LARIMER COUNTY, COLORADO,

AIR POLLUTION AND OUTLOOK

1870

by

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December, 1970

ABSTRACT

Planning for economic and population growth in presently rural areas would be considerably aided from the standpoint of air quality, if an assessment of future air pollution in terms of expected population growth, as a parameter, could be made. This paper attempts to make such an estimate for the foothills area just east of the Colorado Rockies near the northern border of the state. Three problems are taken up in succession, limiting attention to particulate pollution.

At first, "pollution potential", defined as the probability of incidence of air pollution episodes of some minimum duration, is calculated from winds obtained during a field experiment. On the average, 10 episodes per winter taking up one quarter of a winter's time may be expected; this is a substantial fraction of total time.

Next, the mechanisms of present air pollution accumulation and depletion were studied preliminary to developing daytime and nighttime models for future pollution. It is shown that a nighttime model without turbulence can reconstruct the present pollution map quite faithfully, whereas turbulent upward flux must be added in daytime, not unexpectedly.

In the models, it is possible to express future pollution density in terms of wind speed and pollution source strength. Assuming a rate of 50 per cent population increase per decade, estimates of average pollution and also of pollution distribution are prepared until the year 2000.

SUMMARY

In order to obtain information on the first of the objectives cited in the preceding abstract, namely, the degree of "air pollution potential" in Larimer County, a network of stations measuring wind, temperature and the coefficient of haze (COH) was operated in the county during the 1968-69 winter.

Pollution Potential: The mean wind speed over the area mainly determines the amount of pollution likely to accumulate. When wind speed falls below a certain level for an extended period of time, taken as 36 hours minimum, the potential for a pollution episode exists. The number of potential episodes, as well as the percentage of total time such episodes are likely to endure, is determined from the wind and COH record of the stations. It is found that below 4 mph relatively high pollution concentrations existed during the observational period of three months. Hence, 4 mph is defined as the threshold for pollution episodes. Ten episodes with average wind speed below 4 mph lasting 36 hours or longer took place. These occupied nearly one quarter of the total time, a duration that may be taken as a first estimate of the average duration likely to be experienced in later years.

It is seen, that the county indeed has a substantial potential for pollution episodes. Further, wind speeds on the average are lowest in the strip right along the foothills and increase eastward from there (Figs. 3b, 4b). Hence, the area adjacent to the foothills is likely to be much more subject to high pollution levels than the plains farther east.

At present, average pollution density is highest along the foothills with only minor differences between daytime and nighttime (Figs. 5a-b). Pollution decreases rapidly toward east and also from south to north. This distribution results in part from the location of local pollution sources, from the wind speed factor mentioned above, and from the general distribution of sources outside the county, even though a precise correlation between winds from Denver and local air pollution levels could not be found (Fig. 6). As should be obvious from the general rural character of the county, from the population density and from the fact that the mountains normally are still visible in the west, the statistics confirm that present average pollution levels are very much lower than those of, say, Denver; occasional extreme concentrations in Fort Collins, however, do match the average pollution intensity of downtown Denver.

<u>Mechanisms of Air Pollution Accumulation and Depletion</u>: On the average day with pollution potential -- as well as on most other days -- the wind follows a diurnal pattern, blowing from north toward lower land height at night and from south up the slope during the day. Thus, at night, clean air is brought into the county from the north, where practically no pollution sources exist; during day air with higher background pollution is imported from the south. Pollution concentration follows a diurnal pattern which partly matches that of Denver and other large cities, but which deviates in some important respects. Pollution increases in the early morning before and during the time when many sources are turned on. The major

decrease in Denver during the forenoon is not observed; instead pollution density merely steadies (Fig. 8) and resumes an upward trend long before the onset of afternoon commuter traffic. Meteorological factors -- increasing wind from south and overturning of air in the forenoon, cessation of turbulence in the early afternoon -- appear to exercise the main control. The maximum is reached around 5 p.m. when source strength begins to diminish and wind direction changes back to northerly. Thus, pollution decreases throughout the evening, even though turbulence is suppressed.

For further information on the mechanisms leading to air pollution accumulation and depletion, a mass budget was calculated for the particulate pollutants during an average pollution period. The amount of pollutants put into the air as estimated from an inventory prepared by the Colorado Department of Health is 10 tons/day in the annual mean; seasonal variation probably is small except for agricultural burning which is confined to the colder part of the year. Of the average source approximately one-third or 3.3 tons is assumed to fall out of the atmosphere daily through sedimentation. The north winds remove 2.1 tons out of the area at night, whereas the south winds during day bring in a very small addition of 0.1 tons. In order for the observed pollution density to occur, about 4 tons must be removed upward by turbulence in the mean. Values of turbulent transport are found to fluctuate considerably from day to day. When the wind is strong, vertical overturning is enhanced considerably over days with light winds. Hence, removal of pollutants through turbulence is much larger during high compared to weak winds. At mean wind speeds at and below 2 mph cleaning of the air by turbulence is found to cease. Thus, wind speed is a very important parameter during daytime when the thermal stratification of the lowest atmosphere may also be assumed at least to be neutral, i.e. not resisting up- and down-motions of the air.

Pollution Model for Larimer County: The foregoing discussion of wind distribution in the county and of mechanisms of pollution accumulation and depletion furnishes the background required for the construction of pollution models given different source strengths and wind speeds. We consider the travel of air from north to south during night and the inverse during daytime. At night, without turbulence, pollution accumulates at a uniform rate as the air moves over a source at first assumed uniform; this restriction may be dropped. During day, turbulent transport causes the pollution density to decrease as air moves from south to north, in spite of the sources, except at wind speed below 3 mph. At least, this is true at present source intensity. At higher source strengths (Fig. 16), only wind speeds above 4 mph can keep pollution density from growing almost without limit; it is now seen that our empirically determined threshold of 4 mph for pollution episodes, derived from the wind data, was not badly chosen.

The models were used to compute maps of pollution distribution with current average source strength to see whether the observed pollution patterns would be reproduced; this is indeed the case to considerable approximation (compare Fig. 15a and 5a, 17a and 5b). Next, predicted patterns are drawn for source strengths of 25, 50 and 100 tons per day; the latter would correspond to the emission by a major metropolis. Great increases of pollution intensity are calculated around Loveland at night and Fort Collins in daytime (Figs. 15 and 17) with increasing source, whereas the eastern boundary of the county shows very little change due to the mitigating effect of the stronger winds prevailing there.

Table IV lists the average as well as maximum concentrations to be expected in the future in Larimer County, during day and night, assuming a 50 per cent population increase per decade until the year 2000 and a constant per capita emission rate. Different growth rates for the county can, of course, be substituted. It should be emphasized that the maxima given in the table are only the highest values for the *average* pollution episode as experienced at Fort Collins and Loveland. Extreme pollution levels may be expected to be twice as high, if relations obtained for Denver can be applied.

In conclusion, the study shows that presently Larimer County has only a minimal air pollution problem, as would be expected. However, from Table IV, the general air pollution level in the year 2000 is estimated to be twice as high as at present; along the foothills still higher intensities can be expected. Occasional severe pollution episodes may be expected to occur, especially around Fort Collins and Loveland. Early planning can readily forestall such unpleasant situations from materializing. One can think of various schemes; obviously, a shift of development to the eastern margin of the county is a prominent possibility.

ACKNOWLEDGEMENTS

Funds for operating the observational network during the 1968-69 winter were provided by the Colorado Department of Health; instrumentation was available from the Department of Atmospheric Science, Colorado State University, through acquisitions made during previous studies of Denver air pollution funded by the U. S. Department of Health, Education and Welfare. Colorado State University made additional funding available for data processing and report preparation. Mr. Dirk Herkhof participated under a NASA fellowship.

Thanks are due to Drs. A. Betts and K. Fraedrich for critical reading of the report and various discussions; to Professor C. Junge, Mainz, for several important suggestions; to Miss H. Akari for drafting, to Mr. D. Barnhardt for photography and to Mrs. P. Johnson for report preparation.

LARIMER COUNTY, COLORADO, AIR POLLUTION AND OUTLOOK

INTRODUCTION

The study leading to this report developed in consequence of discussions held with officials of the Colorado Department of Health[1], who were interested in obtaining an estimate of changes of air pollution levels in the setting of rapid population and industrial growth which Colorado is experiencing and which may be expected to continue at least for several more decades. Such an assessment should be of assistance in determining the answers to questions such as the following:

(1) How can the pollution source be expected to grow with population?

(2) What are the projected mean concentrations in the atmosphere for different hypothetical sources?

(3) Which are the best areas, from the pollution control standpoint, for major development to take place in the future?

Larimer County, located in the northern part of Colorado (Fig. 1), was considered to represent a typical growth situation, in particular the foothills area with axis from Fort Collins to Loveland (Fig. 2). Population of this area is approaching 100,000, having risen 70 per cent from 1960 to 1970. The area additionally is a logical target for study because of its proximity to Colorado State University, where ten years of local meteorological expertise have accumulated at the Atmospheric Science Department.

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[1] Mr. J. Palomba and Mr. W. May.

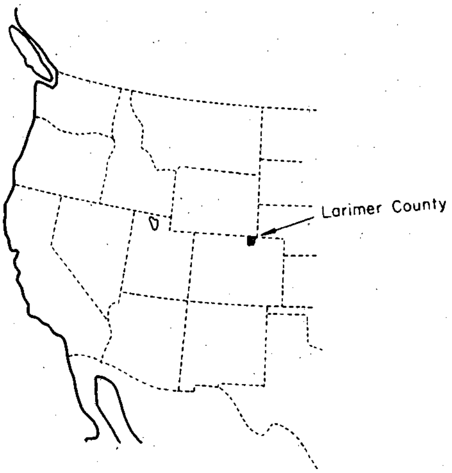

Figure 1. Map of western United States indicating location of Larimer County in Colorado.

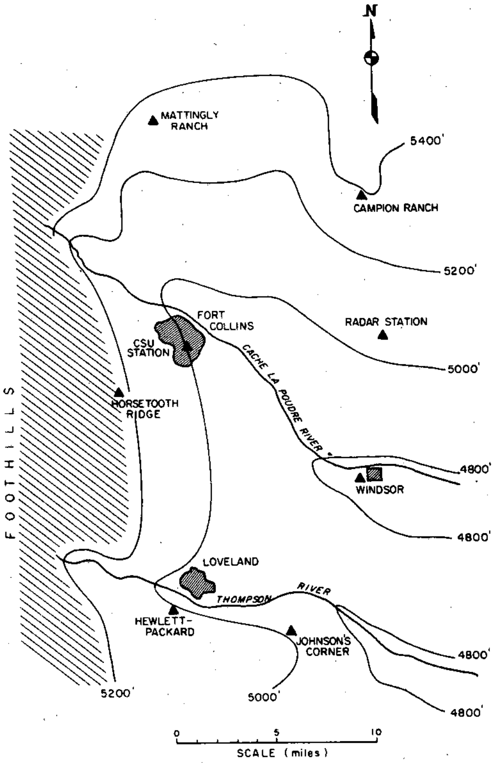

Figure 2. The project area with location of stations measuring wind, temperature and COH; contours of height of land in feet.

The purpose of the study was to investigate the meteorological parameters in the context of the air pollution questions just stated. General discussions of meteorology as related to air pollution have been given by McCormack (1968) and by Neiburger (1969). While increasing pollution control is essential to minimize the problem (Dixon and Lodge, 1965), a rapidly growing population will tend to counteract progress made with control measures. Hence, much importance attaches to questions such as these:

(1) What weather factors cause the highest pollution levels at present?

(2) What is the frequency of weather events that could lead to undesirable pollution levels in the future?

Since the study is meteorological, and not directly concerned with source regulation, particulate pollution was chosen as representative variable for meteorological analysis, just as in a previous study of Denver air pollution (Riehl and Herkhof, 1970). The subject matter naturally divides into three parts, namely:

(A) Determination of "pollution potential" as defined by the frequency of prolonged light wind periods in winter, when thermally stable stratification may be expected at the same time.

(B) Determination of present pollution levels, mechanisms of particulate exchange and rise and fall of pollution levels.

(C) Construction of models for calculating future pollution distributions under various assumptions of population growth and source strength.

These three topics will be taken up in the indicated order.

AIR POLLUTION POTENTIAL

It is readily apparent that wind speed is a major factor in determining pollution intensity in the air. With high winds, the material emitted even from an intense source will be transported away rapidly enough so that the cleanness of air is not materially impaired. With light winds or calm conditions the emission from weak sources may keep building up in the air resulting in what is termed a "pollution episode". Further, vertical overturning dilutes pollution by moving dirty air up and clean air down. Overturning is partly dependent on the distribution of temperature with height and especially hindered by the presence of a "temperature inversion", an air layer in which air temperature increases upward, whereas it normally decreases with height. Overturning also is controlled by wind speed; the higher the wind, the more up-and-down turbulent motions are generated. A strong decrease of temperature with height alone does not guarantee that turbulence will take place. Severe air pollution periods have been experienced in summer with marked upward decrease of temperature but light winds.

For Larimer County, as well as for very many other rural areas, the meterological picture simplifies in winter. During light winds, temperature tends to be stably stratified, with temperature inversions near the ground, at night. With marked warming in the air layer near the surface on clear days--even in mid-winter the mean daily temperature range is near 30° F on such days over the Colorado plains--temperature will decrease with height in the noon and afternoon hours often leading to an increase in wind speed and therewith also to turbulence in the middle of the day. Local topographic features can modify this basic rhythm, as is indeed the case in Larimer County. Large-scale weather systems passing across any region will act to suppress or enhance the normal daily wind pattern.

Network of Stations: In order to determine the normal wind circulation, and also to ascertain the number and duration of periods with exceptionally light winds as imposed by the general weather situation, a network of surface stations was installed and operated from December 1968 to March 1969. Temperature, particulate pollution, wind direction and wind speed were measured. The wind recording instruments were located on towers 10 meters (33 ft) high. No tower installations or upper-wind measurements were available. The station network is shown in Fig. 2; it may be noted that the Horsetooth station was located several hundred feet above the plains on the first ridge, thus giving some indication of winds above the plains. It should be mentioned that except for the two towns--Fort Collins with 43,000 and Loveland with 16,000 inhabitants--the area is entirely rural, with hardly any obstruction to wind motion. There is no forest growth; natural vegetation is of the steppe variety, and topographic features are gentle east of the first ridge of the Rockies. Hence the wind towers are regarded as giving a much more representative picture of wind motion in the layer of primary air pollution than would be true in many other areas.

At each station, wind speed and direction were recorded on strip charts and averaged for 5-minute periods by running each chart through an analogue-to-digital converter. Direction and speed were then averaged over 2-hr periods, the minimum time interval over which pollution levels could be measured. Two-hourly and 12-hourly wind charts, as well as average charts for the whole 3-month period, were prepared and analyzed. It was possible to draw reasonable streamlines and lines of equal wind speed in nearly all instances attesting to the representativeness of the data.[1]

Concentration of particulate pollution was measured in terms of the Coefficient of Haze (COH) by means of Gelman samplers which draw air through filter paper for a selected length of time. COH is determined by measuring the opaqueness of the spot which is darkened by exposure to the air stream. In our case interest centers on the shortest time interval for which a reliable value can be obtained; from previous experience, the minimum time is 2 hours. Charts of COH for 2-hrs and 12-hrs, as well as for the whole period were prepared and analyzed as in the case of the wind observations. Consistent results with a reasonable appearance were again obtained. For the reader's convenience Table I contains a severity index of COH values which is widely used.

Table I

COH	Adjectival Rating
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

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[1] In the case of Windsor an adjustment of wind speed was made based on the seasonal chart. Windsor's speed turned out to be much lighter than that of the stations on either side; this was judged to be a shortcoming of the particular instrument at the site.

Seasonal Wind and COH Fields: Air motion is strongly controlled by the mountains in the west which, for the most part, constrain the atmosphere to move either from north or from south parallel to the mountain range. Occasional days with chinook winds from west, cold front passages, etc., all irrelevant to the air pollution problem, could have been eliminated from the average wind charts. The latter, however, are sufficiently clear-cut (Figs. 3a-b, 4a-b) to make such a refinement unnecessary. During night the wind is from the north traveling toward lower height of land; in the daytime, it reverses and blows uphill from the south. The daytime circulation is not as clearly marked as that of night, just as in the case of Denver where a similar daily wind reversal exists. Wind speeds are lowest at the very edge of the mountains and increase eastward from there. Remarkably enough, the highest station--Horsetooth--almost has the lowest average wind speeds. Differences between day and night wind speeds are much less than might be expected on general climatological grounds. Figs. 3 and 4 portray a very simple pendulum-type of motion that will furnish the model of the wind field to be employed in the later parts of this report.

COH data (Fig. 5a-b and Table II) indicate highest pollution where population density is greatest. In terms of the preceding table of COH rating, all average values are very low indeed, indicating the present rural character of the whole area.[1] Daytime values

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[1] However, at Fort Collins COH values above the level of one unit are occasionally observed. Further, on certain days in February and March, 1969, measurements of NO_2 concentration were carried out on the campus of Colorado State University by Dr. M. Corrin. Observations were all taken at 3 p.m. on 17 different days which averaged to a concentration of 0.050 p.p.m. Surprisingly, this value is comparable to mean values of NO_2 found in big cities. This may be because NO_2 could have its maximum concentration around this time. Also, the station where the observations were made is located next to a big parking lot where automobiles could contribute a great deal to the total concentration observed.

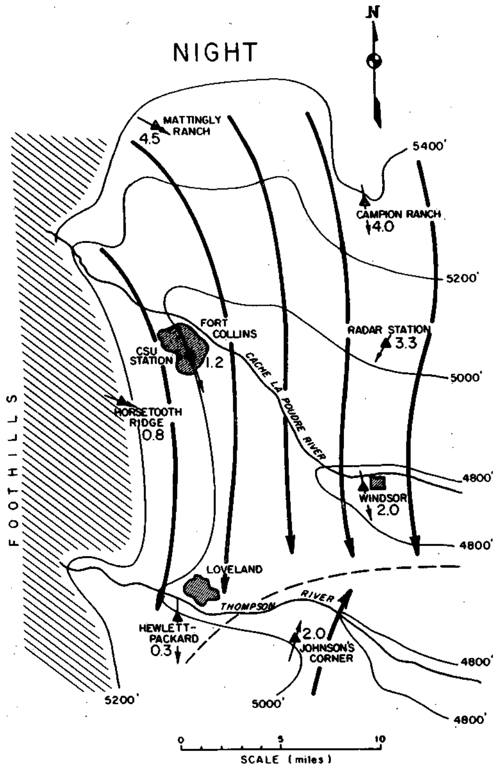


Figure 3a. Resultant streamlines and wind speeds for night (8 p.m. - 8 a.m.).

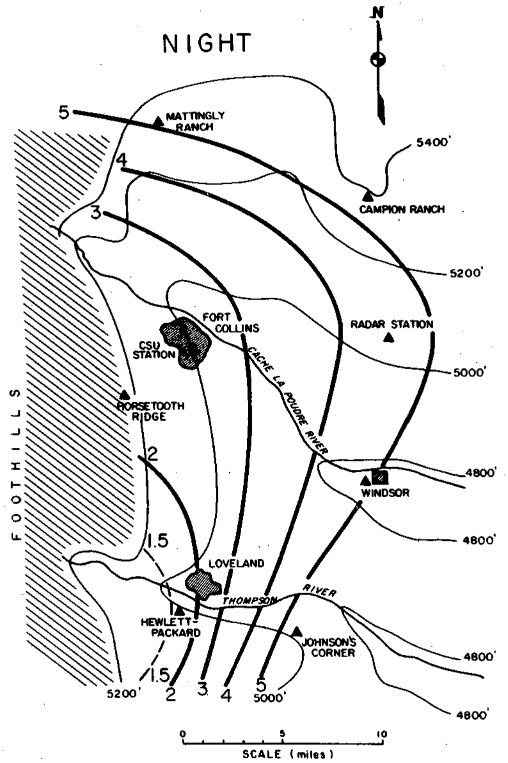
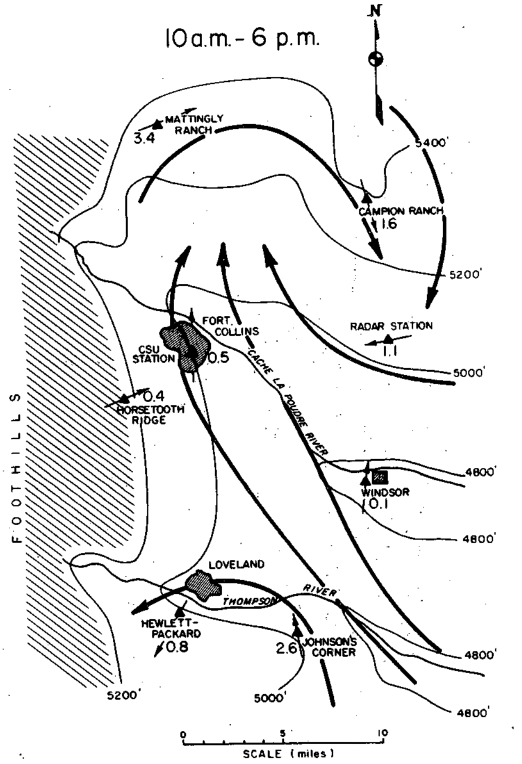


Figure 3b. Wind speed (mph) for night, averaged without regard to direction.

Figure 4a. Resultant streamlines and wind speeds for daytime (10 a.m. - 6 p.m.).



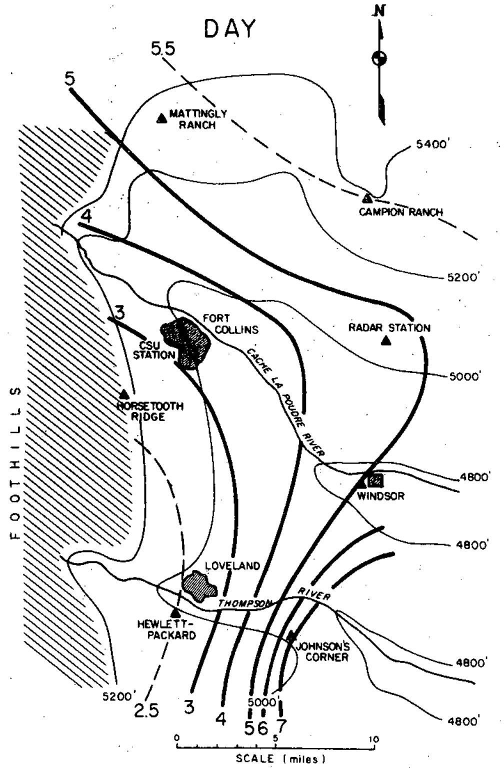


Figure 4b. Wind speed for daytime (8 a.m. - 8 p.m.) averaged without regard to direction.

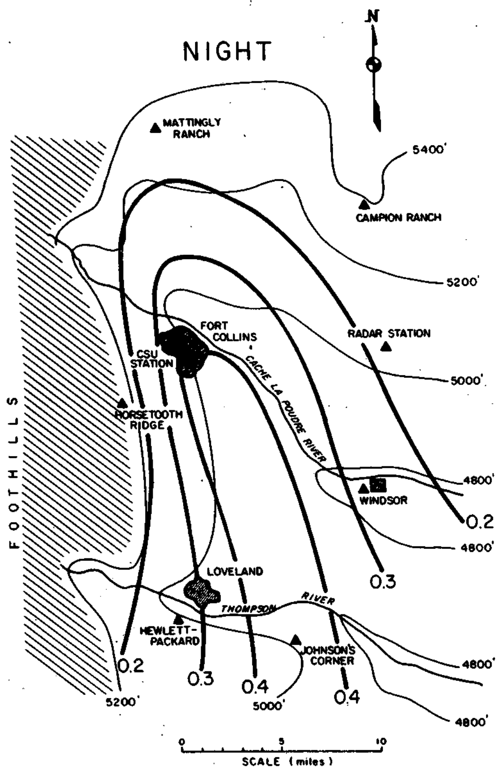


Figure 5a. Average particulate mass distribution (COH units) for night (8 p.m. - 8 a.m.).

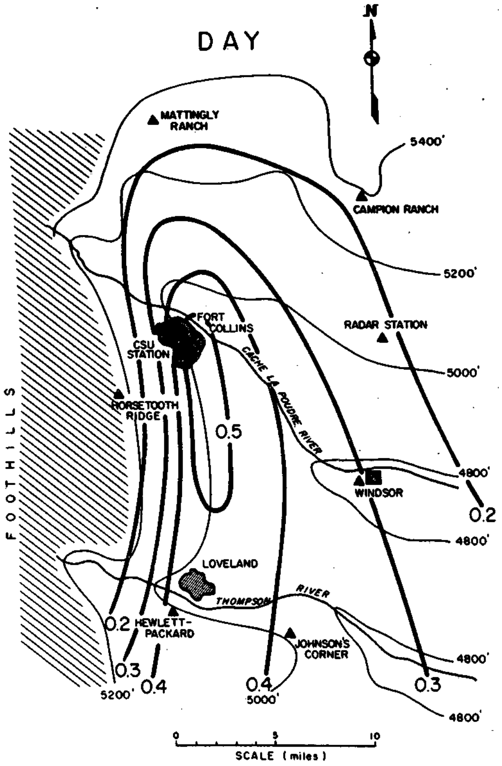


Figure 5b. Average particulate mass distribution (COH units) for daytime (8 a.m. - 8 p.m.). The closed 0.5 line is arbitrary; it could be kept open to the southern border of the area.

slightly exceed those of nighttime; however, the principal deduction to be made from the comparison is that differences between day and night are slight indeed. One might have thought that pollution should be much higher during day than during night, not only because of a larger source in daytime but also because of the predominant wind from south (Fig. 4b) which is bringing air into Larimer County from the high-density population areas, especially Denver. It turns out that this effect is rather slight except for laying down a weak general south-to-north gradient of pollution density which will be incorporated into the models later on. In Fig. 6 the relation between 12-hr wind speed and COH, both averaged over all stations, is plotted. As expected, pollution increases with decreasing wind speed. However, south winds (circled values) are not well correlated with high COH values, showing that the Denver source has little influence 50 miles away, at least at present, even though changes in visibility and sky color can be observed at times on days with exceptionally persistent south winds. It may be noted that Panofsky (1967) also found little effect of distant pollution sources in a study of pollution in the Appalachian steel manufacturing region.

It may be added that Fig. 6 also indicates particularly low COH values during precipitation. Irrespective of the reasons, which may be complicated, situations with precipitation, rain or snow, may be safely eliminated from air pollution considerations. Oddly, high COH values from dust storms, which we expected to find, also did not materialize.

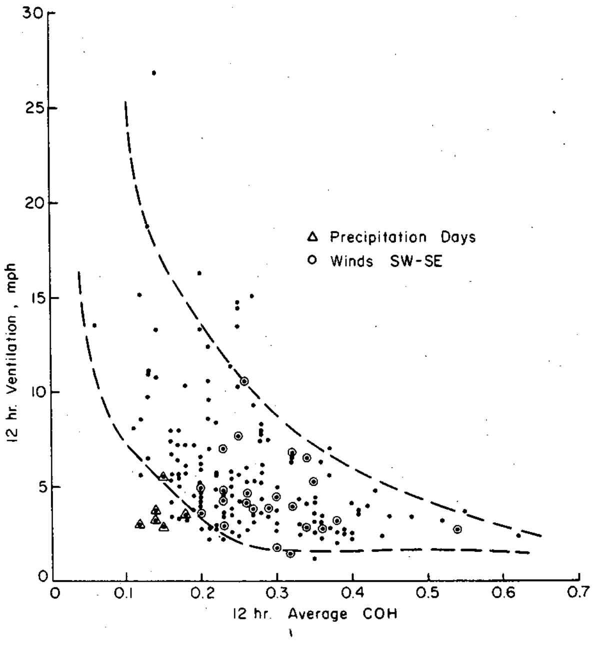


Figure 6. Relation between 12-hr averaged ventilation and COH.

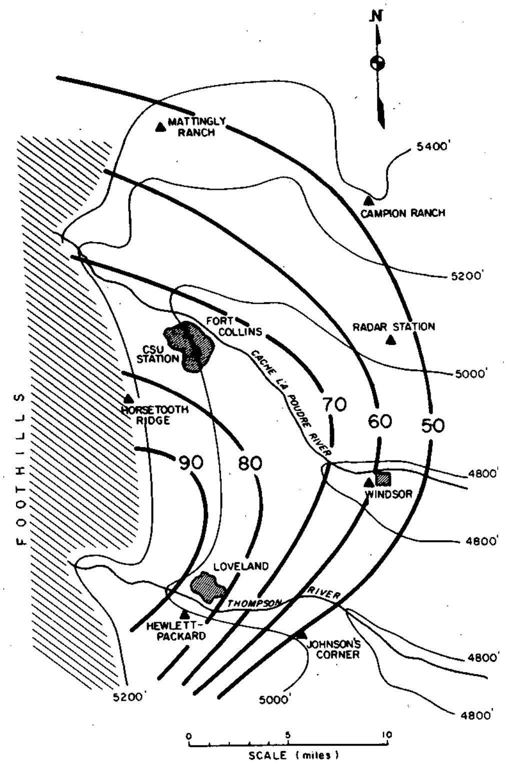


Figure 7. Per cent frequency of occurrence of 2-hr resultant wind speeds less than 5 mph.

Table II

Mean Daytime and Nighttime COH Levels[1]

Station	Night	Day
Fort Collins	0.40	0.54
Horsetooth Ridge	0.11	0.14
Hewlett-Packard	0.27	0.47
Johnson's Corner	0.45	0.37
Windsor	0.29	0.30
Radar Station	0.18	0.21
Campion Ranch	0.11	0.19
Mattingly Ranch	0.13	0.15

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[1] See Fig. 2 for station locations.

Air Pollution Episodes: The study area extends about 25 miles in the north-south and 12 miles in the east-west direction. Thus, at a wind speed of 15 mph, the area would be fully ventilated within 1-2 hours so that air pollution would be held to very low levels. Clearly, a much lower threshold of wind speed is indicated. A frequency distribution of all 2-hr wind values at all stations shows that wind speed was below 5 mph well over half of the time, which may be taken as a first guide. The percentage with low winds varies widely within the county, from 50 per cent in the east to as much as 90 per cent along the foothills southwest of Fort Collins (Fig. 7). There the air pollution potential is highest; the illustration is suggestive in terms of further development of the county in terms of air pollution potential and avoidance.

We now wish to find an index for the entire area indicating the probable frequency of incidence of prolonged light wind periods or "episodes" with high pollution potential. The 12-hr average wind speed for all stations was investigated for duration below certain threshold values, especially less than 6, 5, and 4 mph. A potential pollution episode of increasing severity was thought to exist if wind speed remained below one of these thresholds for at least 3 consecutive 12-hr intervals, i.e., for at least 36 hours. Table III shows the result. We see that, with 12-hr wind speed less than 6 mph, air pollution would occur during no less than 62 per cent of the time, divided in 18 episodes; with wind speed less than 5 mph as threshold, the per cent frequency drops to 44 and the number of episodes to 13; with a threshold of 4 mph the numbers change to 24 per cent and 10 episodes. Finally, a "hard core" situation was defined, with wind speed below 4 mph and duration above 60 hours. Five such cases occurred during the experimental period covering 16 per cent of total time. It may be argued that the experiment should be repeated for several winters to arrive at more representative values, since not all winters are alike. Unfortunately, the present analysis had to be based on the one season's observations. While large year-to-year differences no doubt do exist, experience with weather patterns suggests that the 1968-69 winter was not far from average and that Table III may serve as a first guide to mean climatic conditions.

For further discrimination between the several choices of Table III, running plots of 12-hr wind speed and COH were prepared and compared for correlation between these two quantities. It did turn out that at 5-6 mph COH values often were average or below, and that relative high COH values (0.4-0.5 area average) did not become established until wind speed dropped to and below 4 mph. We may accept the third line of Table III as most indicative of probable pollution potential within the limits of pollution source to be expected in the next several decades, that is 10 periods together lasting one-quarter of the total time in a winter. Further analysis, strengthening this choice, will be offered in the next section.

The preceding calculation suggests that it is indeed worthwhile to be concerned with future air pollution in Larimer County since one-quarter of the time is a large fraction. If we had arrived at, say, less than 10 per cent, the study might well be concluded at this point. As it is, we shall continue to take up the order of subject matter outlined in the Introduction.

Table III

Number of pollution episodes and of per cent duration of pollution in winter, if pollution is defined as occurring below the indicated wind speed thresholds.

Ventilation (mph)	No. of Episodes	No. of 12-hr Periods	Frequency (%)
<6	18	112	62
<5	13	79	44
<4	10	43	24
"hard core"	5	28	16

MECHANISMS OF POLLUTION EXCHANGE

In order to arrive at a basis for calculating future pollution levels, we shall examine the mechanisms generating and maintaining present air pollution above the general rural background, about 0.2 COH units. We may write the equation of mass continuity of pollutants

$$\int \frac{d\rho}{dt}\,\delta\alpha = \frac{\partial}{\partial t}\int \rho\delta\alpha + \int \nabla\cdot\rho V\delta\alpha + \int\frac{\partial}{\partial z}\,(\rho w)\;\delta\alpha. \qquad (1)$$

Here ρ is the density of particulate matter in the volume α with sides L (length), W (width) and Z (depth); t is time, ∇ the two-dimensional gradient operator, V the horizontal vector wind and w the vertical wind component. For determination of ρ the COH values were converted to pollution density with the empirical formula

$$\rho\ (\mu g/m^3) = 125\ \mathrm{COH}, \qquad (2)$$

employed also in our Denver study. The slope of this linear regression line is a little weaker than obtained at the CSU weather station from comparison of COH values and total mass from a high volume sampler as measured by Dr. M. Corrin. However, we have no immediate indication that the slope constant should be changed for the whole area under study (Fig. 2); such a change can be made readily later, should additional data confirm a larger constant.

Local Change: It is pertinent to discuss the variation of pollution intensity in a volume which comprises the living space of the population and, excepting isolated high stacks, all sources of emission. A height of 100 m (330 ft) will satisfy these purposes. Using this height and the area shown in Fig. 2, total mass was calculated at 2-hr intervals across the day from COH values for the whole 3-month measurement period using equation 2. Fig. 8 shows the average diurnal variation of mass so determined for all days, for pollution episodes and for non-pollution days; the 2-hr change of mass for all days is also given (first term on the right side of equation 1). Pollution increases in the early morning hours, levels off during the forenoon, increases further in the afternoon to reach a peak about 5 p.m. and then declines until the minimum is reached around 5 a.m. This diurnal pattern is not unlike that of Denver and many other cities; however, the marked double cycle of Denver is muted in that no marked pollution decrease occurs during the late forenoon. Highest pollution occurs in the late afternoon rather than around 8 a.m. as in Denver. The strong afternoon rise sets in quite early and cannot be related to late afternoon commuter traffic.

Ventilation: The second term on the right side of equation 1 expresses the ventilation of the volume by the horizontal winds, already mentioned as an important factor. Two effects should be considered: (1) the removal of pollutants by the winds blowing across the area, schematically illustrated in Fig. 9; and (2) concentration by net convergence or divergence of mass. The latter term turned out to be very important for Denver which offers much higher frictional resistance to wind movement than the surroundings and which possesses a marked "heat island". For Larimer County neither of these factors exists; hence the wind was assumed to be non-divergent and ventilation calculated on this basis. Glancing at Fig. 2 it may be noticed that the stations were laid out so that line integral calculations could be performed, if the edge of the

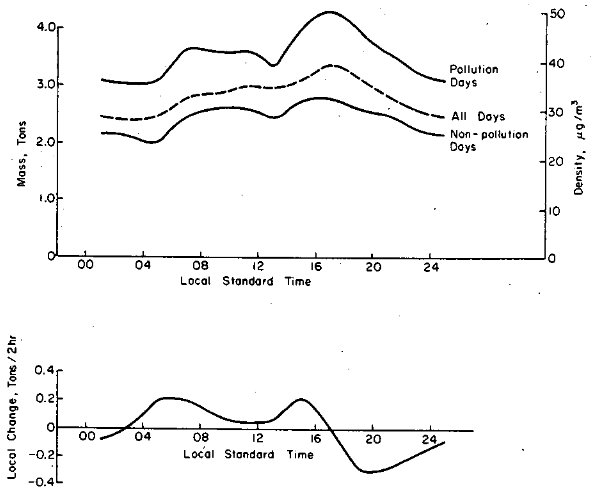

Figure 8. Diurnal variation of total mass for all days, pollution days and non-pollution days. Lower diagram: average 2-hr local change of total mass.

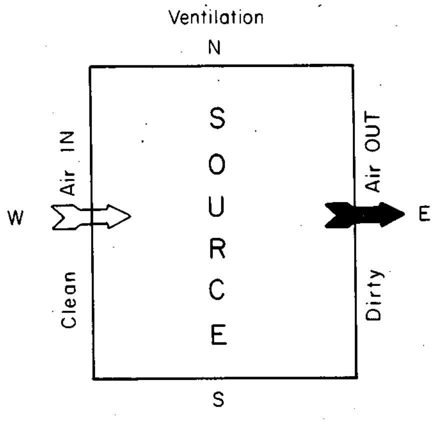

Figure 9. Sketch showing how ventilation removes pollution.

mountains acts as a solid boundary. Further details of the calculation technique may be found in meteorological textbooks; Riehl and Herkhof (1970) give a specific application for the city of Denver.

Since we must rely on ground-based data for all computations, it is important to choose the thickness of the layer considered sufficiently small, so that the variables as measured may be considered representative for the whole layer, at least in the first approximation. Wind towers of greater height would have been preferable, also COH measurements at two elevations. It was assumed that we could use the height of 100 m (330 ft) just mentioned. For COH this height estimate may be somewhat too great during night in the presence of low bases of the temperature inversion; however, calculations presented later reproduce the COH patterns of Figs. 5a-b quite well, so that the error of the approximation cannot be too serious.

Results were as follows: On the average, during non-pollution periods, 1.1 tons of particulates were exported southward during the night (8 p.m. to 8 a.m.) and 0.6 tons imported from south during daytime (8 a.m. to 8 p.m.). During pollution periods, again in the mean, 2.1 tons were exported at night and 0.1 tons reimported during the day. Considering that the particulate mass averages about 3.5 tons over the area on pollution days (Fig. 8), we see that about half of this mass is carried away by the winds in a 24-hr period, so that ventilation acts to clean the air over Larimer County, a fact not obvious prior to computation in view of the strong pollution sources south of the county.

Source and Sink: The left hand side of equation 1

$$\int \frac{d\rho}{dt}\,\delta\alpha = So - Si, \qquad (3)$$

where So is the pollution source and Si the sink due to sedimentation. We obtained So from an inventory prepared by the Colorado Department of Health, which gives 15 tons per day for the whole county. This inventory was not broken down according to seasons, so that we had to apply the mean daily source for the whole year. For our area, which is only a small fraction of the whole county's area, yet which contains most of the population, we estimate a source of 10 tons per day. These values are extraordinarily high, 100 grams per inhabitant per day in contrast to only 60 grams in the Denver metropolitan area. One factor is the agricultural burning which is fairly substantial. We shall use the estimate of the State inventory, noting that all results are subject to revision should a later survey indicate a lower per capita emission.

Records available for sedimentation or "dustfall" were particularly troublesome. Measurements at several locations in the county yielded an average fallout of 15 tons/mi^2/month whereas our (large!) source amounts to only about 1 ton/mi^2/month. It seems obvious that most of the fallout must be country dust of large particle sizes traveling only short distances. However, the precise situation will not be known until chemical analysis is performed and the size distribution of the deposits ascertained, a task well beyond the scope of our project. We had already encountered a similar problem in the Denver study. Following the procedure there adopted we shall set Si = 1/3 So.[1] Then Si = 3.3 tons/day and the net source to be disposed of otherwise is 6.7 tons/day. For our further calculations we also estimated that the whole source of 10 tons/24 hr can be divided into 6 tons during daytime and 4 tons during night. It should be emphasized that these somewhat arbitrary distinctions matter little for our later calculations where sources up to 100 tons/24 hr are considered.

Turbulence: The last term on the right side of equation 1 must be estimated as residual of the imbalance of all other terms since we were unable to make any measurements. As stated earlier, the horizontal wind is assumed to be non-divergent; therefore vertical transport of pollutants by the vertical mean motion is also zero and the total vertical exchange is due to turbulent motions, sketched in Fig. 10. Turbulent flux should occur mostly during daytime hours on pollution days. As determined earlier, there is a net import of 0.1 tons from 8 a.m. to 8 p.m.; if we estimate S = So - Si = 6 - 2 tons = 4 tons, the removal of particulate mass

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[1] Slade (1968) mentions several experiments measuring sedimentation using tracers. Hawley et. al. (1964) and Convair (1959, 1960) conducting experiments at two separate locations measured I^{131} deposition on various surfaces and computed mean deposition velocities of about 2 cm sec^{-1} for soil, grass and water surfaces and 0.5 cm sec^{-1} for snow surfaces. Islitzer and Dumbauld (1963) released uranium particles and came up with deposition velocities of 0.2, 2.4 and 7.1 cm sec^{-1} for inversion, neutral, and lapse conditions respectively.

The above values are quite high. The difficulty with the given results is that they were computed by taking the ratio of the observed concentration of mass in the air to the total deposited on the ground without considering particle size distribution of either the deposited material or that of the source. The above references, therefore, do not give any conclusive answers to our problem.

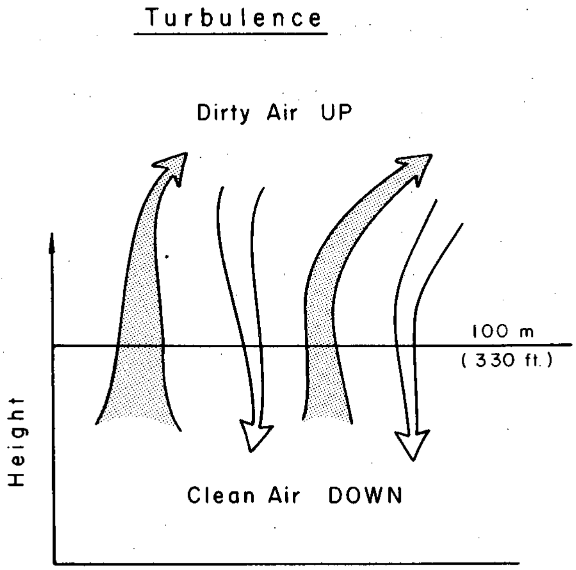


Figure 10. Sketch showing how turbulence removes pollution.

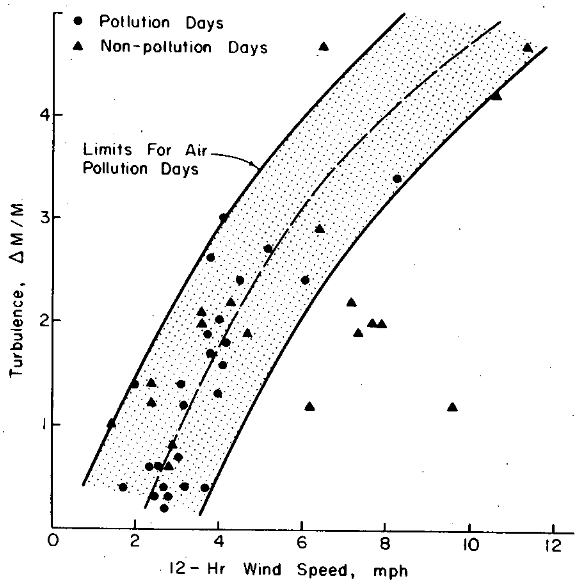


Figure 11. Relation between daytime vertical transport of particulate pollution by turbulence, normalized for the mass of pollutants available for such transport, and 12-hr average wind speed. On non-pollution days most of the mass probably is country dust picked up from the ground.

by turbulence also must be 4 tons since total mass in the volume changes only slightly over this time interval. It is seen that turbulence is a very effective mechanism for removing pollutants, even in the mean. On individual days, the calculated turbulent transport varied considerably with values ranging from 1 ton to as much as 10 tons.

As the intensity of turbulence depends on both wind speed and the vertical temperature distribution, it would be valuable to express the turbulent residual transports in terms of these parameters. We noted earlier that these tend to be correlated so that we may try to use wind speed as a single parameter. In addition, the transport should depend on the reservoir of polluted mass available for dispersion. We shall therefore express the transport in terms of $\Delta M/M$, the percentage of total mass evacuated. As Fig. 11 shows, a good result indeed was obtained for pollution days, whereas large scatter remained on non-pollution days when, with high wind speeds, the presence of much country dust in the air no doubt renders our type of analysis least applicable. If, for a first approximation, the slight curvature of the scatter band in Fig. 11 is neglected, we obtain

$$\frac{\Delta M}{M} = b\ (V - V_o), \tag{4}$$

where V is the 12-hr average wind speed from all stations and V_o = 2 mph, as found in Fig. 11, is the wind speed so defined at which turbulent transfer no longer occurs. It is assumed that turbulent exchange ceases at this speed, so that $\Delta M/M = 0$ for V less than V_o. The slope constant $b = 0.75\ \text{mph}^{-1}$ if V is expressed in mph.

Considering the instantaneous time rate of change of mass in the volume due to turbulence

$$\frac{1}{M}\left(\frac{dM}{dt}\right)_{turb} = b' \, (V - V_o). \qquad (5)$$

Since turbulence in winter is mainly confined to the hours from 10 a.m. to 4 p.m. from experience, b' = 0.125 mi^{-1} when calculated for 6 hours. If turbulence was the only factor operative in the county during daytime, pollution levels should decrease rapidly during the day from equations 4 and 5. Such a decrease is not observed even though, from Fig. 11, turbulence is found to transport multiples of the mass instantaneously present. It follows that pollution source and import of particulates from south ordinarily counterbalance turbulent eviction of particulate mass to higher levels and then away from the area.

Our final picture then is the following: When wind speed drops below 4 mph, the turbulent transport falls to 3 tons or even less and no longer balances the source of 4 tons plus advection. Then pollution concentration in the volume will begin to rise and an episode can be said to begin. From Fig. 8, the average difference in mass between pollution and non-pollution days at present is only 1 ton, an amount that may be expected to increase in the future. Also, the lower limit of wind speed for pollution episodes to occur may increase, as increasing amounts of particulates must be disposed.

A pollution episode will end with the resumption of stronger winds, possibly chinook or cold front passage, when both ventilation and turbulent transport rise far above their average value.

A POLLUTION MODEL FOR LARIMER COUNTY

We are now in a position to set up simple models for intensity and distribution of pollution in Larimer County assuming various values for average source strength and its distribution. The assumptions of the models are summarized again below.

(a) Two models are constructed, for nighttime and daytime. A balanced state is examined during each of these periods.

(b) During night, the only factors considered are S, the net source, and advection; during daytime, turbulent transport is added.

(c) The horizontal flow is considered non-divergent.

(d) The wind is from north during night and from south during day. It may be represented by a single vector $\mathbb{V}$ for the whole area; however, in most calculations, a given distribution of wind speed is utilized. Fig. 12 illustrates the computational arrangement schematically.

(e) Equations 4 and 5, as well as Fig. 11, furnish the method for calculating turbulent transport.

(f) Initially the net source S will be considered uniform over the whole area; later, this restriction will be dropped.

Nighttime Model: From assumptions (c) and (d) above

$$\frac{d\rho}{dt} = V\frac{d\rho}{dx} . \qquad (6)$$

Further,

$$WZ\int_{o}^{L}\frac{d\rho}{dt}\,\delta x = S, \qquad (7)$$

the net source for the whole area. The partial source over the

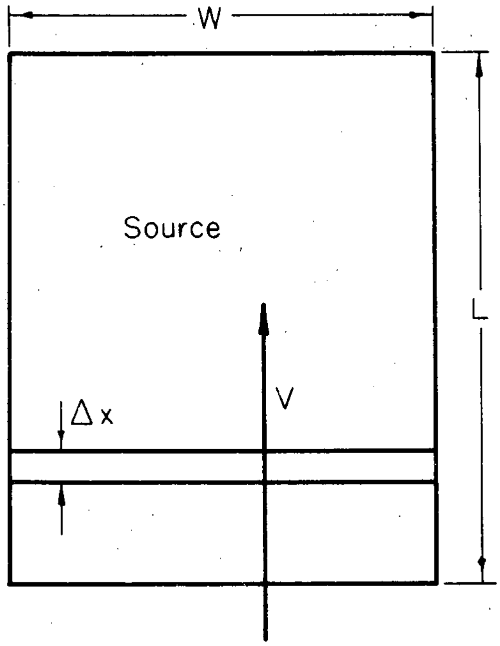


Figure 12. Coordinate system used for calculating models. Symbols are explained in text.

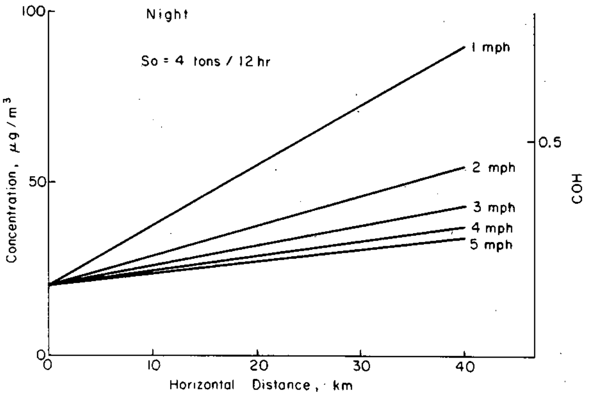


Figure 13. Concentration vs. travel distance for different mean wind speeds for night case with a source of 4 tons/12 hr and initial concentration of 20 $\mu g/m^3$.

distance δx from the boundary $(x = 0)$ to some point x is

$$WZ \int_{o}^{x} \frac{d\rho}{dt}\,\delta x = S\cdot\frac{x}{L}\,, \tag{8}$$

so that

$$S\cdot\frac{x}{L} = \int_{o}^{x} V\,\frac{d\rho}{dx}\,\delta x\delta y\delta Z$$

and

$$S\cdot\frac{x}{L} = VWZ\,(\rho_x - \rho_o)$$

Finally,

$$\rho_x = \rho_o + \frac{x}{L}\,S\cdot\frac{1}{V}\cdot\frac{1}{WZ}\,, \tag{9}$$

where ρ_o is the pollution density of the air at the entrance point into the area. In metric units we take L = 40 km, W = 20 km and Z = 100 m, where use is made of the previous assumptions that the source is mixed uniformly over the lowest 100 m above the ground.

Figure 13 shows the distribution of pollution intensity in micrograms per cubic meter along L for different values of wind speed assuming $\rho_o = 20\ \mu g/m^3$, the typically observed country background. It is seen that an appreciable accumulation in pollution density from north to south takes place only at V = 2 mph or less.

Daytime Model: Following our earlier discussion, a term for vertical turbulence must be added to equation 6 during daytime. Turbulent diffusion may be included by various means. Turner (1964) employed a model with Gaussian diffusion and with the total area divided into sub-areas having various individual sources; further, he utilized diffusion parameters varying according to categories of thermal stability. Miller and Holzworth (1967) proposed a model in which diffusion is Gaussian, but where a ceiling is imposed by the depth of the mixing layer. Diffusion parameters are not identical over rural and urban areas as pointed out by McElroy (1969). Still another model has been put forward by Fortak. In our case, we include turbulent transport as determined empirically previously, which adds a term $\beta\rho$, where β is a measure of the intensity of turbulent exchange and ρ indicates the available reservoir of polluted mass. Then

$$\frac{d\rho}{dt} = V\frac{d\rho}{dx} + \beta\cdot\rho \, . \tag{10}$$

It may be noted that $\frac{d\rho}{dt} = S/LWZ$, the net source per unit volume, is assumed constant for the present. Rearranging

$$\frac{d\rho}{dx} + \frac{\beta}{V}\rho = \frac{S}{LWZ}\cdot\frac{1}{V} \tag{11}$$

Upon integration

$$\rho = \rho_o e^{-\frac{\beta}{V}x} + \frac{S}{LWZ\beta}\left(1 - e^{-\frac{\beta}{V}x}\right). \tag{12}$$

which becomes identical with equation 9 for $\beta = 0$. For computations, we use $\beta = b'(V - V_o)$ from equation 5. Fig. 14 depicts the distribution of ρ for four wind speeds and for several choices of ρ_o at the southern boundary at the current source strength. At V = 2 mph, turbulence is taken as zero from our earlier discussion and so cannot prevent a build-up of pollution in the air volume over the county. Concentration keeps rising unchecked and virtually without limit. However, already at a wind of 3 mph, the turbulence is become sufficiently strong (at present) so that pollution intensity decreases from south toward north. The different concentrations

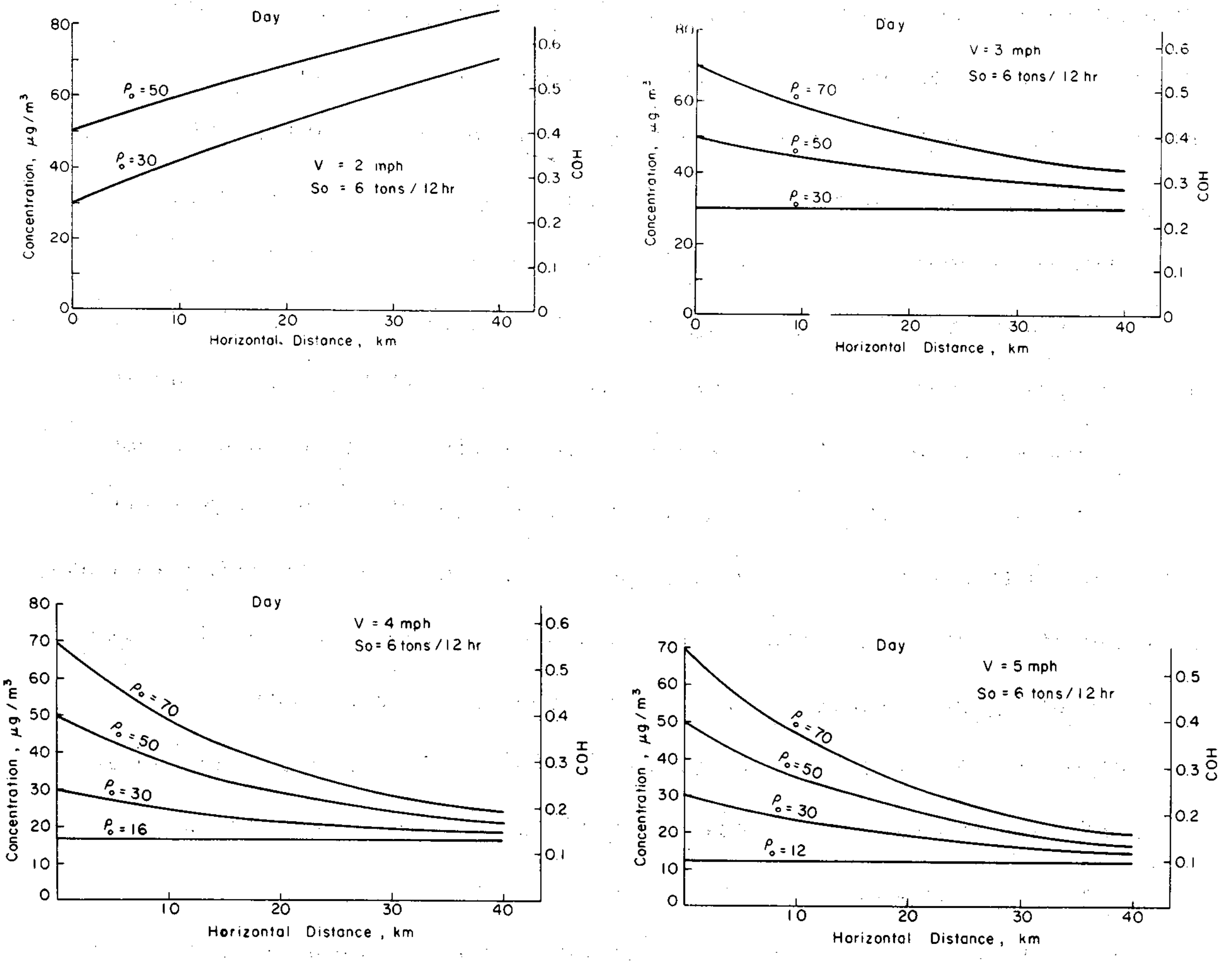


Figure 14. Concentration vs. travel distance for different mean wind speeds and initial concentration, ρ_o, for day case with turbulence and a source of 6 tons/12 hr.

arising from different boundary values tend to converge with distance along the path, so that at the end-points there is remarkably little difference in concentration regardless of initial values. At increasing wind speeds the drop in concentration is increasingly pronounced and the convergence of the curves accentuated. It is of interest that, for a given low value of initial concentration, the concentration remains constant over the whole area. This initial value becomes lower with rising wind speed.

Variable Source at Night: Using equation 9, we shall not compute the pollution distribution for sources of 10, 25, 50 and 100 tons per 24 hrs. In the calculations, only 40 per cent of these sources is assigned to nighttime and one-third is then subtracted for sedimentation as explained earlier. The wind direction is taken as due north, but wind speed is varied according to Fig. 3b, with much higher velocities in the east than along the foothills. Accordingly, the computed concentrations (Figs. 15a-d) show an increase from east to west, especially in the southern part of the county; this follows from Fig. 13.

Figure 15a, calculated for the present-day source, should be compared with Fig. 5a. It is seen that agreement in terms of pattern and magnitude is very good, indicating that our model is realistic. Further improvement would be obtained by varying the source strength, i.e., increase it over Fort Collins relative to the eastern outskirts. For the stronger sources, we see that highest levels are always reached around Loveland. With a source of 25 tons/24 hr concentration already reaches uncomfortable levels there. At

50 tons/24 hr and more the COH values in the southwest attain extreme levels in terms of city concentrations anywhere.

Variable Source during Daytime: Utilizing equation 12, Figs. 16a-c show the variation of pollution intensity with wind speed for variable sources and for a value of $\rho = 50\ \mu g/m^3$ at the southern boundary as commonly observed at present. As noted earlier (Fig. 14) the initial density is relatively unimportant compared to the effect of the mechanisms operating within the county; hence possible changes of pollution density due to further development farther south should affect the county only to the degree indicated in Fig. 14. For all three wind speeds shown, concentration will increase from south to north above some critical source value. This threshold value of source strength increases with wind speed as is reasonable. Thus, with a source of 25 tons/24 hr, the concentration remains constant throughout the county at 3 mph whereas at higher wind speeds it decreases. In order to illustrate the effect of the boundary concentration alone, the case without pollution source in the county has also been plotted. As would be expected from equation 5, concentration decreases northward very rapidly to low values under these circumstances.

Figures 17a-d give the configuration of COH in the county during daytime for various total source strengths and a wind from south with the wind speed pattern furnished by Fig. 4b. In contrast, a uniform speed of 3 mph is assumed for Fig. 17e. In order to improve the realism of the computations, source strength was not kept uniform but varied for different portions of the area in conformity with

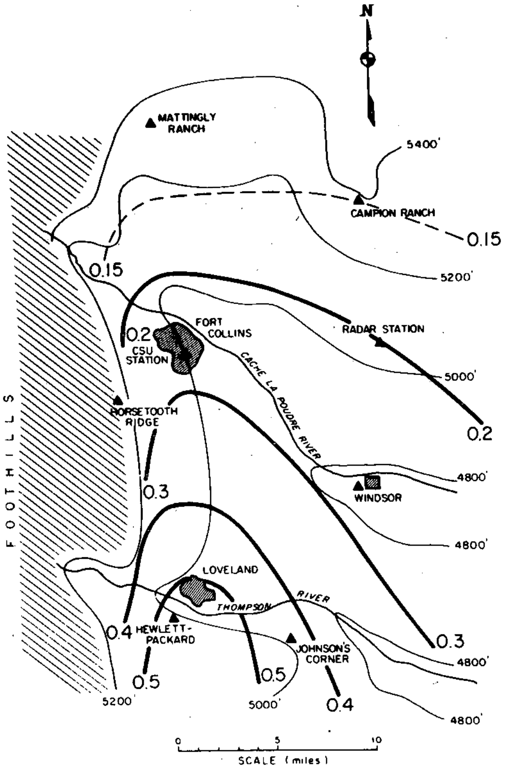


Figure 15a. Calculated COH configuration for nighttime using mean wind field of Figure 3 when source is 10 tons/24 hr.

Figure 15b. Same for source of 25 tons/24 hr.

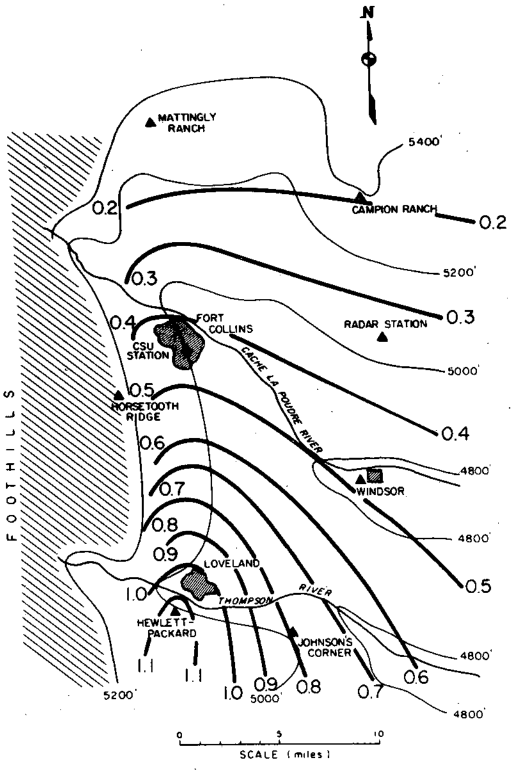
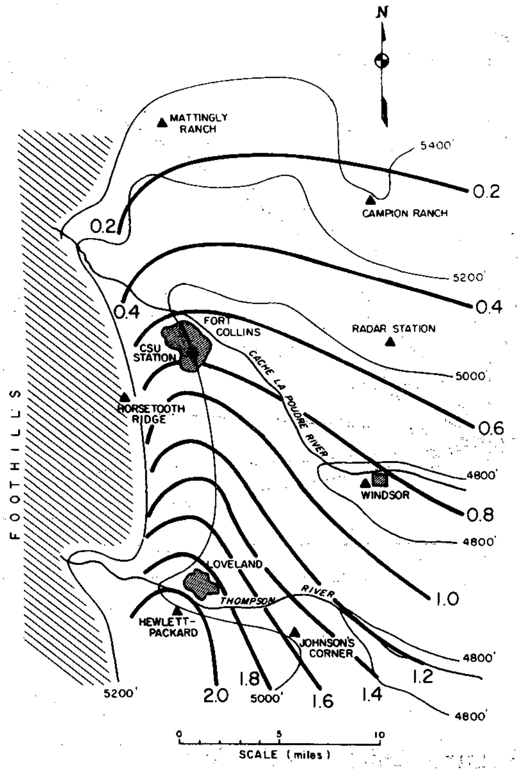


Figure 15c. Same for source of 50 tons/24 hr.



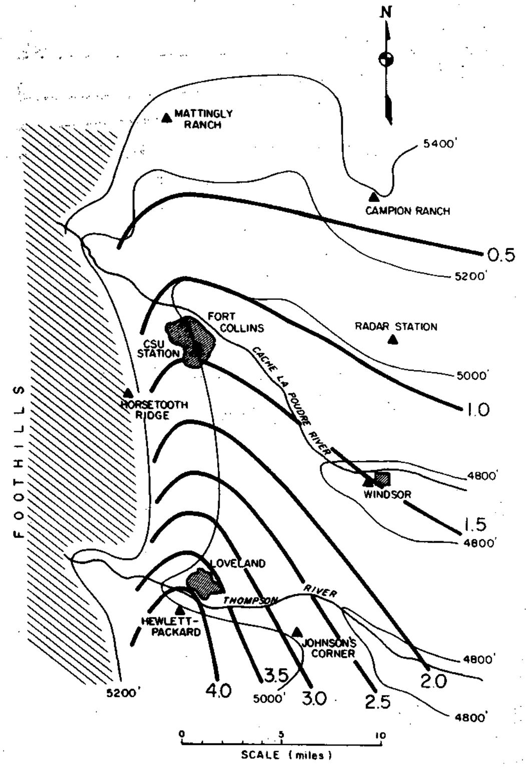


Figure 15d. Same for source of 100 tons/24 hr.

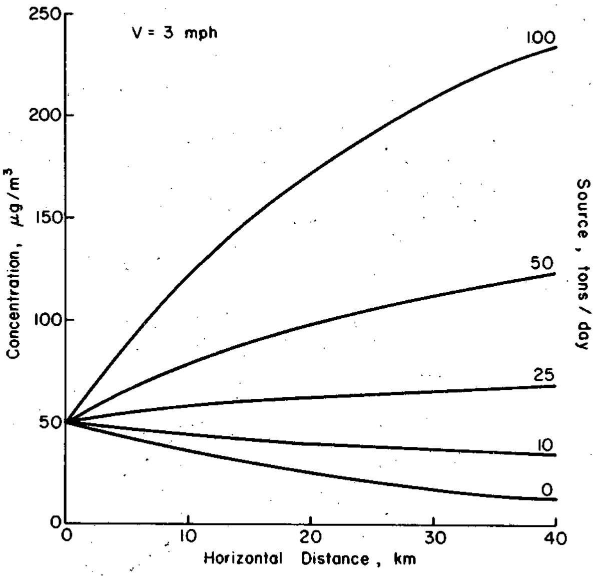
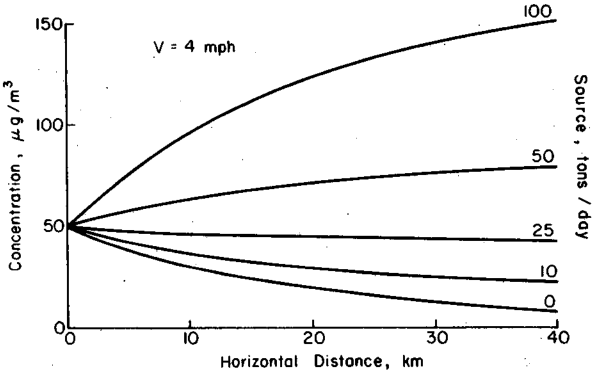


Figure 16a. Concentration vs. travel distance for daytime with wind of 3 mph and source of 0, 10, 25, 50 and 100 tons/24 hr.

Figure 16b. Same for wind of 4 mph.



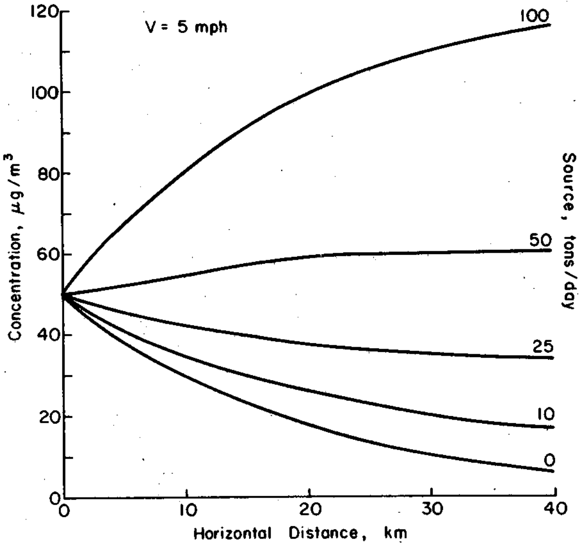


Figure 16c. Same for wind of 5 mph.

present population distribution. Source strength and distribution chosen in each case are indicated in the upper left of each diagram of Figs. 17a-e. The first of these, Fig. 17a, corresponds to the present situation and should be compared with Fig. 5b. As in the night case, agreement is satisfactory suggesting that our pollution mechanisms approximate those of nature reasonably well. At higher sources the pattern remains similar except where a uniform east-west source strength has been assumed. Concentration always reaches maximum values around Fort Collins. Turbulence keeps the COH values there from becoming extreme; but with source strength of 50 tons/24 hr and higher the concentration around Fort Collins becomes unacceptable.

Outstanding in all charts, except Fig. 17e, is the very rapid decrease of concentration eastward away from the foothills, where the average wind speed attains values above 5 mph along the eastern boundary of the county. Even at a source of 100 tons/day, COH does not reach very high values there indicating the great significance of wind speed which provides the mechanism both for high ventilation rates as well as for strong turbulent transport of mass upward.

Average Concentrations and Future Outlook: In conclusion of this study, we shall determine the average concentration of pollution in the county for different source strengths and then estimate the probable source which is likely to materialize in the coming decades. For nighttime, the relation between source strength, wind speed and average concentration, from equation 9, is given in Fig. 18; here, the initial concentration is still held at 20 $\mu g/m^3$. For daytime, the information is contained in Fig. 19 with initial concentration

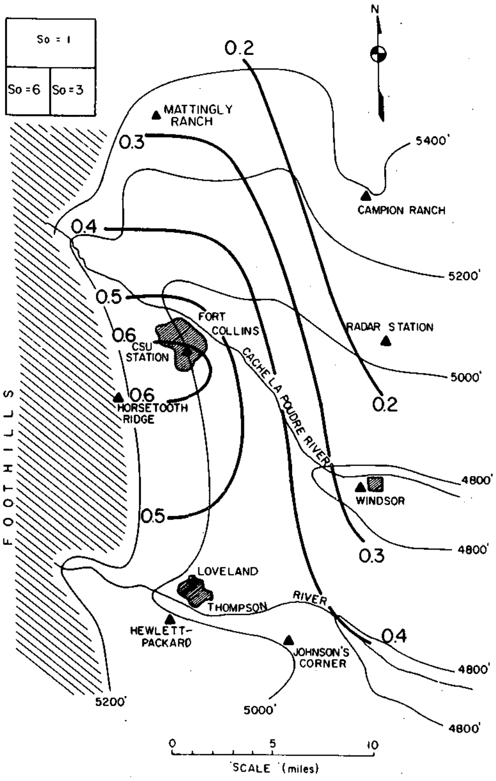


Figure 17a. Calculated COH configuration for daytime with wind from south as given in Fig. 4b for a source of 10 tons/24 hr and a source distribution shown in the upper left insert.

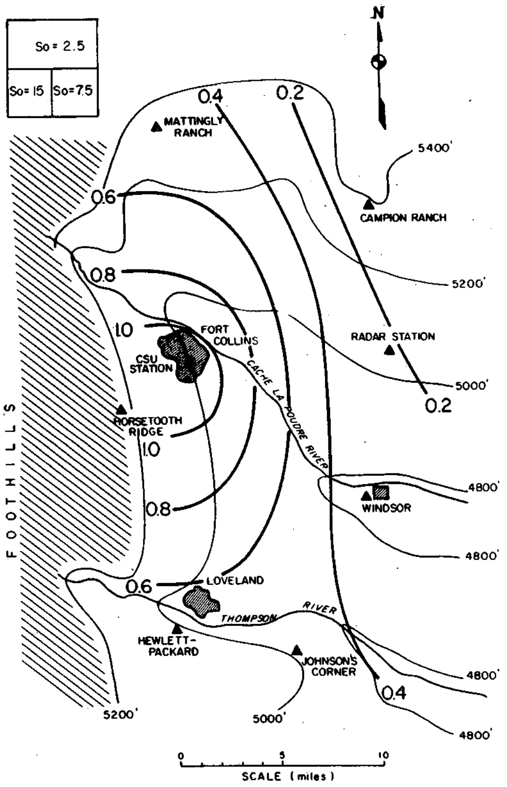


Figure 17b. Same for a source of 25 tons/24 hr.

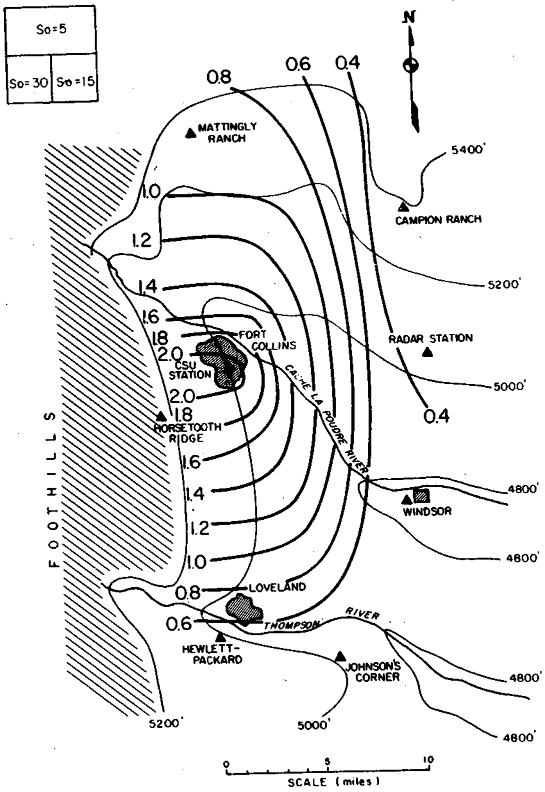


Figure 17c. Same for a source of 50 tons/24 hr.

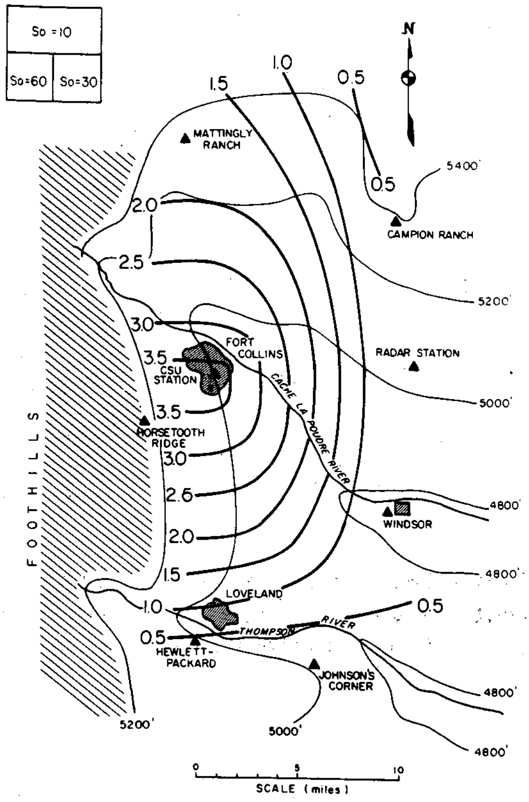


Figure 17d. Same for a source of 100 tons/24 hr.

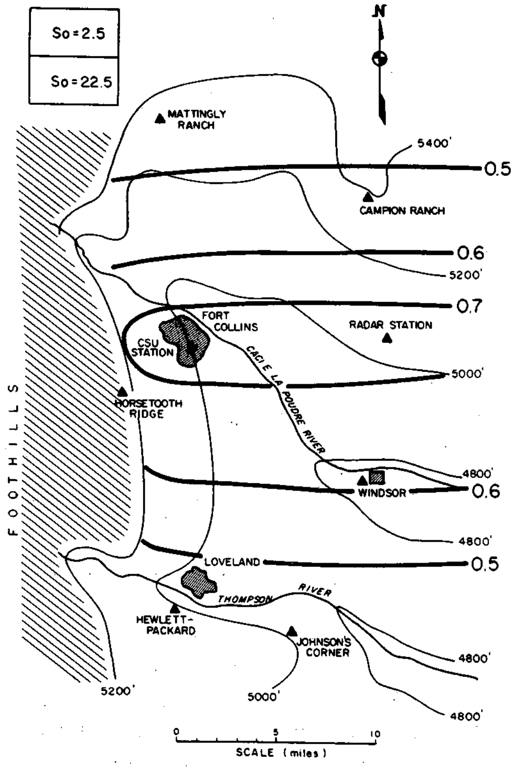


Figure 17e. Calculated COH configuration for daytime with uniform wind from south of 3 mph and uniform source in the east-west direction, illustrating powerful effect of lack of strong wind on eastern part of the area compared with the other maps.

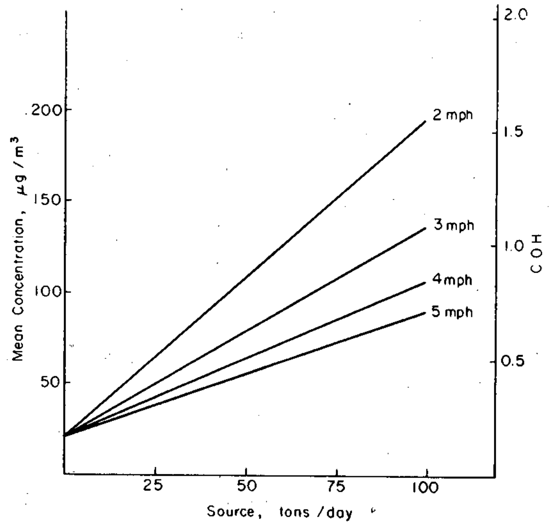


Figure 18. Mean particulate concentration over the county during night, given average wind speeds from north of 2, 3, 4 and 5 mph for various source strengths and for ρ_o of 20 μg/m .

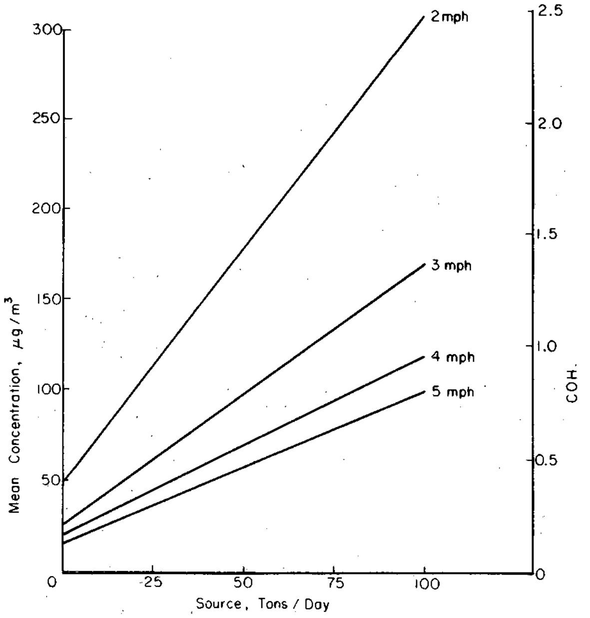


Figure 19. Mean particulate concentration over the county during day, given average wind speeds from south of 2, 3, 4 and 5 mph for various source strengths and for ρ_o of 50 μg/m^3.

of 50 μg/m^3. The outstanding feature of these two diagrams is that, for a given wind speed, concentration will be almost identical during day and night, again resembling the present situation. Evidently, the higher source strength during day, compared to night, compensates for the removal of pollutants by turbulence, an outcome not to be obviously expected. Figs. 18 and 19 can serve as a rough guide for determining pollution levels of the future, if we know what source strengths are likely to be encountered.

Two points of view should be considered: how will source strength vary assuming a static population; and what changes will be produced by population increase? For the first part we shall assume that no per capita increase in emission will take place. Should pollution control laws lead to an actual reduction of unit source intensity, the ensuing prediction can readily be modified to take this improvement into account. It now remains to make an estimate of the probable population increase and of the increase in total particulate source to be expected with the rising population. Stern (1968) has published a table giving a general relationship between average particulate densities and the population of cities. Various publications give information on the estimated source strength of cities. While there are many individual variations depending on the life patterns in terms of industry, etc., comparison of the two types of data indicates that, in the mean, the per capita pollution production is relatively independent of population, an interesting and also rather surprising result. If anything, some large cities appear to have a lower per capita emission than medium-sized cities with much heavy industry. Guided by this information, we shall assume per capita pollution production constant also for Larimer County irrespective of population, noting that we had found that the source inventory made by the Colorado Department of Health appears very high. Whether theirs is an overestimate, or whether agricultural burning really is such a heavy contributor, the fact remains that our present source estimate of 100 grams/person/24 hr is likely not to be exceeded and may go down, especially if agricultural burning is decreased with increased regulatory ordinances.

Considering the past rate of population increase in the county, a constant percent growth is not found, rather a great jump of 70 per cent in the 1960-70 decade related to general population trends in the United States. At this juncture it appears likely that rapid growth of the county will continue though perhaps at a somewhat slower pace than in the last few years. We have assumed a growth rate of 50 per cent per decade up to the year 2000, subject, of course, to modification when more solidly based data come to light. Table IV summarizes our projection on the indicated basis. For the calculations on the right hand side of the table we have chosen a wind speed of 3 mph as a probable average speed for pollution episodes. It may be pointed out again that our wind and COH data from the field experiment suggested that pollution episodes are limited to occasions with wind speed below 4 mph for 36 hours or more. Further, from Fig. 11, it would be very difficult to initiate and maintain a pollution episode at wind speeds much higher than 5 mph in view of the rapidly increasing power of turbulent exchange with wind speed.

Given the information of Table IV we can now go back to Figs. 15 and 17 and select the COH patterns most likely to prevail during pollution episodes. In the next two decades the patterns with a source of 25 tons/24 hr should be approached, thus Figs. 15b and 17b give the outlook for around 1990. It should be emphasized that these types of patterns may be expected during a mean of 10 episodes per season comprising 25 per cent of a winter's days; and that the patterns represent the average only, whereas the most intense pollution episode may lead to values about 75 per cent higher, if our previous data on Denver air pollution can serve as guide.

Table IV

Present and Projected Population and Pollution Density in Larimer County during Pollution Episodes.

Year	Population		Particulate Pollution Source Tons/Day	Pollution Density ($\mu g/m^3$)			
				NIGHT		DAY	
	Amount	% Increase		Ave.	Max.	Ave.	Max.
1970	90,000	70	10	32	66	40	80
1980	135,000	50	15	37	140	48	144
1990	200,000	50	22	46	265	56	251
2000	300,000	50	33	59	512	73	465

CONCLUSION

The outcome of this study shows that, at present, a pollution problem hardly exists in Larimer County. However, pollution levels can be expected to increase to the point where the general concentration of pollutants will be twice as high around the year 2000 than in 1970. This is an average estimate only. Along the foothills levels will be higher; moreover, there will be occasional episodes with very light winds when pollution will build up temporarily to uncomfortable intensities, especially along the edge of the mountains.

A study such as ours must necessarily proceed with considerable simplifications and assumptions that should be modified as time goes on. Nevertheless, we believe our results to be a useful guide for planning purposes. It may be emphasized again that, from the general climatology of the wind field, it will be advantageous for future development to shift to the eastern edge of the county where wind speed is much higher on the average than along the foothills and where, for this reason, a higher efficiency of removal of pollution may be counted upon.

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