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Abstract

During the winters of 1964-65 and 1965-66 a large network of stations measuring wind, temperature and coefficient of haze was maintained in the Denver metropolitan area with the objective of determining the meteorological factors relevant to air pollution episodes in Denver. It turns out that pollution is removed in part by what is called the friction-stovepipe effect, a net indraft of air into the city which rises there and then moves outward again; in part by ventilation from winds blowing across town horizontally; and to a smaller extent by vertical turbulence in the middle of the day. The distribution of pollution sources and of sedimentation is computed with some assumptions. Although the source of pollution is strongest in the center of the city day and night, the outer parts of the metropolitan area also contribute substantially. Strongest pollution concentration remains over and north of the city center. The transport processes carry pollution away but, analogous to a heat source, the highest pollution level remains in the general area of the principal source. The daily course of pollution exhibits two daily maxima and minima as in many cities; the explanation turns out to be rather complex partly dependent on local factors and cannot simply be related to the two waves of commuter traffic.

In general, pollution does not increase or decrease as a uniform blanket over the city during pollution episodes. Rather, it is common for the polluted mass to be concentrated in one part of town while others are relatively clear. The circumstances governing the location of such concentration are explored and an attempt is made to develop a forecasting method, at least partly.

The onset and recession of periods with extreme pollution, as well as the termination of pollution episodes, is analyzed with view to developing transport criteria related to these events. Extreme peaks last only a short time, 2 - 4 hours, while onset and recession may take 8 - 10 hours each, so that an extreme event comprises a time span somewhat less than a day in the mean.

Finally, conclusions and recommendations are presented (a) for operational and (b) for planning purposes.

Introduction

Air pollution in cities may be studied from two viewpoints: (1) the dispersion of pollutants emanating from concentrated sources, mainly stacks, and (2) the behavior of the conglomerate from all sources of pollution. Much attention has been given the first problem; many air samples have been taken to determine the principal components of the conglomerate. Less emphasis has been placed on displacements as well as growth and decay of the conglomerate as influenced by meteorological factors beyond the obvious proposition that air pollution episodes occur with preference during light winds and strong temperature inversions.

The evident answer to pollution is source control, and this is the only answer for placing a constraint on the rising global contamination of the atmosphere. Yet it must be realized that growing city populations and city life will for a long time act as concentrated pollution sources, even though the example set by the city of London in 1956 demonstrated how much control can be achieved in a huge metropolitan complex with forthright determination. Meteorological analysis can assist in alleviating the effects of air pollution in and around cities on the daily time scale in the following ways: (1) determination of onset and disappearance of pollution episodes; (2) description of the role of atmospheric transport processes for producing the observed patterns and concentrations of the polluted mass; (3) description of circumstances leading to extreme pollution, and (4) warnings of pollution levels for regulatory ordinances. On longer time scales such analysis can (a) aid city planning, (b) determine the limit of the spread of pollution beyond a city with serious effects for downstream country activities, notably agriculture, and (c) estimate the "pollution potential" for areas as yet free from major population concentration and pollution generation. Some of these points provided the motivation for the present study. Neiburger (7) has published a more extensive survey of the various aids that meteorology can provide against air pollution.

The City of Denver

The Denver metropolitan area is an attractive location for analyzing air pollution in that it is an isolated source region and not subject to contamination from various other sources as is true, for instance, for the Atlantic coast of the United States. Further, pollution levels in Denver have not yet reached the excessive values measured in some other locations and this holds out some hope for possible prevention of pollution growth to those levels. All meteorological work must, of course, take its departure from two given quantities: the terrain features (Fig. 1) and the size of the city, the city population and the distribution of industrial, commercial and residential areas shown simplified in Fig. 2. The result of an analysis based on a limited observation network was presented by Riehl and Crow (8). Results were encouraging for undertaking a broader study which then was carried out in the winters of 1965 and 1966.

Methodology

Analysis of an air pollution conglomerate, restricted in our study to particulate contamination, may be approached from the viewpoint of atmospheric transport processes as follows. Defining the mass of particulate pollutants carried by a given mass of air as M (mass per unit volume).

$$\frac{dM}{dt} = \frac{\partial M}{\partial t} + \mathbb{V} \cdot \nabla M + w\frac{\partial M}{\partial z} \quad . \tag{1}$$

Here, as customary, d/dt is the substantial change with time following the mass, $\partial/\partial t$ the local change and the real object of the investigation, ∇ the horizontal gradient operator and z height positive upward. Further $\mathbb{V}$ is the horizontal wind vector and w the vertical wind component positive upward.

The equation of mass continuity for air is given to a high degree of approximation by

$$\nabla \cdot \mathbb{V} + \frac{\partial w}{\partial z} = 0 \ , \tag{2}$$

since air density may be taken as a constant. Combination of equations (1) and (2) yields

$$\frac{dM}{dt} = \frac{\partial M}{\partial t} + \nabla \cdot (M\mathbb{V}) + \frac{\partial}{\partial z}(Mw) \ . \tag{3}$$

Upon integration over a suitable volume of air over the city, called α ,

$$\int \frac{dM}{dt} \delta\alpha = \frac{\partial}{\partial t}\int M\,\delta\alpha + \int \nabla \cdot M\mathbb{V}\,\delta\alpha + \int \frac{\partial}{\partial z}(Mw)\,\delta\alpha \ . \tag{4}$$

Fig. 3 shows the horizontal area chosen for computation, as well as subareas roughly oriented with respect to types of city activity and grid points used for data tabulation for computer processing. We took the vertical dimension of the volume as 100 meters which includes the height of almost all emission sources.

The left side of equation 4

$$\int \frac{dM}{dt} \delta\alpha = So - Si \tag{5}$$

where So is the pollution source and Si the pollution sink, often referred to as sedimentation or "dustfall." The source term So should include ground sources as well as transformation of gases to particulates in the air due to photochemical processes. The importance of the latter contribution is estimated to be relatively small in winter at low temperatures; lacking data, this term had to be ignored so that So designates the emission of particulates from surface sources alone.

On the right hand side of equation 4

$$\int \nabla \cdot M\mathbb{V}\,\delta\alpha = \int M c_n\, \delta s\, \delta z \tag{6}$$

with use of Stokes's theorem. In this expression c_n is the component of the horizontal wind perpendicular to boundaries as shown in Fig. 3, positive outward, and s is horizontal distance around any chosen boundary. We can write further

$$\int M c_n\, \delta s\, \delta z = s\int [\,\overline{M}\,\overline{c}_n + \overline{M' c_n'}\,]\,\delta z \tag{7}$$

In equation 7 the bar denotes averages around a boundary such as the whole city outline in Fig. 3 and primes the deviations from this average as determined at the individual grid points of Fig. 3. The quantity $\overline{c}_n$ measures the net velocity convergence or divergence across the boundary whereas $\oint c_n'\,\delta s = 0$ by definition. From mass continuity $\overline{c}_n$ must result in mean vertical motions over the area enclosed by the boundary whereas c_n' describes horizontal motions only. For our purposes we may therefore describe $\overline{M}\,\overline{c}_n$ as the "friction plus stovepipe" term and $\overline{M' c_n'}$ as the ventilation term, both illustrated schematically in Fig. 4. The dependence on z in equation 7 had to be ignored since a network of observation stations could be established only near the ground, mostly around 10 meters height.

The last term in equation 4 finally may be transformed as

$$\int \frac{\partial}{\partial z} (Mw)\, \delta\alpha = \widetilde{Mw}\,]_h\, A, \tag{8}$$

at h = 100 meters, since vertical transport may be assumed to cease at the earth's surface ignoring the slight slope of land. A denotes horizontal area and the tilde averaging over area. The term $\widetilde{Mw}_h$ contains a multitude of motions. One may visualize an average up or down motion over the whole area enclosed by Fig. 3. Then one may consider the mean vertical motion in each of the individual nine subareas of Fig. 3; thus $\widetilde{w} A = \Sigma\, w_i A_i$ where the index stands for the smaller areas. Included also are "turbulent" motions without net transfer through the 100-meter level; these occur on various distance scales, often quite small such as 100 meters, and also motions such as emission from stacks rising rapidly, because of high temperature, to some higher level of equilibrium. This turbulent term we could not measure at all within the limits of our instrumentation, although we knew that it would be important at least in daytime and that we would have to include it in some way, to be described later. Newly developed instrumentation, mainly lidar, should prove very helpful in arriving at measurements of the turbulent transfer in future experiments.

Our position was that, given concentration of the stovepipe effect in a "heat island," we should work with

$$\widetilde{Mw}\,]_h\, A = \sum_1^9 \widetilde{M}_i \widetilde{w}_i A_i + \text{Turb}\,, \tag{9}$$

the last term being the residual turbulence contribution. The heat island was found without difficulty near and north of the city center with temperatures higher than those of the suburbs by 10°F and more at night as noted in many cities. Unexpectedly, the concentrated stovepipe effect did not materialize and so we also could have used a more simplified form of equation 4. Given F as the atmospheric mass flux across a unit area in grams/cm^2/sec, the simplest form for experimental evaluation of equation 4 would be

$$So - Si = \frac{\partial}{\partial t}\int M\, \delta\alpha + \frac{sz}{\rho} F_h (\overline{M} - \widetilde{M}) + sz\, \overline{M' c_n'} + \text{Turb} \tag{10}$$

where ρ is air density and $F_h = \rho\, \overline{c}_n\, s\, z$ is the horizontal air transport across the whole boundary, positive outward. Further, $F_h + F_z = 0$ for atmospheric mass continuity as before; $F_z = \rho\, \widetilde{w}\, A$ is the vertical mass transport of air.

In the following, procedures to evaluate equation 10 will be considered. It may be added that a similar equation can be written for conservation of heat and that it was part of the original plan to use these two equations jointly. However, there are formidable problems because of the changes of temperature lapse rate across the city in the lowest 100 meters as occasioned by night inversions, heat island and other factors. Radiational source and sink terms also leave wide error margins. It was concluded that utilization of the heat budget might create more problems than it would solve and was therefore abandoned except for one order of magnitude calculation related to vertical turbulence.

Evaluation of the Transport Equation

With some assumptions, all terms on the right side of equations 4 or 10 except turbulence, can be computed to yield So - Si; the latter then may be compared with source inventories made by state and city health agencies for verification. Vertical turbulence may be assumed to be zero from about 4 p.m. through the night to 9 a.m., while the temperature inversion is well established.

From January to March 1965 and from December 1965 to March 1967 a network of stations was operated in the Denver metropolitan area, with supplementary observations during early 1968. Principally, wind, temperature and the coefficient of haze (COH) or soiling index were measured. In addition to this network, parious industries and government agencies provided wind and temperature data at their locations[1] (Appendix A). Fig. 5 indicates the station locations used most of the time; changes had to be made over the two seasons. In the first season COH was measured at three elevations of a downtown office building up to 250 feet in height. Some wind data above the city were obtained from trajectories of several tetroon flights at about 100 m altitude. Aircraft reconnaissance and photography gave information on height and distribution of the pollution in the first season.[2] Invaluable assistance was obtained through collaboration of the airborne traffic police who carried a thermometer and supplied excellent information on the vertical temperature structure, especially inversions, during the morning and afternoon traffic hours.

COH was measured with several types of instruments during the first season but only with a Gelman recorder during the second season which proved more satisfactory since all instruments then were compatible and mutually calibrated. High volume sampling also was employed; limited analysis of the constituents was performed with an optical microscope. A Royco particle counter was placed on a truck for collecting samples around selected blocks of 1 square mile, a technique far superior to maintaining the instrument as a fixed location during very light wind conditions. The counter measured particles over the range from 0.3 to 3.0 microns, all biologically significant sizes. There was no interest in still larger particles; at the low end measurements to 0.1 microns or less would have been preferred, but no suitable instrument was available for this purpose.

Temperature and wind instrumentation was kept running continuously. When a weather situation with light winds was expected, the Gelman recorders were turned on and the other sampling equipment mobilized. Experiments were continued until the pollution cleared with a change in the general weather situation. Nearly all measurements were performed from Monday to Friday when the pollution source at a given time of day may be expected to be a constant. There were over 50 experimental days. Because of data problems, unexpected changes in weather, such as premature onset of chinook winds etc., only 27 of these days proved usable for the analysis presented here. Twelve pollution episodes comprise these days. Duration was distributed as follows: One day - 3; two days - 5; three days - 2; and 4 days - 2.

The Gelman recorders were set to accumulate particles for 2-hour intervals, the lowest time interval considered useful for providing reliable COH values at the low pollution levels often experienced in many parts of the city. Other data were examined over various shorter time intervals; however the calculations of this report are based entirely on 2-hour averages to match the COH records. Fig. 6 shows an example of analysis for an individual 2-hour period.

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[1] Details of stations are contained in an intermediate project report (1).
[2] Mr. Charles Grover of Denver

THE AVERAGE POLLUTION DAY

At first we shall consider the diurnal course of the average of all 27 days of the sample and then examine differences between several types of pollution episodes.

The Local Change

Maps of COH-isolines were drawn for all 2-hour intervals, about 300 maps altogether and then tabulated using the grid of Fig. 3, including both boundary and interior points. In order to proceed it is necessary to find a relation between COH and mass. Such a relation may be nonlinear (4, 9, 10); it will also depend on type and size distribution of particulate matter in the air. We examined the results of our high volume samplers which, as it turned out, never sampled at high COH, as well as published relations between COH and mass for several cities of the United States (3, 5). These data are plotted in Fig. 7. The high mass of the sawmills at Berlin, N.H., at low COH deviates markedly from the records of the other cities whose pollution composition should resemble that of Denver more closely. A straight line approximates the values very well except the highest ones. Since even extreme values of COH barely touched the level of four, it was considered permissible to neglect the nonlinearity of the relation within the error margin of all computations. We decided to use

$$\text{Mass (micrograms/m}^3) = 125 \text{ COH} . \tag{11}$$

With this relation the COH charts may be integrated over each subarea of Fig. 3 and over the whole city area. Fig. 8 shows the pollution pattern in 2-hour time steps and also the 24-hour average. The mean daily concentration is highest in the north, as published previously (8). During afternoon the concentration wanders toward south as the winds draining down the Platte River during night and morning tend to reverse in the afternoon to bring the polluted mass evacuated toward northeast back toward town. This normal diurnal reversal of the wind regime has been described by Riehl and Crow (8) and will be examined again later in this report.

Choosing now the volume already mentioned, with outer boundary as given by Fig. 3 and vertical extent of 100 meters, we can calculate the total mass and the local change of mass in 2 hours for this volume with the assumption that the mass is mixed uniformly through this volume, probably a rather good approximation from our data as well as vertical distributions published elsewhere. We then arrive at the curve of local change in Fig. 9 which features increases in morning and afternoon, decreases during midday and night as typically found in many cities. The reasons for the occurrence of the double maxima and minima remain to be discussed later. It should be emphasized that this curve is valid only for the city volume topping out at 100 meters elevation and that it does not indicate the diurnal course of total polluted mass above the city. For the latter purpose the entire vertical extent of pollution above the city needs to be taken into account. For computational purposes it would have been very convenient to adopt a variable upper boundary. Difficult terms such as the turbulent transport through a fixed boundary would have been avoided. All our attempts to locate this boundary from aircraft photos, height of temperature inversion, etc. proved fruitless. It was obvious the boundary moved upward on each day, even with snow cover and nighttime temperatures below 0°F. We had hoped the atmosphere would remain stable and turbulent transport negligible for at least part of our sample. That this was not so is no doubt a peculiarity of Denver, probably not encountered over the central and eastern United States where, with low overcast skies, the diurnal temperature range often is reduced almost to zero. In any event, we shall be constrained to work with the fixed volume throughout this report where, however, it may be noted that, from the viewpoint of developing weather engineering aids for city life, this is of course the significant coordinate system to employ.

In Fig. 9 the polluted mass in the city volume ranges from 3.5 to 5.5 tons, the local change from -1 ton to +1 ton/2 hr. This demonstrates that the local change is a substantial fraction of the mean pollution level leading to rapid changes of intensity of contamination over the city.

Friction - Stovepipe Effect

As Fig. 8 has demonstrated, concentration of mass is greatest in the three industrial sectors of Fig. 3 and decreases outward from there except in the northeast. Given net convergence of mass across the boundary into the city, the subsequent ascent of mass inside the city to upper levels will occur after the incoming air has acquired contamination during passage over the various pollution sources. In that event the term

$$sz\, F_h/\rho\, (\overline{M} - \widetilde{M})$$

in equation 10 will act as a cleansing mechanism. It turns out that there is indeed a net mass inflow of air into the city, no doubt a result of the frictional retardation produced by the buildings and perhaps reinforced by the city heat source. The average net inward component is nearly constant at all hours of the day at 0.3 m/sec, an outcome that was not obvious before the measuring program began. We can now compute $F_h/\rho = \overline{c}_n\, s\, z$. Given $s = 71$ km from Fig. 3 and $z = 100$ m, we find that $F_h/\rho = -21 \times 10^5\ m^3/sec$. The average upward velocity over the area of Fig. 3 is $\widetilde{w} = -F_h/\rho A$. Given $A = 3 \times 10^8\ m^2$, $\widetilde{w} = 0.7$ cm/sec or 25 m/hr or 100 m/4 hr, a surprising result indeed, inasmuch as it indicates that a mass equivalent to that contained in the whole city volume is completely removed six times daily by this average effect alone.

As already noted, the average vertical velocity resulting from the net mass inflow was distributed rather uniformly over the city. Our expectation had been that the inflow would be concentrated mostly in the area of the heat island, especially at night when the heat island is very pronounced (Fig. 6). During daytime, temperatures in city center and suburbs are quite uniform, so that little concentration would be expected in the noon hours. The mass inflow turned out to be quite uniform not only in space when considering the subareas of Fig. 3, but also in time. Again, with a primary stovepipe effect, one would look for largest total convergence at night when the air in the heat island is strongly buoyant with respect to the surroundings, whereas actually almost the same mass inflow was calculated for all times of day. It must be concluded that the primary effect is the difference in ground roughness of the built-up area compared to the steppe environment. Finally, in view of the uniform convergence day and night, we must conclude that the night temperature inversion was forced to remain above the city buildings. Unfortunately, instrument calibration at our single tower site was not sufficiently good to verify or disprove this hypothesis. Clearly, some puzzling and unclarified features remain that can only be settled with a new experiment. However, it is probable that the relatively weak and widespread city heat sources are rather ineffective and a more energetic stovepipe mechanism could be achieved by moving them closer together.

From Fig. 10 the citywide friction-stovepipe evacuates about 0.5 tons/2 hr without marked diurnal variation, or 6 tons/day or about 1.3 times the average particulate mass in the volume considered. If the air coming in from the suburbs was completely clean, the friction-stovepipe effect would remove all pollution six times daily. If our experimental area had included the suburbs and outlying industrial areas, this might have appeared as a more dominant mechanism in relation to total pollution than is true for the metropolitan center. As it is, pollution generated by industry and suburban life outside our boundary, plus possibly some pollution from the city returning inward after descent in the outskirts, produce substantial values of $\overline{M}$ and hold the quantity $(\widetilde{M} - \overline{M}) / \widetilde{M}$ to a small fraction.

The Ventilation Effect

Lateral evacuation of mass by the term $s\,z\,\overline{M' c_n'}$ can constitute a very powerful cleansing mechanism. Denver has a width of about 10 miles from Fig. 3. With wind speed of 10 mph, then, all city air is evacuated in 1 hour. When a west wind develops down the foothills which are almost free of pollution sources, all existing pollution is driven out of the city in short order and the mountains suddenly stand out clearly. It is, of course, the horizontal wind speed which serves for general prediction and warnings of pollution episodes. For air pollution to exist, the wind inside the city must fall to very low values. A stagnant synoptic situation plus, again, the retarding effect of the city itself, can combine to produce nearly calm conditions for many hours. Figs. 18-19 serve to emphasize the frictional retardation. With wind velocities around 1-2 mph over most of the city at night, wind speeds remain at 4-5 mph or greater just outside of the principal built-up area, a major factor for the rapid outward drop of COH values in Fig. 8.

In the 24-hour mean, the lateral ventilation term contributes about 0.66 tons/2 hr or 8 tons/day to the cleansing of the city, somewhat more than the friction-stovepipe effect. Together, the two mechanisms remove 14 tons on an average pollution day. The ventilation is subject to a strong diurnal variation. Its maximum occurs from 8-10 a.m. when winds pick up from nighttime minima and begin to act on the heavy morning concentration (Fig. 10). A remarkable minimum follows shortly in the afternoon and early evening, and this no doubt is again a peculiarity of Denver. As mentioned earlier in the report, winds tend to be southerly during night moving pollution down the South Platte River toward northeast. In the afternoon the winds reverse and return the polluted mass toward town, at least partly. It is this pendulum effect that is numerically reflected in Fig. 10. We may add that the pattern of diurnal variation for the whole city also holds in each of the subareas.

Turbulent Vertical Transport

We have now determined and graphed all terms of equation 10 except turbulent transport. Assuming such transport to be small in comparison with the other terms, we can compute So - Si with the result as shown in Fig. 10. Values from late afternoon through the night into the morning appear reasonable and will be adopted tentatively for later verification against the city source inventory. In the middle of the day, however, the calculated drop of So - Si even to a slight negative value is clearly erroneous. As already stated, nearly all days in our sample were weekdays when the city pollution source should remain constant in the first approximation through the daytime working hours. It follows that we are still missing an important transport mechanism in the middle of the day, obviously the vertical turbulent transport.

Denver's diurnal temperature variation is large on most days even in the middle of winter. Fig. 11 shows two examples of the relation of the surface temperature rise during daytime to the temperature distribution with height in the morning as established by the Denver airborne traffic police and U. S. Weather Bureau radiosonde data. On 3 February (see Fig. 6 and Figs. 15-17) a large inversion was present that maintained itself. Ground heating was insufficient to break the inversion, merely to raise it. In contrast, on December 8, 1965, surface maximum temperature reached a high value leading to upward distribution of particulate matter through a deep volume. This latter example is rather typical of most air pollution episodes. As will also be pointed out later, control of pollution levels in daytime by the inversion turned out to be small or nonexistent. The general conclusion is that even on the day with strongest inversion, February 3, 1965, turbulent transport through the 100-meter surface was not inhibited. Another matter is top and definition of the whole pollution layer. There a large inversion must play a substantial role in holding the top to low levels and to provide for a sharp top, whereas with a deep mixing layer the top may be very diffuse. It is therefore considered to be more than coincidence that the aerial photos on 3 February (Fig. 15) were chosen as our best ones for reproduction in this report.

Turbulent vertical transport through the 100-m level for the average pollution day from 10 a.m. to 4 p.m. has been estimated with the assumption that daytime So - Si may be approximated by using the computed value for the period 4 - 6 p.m. (Fig. 10). The early morning source results from a combination of traffic and general inception of daytime activities and would not represent the source level during the day as well as the afternoon data, when the traffic rush hour coincides with declining industrial and commercial activity.

An attempt was made to establish at least an order of magnitude estimate whether transports of about 1.5 tons/2 hr as computed in Fig. 10 can be expected to be readily executed by the turbulent motions expected to be present. The vertical heat transfer may be assessed as about 100 $cal/cm^2/6$ hr through the 100-meter surface on a clear day of winter at Denver. Since we have no measurements of the correlation between temperature and vertical motion, we shall use a frequently employed device and assume that the temperature difference between ascending and descending air at 100 meters may be approximated by a constant. Then

$$Q_s = c_p \rho \, |w| \, (T_u - T_d), \quad (12)$$

where Q_s denotes the energy transfer, $|w|$ the average turbulent vertical motion, T_u and T_d the temperature of ascending and descending air, respectively. Given $Q_s = 100 \ cal/cm^2/6$ hr as above, $T_u - T_d = 2^oC$, probably a rather large value, and $\rho = 10^{-3} g/cm^3$, we find that $|w| = 10$ cm/sec, in reasonable correspondence to the daytime bumpiness generally experienced close to the ground.

We may now write a transport equation for particulate matter corresponding to equation 12, thus

$$F_z = |w| \, (M_u - M_d). \quad (13)$$

Here F_z is the turbulent vertical transport of particulate mass and $M_u - M_d$ the difference in particulate matter between ascending and descending air. Our first approximation was $M_d = o$, i.e. the downward air currents are completely clean. This assumption overestimated F_z by almost two orders of magnitude. With $F_z = 1.6$ tons/2 hr for the whole city area and $|w| = 10$ cm/sec from the heat transfer calculation, $M_u - M_d = 5$ $micrograms/m^3$, only about 2 per cent of the order of magnitude of mass of particulates in the air. It follows clearly that turbulence can easily accomplish the estimated mass transfer, and that the polluted layer must extend well above 100 meters height in daytime in order for $M_u - M_d$ to be so small.

Source and Sink

Fig. 12 shows the daily course of pollution in relation to So - Si as finally estimated and to the sum of all transport processes. In the early morning the pollution level rises in response to the very large value of So - Si as city life starts up. Then, as the source settles to its mean daytime value and winds increase with the surface heating, the density of pollution in the city decreases first with the increased ventilation and then with the onset of turbulence. In the afternoon, when the pollution reenters the city from the north and when the turbulence gradually dies away, pollution concentration starts to increase again long before the onset of afternoon rush hour traffic. The second maximum is reached around 8 p.m. when, with the low nighttime source and with winds returning to their nighttime pattern of importing clean air from the south, the pollution density declines again until lowest concentration of the whole day is achieved in the small hours before sunrise. Total pollution remains concentrated within the city because of the strength of the source relative to that of the transport processes during pollution periods. The situation is analogous to that of a heat source, where the highest temperature remains at the source in spite of continuous diffusion to colder surroundings. In summary, the daily course of Denver pollution has a very local explanation in several important aspects, even though the double maximum and double minimum of pollution intensity is encountered in many cities.

It will be of interest now to check the total So-Si, computed as 19 tons/day or about 5 tons/sq mi/month from Fig. 12, against the source inventory of particulates prepared by the city of Denver (ref. 2, updated later). From this inventory the Denver source in six winter months, taken roughly to correspond to our area of analysis, was 5,300 tons or about 30 tons/day, only one-third of the whole emission for the greater Denver area including neighboring counties. Given So - Si = 19 tons/day, it follows that Si = 11 tons/day. A check with the "dustfall' recorded at the seven city stations October-December 1966 reveals the uncomfortable fact that this dustfall averaged 40 - 80 tons/day for the city area, far in excess of the pollution source. Of course, this may not be significant because no chemical analysis of the dustfall was made, and it may be safely assumed that it contains a healthy ingredient of country dust swept into the city during chinooks and other strong wind situations. However, even if the dustfall of the outlying stations, or 40 tons/day, is subtracted - surely not quite true - the interior stations still show excessive amounts of sedimentation after this subtraction. One may fall back on the argument that in dustfall measurements great care must be taken concerning the immediate environment of a station. It may be noted however that the problem here is not unique for Denver but also has been encountered in other locations, notably England and Canada, where chemical analysis and weighing of certain constituents of dustfall were performed (6).

We can offer one positive argument supporting our calculated sink value as one-third of the source. The Royco particle counter gave particle size distributions which often, though not always, resembled "Junge" profiles. If the whole mass of interest is contained between 0.1 and 10 microns, the size range 0.1 to 1.0 microns contains half and the size range 0.1 to 2.0 microns contains two-thirds of the total mass. Well over 95 per cent of the number of particles are found in the size range below 1 micron. The Stokes fall velocity begins to exceed 100 meters/day for particles of 2 micron diameter and density of 2. If, on the average, these larger particles comprise the principal sedimentation, while the smaller ones are blown away by the winds, we would have a sink of about 10 tons/day given a source of 30 tons/day, in full agreement with our estimate of So - Si. Of course, a definitive test of constituents in the sediment and their particle size distribution still remains to be made.

Proceeding under the assumption that our estimate is essentially valid, the daily sedimentation will be as indicated in Fig. 13 if the fallout is proportional to total mass of particulates over any part of the city. The source then also may be apportioned and is shown in Fig. 14 for the nighttime hours from 8 p.m. to 4 a.m., for the daytime hours from 8 a.m. to 4 p.m. and for a combination of the two transition periods that contain the principal contribution to pollution by commuter traffic.[1] At all times of day the source is concentrated in the three industrial subareas of Fig. 3, especially so at night when the ratio of center to outskirts reaches 2:1. In the daytime this ratio is about 1.7:1 and in the transition hours 1.5:1, suggestive of the influence of the traffic contribution in the rush hours. Although the center of the source remains along the main industrial activity following the Platte River, the concentration there nevertheless is rather weak. Ordinances concerning pollution warnings and possible shutdown of activities must be framed in a citywide pattern and cannot be restricted to a few isolated sources of intense pollution.

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[1]The chart for 6-8 a.m. plus 4-6 p.m. is quite similar to that for 4-8 a.m. and 4-8 p.m.

It should be noted that the source computations failed in the southwestern area at night and in the northeastern area at all times. The calculations yield too strong a source in the southwest and too small a source in the industrial northeast. These values have been ignored in drawing Fig. 14. The excessive source in the southwest comes from very strong southerly winds at the Gulf Course station there at night, no doubt unrepresentative for this area. With these strong winds an import of excessive amount of clean air is calculated, requiring a fictitious source for its further travel to the high pollution levels inside the city. The reasons for the failure in the northeast are not obvious.

VARIATIONS IN POLLUTION INTENSITY

Concentration of Particulates

We have depicted the distribution of pollution concentration over the average pollution day in Fig. 8. On individual days, the particulate mass more often than not is concentrated in one portion of the metropolitan area at a given hour while, at the same time, other parts of the city might be quite clean. On February 3, 1965, our photographer Charles Grover made two aircraft missions over the Denver area, one beginning at 8 a.m. and one in the early afternoon. Fig. 15 shows three photos from the first flight and one from the second; these are selections from a much larger number of available pictures. Figs. 15 a-b look eastward from the western edge of Denver. There is little pollution in the west, while a heavy mass concentration overlies the east. The city center is only barely visible in Fig. 15a; in Fig. 15b the smoke plume of the utility plant is an outstanding landmark. Fig. 15c, taken from the south of the city looking toward north shows the southern limit of pollution very clearly. The early afternoon photo (Fig. 15d), taken from the north end looking south, indicates a shift of the concentration to the southern part of town.

For comparison of aerial photos and readings from the COH measuring network, Fig. 16 shows the COH maps for 8-10 a.m. and for 12-2 p.m. The early concentration in the east and its subsequent shift toward south are clearly portrayed. For a quantitative procedure to establish relative pollution concentration, the mass of particulates in each subarea of Fig. 3 was expressed in terms of deviation from the mean for each 2-hour interval of the day. The resulting values for the two maps of Fig. 16 are shown in Fig. 17, demonstrating that even during heavy pollution episodes parts of the city may have less than the average pollution level. By forming the differences between the three northern and the three southern areas, then between the three western and the three eastern areas, indices of the deviation from the average concentration north - south and west - east are obtained. For each time of day these differences then may be ordered from highest to lowest and assigned rank numbers; the highest one north - south, for instance, denotes the map with greatest relative concentration in the north while the lowest (negative) one gives the period with greatest concentration in the south.

Each 2-hour sample consists of about 27 cases depending a little on just when individual measurement episodes were started and terminated. The wind fields for the 9 highest and 9 lowest rank numbers in each 2-hour sample were selected and averaged. These composite wind fields are presented in Fig. 18 for north - south and in Fig. 19 for west - east. From the period 8-10 p.m. through the night until 8-10 a.m. the patterns remained quite constant, so that only one 2-hour period is shown, whereas from late morning until evening a remarkable series of contrasting flow patterns was encountered.

Considering the north - south charts (Fig. 18), the flow remains from southwest toward northeast throughout the night irrespective of concentration. The difference lies in the wind speed pattern. With pollution concentration in the north, the southerly flow across the southern parts of the city is stronger by about 2 mph than in the reverse cases, leading to more ventilation by clean air in the south. We also may note that just east of our area of computation wind speed at night is always at least 4-5 mph from south, sometimes more. Thus a site like the Denver airport, while it may contain a strong pollution source, usually has a low pollution level and good visibility at night since the particulates are swept rapidly away toward northeast by the relatively strong winds.

Toward noon, the well known diurnal reversal of wind direction is noted first in the situations with concentration in the south, 2 hours later also during concentrations in the north. It should be remembered that on many days the northerly winds return much of the particulate matter that has drifted northeastward during the night. This returned pollution plus material from the city sources is swept far to the south on a clockwise path when the concentration shifts south while everything is hung up in the north and north-central areas in the other cases, since the north wind is not able to penetrate far past the northern extremity of the city. This leads to a fierce convergence of air and pollution in and north of the city center; the pattern persists until evening when the normal southerly winds come through again. Several charts are quite spectacular, with an almost vortical streamline convergence. In view of the very light wind speeds, this is not significant.

We may conclude from Fig. 18 that concentration in the north occurs with an enhancement of the south component of the wind by 3-4 knots over the cases with concentration in the south, a very clear mechanism that must be impressed on the Denver area by the weather situation on a larger scale. We may immediately anticipate that concentration in the west occurs with enhanced wind from the east and concentration in the east with enhanced wind from west that blows clean air into the western suburbs and transports the polluted mass from the city center to the eastern outskirts. All this is confirmed in Fig. 19 which, again, displays some very spectacular charts during afternoon and early evening. The winds of Figs. 18 and 19 may, of course, be added vectorially to yield concentrations along the NE-SW and NW-SE axes. For simplicity of computation, however, in a situation with a relatively small sample, it was considered best to work with the N-S and E-W patterns separately.

Forecasting: As already stated it must be presumed that the only mechanism for the variable strength of the north-south and east-west components of the wind lies in a difference in the synoptic weather situations. It would be of advantage to isolate the synoptic difference which would make possible the short term prediction of relative pollution concentration given adequate general weather predictions.

With this objective in view, surface and upper-air charts were examined for all periods. The 700-mb level, about 5,000 feet above the ground, proved too high for any correlation with Denver air pollution. The 850-mb chart is largely blank and undefined over Colorado since it lies below the surface. A valuable chart of former days - all pressures reduced to the 5,000-foot level - unfortunately was abandoned by the U. S. Weather Bureau prior to our experiment. This leaves us only with the sea level pressure chart where the problems of reducing pressure to sea level introduces great difficulties and residual inaccuracies, if the chart is to be related to an item such as small deviation of Denver winds from the average diurnal flow during pollution episodes. Nevertheless, lacking better data, we tried to find out whether any specification using sea level maps was possible. We started with the north-south pressure distribution along the lee of the mountains; there the height of all stations does not vary too much and we might assume reduction errors to be fairly uniform. Nevertheless, there were problems, oddly enough in particular with the reduced Denver pressure itself, which turned out to be about 2 mb low in most cases.

Our procedure was to tabulate sea level pressures at stations from northern Wyoming to southern Colorado (Trinidad) against north-south distance for each map and then to find the average profile for the nine cases with strongest pollution concentration in the north of

Denver, and in the south of Denver, at the four daily synoptic map times. The result (Fig. 20) is gratifying in that a northward-directed pressure gradient is correlated with pollution in northern Denver, and that a zero or slightly southward directed pressure gradient is correlated with pollution in southern Denver. The relation held well for individual cases, not only for the composite, but it may prove valuable for prediction of maximum pollution levels given adequate general surface prognoses.

It is very curious that the north-south pressure gradient is related to the north-south and not to the east-west wind component. This would be the geostrophic relation; it was also tried and it gave no relation whatsoever. It follows that wind variations are of a highly ageostrophic character, not unreasonable at least for the type of situation under consideration, though quite evident also during chinooks and cold outbreaks with strong wind speeds. With an appropriate formulation of the equations of motion an attempt may be made to calculate the surface shearing stress and the drag coefficient as a function of distance from the city center toward the steppe areas; this may yield further insight concerning the general mass convergence into the heavily built-up area noted earlier.

TABLE 1. Transport mechanisms during onset and recession of severe air pollution periods, and for episode terminal periods (tons/10 hr).

Local Change	Onset	+3.3	Turbulence	Onset	-1.1
	Recession	-3.3		Recession	-0.5
	Terminal	-2.7		Terminal	-2.0
Friction-Stovepipe	Onset	-2.2	Source-Sink (from Fig. 12)	Onset	+7.5
	Recession	-2.4		Recession	+6.7
	Terminal	-1.3		Terminal	+8.4
Ventilation	Onset	-1.6			
	Recession	-4.3			
	Terminal	-5.6			

The correlation between east-west pressure gradient and the east-west wind component over Denver was approximately zero, not unexpected in view of the problems with reduction of pressure to sea level. Winds at 1,000 - 3,000 feet above Denver also gave no indication of the on-mountain or off-mountain wind component in the city. Hence we have not been able to find a predictor for the east-west concentration of pollution.

Periods of Extreme Pollution

Denver does not yet experience the high pollution levels measured elsewhere. The excess of pollution for the whole city above average was distributed as follows at the peak of each pollution episode:

Concentration above average (micrograms/m^3)	Number of cases
100-150	2
50-100	4
0-50	6

At most, we observe a COH index a little above one unit over average pollution. Nevertheless, as seen in the last section, some part of the city is likely to experience concentrations far above city average. It does not appear premature to inquire into onset, duration, and decay of the pollution peaks. In addition, we should describe onset and termination of pollution periods. It turns out that this can be done for the terminal periods but not for onset since the network usually did not get underway until pollution had already reached a high level. An exception occurred on March 25-26, 1965, when onset, peak, and terminal decay were completely measured (Fig. 21). The rise to peak value took about 8 hours, then a decline of corresponding magnitude set in at once so that the peak value was only held for 2 hours, valid also for 3 February and 6 December, 1965. This pattern of time change verified approximately for all peak cases defined by an increase of at least 50 micrograms/m^3 in 8 hours to a peak value of at least 50 micrograms/m^3 above the value for the average pollution day. A total maxi-event thus lasts 16-20 hours. Cases with persistence of extreme pollution over days have not yet occurred.

Table 1 summarizes the change in citywide pollution during increase and decrease for the seven peak situations that occurred. Of these three cases are illustrated in Fig. 21. The principal difference, as may be anticipated, lies in the ventilation term which is well below average (3.9 tons/day compared to 8 tons/day for the average pollution day) during rapid pollution increase and well above average (10.3 tons/day) during rapid decrease. The friction-stovepipe and turbulence terms, in contrast, are quite indifferent.

For the increasing periods the computed So-Si from local change and transport terms is 6.5 tons compared to 6.1 tons from our earlier calculations, an excellent result that is well within the margin of error of all calculations. During the decreasing periods a rather substantial discrepancy remains. The computed So-Si from Table 1 is 5.0 tons compared to an actual value of 6.7 tons using Fig. 12; during terminal situations the calculation gives So-Si = 6.2 tons compared to 8.4 tons actual. One of our transport terms must be underestimated. It is not likely that the fault is with the ventilation term, since this effect is computationally most stable. Moreover, nearly all individual cases show the same deficiency. Probably the error lies in the turbulence term which, as may be recalled, could not be determined for individual situations but could only be estimated as residual for the average day.

The following table shows the distribution of wind speed, averaged around the boundary of Fig. 3 for the three classes of cases. This average wind speed may be termed a "ventilation factor" that should have some relation to pollution levels.

TABLE 2. Per cent frequency distribution of $|V|$ for onset and recession of extreme pollution periods, and for terminal periods.

Wind (mph)	Onset	Recession	Terminal
0-1	20	5	0
1-2	43	30	8
2-3	33	29	15
3-4	2	18	44
> 4	2	18	33

Table 2 demonstrates that indeed wind speeds are low to very low during onset of severe episodes and they rise to highest values during terminal periods. Unfortunately, there is too much overlap in the three columns in the middle of the frequency distribution for it to be a unique predictor. It is true that practically all onsets of heavy pollution occurred with average wind speed of less than 3 mph, but it does not follow that an onset will occur whenever wind speed falls to or below this level. Conversely, however, wind speed of 4 mph or better surely must mark the end of an episode because the air in Denver is cleared out sideways in 2 hours or less. This is an obvious relation generally used in prediction at the present time.

A study of the intensity of temperature inversions as related to pollution levels and extreme pollution periods produced a far more indifferent result than one might have expected on the basis of general climatological relations between air pollution and inversions. Comparing Figs. 11 and 21, we find an onset of heavy pollution occurred on 3 February with a strong inversion, whereas a similar onset on 8 December took place just when air temperature was high enough to produce mixing through a deep layer. The latter case is by no means an isolated instance; we must conclude that persistence or nonpersistence of an inversion through the noon hours is not a good guide for subsequent pollution levels.

We find that most of the large pollution increases occurred when the wind over the city became northerly, hence many though not all onsets were most pronounced in the afternoon and early evening. Assuming that a previous south wind had moved a polluted mass out of the city in the northeast, then a return of this mass coupled with the heavy daytime source can lead to maximum levels (see also 8). One must know, of course, whether such a previous movement has taken place. If not, then a north wind will bring clean air and a drop in pollution; in fact, several terminal periods occurred with shifts to strong north wind with cold front passages.

In summary, a maximum pollution episode is likely to set in when a polluted layer is available in the northeast for retransport into the city and when the north-south pressure gradient favors spreading of the pollution far toward the southern part of the city.

Start and Termination of Pollution Episodes

Onset of pollution episodes usually occurred one to three days after a cold outbreak depending on the rate at which wind speeds lessened. Fig. 22 is a composite of the 5 a.m. (1200Z) charts on the days when a pollution period began. We observe that Denver does not lie in the center of an anticyclone but rather in the saddle or neutral point between highs to east and west, lows to north and south. Although the situation in most individual cases resembled Fig. 22 considerably, differences in detail of course occurred. At times the low in the north was not present. Then the eastern anticyclone dominated also in the north, and the western anticyclone was weak or absent. On other occasions the western high was the stronger one and ridging extended all through the leeside of the mountains. The low in the south was present on all occasions. Termination of pollution episodes occurred, as already brought out, with increasing wind speed. The synoptic situations were more variable than during onset so that a composite map for termination would be pointless. Three types of large scale situations predominated: (1) arrival of a new disturbance with marked surface pressure fall from the west initiating downslope westerly winds, on occasion of great strength; (2) passage of cold fronts from north to northeast; and (3) outbreak of precipitation, usually from south, with intensification of the southern low pressure area under the subtropical westerly jet stream in the upper troposphere.

Conclusion — Applications for the City of Denver

In spite of uncertainties left over from this investigation of Denver air pollution, various deductions of practical importance for the city can be made. These will be divided into operational and planning recommendations.

Operational recommendations: (a) The beginning and end of pollution periods, as described in the last section, conforms quite well to general knowledge and probably adds little for the experienced forecaster. Episodes end when a pressure fall moving in from the west induces strong down-mountain velocities; when a cold front passes from the north; or when precipitation spreads over the area, mainly from the south. Onset is coupled with a dying down of wind speed; temperature inversions at night may always be expected in winter with light wind velocity. One variation from other areas lies in the fact that the center of a high pressure area seldom will move over Denver itself. Rather the lee-of-the-mountains trough will persist, with a dying out of strong pressure gradients.

(b) Circumstances leading to pollution concentration in particular portions of Denver have been determined. These are controlled by variations in wind. With an enhanced wind component from south by about 2 mph above average the polluted mass is concentrated in the north of Denver; with reduction of this wind component the afternoon penetration from the north sweeps far to the south and southwest over the entire city area. With enhanced wind from the mountains the concentration is in the east, and with enhanced east winds it is in the west.

A predictor has been found for the relative north-south but not for the east-west concentration (Fig. 20). With pressure gradient toward north, the concentration will be in the north; with indifferent pressure gradient or with gradient toward south the concentration will be in the south. Care must be taken to establish the pressure gradient from a succession of north-south profiles in the lee-of-the-mountains from northern Wyoming to southern Colorado, eliminating systematic deviations such as those of Denver itself and watching for bad pressures which from time to time are reported from any of the stations involved. It is suggested to see whether airways altimeter correction charts yield an improvement over sea level charts. It is further suggested to reinstate the old operational chart of pressures at all stations reduced to 850-mb rather than to sea level.

(c) Onset of extreme pollution episodes may be expected mainly when a polluted layer is available north of the city for retransport into the city and when the wind velocity averaged around the whole city is 3 mph or less. Application of this last criterion for warnings would require maintenance of a sufficient number of wind stations on a continuing basis.

(d) From Fig. 14 the Denver pollution source is citywide, with only a relatively weak concentration in the business and industrial areas. Hence any city ordinance designed to shut down pollution sources, when faced with warnings of extreme pollution, must deal with the citywide source; it is insufficient to direct an ordinance at a few sources of concentrated emission alone.

Planning recommendations: (1) The prevailing average wind over Denver in winter is down the Platte River from south-southwest, and this results in maximum levels of pollution in the north of the city well displaced from the maximum source which is in the center of the city. The wind regime is not likely to be changed. Hence it is appropriate to follow in the footsteps of European planning which long ago laid out cities so that the residential areas are situated at the clean end, the industrial areas at the downstream end of a metropolitan complex. It follows that in Denver all industry should be located in the north and northeast, all residential areas and nonsmoke producing activities in the south. There is some tendency toward this distribution in Denver, but to an insufficient degree and probably due to other causes. It is noted that new suburbs have been built recently in the northern outskirts.

(2) We have found that the heat island is of insufficient strength to produce much of a stovepipe effect that could serve as a principal cleansing mechanism. More concentrated industrial development in the north and northeast will enhance this mechanism. Further study is needed to determine just how much of a heat source will have to be generated in a small area before the stovepipe becomes really effective and worthwhile.

(3) As shown by Figs. 18-19 and as is also known from other metropolitan areas, city friction greatly slows down wind speed and therewith reduced the important ventilation

mechanism compared even with the immediate surroundings. It follows that a city should be built so that the frictional retardation is minimized. One way of doing this would be to create large corridors of open space parallel to the prevailing wind, in our case from SSW toward NNE paralleling the river.[4] Another method is to produce a new streamlined architecture. A city, like a ship or airplane, can be considered in "relative motion" against the wind; from aerodynamics one can determine the configuration of buildings required to offer least resistance to the wind.

Conclusion: This investigation of Denver air pollution has been carried through to the deductions originally envisaged and proposed, even though it was necessary to fill in several important points by conjecture and interpolation. It was considered preferable to do this rather than to break off at the difficult places which would have left the investigation in a very inconclusive state. Among other things, it has become quite clear what must be done over the previous experimental design in order to arrive at definitive results of all facets of such an experiment. In view of the uncertainties inherent in the present result the authors must of course reserve the privilege to amend this report in the light of subsequent observations and findings.

A vexing matter during the study was the fact that almost all calculations proved to be more complex than anticipated - for instance, the conversion of COH to mass, the sedimentation far in excess of the pollution source, the lack of relation between temperature inversion and pollution levels, the lack of adequate synoptic weather charts for correlation and prediction purposes. Such obstacles will also be encountered in the future; it is regarded as particularly important not to rely on any "classical" or "standard" model of pollution in the design of future experiments.

Acknowledgments

This investigation was supported by the United States Department of Health, Education and Welfare, Public Health Service Grant No. AP 00216 from the National Center for Air Pollution Control. Thanks are expressed to the many collaborators in Denver who either permitted the installation of our instrumentation on their premises or who furnished us with reports from their own instruments. Appendix A contains the list of all collaborators.

Special acknowledgment is due to Mr. L. A. Dobler, City of Denver air pollution engineer, and to Mr. J. Palomba, Jr., Colorado Public Health Department, who assisted the investigation in many ways and who made their facilities readily available in support of our program.

[4] Dr. J. E. Cermak, Colorado State University, has reported similar conclusions based on wind tunnel modeling of air pollution.

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Appendix A

Collaborating Organizations and Individuals

Adams City Health Center
4301 E. 72nd Avenue

Arapahoe County Health Center
4857 E. Broadway

Mrs. A. Barbre
3601 E. Dartmouth

Barteldes Seed Company
3770 E. 40th Avenue

Buckley Field

Byers Jr. High School
150 So. Pearl

Cherry Creek Dam
Parker Road (Southeast)

Cherry Creek Water & Sanitation Dist.
8501 E. Illiff Avenue

Denver Research Institute
2050 E. Illiff Avenue

Denver Sewage Treatment Plant
52nd at Downing Street

Dog Pound
4501 Youngfield

Denver School Administration Bldg.
414 14th Street

Dow Chemical Company
Rocky Flats, Colo.

Federal Center
6th & Kipling

General Chemical Company
1271 W. Bayoud

Hested Store Company
(FHL Corporation)

Hull Photo
5105 E. 38th Avenue

Jefferson County Health Center
260 So. Kipling

Jefferson High School
2305 Pierce Street

Kepner Junior High School
911 So. Hazel Court

Kunsmiller Jr. High School
2250 So. Quitman

Lake Junior High School
1820 Lowell Boulevard

Lowry Air Force Base

Martin Marietta Corporation
Waterton, Colorado

Merrill Junior High School
1551 So. Monroe Street

Morey Junior High School
840 E. 14th Avenue

North Denver High School
2960 No. Speer Boulevard

Northwest Engineering Corporation
6001 Dexter Street

Overland Municipal Golf Course
Santa Fe Drive & West Jewell Avenue

Gerald H. Phipps Inc.
1530 W. 13th Avenue

Public Service Company
West 7th & Alcott Street

Public Service Co. - Bellview Service
Center, Bellview at Windemere

Radio Station KIMN
5350 W. 20th Avenue

Radio Station KLZ
131 Speer Boulevard

Rocky Mountain Arsenal
Fire Department Station #1

Shwayder Brothers Inc.
1050 So. Broadway

Sigman Meat Company
6000 W. 54th Avenue

Signal Radio-TV Career School
1601 Arapahoe Street (D&F)

State Public Health
4210 E. 11th Avenue

U.S. Weather Bureau
19th & Stout Street (Downtown)

U.S. Weather Bureau
Stapleton International Airport

Western Research Labs
301 So. Cherokee Street

Wheatridge Fire Station
4184 Wadsworth Avenue

Yellow Cab Company
3455 Ringsby Court

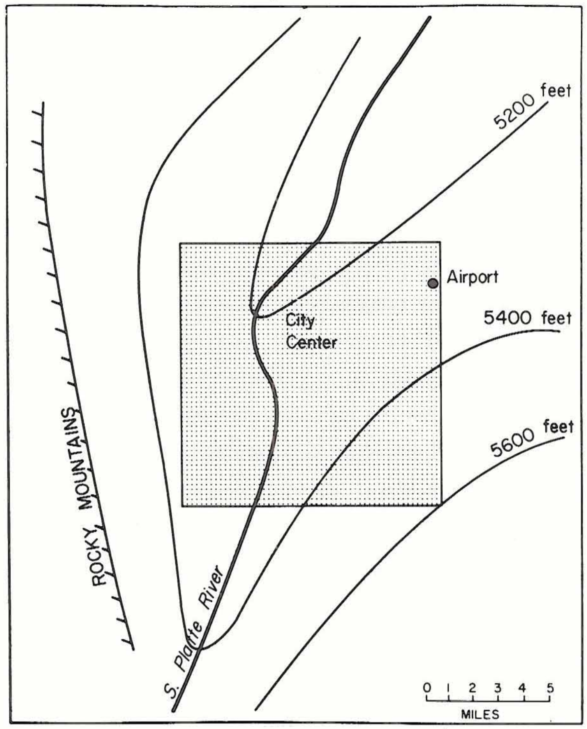


Fig. 1. Approximate city outline and environs of Denver.

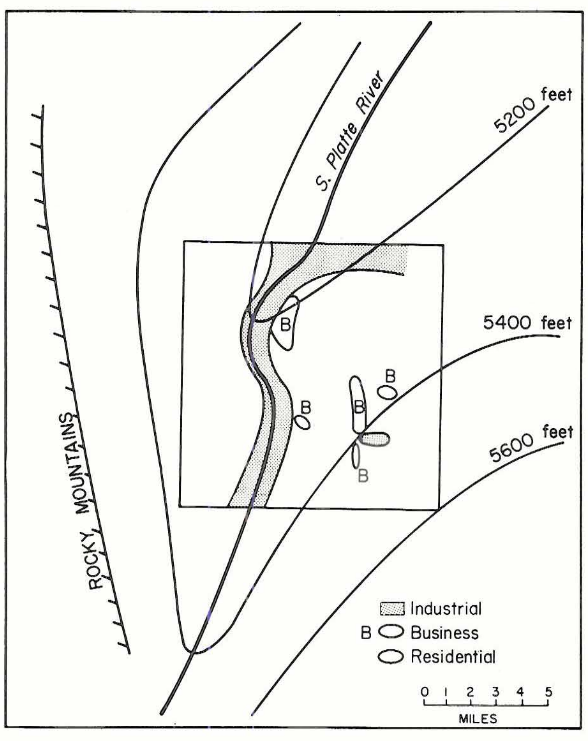


Fig. 2. General outline of principal activities within Denver.

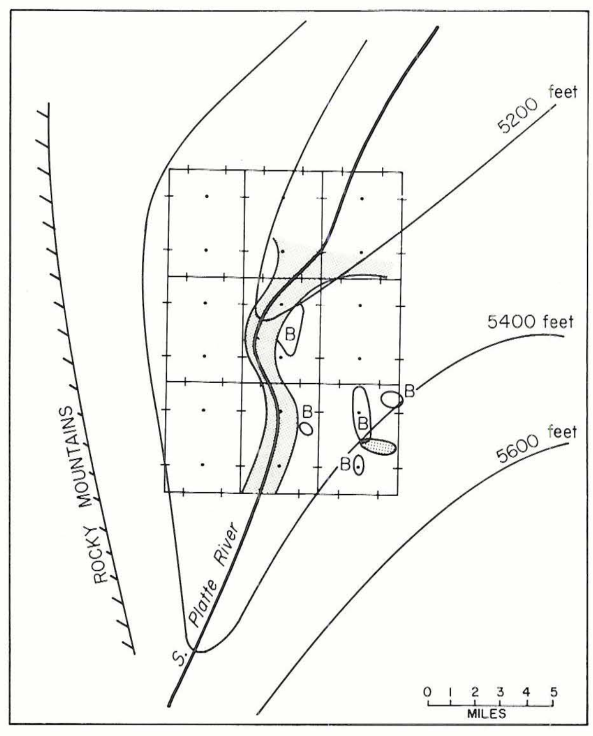


Fig. 3. General outline of principal activities in Denver with computation grid superimposed. This grid does not match the city outline precisely. It is designed to separate areas with different principal activities as much as possible. Note concentration of industry in the three central subareas.

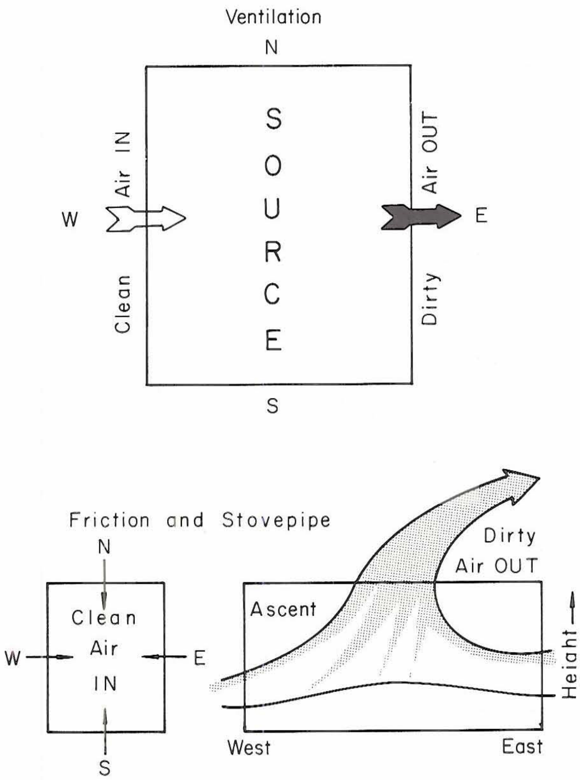


Fig. 4a. A sketch of ventilation and friction-stovepipe cleansing effects.

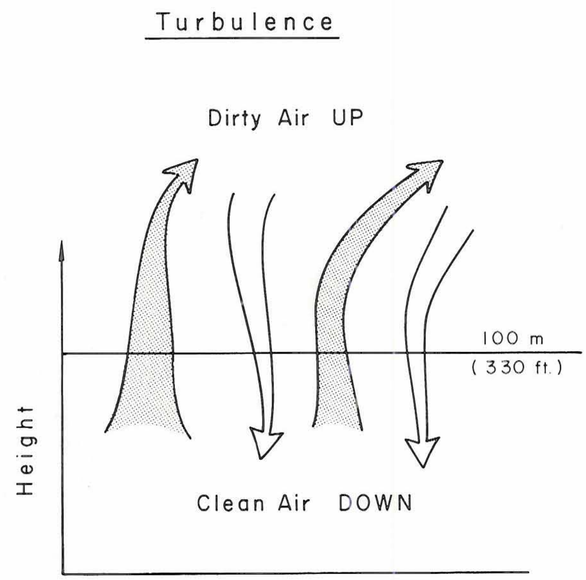


Fig. 4b. Sketch of turbulence cleansing effect.

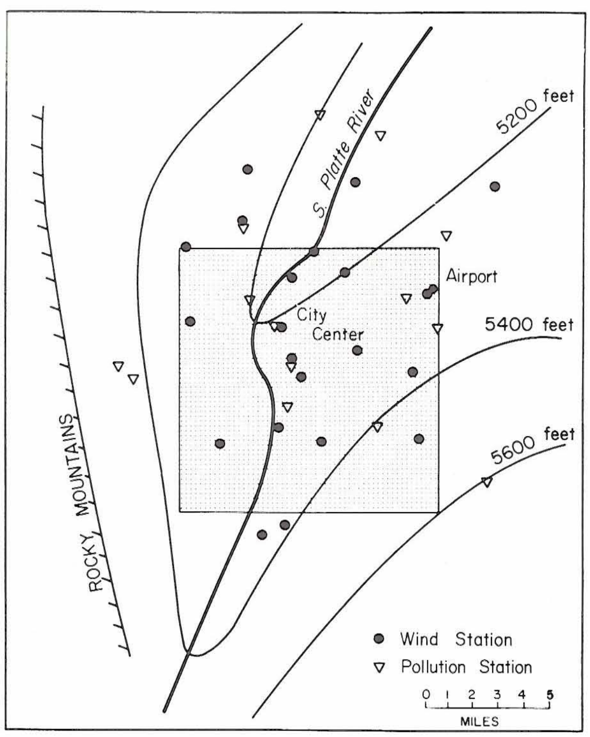


Fig. 5. Principal station network used during experiments.

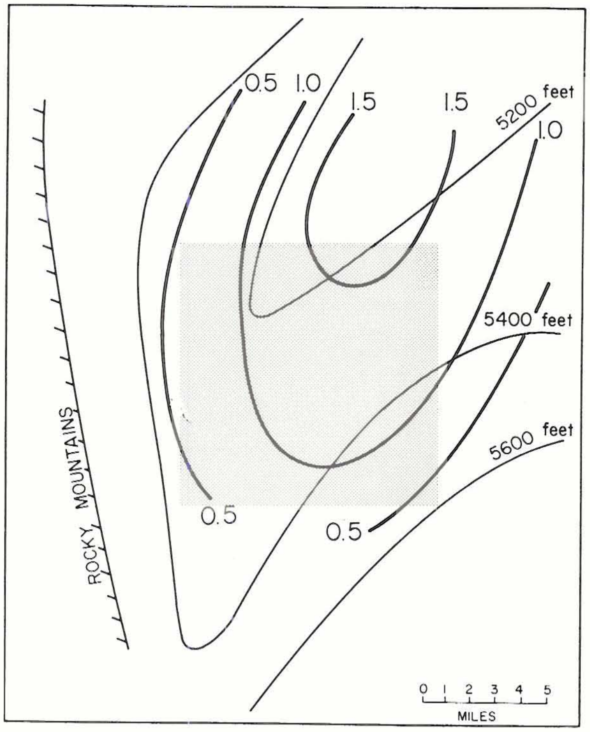


Fig. 6a. Example of individual map: Coefficient of haze, 2-4 a.m., February 3, 1965. (COH Units).

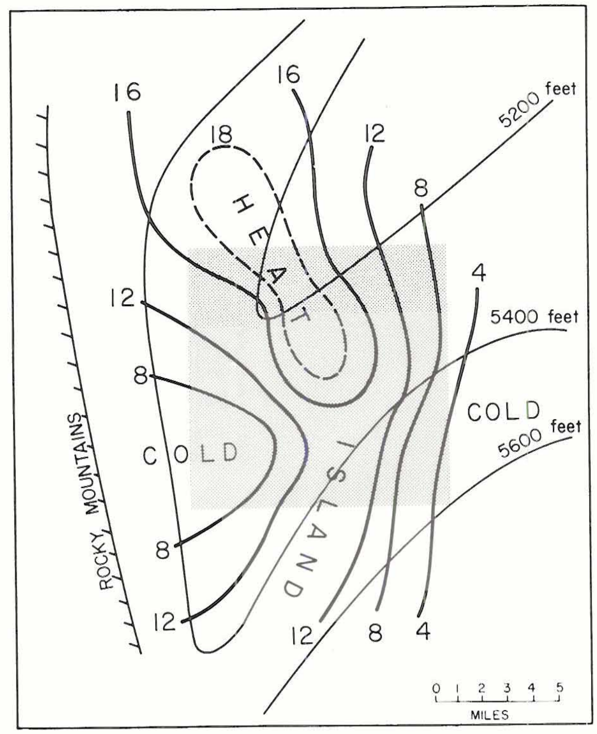


Fig. 6b. Temperature distribution (°F) for same period, showing elongated heat island.

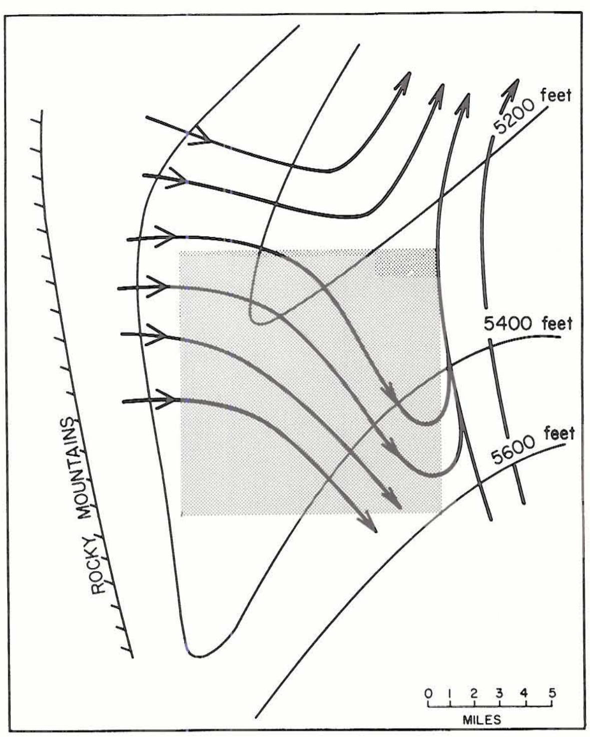


Fig. 6c. Streamlines showing direction of wind, same period.

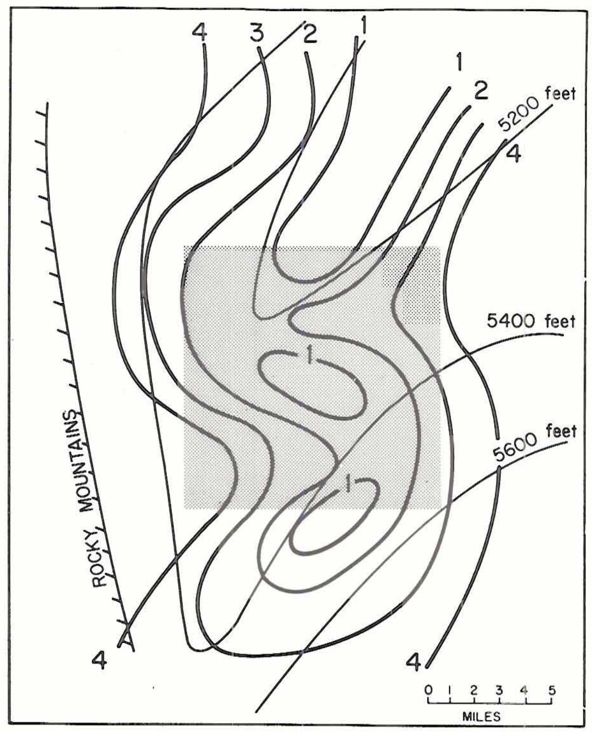


Fig. 6d. Wind speed, mph, same period. Note the typically low speeds inside built-up city area, much stronger winds just outside.

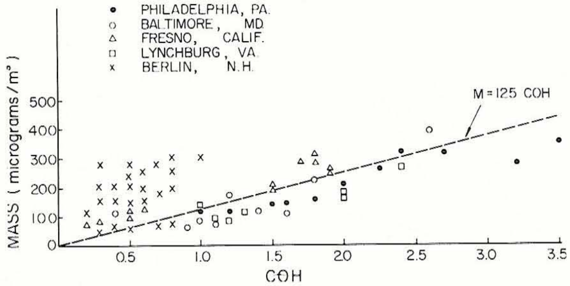


Fig. 7. Relation between COH and mass of particulates from several locations in the United States. Linear regression used in this report shown as dashed line.

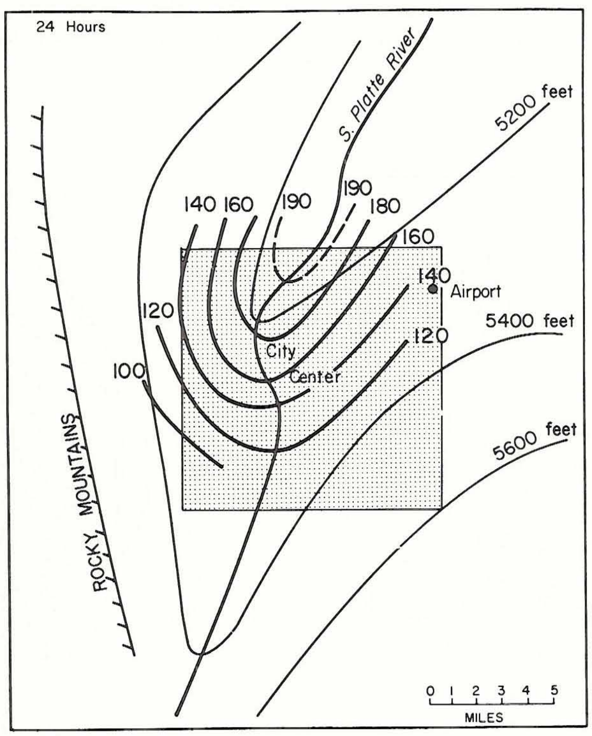


Fig. 8a. The 24-hour average distribution of particulate mass (micrograms/m^3).

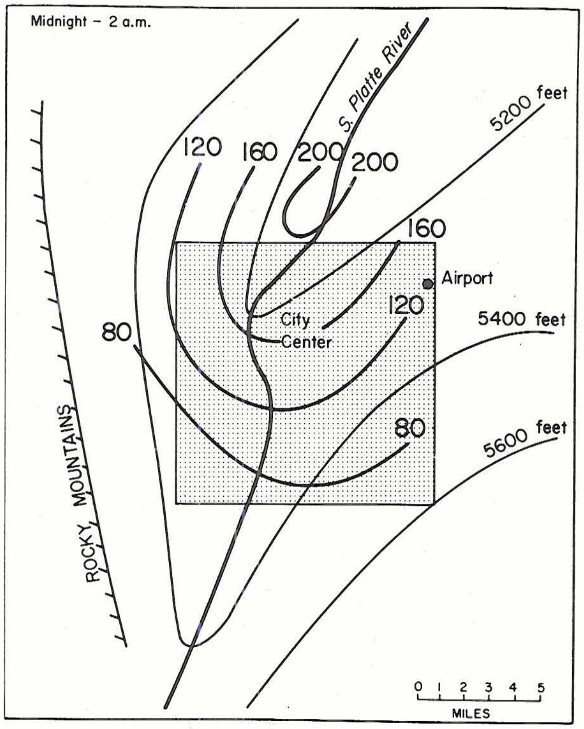


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

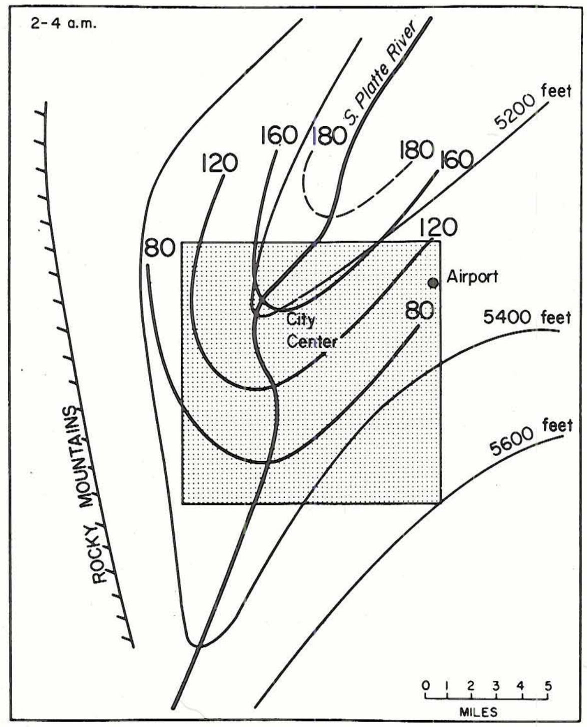


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

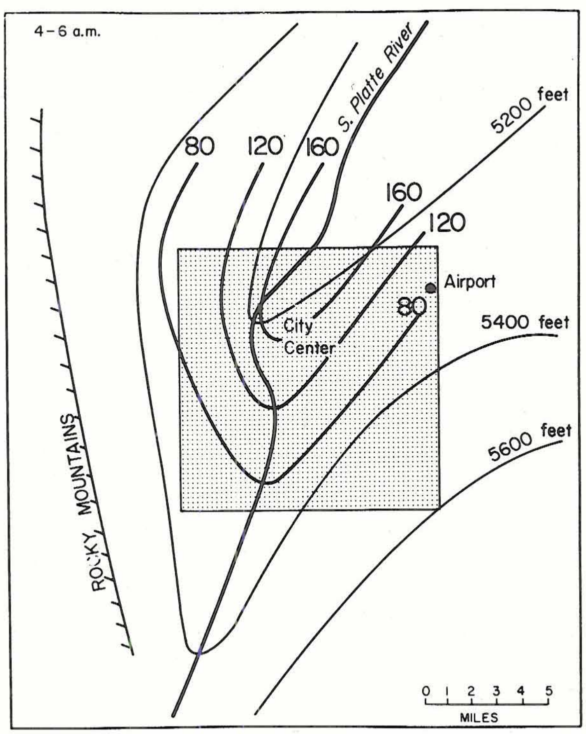


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

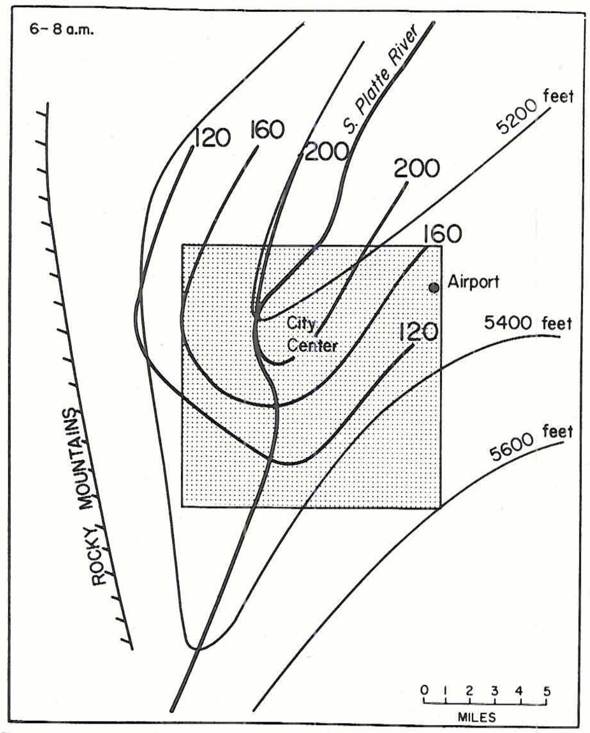


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

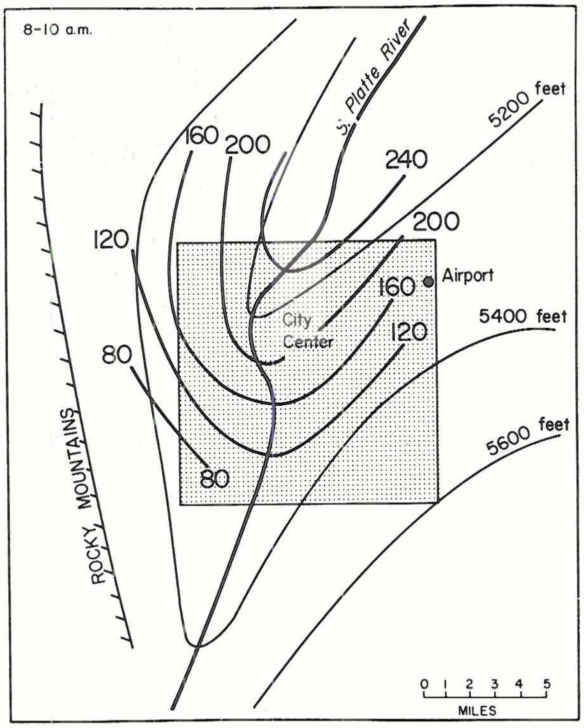


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

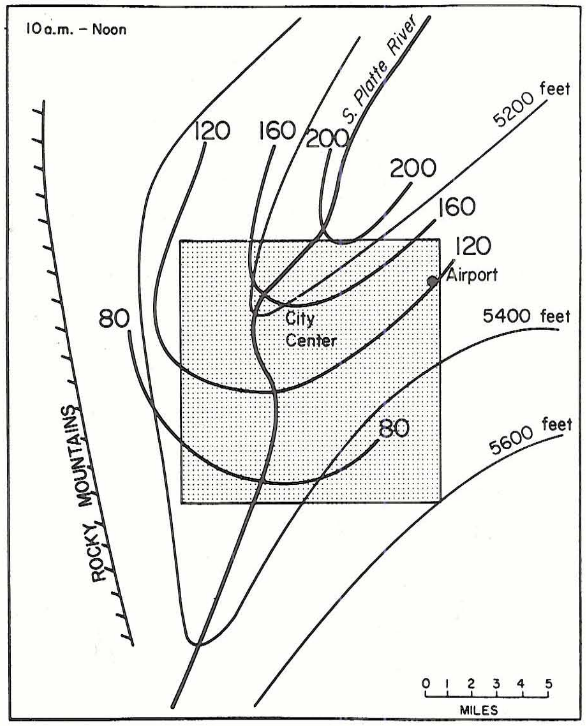


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

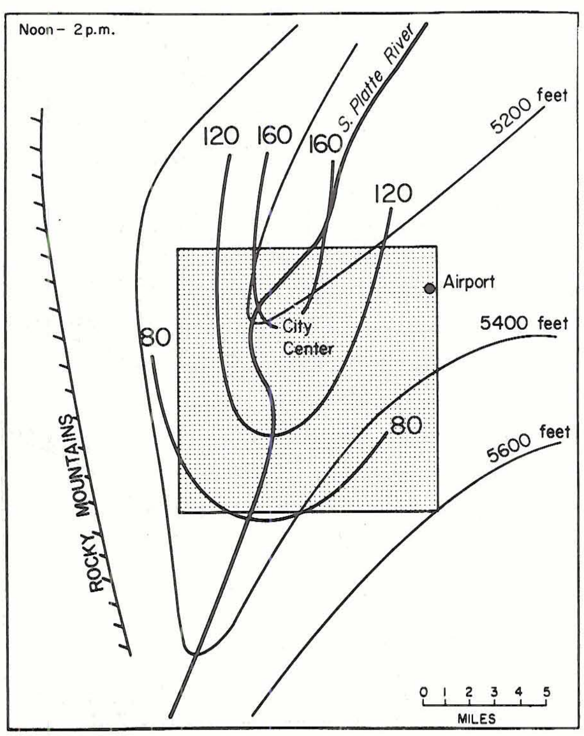


Fig. 8b. The average daily course in distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

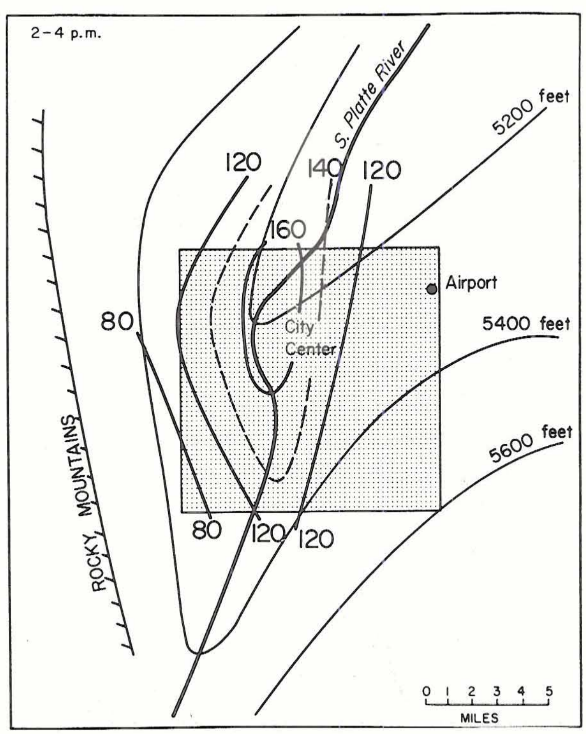


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

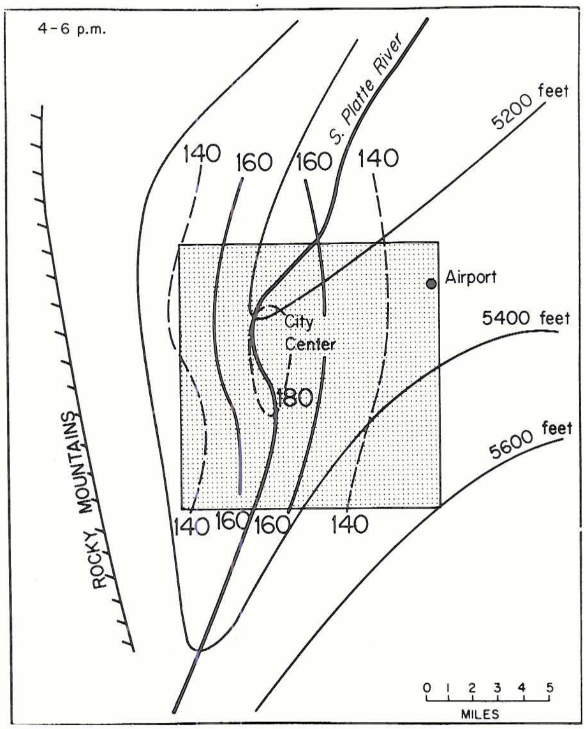


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

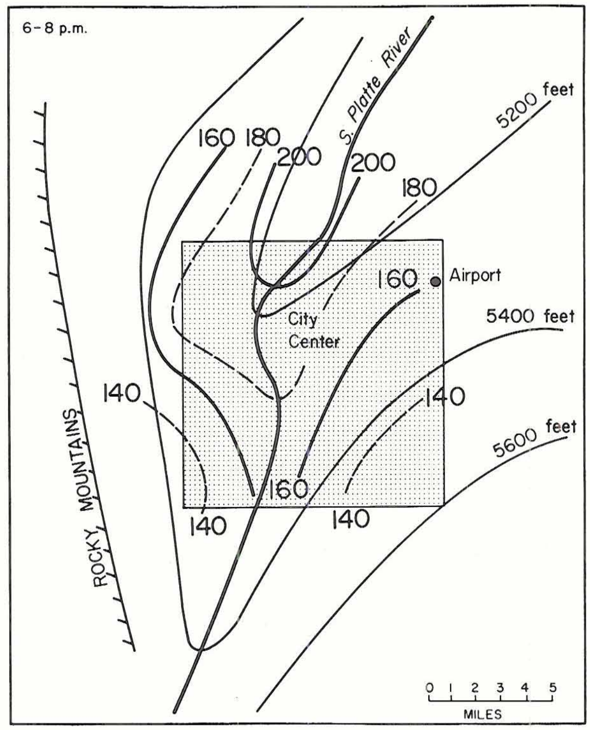


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

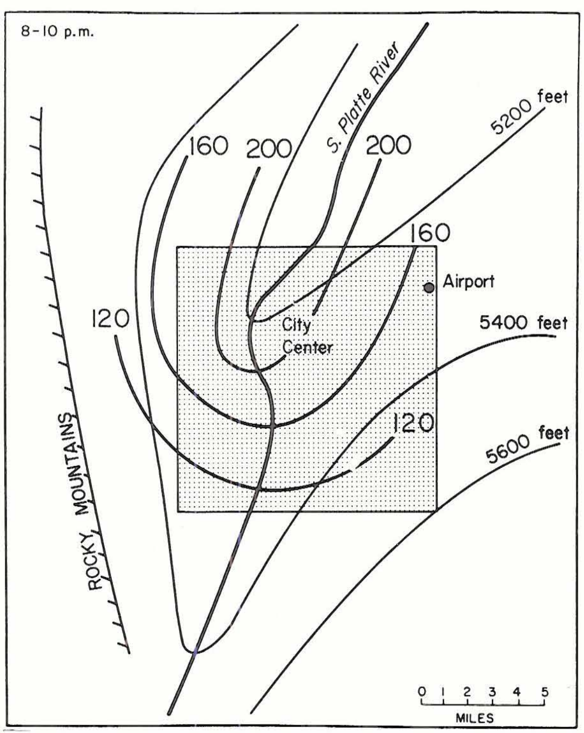


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

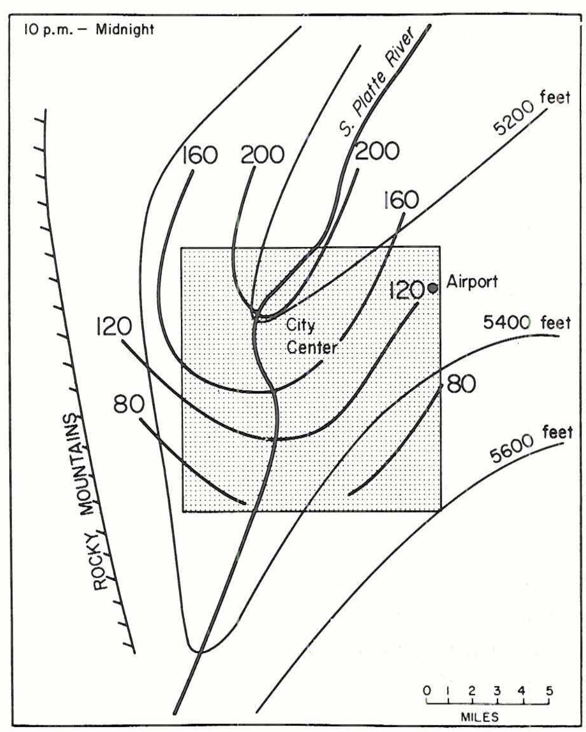


Fig. 8b. The average daily course of distribution of particulate mass in 2-hr. time steps during pollution episodes (micrograms/m^3).

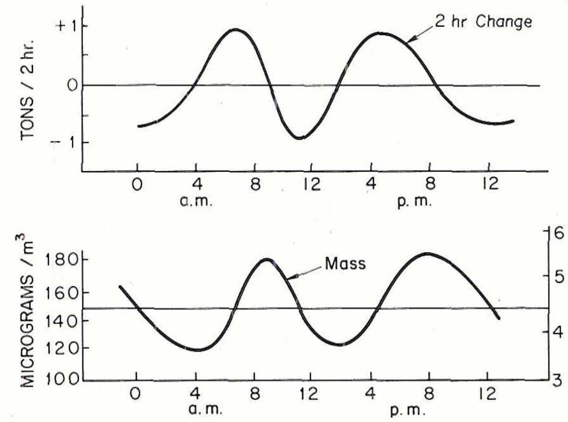


Fig. 9. Graphs showing average daily course of 2-hr. time changes and of total particulate mass over the city during pollution episodes (area of Fig. 3).

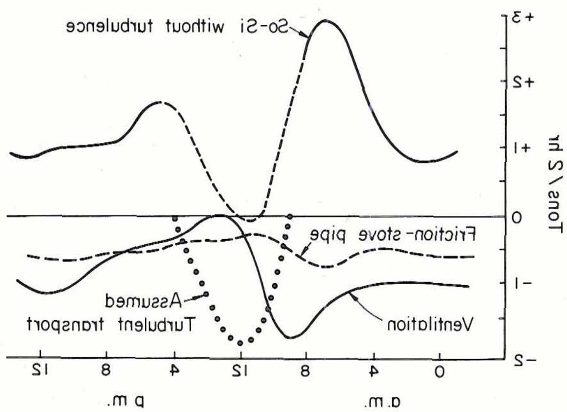


Fig. 10. Daily variation of average contribution of all transport mechanisms to removal of particulate mass, and So-Si calculated before inclusion of turbulence during pollution episodes.

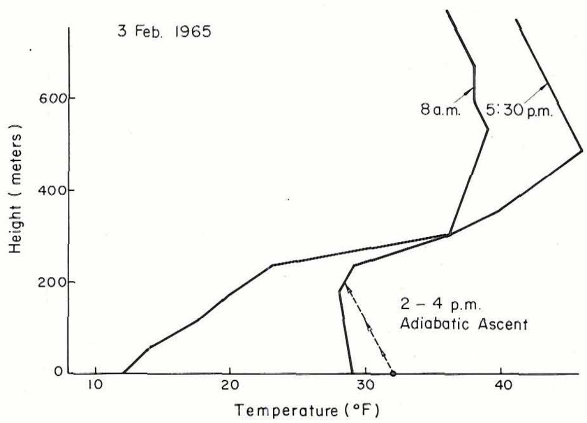


Fig. 11a. Temperature distribution with height as given by the Denver Airborne Traffic Police on February 3, 1965. Note intense and persisting inversion. Line with arrows indicates adiabatic ascent at time of maximum temperature, depth of mixing layer is limited to 200 meters.

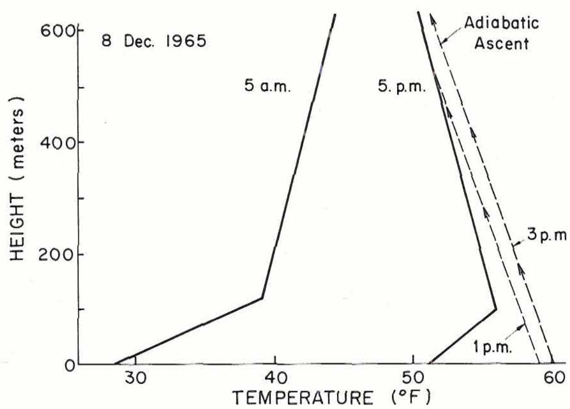


Fig. 11b. Same for December 8, 1965, from U.S. Weather Bureau soundings at Stapleton Field. In this case afternoon mixing theoretically can reach to 600 meters or higher as the temperature inversion structure is broken.

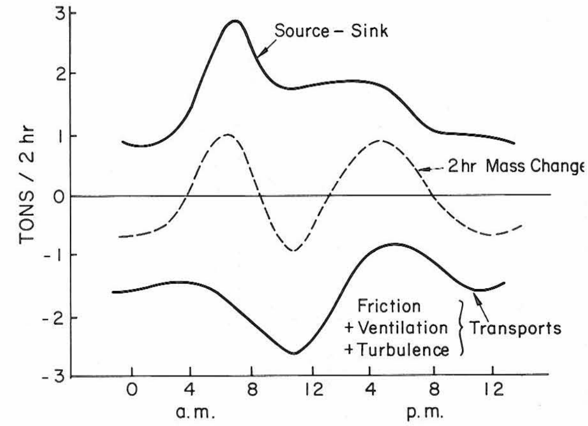


Fig. 12. Final graph of calculated So-Si and the sum of all transport processes showing how the average daily course of change in particulate mass is produced during pollution episodes.

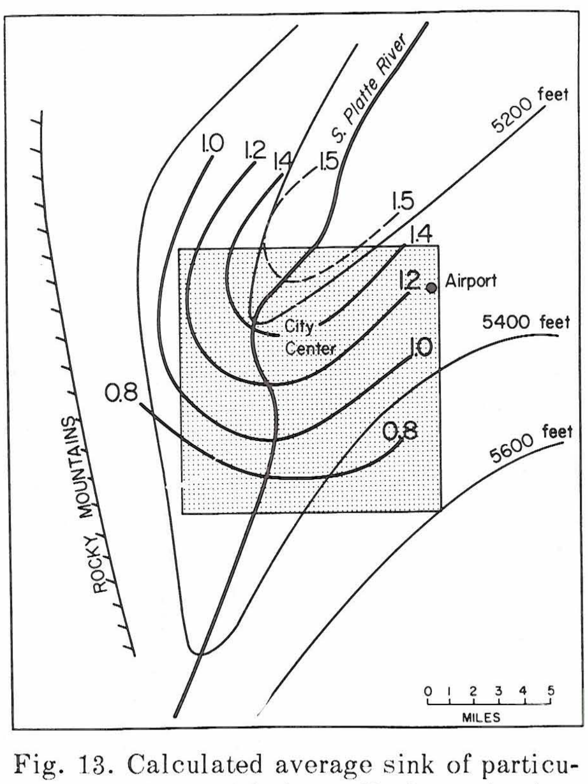


Fig. 13. Calculated average sink of particulates in 24 hours during pollution episodes. Units in tons per day for areas with size of the subareas in Fig. 3.

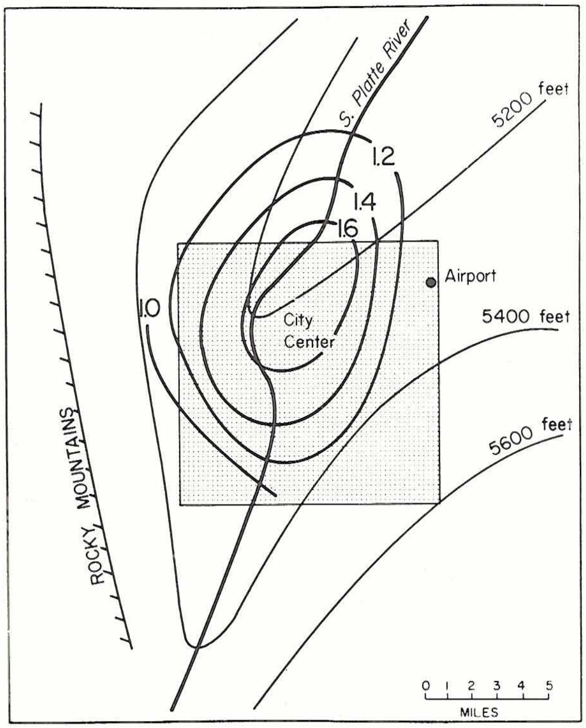


Fig. 14a. Calculated pollution source, 8 a.m. to 4 p.m. Unit in tons per 8 hours for areas with size of the subareas in Fig. 3.

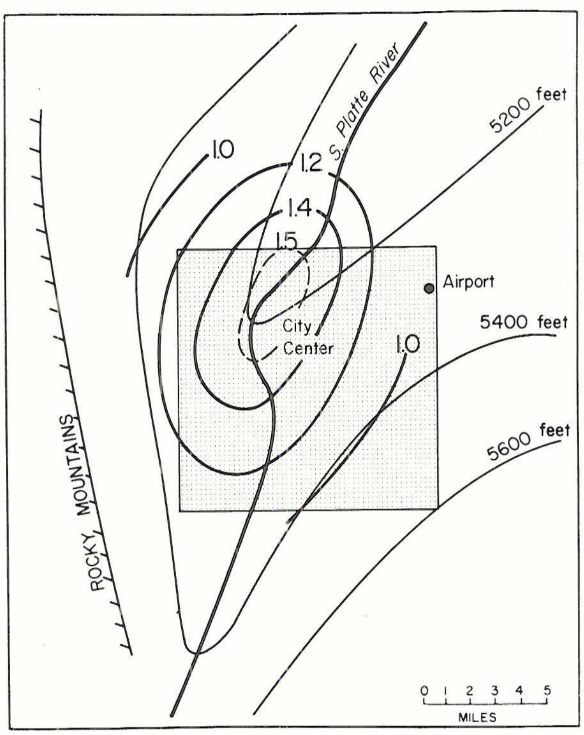


Fig. 14b. Calculated pollution source, 4 a.m. to 8 a.m., and 4 p.m. to 8 p.m. Note rather uniform source in these transition hours.

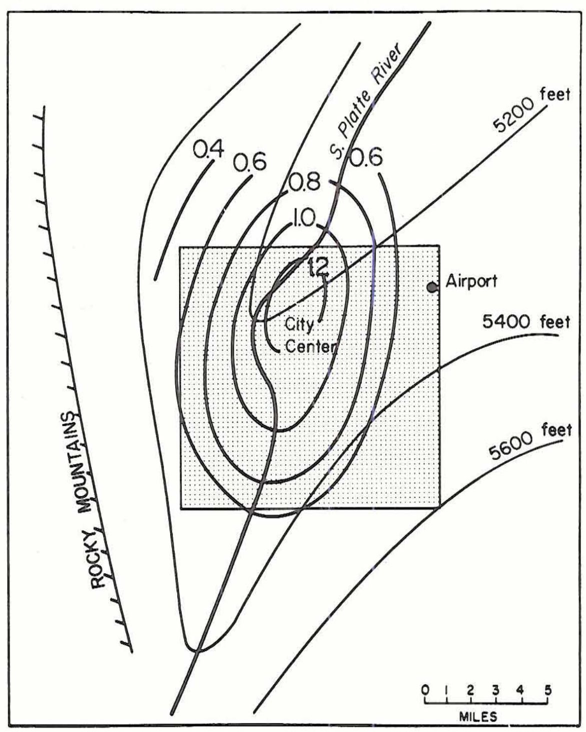


Fig. 14c. Calculated pollution source, 8 p.m. to 4 p.m. Note strong decline of source from city center outward at night.

Fig. 15a. Photo taken by Mr. Grover from airplane at 7,000 feet altitude about 8:30 a.m. on February 3, 1965. The view is toward east from the west edge of Denver across Sloan Lake. City center is barely visible.

Fig. 15b. Another shot highlighting the rather clear air in the western suburbs and the concentrated mass of pollutants farther east.

Fig. 15c. Photo looking toward north from the Valley Highway at Sedalia south of Denver a few minutes later. The southern edge of the pollution and its concentration in the eastern portion of the photo are clearly marked.

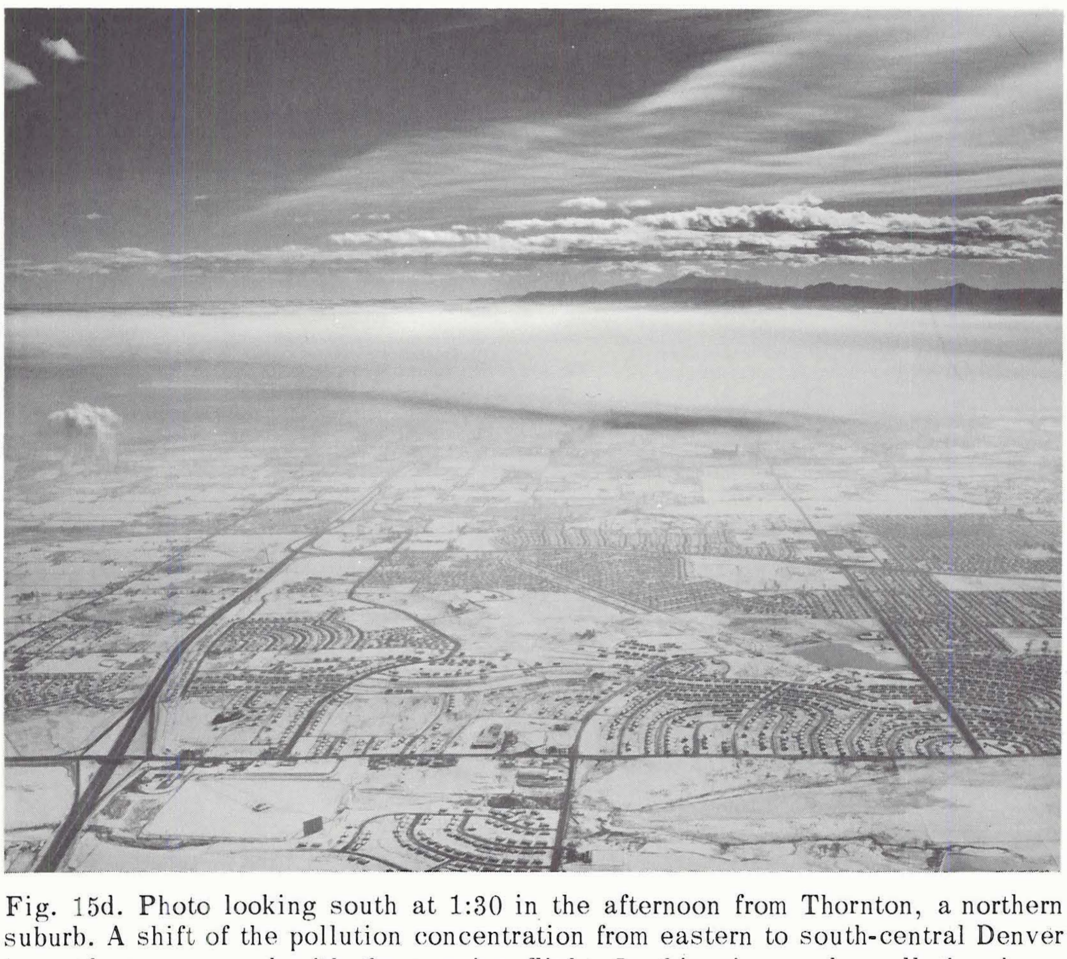


Fig. 15d. Photo looking south at 1:30 in the afternoon from Thornton, a northern suburb. A shift of the pollution concentration from eastern to south-central Denver is evident, compared with the morning flight. In this picture the pollution is so thick that no buildings in downtown Denver are visible.

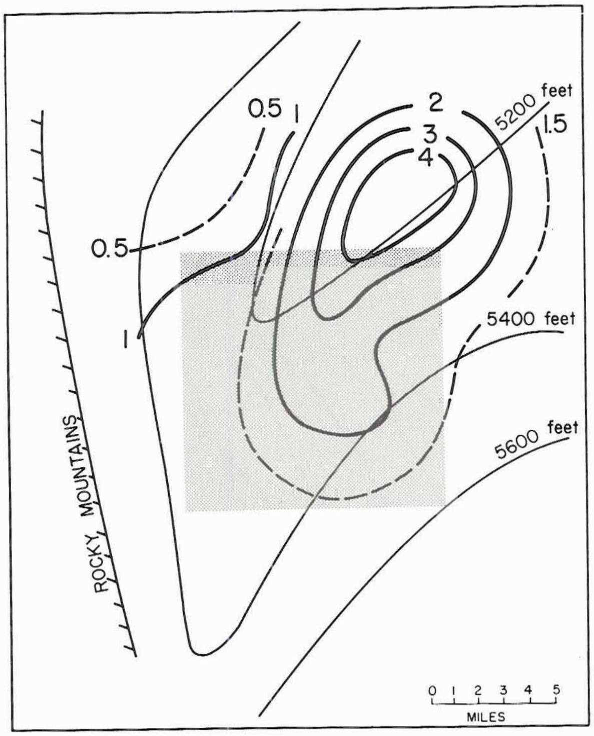


Fig. 16a. Chart showing distribution of coefficient of haze, February 3, 1965, 6 to 8 a.m. (COH units)

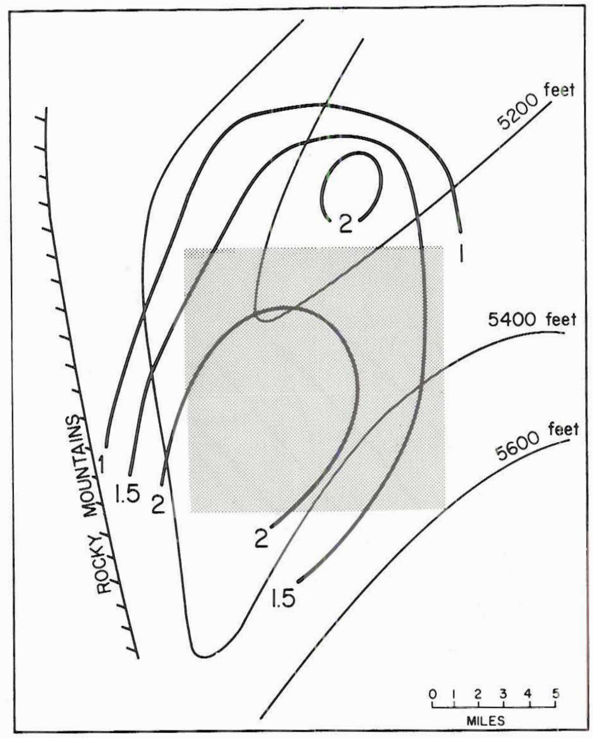


Fig. 16b. Same for noon to 2 p.m. on same day.

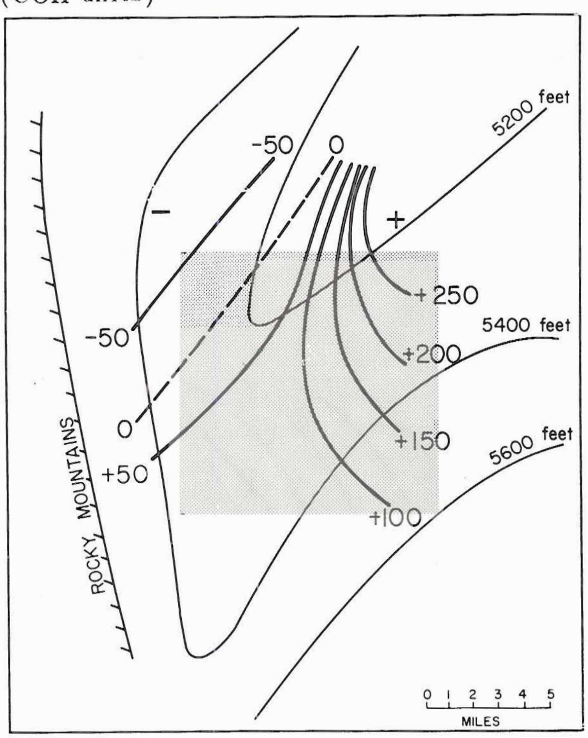


Fig. 17a. Deviation of the field in Fig. 16a from that for the corresponding time of day in Fig. 8. Units: micrograms/m^3. In spite of very heavy concentration in the northeast, the western outskirts of Denver have rather breathable air—see photographs above.

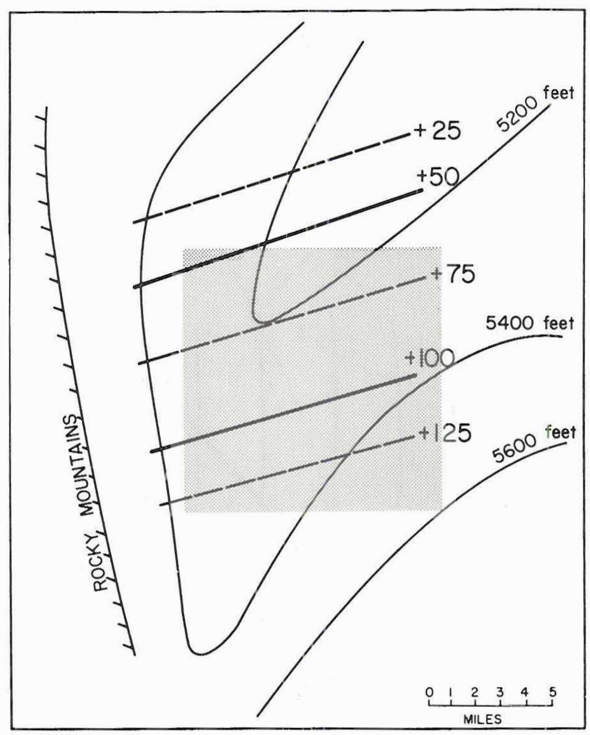
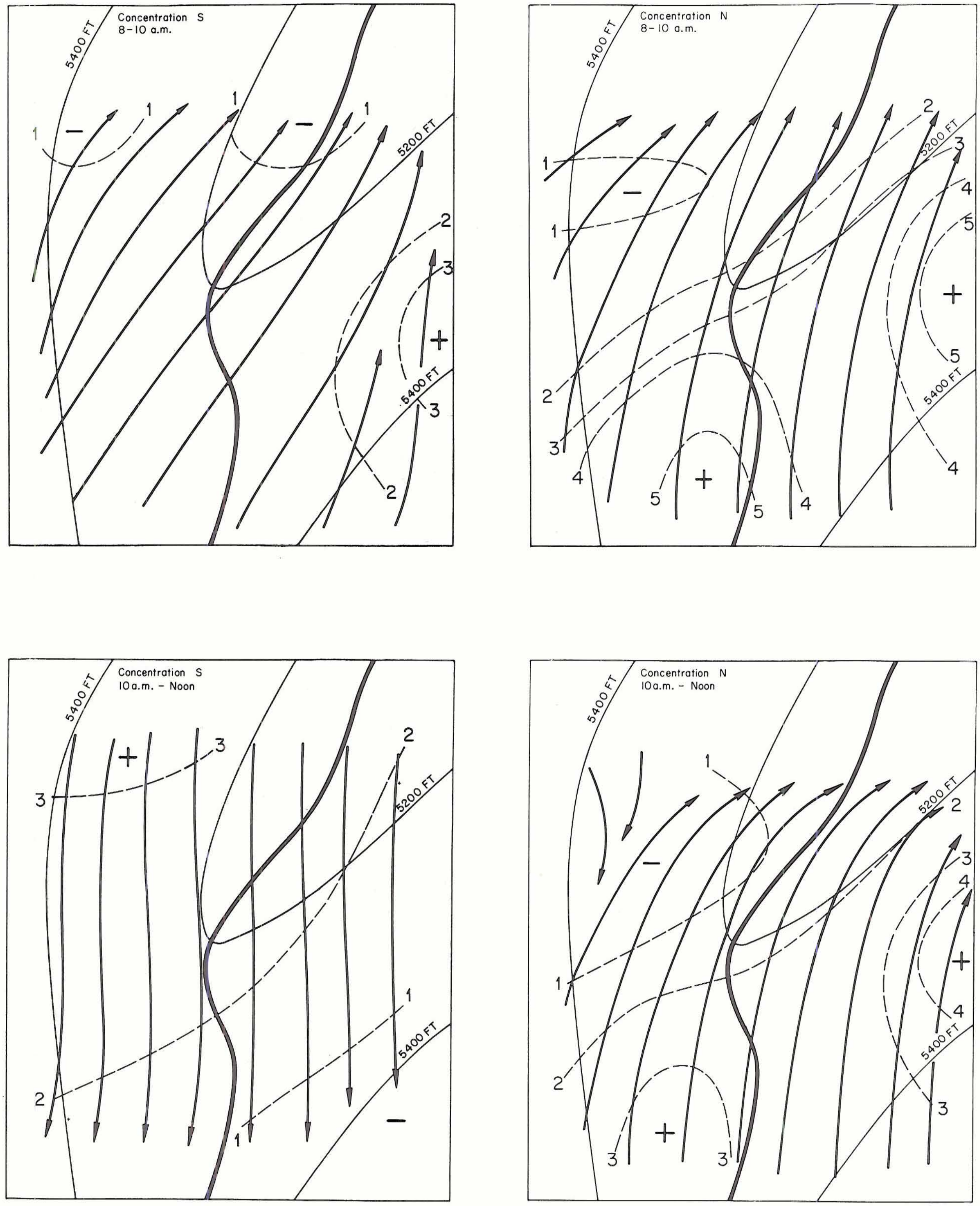
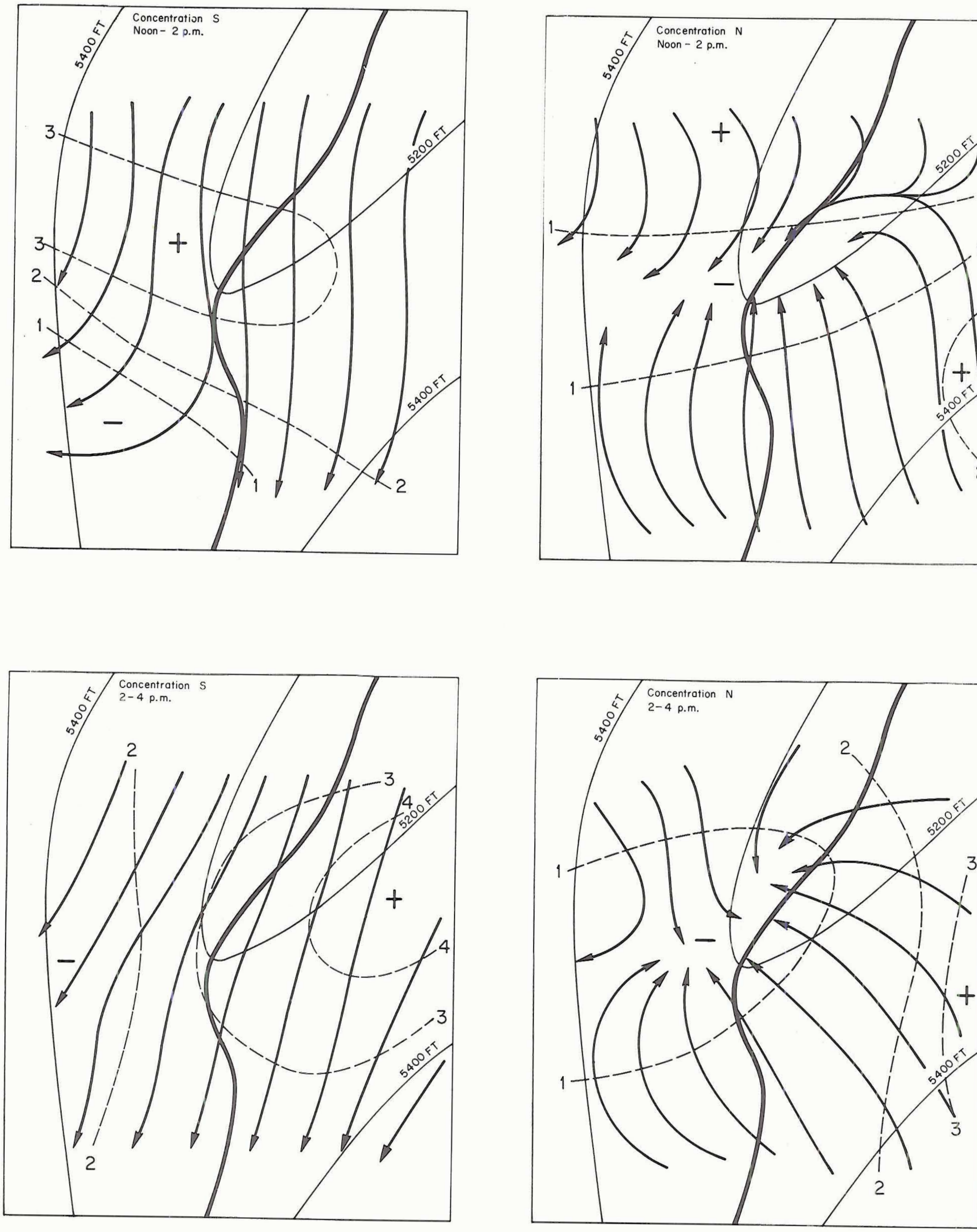
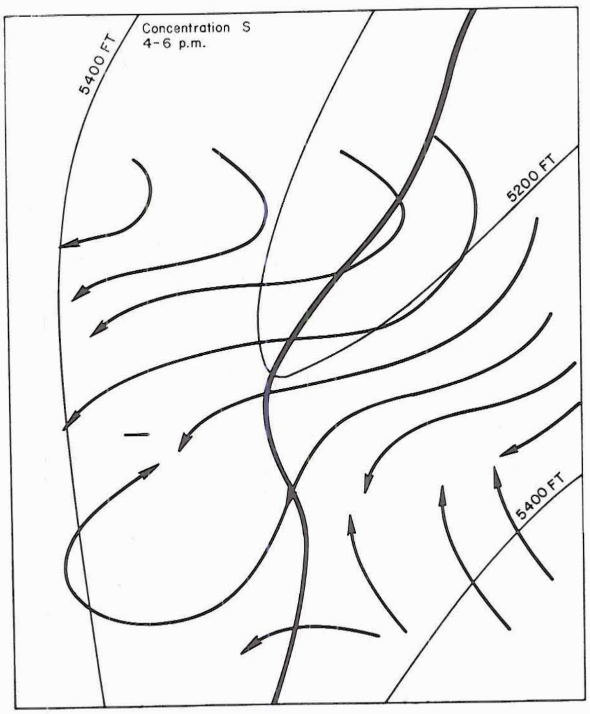


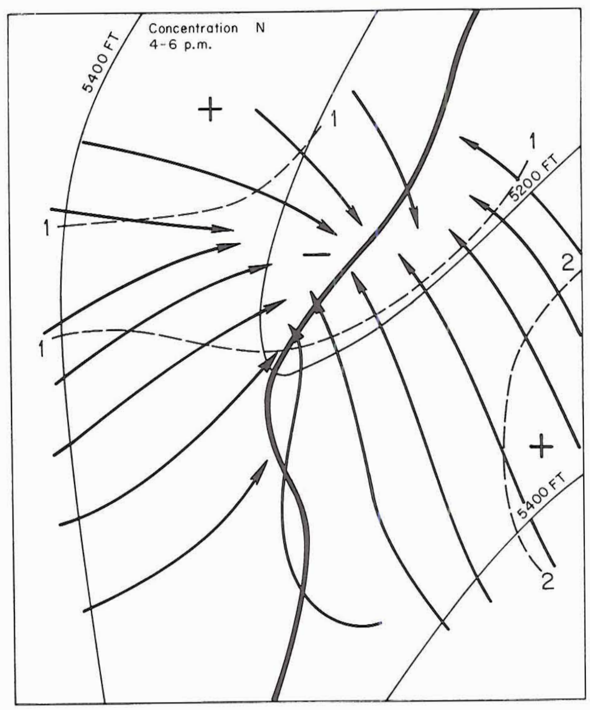
Fig. 17b. Same for noon to 2 p.m. Observe shift on concentration toward south as verified by airborne photograph.

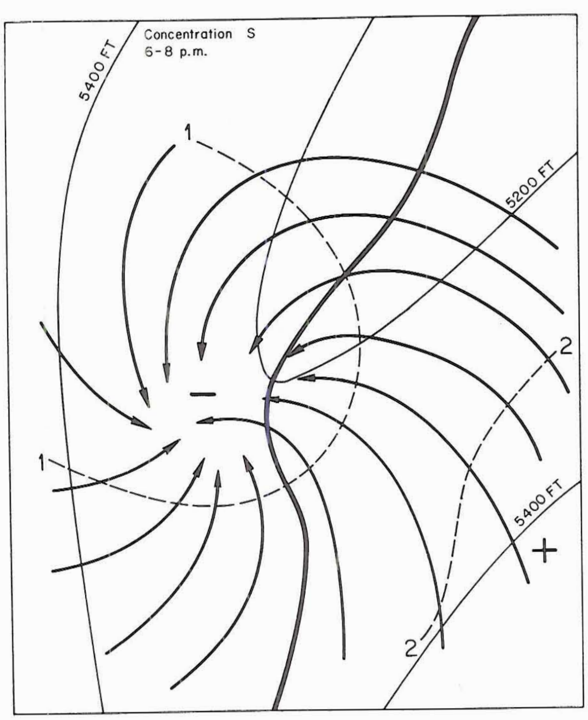
Fig. 18. Comparison of wind field (streamlines and isotachs in mph) during periods with pollution concentration in North Denver and in South Denver at various times of day. Note spectacular patterns in afternoon.

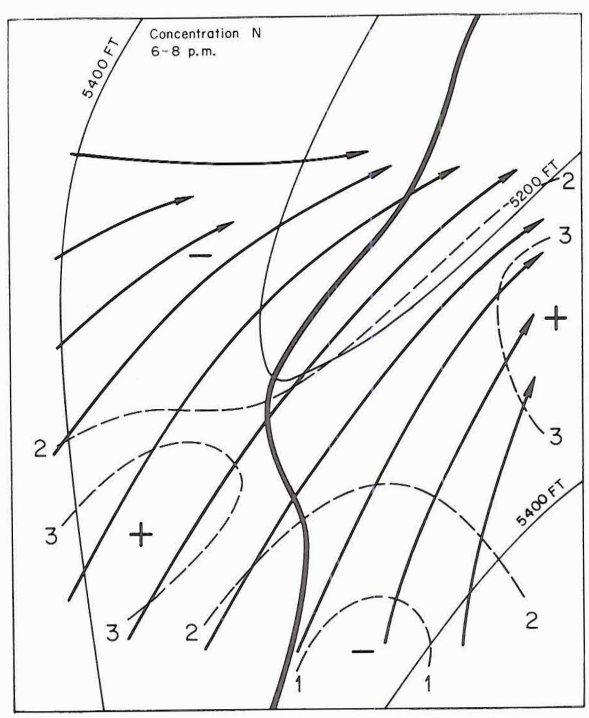


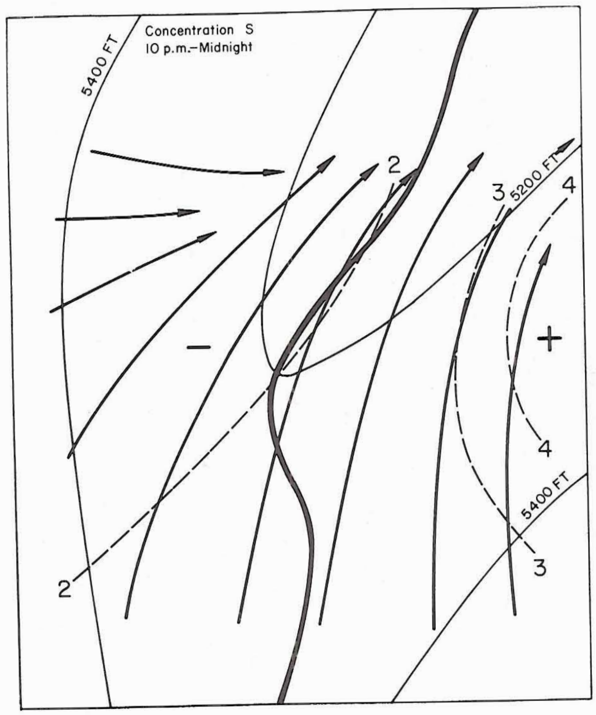

Concentration S
Noon - 2 p.m.
5400 FT
5200 FT
5400 FT
Concentration N
Noon - 2 p.m.
5400 FT
5200 FT
5400 FT
Concentration S
2-4 p.m.
5400 FT
5200 FT
5400 FT
Concentration N
2-4 p.m.
5400 FT
5200 FT
5400 FT


Concentration S
4-6 p.m.
5400 FT
5200 FT
5400 FT
–

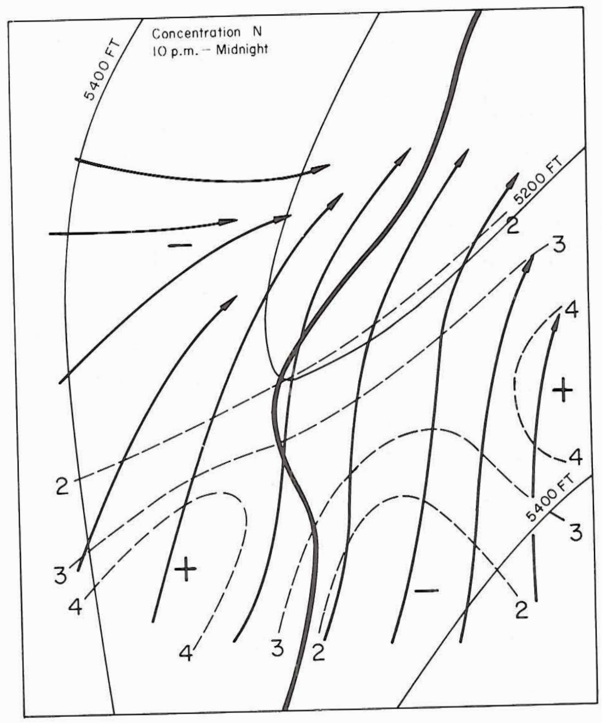

Concentration N
4-6 p.m.
5400 FT
5200 FT
5400 FT
+
–
+
1
1
1
1
2
2


Concentration S
6-8 p.m.
5400 FT
5200 FT
5400 FT
1
1
2
2
–
+


Concentration N
6-8 p.m.
5400 FT
5200 FT
5400 FT
–
+
+
–
2
3
3
2
3
3
2
2
1
1

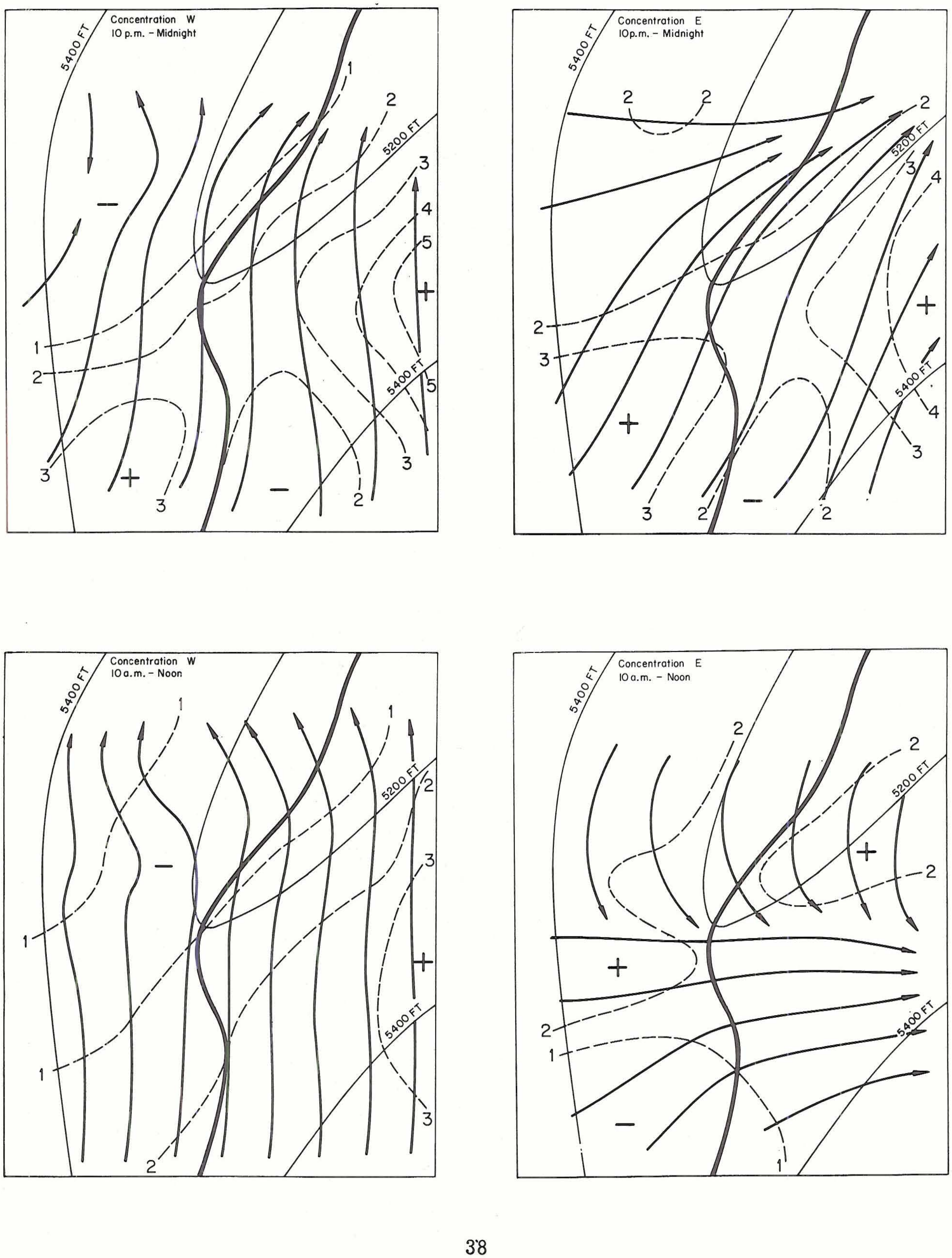


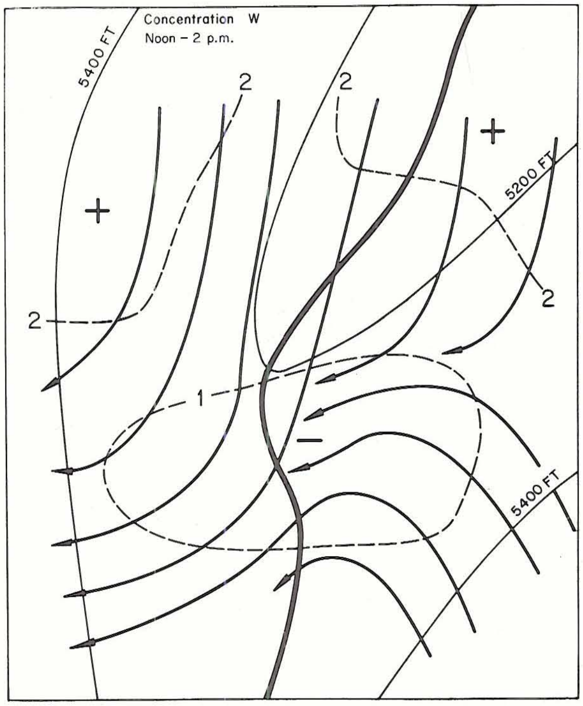
Concentration S
10 p.m.–Midnight
5400 FT
5200 FT
5400 FT
2
3
4
2
3
4
–
+

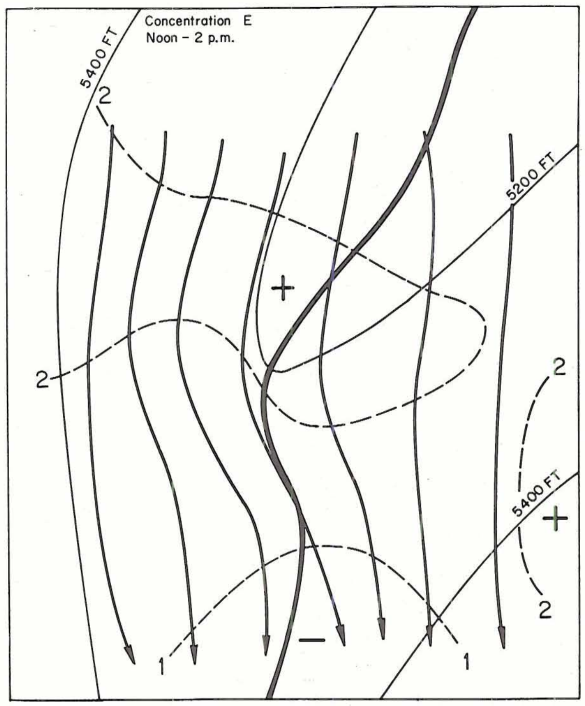


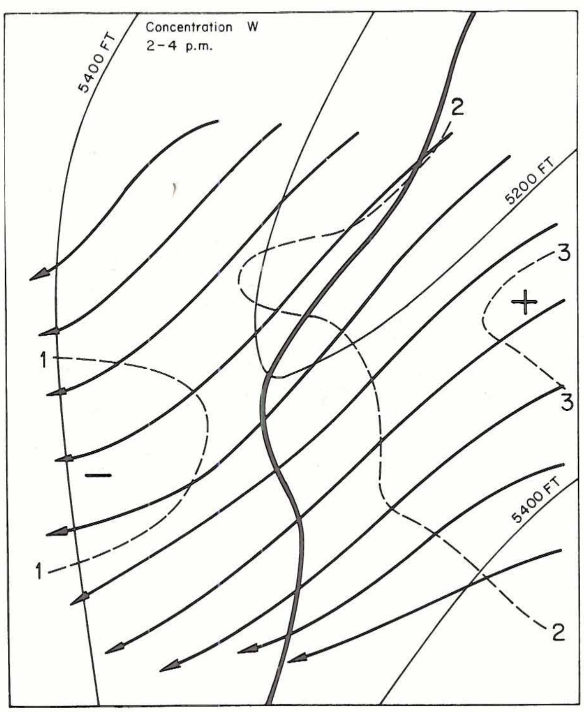
Concentration N
10 p.m. – Midnight
5400 FT
5200 FT
5400 FT
2
3
4
4
3
2
2
3
4
4
3
2
–
+
+
–

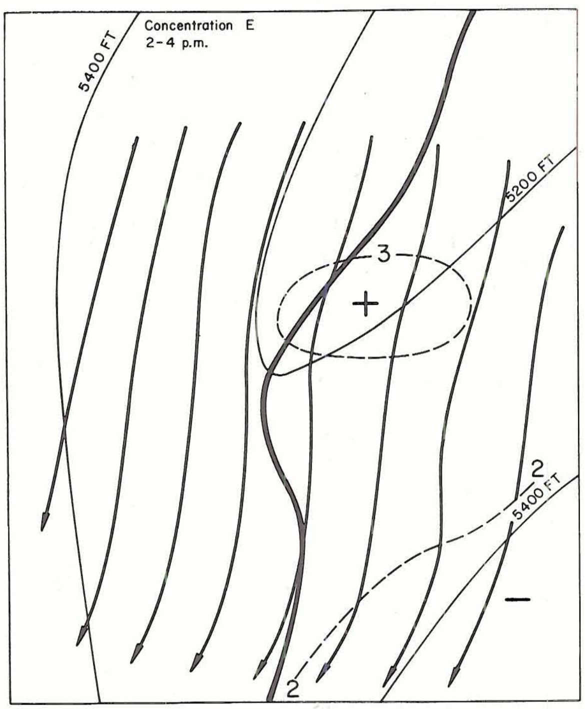
Fig. 19. Comparison of wind field (streamlines and isotachs in mph) during periods with pollution concentration in West Denver and in East Denver at various times of day.

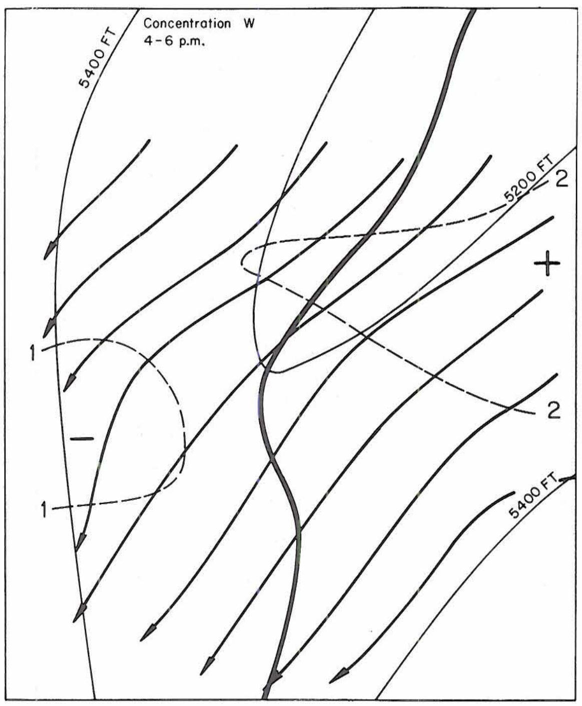


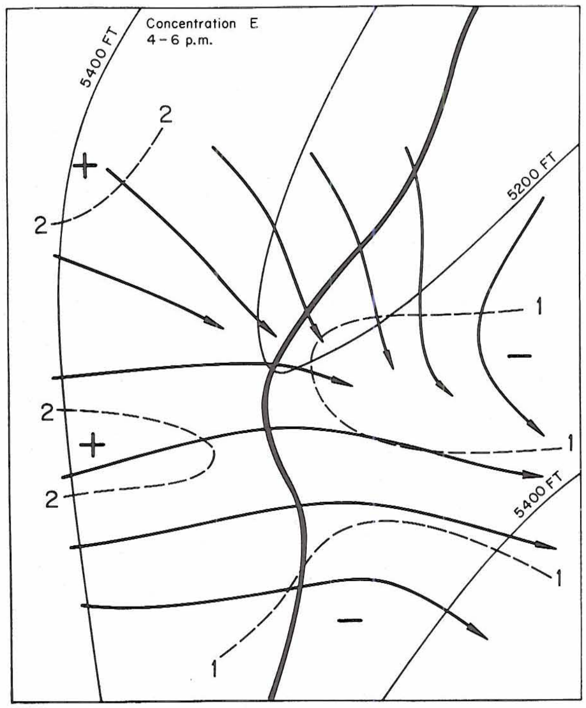

Concentration W
Noon – 2 p.m.
5400 FT
5200 FT
5400 FT
2
2
2
2
1
+
+
–

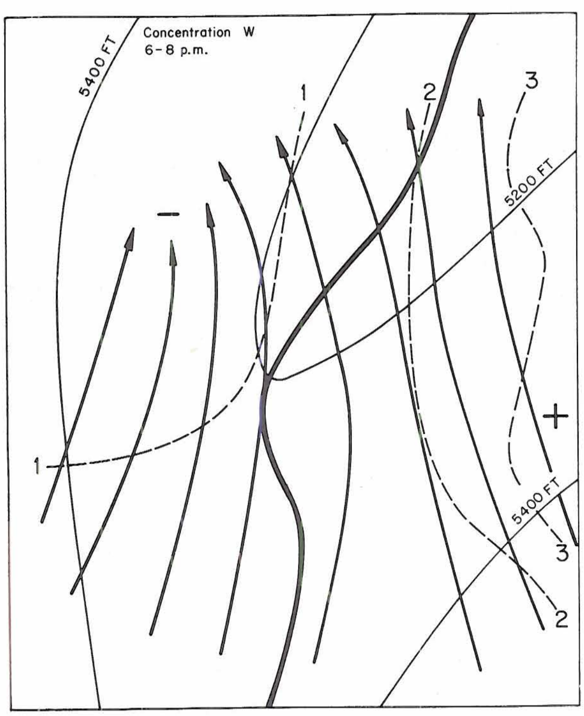

Concentration E
Noon – 2 p.m.
5400 FT
5200 FT
5400 FT
2
2
2
2
1
1
+
+
–

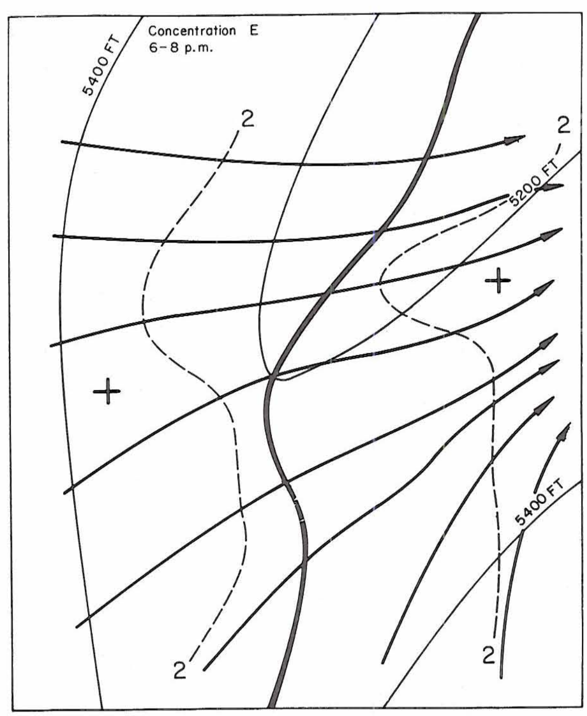

Concentration W
2–4 p.m.
5400 FT
5200 FT
5400 FT
2
3
3
1
1
2
+
–


Concentration E
2–4 p.m.
5400 FT
5200 FT
5400 FT
3
2
2
+
–


Concentration W
4 - 6 p.m.
5400 FT
5200 FT
5400 FT
2
1
2
1
+
−


Concentration E
4 - 6 p.m.
5400 FT
5200 FT
5400 FT
2
2
1
1
2
2
1
1
+
+
−
−


Concentration W
6 - 8 p.m.
5400 FT
5200 FT
5400 FT
1
2
3
1
3
2
−
+


Concentration E
6 - 8 p.m.
5400 FT
5200 FT
5400 FT
2
2
2
2
+
+

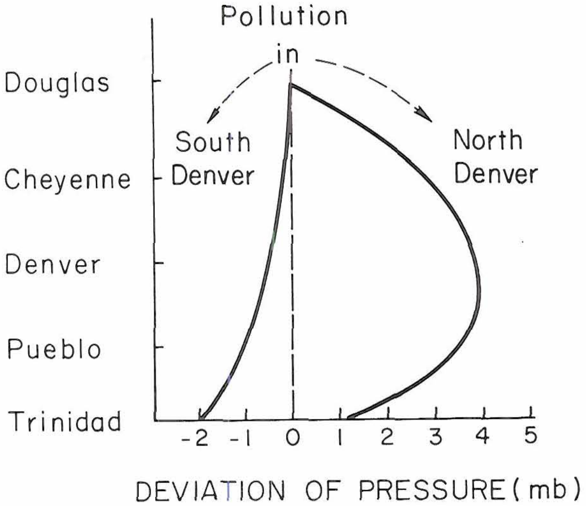


Fig. 20. Profile of pressure reduced to sea level from Douglas, Wyo., to Trinidad, Colo., during periods of pollution concentration in North Denver and in South Denver. Smoothed average from nine cases using 6-hourly Weather Bureau maps at 5 a.m., 11 a.m. and 5 p.m. MST.

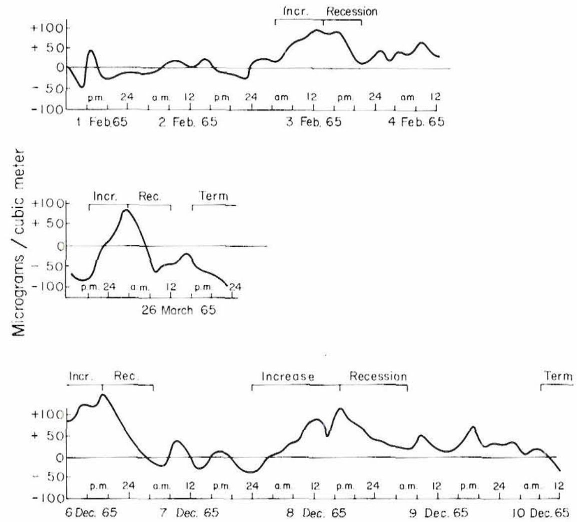


Fig. 21. Time history of citywide pollution for 3 pollution episodes. Unit is micrograms/m^3, expressed as deviation from the average daily trend in Fig. 9. Note the short duration of peak pollution and rather symmetric onset and recession.

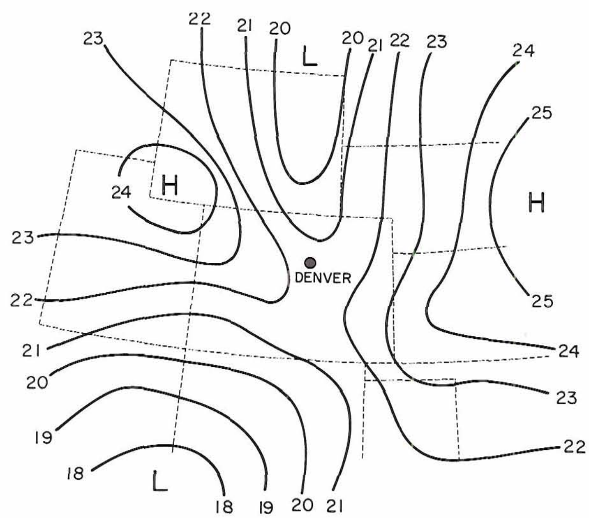


Fig. 22. Composite 5 a.m. map of sea level pressure (mb, first two digits omitted) for days with start of pollution episodes.