

## Urban Influence on Nighttime Airflow Estimated from Tetroon Flights<sup>1</sup>

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### ABSTRACT

Constant-volume balloon (tetroon) flights tracked by radar across Columbus, Ohio, in March 1969, illustrate the effect of a city on the nighttime airflow at heights of 100–200 m. On the average, the urban influence on wind direction is small at a height of 100 m, but an anticyclonic turning of 10° is observed at 200 m. The anticyclonic turning is greater under inversion than under lapse conditions and greater after midnight than before; it appears to result both from an increase in the frictional force due to increased vertical mixing and from a mesoscale high pressure system formed aloft as the result of the warmer temperatures within the city. The decrease in wind speed across the city averages nearly 20% of the upwind speed under lapse conditions but is very small under inversion conditions. In both cases the region of maximum deceleration tilts downwind with height. The average upward air motion exceeds 4 cm sec<sup>-1</sup> above the down-town area under light wind conditions, and increases to 1 m sec<sup>-1</sup> as the wind speed approaches 20 m sec<sup>-1</sup>. In the case of strong winds, alternating regions of upward and downward motion occur downwind of the city.

### 1. Introduction

There have been a number of studies dealing with temperature differences between rural and urban areas (e.g., Sundborg, 1950; Duckworth and Sandberg, 1954; DeMarrais, 1961; Chandler, 1967; Bornstein, 1968; Clarke, 1969; and others), but relatively few studies of airflow in the vicinity of cities. In recent years extensive surface wind analyses for urban areas have been presented by Chandler (1960), Pooler (1963) and Davidson (1967); the work of Pooler was noteworthy in showing a nighttime drift of air toward downtown Louisville, Ky., when the synoptic-scale pressure gradient was small. There are even fewer data on the airflow above the surface boundary layer in urban areas; although Graham (1968) has shown that at Fort Wayne, Ind., at a height of 60 m during the evening hours, the wind is backed by 10° and reduced in speed by one-third from its value at the same height upwind of the city. Druyan's (1968) comparisons between tetroon trajectories at a height of a few hundred meters over New York City and trajectories derived from surface wind data indicate that the assumption of an Ekman wind profile is often a poor one over a city. In general, however, there is a sparsity of reliable wind information in urban areas due to the difficulties involved in obtaining representative wind statistics within the built-up areas of a city.

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One way of obtaining wind information above the surface boundary layer is to fly constant-volume balloons (tetroons) across the cities. This paper reports on nighttime wind information obtained in this way at Columbus, Ohio, between 12 and 23 March 1969. The tetroon experiment was part of a larger experiment mounted by the Air Resources Laboratories Division of Meteorology (National Air Pollution Control Association), which had as its purpose the investigation of the influence of Columbus on mesoscale wind and temperature fields, particularly at night. Included in this larger measurement program were vertical temperature soundings obtained by helicopter and simultaneous wind soundings obtained by double-theodolite pibal observations at sites within and on the outskirts of the city. Unfortunately, since nearly one-half of the successful tetroon flights took place at a time when vertical sounding data were not obtained, the vertical and horizontal sounding data are not easily combined in a systematic fashion. This paper deals mostly with the data obtained from the tetroon flights, although the helicopter-derived temperature variation with height is used as background information.

### 2. Procedures

The solid lines in Fig. 1 represent an approximate partition of Columbus according to building height. Zone 1 represents downtown Columbus with a mean building height of ~30 m, zone 2 less built-up commercial and industrial areas with a mean building height of ~15 m, zone 3 residential areas with a mean building

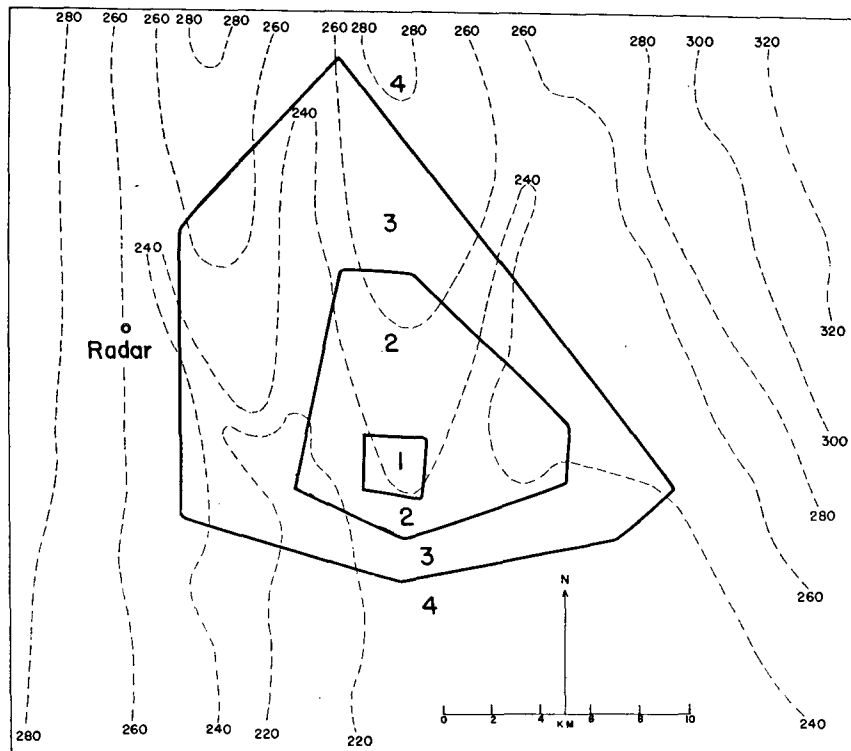


FIG. 1. Map of the Columbus, Ohio, area showing the location of the M-33 tracking radar, the partitioning (solid lines) of the city according to building type (1, downtown area; 2, other commercial and industrial areas; 3, residential area; 4, rural area), and the terrain height in meters MSL (dashed lines).

height of  $\sim 7$  m, and zone 4 rural areas. The M-33 radar used to track the tetroons was located on an overpass on an uncompleted portion of the Columbus "beltway," 12 km west-northwest of downtown. Terrain height above sea level is shown in Fig. 1 by dashed lines at 20 m intervals. North of downtown, north-south oriented river valleys alternate with ridges, resulting in irregular terrain height differences of nearly 30 m, whereas to the south the terrain is bowl-shaped.

The tetroons, with transponders attached, were released  $\sim 16$  km upwind from downtown. Upwind launches were made possible by outfitting a moving van as a tetroon inflation shelter. The transponders ensure that the tetroons can be tracked at very low heights without interference from ground clutter, and continuous monitoring of the radar magnetron power permitted unusually precise tetroon positioning. Tetroon range, azimuth and elevation angle data were obtained at 10-sec intervals, from which 1-min average values of wind direction, wind speed, and approximate vertical velocity were determined.

Fig. 2 shows the mean helicopter-derived temperature variation with height over downtown and the outskirts of the city (when available) as the tetroons moved across the city from the northwest and from the southwest or southeast before and after midnight. Obvi-

ously, at this time of year, the atmospheric stability in the lowest 150 m is considerably less when the wind is from the north than when it is from the south. In the following we frequently divide the tetroon data on the basis of wind direction, or, according to Fig. 2, on the basis of low-level stability. In so doing we denote by "lapse" the stability conditions when the wind is from the northwest and by "inversion" the stability conditions when the wind is from the southwest or southeast. It should be clearly understood that by "lapse" we mean only that the temperature decreases slightly with height above the city, not that the temperature decrease exceeds the dry adiabatic value.

Although tetroon-derived velocities are available at 1-min intervals, we have used averages over 10-min intervals since our purpose was that of studying the gross influence of the city on airflow. These 10-min average changes in wind direction and speed are transformed into 4-km average changes through the use of the mean wind speed along the flight. Then, the spatial changes obtained from different trajectories on different nights, together with the vertical velocities, are plotted on maps, and average values of the parameters determined for 4-km intervals upwind and downwind of downtown. In combining data obtained on different nights, we implicitly assume steady-state conditions.

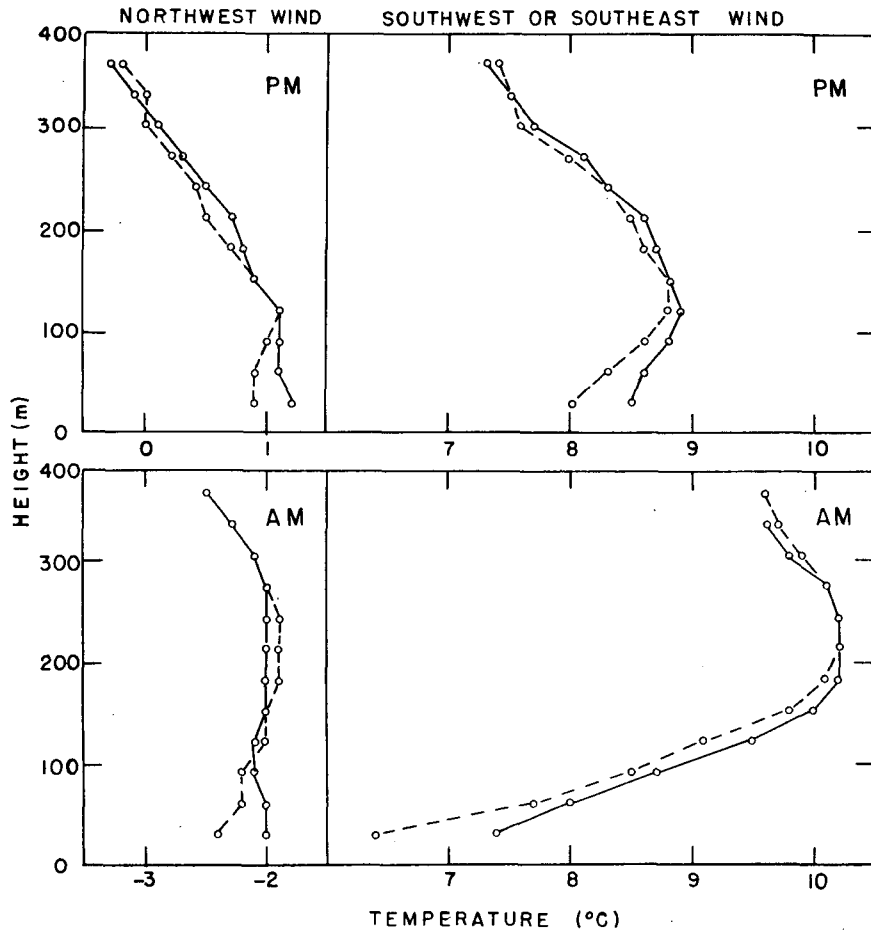


FIG. 2. Mean helicopter-derived variation of temperature with height over downtown (solid lines) and over the city outskirts (dashed lines) before and after midnight for winds from the northwest, or from the southwest and southeast, during the experiment.

**3. Wind direction change across the city**

Examples of sequential tetron trajectories across Columbus at height near 150 m on two separate nights are presented in Fig. 3. The tetron positions are indicated by dots at 10-min intervals, and the adjacent numbers represent wind direction change in degrees per 10 min. There is a tendency for the anticyclonic turning (negative numbers) to be a maximum over downtown, as shown by the dashed lines. In the case of flight 21, which passed directly over downtown at 1900 local time, an anticyclonic turning of 10° in 10 min just upwind of downtown is followed by a cyclonic turning of 10° in 10 min just downwind of downtown, with this wave-shaped oscillation set up by the city continuing downwind in damped form. Flight 71 exhibits a similar tendency, but the cyclonic turning occurs further downwind.

Let us examine the change in wind direction over the city on a statistical basis. The top diagram of Fig. 4 shows the average trajectory curvature (degrees per 4 km) as a function of height above ground, and upwind

and downwind distance from downtown, based on 43 tetron flights across the city (zones 1, 2 and 3 in Fig. 1) on 10 different nights with "normal" weather conditions. In this and subsequent figures, negative abscissa values signify upwind distance from downtown and positive values downwind. Of importance is the observation that the anticyclonic trajectory curvature is a maximum almost directly above downtown and that this curvature goes to zero near the city outskirts. This represents solid proof that the anticyclonic trajectory curvature is induced by the city and is not the result of synoptic-scale circulations or of inertial oscillations resulting from the decoupling of earth and atmosphere due to the increased stability at night. Note that the anticyclonic trajectory curvature increases with height from a small value at 100 m to a maximum of about  $2.5^\circ (4 \text{ km})^{-1}$  above 200 m.

The bottom diagram of Fig. 4 shows the total wind direction change across the city obtained by summing the wind direction changes at 4-km intervals in the top diagram. On the average, the influence of the city on

wind direction is a maximum 10 km downwind of downtown at heights above 200 m, where the wind has veered by 10° from its direction upwind of the city. Longer tetron trajectories are needed to determine where the city effect disappears, but it appears to be at least 30 km downwind of downtown.

As an aid in determining the cause of the anticyclonic turning above the city, it is useful to divide the data into four categories depending upon whether the trajectories were obtained under lapse or inversion conditions before or after midnight. Fig. 5 shows the total wind direction change across the city for these categories. The maximum anticyclonic wind shift (>20°) is found at a height near 200 m under inversion conditions after midnight, or at the time when the heat island effect in the lowest 200 m is most pronounced (Fig. 2). Once again the rate of change of direction is a maximum over downtown so that there is every evidence that the turning is city-induced. After midnight under lapse conditions the turning is about half as great and appears to occur slightly further upwind. In both cases there is a rapid increase in anticyclonic turning between heights of 100 and 200 m.

Anticyclonic turning of the wind is not so evident before midnight. Under inversion conditions there is negligible wind direction change upwind of downtown,

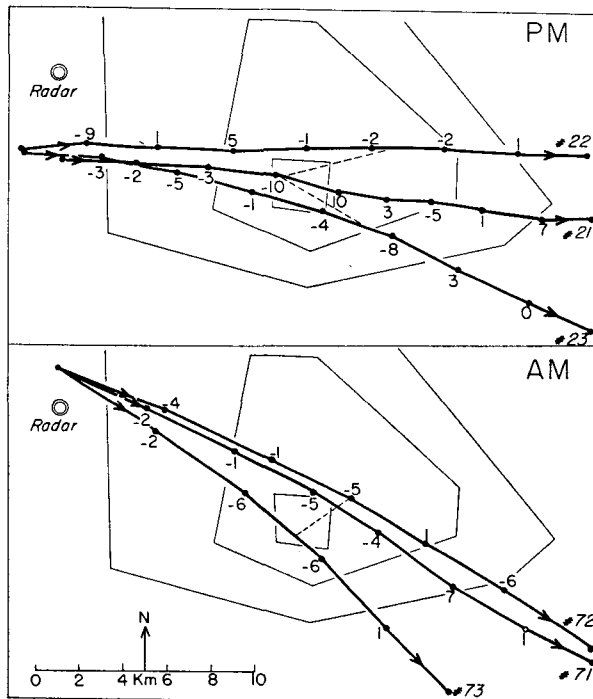


FIG. 3. Examples of sequential tetron trajectories across the city at a mean height of 150 m under lapse conditions before midnight (top) and after midnight (bottom). The dots indicate tetron positions at 10-min intervals, the adjacent numbers wind direction changes [deg (10 min)<sup>-1</sup>] along the trajectories (negative numbers signify anticyclonic turning). The dashed lines connect regions of maximum anticyclonic turning.

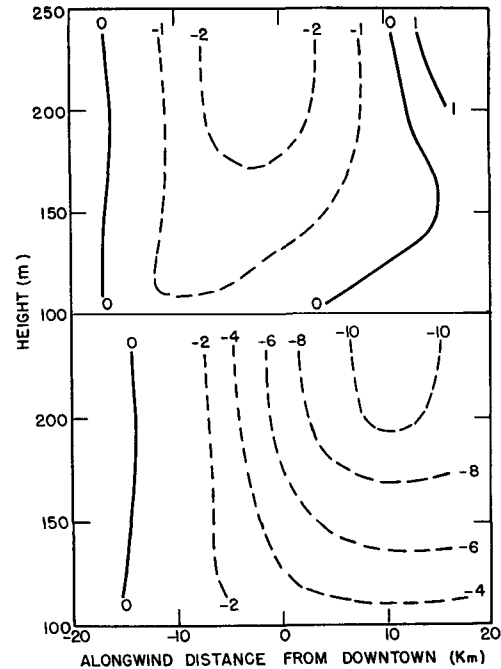


FIG. 4. Average trajectory curvature [deg(4 km)<sup>-1</sup>] determined from 43 tetron flights across the city (top), and the total wind direction change (deg) from the value 16 km upwind (bottom). Negative numbers and dashed lines indicate anticyclonic curvature or turning. Negative abscissa values signify upwind distance from downtown, positive abscissa values downwind distance from downtown.

and the slight anticyclonic turning downwind of downtown appears to represent the incipient stages of the larger turning occurring after midnight. Before midnight under lapse conditions there is a gentle anticyclonic turning which is invariant with height between 100 and 200 m, suggesting a different cause for the turning.

It is also of interest to compare the turning along those flights that passed over downtown (zone 1 in Fig. 1) and those that passed over zones 2 and 3 to either side of downtown. This can only reasonably be done for the lapse cases because of the few flights that passed over downtown under inversion conditions (the center of the city was harder to "hit" under inversion conditions). Fig. 6 shows that the anticyclonic turning was more than twice as large along the flights that passed over downtown, and apparently extended to lower heights. This provides additional evidence that the turning is city-induced. Note that the cyclonic turning downwind of the city center along flights 21 and 71 (Fig. 3) does not show up in the average. This is because the cyclonic turning, when it does occur, is found at different distances downwind of downtown, as illustrated in Fig. 3.

Fig. 4 indicates that, on the average, the anticyclonic turning over the city disappears at a height near 100 m. The question arises as to whether, at lower heights, cyclonic turning would occur. The lowest mean height of any flight was 80 m, and Fig. 7 shows that this flight,

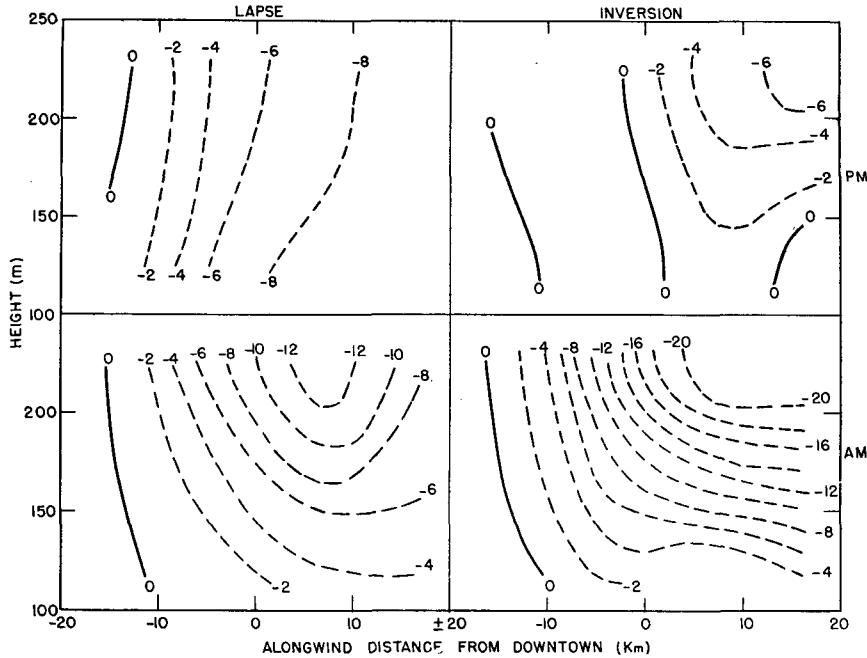


FIG. 5. Total change in wind direction (deg) from the value 16 km upwind of downtown determined from flights across the city under lapse and inversion conditions before and after midnight. Negative numbers and dashed lines indicate anticyclonic turning.

under inversion conditions after midnight, turns cyclonically by  $7^\circ$  as it passes 4 km to the west of the downtown, in fair agreement with the results of Graham (1968). There is also a hint in this trajectory of the indraft

toward city center found by Pooler (1963) in his study of surface winds, but it is apparent that the tetroons will have to be flown extremely low if this indraft is to be delineated with confidence.

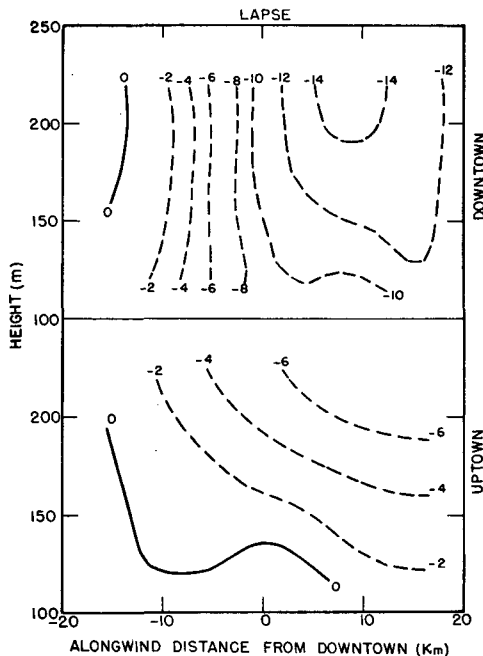


FIG. 6. Total change in wind direction (deg) from the value 16 km upwind of downtown determined from flights passing over downtown (top) and over less built-up areas of the city (bottom) under lapse conditions. Negative numbers and dashed lines indicate anticyclonic turning.

#### 4. Possible causes of anticyclonic turning over the city

The cause (or causes) of the anticyclonic turning observed over the city is still somewhat controversial. We have examined the possibility that the turning is brought about by 1) ascending motion in a wind field veering with height, 2) a change in frictional drag due to enhanced vertical mixing over the city, and 3) the formation of a mesoscale high due to warmer temperatures within the city (urban heat island effect).

If the variation of wind with height in the urban boundary layer is in accord with the Ekman spiral, an ascending air parcel (or tetroon) would turn anticyclonically and a descending air parcel cyclonically as the parcel mixed with and attained the momentum of its new environment. On the average the wind did veer with height during the day at Columbus (based on the noontime pibal at the airport), but we as yet have no data on the nighttime variations. In any event, the correlations between tetroon-derived vertical velocity (Fig. 12) and anticyclonic curvature (Fig. 5) were unimpressive and this makes it unlikely that upward motion in a wind field veering with height is the primary cause of the anticyclonic turning.

In order to estimate the possible effects on trajectories of a change in frictional drag between rural and urban

areas, we have estimated the frictional force over the city from values of acceleration and Coriolis force obtained from the tetroons, and the pressure gradient force obtained, on the hour, from the sea level pressure differences between the Weather Bureau stations at Toledo, Ohio, and Huntington, W. Va., and Cleveland and Cincinnati, Ohio. The wind, and hence the Coriolis force, was determined from the tetroon displacement over the half-hour interval centered on the hour, while the individual acceleration was determined as the difference in tetroon velocity for the half-hour interval before and after the hour. With the assumption of negligible thermal wind between the surface and 100–200 m, the frictional force was then evaluated by making the vector sum of the three specific forces equal to the vector acceleration.

Fig. 8 shows the orientation and magnitude of the various forces, obtained by averaging the results from individual trajectories at heights of about 100 and 200 m under lapse and inversion conditions. It is apparent that the individual acceleration has the same magnitude as the specific pressure gradient and Coriolis force and cannot be neglected in a study of this sort. The frictional force, derived as the residual of other forces each of which is partly in error, may of course be considerably in error, but to a first approximation its magnitude appears to be similar to that of the other forces. In all four examples presented in Fig. 8 the frictional force is basically directed opposite to the wind, but with a component in the direction of the Coriolis force. An increase in the magnitude of this latter component between rural and urban areas would result in increased anticyclonic turning of the trajectories passing over the city, and some increase would certainly be expected due to the increased vertical mixing over the city (Fig. 11). In fact, it is interesting to note, with the given values of the Coriolis and pressure gradient forces in Fig. 8, that if anticyclonic turning had *not* occurred over Columbus, that is, no component of  $\dot{\mathbf{V}}$  in the direction of  $\mathbf{C}$ , the derived frictional force would have had a component directed opposite to the Coriolis force, an orientation incompatible with vertical mixing in an Ekman layer. Thus, it is plausible that some of the anticyclonic turning observed over the city, at least under lapse conditions, is due to an increase in the frictional force brought about by increased vertical mixing over the city. It is not likely, however, that this effect would explain most of the anticyclonic turning observed under inversion conditions or the increase in turning with height.

If an urban heat island is present, the higher temperature in the city in comparison with the surrounding countryside would cause a low pressure system to form near the surface and a high pressure system to form at greater heights, with ascending air motion over the city (observed in Fig. 12) providing the connecting link between slight inflow near the surface and slight outflow

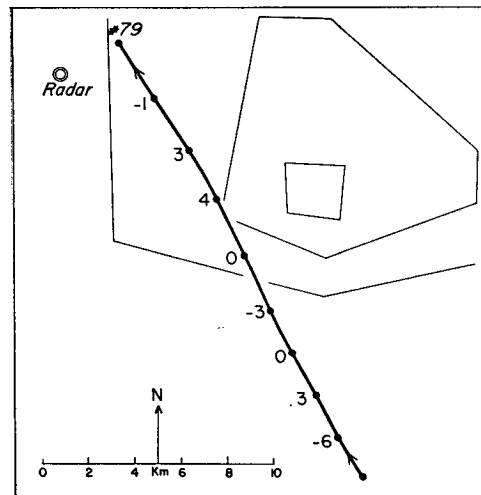


FIG. 7. Trajectory of flight 79 at a mean height of 80 m. The dots indicate tetroon positions at 10-min intervals, and the adjacent numbers wind direction changes [deg (10 min)<sup>-1</sup>] along the trajectory (negative numbers signify anticyclonic turning).

aloft. The anticyclonically and cyclonically curved isobars would induce anticyclonically and cyclonically curved trajectories if the airflow followed the isobars with some fidelity, and evidence that such is the case has already been presented, including 1) the cyclonic turning along flight 79 at a height of 80 m (Fig. 7), 2) the

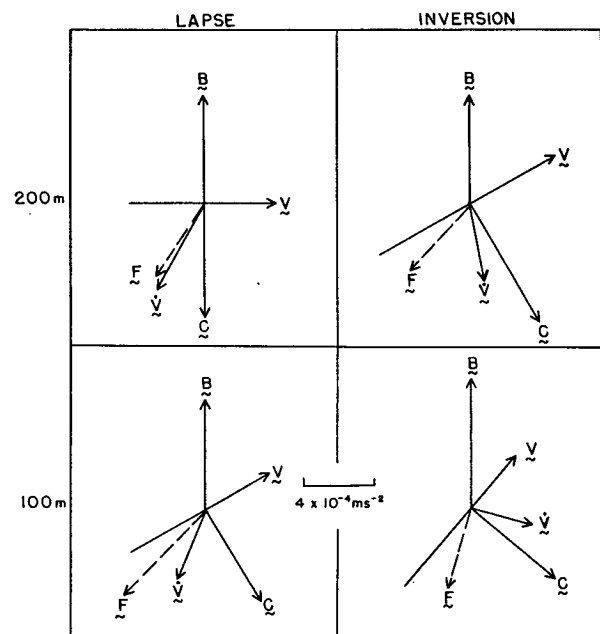


FIG. 8. Balance of specific pressure gradient force ( $\mathbf{B}$ ), specific Coriolis force ( $\mathbf{C}$ ), tetroon-derived individual acceleration ( $\dot{\mathbf{V}}$ ) and derived specific frictional force ( $\mathbf{F}$ ), in relation to tetroon velocity  $\mathbf{V}$ , under lapse and inversion conditions at heights near 100 and 200 m. All force parameters are evaluated in the horizontal plane; the specific force scale is given at center bottom.

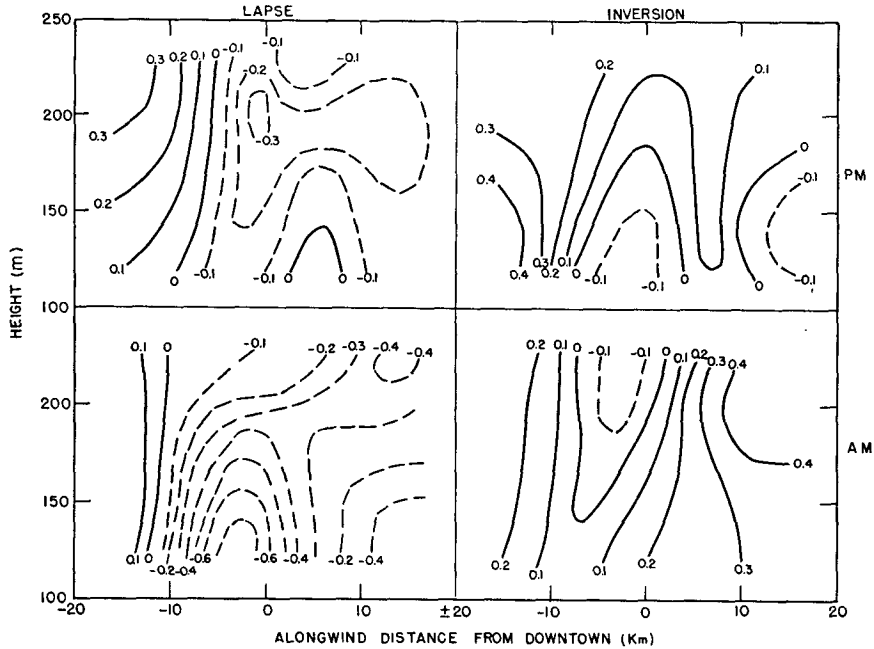


FIG. 9. Spatial wind acceleration [ $m\ sec^{-1}\ (4\ km)^{-1}$ ] determined from flights passing across the city under lapse and inversion conditions before and after midnight. Negative numbers and dashed lines indicate deceleration.

increase in anticyclonic turning with height above 100 m after midnight (Fig. 5), and 3) the greater anticyclonic turning after midnight than before midnight observed in this same figure.

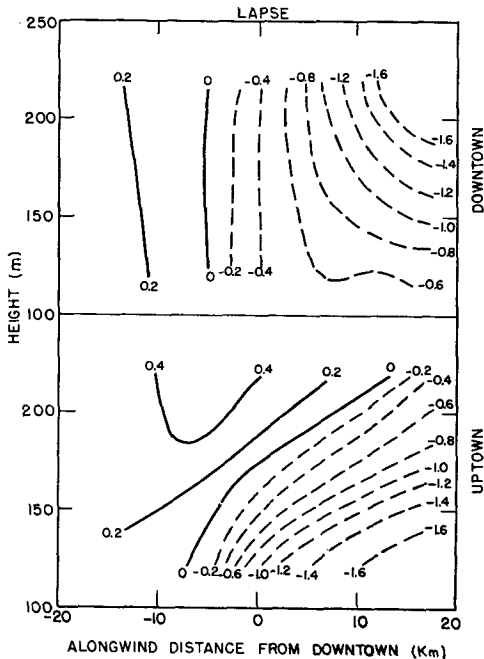


FIG. 10. Total change in wind speed ( $m\ sec^{-1}$ ) from the value 16 km upwind of downtown, determined from flights passing over downtown (top) and over less built-up areas of the city (bottom) under lapse conditions. Negative numbers and dashed lines indicate wind speed decrease.

Let us see if the magnitude of the anticyclonic turning above the city after midnight under inversion conditions can reasonably be explained by the urban heat island effect. Fig. 5 suggests that the trajectory curvature, and hence (with our assumption) the isobaric curvature, is negligible at heights near 100 m. According to the lower right-hand diagram of Fig. 2, the temperature excess above the city between 100 and 200 m averages 0.25C; based on the hydrostatic equation, this would lead to a pressure excess above the city at a height of 200 m of 0.01 mb. We assume this pressure excess goes to zero 10 km from downtown. Since we do not know the extent to which the flow is geostrophic or gradient on such a small scale, let us evaluate the trajectory turning resulting from the two extremes of geostrophic flow and Eulerian flow (pressure gradient force balanced by the acceleration). With the given urban pressure gradient of  $0.01\ mb\ (10\ km)^{-1}$  and an ambient geostrophic wind of  $10\ m\ sec^{-1}$ , the assumption of geostrophic flow yields an anticyclonic trajectory turning of  $15^\circ$  whereas the assumption of Eulerian flow yields a turning of only  $2^\circ$ . The actual anticyclonic turning due to the heat island effect presumably lies somewhere between these two extremes, and thus the heat island appears to play a fairly important role in causing the observed anticyclonic turning of the trajectories over the city, at least under inversion conditions after midnight.

In summarizing this section, it is hypothesized that under lapse conditions before midnight (upper left-hand diagram of Fig. 5) most of the anticyclonic turning is caused by an increase in the frictional force due to enhanced vertical mixing over the city, whereas under

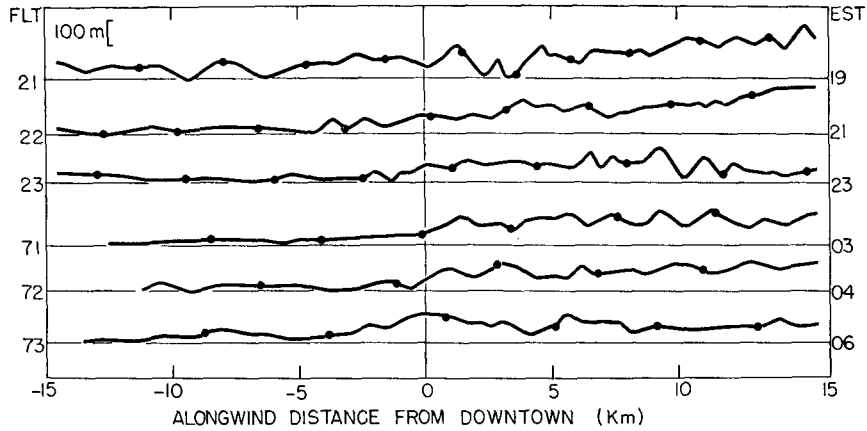


FIG. 11. Tetron height variation along the trajectories of Fig. 3. The dots indicate tetron positions at 10-min intervals, with the flight number indicated at left, the local time of the flight at right, and the height scale at upper left.

inversion conditions after midnight (lower right-hand diagram of Fig. 5) most of the turning is due to anti-cyclonic curved isobars associated with the urban heat island effect. The other two diagrams of Fig. 5 presumably illustrate nearly equal contributions from both effects.

**5. Wind speed change across the city**

The spatial rate of change of wind speed across the city under lapse and inversion conditions before and after midnight is shown in Fig. 9. In general, the region

of maximum deceleration is found just upwind of downtown, but there is a downwind tilt of this region, particularly under lapse conditions. The deceleration is much more pronounced under lapse than inversion conditions; indeed, in the latter case, the small region of deceleration is superimposed on an overall acceleration, perhaps associated with the rise in terrain height as the air moves northward.

Under lapse conditions before midnight and inversion conditions after midnight, the maximum deceleration does not occur at the lower level. Such a tendency is more strongly brought out in Fig. 10, which shows the

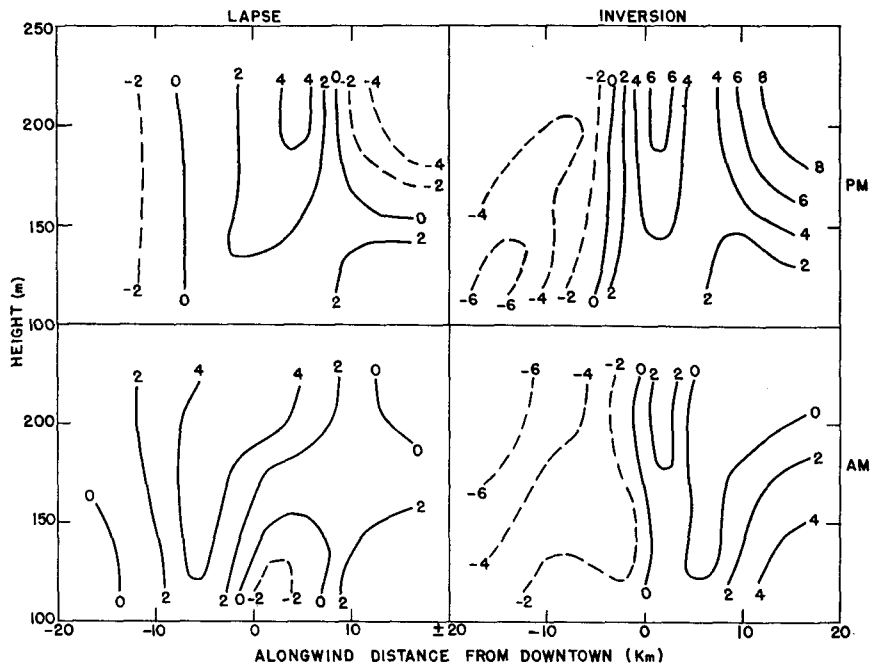


FIG. 12. The vertical velocity ( $\text{cm sec}^{-1}$ ) determined from flights passing across the city under lapse and inversion conditions before and after midnight. Positive numbers and solid lines indicate upward motion.



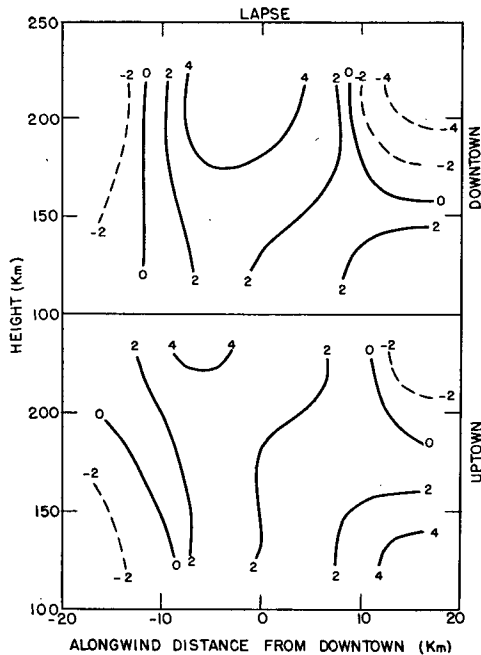


FIG. 13. The vertical velocity ( $\text{cm sec}^{-1}$ ) determined from flights passing over downtown (top) and over less built-up areas of the city (bottom) under lapse conditions. Positive numbers and solid lines indicate upward motion.

total change in wind speed under lapse conditions along flights passing over downtown and to either side of downtown. The maximum decrease in wind speed (amounting to at least  $1.6 \text{ m sec}^{-1}$  or about 20% of the upwind speed) is found at heights near 200 and 100 m, respectively. The observation that the maximum deceleration does not occur at the lower level for the flights over downtown may point up the effect of increased vertical mixing in transporting momentum downward.

6. The vertical velocity above the city

The height variations along the tetron trajectories of Fig. 3 are presented in Fig. 11. The most noticeable feature is the small variation in height upwind as

compared to downwind of downtown, and the smaller height variations as the night progresses. Apparently, under the lapse conditions in which these flights were made, the increased roughness of the city considerably increases the vertical eddy velocity at heights of 100–200 m.

The average tetron-derived vertical velocity across the city under lapse and inversion conditions before and after midnight is shown in Fig. 12. A maximum upward velocity of  $\sim 4 \text{ cm sec}^{-1}$  occurs above the city center in all four cases, implying an average wind indraft toward the city center of  $\sim 1 \text{ m sec}^{-1}$  below 100 m. Recent theoretical work by S. Hanna (Air Resources Turbulence and Diffusion Laboratory, Oak Ridge) and W. Hoecker has suggested that the vertical tetron displacement provides a good estimate of the magnitude and spatial location of the vertical air displacement only when the vertical velocity is relatively large and the period of oscillation relatively small, say  $1 \text{ m sec}^{-1}$  and 10 min, respectively. However, over Columbus at night the vertical velocities are usually small, and on the basis of computer simulations it is estimated that in Fig. 12 the actual vertical air velocity exceeds the tetron-derived vertical velocity by about a factor of 2, and that the region of maximum upward air motion is displaced downwind from the region of maximum upward tetron motion by 2–4 km.

The inversion cases differ from the lapse cases in showing an overall tendency for sinking motion upwind and rising motion downwind of downtown. This tendency may be partly due to the tetroons following isopycnic surfaces which slope downward toward the city center owing to the heat island effect, although, on the basis of Fig. 2, such an effect should produce a vertical velocity of no more than  $1 \text{ cm sec}^{-1}$ . Thus, the reason for the indicated sinking motion upwind of the city under inversion conditions is still not clear, but variation in terrain height may be an important factor. Note also the sinking motion in the lower levels just downwind of downtown under lapse conditions after midnight, a motion illustrated by flight 73 in Fig. 11. Fig. 13 shows that there is little difference in the

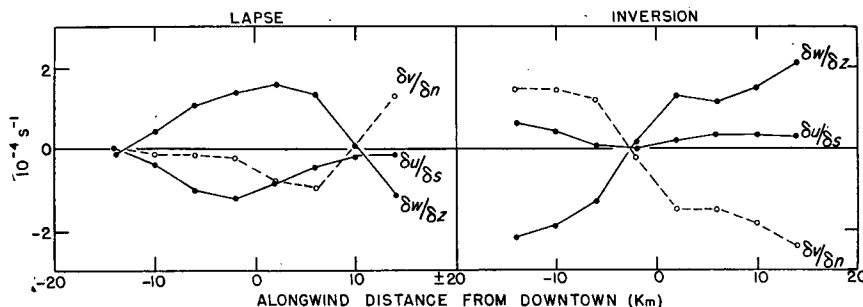


FIG. 14. Longitudinal and vertical spatial velocity derivatives (solid lines) obtained across the city at a height of 100 m under lapse and inversion conditions under the steady-state assumption, and the lateral spatial velocity derivative (dashed line) at this height derived from the equation of continuity. The cross-wind direction  $n$  is to the left of the flow looking downwind.

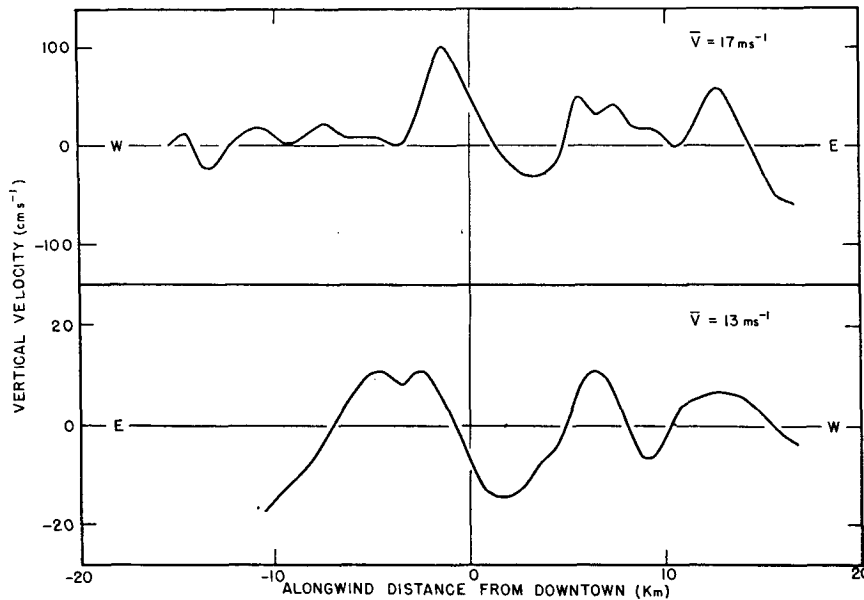


Fig. 15. The average vertical velocity ( $\text{cm sec}^{-1}$ ) determined from flights passing across the city on individual nights with strong winds from the west (top) and from the east (bottom). Note the fivefold difference in vertical velocity scale.

vertical velocity pattern determined from flights passing over downtown and to either side of downtown under lapse conditions, except in the expected sense that the upward motions are slightly larger over downtown.

Comparison of Figs. 9 and 12 shows that there is a tendency for the region of maximum wind deceleration to correspond to the region of maximum upward velocity, as would be expected from the equation of continuity. Assuming steady-state conditions, and making use of the equation of continuity, the left-hand diagram of Fig. 14 presents the lateral velocity divergence ( $\delta v/\delta z$ ) at a height of 100 m under lapse conditions as derived from the sum of the longitudinal velocity divergence ( $\delta u/\delta z$ ) at 100 m and the vertical velocity divergence ( $\delta w/\delta z$ ) between the ground (where the vertical velocity is assumed negligible) and 200 m. The derived lateral divergence is small except just downwind of downtown where some pinching together of the trajectories is indicated. Since the tetrons underestimate the vertical air velocity, this trajectory confluence would actually be larger than illustrated. Under inversion conditions (right-hand diagram) a quite large trajectory diffluence upwind and confluence downwind of downtown is indicated, similar to the flow of water around an obstacle in a stream. We have not been able to verify these indirectly obtained confluences and diffluences directly from the trajectory data, for this really requires simultaneously tracked tetron flights on both sides of the city.

The city-induced vertical velocities become much larger on windy nights. Six tetron flights were made on a night when the wind averaged  $17 \text{ m sec}^{-1}$  from the west (at tetron height) and there were snow showers in

the area. The top diagram of Fig. 15 shows that under these conditions, in the mean, a maximum upward air motion of at least  $1 \text{ m sec}^{-1}$  occurred very near city center, with evidence that this impulse set off upward- and downward-directed air motions farther downwind. Five flights when the wind was from the east at  $13 \text{ m sec}^{-1}$  resulted in a similar but less pronounced vertical velocity pattern, as shown in the lower diagram of Fig. 15. At least under such windy conditions, one would expect the city-induced vertical velocity patterns to extend to considerable heights.

## 7. Conclusions

Of considerable practical importance to the study of pollutant transport is the observation that the city induces a spatial veering of the wind at heights above 100 m during the night. The veering is greatest (at least  $20^\circ$  at 200 m) on nights when the urban heat island effect is strongest and appears to be associated both with an increase in frictional drag due to enhanced vertical mixing over the city and to the formation of a mesoscale high aloft due to the higher temperatures within the city.

A matter of importance that cannot be properly dealt with using the Columbus data is whether or not the city, particularly under inversion conditions, acts like a rock in a stream, and causes the air to flow around it as well as over it. Indirect evidence for trajectory diffluence upwind and confluence downwind of Columbus under inversion conditions was obtained with the help of the equation of continuity, but a proper evaluation requires simultaneous tetron flights on both sides of downtown. A more complete understanding of the mechanisms

involved will require profiles of temperature and wind within the city and external to it, both up- and downwind. If, in addition, simultaneous tetron flights could be made at heights, say, of 50 and 150 m on both sides of the city (four simultaneous flights in all), it should be possible quantitatively to determine the variety of urban influences on the airflow. This is our goal, and experiments of this type are being planned.

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