VOL. 15, NO. 3 JOURNAL OF APPLIED METEOROLOGY MARCH 1976

Tetroon Trajectories in the Los Angeles Basin Defining the Source of Air Reaching the San Bernardino-Riverside Area in Late Afternoon

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(Manuscript received 24 April 1975, in revised form 14 November 1975)

ABSTRACT

Tetroon trajectories within the Los Angeles Basin in the autumn of 1973 show that, on non-stagnation days, air located in the Los Angeles area in the morning can pass over the Puente Hills and reach the San Bernardino-Riverside area by mid-afternoon of the same day. However, the enhanced vertical mixing associated with these Hills would be expected to dilute any pollution present. Of perhaps more importance is the evidence that, on stagnation days when the atmosphere is stable, air from the Los Angeles area may drift southward in the early morning katabatic flow, stagnate for 2–3 h in the industrialized and high vehicle-density region north of Long Beach, and then move rapidly eastward with the sea breeze flow through Santa Ana Canyon, reaching the Riverside-San Bernardino area in late afternoon. In this case there would seem to be more potential for severe pollution in the latter area. However, the frequency of occurrence of this particular trajectory pattern is uncertain.

1. Introduction

There has been considerable controversy regarding the extent to which pollution in the San Bernardino-Riverside area of the Los Angeles Basin is due to local sources and the extent to which it is due to pollution transported eastward from the Los Angeles area itself. It is not the purpose of this paper to enter directly into this controversy, but rather to present specific examples of low-level (about 350 m MSL) constant-volume balloon (tetroon) trajectories that pass from the western to the eastern area of the Basin within a single day, thus pointing up the diurnal interplay between the two regions. Details of the tetroon system may be obtained from a previous paper (Angell *et al.*, 1975) dealing with the estimation of relative diffusion from the spreading of tetroon triads released during the Los Angeles Reactive Pollutant Program (LARPP). The tetroon trajectories considered here were obtained during this same program in the autumn of 1973. The transponder-equipped tetroons were tracked by an M-33 radar located on Flint Peak (elevation 580 m) 3 km west of the Pasadena Rose Bowl. From this site the tetroons could be tracked from Santa Monica in the west to San Bernardino in the east. Fig. 1 illustrates the relation of the various cities mentioned in the text, and plotted in subsequent figures, to area topography.

Air trajectory estimates in the Los Angeles region have been obtained from earlier tetroon experiments (Holzworth *et al.*, 1963; Pack and Angell, 1963; Angell *et al.*, 1966, 1972), but because of the location of the tracking radar, in these earlier experiments the tetroons were not followed eastward as far as the San Bernardino-Riverside area. In the case of bulk tracer experiments, the data of Neiburger (1955) were pretty much confined to the Los Angeles-Long Beach area, whereas Drivas and Shair (1974) have described only a single release of sulfur hexafluoride at Anaheim, which was sampled as far east as Palm Springs 80 km to the east-southeast of San Bernardino. Several groups have deduced air trajectories from surface winds, the most comprehensive study probably being that of Taylor (1962) who calculated "normalized" trajectories for days of smog and no smog. Contrary to the results to be presented here, these normalized trajectories did not show much evidence for flow from the Long Beach area through Santa Ana Canyon in either case.

The chief advantage of the tetroon is that it gives a good estimate of the actual air parcel trajectory, although at some height above the surface. The disadvantage in the use of tetroons is that trajectories are only obtained on those relatively few days when a field experiment is being conducted, and consequently it is difficult to generalize to a climatological trajectory pattern.

2. Flow across the Puente Hills

Fig. 2 presents the trajectories of tetroon flights that passed over the 200–500 m high Puente Hills in relatively strong westerly flow. It is seen that:

1) In experiment 16 (top diagram) one of the three tetroons released simultaneously from Downey at 0700 (all times Pacific Standard) on 10 October passed south of Riverside shortly before 1500. The tetroon was found grounded in Banning (about 50 km east of Riverside)

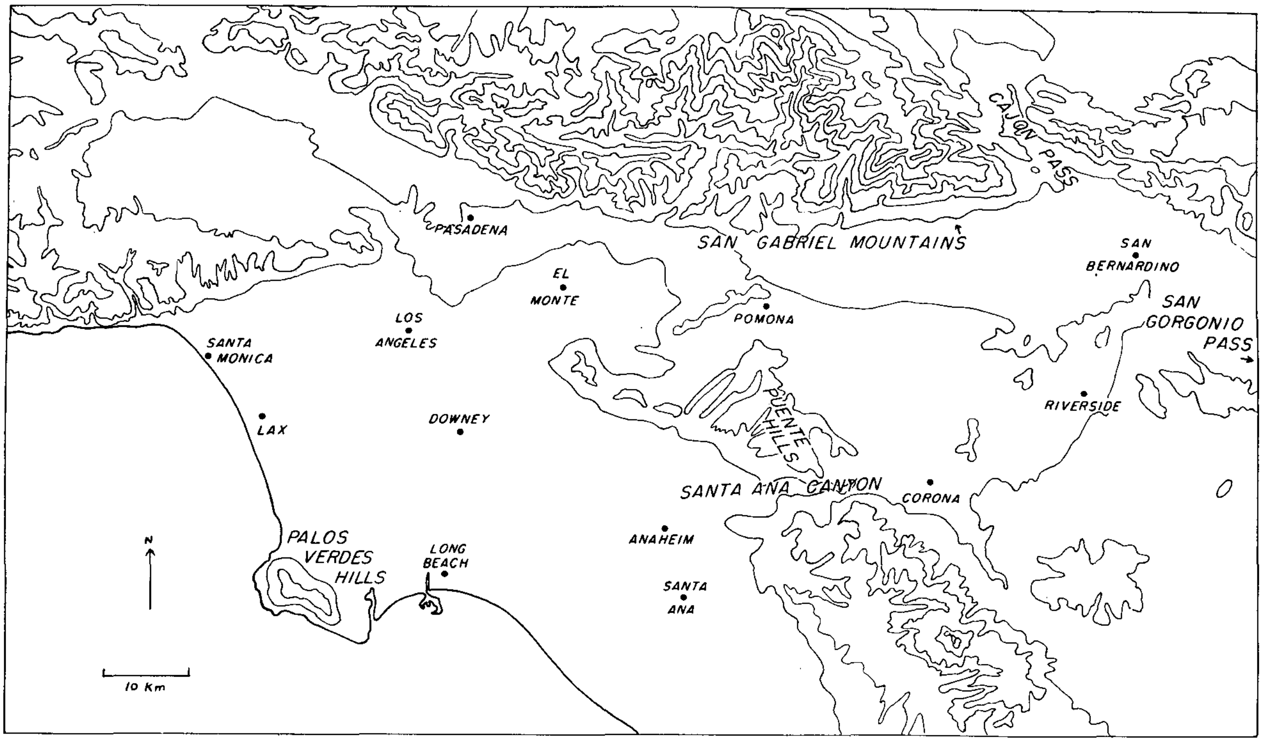

FIG. 1. Map of the Los Angeles Basin showing the relation of the cities to the topography. Terrain height is indicated by contours at 150 m, 300 m, and at successive intervals of 300 m.

at 1800 of the same day. Obviously, it had been embedded in air moving toward the Palm Springs area by way of San Gorgonio Pass. This flight was tracked to the limiting tracking range of the M-33 radar (100 km due to the pulse repetition rate). As shown in the top diagram of Fig. 3, the tetroon floated at a height of about 200 m MSL until it encountered the sea breeze from the Long Beach area at 1000, at which time it began a slow ascent to about the 1000 m level (the tetroon may have expanded slightly in the updrafts over the Puente Hills and thereby attained a slightly higher equilibrium float surface). The trajectory direction and speed agree well with the 1000 mb wind direction at Los Angeles Airport (LAX) at 1200 (unfortunately no wind data were obtained from the National Weather Service station at El Monte at this time). There can be little doubt that, in non-stagnation conditions such as this, air located in the Los Angeles area in early morning may reach the San Bernardino-Riverside area by mid-afternoon of the same day. However, the tetroon height trace suggests that the enhanced vertical mixing associated with the Puente Hills and with heating of the eastern Los Angeles Basin generally (Edinger, 1963) would aid in diluting any pollution present.

2) In experiment 22B (Fig. 2, middle diagram) one of the three tetroons released simultaneously from Downey at 1100 PST 18 October (4 h later than the 10 October release) reached the vicinity of Cajon Pass by 1600, almost certainly headed for the Victorville-Barstow area to the north. The second diagram from the top in Fig. 3 shows that once again the tetroon apparently was forced above its initial equilibrium surface by the Puente Hills, although it should be noted that in order to move through Cajon Pass, the tetroon (and the air in which it is embedded) would have to rise to at least 1000 m MSL. The trajectory direction and speed agree well with the El Monte 1000 mb wind at 1200. Experiments 16 and 22B tend to confirm what has long been apparent from conventional wind measurements, namely, that in the afternoon there is an appreciable exodus of air from the Los Angeles Basin by way of both Cajon Pass and San Gorgonio Pass, and that as a result there is a tendency for streamline (and trajectory) difluence in the San Bernardino area (DeMarrais *et al.*, 1965).

3) In experiment 27 (Fig. 2, bottom diagram) two of the three tetroons released simultaneously from downtown Los Angeles at 1100 on October 28 also appeared to be heading for Cajon Pass, but their height was not sufficient to enable them to be tracked much beyond Pomona (Johnstone Peak north of Pomona cuts off the radar view looking straight east). The third diagram from the top in Fig. 3 shows clearly how the one tetroon ascended and then descended while passing over the Puente Hills between 1300 and 1400. While there were no wind data at El Monte on this day, the 1200 wind speed and direction at LAX at both the

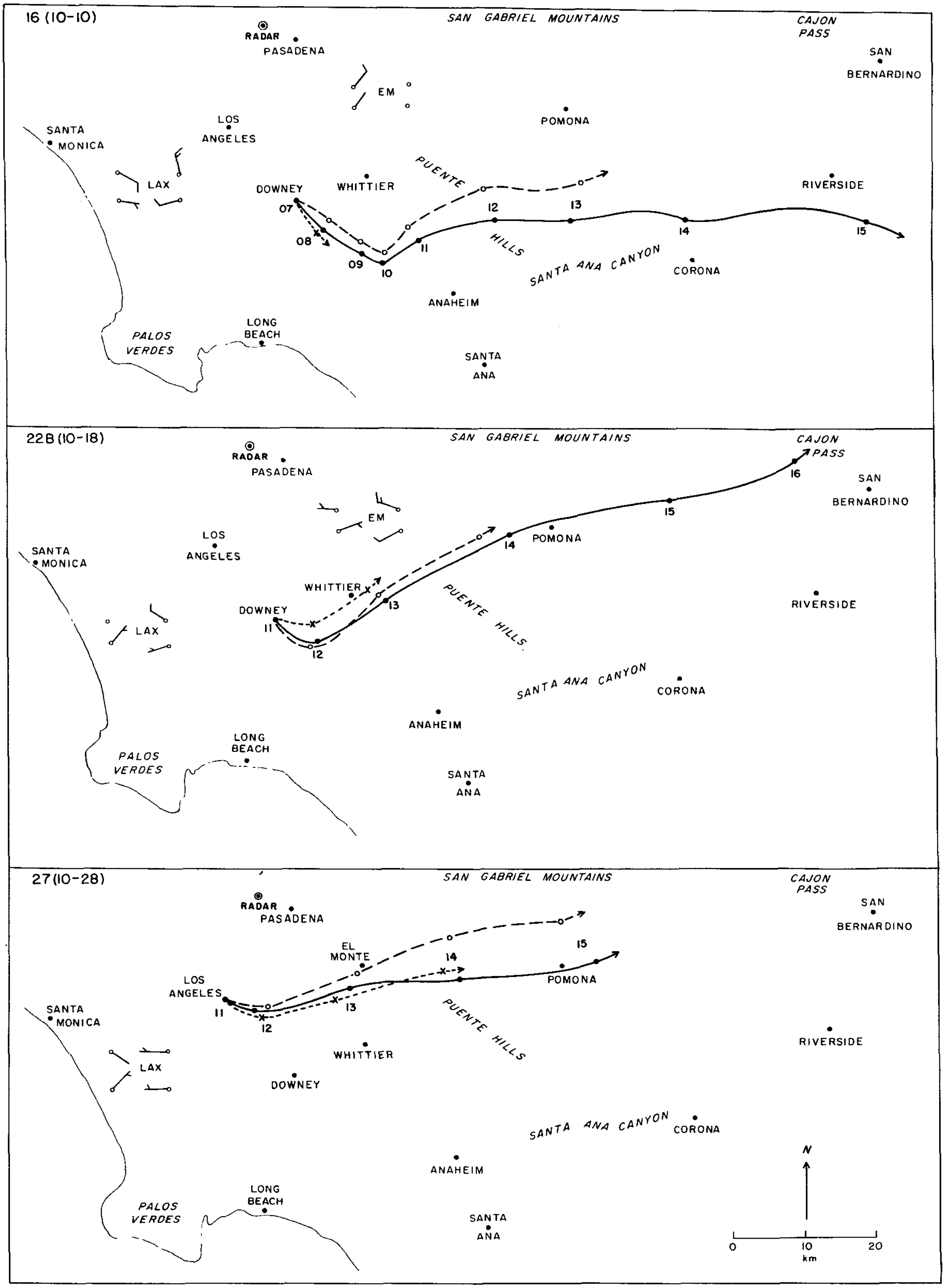

FIG. 2. Tetroon trajectories passing over the Puente Hills, where in each diagram three tetroons were released simultaneously from the same location. The experiment number and data (parentheses) are given at upper left. Balloon locations are indicated at hourly intervals (Pacific Standard Time) along the trajectories. The winds at Los Angeles Airport (LAX) and El Monte (EM) at about 0600 (left) and 1200 (right) are presented for the 1000 mb (bottom) and 850 mb (top) surfaces (no barb, 1–2 kt; half barb, 5 kt; full barb, 10 kt, etc.).

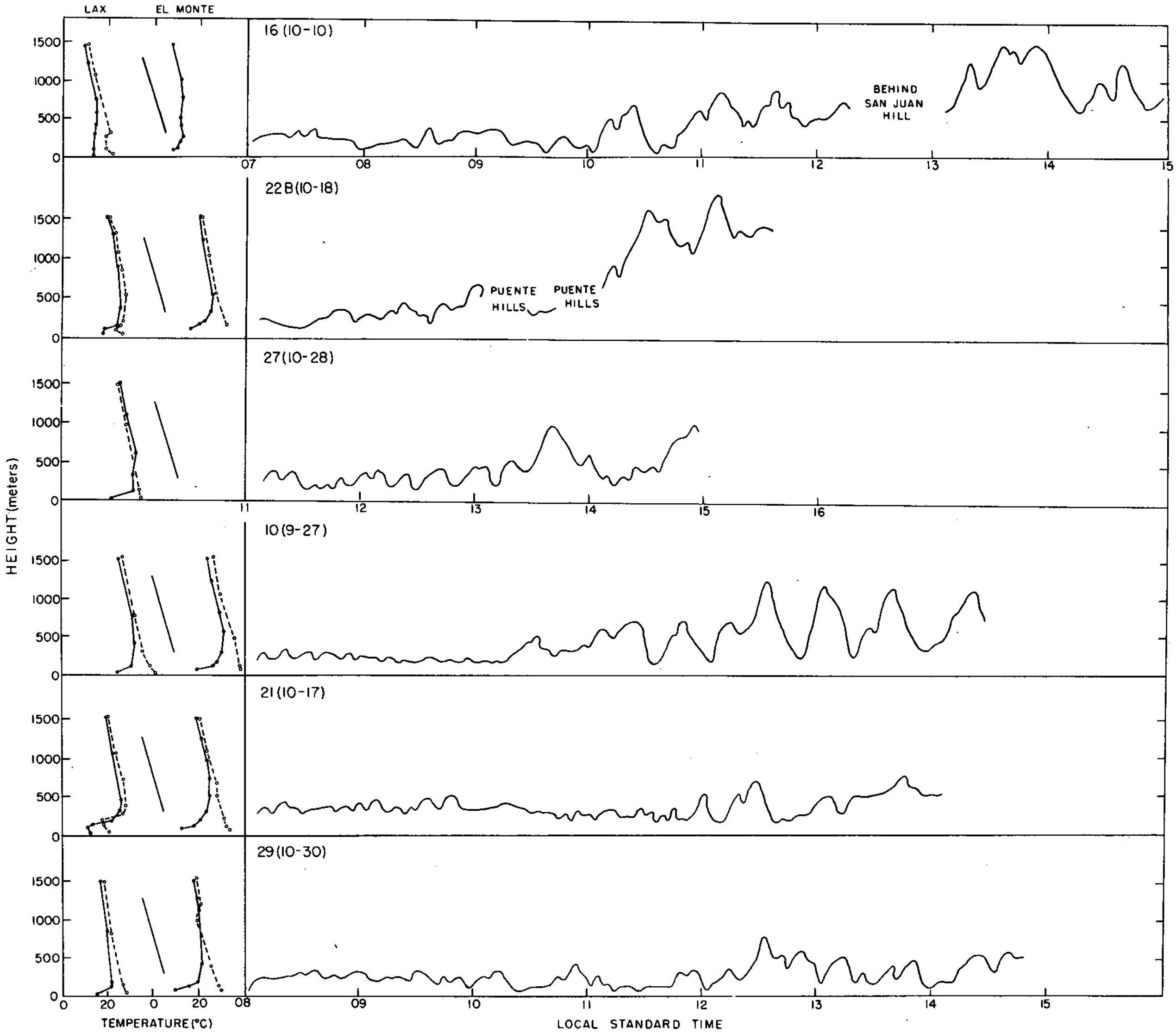

FIG. 3. Tetroon height traces for the six solid trajectories in Figs. 2 and 4. The local time is given along the bottom of three of the traces. The left-hand boxes show the lapse rate at LAX (left) and El Monte (right) for about 0600 (solid line) and 1200 (dashed line) on the given dates (the straight line is the dry adiabat).

1000 and 850 mb surfaces generally agree with the trajectory direction and speed. Assuming persistence in direction and speed, the tetroons would have reached the Cajon Pass area before 1700. Note that on both 18 and 28 October any pollutant released into the atmosphere in the Los Angeles area near 1100 would probably, in the main, have been transported through Cajon Pass and *not* reached the San Bernardino-Riverside area.

3. Flow through Santa Ana Canyon

Fig. 4 presents an interesting alternative to flow *over* the Puente Hills, and that is flow *through* Santa Ana Canyon to the south of the Puente Hills and east of Anaheim (Disneyland). The inferences from these particular tetroon flights are in basic agreement with the results obtained by Drivas and Shair (1974) from a single release of sulfur hexafluoride at Anaheim near noon on 19 July 1973, but of course generalization is hazardous. One problem with tetroon flights through Santa Ana Canyon is that the Puente Hills block the radar view in this direction, so that while the tetroons could be tracked into the Canyon, they could not be tracked to the east of the Canyon (some may have grounded in the Canyon of course) because of the intervening hills; consequently the trajectory pattern in the vicinity of Riverside is not delineated by these flights. Examining the experiments individually, it is seen that:

1) In experiment 10 (top diagram) the three tetroons

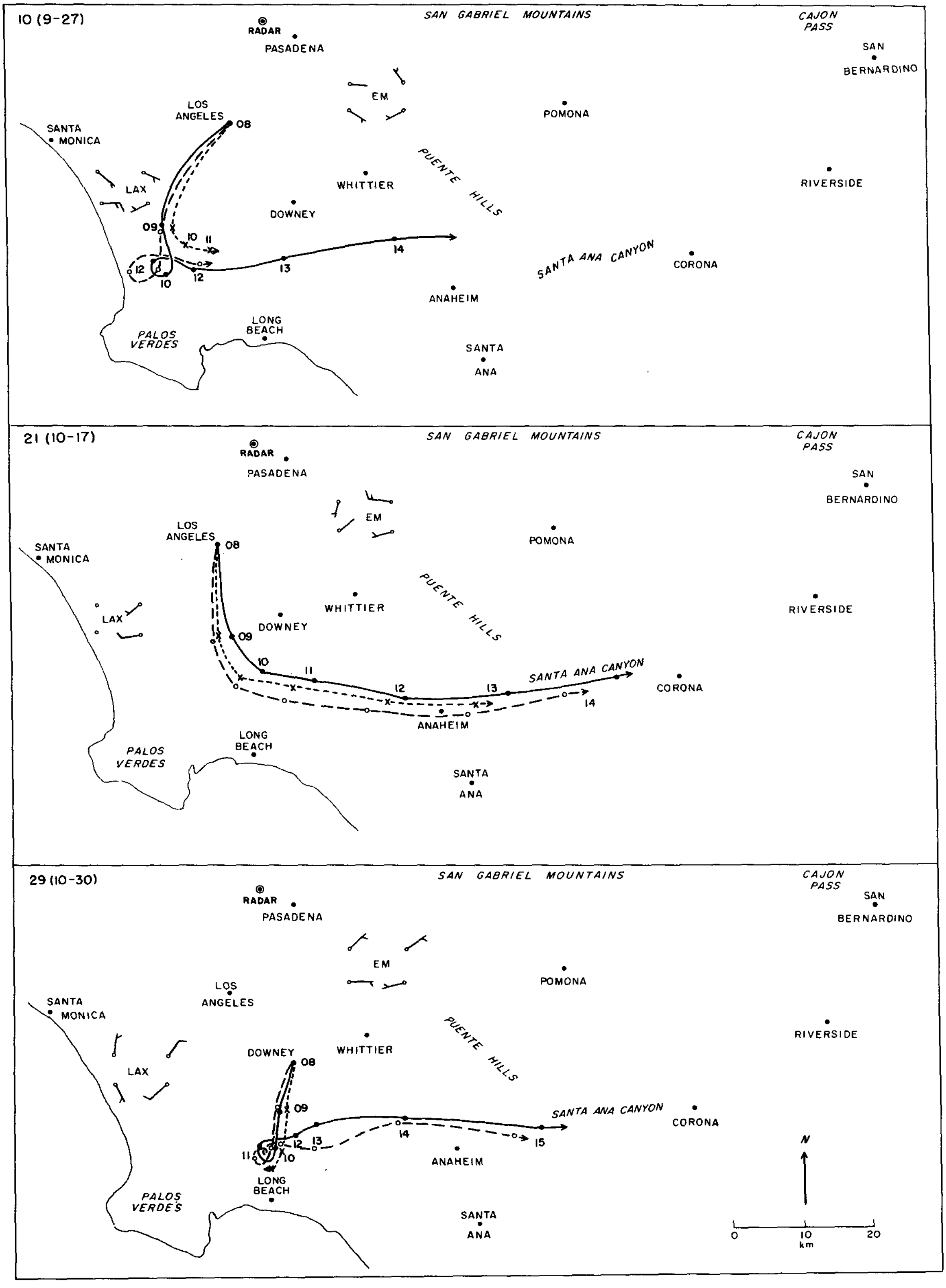

FIG. 4. Tetroon trajectories passing, or appearing about to pass, through Santa Ana Canyon. Note the stagnation (actually anticyclonic loops) on experiments 10 and 29. Otherwise, see Fig. 2 legend.

TABLE 1. The average difference in temperature (°C) between a height of 100 and 500 m ($T_{500}-T_{100}$) at Los Angeles Airport (LAX) and El Monte at about 0600 and 1200 PST on the three days when the tetroon flights passed through Santa Ana Canyon (Fig. 4) and the three days when they passed over the Puente Hills (Fig. 2). Appended is the temperature difference on the day of the over-hill flights in Fig. 5 (Experiment 33).

	LAX		El Monte	
	0600	1200	0600	1200
Through Canyon	2.3	0.4	2.8	−1.8
Over hills	0.5	0	1.9	−2.3
Experiment 33	−0.7	−3.3	0.6	−4.0

released simultaneously from downtown Los Angeles at 0800 PST 27 September moved southwestward in the downslope (katabatic) flow from the San Gabriel Mountains, and two of the tetroons traced out anticyclonic paths before moving eastward in the sea breeze flow (the third tetroon did not trace out an anticyclonic loop). While only one balloon was tracked eastward by the radar, a vehicle sampling beneath the tetroons reported two tetroons still aloft as far east of Anaheim so that one of the transponders must have failed. The third diagram from the bottom in Fig. 3 illustrates beautifully the transition from stable flow in the morning to convective flow in the afternoon on this date. The one remaining tetroon was lost to radar view, as it approached the entrance to Santa Ana Canyon, while in the descending limb of the convective circulation.

2) In experiment 21 (Fig. 4, middle diagram) two of the three tetroons released simultaneously from downtown Los Angeles at 0800 on 17 October moved southward and then eastward and were tracked well into Santa Ana Canyon before being lost to radar view (recall that the 18 October release at 1100 moved over the Puente Hills, so the trajectories are undoubtedly related to time of release). Assuming persistence in wind speed and direction, these tetroons would have been in the Riverside area before 1600. Although these trajectories exhibit no stagnation tendency, they did pass over some heavily industrialized and high vehicle-density areas north of Long Beach, and one would surmise that air passing through Santa Ana Canyon was quite polluted, especially since the LAX and El Monte soundings showed that an unusually intense and persistent inversion existed (second diagram from the bottom in Fig. 3). In accord therewith, note the small vertical oscillation of the tetroon. On this particular day there is almost incontrovertible proof that polluted air from both downtown Los Angeles and Long Beach reached the Riverside area by way of Santa Ana Canyon.

3) In experiment 29 (Fig. 4, bottom diagram) two of the three tetroons released simultaneously from Downey at 0800 on 30 October moved southward, traced out anticyclonic loops north of long Beach (one of the trajectories traced out a double loop), and then moved eastward into Santa Ana Canyon where they were lost to radar view. Assuming persistence in wind speed and direction, these tetroons would have been in the Riverside area by 1700. Due to the 2–3 h stagnation of the air in the industrialized and high vehicle-density area north of Long Beach, and the small vertical mixing indicated by the tetroon height trace (bottom diagram of Fig. 3), one would anticipate that also on this day quite heavily polluted air from the Los Angeles-Long Beach area reached the Riverside area by way of Santa Ana Canyon.

4. The hypothesis

Why did the tetroon flights of Fig. 4 tend to go through Santa Ana Canyon while the flights of Fig. 2 went over the Puente Hills? Partly this results from the fact that two of the tetroon triads in Fig. 2 were released at 1100 rather than 0700–0800, but even so Table 1 shows that on the average there *was* a difference in atmospheric stability during the two periods, particularly at LAX at 0600. Of course, when the stability is greatest, the pollution is worst due to the lack of vertical ventilation, and consequently it is important that it is just at this time that the eastward moving air may tend preferentially to funnel through Santa Ana Canyon.

The hypothesis to be considered, but by no means proved from the data at hand, is that the worst pollution in the Riverside-San Bernardino area (if the bulk of it is not created locally) is not associated with air flow from the west over the Puente Hills (the enhanced vertical mixing presumably dilutes the pollution in this case), nor with air flow from the west-northwest around the northern edge of the Puente Hills (probably most of this air goes through Cajon Pass), but rather with air flow from the west-southwest through Santa Ana Canyon.

It should be emphasized at this point that, as we have presented it, a necessary part of this hypothesis (at least as far as downtown Los Angeles pollutants are concerned) is that during the morning hours there be a southward directed land breeze (katabatic flow from the San Gabriel Mountains) which transports the Los Angeles pollutants far enough south that they can reasonably be expected to move into Santa Ana Canyon with the onset of the sea breeze. Such a regime would most likely exist in winter. It would be of interest for air pollution meteorologists in the Los Angeles area to see if there is any evidence that the most severe smog in the Riverside-San Bernardino area indeed occurs when there is an early morning katabatic flow southward from the western San Gabriel Mountains, or perhaps more directly, simply to note the time variation of the pollution in air moving eastward through Santa Ana Canyon.

The importance of stability in this context is supported by Fig. 5, which shows that on experiment 33

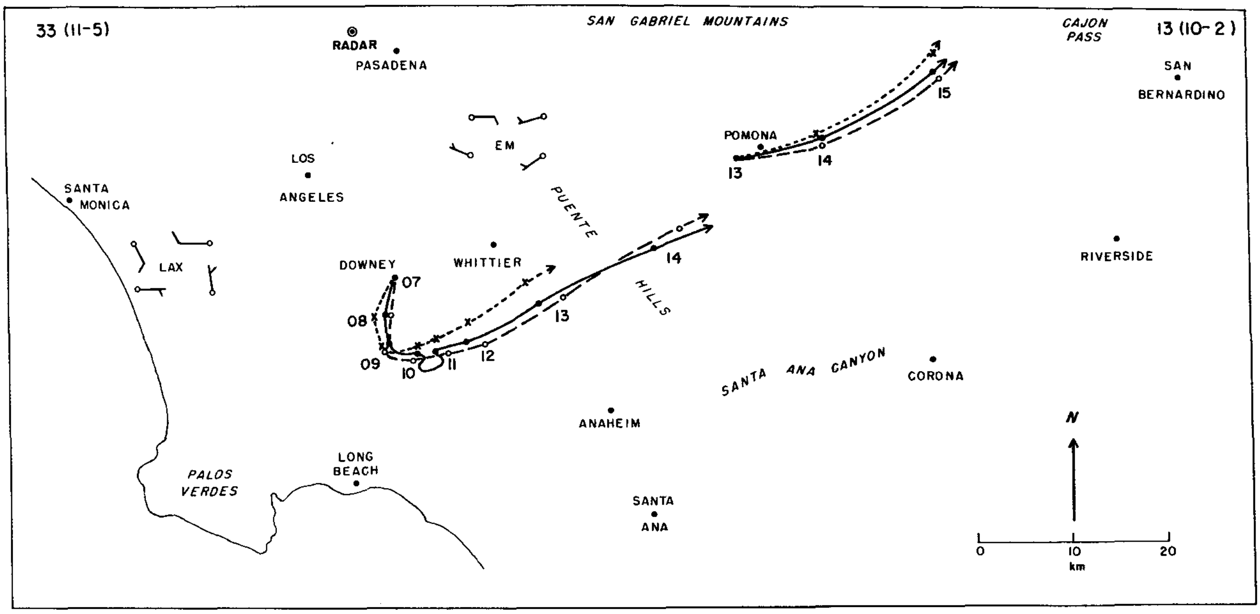

FIG. 5. Tetroon trajectories passing over the Puente Hills after near-stagnation (left), and the trajectories of flights released near Pomona (right). El Monte and LAX winds are not presented for the latter case. Otherwise, see Fig. 2 legend.

the three tetroons released simultaneously from Downey at 0700 on 5 November moved southward initially and then stagnated, just as on experiment 29 (note the similarity in release time in these two cases). With the onset of the sea breeze flow at about 1100, however, the 5 November tetroons (and presumably the air in which they were embedded) moved northeastward right over the Puente Hills and showed no inclination whatsoever to funnel through Santa Ana Canyon. The bottom line of Table 1 shows a possible reason why: there was practically a dry adiabatic lapse rate at 1200 at both LAX and El Monte on this date. The three simultaneous tetroon releases from near Pomona in this diagram (experiment 13) offer additional support for the concept that any polluted air located north of the Puente Hills in the afternoon will frequently move northeastward into Cajon Pass and not eastward into the San Bernardino-Riverside area.

5. Conclusion

It is probably unwise to generalize from such a small number of tetroon trajectories, but the following points concerning the source of air reaching the San Bernardino-Riverside area in the afternoon are worth keeping in mind:

1. On non-stagnation days a volume of air located near downtown Los Angeles in early morning can move almost directly eastward and reach the San Bernardino-Riverside area by mid-afternoon. The question is, does the enhanced vertical mixing associated with passage over the Puente Hills so dilute the pollution that the effect of this advected pollution is negligible?
2. On stagnation days with a relatively stable atmosphere and a southward-directed katabatic flow in early morning, a volume of air located near downtown Los Angeles may move southward, stagnate for 2–3 h north of Long Beach, and then move eastward through Santa Ana Canyon in the sea breeze flow, reaching the Riverside area in late afternoon. Because of the stagnation in a heavily industrialized and high vehicle-density area, and the limited vertical ventilation due to the stability, this air would be expected to be more polluted than air which moved relatively rapidly eastward and underwent considerable vertical mixing over the Puente Hills. What is uncertain at this time is the frequency of occurrence of this particular trajectory pattern.
3. Questions also remain as to the extent of the pollution in the San Bernardino-Riverside area due to air which moves eastward north of the Puente Hills. The limited evidence from the tetroon trajectories suggests that much of this air may be funneled northward through Cajon Pass. On the other hand, the air which has moved through Santa Ana Canyon probably is generally funneled eastward through San Gorgonio Pass to the Palm Springs area (Drivas and Shair, 1974).

Finally, if not already done, it would be of interest to set up sampling stations in Santa Ana Canyon to note the extent of the pollution in eastward moving air under varying stability conditions. If further trajectory work is desirable, it would be possible (based on our reconnaissance) to transport the M-33 tetroon-tracking radar to the 1000 m high Sierra Peak just south of Santa Ana Canyon, and from this vantage point tetroons could be tracked through Santa Ana Canyon as well as eastward into San Gorgonio Pass, northward into Cajon Pass and throughout the Los Angeles Basin as far northwestward as the San Fernando Valley. Centrally located Sierra Park would be an ideal radar location for a really comprehensive tetroon-trajectory program in the Los Angeles Basin.

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