A Study of Denver Air Pollution

By
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Department of Atmospheric Science
Colorado State University
Fort Collins, Colorado

A report on research conducted under a Grant by the Helen Dean
Yetter Foundation to Colorado State University
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Colorado State University

Department of Atmospheric Science

Paper No. 33

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A sample of Denver air pollution, 15 December 1961.

Technical Report 33
Department of Atmospheric Science
Colorado State University
Ft. Collins, Colorado

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Picture on cover: Picture was taken by photographer Charles Grover from the air at 3, 000 feet. The camera was pointed north toward downtown Denver from over Englewood. Time was about 2 p.m., 15 December 1961. Note clear area in lower right corner of picture and shape of southern edge of polluted mass which was advancing toward south at the time. Only tops of downtown buildings are visible in center of picture.

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and

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Introduction

In the last decade air pollution in the Denver area has risen to a sufficient degree to attract civic attention and to raise the question of possible remedial measures. In what portion or portions of town should new industries be encouraged to develop? What can be done to restore the unrestricted mountain view for tourists? Where should residential areas be developed for optimum scenic view?

If the problem is to be solved, it must at first be studied adequately. With this thought in mind, an agreement was made between the Helen Dean Yetter Foundation of Denver and Colorado State University to conduct preliminary measurements of meteorological conditions attending Denver pollution during the 1961-62 pollution season. The main objective of the measurements was establishment of an effective approach for a large-scale measuring program. It was not expected that the limited program carried out could solve all of the meteorological problems. The results of the investigation, described in the following, must be viewed in this context, and they may be considered as a continuation and expansion of previous work on Denver pollution undertaken by the City of Denver and by the State of Colorado.

General Aspects of Air Pollution

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

The metropolitan area of Denver (fig. 1) essentially is contained within a seven-mile radius from the State Capitol. With winds of 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 five hours. In this case the travelling air will accumulate five times as much material from the emission of the various pollution sources as it will accumulate during the fast traverse. It follows that chances for pollution are greater when, in the general weather picture, winds are very light. Such light winds preferentially occur in Colorado a day or two after an outbreak of cold air from the north. Quite often a period of several days' duration occurs 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.

The temperature distribution with height influences pollution intensity because, with strong upward decrease of temperature, air can move up and down freely over considerable distances. In this event material emitted from pollution sources near the ground is rapidly mixed upward through a deep layer of air and no marked concentration occurs near the ground. In contrast, when the air temperature increases upward, vertical movement of air is inhibited and pollutants remain near the ground, as may be seen readily from horizontal drift from smoke stacks under such conditions. In the warm season, with much ground heating, temperature normally decreases strongly with height in Colorado while in winter, especially with snow cover, upward temperature increases are frequent. The cold part of the year is the main pollution season. Further, with ground cooling during night and warming in daytime, the temperature distribution with height has a normal daily course: upward decrease is most common in late morning and afternoon; upward increase during night and early morning. For example, witness the balloon sounding observation made by the United States Weather Bureau at Stapleton Field on 12 January 1962, drawn on a diagram of temperature versus height in fig. 2. At 5 a.m. the surface temperature was 5°F., while at 1100 feet 36°F. was recorded. By noon surface

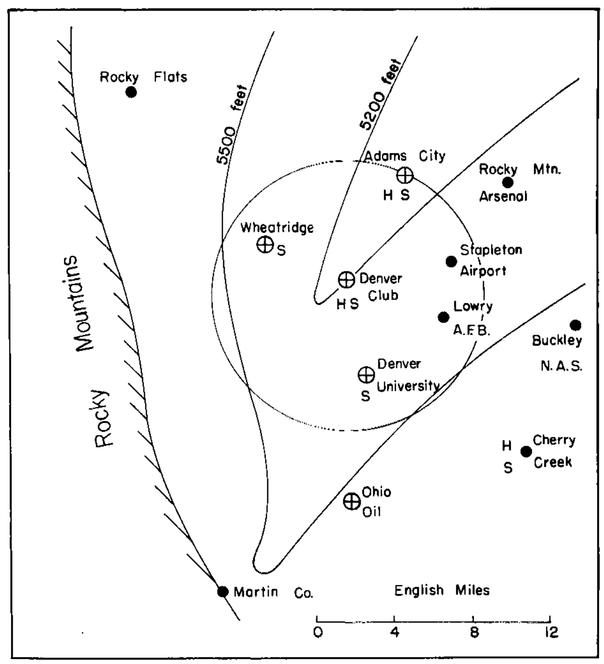

Fig. 1. Outline of Denver area and location of stations furnishing data for study. Circle indicates main city area, edge of Rockies and land elevations of 5500 and 5200 feet marked. Stations with crosses are special project stations, those with dots are regular weather observation stations contributing data. H denotes location of high volume sampling equipment, S location of soiling index samplers, all operated by the City of Denver.

temperature had risen to the low forties. Above the city, using the 5 p.m. Weather Bureau observation, temperatures also were in the forties. Thus, the large upward increase of about 30°F. in 1000 feet was wiped out and there may have been a period of free mixing along the dashed line of fig. 2.

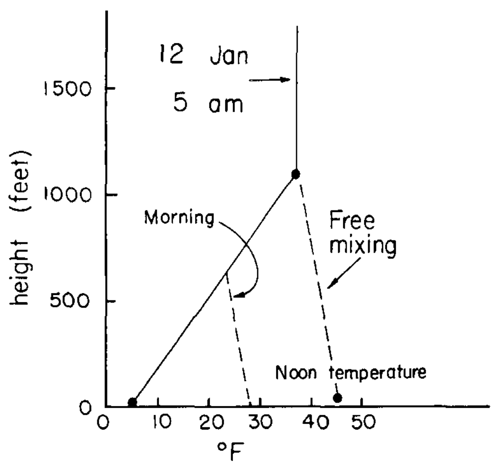

Fig. 2. Graph of temperature against height. Solid line, as observed at Stapleton Airfield by Weather Bureau at 5 a.m.; dashed lines are suggested temperature-height distributions during morning and noon hours. The polluted layer would extend to the top of the dashed lines, i.e. 700 and 1000 feet above ground.

Combining wind and temperature factors, a pollution 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 influence pollution occurrence in any industrial area of the globe. To them now must be added local features. Denver is an isolated metropolitan area. All pollution occurring there must be ascribed to sources within or near the city. This differs from, say, the position of many Atlantic Seaboard cities which not only generate pollution but may also receive accumulated material from other industrial areas located upstream. The topographic features around Denver strongly determine the local wind regime which is most developed when the general weather situation is calm. 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 the following daily wind regime, the reasons for which are not fully understood though hypotheses are abundant. During night and morning, air drains down the Platte toward the northeast; but this movement apparently stops just beyond the northeastern suburbs. During afternoon, the flow reverses sharply and much of the air that has traversed the city earlier going north, re-crosses the city moving southward. This pendulum-type oscillation will persist as long as the local light velocity wind regime remains dominant. Such alternation of wind direction during the day strongly influences Denver pollution and renders it unique.

Methods of Pollution Study

While techniques vary widely dependent on the particular objective of an investigation, we may in the main distinguish two primary approaches for pollution studies. 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 human health? This type of study is concerned mainly with small wind eddies, perhaps of the size of a city block or even less. One refers to the operation of this type of wind eddy on a smoke plume as "diffusion". The subject of diffusion has been and is being pursued widely and vigorously. It is improbable that such a study conducted in Denver will add materially to the knowledge gained by very substantial efforts elsewhere.

In the second approach, the pollution of a metropolitan area is investigated in bulk. 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 air mass? To what extent does this mass remain unified and to what extent is it diffused by small-scale motions? This second question, curiously enough, has received far less attention than the first. Yet the solution is of paramount importance for assessing the effect of the bulk pollution on city welfare and commerce. This investigation was devised with the objective of gathering preliminary data toward the solution of the second set of questions.

Plan of Observational Program

Observations were made during five pollution episodes at five special project stations (fig. 1). Taken in conjunction with six additional stations maintained by cooperating agencies the station density, while far from satisfactory, approached that of the most complete city-wide air pollution projects carried out in the United States. The meteorological data consisted of wind direction, wind speed and temperature. These observations were supplemented by ground and aerial photography, by visual observations and by measurements of sunlight intensity.

In conjunction with the meteorological program, the City of Denver conducted an air sampling program during the four pollution episodes in 1962. At three stations (see fig. 1) the total weight of particulate matter collected in high-volume samplers over 24 hours was determined. At these and at several other stations (fig. 1) the so-called "soiling index" was measured in addition. This index is determined by comparing light transmitted through paper tape exposed to the airflow for two-hour periods with light transmitted through clean tape. The index, a rather fuzzy measure, is given in arbitrary units which provide a measure of dark-colored airborne particles. No gaseous sampling was carried out, nor was the composition of the collected particulate matter analyzed. It was recognized from the outset that these rather difficult and expensive analyses could not be fitted into the present initial program and that therefore the relative contribution of individual pollution sources to total pollution could not be determined.

The appendices contain details of the observational plan, information on station locations, type and exposure of instruments, and acknowledgements to all governmental and private groups who cooperated in the program. The following sections summarize results of the study.

General Weather Situation

As already indicated, the pollution periods occurred during calm conditions, with barometric high pressure, subsequent to a cold outbreak. Snow was on the ground during several of the periods.

Air Sampling

High volume: All three stations were operative on the following days: 12 January, 16 January, 1 March and 6 March, all in 1962. Averaging, we obtain (in micrograms per cubic meter of air passed through the filter in 24 hours):

Cherry Creek	60
School Adm. Bldg.	170
Adams City	290

The first result then is that the mean pollution intensity increases by a factor of five from south to north across the city. Individual values ranged by a factor of two at all three stations.

Soiling index, average values: Due to instrumental difficulties, the stations were not operative on all days. Nevertheless, for maximum data at each site, the four days mentioned above were utilized and 15 January 1962 was also added, since it had a complete record. The dissimilarity of weather on the several dates used in forming the average at each station must be kept in mind. We obtain the following mean values from 12 two-hour readings per day at each station:

Cherry Creek	0.46
Denver University	1.04
Denver Club	1.00
Wheatridge	1.25
Adams City	1.39

Qualitatively, the result compares well with that from the high-volume samplers. An exception is the Denver Club where a low value has been computed. This is the only station located several hundred feet above the ground and there is a suggestion that at night the pollution concentrates below the sampling site. This may account for the relatively low value. For comparison with the preceding table, the average value for Los Angeles (not just heavy pollution days) is about four.

Soiling index, daily course: Analysis of the two-hour sequence of soiling index at the five stations proved to be rather difficult. While some of the variations were in accord with those to be expected on the basis of wind movement, it was not possible to fit all values into a simple pattern. On several occasions sudden large changes occurred in the middle of the night with light winds, suggestive of pronounced local differences in the polluted air mass. At the Denver Club, several extreme values, one above 10, were measured. These are ascribed to a smoke plume from a nearby hotel which drifted directly across the observation site, rendering the observations unrepresentative; they were omitted.

In the face of these difficulties, a general pattern of daily variation was obtained (fig. 3). Pollution rises sharply during each morning with onset of daily business activity. Then, with warming and increasing vertical motion of air, pollution density decreases — though, presumably, the total amount of polluted matter in the whole atmosphere above the city continues to increase. The displacement of the peak at the Denver Club to late morning again may be related to the high location of the station. With increasing vertical motion of the atmosphere polluted matter is transported upward to the observation site.

With lowering temperatures in the afternoon, pollution next begins to increase again. At the Denver Club and Denver University the air movement from north to south also plays an important role in bringing about an afternoon increase. It is not understood why there is a secondary peak at all stations and why this peak is displaced to late evening at Wheatridge and Adams City. With very light winds during the night increasing or at least steady pollution levels would be expected. The observed nighttime decrease at all stations must be left for further investigation, though the possibility of a high rate of gravitational settling may at least be suggested.

Photographic and Sun Photometer Observations

Photographic monitoring of the course of pollution during daytime, especially from the air, proved very effective. On account of difficulties of reproduction the series of spectacular photographs obtained cannot be shown here. The success of the photography was due entirely to the fact that the polluted air mass maintained, by and large, a rather sharp edge, especially along the southern boundary. At times, the division between polluted and clear air was very pronounced. From a given observation point certain distant parts of the city could be seen distinctly while others, nearby, were blacked out. Maintenance of the polluted mass as a body indicates that the daily course of pollution in bulk is not governed by small-scale lateral diffusion but by the air circulation on the scale of the whole city or larger. This is a main result of the investigation. It also demonstrates that the observational approach chosen fits the problem studied.

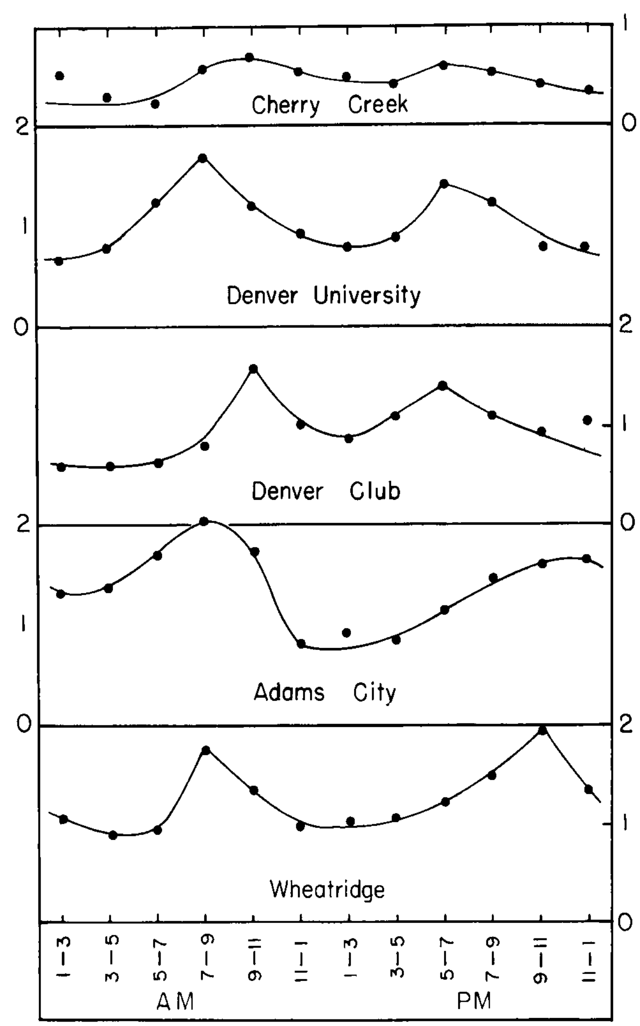

Fig. 3. Two-hour course of soiling index, mean for pollution episodes. Scale on border of diagram.

Fig. 4 shows the location of the southern edge of the polluted mass, from photographic and eye witness evidence, at one-hour intervals during several pollution episodes. The polluted mass progressed southward during the afternoon in all instances, though at variable rates. The principal advance took place along the Platte River, coupled with some lateral spreading toward west and southeast. Elevations above 5,500 feet remained relatively protected. On at least one occasion the leading edge had the form of several fingers. Much additional data will be required to determine whether the fingers should be interpreted as due to random motion along the leading edge or otherwise.

The sequences of fig. 4 at first appear to be at variance with the daily course of the soiling index given in fig. 3. In particular, one might look for a sharp rise in this index at the Denver Club and Denver University when the polluted mass arrives at these stations. Actually, this happened only once, on 12 January, when there is also a suggestion of high pollution concentration at the front edge of the polluted body. We must note now, however, that the soiling index gives the concentration of dark particles at the sampling sites, mostly located near the surface, whereas the photography essentially gives an index of total dark-particle inventory in the air above Denver. As already stated, it is probable that the total polluted matter in the atmosphere increases throughout the day, while the surface concentration diminishes with vertical mixing in the middle of the day. Given this hypothesis, the two records are readily reconciled. Verification would require sampling at various elevations of several tower sites. However, at least one instrument indicating pollution depth was used throughout the program, namely the Voltz sun photometer, which measures the intensity of sunlight reaching the instrument. Compared to normal clear-air values of 35 to 40, on an arbitrary scale, in the middle of the day, the photometer gave readings of 20 and, on occasion even of less than 10, under the polluted mass. This demonstrates that the optical thickness of pollutants was high, even though surface concentration may have been low.

Wind Observations

A main objective for taking wind observations is the construction of actual paths of air movement across the city. Such movements or "trajectories", when combined with detailed samp-

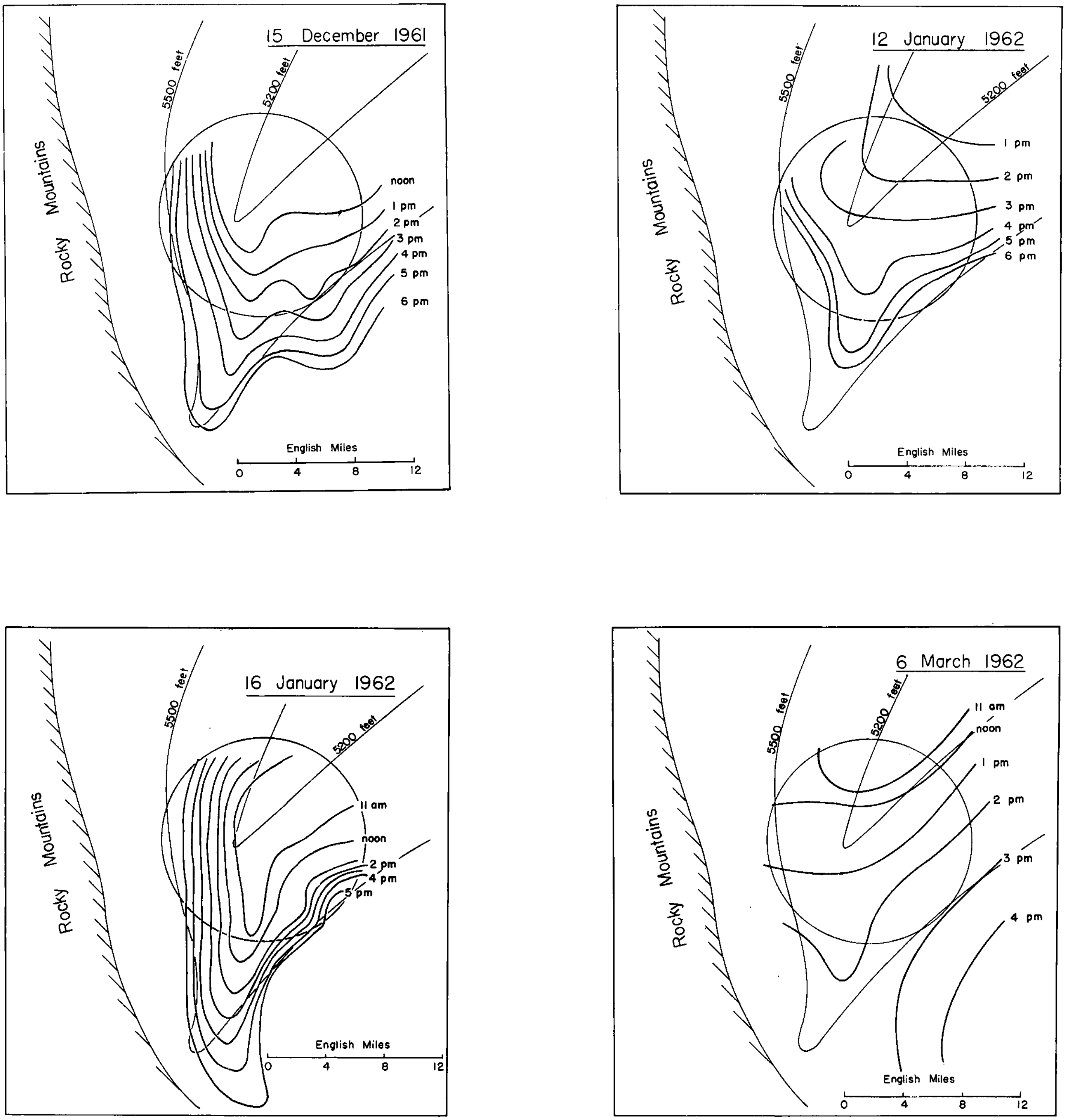

Fig. 4. Curves indicating forward edge of polluted mass at the indicated times during southward advance of the polluted mass.

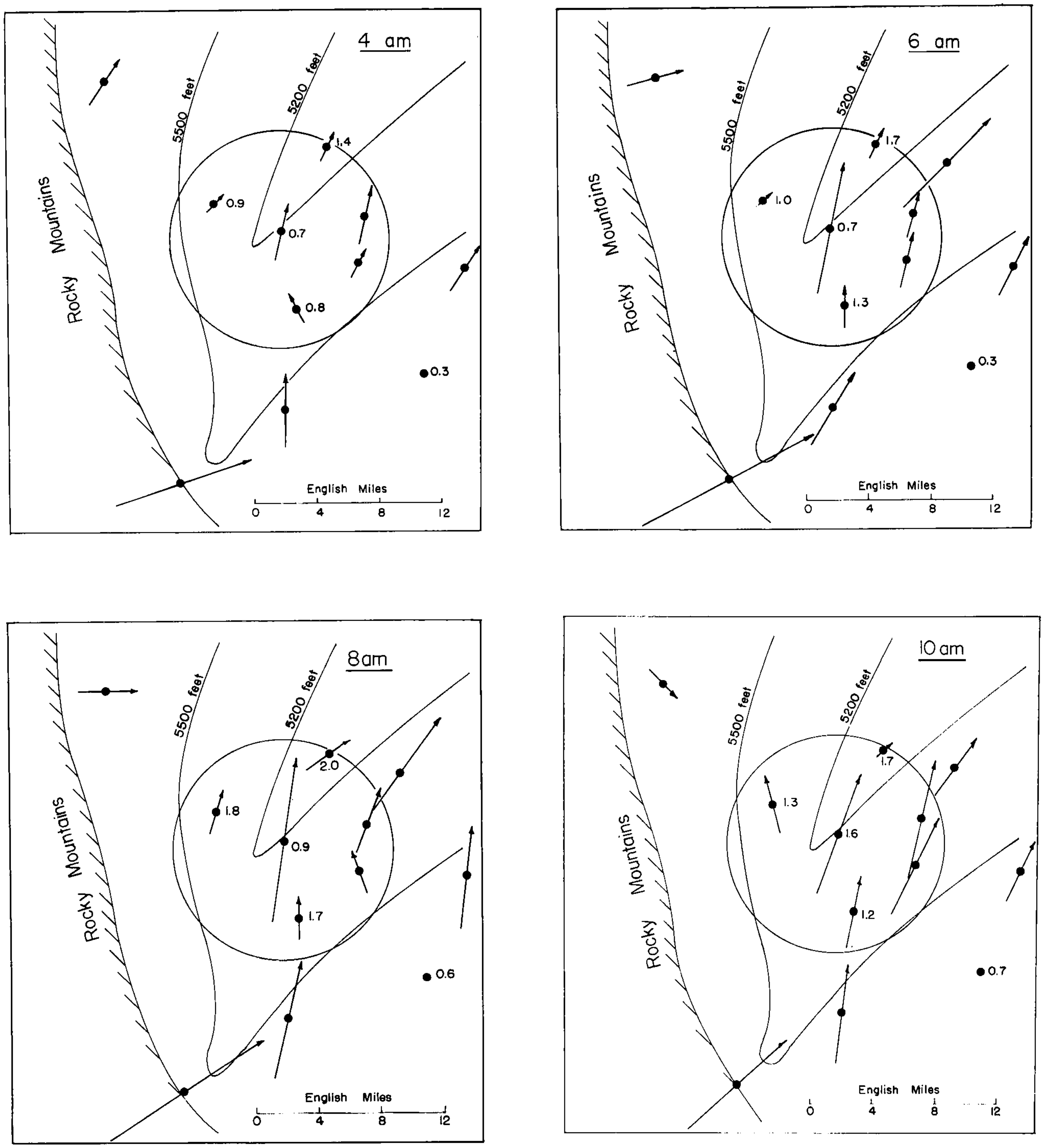

Fig. 5. Average wind during pollution episodes from 4 a.m. to 10 p.m. Values of soiling index from fig. 3 are indicated. Length of arrow indicates one-hour air movement.

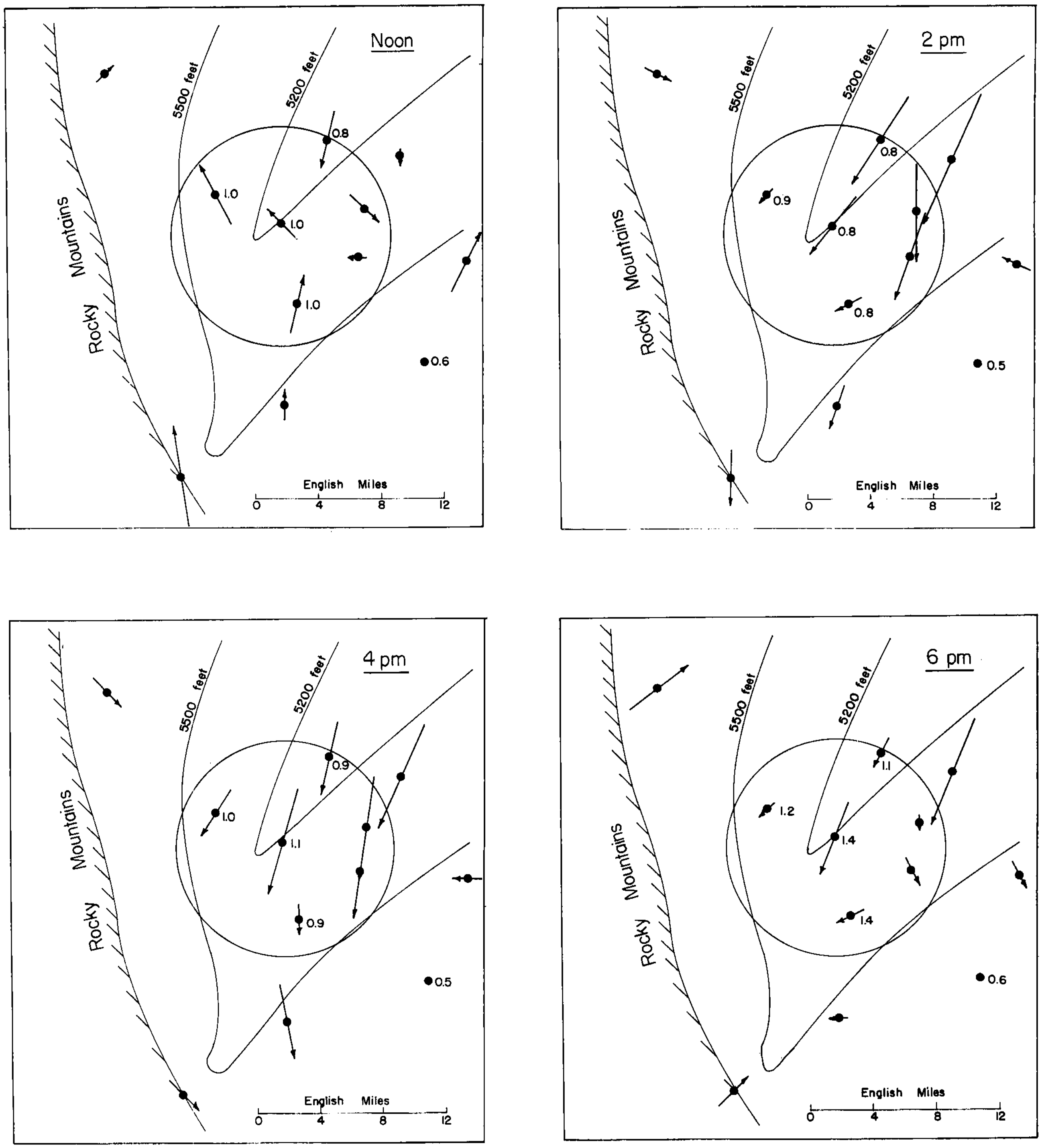

Fig. 5 (cont.) Average wind during pollution episodes from noon to 6 p.m. Values of soiling index from fig. 3 are indicated. Length of arrow indicates one-hour air movement.

ling and parameters indicative of the vertical transport of pollutants, must be capable of explaining the observed state of pollution at a given time and place. Computation of air trajectories therefore should be a primary task of a study wishing to explain bulk pollution.

A major problem lies in the observed variation of wind with height. It is impossible to insist that measurements at some particular height above ground may be taken as standard. Lacking a network of observation towers with wind instrumentation at numerous altitudes, one compromises by choosing the top of well exposed buildings for measuring sites. Such buildings should not be too high lest the observations are made too far above the "living space" and the layer representative of transport of material. The Denver Club undoubtedly is not a very good site during night and morning. Nor should the instruments be placed too close to the ground in order to avoid mere recording of immediate local conditions at an observation site. Clearly, the transport of material at some distance above the ground is relevant to people at street level, since the pollution will mix down in the small wind gusts present in the atmosphere. These gusts are enhanced by high frictional interference with air motion produced by a city's buildings.

The compromise plan was put into effect as best possible for the special project stations. Nevertheless, from Appendix I, complete uniformity and exposure of instrument location could not be achieved. When the location of the cooperating stations is also taken into account, it is evident that only a very rough approximation to air trajectories can be expected from this preliminary record.

Another difficulty lies in the fact that not all stations were operative on all occasions. This rendered rather poor the chances for adequate representation of the air flow on any given day. Because of the relative similarity of the episodes, it was considered permissible to combine them to yield a mean wind field. This has the drawback that the sharpness of events at a given time is washed out. But the evolution over several hours is well indicated when four episodes are combined. The important episode of 16 January 1962 was omitted because too many stations were not active on that day.

The result, in two-hour time steps from 4 a.m. to 6 p.m. is contained in fig. 5. Here, the one-hour air transport is shown assuming that the air moved with the direction and speed at the observation site for one hour. At the project stations actual 30-minute averages of direction and speed, as given by continuous recorders, were computed. At the cooperative stations, instantaneous readings once per hour were made following normal practice.

In spite of the many assumptions and compromises required to arrive at fig. 5 the result is informative. During the night, winds were light and variable except for downslope drainage and channelling at Martin Company. During late night and early morning wind movement from south was established at all stations. This movement increased everywhere as the morning progressed except in the northern suburbs where, as noted photographically, the polluted mass "piled up".

A remarkable change occurred around noon; its onset varied on individual days from late morning to early afternoon. Winds reversed, at first at the northernmost stations, then progressively farther south. Therewith the polluted mass reappeared over the city, rolling southward as depicted in fig. 4. Toward sunset the movement stopped and light and variable winds, predominantly from south, resumed. Thus the polluted mass, or at least a portion of it, oscillates back and forth over the city as long as the general light wind regime holds.

Drainage of cold air down the Platte River may be advanced as a reason for the nighttime and morning wind movement, though this will not explain the stoppage of the movement north of the city. The noontime reversal is even more complicated. Evidently the topography plays a major role. In summer upslope motion occurs regularly along mountain sides and, while theories differ, the primary effect of slope heating is generally acknowledged. In winter, especially with snow cover, this solution is not directly acceptable. Even if it were, however, this would not explain the initial sharp onset of northerly wind at the northern edge of the city, followed by southward propagation along a line of rapid wind change.

On one occasion, 12 January 1962, the temperature field was correlated with the wind field in a most interesting way (fig. 6). As already discussed, temperature rose from near 0^{o}F. to the low forties by noon. Then, as the wind shifted, temperatures suddenly dropped back well below the freezing point. We might conclude that heating took place generally except in the polluted mass where the pollution itself shielded the earth's surface against solar radiation. Given this hypothesis, an explanation of the southward advance of the polluted mass is readily given, since cold air tends to underrun warm air once a sufficiently strong temperature contrast has been established. Large temperature differences were not observed in the other cases, but the wind jump was nearly identical with that of 12 January.

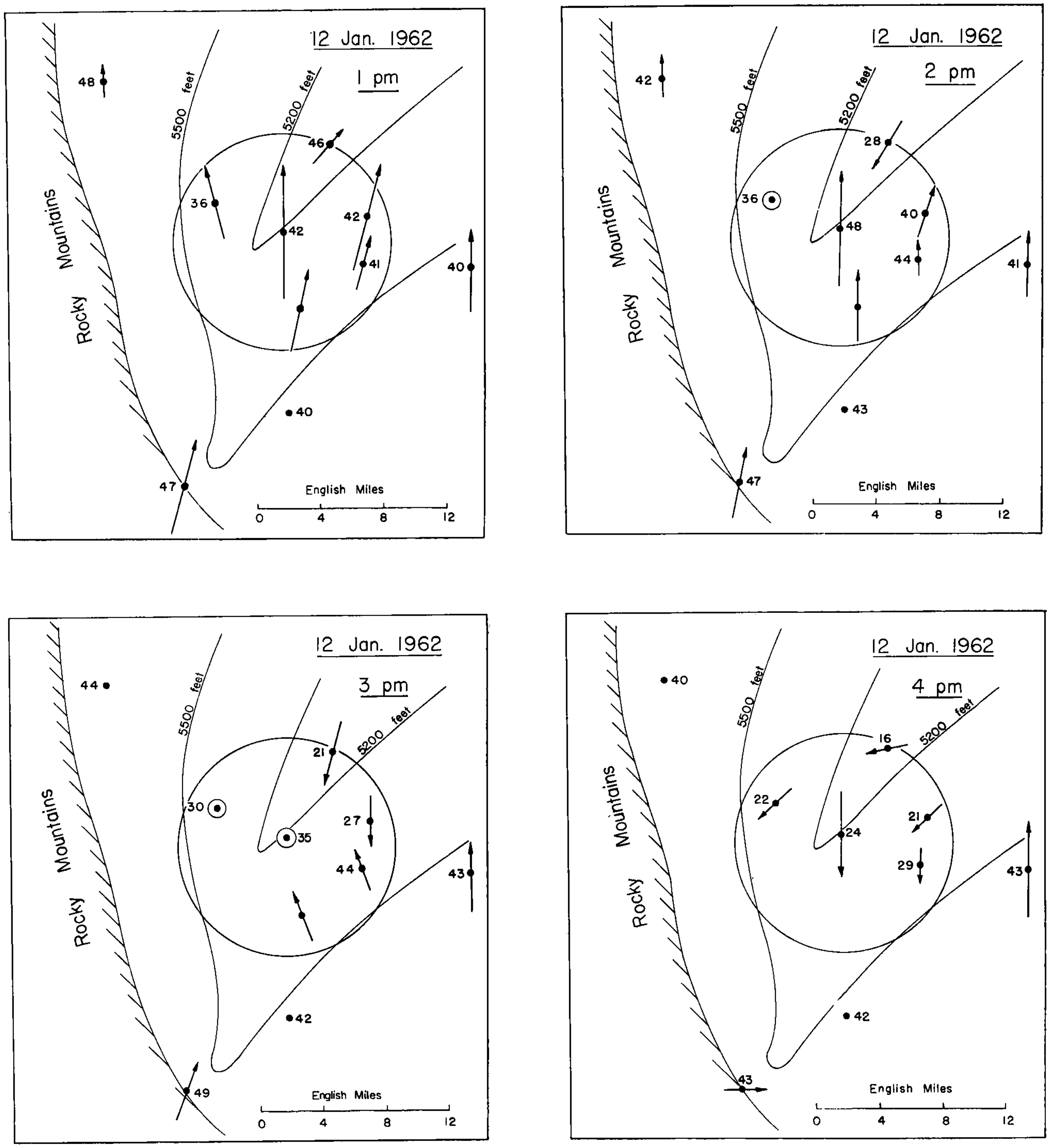

Fig. 6. Winds and temperatures (degrees F.) from 1 p.m. to 4 p.m. on 12 January 1962 during sharp reversal of wind regime. Note association of strong temperature fall with wind change.

Sample Trajectories

Two sample trajectories were computed from fig. 5; these were chosen so as to pass through the eastern half of the city where observations were most dense. The first trajectory, for morning (fig. 7), leads northeastward across the whole city in five hours. The second, for afternoon (fig. 8), shows the wind reversal and the return current to the southern outskirts in six hours. This trajectory is a little slower than would be computed from the advance of the polluted mass in fig. 4. This may be due to averaging; then again the rate of advance of the polluted mass may be controlled by winds at a somewhat higher level than that sampled by most of our instruments. The difference is not material for present purposes which are merely exploratory.

The pollution level at a given site is due to local sources plus transport of material injected into the atmosphere elsewhere and moved to that site. Since night is the time with least vertical diffusion, the air on the morning trajectory may be picking up and storing material all along the way as it moves toward Adams City. If this is true, then the average northward increase of pollution revealed by the samplers is explained on this basis, and we cannot conclude that local sources in the north are entirely responsible for the relatively high pollution count there. During the southward advance of the material in the afternoon, at the time of maximum ground temperature, the material must disperse vertically much more rapidly than in the morning, and we might even observe a decrease in concentration following the polluted mass. Granted this argument, a gradient of pollution directed northward should exist in the mean and almost throughout the entire day, even if there was merely a constant and uniform pollution source over the whole city without localized major sources of emission.

In fig, 7, values of the soiling index, our only available measure of pollution in short time steps, have been estimated along the trajectory. In view of the large distances between samplers and lack of source monitoring, such estimation is most risky. It must be emphasized that this has been done here merely in order to illustrate the ultimate computation toward which meteorological observations and analyses are aimed. No actual meaning must be attached to the trajectory. If, however, the values of the index as given in fig. 7 were realistic, then it would follow that accumulation of material indeed occurred along the entire air path and that this established the relatively high values of the index in the north.

The afternoon trajectory is quite different in that a constant value is obtained until 3 p.m. when, with decreasing temperature and increasing vertical stability of the air, a slow increase of soiling index began. This constant value cannot be interpreted to mean that there was no pollution source. It merely signifies that material was carried upward from the ground at such a rate that concentration following the moving surface mass did not increase. For an estimate of emission, it would be necessary to take a pollution inventory, i.e. the computation here performed must also be made at higher elevations to the upper boundary of the polluted mass several hundred feet above the ground.

Conclusion

This study has served to bring out the history of air pollution episodes in Denver. Such description alone is of value for civic authorities. Further, as stressed repeatedly, the main objective of the study was to explore methods for a systematic approach leading to definitive computations explaining Denver pollution. Such computations are necessary for formulation of sound remedial measures.

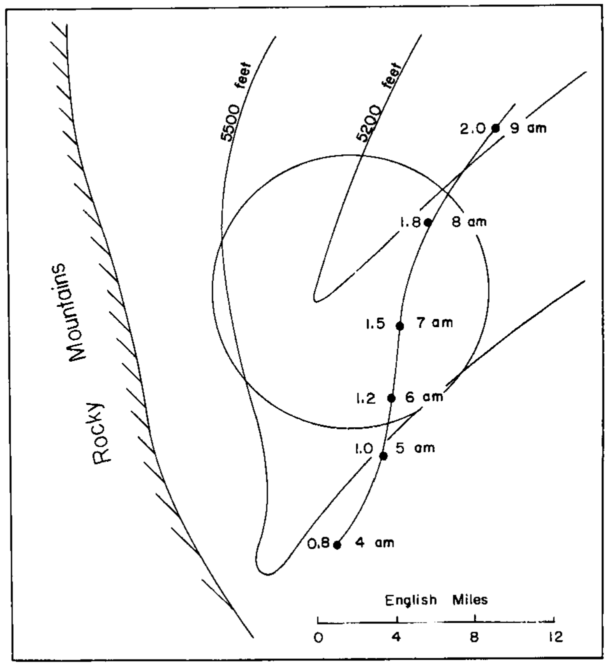

Fig. 7. Morning trajectory of air across Denver interpolated from the wind and soiling index measurements given in fig. 5. Time is marked to right of trajectory, and soiling index value to left.

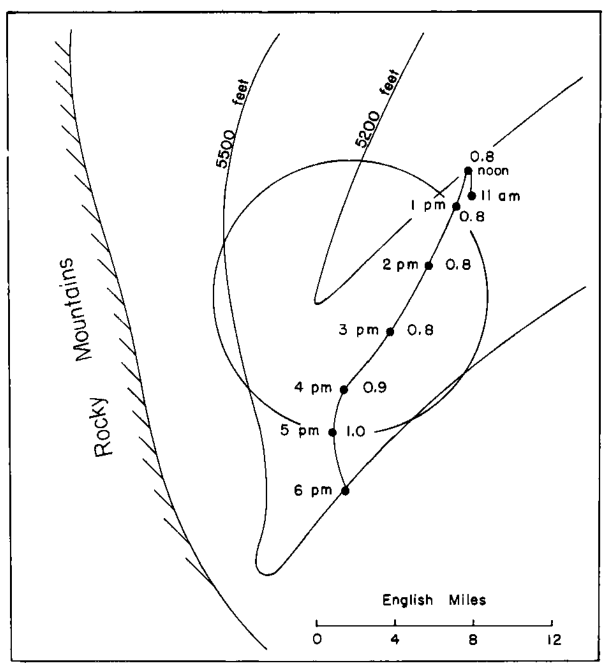

Fig. 8. Afternoon trajectory of air across Denver. Same as fig. 7.

Acknowledgements

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Much gratitude is due to the many people who cooperated in the data collection. This includes those who permitted installation of equipment: the authors particularly wish to thank Dr. Jacque Yost, Ohio Oil Company Research Center; Dr. Arley Paige, University of Denver; Chief Leo Geyser, Wheatridge Fire Department; Mr. Peter J. Murray, Tri-County Health Department at Adams City; Mr. Gerald Hart, Denver Club Building; Mr. Herman Kingsley, Tower Building of the Denver-U.S. National Bank; Mr. M. Lakin Hunter, John Hancock Life Insurance Company.

Persons assisting in the actual observations included Dr. T. S. Chapman and Mr. E. L. Ray of Rocky Flats Plant, Dow Chemical Company; Mr. Robert Bliss and Mr. Wayne May at the Martin Company Facility; Mr. Joe Berry and Mr. Morris Steinberg of the U.S. Weather Bureau City Office; Sergeant Joseph Taylor and fellow observers at Buckley Field; staff members at the Weather Bureau Office at Stapleton Field and the Weather Station at Lowry Air Force Base; the entire engineering staff at the KLZ Television Tower site on Lookout Mountain; Mr. Melvin VanLewin of U. S. Geological Survey, Denver Federal Center; Chief James Hubbard of Fire Station No. 1, Rocky Mountain Arsenal; Mr. Hugh Duggan, Denver-U.S. National Bank Building; Mr. Don Martin, Radio Station KIMN; the staff of the Denver Building Department under Mr. Walter Krstich and Air Pollution Engineer Leonard Dobler, who gave liberally of their time to take special observations during the epoch periods; and D. U. students Myles Gilbert, John Guest, Jack Bartlett, Richard Gans, and James Murray, who assisted on a part-time basis in collection of data.

Special thanks go to Mr. Henry Harrison, Meteorology Department of United Airlines, and his staff who took many pictures, and to Mr. Charles Grover, photographer, for the aerial photographs. Dr. Glen Hilst, Travelers Research Center, and Dr. James P. Lodge, National Center of Atmospheric Research, participated in the early planning stages.

Appendix I

Location and Instrumentation of Fixed Observation Sites

The following temporary installations of wind and temperature recording units were made (cf. fig. 1):

Tri-County Health Department Building, 4355 E. 72nd Street, Adams City.
Roof (12 ft.) unrestricted. Instruments on roof.

Denver Club Building, 518 17th Street, Denver.
Roof (240 ft.) almost unrestricted, wind only.

Tower Building of Denver-U.S. National Center, 1700 Broadway, Denver.
Roof (300 ft.) (unrepresentative building effects with south winds), temperature only.

Fire Department Building, W. 39th and Upham Streets, Wheatridge.
Roof (30 ft.) unrestricted, wind on roof, thermometer shelter on ground.

Henry Green Building, University of Denver, South Denver.
Roof (25 ft.) slightly restricted, wind on roof, thermometer shelter on ground.

Ohio Oil Company Research Center, south of Littleton.
Roof (20 ft.) unrestricted, instruments on roof.

The equipment, loaned by the Taft Sanitary Engineering Center, HEW, consisted of the following:

5 Beckman and Whitley wind speed and direction units (mast 10 ft.).
Esterline-Angus recording units.

5 Thermographs with ventillation screen (shelter 5 feet high).

Additional observations were obtained from the records maintained on both wind and temperature at the Martin Company, southwest of Denver; Dow Chemical Company, Rocky Flats Atomic Energy Plant, northwest of Denver; Stapleton Field; Lowry Air Force Base; and Buckley Field.

Brief records of wind direction and velocity were obtained from Rocky Mountain Arsenal and the U. S. Geological Survey at the Denver Federal Center.

A large number of 35 mm photographs were taken by United Airlines meteorological personnel at Stapleton Field. Time-lapse photographs were made by a camera located at 655 Broadway Building. Still pictures were obtained from Lookout Mountain at the KLZ Television Tower installation.

Appendix II

Data Collection Procedure

The chief objective of the study was to obtain data during intense air pollution periods. The procedure for such collection was:

A. The Field Director chose the first day of each episode prior to 9:00 a.m. of that day, based on the local weather pattern and the vertical temperature profile (cf. fig. 2).

B. Telephone calls were made to all points where supplemental information was contributed (cf. acknowledgements).

C. Request was made for aerial photographs, and a general two-hour time period was chosen during which the best pictures might be obtained.

D. After the first episode a fixed volume balloon (a tetroon), set to float at some level below the main inversion, was released between 11:00 a.m. and 12:00 noon from the roof of the Denver Club Building and followed by automobile on the ground.

E. Visual observations and readings with the Voltz meter, which measures intensity of sunlight reaching the ground, were made on a fixed path around a square with length of each side about five miles centered around downtown Denver.

F. Hourly photographs were taken by the United Air Lines meteorology staff from the roof of the Operations Base at Stapleton Field with the camera aimed in various directions — predominantly toward southwest, west, and northwest.

G. Hourly photographs were taken from Lookout Mountain with the camera aimed toward downtown Denver.

H. Time-lapse photographs were made with a motion picture camera from the 655 Broadway Building with the camera aimed toward downtown Denver.

I. The Field Director obtained photographs with a 35 mm camera, where interesting details came into view throughout the metropolitan area.

J. When continuation of the air pollution episode for a second day was declared, the above procedure was repeated.

K. Data from the wind and temperature records from all available locations were subsequently placed on hourly maps to portray the sequential changes in the air movement over the metropolitan area (cf. figs. 5 and 6).