Urban Influence on a Strong Daytime Air Flow as Determined from Tetroon Flights[1]

J. K. ANGELL,[2] W. H. HOECKER,[2] C. R. DICKSON[3] AND D. H. PACK[2]
Air Resources Laboratories, NOAA

(Manuscript received 13 February 1973, in revised form 10 May 1973)

ABSTRACT

Tetroon flights across Oklahoma City indicate the influence of an isolated urban area on the horizontal and vertical air velocity at heights near 400 m in relatively strong (13 m $\sec^{-1}$) daytime flow. The Lagrangian measurements so obtained are collated with fixed-point measurements of horizontal and vertical velocity on a 460 m television tower. Above the city in the morning there is a mean trajectory turning toward lower pressure of 10°. This turning, presumably frictionally induced, is noted only weakly in the afternoon and not all in the evening, but there is slight evidence for a bending of the trajectories around the city at these later times. During the day the city appears as the source of a plume of ascending air motion extending at least 30 km downwind of the city, with both tetroon and tower measurements indicating a mean upward velocity of almost 0.4 m $\sec^{-1}$ ten kilometers downwind of city-center at heights near 400 m. On the average the magnitude of the stress determined from the covariance of the eddy velocity components along the tetroon flights is about 70% of the magnitude measured on the tower, and there is a correlation of nearly 0.5 between individual measurements of stress by the two techniques. The magnitude of the tetroon stress is intimately related to building height and density, with a stress maximum of at least 3 dyn cm^{-2} located 10 km downwind of city-center in comparison with stress values near 1 dyn cm^{-2} beyond the city outskirts. The fraction of the stress associated with Lagrangian oscillations of 1–10 min period (in comparison with 1–30 min period) increases from 20% upwind of the city to 80% downwind of the city in the daytime average.

1. Introduction

There have been relatively few studies of the air flow in urban areas, partly because of the difficulties in obtaining representative wind statistics within the built-up areas of the city. Among the more recent studies along this line involving the use of what might be called conventional instrumentation (surface or tower anemometers and pilot balloon ascents), we should mention the work of Chandler (1960), Pooler (1963), Davidson (1967), Graham (1968), Druyan (1968), and Findlay and Hirt (1969). Tetroons (constant volume, superpressured balloons) have recently been used to determine the nighttime air flow over Columbus, Ohio (Angell *et al.*, 1971), and the daytime and nighttime flow over Los Angeles (Angell *et al.*, 1972) at heights of a few hundred meters. The trajectory-type data obtained from tetroon flights permit the delineation of quite subtle urban effects on the air flow, including an estimate of city-induced vertical velocity.

Between 25 September and 12 October, 1971, 56 tetroon flights were made past the instrumented 460 m WKY-TV tower located on the northern outskirts of Oklahoma City. The tetroon flights were part of a larger experiment carried out by the Air Resources Laboratories, which included the obtaining of numerous pilot balloon and radiosonde data in the Oklahoma City area, as well as evaluation of the mesoscale wind field from anemometers 30 m above the ground. The primary purpose of the tetroon portion of the experiment was to compare the Reynolds stress obtained from the covariance of the velocity components along the tetroon trajectories with the stress measured in conventional fashion on the tower (in this case, through the use of a three-component orthogonal system of Gill propellers located at two levels on the south-southwest side of the tower). However, in the prevailing southerly flow of that area, in order to fly the tetroons close to the tower, it was necessary to overfly Oklahoma City, and these flights across the city provide some interesting insights into the effect of an isolated urban area on the three-dimensional air flow.

Fig. 1 presents a highly simplified map of the Oklahoma City area. The solid lines indicate the approximate partitioning of Oklahoma City according to building type, zone 1 representing downtown Oklahoma City with a mean building height of ∼70 m

---

[1] Research carried out under the joint sponsorship of the Environmental Protection Agency (Air Pollution Control Office), the Atomic Energy Commission (Division of Reactor Development and Technology), and the National Oceanic and Atmospheric Administration.

[2] Silver Spring, Md.

[3] Idaho Falls, Idaho.

(maximum building height nearly 150 m), zone 2 less built-up commercial and industrial areas with a mean building height of ~30 m, and zone 3 the residential areas with a mean building height of ~10 m. The dashed lines give the terrain height above mean sea level in 40 m intervals. The slight variation in terrain height is mainly associated with the three river systems in the area, the Cimarron River to the north, the North Canadian River which passes through the southern edge of Oklahoma City, and the Canadian River which passes about 30 km to the south of Oklahoma City, or near Norman, Okla. Superimposed on these basically north-south height variations is a tendency for the terrain to rise to the west.

Fig. 1 also shows the location of the meteorologically instrumented WKY-TV tower to the north-northeast of downtown Oklahoma City, as well as the location of the tetroon-tracking radar 10 km southeast of the tower. In order to fly tetroons past the tower with the prevailing south-southwest winds, a tetroon launch site was established on high ground overlooking the Canadian River, approximately 40 km south-southwest of the radar. Note that downtown Oklahoma City lies almost directly beneath the straight line track between this tetroon launch site and the television tower.

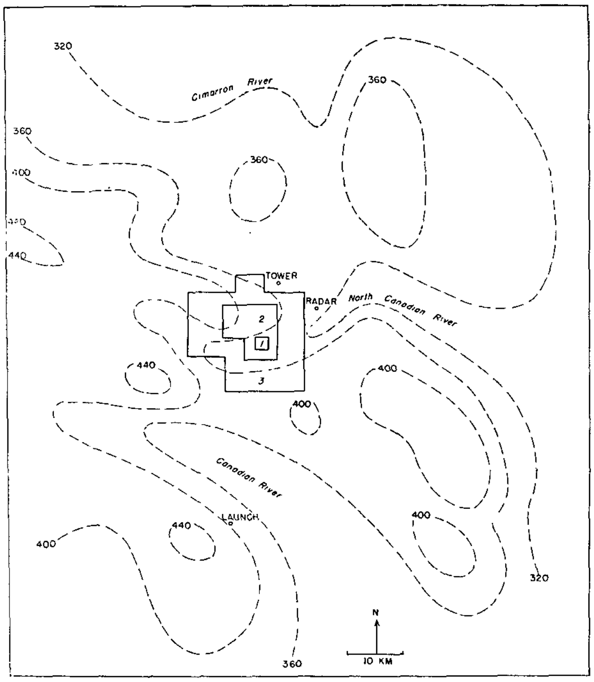

FIG. 1. Map of the Oklahoma City area showing the approximate partitioning (solid lines) of the city according to building type (1, downtown area; 2, other commercial and industrial areas; 3, residential areas), the location of the tracking radar, the instrumented WKY-TV tower, and the usual tetroon launch site; the terrain height is given in meters MSL (dashed lines).

2. Procedures

The tetroons were positioned by an M-33 tracking radar from the Air Resources Field Research Office, Idaho Falls. Tetroon launch mobility was provided by a large truck fitted out as an inflation van. As usual, transponders were attached to the tetroons to avoid the problem of ground clutter and hence to permit accurate tetroon positioning at very low elevation angles. The range, and azimuth and elevation angles of the tetroons were stored on magnetic tape at 1-sec intervals. These 1-sec readings were later averaged to provide 30-sec average tetroon positions and derived velocities. Velocity components were computed in zonal and meridional directions as well as along and normal (perpendicular) to the mean flight path, where the mean flight path was defined as the straight line joining tetroon launch site and terminal position (the point at which the transponder signal was lost). The tetroons were inflated to float at a height of 300 m in order that realistic comparisons could be made with the Reynolds stress obtained (usually) at heights of 177 and 355 m on the tower. However, it will be shown that the tetroons were forced to greater heights due to the influence of the city, and the actual mean tetroon flight level was about 400 m.

During the first week of the experiment the daytime winds at a height of 355 m were consistently from the south or south-southwest at a speed of 10–16 m sec^{-1}. Similar winds existed on three other days of the experiment. The relative uniformity and consistency of these winds make reasonable the averaging of data obtained on these days. Accordingly, in the subsequent analysis, diagrams are presented showing the mean variation, over Oklahoma City and environs, of normal velocity, vertical velocity and longitudinal stress, obtained by averaging the data for the 32 flights made on 10 different days when the air flow was southerly with a mean speed of about 13 m sec^{-1}. Of the 32 tetroon flights, 10 were basically in the morning (between 0900 and 1200 local time), 15 in the afternoon (1200–1800), and 7 in the evening (1800–2100), so that in subsequent diagrams the results obtained for the afternoon should be the most representative and those for the evening least representative.

3. Tower data

In addition to the three-dimensional velocity data obtained every 1/10 second by means of the Gill anemometers at heights of 355 m and either 177 or 44 m, wind speed, wind direction and temperature were obtained at eight other levels on the tower at 1-min intervals (the latter data are obtained more or less routinely by the National Severe Storms Laboratory). Fig. 2 shows the mean variation with time of day of lapse rate, and wind speed and direction shear on the WKY tower during flight days with relatively strong southerly flow. The mean values obtained with northerly and westerly winds are designated by letters

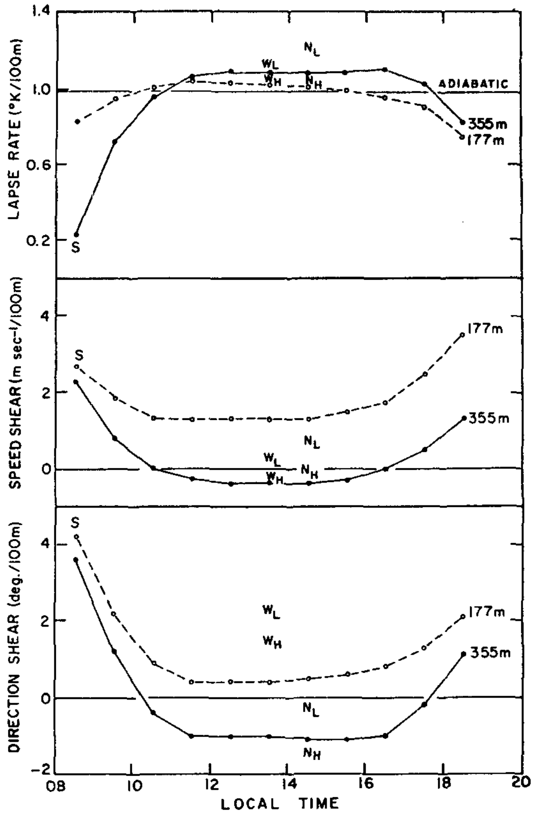

FIG. 2. Mean variation of lapse rate, and wind speed and direction shear with time of day at 355 m (solid lines) and 177 m (dashed lines) on the WKY tower during tetroon flight days with strong sourtherly flow. The letters indicate the mean variations at the higher (H) and lower (L) levels in northerly (N) and westerly (W) flow.

since there were not enough data at the time of the tetroon flights to define a daily trend. Temperature and velocity differences between tower heights of 90 and 266 m were used to provide lapse and shear estimates at 177 m, and differences between ower heights of 266 and 444 m provided lapse and shear estimates at 355 m.

In the case of southerly flow, the lapse rate traces show that by 1030 (all times CDT) the lapse rate is essentially dry adiabatic at all levels on the tower. As anticipated, at earlier times the lapse rate is more stable at higher than lower levels, that is, the neutral lapse rate regime propagates upward from the surface. The evidence that near midday the lapse rate is more unstable at the higher level should be verified by careful recalibration of the thermometers. After about 1700 the atmosphere begins to stabilize at the two tower heights. Similar midday lapse rates are obtained with winds from the north and west.

At heights near 177 m (in southerly flow) the wind speed increases with height and the wind direction veers with height, both throughout the day, but these tendencies are much less pronounced at midday than in morning or evening. At heights near 355 m there is the unexpected result that at midday the wind speed decreases slightly with height and the wind direction backs slightly with height in the mean, the opposite of the variation usually associated with the Ekman spiral.

For the subsequent discussion it is desirable to know the mean location of the tetroon relative to the well-mixed surface layer, since one would anticipate quite different influences of the city on tetroon-derived velocity depending on whether or not the tetroon was embedded within this mixed layer. For the days with southerly flow, Fig. 3 shows the average variation with time of day of mean tetroon height, the maximum height attained by the tetroons, and the mixing depth, the latter defined as the height of intersection of the temperature-height curve and the dry adiabat through the surface temperature. The mixing depth was determined in morning and evening from the average of tower temperatures throughout the period of southerly flow, and near midday from occasional radiosonde ascents in the Oklahoma City area made by Air Force mobile crews (6th Weather Squadron) from Tinker Field. Note that the tower data may not accurately represent the mixing depth over the *center* of the city in morning and evening.

Fig. 3 suggests that during the morning (0900–1200) the tetroons are generally flying near the top of the mixed surface layer, and any vertical oscillations are probably somewhat inhibited by the presence of the stable layer above. In early afternoon (1200–1500), however, the mixing depth considerably exceeds the maximum height attained by the tetroon; i.e., the vertical oscillations of the tetroons are limited by their own buoyancy restoring force, not by atmospheric stability. In late afternoon the mixing depth again falls below the mean tetroon height, and in the evening (1800–2100) the tetroons obviously are flying above the mixed layer, which, in fact, becomes of negligible

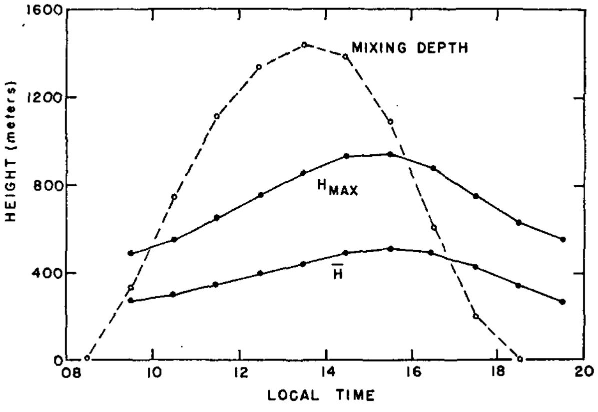

FIG. 3. Variation with time of day of the mean tetroon height ($\bar{H}$), the maximum height attained by tetroons (H_{max}), and mixing depth, on days with strong southerly flow. The mixing depth was determined from the intersection of the temperature-height curve and the dry adiabat through the surface temperature, as determined from tower data in morning and evening, and radiosonde data in midday.

thickness after 1900. Thus, the tetroon-derived data should be much more independent of surface roughness elements in the evening than in morning or afternoon.

4. Urban influence on horizontal trajectories

Fig. 4 shows tetroon trajectories across Oklahoma City on 30 September and 1 October. On days with a southerly flow the wind direction backed during the daylight hours, and thus sequential tetroon releases from the same site were like a searchlight beam probing the city from east to west. However, Fig. 4 also shows that there were subtle day-to-day changes in mean wind direction (on 1 October the winds were about 10° more southerly than on September 30), and this should increase the representativeness of the results presented herein in that one is thereby assured that certain sections of the city and environs were not overflown by tetroons only at certain times of day.

Careful inspection of Fig. 4 reveals some interesting directional shifts in wind direction. For example, while crossing the city, flights 20, 21 and 24 all undergo about a 10° turning to the left looking downwind (flow toward lower pressure or "indraft" flow), followed by a return to almost the original direction. Based on all 32 flights during the 10 days of southerly flow, the left-hand diagram of Fig. 5 presents a smoothed plot of the average normal or lateral velocity (m sec^{-1}) over Oklahoma City and environs. It is seen that, under these

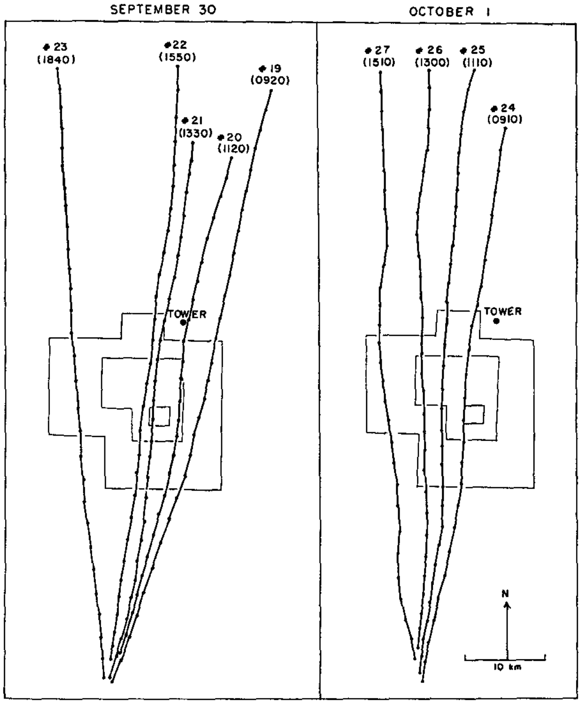

FIG. 4. Tetroon trajectories across Oklahoma City at heights near 400 m on 30 September and 1 October. Tetroon positions are shown at 3-min intervals, with the flight number and local time of closest approach to city center (parentheses) indicated at trajectory end points.

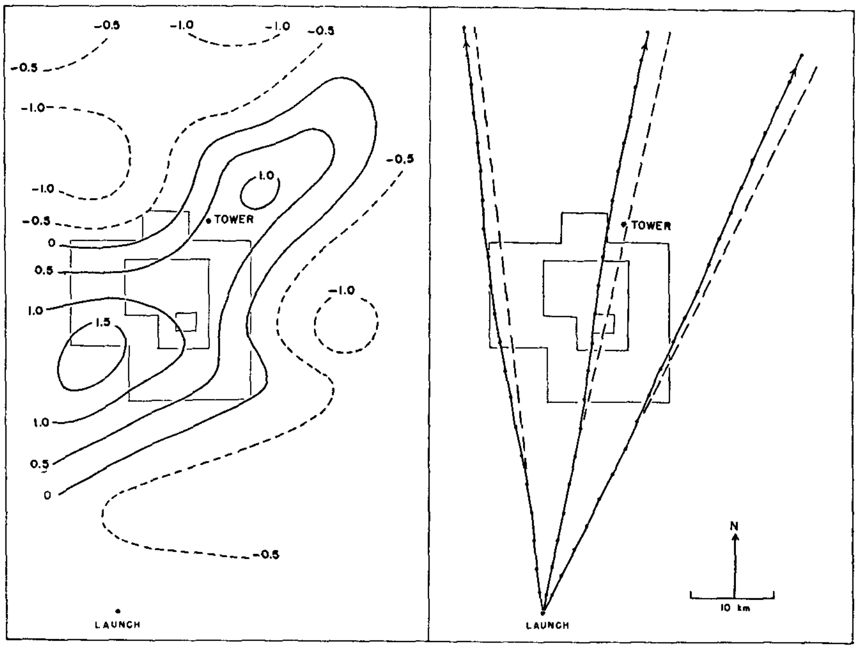

FIG. 5. Smoothed distribution of normal or lateral velocity (m sec^{-1}) at heights near 400 m in the Oklahoma City area based on 32 daytime tetroon flights on days with strong (13 m sec^{-1}) southerly flow (left); at right the mean trajectories are obtained by integrating the normal velocities along straight lines passing across city-center and the city outskirts. The positive values (solid lines) at left signify flow to the left of the mean flight path looking downwind. The mean trajectory positions at right are plotted at 4-min intervals, with the dashed lines representing linear extrapolations of initial trajectory directions.

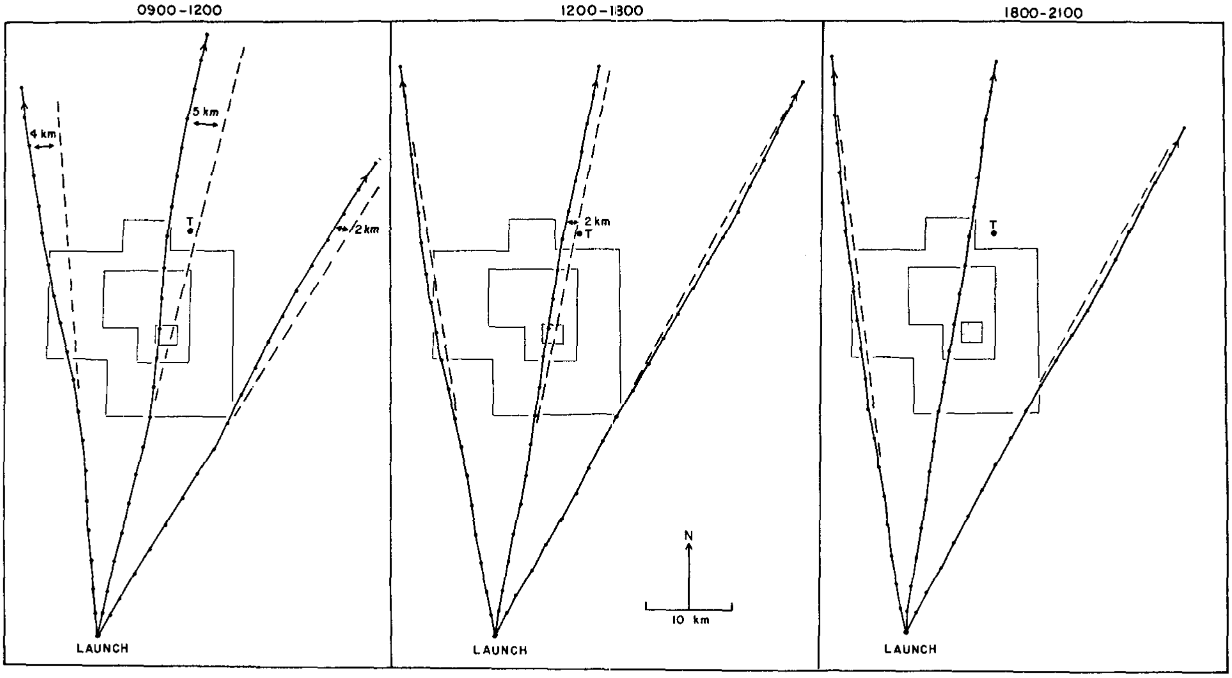

FIG. 6. Mean trajectories obtained by integrating the normal velocities along straight lines passing across city-center and the city outskirts during morning (left), afternoon (center), and evening (right) of days with strong southerly flow. Simulated trajectory positions are indicated at 4-min intervals. The dashed lines are straight-line extrapolations of initial trajectory directions, and the derived city-induced lateral trajectory displacement is shown along some trajectories.

strong wind conditions, the city induces an additional ageostrophic flow toward low pressure of at least 1 m sec^{-1} at heights near 400 m. Note, however, that the maximum flow toward lower pressure is not located over city-center but rather to the southwest and northeast thereof, suggesting a superposition of city-induced frictional turning and of a tendency for air flow around the city.

Inasmuch as the surface stress can be expressed as the vector cross product between the vertical component of the Coriolis force and the total mass transport due to the ageostrophic flow (Holmboe *et al.*, 1945), it is possible from the data of Fig. 5 to estimate the urban contribution to the stress. With the assumption that the city-induced ageostrophic flow extends through the approximately 1000 m depth of the mixed layer (Fig. 3), and that the mean ageostrophic flow in this layer is 1 m sec^{-1}, then the additional stress due to the city is determined to be about 1 dyn cm^{-2}. It will be shown in Section 6 that we obtain a direct estimate somewhat larger than this.

In order to present the urban influence on the flow in more obvious terms, the right-hand diagram of Fig. 5 shows the mean trajectories obtained by integration of the normal velocities along straight lines passing over downtown and the eastern and western city outskirts. The dashed lines are a linear extrapolation of the initial trajectory directions and presumably represent the approximate trajectories which would result if the city did not exist. With this assumption, at a height of about 400 m, downtown Oklahoma City induces a mean trajectory turning toward lower pressure of $\sim 5°$, resulting downwind of the city in a trajectory displacement toward lower pressure of 2–3 km. Since the tetroons ascend in the mean by only about 100 m while passing over Oklahoma City, one would presume that the mean backing of the wind with height observed in Fig. 2 $[1°(100\text{ m})^{-1}]$ does not contribute appreciably to this directional shift, but we can not be absolutely sure of this because the tower is located downwind of the city and hence is under the influence of the city.

Fig. 6 presents similarly derived mean trajectories over city-center and the city outskirts obtained from tetroon flights during morning, afternoon and evening (left to right). In the morning the downtown section of the city induces a trajectory turning toward lower pressure of nearly 10°, resulting, downwind of the city, in a trajectory displacement toward lower pressures of nearly 5 km. In the afternoon, however, the mean trajectory across downtown exhibits only about a 4° turning to the left and only about a 2 km displacement toward lower pressure downwind of the city. It is an interesting point as to why the city-induced angle of indraft is 2–3 times as large in the morning as in the afternoon. Part of the difference is probably due to the greater mean height of the tetroons above the city in the afternoon than in the morning (Fig. 3). We suggest that another reason is the different depth of the mixed layer during these times, as also indicated in Fig. 3. In the morning, when the mixing depth is only a few hundred meters, the effect of the increased frictional drag caused by the city is confined to a shallow layer and hence is noted strongly at all levels within that layer, whereas in the afternoon, when the mixing depth frequently exceeds 1000 m, the effect of the increased frictional drag of the city is spread through a much deeper layer and hence is noted only weakly at any particular level within that layer.

In the afternoon the tendency for the air to flow around the city is more obvious than in the morning, as illustrated by the outermost trajectories in the middle diagram of Fig. 6. Even so, the dashed lines show that this effect is small, with trajectory deviation from straight line flow of only 2 km. The observed tendency for flow around the city would be expected in the evening (and night) when stability inhibits the rise of air above the city, but it is a little surprising to find it occurring also in the afternoon. It appears to be the result of a barrier effect of the city which is uncompensated by vertical motion. Note that the mean evening trajectory across city-center exhibits negligible turning, presumably because the tetroons are flying in stable air well above the surface mixed layer. This is in agreement with the findings at Columbus, Ohio (Angell *et al.*, 1971).

5. Urban influence on vertical velocities

Fig. 7 shows the height traces for the flights of Fig. 4 which passed most directly over the city. Variations in terrain height and schematic variations in building height are also presented. Quite apparent is the much greater amplitude of the tetroon oscillations in the afternoon than in the morning. Note the tendency for descending motion upwind of the city along flights 25 and 22.

Based on all 32 flights during the 10 days of relatively strong (13 m sec^{-1}) southerly flow, the left-hand diagram of Fig. 8 presents a plot of the average tetroon vertical velocity (m sec^{-1}) at heights of about 400 m in the Oklahoma City area. The solid lines signify upward motion and the dashed lines downward motion. The mean upward motion exceeds 0.3 m sec^{-1} just *upwind* of city-center, but the area of appreciable ascending motion is quite localized, extending only about 10 km in alongwind and crosswind directions despite the considerable smoothing. Except in the downwind sector there is a tendency for sinking motion over the city outskirts. This sinking motion is best defined in the Lake Hefner area to the northwest of the city, and recalls the consistent sinking found over the Hudson and East Rivers in the New York City tetroon experiment (Hass *et al.*, 1967). At this time we are not sure of the reason for the mean descending motion 10 km upwind of the city.

Since the restoring force acting to return the tetroon to its equilibrium float surface is generally well known, it is possible to obtain a better estimate of the vertical air motion than that given by the tetroon itself. This problem has been thoroughly discussed by Hoecker and Hanna (1971), to which the reader is referred for the computational technique of passing from tetroon vertical velocity to "air parcel" vertical velocity. The drag coefficient used for this evaluation is 0.75, a value obtained by Hoecker (1973) from experiments in Idaho in which the rise rates of tetroons with given free lifts were determined with great accuracy.

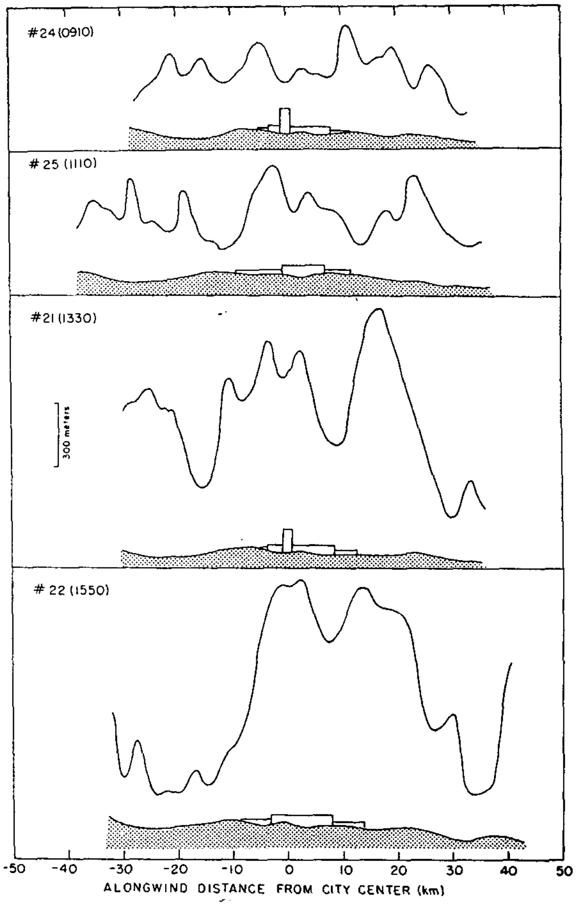

Fig. 7. Height traces for the tetroon flights of Fig. 4 which passed most directly over the city. Terrain height (stippling) and schematic building height are also shown. The height scale is indicated at middle left, and the local time of passage over city-center at upper left in individual diagrams.

The right-hand diagram of Fig. 8 shows the derived *air parcel* vertical velocity (m sec^{-1}) over Oklahoma City and environs, as obtained from the mean *tetroon* vertical velocities in the left-hand diagram of Fig. 8 through consideration of the restoring force acting on the tetroon (with the assumption that the equilibrium float surface of the tetroon was the design altitude of 300 m). A plume of ascending motion is now indicated to extend at least 30 km downwind of the city center. Basically, this "plume effect" results from the observation that the tetroons, though forced considerably above their equilibrium float surface upon approach to

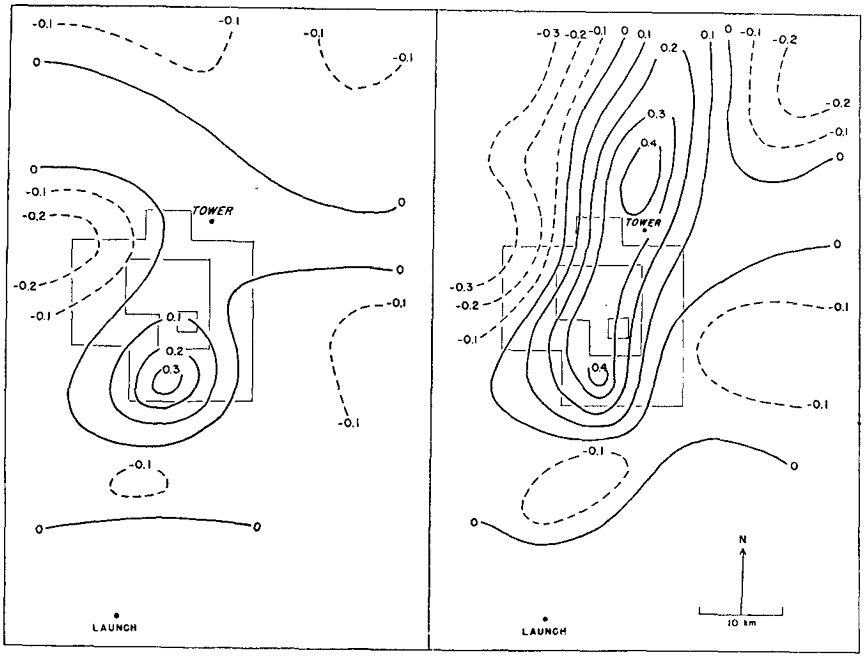

FIG. 8. Smoothed daytime distribution of tetroon vertical velocity (m sec^{-1}) at heights near 400 m in the Oklahoma City area based on 32 tetroon flights on days with strong (13 m sec^{-1}) southerly flow (left), and at right the distribution of derived air parcel vertical velocity. Positive values and solid lines signify upward motion.

downtown, did not descend until some distance downwind of the city (left-hand diagram of Fig. 8), implying a sustained upward air motion. It should be pointed out, however, that the magnitude of the indicated ascending motion downward of the city may be exaggerated owing to the fact that the tetroons tend to expand slightly when forced far above their equilibrium float surface, thereby seeking a higher equilibrium surface which we then take as evidence for a sustained upward air motion.

Fig. 9 shows the derived air parcel vertical velocity in the Oklahoma City area determined from tetroon flights during morning, afternoon and evening (left to right). In the afternoon the mean upward motion exceeds 0.7 m sec^{-1} just upwind of city-center, with a secondary maximum of 0.5 m sec^{-1} downwind of the

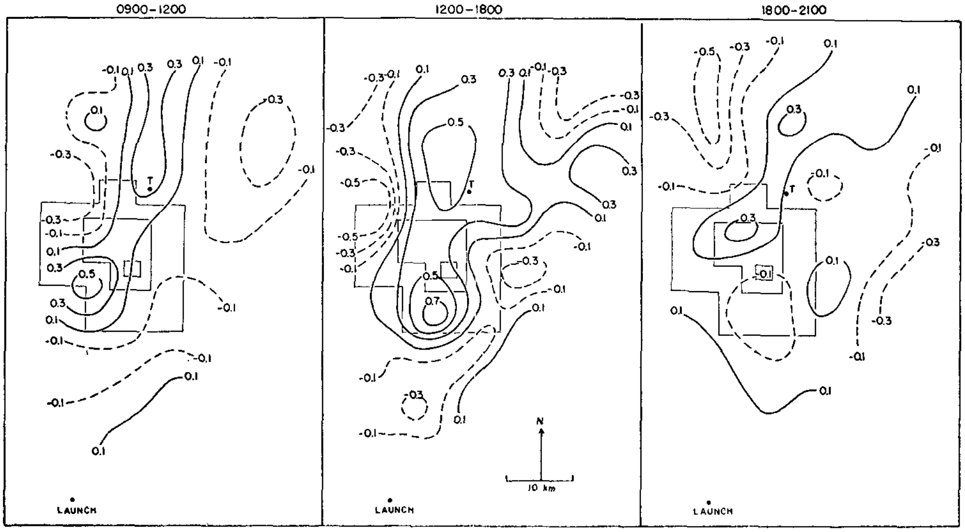

FIG. 9. Smoothed distribution of derived air parcel vertical velocity (m sec^{-1}) at heights near 400 m during morning (left), afternoon (center) and evening (right) of days with strong southerly flow. Positive values and solid lines signify upward motion.

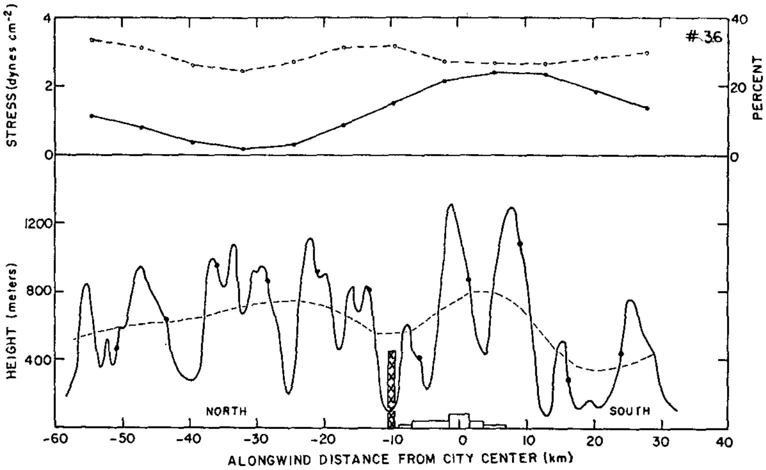

FIG. 10. Height variation of tetroon flight 36 upwind and downwind of Oklahoma City on an afternoon with weak (4 m sec^{-1}) northerly flow. The dots are at 30-min intervals and Oklahoma City buildings and the instrumented television tower are indicated schematically at bottom. The solid line in the top diagram shows the variation of tetroon-derived stress along the flight path, based on Lagrangian oscillations of approximately 1–30 min period, while the dashed line shows the percentage of this stress due to oscillations of approximately 1–10 min period.

city (this tendency for a double maximum is apparent along flights 21, 22 and 25 in Fig. 7). In the morning a mean ascending motion exceeding 0.5 m sec^{-1} is found upwind of the city but displaced somewhat to the west of the afternoon location. The reason for the westward displacement of the maximum is not clear; it may merely represent a data bias due to the relatively few morning flights which passed to the west of downtown.

In the evening the indicated vertical motion pattern is quite different, with the maximum ascending motion occurring just downwind of city-center rather than just upwind as in morning and afternoon, and there is a region of descending motion upwind of the city where, in morning and afternoon, there was a maximum ascending motion. The nearly out-of-phase relation between vertical motion in evening and morning-afternoon is puzzling, but may partially reflect the dip of the isopycnic surfaces due to the urban heat island effect; i.e., during the day the tendency for the tetroons to follow isopycnic surfaces is completely overshadowed by the vertical air motion, but in the evening (and at night) this may not be so.

The bottom diagram of Fig. 10 shows the mean height trace of Flight 36, a flight which passed close to the tower and directly over the center of the city in the afternoon after being released from a point 60 km to the *north* of the city (a considerable tour de force by the way). In contrast to the 13 m sec^{-1} southerly flow discussed previously, the northerly wind speed was only 4 m sec^{-1} at tetroon flight level. Also in this case the influence of the city can be seen in the greater height of the convective elements over the city, as well as by the tendency for descent just upwind of the city, but the city-induced mean upward motion is at most 0.1 m sec^{-1}, far from the 0.3 m sec^{-1} found in the average for strong southerly flow. Furthermore, in Fig. 10 there is no evidence of an upward motion plume extending downwind of the city; in fact, the tetroon floats at a lower level downwind than upwind of the city. Both of these factors support the concept that the bulk of the upward motion found over and downwind of the city in strong southerly flow is due to the city acting as a barrier to this flow, and is not due to a thermal plume brought about by a daytime urban heat island.

As a check on the representativeness of the vertical velocities derived from the tetroon flights, it is useful to consider the vertical velocities measured (at the time of the tetroon flights) on the WKY tower. Because of the precise leveling of the Gill anemometers, the mean vertical velocity estimates on the tower should be unusually accurate.

The left-hand diagram of Fig. 11 shows the variation with height of the vertical velocity on the tower under conditions of southerly (S), westerly (W) and northerly (N) flow, based on the average of mean-hourly values of vertical velocity. The relocation of the lower anemometer from 177 to 44 m toward the end of the experiment accounts for the difference in heights sampled. Noteworthy features include the evidence that the mean upward flow is considerably greater in southerly than in northerly or westerly flow (this is true even when one considers the variation of mean upward motion with wind speed) and the evidence that in southerly flow the mean upward motion increases with height whereas in the other two flows it decreases with height. Both of these features presumably point up the city influence on the vertical air motion.

With the assumption that in southerly flow the tower-derived vertical velocity keeps increasing with height at the indicated linear rate, the average ascending

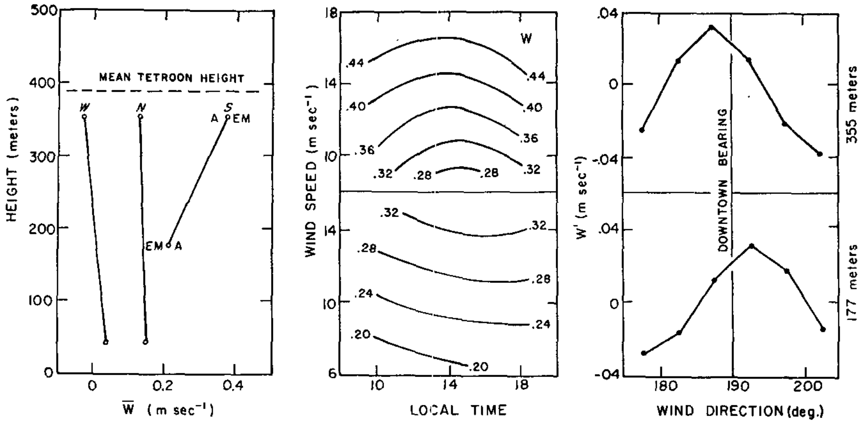

FIG. 11. Variation of mean vertical velocity with height and general wind direction (S = South, W = West, N = North) on the WKY tower (left), where M, A and E indicate mean south-wind values for morning, afternoon and evening; variation of vertical velocity with wind speed and local time at heights of 355 and 177 m in southerly flow (center); and the variation of vertical velocity with wind direction at these levels (right), as obtained from the deviation of the vertical velocity from the mean pattern (center diagram) for given wind directions.

motion at mean tetroon height (390 m) would be 0.41 m sec^{-1}. From the right-hand diagram of Fig. 8 the mean tetroon-derived estimate of ascending motion at the tower location (based on data for the same times) is 0.33 m sec^{-1}. Thus, even after correcting for the restoring force acting on the tetroon, the tetroon seems still to underestimate the mean vertical air motion, although it must be admitted that the approximate agreement is heartening and lends credence to the overall representativeness of the vertical velocity pattern shown in Fig. 8.

The letters M, A, and E in the left-hand diagram of Fig. 11 indicate the mean vertical velocities in morning, afternoon and evening, respectively, of days with southerly flow. Note that the rate of increase of upward motion with height is half as large in the afternoon as in morning or evening, presumably reflecting the increased convection (vertical mixing) in the afternoon. Linear interpolation and extrapolation of the average tower vertical velocities to the mean tetroon heights of 310, 460 and 330 m in morning, afternoon and evening yields mean upward velocities of 0.36, 0.39 and 0.36 m sec^{-1}, respectively. From Fig. 9 the tetroon-derived estimates at the tower location are 0.32, 0.48 and 0.08 m sec^{-1} at these times. In morning and afternoon the comparisons are good, with the tetroons even giving a somewhat larger estimate of the mean ascending motion in the afternoon than do the tower measurements. In the evening, however, the comparison is poor, and as pointed out earlier, this may be due to the tendency for the tetroons to follow sloping isopycnic surfaces at this time.

The middle diagram of Fig. 11 shows the variation with wind speed and time of day of the mean upward velocity at heights of 177 and 355 m on the tower during days with southerly flow. The much greater variation of rising motion with wind speed than with time of day makes it likely that this upward motion results more from a barrier effect of the city than to a thermal effect (in agreement with the results deduced from Fig. 10). Note that at the upper level (at a given wind speed) the upward motion is a minimum in mid-afternoon, whereas at the lower level it tends to be a maximum in mid-afternoon; this contradiction makes difficult any estimation of the thermal contribution to the mean vertical velocity.

It was shown in the left-hand diagram of Fig. 11 that when the tower data are divided according to gross wind direction, the mean upward velocity is much larger when the wind is from the south than when it is from the west or north. This reflects the influence of the city on the vertical air flow, the tower being downwind of the city for southerly flow but not otherwise. The question then arises as to whether subtle changes in southerly flow direction would not be related to changes in mean upward motion, with presumably the maximum upward motion occurring when the wind direction was 190°, i.e., the bearing of city-center from the tower.

In order to isolate the variation of mean upward air motion with wind direction, we have taken the deviation of 1-hr average tower vertical velocities from the mean patterns in the center diagram of Fig. 11, and plotted these deviations as a function of wind direction. The right-hand diagram of Fig. 11 shows at both 177 and 355 m that there is indeed a tendency for the upward motion to be a maximum at approximately the downtown bearing of 190°, with an additional upward motion of about 0.06 m sec^{-1} over that found at bearings of 180° and 200°. The fact that at the upper level the maximum upward motion occurs at a bearing of 188°, and at the lower level at a bearing of 192°, is

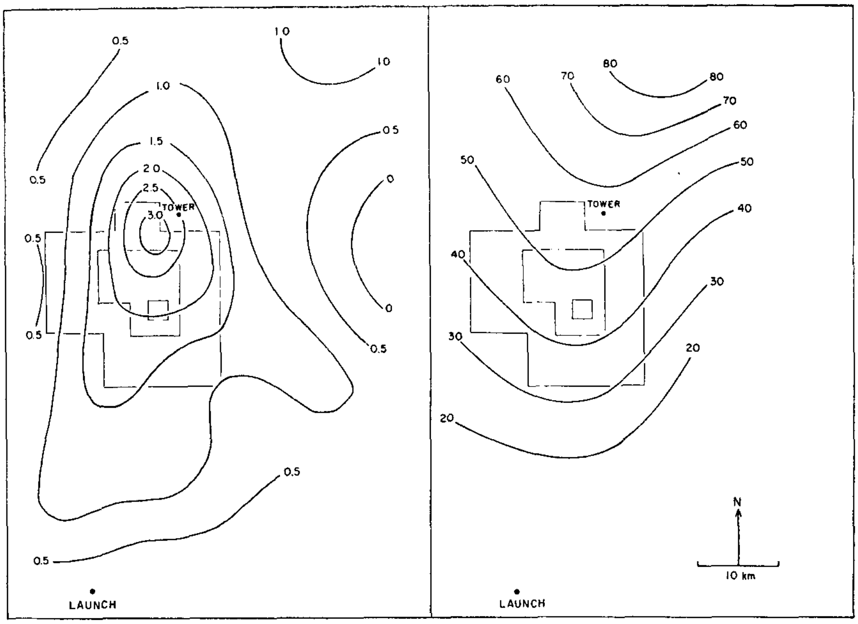

Fig. 12. Smoothed daytime distribution of tetroon-derived longitudinal stress (dyn cm^{-2}) in the Oklamona City area based on Lagrangian oscillations of approximately 1–30 min period (left), and at right the percentage of this stress due to oscillations of approximately 1–10 min period. The tetroons, at an average height of 400 m, were embedded in a mean southerly flow of 13 m sec^{-1}.

probably well within the experimental error of the technique and is of no significance.

6. Urban influence on Reynolds stress

As mentioned in the Introduction, the primary purpose of this experiment was to compare tetroon-derived stress estimates with the longitudinal Reynolds stress obtained from conventional tower measurements. The former stress may be estimated either from the covariance between tetroon vertical and longitudinal eddy velocity or from the covariance between derived air parcel vertical velocity (Sections 5) and tetroon longitudinal velocity, the latter a necessity because it is not possible to obtain realistic estimates of the longitudinal velocity at the position of the air parcel (i.e., at some other location in the vertical).

In order to estimate the spatial or temporal variation in stress, it is necessary to evaluate the eddy-velocity covariance along successive segments of the tetroon trajectories. This was done both by determining the deviation of 30-sec average velocity from 5-min average velocity, providing successive block estimates (at 5-min intervals) of the stress in the Lagrangian period interval 1–10 min, and by determining the deviation of 30-sec average velocity from 15-min average velocity, providing successive block estimates (at 5-min intervals) of the stress in the Lagrangian period interval 1–30 min.

The left-hand diagram of Fig. 12 presents, based on Lagrangian oscillations of approximately 1–30 min period, the smoothed distribution of longitudinal Reynolds stress at a mean height of 400 m in the Oklahoma City area, as determined from the 32 tetroon flights in relatively strong southerly flow. The maximum stress of 3 dyn cm^{-2} is found about 10 km downwind of city-center, and, in general, the stress magnitude appears to be intimately related to building height and density, with evidence for a stress of only about 1 dyn cm^{-2} beyond the city outskirts.

The right-hand diagram of Fig. 12 shows the percentage of this stress due to Lagrangian oscillations of approximately 1–10 min period. It would appear that the city sharply increases the fraction of the stress due to higher frequency oscillations, with the ratio of the stress in the 1–10 min period interval to that in the 1–30 min period interval increasing from 20% upwind of the city to 80% downwind of the city. Presumably, this reflects the tendency of the city to form its own internal boundary layer made up of smaller scale eddies, and hence to shift the burden of the vertical momentum flux also to smaller scale eddies.

The top diagrams of Fig. 13 show the distribution in morning, afternoon and evening (left to right) of the longitudinal Reynolds stress determined from tetroon oscillations of approximately 1–30 min period. In all three cases the maximum stress of ~ 3 dyn cm^{-2} is found more or less 10 km downwind of city center, but the similarity in stress magnitude is somewhat misleading because of the difference in mean tetroon height at those times; i.e., with the given decrease in stress with height, at a specific height the tetroon-derived stress would actually be greater in the afternoon. The relatively large value of the stress in the evening implies

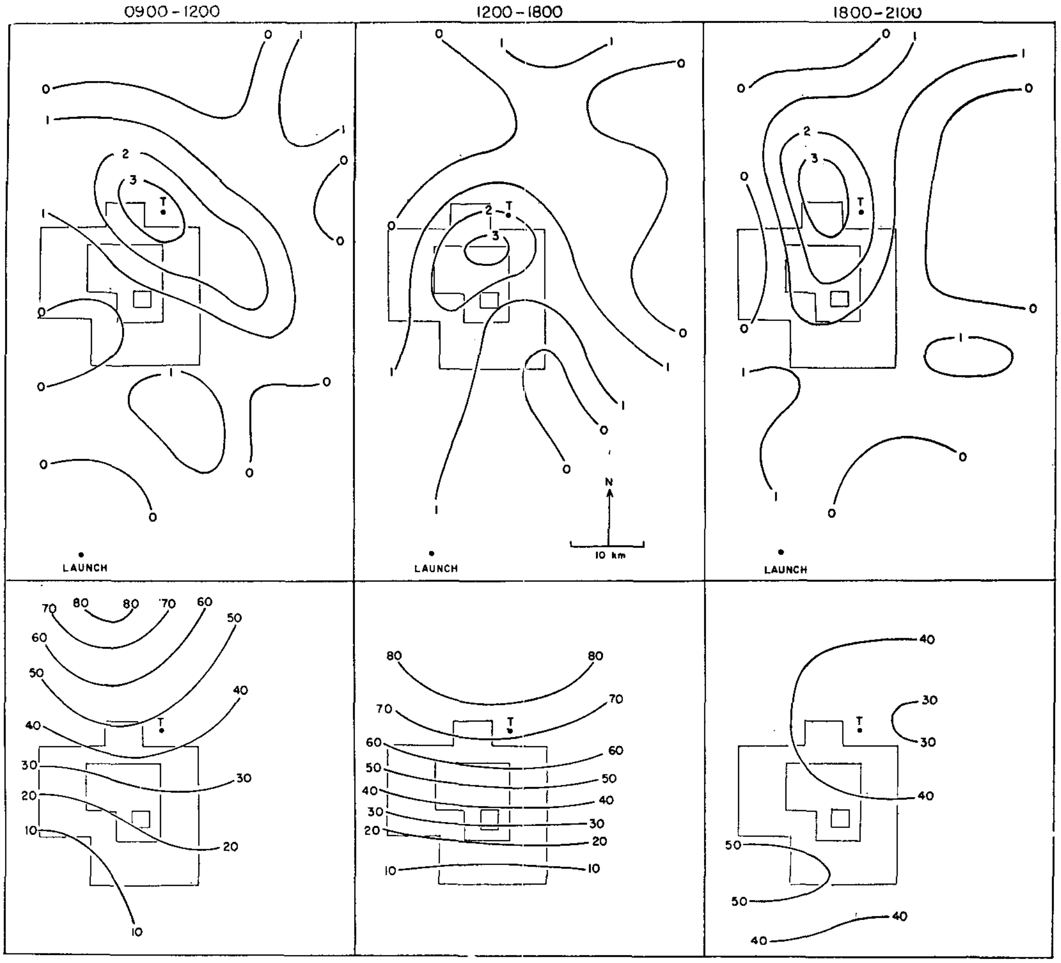

FIG. 13. Smoothed distribution of tetroon-derived longitudinal stress (dyn cm^{-2}) based on Lagrangian oscillations of approximately 1–30 min period during the morning (left), afternoon (center) and evening (right) of days with strong southerly flow (top), and at bottom the percentage of this stress due to oscillations of approximately 1–10 min period.

that also in stable conditions there is a mechanism by which the city can induce large downward transports of momentum.

The bottom diagrams of Fig. 13 show the percentage of the above stress due to Lagrangian oscillations of approximately 1–10 min periods. The effect of the city in increasing the percentage of the stress associated with higher frequency oscillations is most pronounced in the afternoon and is not at all apparent in the evening. This result would follow from the extent to which the tetroons are shielded from surface roughness elements by the atmospheric stability in the evening (Fig. 3).

As a check on the representativeness of the stress derived from the tetroon flights, we consider the stress values measured on the WKY tower. The left-hand diagram of Fig. 14 shows the variation with height of the longitudinal stress on the tower under conditions of southerly (S), westerly (W) and northerly (N) flow, as determined by averaging hourly-mean values of the stress. Noteworthy features include the evidence that the stress is considerably greater in southerly flow than in northerly or westerly flow (this is true even taking into account the variation of stress with wind speed), and the evidence that in southerly flow the stress decreases with height more rapidly than in the other two flows. Both of these features presumably point up the city influence on the stress.

With the assumption that in southerly flow the tower stress keeps decreasing with height at the indicated linear rate, the average stress at mean tetroon height (390 m) would be 3.6 dyn cm^{-2}. From the left-hand diagram of Fig. 12, the mean tetroon derived stress estimate at the tower location (based upon data for the same times) is 2.5 dyn cm^{-2}. Thus, it would appear that on the average the tetroons are underestimating the stress by about 30%. The letters M, A, and E in the left-hand diagram of Fig. 14 represent the mean longitudinal stress in morning, afternoon and evening of days with southerly flow. Linear interpolation and extrapolation of the above tower stresses to

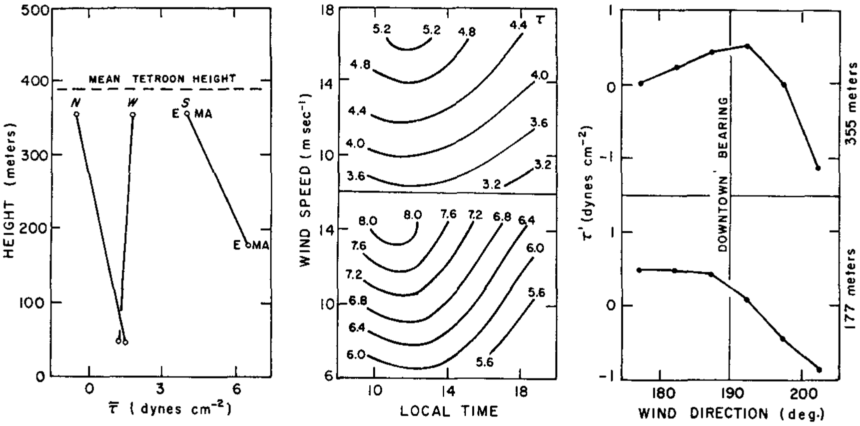

FIG. 14. As in Fig. 11 except for the mean longitudinal stress.

the mean tetroon heights of 310, 460 and 330 m at those times yields mean stress values of 4.9, 3.1 and 3.5 dyn cm^{-2}. From Fig. 13 the tetroon-derived estimates at the tower location are 3.3, 2.0 and 2.5 dyn cm^{-2}, respectively. At all three times the tetroon stress is approximately 70% of the tower stress, adding support to the representativeness of this particular value.

The middle diagram of Fig. 14 shows the variation with wind speed and time of day of the longitudinal stress at heights of 177 and 355 m on the tower during days with southerly flow. As expected, there is a strong tendency for stress to increase with wind speed. There is also some tendency, more obvious at the lower level, for the stress maximum (at a given wind speed) to occur near midday, i.e., an increase in convection is usually associated with an increase in stress, as also deduced from the tetroon flights. Flight 36 is of particular interest in this regard. The top diagram of Fig. 10 shows that, despite a north wind of only 4 m sec^{-1}, there is an increase in stress above the city of about 2 dyn cm^{-2}, nearly as large as that found in the strong southerly flow. However, in the light-wind case there is no cross-city increase in the fraction of the stress due to oscillations of 1–10 min period, although this may be partly due to the greater mean height of this flight in comparison with the flights in southerly flow. Thus, it would appear that in light-wind cases the increase in stress above the city is associated mainly with enhanced thermal convection, whereas in strong-wind cases the increase in stress is associated more with an enhancement of the "mechanical" turbulence.

The right-hand diagram of Fig. 14 shows the variation of tower stress with wind direction, obtained in the same way as was the mean vertical velocity. At the upper tower level the stress is a maximum for winds blowing directly from downtown, but at the lower level the stress is a maximum for winds from due south. Thus, at the lower level it would appear that the residential area about 2 km directly south of the tower has a greater influence on the stress than the downtown area about 10 km to the south-southwest of the tower. Note that this is not the result obtained in the case of the vertical velocities, but it is not *a priori* obvious that the portion of the city mainly affecting the mean flow at a point need be the same as the portion mainly affecting the eddy fluxes at a point. Interesting in this regard are Pasquill's (1972) estimates of the distances and dimensions of the upwind area dominantly affecting point measurements of wind structure at a given height.

As indicated previously, our preliminary estimate of the ratio of tetroon-derived stress and actual (tower) stress is about 0.7, but it must be admitted that there is some uncertainty in this ratio because a considerable portion of the stress appears to be associated with oscillations $>$30-min period. Moreover, if the tetroon stresses are to be of real use, it has to be shown that there is a significant correlation between individual values of the stress obtained by the two techniques. If, for the 32 cases in strong southerly flow, we evaluate the tetroon stress for the 30-min period when the tetroon was closest to the tower, and normalize the tetroon stress to a height of 355 m by assuming a linear variation of stress with height, then a correlation of 0.48 (significant at the 5% level) between tetroon and tower stress results from direct use of the tetroon vertical velocities and a correlation of 0.44 from use of the derived "air parcel" vertical velocities. On the basis of the regression line, the expression.

$$\text{Actual stress} = 3.9 + 1.7\,(\text{tetroon stress} - 2.8), \quad (1)$$

where the stresses are measured in dynes per square centimeter, is the most appropriate one.

While Eq. (1) represents our best estimate of the relation between tetroon-derived stress and actual stress, with a correlation of only 0.48 one must expect that on occasion an individual tetroon flight gives a poor estimate of the stress magnitude. The extent to which this is due to tetroon positioning errors is uncertain, but certainly any tetroon data used for this purpose should be carefully screened to ensure that such errors are held to a minimum (the screening may not have been careful enough in the present instance). With the possibility of averaging data from a number of flights, and care in data acquisition and reduction, it is believed the tetroon-transponder system can provide highly useful information concerning the spatial variation of stress in urban and other areas.

7. Conclusion

The following are some of the significant points brought out by the foregoing analysis of daytime tetroon flights across Oklahoma City at heights near 400 m on days with relatively strong (13 m sec^{-1}) southerly flow at this level:

1) The frictional trajectory turning toward low pressure induced by the city amounts to about 5° on the average, with the turning most pronounced in the morning (10°), and practically non-existent in the evening due to the shielding of urban roughness elements by the stable atmosphere.

2) There is a weak tendency for the air to flow around the city in afternoon and evening, apparently because the barrier effect of the city is not completely compensated by vertical motion.

3) In the mean, a plume of ascending air motion is found to extend from just upwind of city-center to more than 30 km downwind of the center, but descending motion prevails over other city outskirts. This ascending motion is more likely caused by the barrier effect of the city rather than any thermal effect of the city (daytime urban heat island), but this remains to be clarified.

4) The indicated average ratio of tetroon-derived stress and actual (tower) stress is 0.7, and the correlation between individual hourly stress estimates by the two techniques is 0.48. However, these values are still somewhat uncertain owing to the considerable portion of the longitudinal stress due to oscillations of period >30 min.

5) The influence of the city on longitudinal stress appears clear-cut and large, with the tetroon-derived stress 10 km downwind of city center at least 2 dyn cm^{-2} larger than over the surrounding countryside. Except in the evening, the city sharply increases the fraction of this stress associated with the smaller scale eddies.

Finally, on the basis of these data it is apparent that the stress measured on towers downwind of urban areas cannot be considered representative of the stress over the surrounding countryside, and, in general, because of the above evidence for large spatial variations in stress, the significance of the stress measured at *any* particular location must be carefully considered. The tetroon-transponder system represents a feasible way of examining spatial variations in stress, and should prove useful in mapping the stresses associated with natural and man-made objects and in estimating the representativeness of stress estimates at particular tower locations.

Acknowledgments. This tetroon experiment would not have been a success without the able assistance of G. White, L. Wendell, G. Start and J. Young in the radar, A. Gairrusso at the launch site, and H. Boen in the subsequent data reduction. Special thanks are due G. White for keeping the sensitive radar in good running order. The tower data were obtained under the supervision of G. Herbert, and data reduction was mainly accomplished by H. Boen and A. Giarrusso. Most of the tedious hand calculations were performed by M. Hodges, who also did the drafting.

REFERENCES

Angell, J. K., D. H. Pack, C. R. Dickson and W. H. Hoecker, 1971: Urban influence on nighttime airflow estimated from tetroon flights. *J. Appl. Meteor.*, **10**, 194–204.

——, ——, L. Machta, C. R. Dickson and W. H. Hoecker, 1972: Three-dimensional air trajectories determined from tetroon flights in the planetary boundary layer of the Los Angeles Basin. *J. Appl. Meteor.*, **11**, 451–471.

Chandler, T. J., 1960: Wind as a factor in urban temperatures. *Weather*, **15**, 204–213.

Davidson, B., 1967: A summary of the New York urban air pollution dynamics research program. *J. Air Pollution Control Assoc.*, **17**, 154–158.

Druyan, L. M., 1968: A comparison of low-level trajectories in an urban atmosphere. *J. Appl. Meteor.*, **7**, 583–590.

Findlay, B. F., and M. S. Hirt, 1969: An urban-induced mesocirculation. *Atmos. Environ.*, **3**, 537–542.

Graham, I. R., 1968: An analysis of turbulence statistics at Fort Wayne, Indiana. *J. Appl. Meteor.*, **7**, 90–93.

Hass, W. A., W. H. Hoecker, D. H. Pack and J. K. Angell, 1967: Analysis of low-level constant volume balloon (tetroon) flights over New York City. *Quart. J. Roy. Meteor. Soc.*, **93**, 483–493.

Hoecker, W. H., 1973: Tetroon drag coefficients from experimental free-flight data. *J. Appl. Meteor.*, **12**, 1062–1065.

——, and S. R. Hanna, 1971: Computed response of tetrahedral constant-density balloons to vertical sinusoidal and helical air motions. NOAA Tech. Memo. ERL ARL-31, 31 pp.

Holmboe, J., G. E. Forsythe and W. Gustin, 1945: *Dynamic Meteorology*. New York, Wiley, 378 pp.

Pasquill, F., 1972: Some aspects of boundary layer description. *Quart. J. Roy. Meteor. Soc.*, **98**, 469–494.

Pooler, F. J., 1963: Airflow over a city in terrain of moderate relief. *J. Appl. Meteor.*, **2**, 446–456.