 illustrate the three tetroon heights on each of these experiments. In experiment 9 the solid line represents the height of the tetroon which moved eastward through Santa Ana Canyon. There is no doubt that during the first hour after release, when the separation was becoming appreciable, the height of the Santa Ana flight was about 100 m greater than that of the other two (though this was not so later on), and with more evidence of convection. Thus, perhaps because of slightly greater free lift, this flight may have moved into a more unstable layer of slightly different wind direction. The greater height of this tetroon toward the end of the flight is the result of its passage through Santa Ana Canyon. In experiment 25, on the other hand, there is no systematic difference in tetroon height. These two "anomalous" experiments are included in the subsequent statistical analysis, but because of them we shall deal with the median as a measure of central tendency rather than the average.

4. Lateral and longitudinal relative diffusion derived from tetroon triads

The relative diffusion has been estimated from the separation rate of the tetroons making up each triad. Toward this end, the lateral and longitudinal standard deviation of tetroon position for each triad was determined at 15 min intervals by drawing perpendiculars from the balloon locations to the straight line joining the triad centroid $\frac{1}{2}$ h earlier and $\frac{1}{2}$ h later (thereby obtaining, by the usual rms calculation, the longitudinal standard deviation of position), and by drawing of perpendiculars from the balloon locations to a line normal to this connecting line (thereby obtaining the lateral standard deviation of position). Note that the use of the 1 h average wind direction tends to minimize variations on the scale of the sea breeze. Because of the error in radar positioning (a few meters in range, about $\frac{1}{10}$ of a degree in azimuth and elevation angle), calculations of standard deviation were made only to the nearest 10 m. Accordingly, the basic data for the

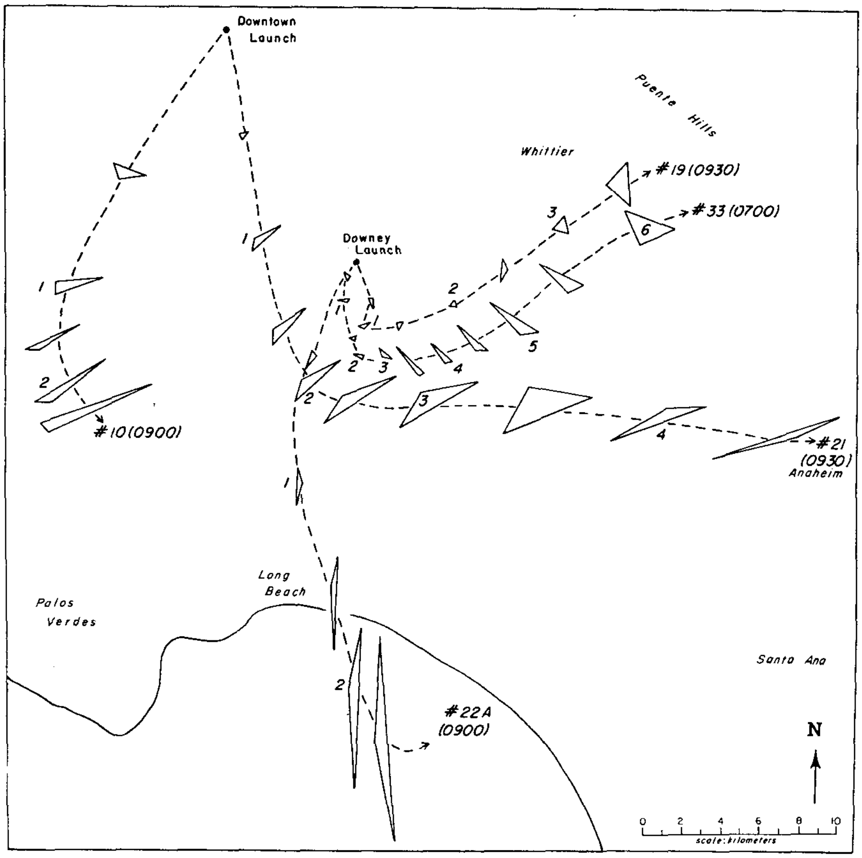

FIG. 3. As in Fig. 1 except for cases of trajectory turnings toward the east associated with the transition from land breeze to sea breeze.

subsequent analysis consist of lateral and longitudinal standard deviations of position at 15 min intervals for the 35 experiments for which the tetroon triad was positioned at least 30 min. Of course, due to loss of balloon members of the triad, the number of experiments decreases slightly with increase in travel time beyond 30 min.

Before discussion of the relative diffusion values obtained, possible sources of bias in the technique should be considered. First of all, while the tetroons were released simultaneously only a few meters apart on the ground, by the time they reached float altitude (typically 250–300 m above ground) they frequently were a few tens of meters apart due to varying ascent rates and the effect of varying wind shear between surface and float level. Thus, at float level (zero time) we are not really starting with a point source, and the subsequent standard deviations are undoubtedly somewhat too large because of this. A more serious bias arises from the fact that the tetroons cannot be placed at exactly the same height, and thus the relative diffusion is overestimated because of the effect of wind shear in the vertical (see Table 1 for mean tetroon height differences). The effect of wind shear on relative diffusion can be calculated (Pasquill, 1974), but the calculation will not be attempted here because wind shear data are available at only two points in the Los Angeles Basin. The above influences are counterbalanced to some extent because of the tendency for the tetroon to return to an equilibrium float surface, almost ensuring that the vertical oscillations of the tetroon are smaller than that of the surrounding air (Hanna and Hoecker, 1971). In general, one would anticipate that the turbulent diffusion is usually being overestimated through use of the tetroons, but presumably less so in unstable conditions than in stable conditions when the wind shear may be relatively large.

The left-hand diagram of Fig. 5 shows the derived variation of median lateral (dots) and longitudinal (circles) standard deviations of tetroon position with travel time. The vertical bars embrace 68% of the observations. Note the large variability of the standard deviations at given travel times when one is involved with sea breeze reversals as well as straight flow. There is little difference between the lateral and longitudinal standard deviation, i.e., the diffusion is horizontally isotropic. Both standard deviations increase approximately as the 1.1 power of time; however, it should be

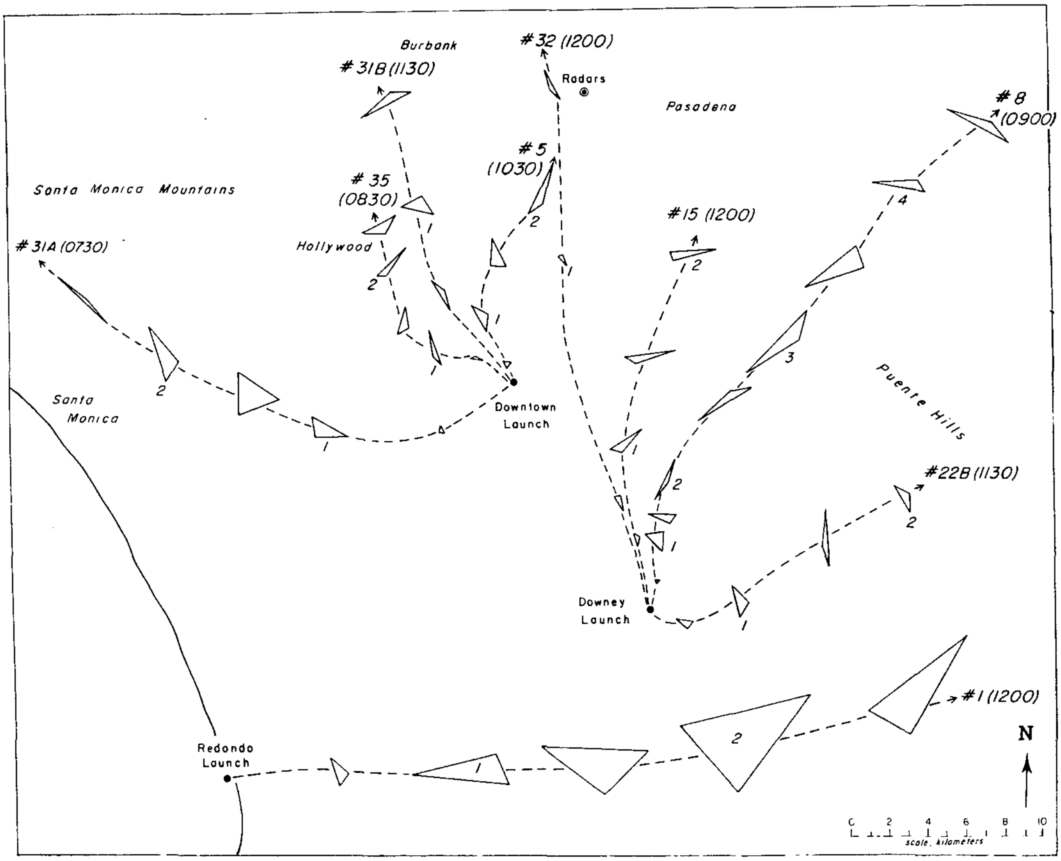

Fig. 4. As in Fig. 1 except under conditions of relatively straight flow.

remembered that the longest tetroon flights are those that involve a sea-breeze reversal, and we have already seen that the relative diffusion in these cases is unusually large. The left-hand portion of Table 2 gives the numerical values for the given travel times. On the average, the median lateral standard deviation of position is shown as varying from 90 m after a travel time of 15 min to 800 m after a travel time of 2 h, but 16% of the time the lateral standard deviation was less than 30 m after 15 min and less than 310 m after 2 h.

The right-hand diagram of Fig. 5 presents the comparison between the variation of median lateral standard deviation (and 16 and 84% limits) with travel time in the Los Angeles Basin, and the mean (HM), upper (HU) and lower (HL) bounds of lateral relative diffusion estimated by Hage (1964) from a variety of experiments. Heffter's (1965) synthesis yielded results similar to Hage's, and Bauer (1974) has summarized these and more recent findings using Hage's apparently representative estimates as a basis for comparison. Most of these results are based on smoke puff data. Some caution is required when comparing with these other results because the tetroon separation was measured at a height of 100–300 m above the ground, while most other relative diffusion experiments were carried out at a somewhat lower level where mechanical turbulence might be expected to play a major role in the diffusion. The median value within the Los Angeles Basin falls very nearly along Hage's lower bound, suggesting that within the Basin, at these heights, the relative diffusion with respect to travel time is indeed much less than has been found in most other experiments. That this difference is not merely a function of the measurement technique is shown by the factor of 4 difference between the results at Los Angeles and the results obtained from the release of triads of tetroons (T) for flight at a height of 3000 m MSL at Las Vegas, Nev. (Angell *et al.*, 1971).

Fig. 6 is similar to Fig. 5, but with travel distance rather than travel time as the independent variable. In the Los Angeles Basin, the lateral and longitudinal standard deviations of tetroon position increase as about the 0.9 power of distance, a result generally in agreement with that found by others (Pasquill, 1962, Fig. 4.12). The right-hand portion of Table 2 shows that, in the average, the median lateral standard deviation varies from 140 m at a travel distance of 2 km to 1000 m at a travel distance of 20 km, but 16% of the time the values were less than 40 and 430 m, respectively. The right-hand diagram of Fig. 6 shows the comparison of

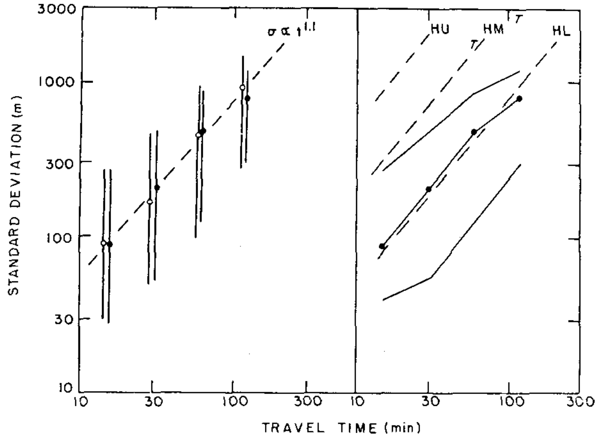

Fig. 5. Median value of lateral (dots) and longitudinal (circles) standard deviation of tetroon position as a function of travel time, where the vertical bars embrace 68% of the observations. At right is shown the median and 16 and 84% limiting values of lateral standard deviation in Los Angeles (solid lines) in comparison with the mean (HM), upper (HU) and lower (HL) bounds of Hage, as well as the results obtained from tetroon triads at Las Vegas, Nev. (T).

the median lateral standard deviation (and 16 and 84% limits) at Los Angeles with the results from bulk-tracer diffusion experiments, as summarized by Slade (1968) in *Meteorology and Atomic Energy*. The median values at Los Angeles nearly coincide with the neutral-unstable results obtained at Idaho Falls (I) and Edwards Air Force Base (S), but the relative diffusion at Point Arguello (P) is considerably greater under both stable and unstable conditions, presumably because of the hilly terrain in the latter area. In about 10% of the cases the relative diffusion in Los Angeles is indicated to be less than that measured by Högström (1964) at a height near 50 m in stable conditions (dot-dash line labeled H). In general, Figs. 5 and 6 suggest that, in comparison with other experiments, the relative diffusion within the Los Angeles Basin is much smaller with respect to travel time than travel distance, presumably at least partly as a result of the light winds in the Basin.

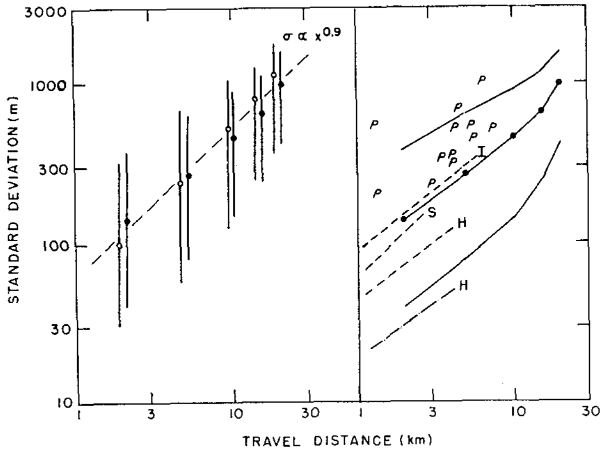

FIG. 6. As in Fig. 5 except as a function of travel distance. At right results are compared with those obtained by Högström (H) under stable conditions (dot-dash line), and at Idaho Falls (I), Edward Air Force Base (S), and by Högström (H) under neutral or unstable conditions (dashed lines). P represents results obtained at hilly Point Arguello under both stable and unstable conditions.

TABLE 2. Lateral standard deviation of tetroon position (m) as a function of travel time and distance. The top row gives the median value, the middle row the value exceeded in 84% of the cases, and the bottom row the value exceeded in 16% of the cases.

Travel time (min)				Travel distance (km)				
15	30	60	120	2	5	10	15	20
90	210	490	800	140	270	460	660	1000
30	50	130	310	40	80	150	240	430
70	490	880	1220	380	630	900	1160	1580

5. Variation of relative diffusion with atmospheric stability

Until now we have treated all 35 tetroon relative-diffusion experiments without regard for the possible effect of atmospheric stability on the diffusion. The relationship is examined in this section, albeit in a crude way and for the lateral direction only. Toward this end, the mean lapse rate between 1000 and 950 mb (approximately the lowest 500 m of the atmosphere) was evaluated at the EMSU (Environmental Meteorological Support Unit) station at Los Angeles International Airport, just north of El Segundo (Fig. 1), and at El Monte, about 10 km north of Whittier (Fig. 3), during the days of tetroon experiments.

It is, of course, difficult to estimate the mean lapse rate along tetroon trajectories from only two sounding stations. We have attempted to do so by first interpolating at both stations with respect to time, and then interpolating in space. Fig. 7 shows the comparison between the lapse rate so estimated and the average rms vertical velocity (σ_w) of the tetroons making up the triad. The correlation of 0.65 between the two suggests that the derived lapse rates have some validity. Of perhaps more interest is the evidence for an abrupt "break" in the value of σ_w at the position of the vertical dashed line, or at a lapse rate of about 0.3°C $(100\ \text{m})^{-1}$. There is the suggestion that σ_w remains relatively small until a critical lapse rate is reached, at which point it may become relatively large. We somewhat arbitrarily denote these two stability classes as "neutral" and "stable."

The left-hand diagram of Fig. 8 shows the lateral standard deviation of tetroon position as a function of travel time for these "neutral" and "stable" cases. In general, the standard deviation is about twice as large in "neutral" as in "stable" conditions. Thus, Table 3

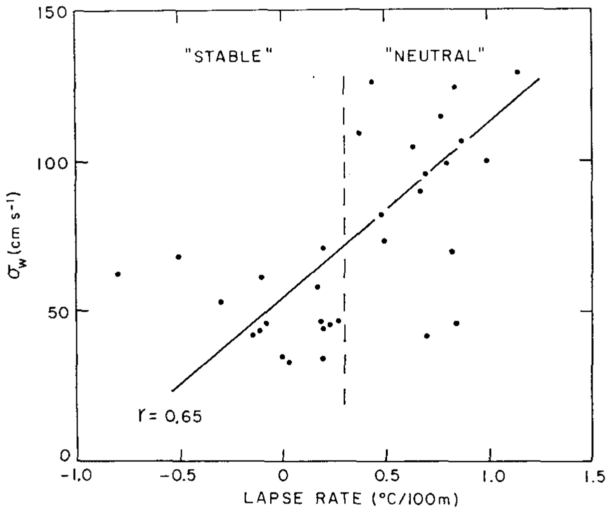

FIG. 7. Comparison between lapse rate (surface to 500 m) estimated along tetroon-triad paths, and the average root mean square vertical velocity of the tetroons making up the triad. The solid line is the regression line, while the vertical dashed line shows the subjective division into neutral and stable stability.

TABLE 3. Lateral standard deviation of tetroon position (m) as a function of travel time, distance and stability. The top row gives the median value, the middle row the value exceeded in 84% of the cases, and the bottom row the value exceeded in 16% of the cases. "Stable" refers to a lapse rate <0.3°C (100 m)$^{-1}$, "neutral" to a lapse rate >0.3°C (100 m)$^{-1}$.

Travel time (min)					Travel distance (km)				
15	30	60	120		2	5	10	15	20
				Stable					
80	160	310	620		100	180	350	540	710
20	50	80	270		30	50	100	190	290
200	430	800	1060		260	570	790	1000	1340
				Neutral					
100	250	570	950		190	350	530	830	1250
30	70	220	360		60	140	210	340	610
380	600	1000	1410		440	730	1000	1280	1810

shows that after a travel time of 60 min, 84% of the time the lateral standard deviation is greater than 80 m under "stable" conditions but greater than 220 m under "neutral" conditions. These differences have probably been underestimated because of the relatively greater effect of vertical wind shear on tetroon dispersion (when the tetroons are at slightly different mean heights) in stable conditions. Because of the relationship between stability and time of day, it is not surprising that the lateral standard deviation was also about twice as great for tetroon triads released between 0900 and 1400 local time as between 0700 and 0900 local time.

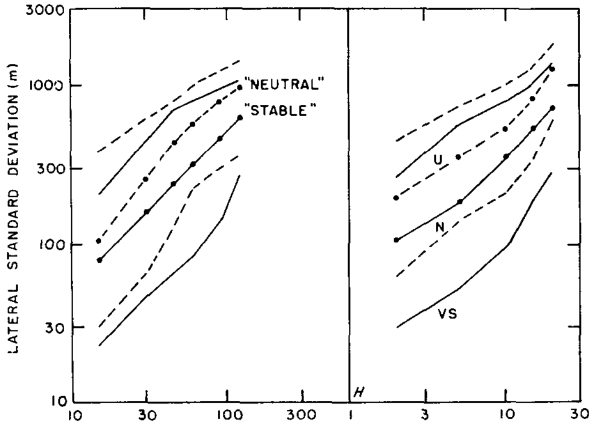

FIG. 8. Median and 16% and 84% limiting values of lateral standard deviation in Los Angleles as a function of travel time (left) and distance (right) under stable (solid lines) and neutral (dashed lines) conditions (see Fig. 7). The letters U, N and VS at right represent "suggested estimates" (Slade, 1968) under unstable, neutral, and very stable conditions. H indicates the smallest lateral dispersion measured by Högström.

The letters U, N and VS in the right-hand diagram of Fig. 8 (lateral standard deviation as a function of travel distance) indicate the lateral standard deviations under unstable, neutral and very stable conditions suggested for use by *Meteorology and Atomic Energy*. The suggested values appear conservative (small), the Los Angeles "stable" values corresponding with the suggested neutral and the Los Angeles "neutral" values corresponding with the suggested unstable. About 10% of the time in "stable" conditions the derived Los Angeles lateral standard deviation is less than that suggested for very stable conditions in *Meteorology and Atomic Energy*. Finally, the letter H in the lower left corner of this diagram represents the smallest lateral standard deviation obtained by Högström (1964) under very stable conditions.

It would also have been of interest to examine the lateral standard deviation of tetroon position as a function of lateral turbulence intensity. However, because of the complexities introduced by trajectory turnings the latter has not been evaluated. Instead, the vertical turbulence intensity has been evaluated based on the ratio of tetroon-triad σ_w and mean speed. As expected, the lateral diffusion is indicated to be about twice as large when the vertical turbulence intensity exceeds 0.3 as when it is less than this value. Furthermore, the lateral diffusion is found to be more closely related to the vertical turbulence intensity itself than to the square of the turbulence intensity.

6. Conclusion

The relative diffusion has been estimated from the rate of separation of individual members of tetroon triads at heights of about 350 m MSL in the Los Angeles Basin. Bearing in mind that through the use of this technique the relative diffusion has probably been *overestimated* because of the dispersion arising from the effect of the vertical wind shear on tetroons located at slightly different mean heights, the following points are worthy of emphasis:

1) In most cases a single tetroon trajectory appears to represent a good estimate of the air trajectory, since in only 2 out of the 35 experiments was there a wide diversity of trajectories within the tetroon triad.

2) The relative diffusion in the Los Angeles Basin at these heights is frequently very small with respect to travel time, the median value within the Basin falling along the lower bound determined from other (mostly smoke puff) experiments.

3) In general, the relative diffusion in the Los Angeles Basin is not unusually small with respect to travel distance (partly the result of the light winds in the Basin), although in about 10% of the cases the diffusion was less than that suggested for very stable conditions in Slade (1968).

4) The relative diffusion is about twice as large in neutral [lapse rate $>0.3°\text{C}\ (100\ \text{m})^{-1}$] as in stable conditions, but this difference has probably been underestimated because of the relatively large effect of vertical wind shear on dispersion when the tetroons are located at slightly different mean heights in a stable atmosphere.

5) As expected, the relative diffusion is increased by a factor of at least 2 when the trajectories undergo directional reversals due to the encroachment of the sea breeze. There is evidence of horizontal convergence and strong upward motion at the sea breeze "front."

Finally, the use of tetroons in the Los Angeles Basin to "tag" a given volume of air appeared to be completely successful, and points the way to further experiments using this technique.

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Finally, in the overall context of LARPP, we wish to express our appreciation to the experiment director, W. Perkins, for his unfailing support and able direction, as well as to the helicopter crews, ground crews and all others who helped make this experiment a milestone in the study of urban pollution.

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