Weather Factors in Denver Air Pollution

by

Herbert Riehl and Dirk Herkhof

February 3, 1965, happened to be a very smoggy day in Denver. Here is a photo taken from an airplane at 7,000 feet altitude about 8:30 a.m. The view is toward east from the west edge of Denver across Sloan Lake. The city center was barely visible while the air in the western suburbs was quite clean.

Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

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Herbert Riehl

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An abridged version of the final report to
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ABSTRACT

This report is concerned with determining the meteorological influences on air pollution in the city of Denver. Objectives are:

(1) To provide information suitable for aiding city authorities in framing effective ordinances on occasions when dangerous pollution levels may develop for hours or days,

(2) To provide information on the normal course of air pollution that may serve as a guide for possible gradual restructuring of the city for maximum air quality.

The sources of pollution are roughly the same day for day, at least Monday through Friday. But the intensity of pollution may cover a large range during a week, from brilliantly clear to very dirty skies with the mountain view blotted out. <u>Only meteorological factors</u> can account for the difference. In order to ascertain these factors in detail for Denver, a large network of stations measuring wind, temperature and coefficient of haze was maintained in the metropolitan area during the winters of 1964-65 and 1965-66.

Wind is the most important factor, acting in three ways. Pollution is removed from the city in part by what may be termed the "friction-stovepipe" effect, a net indraft of air into the city which rises there and moves away at higher elevations; in part by ventilation from general winds blowing across town from one side to the other; and to a smaller extent by turbulent up-and-down air motions in the middle of the day.

When the strength of the winds falls below normal levels, a pollution episode begins. The city sources put more pollutants into the air than the winds will remove. However, in general, pollution does not increase as a uniform blanket over the city. Rather, it is common for the polluted mass to become concentrated in one part of town by the winds, while other parts are quite clear. The circumstances governing the location of such concentrations have been explored together with an attempt to forecast them as far as possible.

Citywide rises of pollution intensity also occur, so far, fortunately, without attaining extreme levels experienced elsewhere. The onset and recession of these periods have been analyzed. 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 roughly of one day. In this sequence, changing winds also play the determining role.

The source of pollution is strongest in the center of the city day and night. However, the outer parts of the metropolitan area also contribute substantially, so that any ordinance designed to prevent extreme pollution levels must be directed against citywide sources rather than just a few particular industries.

Highest pollution levels normally are encountered north and northeast of Denver, even though the strongest source lies in downtown Denver. The winds are predominantly from south, down the Platte River; thus highest pollution levels are situated well downstream from the strongest source. Pollution intensity in South Denver averages only half that of North Denver. These relations between prevailing wind flow and concentration of pollution are suggestive for long term city planning.

Introduction

In 1970, wide segments of the population of the United States and of other nations have become alert to the dangers for human existence inherent in world-wide contamination from air pollution. Experience with this problem, of course, dates far back; it has led to strong pollution control measures in cities such as London, England, Pittsburgh and St. Louis. Regarding Denver, an exploratory experiment on the role of the weather factors on air pollution was conducted in the winter of 1961-62 under a grant from the Helen Dean Yetter Foundation to Colorado State University, with collaboration by the Colorado State Department of Public Health, the City of Denver Air Pollution Engineer, and various other organizations and private individuals. The report on this experiment is entitled A STUDY OF DENVER AIR POLLUTION, by Herbert Riehl and Loren W. Crow, published by Colorado State University in June 1962.

A more extensive set of experiments was carried out in the winters of 1964-65 and 1965-66, with supplementary observations in early 1968. This project was sponsored mainly by the United States Department of Health, Education and Welfare; again the State Health and City authorities collaborated extensively, and many other organizations and individuals worked closely with the field program manager, Mr. Don Livingston (Appendix A). The primary purpose of this publication is to communicate the results of these experiments and to evaluate them in terms of operational procedures and long term planning for Denver. For completeness and for the reader's convenience, the initial portions of the 1962 report are repeated here, with amendments.

Principal Weather Factors in Air Pollution

Incidence and intensity of air pollution over a city, complex with pollution sources, quite generally depends on (1) wind speed and direction, (2) the temperature distribution with height above the surface and (3) local factors, especially location and strength of pollution sources and topographic features.

The metropolitan area of Denver (Fig. 1) essentially is contained within a radius of 5-7 miles from the State Capitol. With winds of 10-15 m.p.h. air will cross the city from one end to the other in an hour. With winds of 3 m.p.h. and constant wind direction the traverse requires 3-5 hours. In this latter case the travelling air will accumulate 3-5 times as much material from the emission of the various pollution sources as will accumulate during the fast traverse. It follows that chances for pollution are enhanced when, in the general weather picture, winds are very light. Such light winds

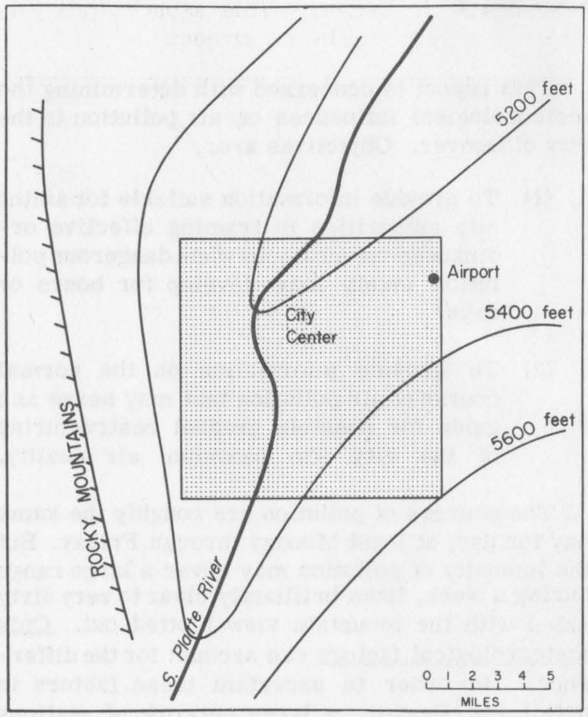


Fig. 1. Approximate city outline and environs of Denver.

normally occur a day or two after an outbreak of cold air from the north. Quite often, a quiet period of several days' duration intervenes between such an outbreak and the arrival of the next general weather disturbance from west or north. In this interval, when atmospheric pressure is high, light winds are most prevalent and chances for heavy pollution are greatest.

The temperature distribution with height influences pollution density because with strong upward decrease of temperature air can move up and down freely over considerable vertical distances. In this event material emitted from pollution sources near the ground may be mixed upward through a deep layer so that no marked concentration occurs near the ground. In contrast, when the air temperature increases upward, vertical interchange of air is inhibited and pollutants tend to remain near the ground, as may be observed readily by watching smoke drift horizontally from stacks or even come down to the ground. In the warm season, with much ground heating, temperature normally decreases strongly with height in Colorado, while in winter, especially during snow cover, situations with temperature increasing with height--called temperature inversions--are most frequent and persistent. The cold part of the year thus is the main pollution season for most contaminants, especially particulate matter emptied into the air, the type of contamination mainly treated in this report. In recent years summertime photochemical transformations of the type responsible for much of the Los Angeles smog, have become increasingly evident also in Denver. This aspect of air pollution is not covered by our project.

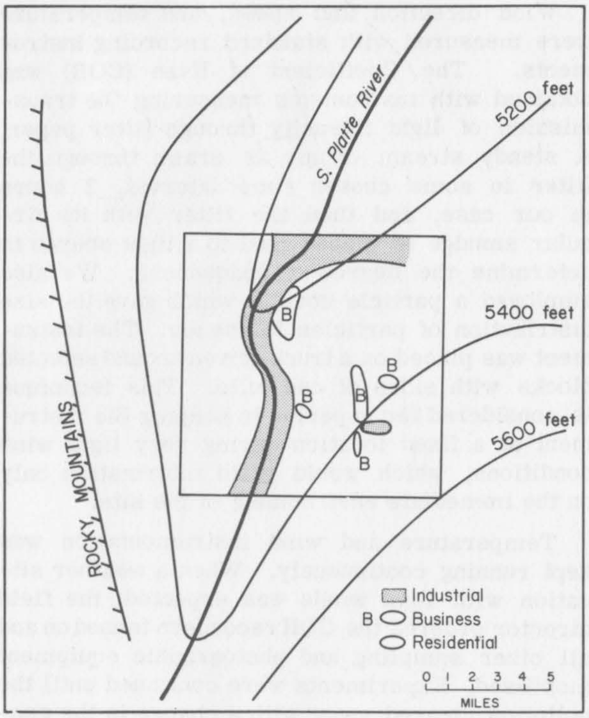


Fig. 2. General outline of principal activities within Denver.

Combining wind and temperature factors, a pollution period, often called episode, will be most severe when a light wind regime persists for an exceptionally long time in conjunction with very cold air near the ground. These two factors favor pollution occurrence in any industrial or heavily populated area of the globe. To these now must be added local factors. Denver is an isolated metropolitan area; Fig. 2 depicts the areas with chief industrial and commercial activity. The topographic features around Denver strongly determine the local wind regime which is most developed when the general weather situation is calm and does not interfere with locally induced flow. Outstanding, of course, is the rise of the Rockies west of the city (Fig. 1). Moreover, Denver is situated in the depression of the South Platte River, with land elevation generally decreasing toward northeast. This topographic pattern gives rise to a special daily wind regime. During night and morning, air drains down the Platte toward northeast; but this movement may stop just beyond the northeastern suburbs of Adams County. During the afternoon, the flow reverses sharply and much of the air that has traversed the city earlier going north, re-enters the city limits going south. This pendulum-type oscillation will persist as long as the local light velocity regime remains dominant. The double reversal of wind direction during the day strongly influences Denver pollution.

Methods of Pollution Study

In the main, two primary approaches for pollution study may be distinguished. One of these is concerned with the emission from strong individual sources and the question asked is this: What is the downstream rate of dilution of particulate matter, or gases, possibly poisonous, from the emitting stack? Under what conditions is the dilution rate likely to be a minimum, therefore most hazardous to health?

In the second approach, the pollution of a metropolitan area is investigated in bulk; the importance of this type of outlook has been bolstered greatly in the last decade by the recognition of the heavy contribution of surface traffic to pollution levels. Here the question becomes: What is the general history of pollution periods over the city? What are the atmospheric controls and what are the main ingredients making up the polluted mass of air? What leads to concentrations of pollution in particular parts of a city, and when should one expect maxi-pollution?

The second set of questions, curiously enough, has received far less attention than the first. Yet it is the solution of these questions that is of paramount importance for assessing the effect of bulk pollution on city health, welfare and commerce. The present investigation, just as in 1962, was devised with the objective of gathering data suitable for making recommendations to local and state authorities and legislators toward alleviating city bulk pollution. Meteorological analysis can assist in mitigating 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 air motion 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 rural activities, notably agriculture; and (c) estimate the "pollution potential" for areas as yet free from major population concentration and from pollution generation. In addition, meteorology has a role for local and worldwide monitoring to ascertain whether overall pollution levels are indeed rising as feared, and at what rate the rise, if any, is occurring.

Plan of the Observational Program

A network of primary stations measuring temperature, wind, and the coefficient of haze was established in the fall of 1964 in all parts of the city of Denver, so that afterwards maps of these quantities could be drawn for the whole city. In addition, as already mentioned, the City of Denver, the Colorado State Health Department, the United States Weather Bureau and various industries provided supplementary data. Fig. 3 indicates the station locations used most of the time; changes had to be made over the seasons.

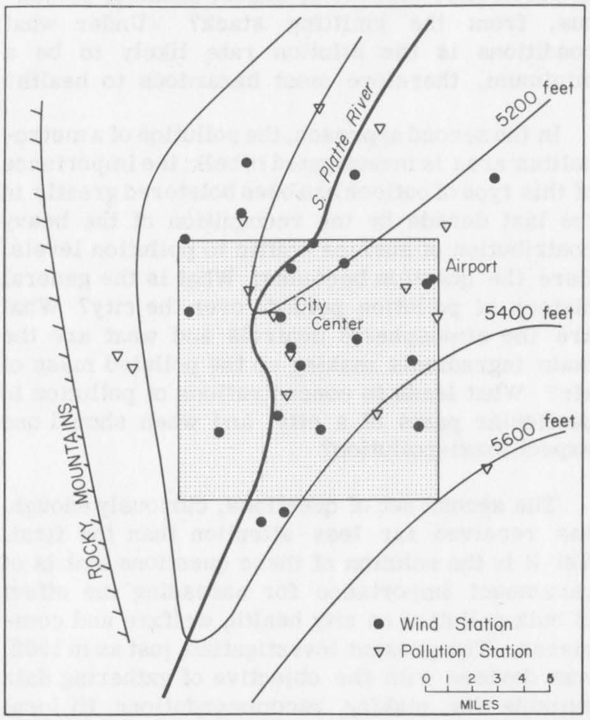


Fig. 3. Principal station network used during experiments.

Many stations were located on the roof of school buildings at a height of 25-30 feet. Observations made a little above the ground are more representative of their wider surroundings than stations right at the surface. Further, relatively free standing buildings were chosen, not hemmed in by higher structures around them. This also helped to make the observations representative for the distances of 2-3 miles to the next station and to make the whole network compatible, although complete success could not be achieved. In the first season the coefficient of haze was measured at three elevations of the Daniels & Fisher Tower on 16th Street downtown. Some wind data above the city were obtained by releasing several balloons to float at about 300 feet altitude and following their path across town by car at night. Aircraft reconnaissance and photography by Mr. Charles Grover (see cover of this report) gave information on height and distribution of the pollution in the first season. Invaluable assistance was obtained through collaboration of the airborne traffic police who carried a thermometer and gave excellent data on the temperature structure with height, especially temperature inversions, during the morning and afternoon traffic hours. Measurements from the balloon ascents made by the United States Weather Bureau at Stapleton Field also were made readily available and utilized.

Wind direction and speed, and temperature were measured with standard recording instruments. The Coefficient of Haze (COH) was obtained with instruments measuring the transmission of light intensity through filter paper. A steady stream of air is drawn through the filter in some chosen time interval, 2 hours in our case, and then the filter with its circular smudge is placed next to a light source to determine the degree of opaqueness. We also employed a particle counter which gave the size distribution of particles in the air. The instrument was placed on a truck driven around selected blocks with sides of one mile. This technique is considered far superior to keeping the instrument at a fixed location during very light wind conditions, which would yield information only on the immediate environment of the site.

Temperature and wind instrumentation was kept running continuously. When a weather situation with light winds was expected, the field director ordered the COH recorders turned on and all other sampling and photographic equipment mobilized. Experiments were continued until the pollution cleared away 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 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 analysis. Twelve pollution episodes comprised these days. Duration was as follows: One day - 3; two days - 5; three days - 2; and 4 days - 2.

All data from the experiments were put on punchcards at Colorado State University, averaged for 2 hours, and analyzed on maps. Of these, Fig. 4 shows a sample for the night hours preceding the photographic excursions made by Mr. Grover on February 3, 1965 (see cover and Fig. 14). In the temperature field, the so-called "heat island" is clearly visible--higher to much higher temperatures in the city center compared with the suburbs--as encountered in most of the world's major cities at night. The heat island disappears during daytime as the suburbs warm up more rapidly than the interior. Winds were mostly from the south, though with some irregularity; especially east of the city wind speed was much higher than inside the built-up area, the usual situation. Heavy pollution was centered northeast of the downtown area.

In the following the history of an average pollution day will first be presented. Later, we shall consider situations conducive to high pollution intensity in different portions of Denver.

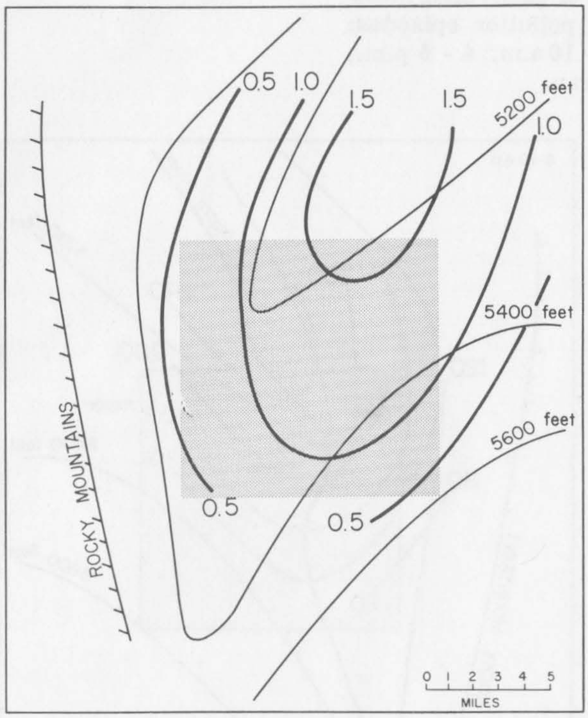


Fig. 4a. Example of individual map: Coefficient of haze, 2-4 a.m., February 3, 1965. (COH Units).

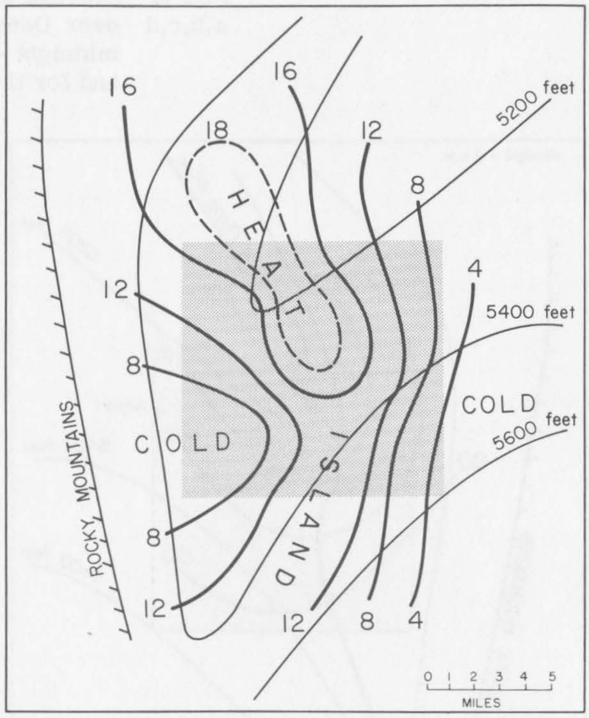


Fig. 4b. Temperature distribution (°F) for same period, showing elongated heat island.

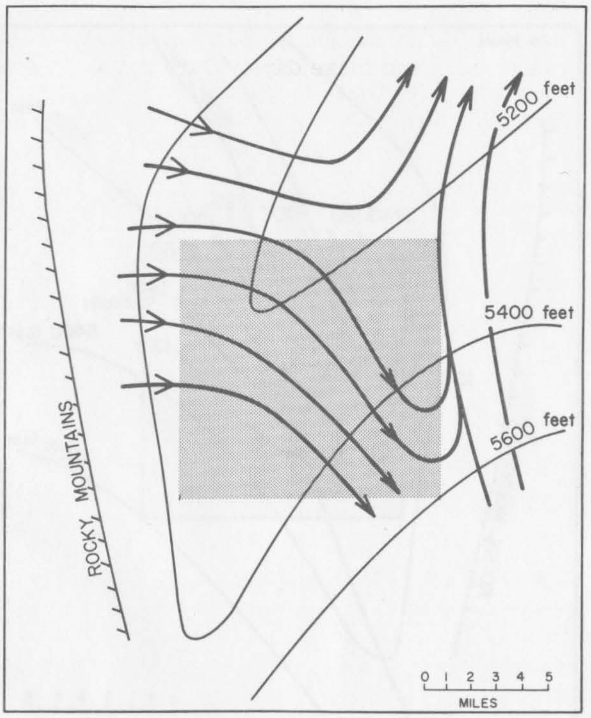


Fig. 4c. Streamlines showing direction of wind, same period.

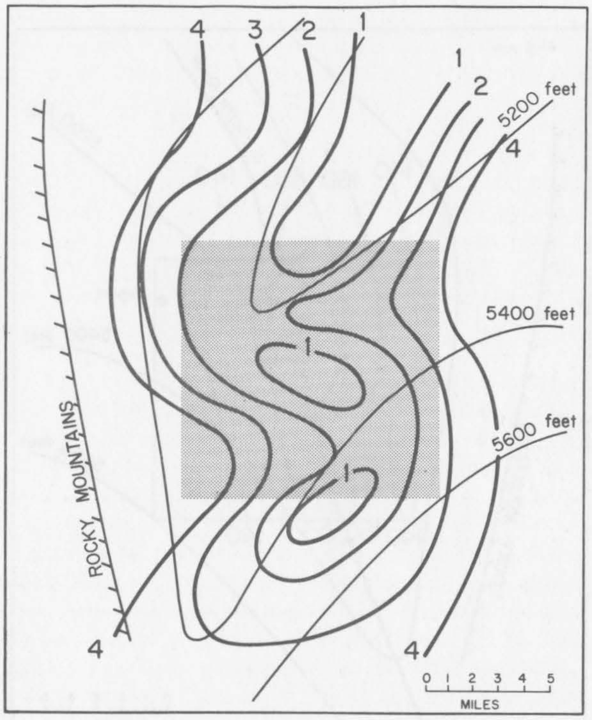
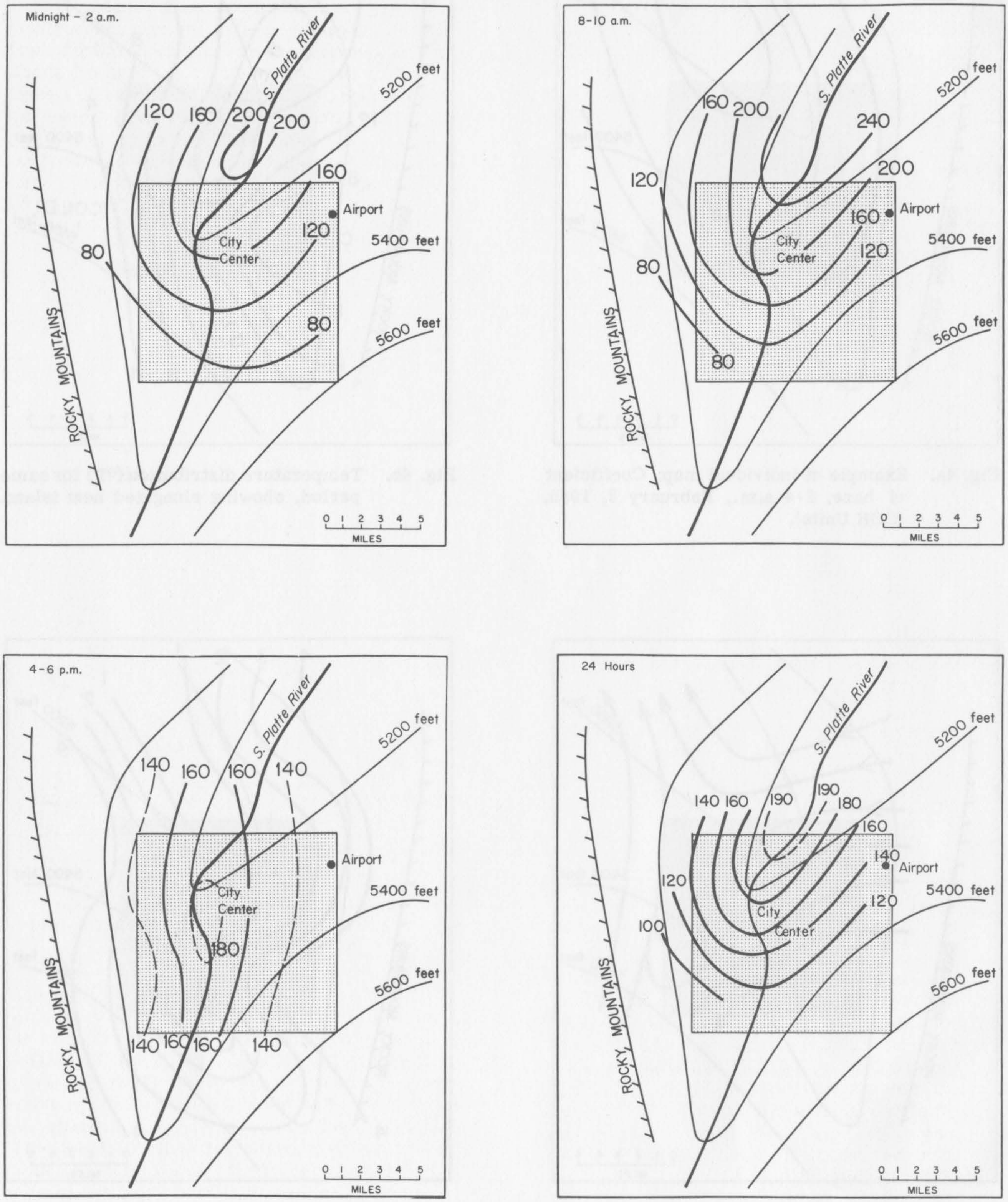


Fig. 4d. Wind speed, mph, same period. Note the very low speeds inside built-up city area, stronger speeds just outside.

Fig. 5. a,b,c,d Average distribution of particulate mass over Denver during pollution episodes: midnight - 2 a.m.; 8 - 10 a.m.; 4 - 6 p.m., and for the 24-hr mean.



THE AVERAGE POLLUTION DAY

The Daily Course of Pollution

Fig. 5 shows the pollution pattern at several times of the day and also the 24-hour average. Mean daily concentration is highest in the north, as previously published. During the afternoon the concentration wanders toward south as the winds draining down the Platte during night and morning tend to reverse in the afternoon to bring the polluted mass evacuated toward northeast back toward town.

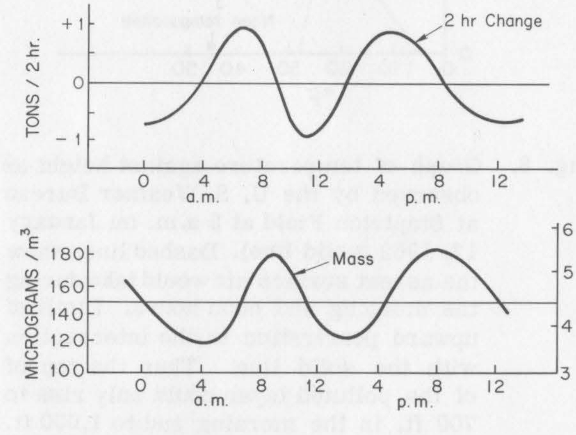


Fig. 6. Graphs showing average daily course of 2-hr time changes and of total particulate mass over the city during pollution episodes.

Next, we see the daily course of total polluted mass and its change in 2-hr. time steps in Fig. 6, for a volume with area[1] shown in Fig. 2 and a height of 330 feet--about to the top of the highest buildings. Up to this height pollution is assumed to be uniformly mixed, as suggested by the Daniels and Fisher Tower data and observations elsewhere. Total polluted mass in this volume averages about 4.5 tons, with range from 3.5 to 5.5 tons. The 2-hr. change ranges from -1 to +1 tons, a substantial fraction of the entire mass. Clearly, with changing wind systems, rapid percent changes of pollution intensity can readily take place.

It should be stressed that the course of 2-hr. changes, with its typical double cycle, is valid only for the city volume as chosen here, and that it does not indicate the daily course of total polluted mass above the city. For the latter purpose the entire vertical extent of pollution, not just the lowest 330 feet, need be taken into account. However, from the viewpoint of developing weather engineering aids for city life and commerce, the city volume itself up to the top of the higher buildings is, of course, the most significant to objective of analysis.

[1] Boundaries are: Wadsworth in the west; Quebec in the east; Hampden in the south, and Wyoming in the north.

Our next purpose will be to ascertain how air movements, coupled with pollution sources and sinks, produce the rythmic variation of Fig. 6.

Friction - Stovepipe Effect

As Fig. 5 has demonstrated, concentration of mass is greatest in the central and northern parts of Denver and decreases outward from there except in the northeast. Now, if there should be a net indraft of air from all sides into Denver which then ascends and moves away higher up, this air will enter relatively clean and it will leave after picking up particulate matter from the various sources. Thus it will act as a cleaning mechanism, taking more pollution away than it is bringing in. The process is illustrated with a sketch in Fig. 7.

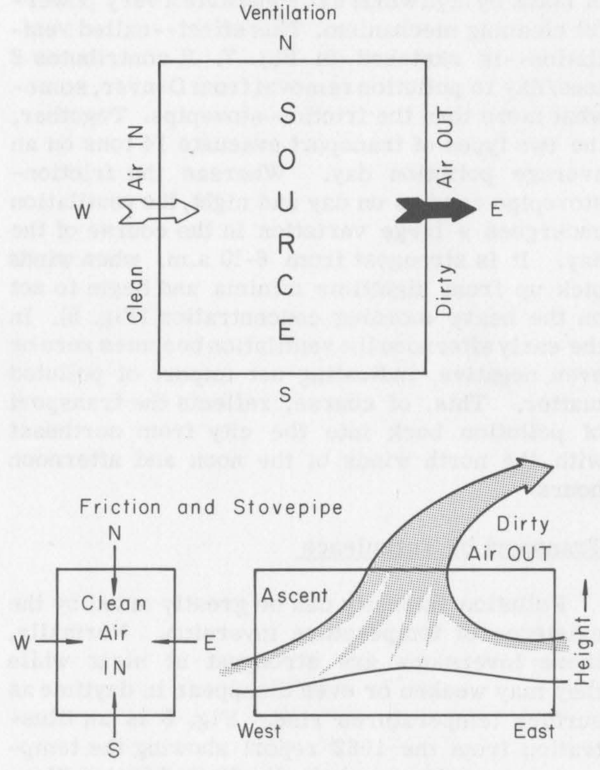


Fig. 7. Sketch of ventilation and friction-stovepipe cleansing mechanisms.

The net indraft of air is an entirely man-made wind. Two possible causes exist. One is the high friction encountered from the mass of the various structures, compared to the broad flatlands all around, except west, slowing down air movement. The other cause is the heat island that could act like a stovepipe. Actually, the wind data do show a net indraft of about 1/2 mph, a powerful effect indeed since it alone completely removes the entire city air 6 times in the course of 24 hours. This indraft persists day and night, whereas, if it was mainly due to the stovepipe heat island, it should be strongest at night. We must conclude that the indraft is mainly due to friction, and that the heat island is surprisingly ineffective, perhaps because industry is not as plentiful and as concentrated as in some other cities.

The particulate mass removed by the friction-stovepipe effect is 6 tons/day or about 1.3 times the average particulate mass in the city volume. If the air coming in from the outside was completely clean, the friction-stovepipe would remove all pollution six times daily. We observe here a consequence of the spreading of industry and general human activity beyond the city limits in that considerable pollution sources also exist throughout the suburbs.

The Ventilation Effect

As stated in the Introduction, lateral evacuation of mass by high winds can constitute a very powerful cleaning mechanism. This effect--called ventilation--is sketched in Fig. 7. It contributes 8 tons/day to pollution removal from Denver, somewhat more than the friction-stovepipe. Together, the two types of transport evacuate 14 tons on an average pollution day. Whereas the friction-stovepipe carries on day and night, the ventilation undergoes a large variation in the course of the day. It is strongest from 8-10 a.m. when winds pick up from nighttime minima and begin to act on the heavy morning concentration (Fig. 5). In the early afternoon the ventilation becomes zero or even negative, indicating net import of polluted matter. This, of course, reflects the transport of pollution back into the city from northeast with the north winds of the noon and afternoon hours.

Transport by Turbulence

Pollution intensity can be greatly aided by the existence of temperature inversion. Normally, these inversions are strongest at night while they may weaken or even disappear in daytime as surface temperatures rise. Fig. 8 is an illustration from the 1962 report showing the temperature sounding made by the United States Weather Bureau at 5 a.m. on January 12, 1962, and surface temperatures during morning and noon hours. Temperature rises from 5° to 45° F, a large increase not uncommon in Colorado even in mid-winter. As a result, the temperature inversion is replaced by a layer where temperature decreases so strongly with height that air parcels can circulate freely up and down--those from below having a high density of pollution and those from above bringing cleaner air down as sketched in Fig. 9. One calls these movements turbulent exchange or mixing, a difficult quantity to measure, whose importance for Denver we tried to calculate but which we could not observe directly. The estimated contribution is 5 tons/day, somewhat smaller than the friction-stovepipe or the ventilation transports.

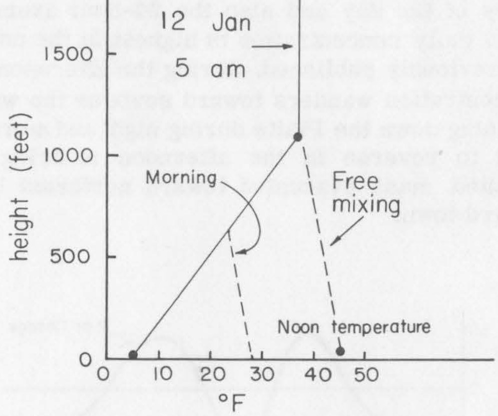


Fig. 8. Graph of temperature against height as observed by the U. S. Weather Bureau at Stapleton Field at 5 a.m. on January 12, 1962 (solid line). Dashed lines show the ascent surface air would take during the morning and noon hours. Limit of upward penetration is the intersection with the solid line. Thus the top of of the polluted layer could only rise to 700 ft. in the morning and to 1,000 ft. at noon.

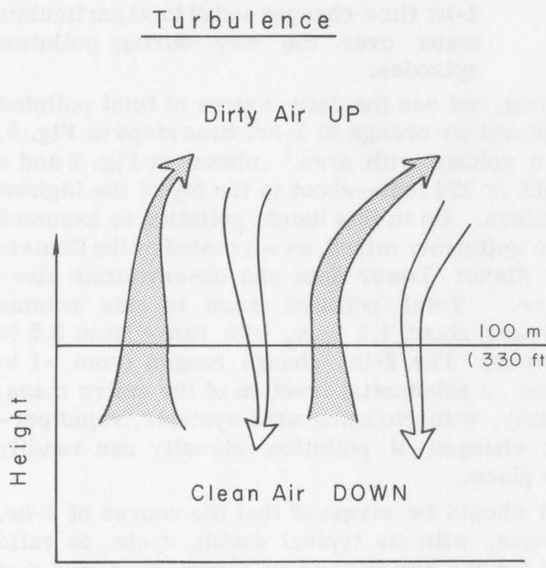


Fig. 9. Sketch of turbulent cleansing mechanism.

The inversion does not break on all days. Even in those instances, however, ground heating is sufficient to raise the inversion and initiate turbulent transport of particulates upward. In Fig. 10 we see the inversion, observed by the Denver traffic police, on the day of the photos in this report. When the inversion persists, the definition of the top of the polluted layer should be very sharp, whereas with a deep mixing layer it would be diffuse. For this reason, probably, the pollution layer on February 3 was especially photogenic, since the inversion held with unmitigated strength.

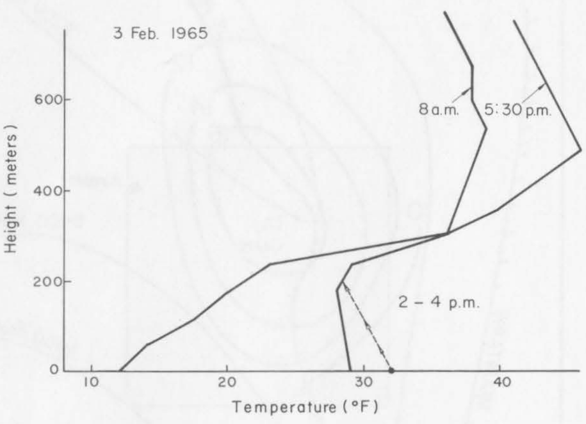


Fig. 10. Temperature distribution with height as given by the Denver Airborne Traffic Police on February 3, 1965. Note intense and persisting inversion. In this instance, depth of the mixing layer is limited to 200 meters (about 700 ft.) in the noon hours.

Pollution Sources and Sinks

The sum of the three transport mechanisms just discussed gives the total daily pollution source over Denver minus the fallout or sink of particulate matter. It amounts to 19 tons per day. The daily course of Source minus Sink, of the combined effect of all types of transport and of the resulting change in pollution is shown in Fig. 11;

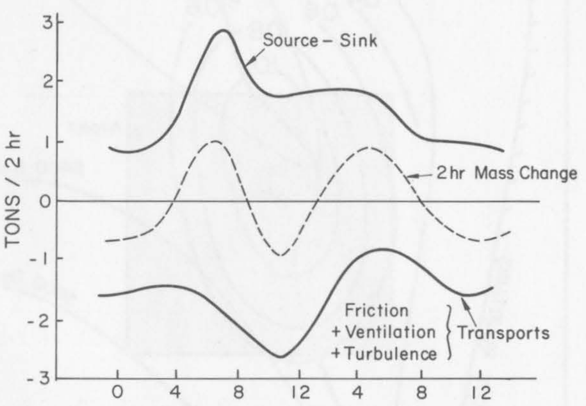


Fig. 11. Graph of calculated Source minus Sink and the sum of all transport processes, showing how the average daily course of change in particulate mass is produced during pollution episodes.

the total mass of the particulate pollutants of Fig. 6 may also be compared. In the early morning the pollution level rises in response to the very high value of the source as city life starts up. Then, as the source settles to its mean daytime value and winds increase with the warming of the air, 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 re-enters the city from the north and when the turbulence gradually dies away, pollution concentration starts to rise again long before the onset of afternoon rush-hour traffic. The second maximum is reached around 8 p.m. when, with low nighttime source and with winds returning to their nighttime pattern of importing clean air from the south, 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 cleansing transports during pollution periods. When the winds are stronger, the particulate emission is carried away more rapidly so that the city air remains cleaner and the skies brighter. In summary, the daily course of Denver pollution has a very local explanation in several important aspects, even though the double maximum of pollution intensity is encountered in many cities.

It will be of interest to check the results of our calculations against the pollution source inventory prepared by the city of Denver. From this inventory the source is about 30 tons/day. Our computation of source minus sink gives 19 tons/day and so the sedimentation, or the mass that falls out, should be 11 tons per day, or about one-third of the source. A check with the "dustfall" recorded at 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. Using a more theoretical approach and the data on particle size distribution from our mobile counter, described earlier, the weight of the larger particles that would readily fall out during a day should be one-third of the total mass, making the sedimentation of 11 tons per day plausible. Assuming such a sink and that fallout is proportional to the mass of pollutants in the air, the total fallout during 24 hours is distributed as shown in Fig. 12, with highest fallout in the north of Denver where pollution is densest.

Now we can also map the distribution of pollution sources at different times of day, shown in Fig. 13 for the nighttime hours from 8 a.m. to

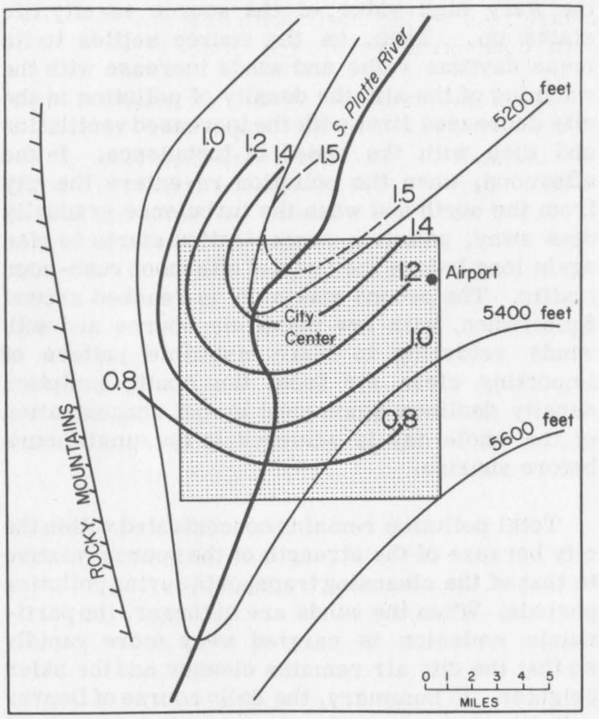


Fig. 12. Calculated average sedimentation, or sink of particulates, in 24 hours during pollution periods. Unit in tons per day per 130 square miles.

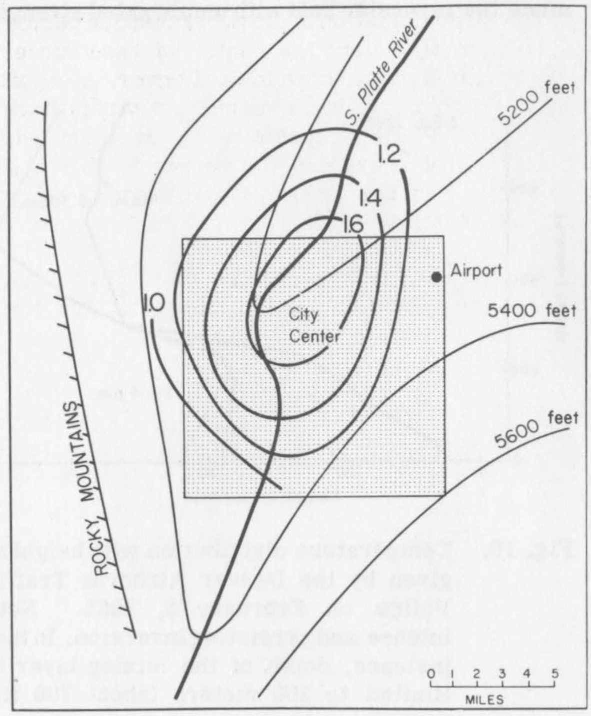


Fig. 13a. Calculated pollution source, 8 a.m. - 4 p.m. Unit in tons per 8 hours.

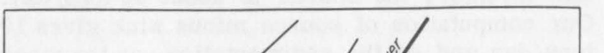


Fig. 13b. Calculated pollution source, 4 a.m. - 8 a.m. and 4 p.m. - 8 p.m. Note rather uniform source in these transition hours.

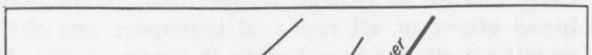


Fig. 13c. Calculated pollution source, 8 p.m. - 4 a.m. Note strong decline of source from city center outward at night.

4 p.m., for the daytime hours from 8 a.m. to 4 p.m. and for a combination of the two transition periods. At all times of day the center of the source is concentrated near downtown Denver, elongated north-south along the industrial activity following the South Platte, especially so at night when the ratio of source in the center to that of the outskirts reaches 2:1. In daytime, the ratio is less, suggestive of enhanced traffic and city activity in all parts of town. The concentration in the central area 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. It should also be pointed out that, comparing Figs. 5 and 12, the strongest pollution source lies well south of the area with densest pollution, indicating the role of the predominant winds from south in moving particulate matter toward northeast. As is frequently true, one cannot assume that the area with strongest concentration is the area with strongest source.

VARIATIONS IN POLLUTION INTENSITY

Concentration of Particulates

We shall now look into departures from the average pollution pattern; of special concern are cases in which pollution levels reach very high values. On individual days, the particulate mass more often than not is concentrated in one portion of the metropolitan area while, at the same time, other parts of the city might be quite clean. On February 3, 1965, Mr. Grover made two aircraft photography missions over the Denver area, one beginning at 8 a.m. and the other one in the early afternoon. The frontispiece shows a shot looking eastward across Sloan Lake in the morning. We observe very little pollution in the west, while a heavy mass concentration overlies the east, so that the city center is only barely visible. Fig. 14 contains three additional frames. In the first of these, also taken in the morning from western Denver, the smoke plume from a utility plant is an outstanding landmark. The second, taken south of Denver looking north, shows the southern limits of the pollution very clearly as frequently encountered. The third photo, made in the early afternoon, reveals strikingly that by that time the whole polluted mass had shifted well toward south.

From the photography during various pollution episodes plus COH maps as illustrated in Fig. 4, we could distinguish readily between periods with pollution concentration in north or south, east or west, or in the center of Denver. For any given time of day only differences in wind movement can account for these different concentrations, that is variations of the scheme of Fig. 7. We can determine what these variations are by contrasting the wind field for the cases with concentrations in the north with that for the cases with concentrations in the south (Fig. 15).

The flow remains from southwest toward northeast throughout the night and morning in all instances. The difference lies in the wind speed pattern. With concentration in the north the southerly flow across the southern part 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 may note, incidentally, that just east of our boundary of computation wind speed is at least 3-5 mph from south, sometimes more. A site like Stapleton Field, while it may contain a strong pollution source, usually has low pollution and good visibility at night, since the particulates are swept rapidly away toward northeast by the relatively strong winds.

Toward noon, the reversal of wind direction mentioned before is noted first in the situations with concentrations in the south, later also during concentrations in the north. The polluted mass returning from northeast, plus additional material picked up from the city source pattern, is swept toward southern Denver when the concentration shifts south, while everything is hung up in the north and north-central areas in the other cases where the north wind is not able to penetrate far beyond the northern part of the city. A fierce convergence of air and thick pollution then develops north of the city center; herein lies the daytime difference between the two types of cases. In summary, concentration will occur in the north when the general wind has a south component stronger by 3-4 mph over the cases with concentration in the south--that is, a reduced flow from north in daytime.

We may immediately anticipate that concentration in the west occurs with an enhanced wind from east and concentration in the east with an 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 as in Fig. 7.

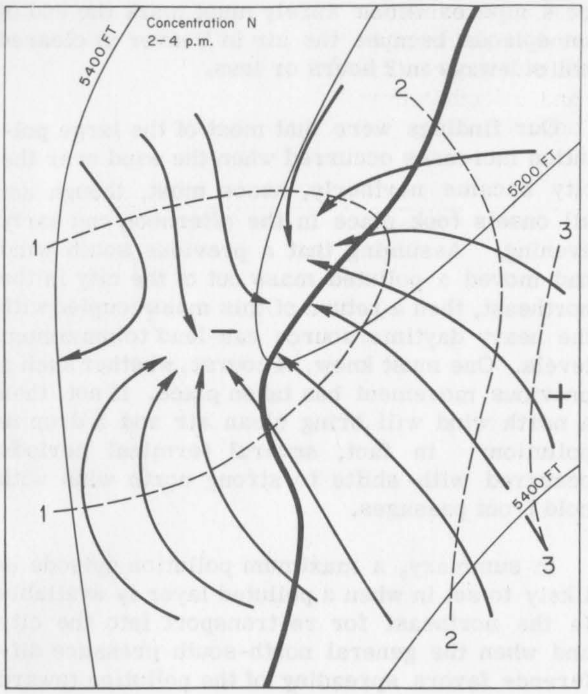
From the foregoing, the cause of the variable concentration cannot be local but must be sought in the broader wind and pressure field over several states. If the significant differences in the pressure field could be specified, then the concentrations could be predicted from prognostic charts of the whole pressure field issued by the United States Weather Bureau in Washington, provided these are accurate enough. With this possibility in mind, we inspected the weather charts for all situations. For concentration in north or south, these charts do furnish a criterion. We found that the south winds are strongest and that pollution is concentrated in northern Denver when there is a small but general pressure drop from southern Colorado to northern Wyoming. In contrast, the

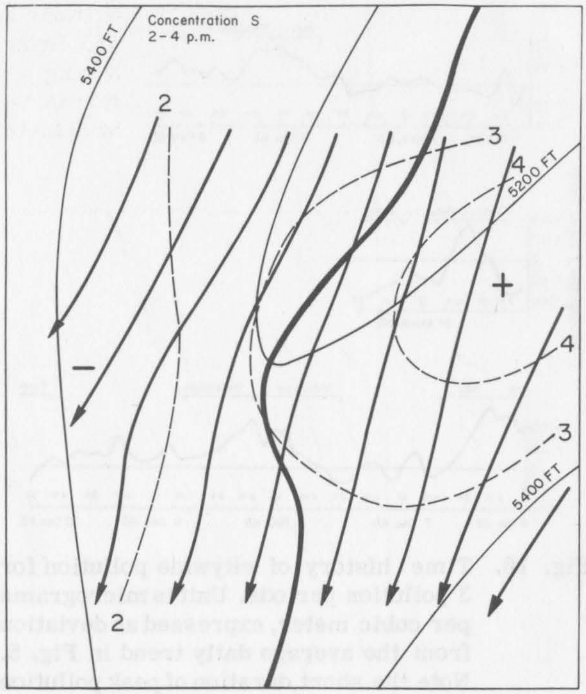
Fig. 14a. Another shot highlighting the rather clear air in the western suburbs and the concentrated mass of pollutants farther east during the morning of February 3, 1965.

Fig. 14b. 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. 14c. 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. 15. Comparison of wing field (streamlines and lines of equal wind speed in mph) during periods with pollution concentration in North Denver and in South Denver at selected times of day.





pressure field is flat or has higher pressure in the north than in the south when the pollution moves into southern Denver. Of course, we are talking about weak pressure differences compatible with air pollution episodes in Denver. When the pressure differences become strong, the whole polluted mass moves out of Denver and at times has even been observed to arrive at Fort Collins while skies were nice and bright over Denver.

Periods of Extreme Pollution

When pollution is concentrated in one part of town, the level of contamination there may be quite high, while elsewhere in the city the air may be rather clean as just seen. On occasion, however, the entire citywide pollution rises well above the levels of the average pollution day. If we express total concentration in terms of excess over the average levels of Fig. 5, then our 12 episodes at peak intensity divide as follows:

Concentration above average (COH units)	Number of cases
0.8 - 1.5	2
0.4 - 0.8	4
0 - 0.4	6

While the peak value of COH on the average pollution day is around 1.5 units, citywide maxi-values have attained 3 COH units. For orientation the following table contains ratings of COH values in terms of pollution intensity as defined qualitatively in the state of New Jersey.

Smoke Concentration	Adjectival Rating
COH	
0.0 - 0.9	light
1.0 - 1.9	moderate
2.0 - 2.9	heavy
3.0 - 3.9	very heavy
4.0	extremely heavy

Comparing these ratings with COH as observed in Denver, we find that fortunately the city does not as yet experience very high pollution levels as reported from some other cities. But it does come up to the "heavy" class on a few occasions; rarely, COH above 4 units has been measured in a limited portion of town. Thus it does appear worthwhile to inquire into onset, duration and decay of pollution peaks. Fig. 16 shows the time history of several pollution episodes. An onset to peak value takes about 8 hours; then a decline of corresponding magnitude sets in almost at once, so that the peak value itself is only held for perhaps 2 hours or a little longer. A complete maxi-event thus lasts a little less than a day. Cases with persistence of extreme pollution over days have not yet happened.

The rise and decline of the peaks might come from variations in the rate of pollution removal by our several transport mechanisms; it may also be produced by especially intense and persistent temperature inversions inhibiting cleansing by turbulence. It turned out that the friction-stovepipe effect was quite indifferent yielding the same transports during onsets and recessions.

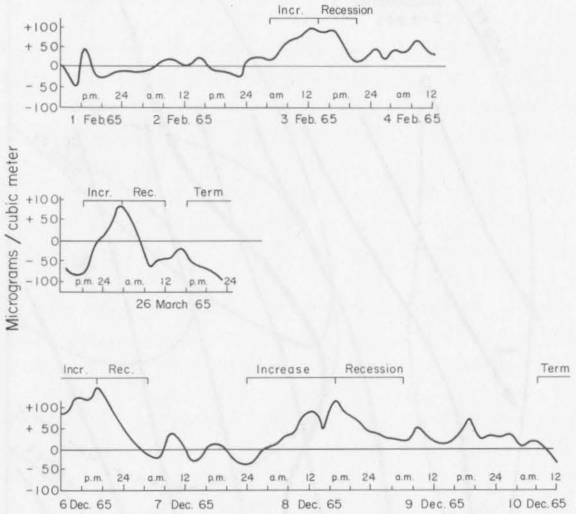


Fig. 16. Time history of citywide pollution for 3 pollution periods. Unit is micrograms per cubic meter, expressed as deviation from the average daily trend in Fig. 5. Note the short duration of peak pollution and rather symmetric onset and recession.

The ventilation, however, varied considerably. Onset was coupled with very small amounts of cleansing by the wind blowing across town, while the ventilation removed larger amounts of material during recessions and also during terminal periods of entire episodes. One might think of computing a "ventilation factor", the average wind speed around the whole boundary of Denver. Table 1 shows the relation of this factor to onset, recession and episode termination.

TABLE 1

Percent frequency distribution of Ventilation Factor 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 1 demonstrates that indeed wind speeds are low to very low during onset of severe episodes and that they rise to highest values during terminal periods. Unfortunately, there is too much overlap in the three columns in the middle of the distribution for it to be a unique predictor. It is true that practically all onsets of heavy pollution occurred with a ventilation factor of less than 3 mph, but it does not follow that an onset will occur whenever the factor 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.

Our findings were that most of the large pollution increases occurred when the wind over the city became northerly, hence most, though not all onsets took place 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. 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 re-transport into the city and when the general north-south pressure difference favors spreading of the pollution toward the southern part of the city.

CONCLUSION--APPLICATIONS FOR THE CITY OF DENVER

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

Operational Aspects

(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.

(b) Circumstances leading to pollution concentration in particular portions of Denver have been determined. These are controlled by variations in wind. With an enhanced general wind movement from south by about 2 mph the polluted mass is concentrated in the north of Denver; with less than average winds from south the afternoon penetration from the north sweeps 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. With a general pressure drop toward north, the concentration will be in the north; with an indifferent pressure field or with pressure lower in south than north the concentration will be in the south.

(c) Onset of extreme pollution episodes may be expected mainly when a polluted layer is available north of the city for re-transport into the city when the wind velocity averaged around the whole city is 3 mph or less and when the general wind field favors spread of pollution as far as South Denver.

(d) From Fig. 13 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 city-wide source; it is insufficient to direct an ordinance at a few sources of concentrated emission alone.

Planning Aspects

(1) The prevailing average wind over Denver in winter is down the Platte River from south-southwest, resulting in maximum levels of pollution in the north of the city, well displaced from the maximum source which is in the center of Denver. The wind regime is not likely to be changed. Hence it appears 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 area at the downstream end of a metropolitan complex. It follows that in Denver all industry should be located in the north and north east, residential areas and non-smoke producing activities in the south. There is some tendency toward this distribution in Denver, but to an insufficient degree.

(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 before the stovepipe becomes really effective in removing pollution to levels well above the city, where the polluted mass is carried away from the whole area by the upper winds.

(3) City friction greatly slows down wind speed and therewith reduces the important ventilation mechanism compared even with the immediate surroundings. Thus, 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.[1] Another method would be to produce a new streamlined architecture.

ACKNOWLEDGEMENT

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

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