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16. ABSTRACT

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ABSTRACT

High winter carbon monoxide levels in Anchorage, as in Fairbanks, are due to intense nocturnal (ground-based) inversions persisting through the periods of maximum emissions and at times throughout the day. The problem is exacerbated by the large amounts of carbon monoxide emitted during cold starts at low temperatures. The Anchorage situation is unusual in that the nocturnal inversion develops most often with a substantial north-south pressure gradient and easterly geostrophic winds. The Chugach Range to the east sometimes produces a "wind shadow" effect in the city, and almost all the CO violations examined occured in these conditions. There is evidence that inversions are significantly stronger, and dispersion conditions probably worse, near the mountain front than at the airport weather observation station. CO forecasting in Anchorage would require close cooperation between the U.S. NOAA Weather Service and the Municipality; improvement in communications between the Fairbanks North Star Borough and the Weather Service is also essential if the quality of the Fairbanks CO forecasts is to be improved. Measurements of mixing heights in Fairbanks suggest that a mixing height of 10 m be considered the maximum for worst-case modeling of surface-source pollutants; values as low as 6 m were observed. As an interim measure, similar values are recommended for Anchorage.

This report was submitted in fulfillment of grant 808485-02 by the Geophysical Institute, University of Alaska, Fairbanks under sponsorship of the U.S. Environmental Protection Agency. This report covers analysis of existing data and new data collected in late 1981, 1982, and early 1983. The study was completed September 1983.

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SECTION 1

EXECUTIVE SUMMARY

Urban winter air pollution problems in Alaska appear to be out of all proportion to the size of the cities involved. Both Anchorage (population around 175,000) and Fairbanks (population around 40,000) exceeded the 9 ppm 8-hour CO level 35 days or more during the period November 1982 through February 1983, and levels of 15 ppm were reached twice in Anchorage and seven times in Fairbanks. Longer term records are similar, but with less contrast between the two cities in the number of days with very high carbon monoxide levels. This study was carried out to clarify the meteorological conditions responsible for these high levels in Anchorage, to provide real data for mixing heights in Fairbanks and to evaluate the CO forecasting scheme used in Fairbanks.

The CO problem in Anchorage, like that in Fairbanks, is due to a combination of strong ground inversions and low wind speeds which persist through the hours of maximum emissions. At lower latitudes, these "nocturnal inversion" conditions are confined to the night, when emissions are low. At latitudes north of 60°N, however, they persist throughout the day. In most places, including Fairbanks, nocturnal inversions are associated with anticyclones. In Anchorage, however, they are associated with winds from the east being blocked by the Chugach Range east of Anchorage. There is good reason to think that the eastern and most sheltered part of the city is more vulnerable to pollution than is the western part where the majority of monitoring sites are located.

Conventional air pollution models do not perform well in high-latitude winter situations. One major problem is that the combination of extremely poor vertical mixing with highly variable wind directions is normal at high latitudes; another is that time-averaged wind directions frequently vary by as much as 180° across a city, or over a height difference of a few meters. Existing models could easily be modified to handle the first problem, and this is essential if computer models are to be used to evaluate the impact of changed source distributions. The correct handling of the complex wind fields in sheltered high-latitude cities may require designing models for individual locations after collecting the necessary data on the wind fields.

Actual measurement of mixing heights within a city block of the CO monitoring site in Fairbanks has confirmed that complete mixing is confined to a layer which may be as little as 6 meters deep. Some additional dispersion may occur from updrafts along heated buildings, but the deepest mixing layer which should ever be used for worst-case modeling of dispersion from surface sources in Fairbanks is 10 m. (Some past attempts have been based on a 100-m or even 200-m mixing layer.) Similar measurements are needed in Anchorage, but for the present, 10 m should be considered a maximum worst-case mixing height for that city also. For elevated sources, worst-case modeling should be based on a mixing layer just deep enough to include the source.

The Fairbanks forecasting scheme has not been successful in forecasting CO levels above 15 ppm, but dces show a correlation coefficient of the order of 0.6 between forecast and observed levels. The single most important factor in improving forecasts is better communications between the CO forecaster (at the Fairbanks North Star Borough) and the NOAA Weather Service office in Fairbanks, which provides the dispersion forecasts on which the CO forecasts are in part based. Several meteorological situations were found to be associated consistently with high CO levels: moderate winds at the airport while winds downtown were calm, low-level transport of warm air into the area, and sunset times shortly before the evening traffic rush.

This study was based on existing data and on that collected by state and local agencies. We found that additional data were needed on the wind field and variation of inversion strength across Anchorage. A data collection and interpretation program involving roughly 10 meteorological towers in conjunction with tethered balloon measurements is strongly recommended for the Anchorage area. Successful modeling of the effects of changing source distributions in the Anchorage area cannot be expected without these data.

SECTION 2

THE PROBLEM

DISCOVERY OF THE CO PROBLEM

Air pollution in the sparsely settled Arctic, unlikely as it may at first sight seem, is a very real and serious problem. In Fairbanks, ice fog was recognized by 1949 as being due to H_2O released by human activity (Oliver and Oliver, 1949), and the continued study of ice fog led to identification of other potential pollutants (e.g. Benson, 1965). The presence of high lead and halogens was confirmed shortly thereafter (Winchester et al., 1967). The first measurements of particulates and gaseous pollutants, however, were unrelated to the ice fog studies (Holty, 1983, personal communication). Background measurements of particulates and sulfur oxides were initiated by the Public Health Service in 1967 and carbon monoxide measurements were added in 1969. Levels of CO were found from the start to be shockingly high - hourly averages of almost 70 ppm were recorded in early years (Holty, 1973). CO monitoring was taken over by the state and the Fairbanks North Star Borough in the early '70's and continued to the present.

Once the existance of a CO problem was discovered, the previous work on ice fog identified the causes. Fairbanks in winter has about as close to zero dispersion as is found in nature. Both exceptionally strong ground-based inversions and very low wind speeds (Benson, 1965) contribute to the problem. The only larger city in the State, Anchorage, is notorious for its winter winds and, being considerably warmer, lacked the tell-tale ice fog. Still, in the early '70's a CO monitor was installed in a downtown location, at 7th and C streets. Once initial problems in calibration were overcome, it was clear that Anchorage also violated Federal Standards for CO. Both Fairbanks and Anchorage were designated non-attainment areas in 1978.

FAIRBANKS

The meteorology of air pollution in Fairbanks has been studied extensively with reference to ice fog (Benson, 1965, 1970; Weller, 1969; Bowling 1967, 1970; Bowling et al., 1968; Fahl, 1969; Holmgren et al., 1975; Holty, 1973; Ohtake, 1970; Bowling and Benson, 1978; Jayaweera et al., 1975; Wendler, 1975) and is reasonably well understood. The city is located in a southward-opening arc of hills in the northwest corner of a larger southwest-facing arc on the north side of the Tanana River valley (Figure 2-1). The shelter of the hills keeps wind speeds down, and the very low elevation of the winter sun (less than 2° above the horizon at noon near the winter solstice) allows some of the most intense radiative inversions in the world to form and to maintain themselves for days at a time. (Midlatitude cities may develop strong ground-based inversions on clear, calm nights, but solar heating on clear days will assure

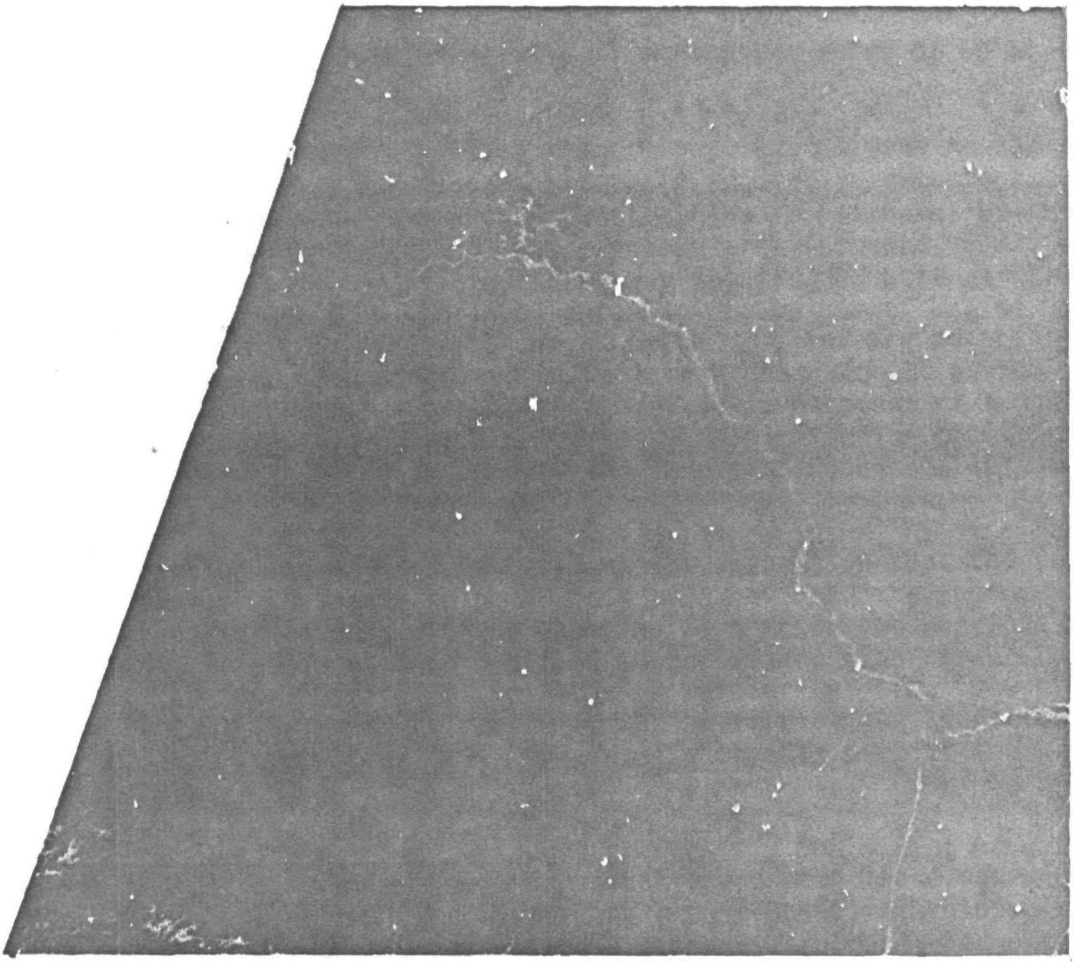

Figure 2-1. Landsat photo of Fairbanks area

that the inversions are at least weakened during the day when pollutant inputs are strongest.) The problem is made worse by the fact that cold starts of automobiles produce CO levels an order of magnitude greater than the same car produces at warm idle. Given the usually short distance that a car is driven on a single trip in a small town such as Fairbanks, these cold starts may account for as much as 75% of the CO produced. Furthermore, catalytic converters do not operate efficiently until they warm up (Leonard, 1975). Luckily this problem is to some extent self-limiting, as few automobiles will start at temperatures of -30°C or lower without preheating the engine (usually with an electrical heater which may act on the oil, the coolant, or the engine block itself).

Such preheaters, properly used, virtually eliminate the surge of CO of a true cold start.

Because of the extremely limiting meteorology, the CO problem can only be ameliorated by controlling emissions - primarily automotive emissions. The first line of attack was improvement of traffic flow in Fairbanks by the creation of a grid of one-way streets in the downtown area (Leonard, 1977) and, later, by the building of the Steese Expressway Bypass. Additional strategies were aimed at minimizing cold starts by encouraging the use of engine heaters at temperatures considerably above those at which plug-ins are necessary if the engine is to start, and discouraging vehicle traffic during periods of poor dispersion. The latter approach has involved development of a public transit system, forecasting of high CO levels, and elimination of fares on the transit system when forecast or observed levels of CO exceed 15 ppm on an 8-hour basis.

The forecasting scheme used is based on the assumption that the ratio of daily 8-hour maximum CO levels to the 8-hour average immediately preceeding the time the forecast is made will be the same as that of the previous day. This preliminary forecast is then modified in accordance with dispersion forecasts made by the local office of the National Weather Service. One of the aims of the present study was to determine the meteorological conditions which lead to "good" and "bad" forecasts. The results of this part of the project are given in Chapter 3.

A second objective for Fairbanks was to quantify the mixing heights occurring within the city. Previous work had established that lapse rates outside the built-up area were normally dominated by ground-based inversions (Billelo, 1966; Benson, 1965) frequently possessing a stepped structure when examined in detail (Holmgren et al., 1975). In addition, studies of the Fairbanks heat island had established that an inversion existed at some point between the surface and 90 m under conditions of strong background inversion (Bowling and Benson, 1978). Although the mixing height was estimated from the heat island intensity to approximate 60 m, any value from 0 to almost 90 m was consistent with the observations. Mixing height is a critical parameter in dispersion models, and there has been a lamentable tendency to run "worst-case" models with a 100-m mixing height. Therefore we used a Tethersonde (T.M.) system to measure the lapse rate within and outside the city of Fairbanks and compared the two to estimate mixing height. The results are given in Chapter 5.

ANCHORAGE

In contrast to Fairbanks, Anchorage was virtually unstudied before this research began. As mentioned above, observations began in the early 70's at 7th and C, a block south and a couple of blocks east of the core business area

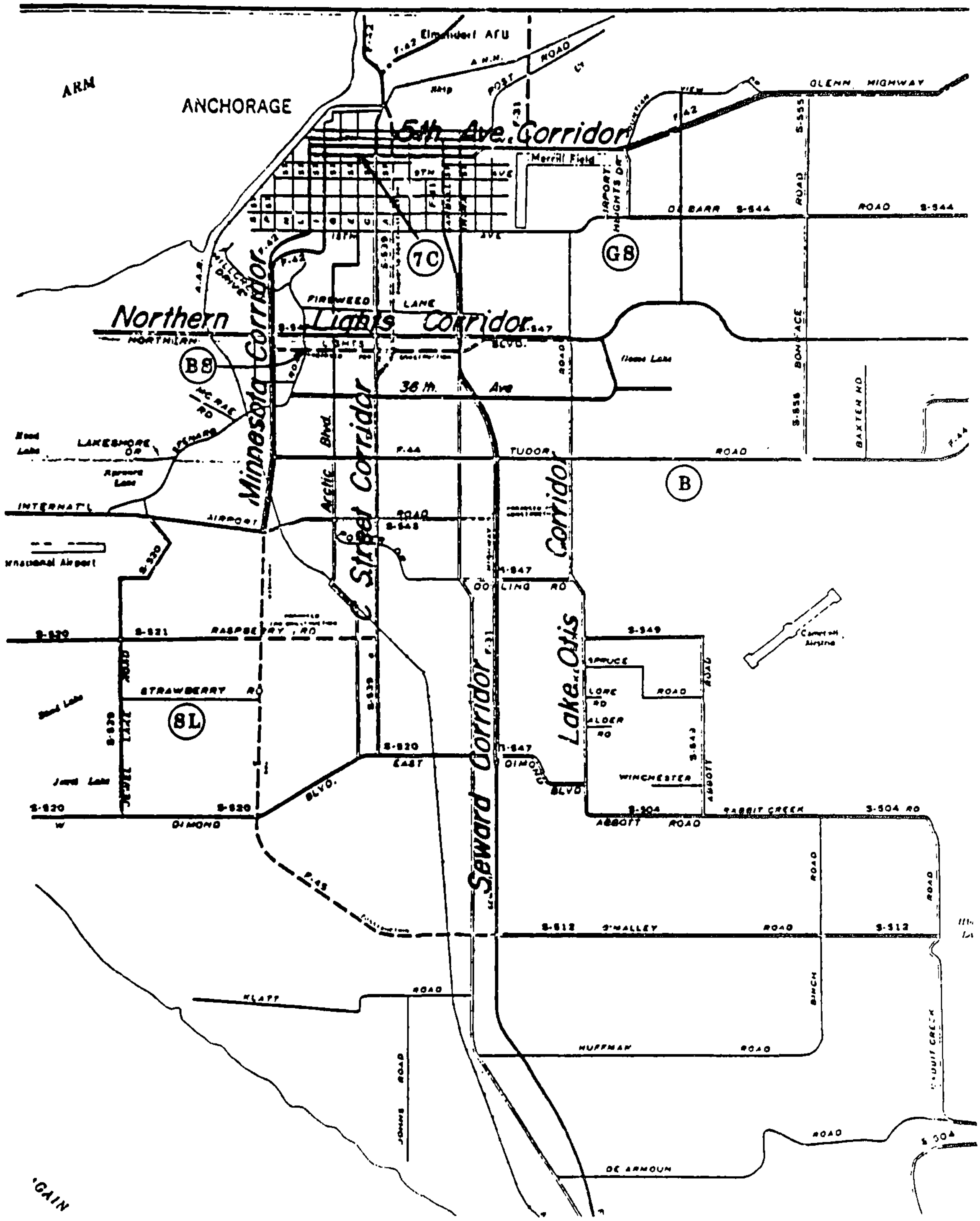

Figure 2-2. Map of major Anchorage streets, showing CO monitoring stations. 7C = 7th and C, BS = Benson and Spenard, GS = Garden Site, and SL = Sand Lake. B = Bus Barn, site of Tethersonde ascent.

(Figure 2-2). Although CO levels were high enough to result in Anchorage being designated a non-attainment area in 1978, substantial improvement was obtained by a change in traffic flow patterns (La More, 1983, personal communication). In December 1978 a second station was added at Benson and Spenard (Figure 2-2). The intake for this station was only 17 feet from the curb, 100 ft. upstream from a traffic light on a four-lane one-way street, and the chart record suggested that at least some of the high values recorded might be due to instrument error. But even so, the comparison with the "downtown" station was startling. 7th and C, for instance, had one day in January 1979 with an 8-hour average of 9 ppm or more, the highest 8-hour average for the month being 12.4 ppm. Benson and Spenard had 13 violation days, with a maximum 8-hour average of 20 ppm and 3 days with 8-hour averages exceeding 15 ppm. A third site was installed as a check in fall 1979. This site, the Garden Site, is located in a church parking lot in a residential area. The nearest traffic light is several blocks away, and most streets in the immediate area are so lightly travelled that few stop signs are even present. Maximum 8-hour averages and the number of violation days normally exceed those at 7th and C, the downtown station. A fourth station, also residential in character, was added in the fall of 1980. This station, variously known as Jewel Lake or Sand Lake, shows CO levels near those at 7th and C.

At the time our study began in 1980 the only thing known about the meteorological conditions leading to the CO problem was that CO levels increased as temperatures dropped (Hoyles, 1980) and wind speeds were low (usually 3 m sec^{-1} or less). At least four possiblities existed based on the initial two stations: a street-canyon effect when winds blew along the major streets; a Fairbanks-type ground-based radiative inversion, a modified Los Angeles-type situation with cold air from the Alaskan interior being overridden by warm air from the Pacific Ocean, or a fumigating lapse rate (one resulting from heating from below allowing an elevated pollutant layer to mix down to the surface) when cold air from Interior Alaska flowed over the incompletely frozen waters of Knik Arm north of Anchorage before entering the city. Nothing was known of the synoptic situation associated with CO episodes, and there was no indication of whether forecasting was even possible. Nor was the distribution over the city well understood.

RESEARCH PLAN

Our approach to these problems was as follows:

1. Fairbanks Forecasts

This was a relatively minor part of the study. Fairbanks morning forecasts (6 am) were compared with the levels actually reached that day. We placed primary emphasis on cases involving forecast and observed levels on opposite sides of the 15 ppm level, and secondary emphasis on cases at the 9 ppm level. The results are in Chapter 3.

2. Anchorage Meteorology

Comparison of daily and hourly values at different stations allowed us to determine almost at once that the problem was city-wide, ruling out the street-canyon hypothesis. Airport soundings and hourly observations were used to determine cloud cover, wind speed and direction, temperatures and lapse rates at the airport; temperatures and winds from the monitoring stations allowed us to estimate how these factors changed over the greater Anchorage area. Thermal infrared satellite photos also provided qualitative information on how temperature and lapse rate varied over the area. Historical maps of meteorological conditions allowed us to isolate the types of synoptic events most often associated with high CO levels. The state and the Municipality of Anchorage provided data on CO levels at the monitoring sites and at some short-term bag sampler sites. Attempts were made to use a Tethersonde (TM) system to monitor the variation of lapse rate across Anchorage late in the winter of 1981-82 and again in 1982-83; and while due to instrument problems only one good record was obtained, that record agrees well with deductions from other data. Some informal forecasting of high CO episodes was attempted, with reasonable success, during the 1982-83 season. Some relatively simple changes in the application of standard dispersion models were suggested, and CO levels, normalized to time of day and day of week, were compared with the modified stability classes. The results of all these observations are given in Chapters 4 and 5.

3. Fairbanks mixing heights

The Tethersonde system was operated in Fairbanks in March 1981 and in December 1981. Three good sets of ascents showing both background and city lapse rates were obtained in December. The results are given in Chapter 5.

Overall results of the study have been promising. Although more low-level soundings are needed in Anchorage due to to the equipment breakdown in Jan. 1983, it is now possible to state what is going on physically to trap CO in the area, to recommend a forecasting scheme, and to indicate those parts of the city where the potential for pollution is highest. Some comments can also be made about the situation in the Cook Inlet basin as a whole.

SECTION 3

FAIRBANKS CO FORECASTS

FORECASTING METHOD

Forecasting of CO levels in the Fairbanks area has two goals. One is to provide a warning of dangerously high CO levels to individuals with health problems which make them particularly susceptible to this pollutant, so that they can avoid going into high pollutant areas. The other is to discourage unnecessary driving and encourage preheating of cars which must be driven when high CO levels are expected, in an effort to keep the CO concentrations from reaching health-threatening levels. To aid in this effort, Borough bus fares are suspended whenever an air pollution alert (based on a combination of observed and forecast levels) is called. Forecasts are made twice a day, between 6 and 7 am and around 3 pm. In this study, we concentrated on the morning forecast, as this is the one which has the greatest potential for modifying people's choice of transit modes or shopping plans. It should be pointed out that in general the 3 pm forecast is the more accurate of the two.

The forecasting method is fairly simple. An objective, persistance-based forecast is prepared by assuming that the ratio of the highest 8-hour CO level for the day to the most current 8-hour CO level available will be the same as the same ratio for the previous day. Thus if the mean CO level from 10 pm last night to 6 am this morning were 3 ppm, the mean level from 10 pm night before last to 6 am yesterday were 2 ppm, and yesterday's maximum 8-hour level were 8 ppm, the maximum 8-hour CO level forecast (made at 6 am) for today would be obtained from the equation

$$\frac{X}{3} = \frac{8}{2}$$

and the preliminary forecast would be 12 ppm. This forecast is then modified subjectively by comparison with a dispersion forecast issued by the Fairbanks office of the National Weather Service. The dispersion forecast consists of a categorization of the anticipated dispersion (excellent-good-fair-poor-very poor), comments on how the dispersion is expected to change through the day, a copy of the 2 am airport sounding, and usually some comments on any expected weather changes. Continuing with the example of our preliminary forecast above, suppose the dispersion forecast showed clear skies and a substantial inversion at 2 am, but by 6 am clouds were visible in the west and snow with 10 knot winds was forecast by noon. The dispersion forecast itself might be "dispersion fair to poor becoming good by afternoon". The forecast would almost certainly be modified downward from the initial 12 ppm, and as released would probably be somewhere in the 6-8 ppm range.

The 6 am forecast of the maximum 8-hour CO level anticipated has been compared with the maximum 8-hour level actually reached for the three winters 1979-80, 1980-81 and 1982-83. On the basis of the first two winters, we suggested that comparison of winds at the airport with winds measured downtown be considered as part of the forecast. This was not possible during 1981-82, and unfortunately was not implemented in 1982-83 either. The 1982-83 winter had 7 days with 15 ppm or greater compared with 5 for the two winters previously studied, so it was added to the earlier set to expand the number of missed forecasts available.

FORECAST PERFORMANCE

Figures 3-1, 3-2 and 3-3 are scatter diagrams of early morning forecasts against observed 8-hour maximum CO levels for the three winters studied. Not quite half of the 1982-83 forecasts were within > 2ppm of the observed level. Although there is some positive correlation (on the order of .6) between forecast and observed levels, the prediction of alert levels is poor. Of 12 days over the three winters with 8-hour maximum CO levels of 15 ppm or more, not one was forecast to exceed 15 ppm, and 5 were not even forecast to exceed 9 ppm. These 12 days are listed in Table 3-1, along with 15 days with observed levels of 9 ppm or more which exceeded forecast levels by at least 5 ppm. An alert was in effect Dec. 21, 1982, but this was due to a forecast of 17 ppm (maximum observed 14.5 ppm) the previous afternoon. There is a psychological resistance to forecasting 15 ppm or greater without strong indications, due to the alert mechanism and the cost of free transit fares. However, case 9 is the only one which was even a near miss.

Separate plots were made for 1982-83 of the preliminary persistance forecast against observed levels (Figure 3-4) and the Weather Service dispersion forecast against observed levels (Figure 3-5). Neither was as accurate as the Borough's forecast as issued. There is roughly a 2 ppm bias in the 1982-83 Borough forecasts, but forecasts that year were by a new forecaster. Regular comparison of his own forecasts with reality by the forecaster might be of help here. The cases in Table 3-1 are identified by number or letter in Figures 3-1 through 3-5, so that the contributions to the errors on individual cases can be analyzed. Starting out with Category A, all four of the 1982-83 cases were underforecast by persistance and then modified downward. Category A cases are shown in detail in Figure 3-6.

Case 1 was a clear case of a dispersion forecast which verified with good winds at the airport but which on the basis of CO levels probably had very light winds downtown. This is one of the cases which led us to recommend that wind downtown be used in forecasting.

In Case 2, forecast dispersion was fair becoming good based on cloud cover. The rise in CO correlated with a brief break in the cloud cover around 8 am and ceilings above 10,000 feet after that time, but the critical factor appeared to be a combination of strong warm air advection below 900 mb with radiative cooling at the surface. The result was an inversion of 15.3° over

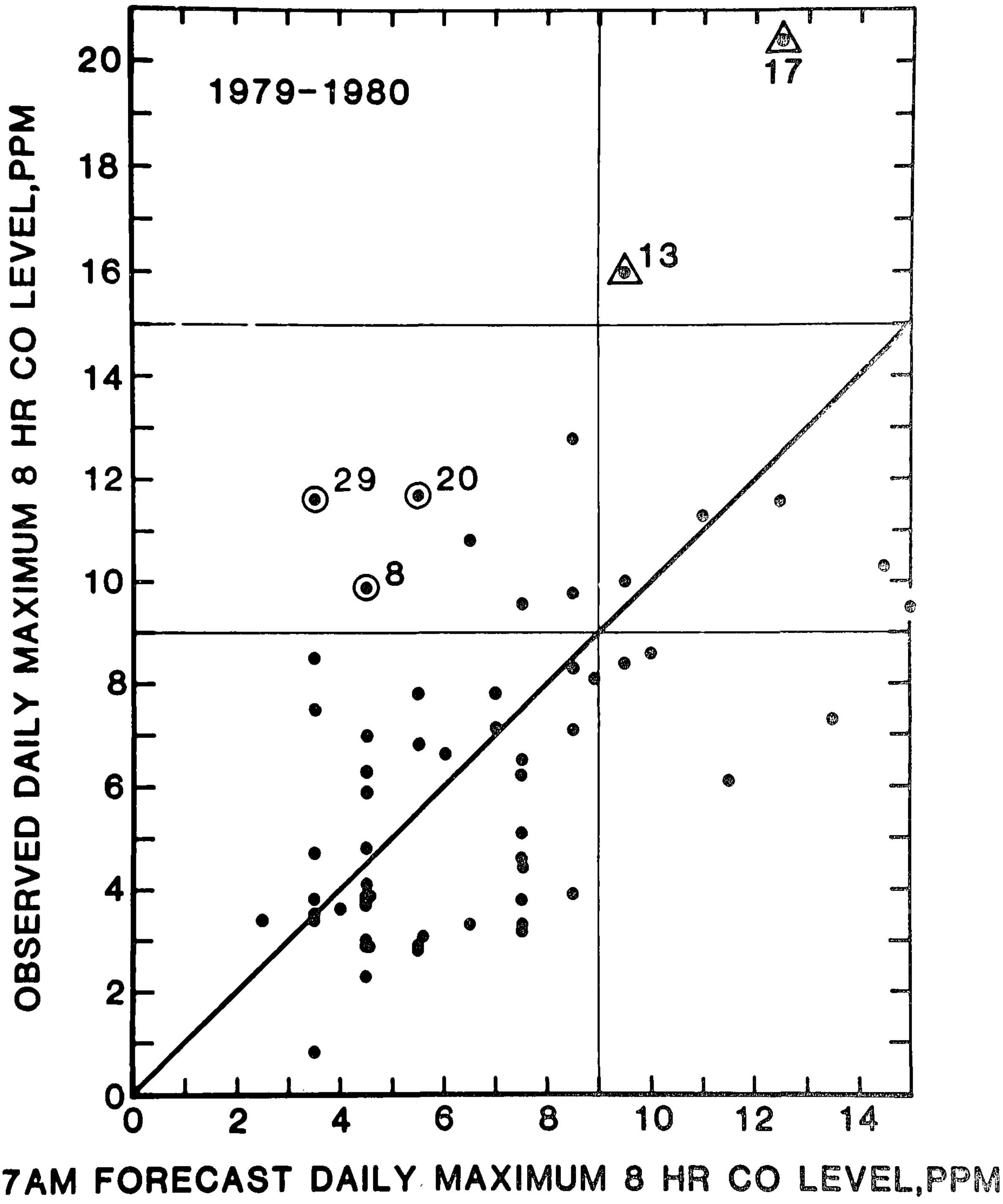

Figure 3-1. 7:00 am forecast of day's highest 8-hour CO level against maximum 8-hour level observed the same day, 1979-1980. Numbered points are in Table 1.

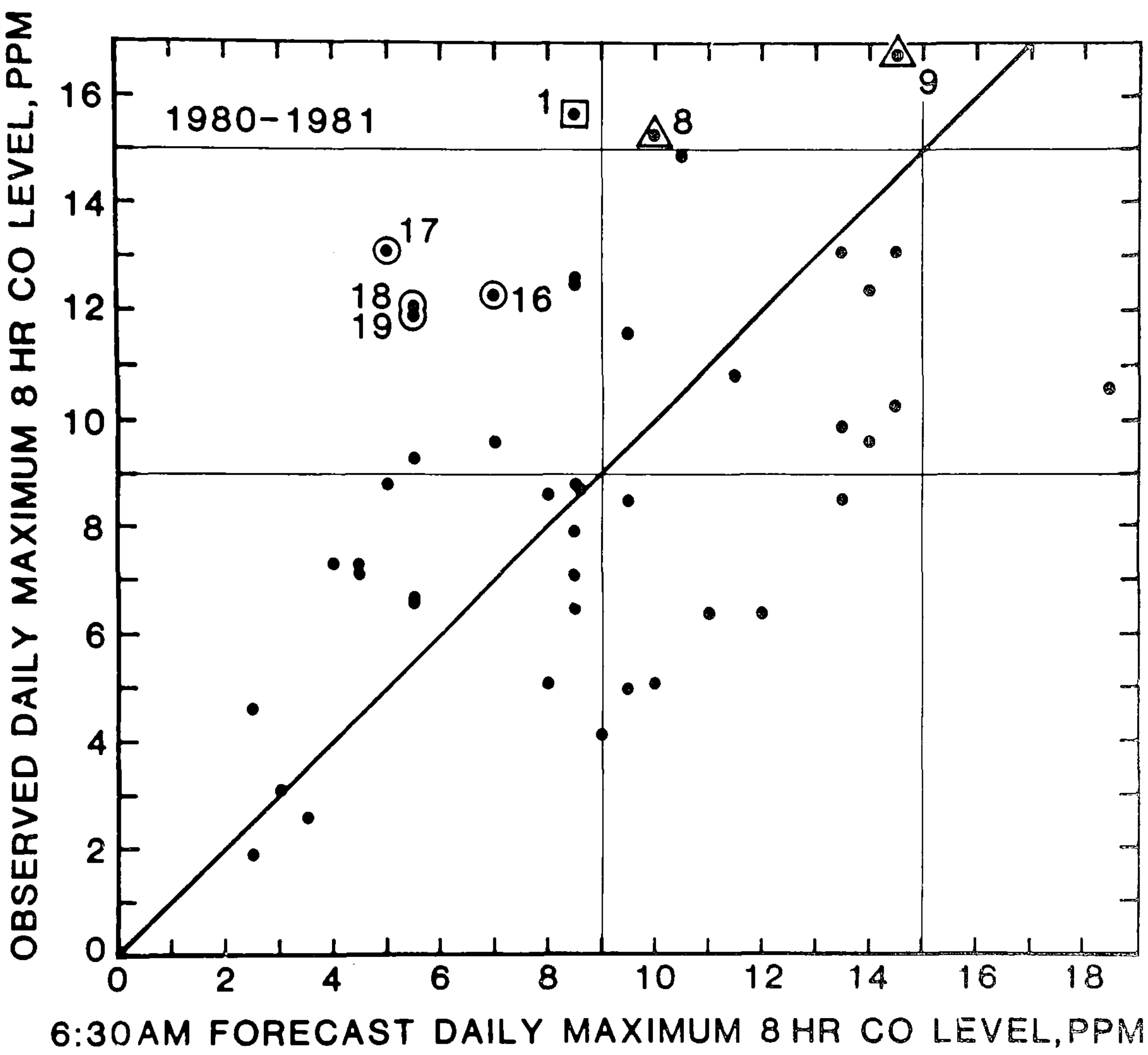

Figure 3-2. 6:30 am forecast of day's highest 8-hour CO level against maximum 8-hour level observed the same day, 1980-1981. Numbered points are in Table 1

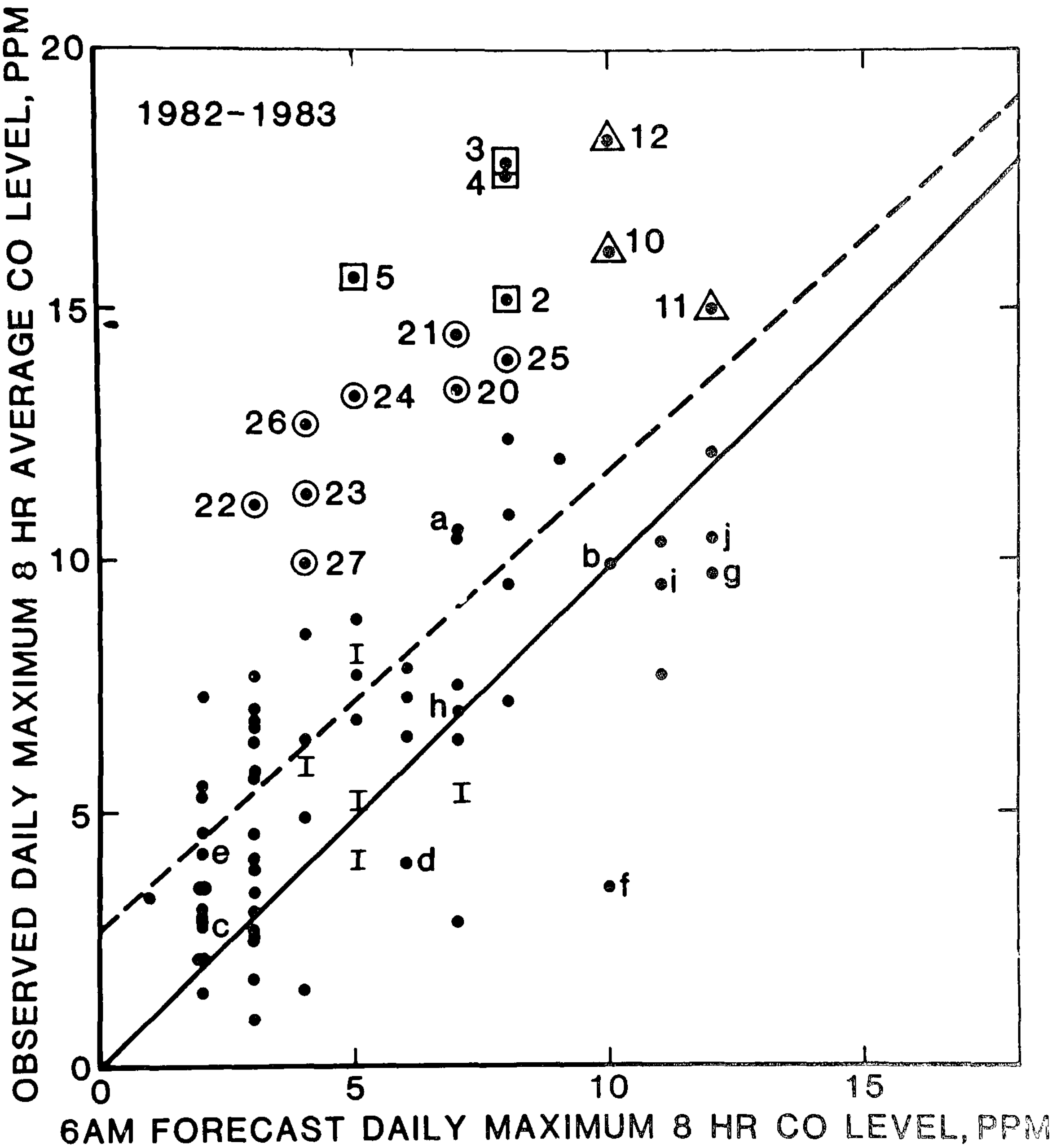

Figure 3-3. 6:00 am forecast of day's highest 8-hour CO level against maximum 8-hour level observed the same day, 1982-1983. Numbered points are in Table 1; I's are ice fog days.

Table 1: Poorly forecast cases examined in detail. Arrows show forecast changes with time; the underlined dispersion category was used for Figure 3-5.

Category A: observed > 15 ppm, forecast < 9 ppm

			observed	forecast	dispersion	persistance
1	Jan 29	1981	15.7	8.5		
2	Dec 8	1982	15.2	8	F → G	9
3	Dec 15	1982	17.8	8	F → P	10
4	Feb 4	1983	17.6	8	P → G → P	(13.4)
5	Feb 22	1983	15.6	5	F	8

Category B observed > 15 pm, forecast > 9 ppm, < 15 ppm and low by more than 2 ppm

			observed	forecast	dispersion	persistance
6	Dec 17	1979	20.4	12.5		
7	Feb 13	1980	16.0	9.5		
8	Nov 19	1980	15.5	10		
9	Dec 23	1980	16.8	14.5		
10	Dec 21	1982	16.1	10	F-P → P	19
11	Jan 21	1983	15.0	12	P	22
12	Feb 23	1983	18.3	10	F → G	28

Category C observed > 9 ppm and more than 5 ppm above forecast

			observed	forecast
13	Nov 20	1979	11.6	5.5
14	Jan 29	1980	11.6	3.5
15	Feb 8	1980	9.9	4.5
16	Nov 12	1980	12.3	7
17	Nov 17	1980	13.1	5
18	Dec 29	1980	12.1	5.5

Category C cont.

			observed	forecast	dispersion	persistance
19	Jan 15	1981	11.9	5.5		
20	Dec 13	1982	13.4	7	F-G	10
21	Dec 20	1982	14.5	7	F	7
22	Jan 14	1983	11.1	3	G-Ex	10
23	Jan 20	1983	11.3	4	F	4
24	Jan 25	1983	13.3	5	F	10
25	Jan 27	1983	14	8	P → F → P	10
26	Jan 31	1983	12.7	4	G	15
27	Feb 3	1983	9.9	4	P → G	7.5

Category D - extreme deviations on either dispersion or persistance forecast, and forecasts low by more than 5 ppm

a	Dec 27	1982	10.6	7	G-Ex	19
b	Nov 12	1982	9.9	10	G-Ex	15
c	Nov 9	1982	2.7	2	Ex → F-P	1.5
d	Dec 30	1982	4.0	6	F → P	18
e	Feb 7	1983	4.2	2	F → G → P	2
f	Nov 24	1982	3.5	10	G	13*
g	Dec 22	1982	9.7	12	F-P	22
h	Jan 4	1983	7.0	7	F → P	24
i	Dec 16	1982	9.5	11	F → P	25
j	Nov 17	1982	10.4	12	F-P	26

*Note on forecast sheet that lock change on building necessitated estimating data. Use of actual data gives 11.

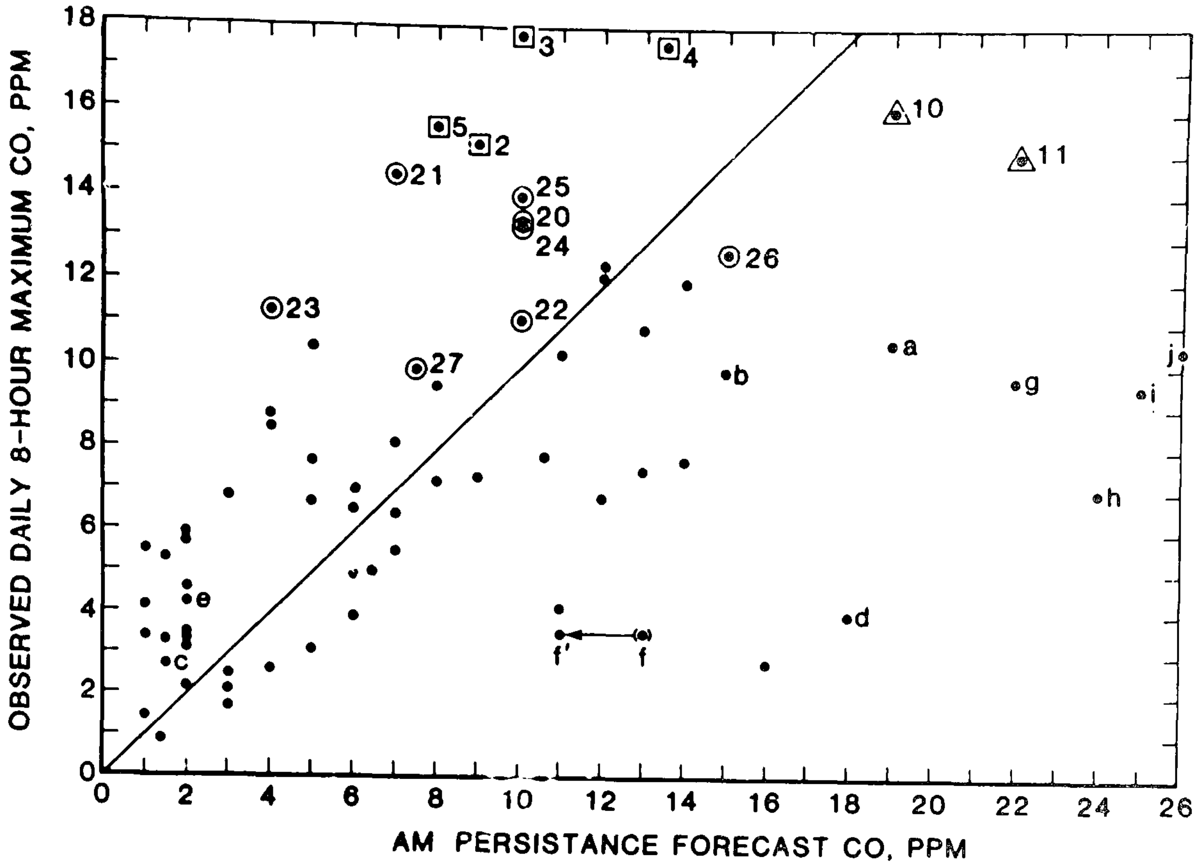

Figure 3-4. 6:00 am persistance forecast of day's highest 8-hour CO level against the highest 8-hour CO level actually observed the same day, 1982-1983. Numbered and lettered points match those in Figure 3-3.

the lowest 113 m of the atmosphere (13.5°C/100m) at 2 pm, compared with 3° over the same height (2.6°C/100 m) at 2 am. Low level warm air advection was a critical factor in several other cases, and needs more attention in dispersion forecasting.

Case 3 was again cloudy, with high CO levels when the ceiling rose. This is another case where airport soundings and winds show reasonably good dispersion, and differences between airport and downtown conditions are likely.

In the two remaining cases, time of day was a critical factor. The noon solar elevation in February is high enough to allow substantial solar heating

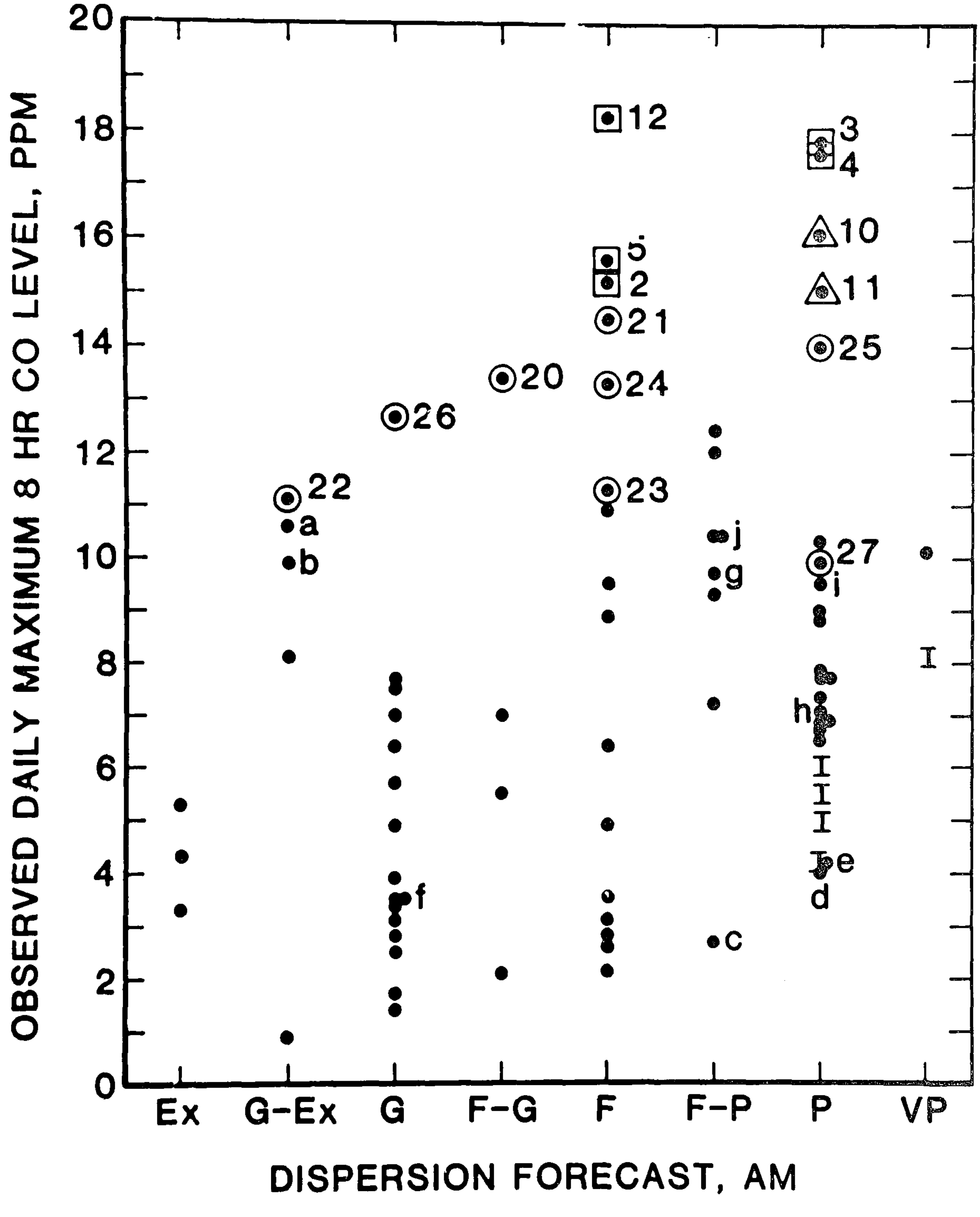

Figure 3-5. Morning dispersion forecast against maximum 8-hour level of CO observed the same day, 1982-1983. Dispersion plotted is the lowest forecast for the day; i.e., a forecast of good becoming poor is plotted as poor. I's are ice fog cases.

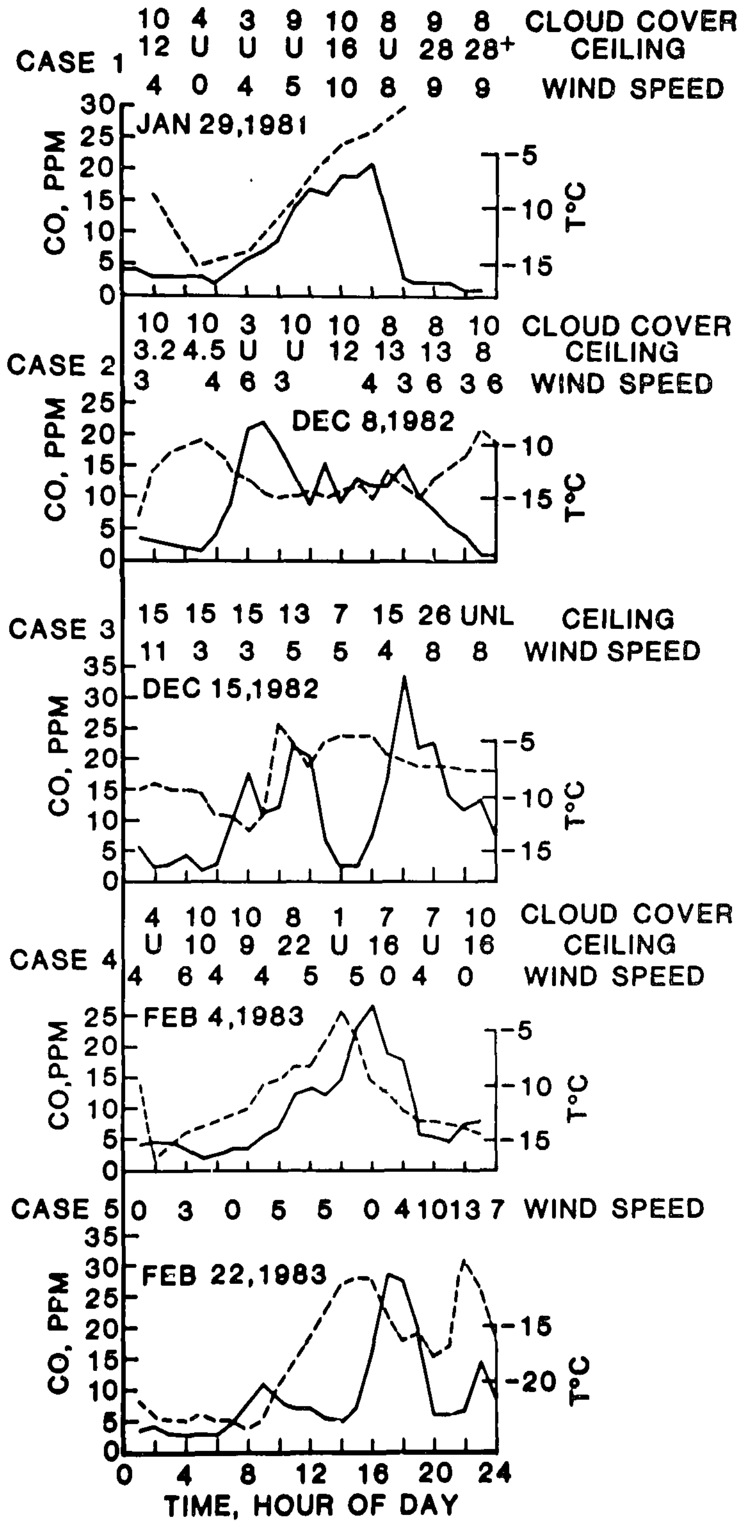

Figure 3-6. Individual plots of cases with observed 8-hour CO levels 15 ppm or more forecast at less than 9 ppm. Solid line 1-hour average CO, dashed line temperature. Cloud cover is in tenths, ceiling in thousands of feet, and windspeed in knots, following NOAA Weather Service usage.

with a break in the inversion, and the observed warming from 2 am to 2 pm on February 4 (Case 4) was just about enough to break the surface inversion observed at 2 am. However, sunset on that day was about 3:45 pm, so a ground inversion had become reestablished by the time of the evening traffic peak. In Case 5 skies were clear all day and the coincidence of the rapid cooling and inversion development near sunset with the evening peak of traffic was even sharper. Given the depth and intensity of the early morning inversion (19°C over 450 m, or 4.2°C/100 m) and the clear skies, the fair dispersion forecast seems a little weak, and in fact a 10°C inversion over the lowest 250 m (4°C/100 m) was still present at 2 pm. Development of an additional steep ground inversion after 4 pm, just before the rush traffic, was undoubtedly responsible for the sharp maximum from 4-7 pm. Case 12, the following day, had even higher CO levels. It was forecast higher than Case 5 primarily because of similarity to the previous day's conditions, and in the face of a dispersion forecast of "fair becoming good late this afternoon", with 5-15 mph winds. The winds materialized just too late to offset the effect of the traffic peak while the inversion was building after sunset. This coincidence of dusk with peak traffic in February is a risk factor not previously recognized.

Of the cases with 15 ppm or more with 9-14.9 ppm forecast, Case 6 follows the pattern of 1, Case 7 is similar to Cases 4, 5 and 12, Case 8 resembles Case 2, with over 8°C warming at 950 mb between 2 am and 2 pm, and 9 is a classic clear-sky, low-wind situation which was relatively well forecast (14.5 ppm forecast, 16.8 pm observed). Case 10 was overforecast on the persistance forecast, then modified downward to little more than half the persistance level on the basis of a dispersion forecast of "fair to poor becoming poor tonight" -- clear and light winds in the Christmas shopping period. This episode was caught by an alert based on a high forecast the previous afternoon. Case 11 was again a classic clear and calm situation, with a steep ground inversion which hardly changed in overall strength through the day.

Two of the category C cases -- 22 and 26-- are worth discussing, as are Cases a and b. The lowest CO levels in situations forecast to have poor or very poor dispersion are also of interest. Cases 22, 26, a and b had CO levels above 9 ppm with good to excellent or good dispersion forecasts. Cases a and b were forecast relatively well by the Borough. Both were cases of high overcast conditions with ground inversions, and the overcasts probably led to the good-excellent dispersion forecasts. Case 22, however, has to be classed as a very bad dispersion forecast. The 2 am sounding showed a 12°C inversion in the bottom 50 m (24°C/100 m), with warm air advection in the lowest 50 mb in progress. Case 26 appears to fall into the same category as Case 1--good winds at the airport but probably not downtown--with the added complication of low level warm advection.

The majority of the poor dispersion cases with CO levels below 6 ppm were ice fog situations, and the Borough forecasters were aware enough of the tendency for CO levels to fall off during ice fog that these cases were fairly well forecast (See I's on Figure 3-3). There are several possible reasons for this association. The cold-start contribution weakens during ice fog, as a vehicle which is not pre-warmed will not generally start at ice fog temperatures. The radiative effects of ice fog tend to improve vertical mixing (Bowling, 1970) and the difficulty and discomfort of driving at -40°C tends to discourage unnecessary trips.

There were three cases with poor or fair to poor dispersion forecasts without ice fog and with CO levels less than 6 ppm. Case c had fair to poor evening dispersion forecast on the basis of snow expected to stop by evening; in fact snow was falling and there was a complete overcast through 2 am the following day. The remaining two Cases, d and e, could be described as inverses of Case 2, with strong cold air advection in the lowest 100 mb of the atmosphere, and overcast skies which in both cases had been expected to become partly cloudy by evening. Case f, the worst low forecast by the Borough, was not a real forecast, as a change in locks on the building barred the forecaster from data on current CO levels.

RECOMMENDATIONS

The general impression received from these analyses and from discussions with Borough and Weather Service personnel is that the single most critical factor in improving forecasts is improved communications between Borough and Weather Service. At the present time, the Weather Service forecasters have no access to CO levels, either as immediate forecast input or to check how accurate their forecasts were. Figure 3-5 is the first such comparison made. Borough forecasters often receive forecasts which are no more than the current sounding and a one or two word dispersion forecast.

Several specific meteorological situations do seem to be important in CO violations. One, recognized quite early, involves wind speeds adequate for dispersion at the airport with near-stagnation conditions downtown. This pattern was documented in Bowling and Benson (1978) although its significance for high CO levels was not recognized at that time. Low level (below 900 mb) advection of warm or cold air may also be critical, with warm air advection enhancing and cold air advection inhibiting ground-based inversions. A high or thin cloud cover may, as in Anchorage (see next chapter) allow the formation of a sufficiently steep inversion to promote unacceptably high CO levels if winds are very low. Finally, as illustrated by the February sunset cases, the exact timing of changes in dispersion is critical. An increase in wind speed at 4 pm, just before the traffic peak, will have a far different effect from a similar increase four hours later. This kind of exact timing is an extremely difficult forecasting problem, but changes linked with solar elevation angle are more tractable. The potential for rush hour CO peaks just after sunset in February, for instance, needs to be recognized. (This problem will have a shift in timing as the new time zone comes into effect this year, and may become more of problem for Anchorage in late January and early February). The effects of high CO inputs during the Christmas shopping season need also to be kept in mind.

SECTION 4

ANCHORAGE

INTRODUCTION

Anchorage, looked at on a small scale, is on a peninsula jutting into the head of a major inlet of the Pacific Ocean - Cook Inlet. The area is noted for being windy and stormy, and scarcely seems a likely candidate for a major air pollution problem. However, if the larger area is considered, it becomes apparent that the whole inner half of Cook Inlet, together with the lower parts of the Matanuska and Susitna Valleys, form a single large basin (Figure 4.1). Furthermore, it is apparent from thermal infrared satellite imagery that the land portions of the basin floor are often substantially colder than the surrounding uplands - in other words, inversions are common (Figure 4.2). Finally, the precipitation anomalies of Anchorage tend to parallel those of the Interior rather than those of much closer coastal stations located directly on the shores of the Gulf of Alaska - an additional indication that Anchorage does not have an exposed, fully maritime climate, but is sheltered by the Chugach and Kenai Ranges, Nevertheless, it was not immediately clear why CO levels in Anchorage were so high.

OBSERVED CARBON MONOXIDE LEVELS

Our first step toward solving the problem was to compare the CO levels as a function of time at the three sites then available. Figure 4.3 shows hourly CO levels, together with temperatures and airport lapse rates, for the three stations operating in February 1980. The similarity of behavior at the three stations strongly suggests that the problem is area-wide rather than due to such quasi-local causes as wind alignment parallel to heavily travelled streets. The fact that Garden Site, a residential area with no concentrated local sources, frequently had CO levels above the downtown site, 7th and C, and on occasion even exceeding the levels at Benson and Spenard (a high traffic site) was startling. This behavior is one of the major pieces of evidence for the wind-shadow model to be presented later.

Comparison of the CO levels directly with meteorological data was complicated by the fact that CO levels depend on sources as well as on dispersion. Figure 4-4 gives some idea of how current traffic counts vary with time of day. In an attempt to remove the regular diurnal variation in source strength and meteorology, we calculated for each site a series of hourly normal CO levels. Hourly means and standard deviations were calculated separately for 1) each month, 2) each Friday, Saturday, Sunday and 3) each Monday through Thursday. Normalized CO values were then constructed using the formula

Figure 4-1. Composite Landsat photo of the Cook Inlet area.

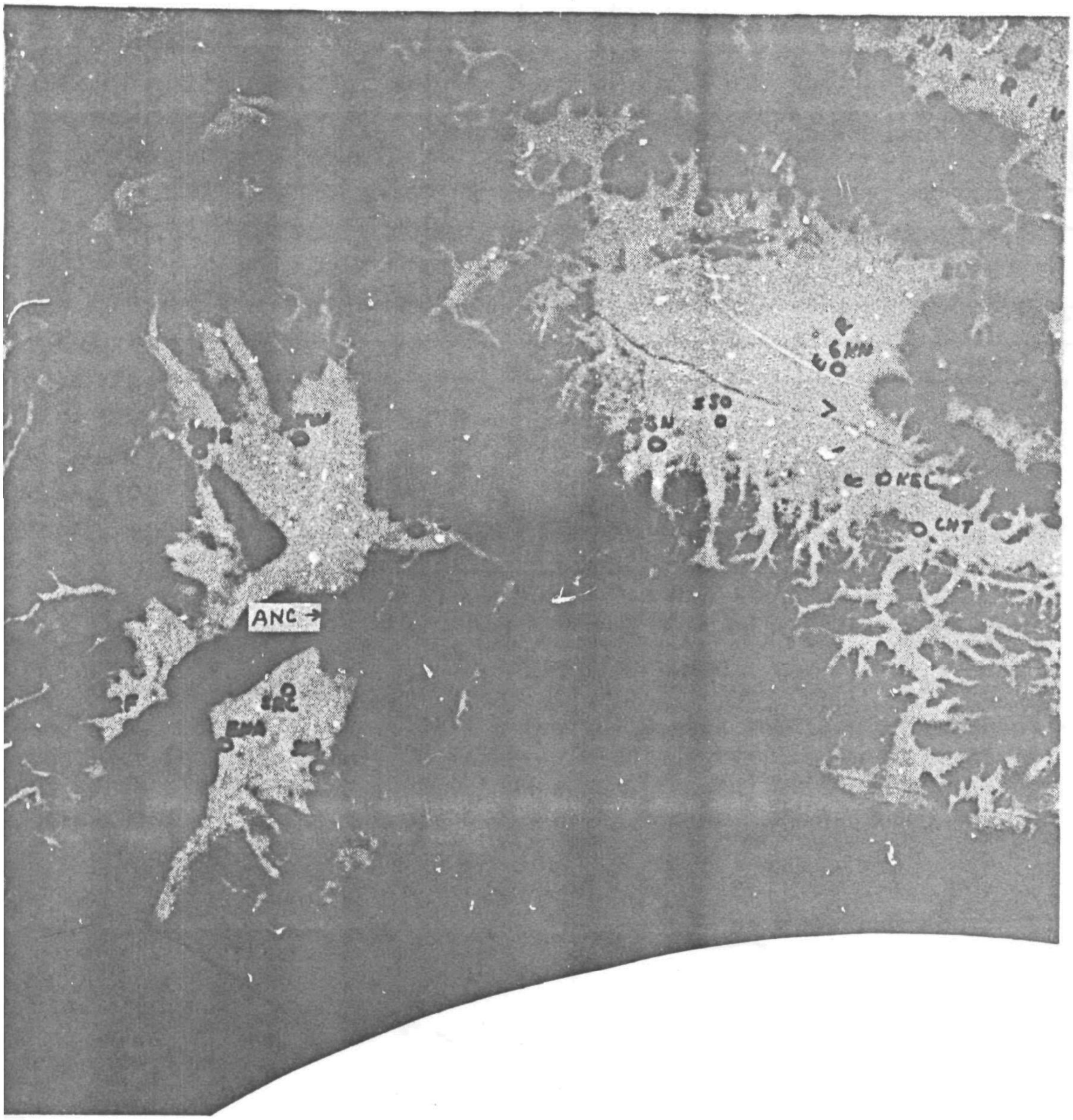

Figure 4-2. NOAA-4 thermal infrared image of the Cook Inlet area. Anchorage is at ANC, and light tones are cold.

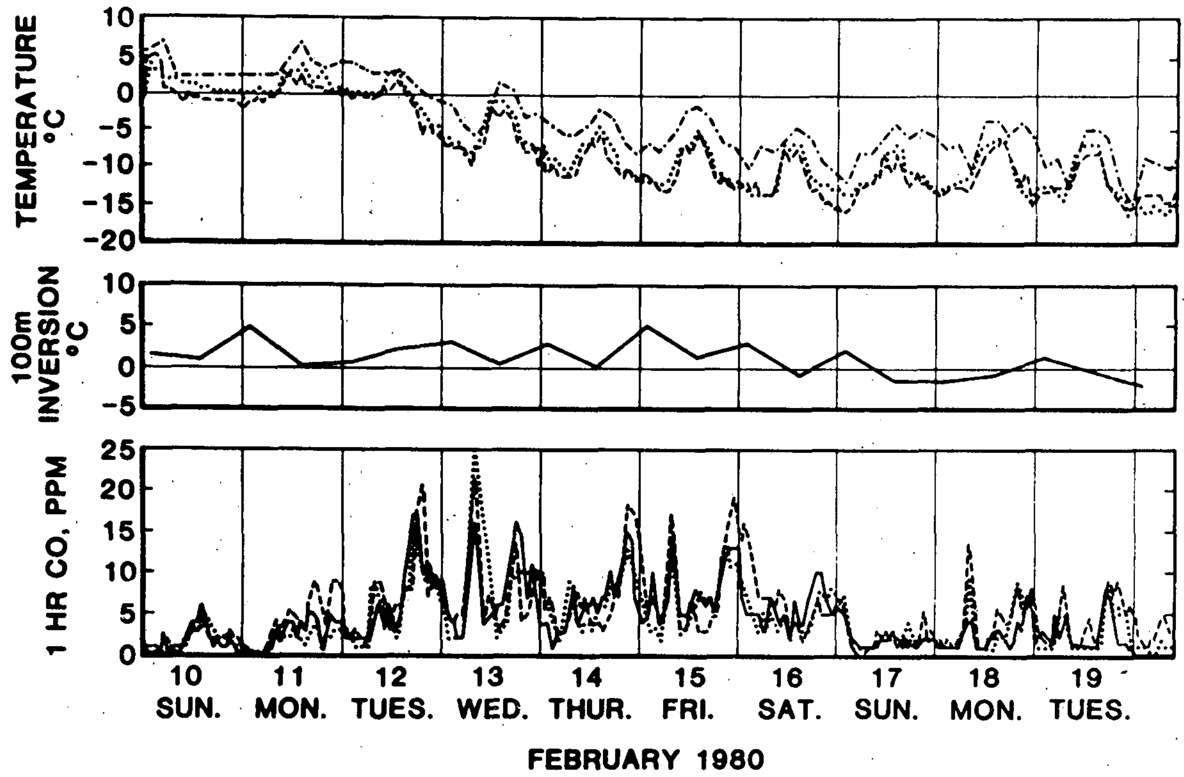

Figure 4-3. Lower curves: 7th & C (solid) Benson and Spenard (dashed) and Garden Site (dotted) hourly CO values. Middle curve: 100-m temperature minus surface temperature (100-m inversion strength) at Anchorage airport. Upper curves: Airport (dot-dashed), Benson and Spenard (dashed) and Garden Site (dotted) surface temperatures.

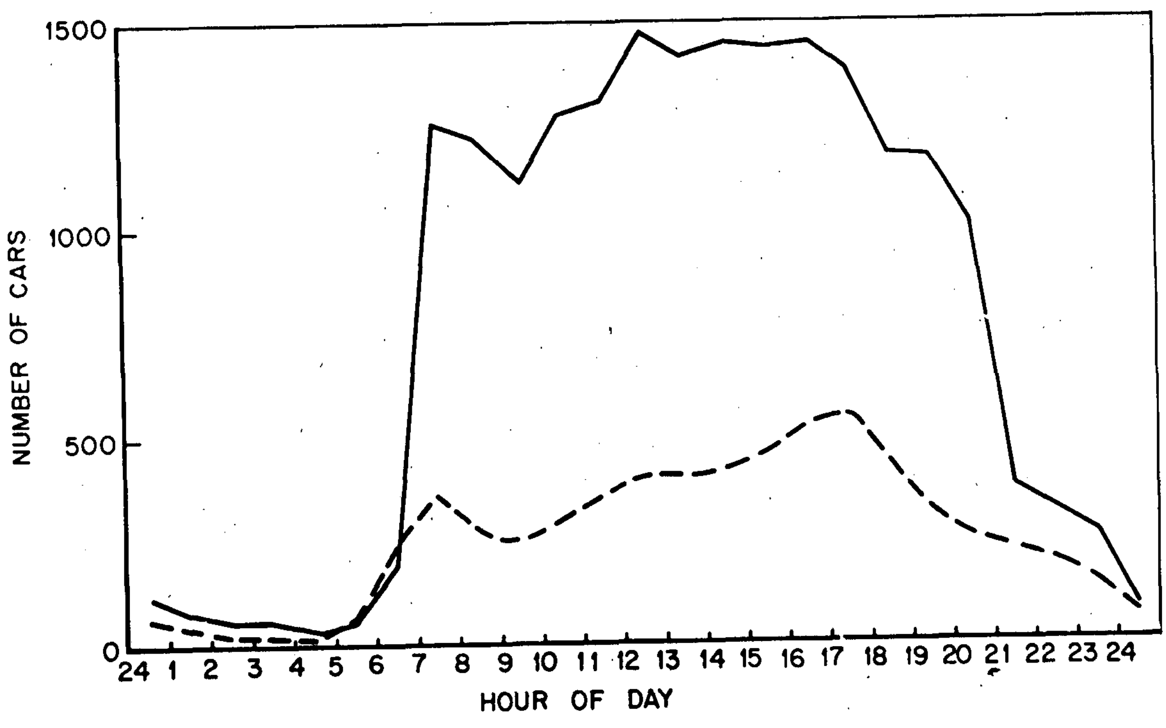

Figure 4-4. Traffic counts (averaged over 5-8 days) for Benson and Spenard (solid line) and Sand Lake (dashed line). Based on December 1982 and January 1983 data.

$$CO_{norm} = \frac{CO_{obs} - CO_{mean}\ \text{(month, hour, day of week)}}{\sigma_{CO}\ \text{(month, hour, day of week)}},$$

where CO_{norm} is the normalized CO level, CO_{obs} is the measured CO level, CO_{mean} is the mean and σ_{CO} the standard deviation of all CO observations taken at the same month, hour, and day of the week (Monday through Thursday considered as the same day) as CO_{obs}. The resulting values of C_{norm} for the same time period as Figure 4.3 are shown in Figure 4.5, together with wind speeds and cloud cover measured at the airport.

METEOROLOGY

High normalized CO levels tend to be associated with clear skies or fog, low wind speeds, substantially lower temperatures at the measuring sites than at the airport, and inversions or isothermal lapse rates in the lowest 100 m of the airport sounding. The presence of a well developed inversion throughout the area on the morning of Saturday, 16 February can be inferred from the thermal infrared image shown in Figure 4.6, which shows the low-lying peninsula

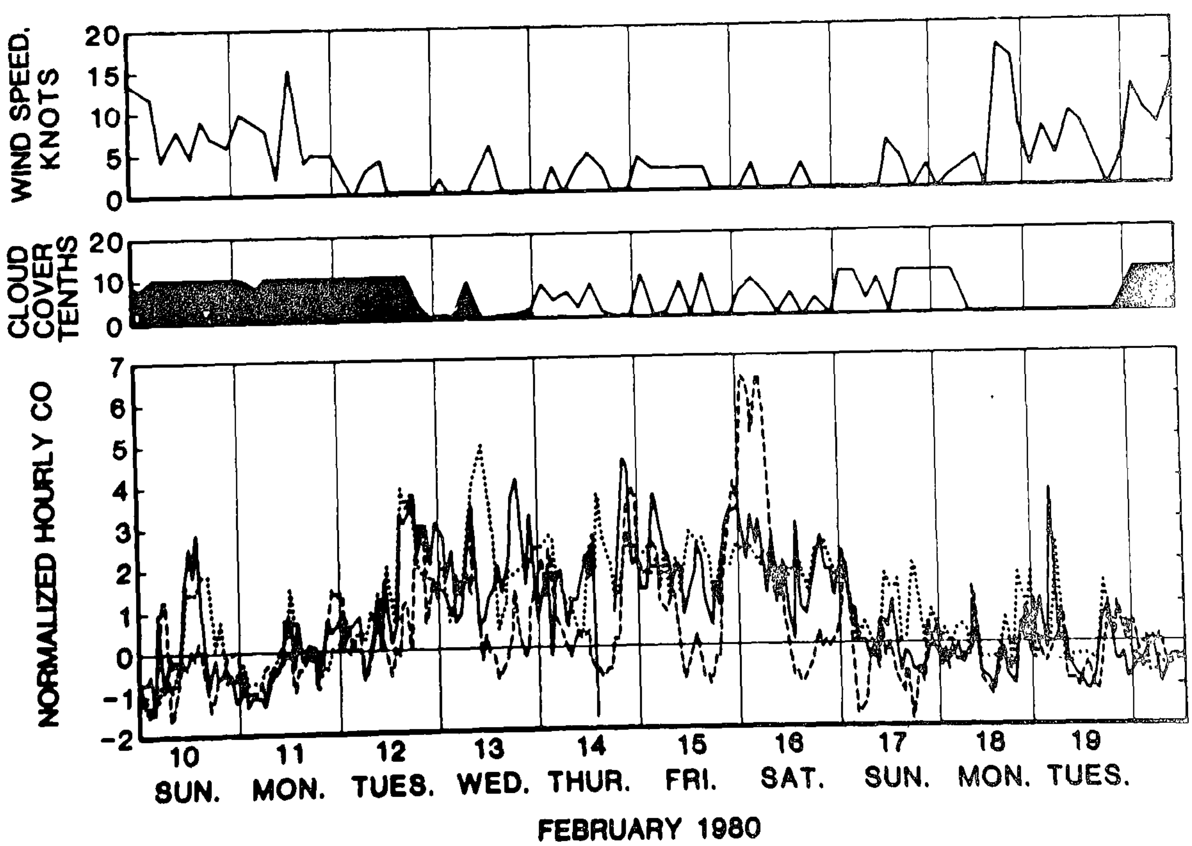

Figure 4-5. Lower curves: Normalized hourly CO values for same stations and time periods as Figure 4-3. Middle curve: cloud cover; solid area cloud, open area fog. Top curve: windspeed.

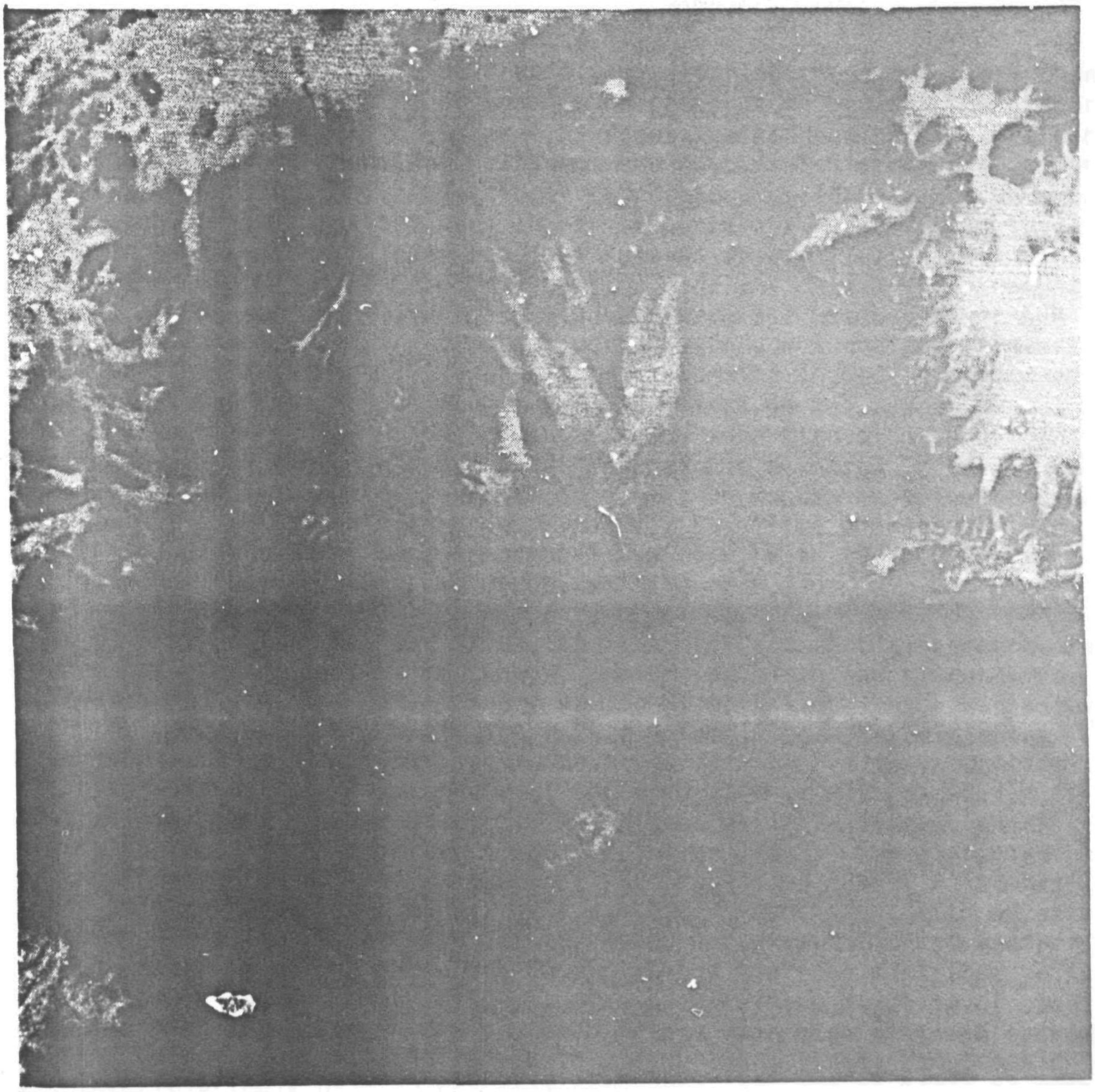

Figure 4-6. NOAA-6 thermal infrared image, 16 Feb 1980. 8:39 am.

on which the city is situated to be distinctly colder (lighter in color) than the neighboring mountains. (The difference in temperature between the airport and the measuring sites seen in Figure 4.3 argues against the direct applicability of the Anchorage airport soundings, although the combination of inversions at the airport with substantial (5°C or more) temperature differences between the airport and the monitoring sites does appear to correlate well with CO levels.) By 2 pm Saturday the airport lapse rate was superadiabatic (2.7°C/100 m) for the first 67 m, capped by a 2°C/100 m inversion over the next 127 m. Ground temperatures at the measuring stations, however, were all below that at the top of the superadiabatic layer at the airport. Although the airport inversion reestablished itself overnight, the 2 pm Sunday sounding showed an even more superadiabatic lapse rate - 4.6°C/100 m over the first 46 m - capped by a 1.5°C/100 m inversion to 280 m. Although a ground inversion might have persisted at Benson and Spenard (which was 4.4°C colder than the airport) CO levels were near normal for Sunday. CO levels remained normal on Monday in spite of clear skies and relatively light winds at the airport. Satellite photography and the airport sounding clearly show a normal lapse rate, with the peninsula distinctly darker (warmer) than the mountains (Figure 4.7).

This general pattern - clear skies, light winds, substantial temperature differences between the airport and the CO monitoring sites and evidence for ground inversions from satellite imagery and/or airport soundings - was associated with the majority of the violation days examined. Locally developing radiative inversions of the same type responsible for the Fairbanks problem are thus strongly suggested as a cause of the Anchorage problem as well. Neither the inversions nor the calms are as intense as in Fairbanks, which agrees with the fact that Anchorage (1980 population 174431) has a problem similar in magnitude to that of Fairbanks (1980 population 22645; Fairbanks North Star Borough population 53983). The pattern is consistent with an anticyclonic core situation as is seen in Fairbanks, but examination of weather maps for the majority of the Anchorage CO violations over the last four years has shown no truly anticyclonic episodes. The overwhelming majority of cases have occurred with Anchorage in the southern fringe of a high pressure system, often with a fairly substantial north-south pressure gradient. Geostrophic surface winds invariably have an easterly component, and can at times be quite strong. The observed winds at the Anchorage airport, however, are normally quite light. The weather map during the most severe episode of 1982-83, with violations at all four stations, is shown in Figure 4.8. A similar map for 2 pm the afternoon of Friday. February 16, 1980 appears as Figure 4.9; this is one of the most strongly anticyclonic cases observed.

A second type of weather situation was noted on two occasions: 26 December 1979 and 7 February 1983. In both cases the core of a dissipating low pressure system was situated over Anchorage. The 1979 case occurred in the late afternoon and evening; the sky was overcast, ceiling 4,000 - 6,000 feet and airport winds were 4-7 knots. The 2 pm sounding showed a 2°C/100 m inversion. Observations from Merril Field, fairly close to Garden Site, indicate winds of 2-3 knots until about 5 pm, then 4-8 knots; Merril Field also reported that the

Figure 4-7. TIROS-N thermal infrared image, 18 Feb 1980. 1:35 pm.

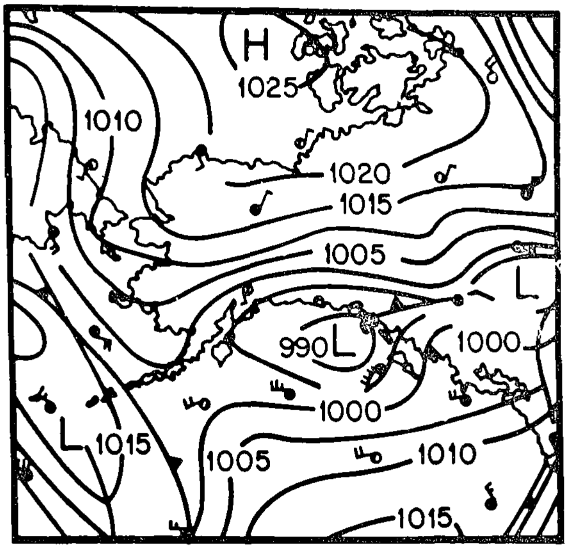

Figure 4-8. Weather map, 2 pm AST
3 Dec. 1982.

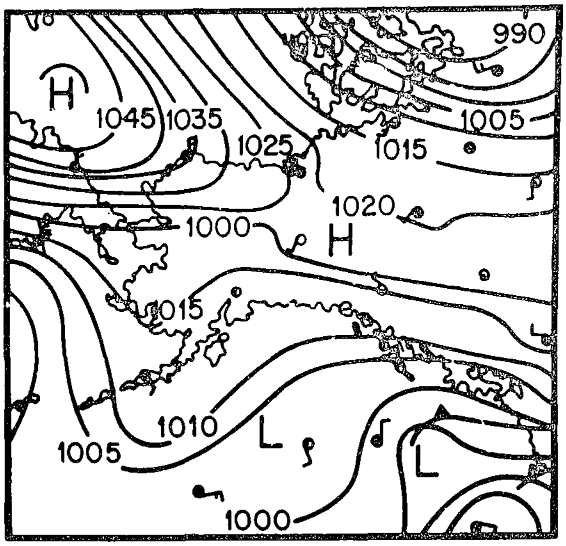

Figure 4-9. Weather map, 2 pm AST
16 Feb. 1980.

moon was visible through the clouds around 9 - 10 pm. The meteorological data from the monitoring stations themselves show wind speeds generally 2-3 mph. The 1983 case had a major spike coinciding with the 8 am rush hour; although hourly levels reached 21 ppm at Garden Site, they exceeded 6 ppm for only 4 hours. The sky was overcast except for 9/10 cloud with less than 3,000 ft. ceiling at 8 am. Winds were light, with a calm at 8 am.

TRAFFIC AND SEASONALITY

The mean values calculated in the course of normalizing the CO levels contain a good deal of information in their own right. Figure 4-10 shows the February mean hourly values for the period of record for each station. Note that the years over which the means were calculated differ for the different stations; consequently the absolute values for the various stations should not be compared. However, the behavior with time of day and to some extent with time of week is worth studying.

All of the stations show what appears to be the classic commuting peaks at 8 am and 4-6 pm, the morning peak being advanced and the evening one delayed somewhat at the residential location, Garden Site. Evening levels tend to be higher on weekends at Benson and Spenard (which is closer to being an entertainment district). Morning peaks on Saturday and Sunday are much lower and delayed Garden Site is in a church parking lot, but Sunday values show little effect of this location.

The midday dip in CO levels is due to a combination of factors--not only is traffic presumed to be lighter (though Figure 4-4 does not indicate this), solar heating increases dispersion. Because Anchorage is so far north, however,

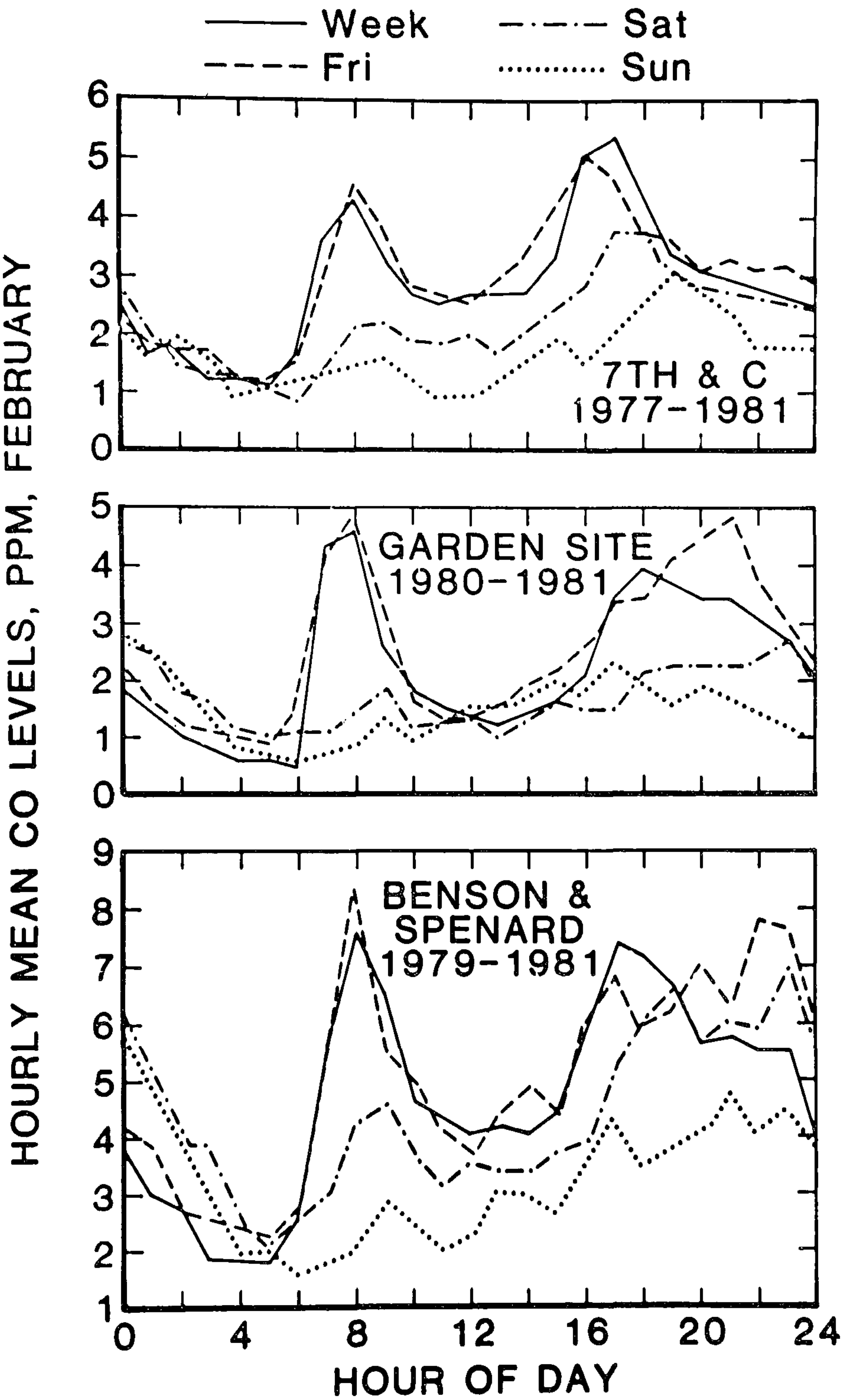

Figure 4-10. February mean hourly values of CO for the three stations with the longest periods of punched data.

solar heating is relatively weak in December and early January. This allows traffic and solar effects to be disentangled to some extent, as can be seen in Figure 4-11. The sharp rise at 8 am is still present on weekdays, but at all but the residential site the CO levels now remain high through the day. The evening peak appears as an additional rise from the level reached in the morning. Christmas shopping may be having some effect, but comparison with January means (which are influenced more by solar heating than December's) suggests that the major cause of the dip between the peaks in February is meteorological. Garden Site does retain separate morning and evening peaks in December, but the minimum between them is now a distinct lunch-hour low point rather than a broad period of low CO levels.

VERTICAL TEMPERATURE STRUCTURE

Anchorage is over 3 1/2° south of Fairbanks and we had initially assumed that midday solar heating would be sufficient to break the nocturnal inversion for at least an hour or so a day. However, this is not the case. Attempts to modify standard dispersion-typing schemes to fit Anchorage first suggested that inversions probably persisted through the day in midwinter, and this was confirmed by the December mean hourly CO values and by December soundings at the airport. Figure 4-12 shows a number of soundings taken at 1 am and 1 pm during the period from 15-24 Dec. 1982. Although the strongest inversions are for 1 am, the systematic difference in inversion strength between 1 am and 1 pm is minor and there are cases (e.g., Dec. 14) where a 1 pm sounding has a stronger ground inversion than either of its flanking 1 am soundings.

Unfortunately, airport soundings are even less appropriate measures of lapse rates at the monitoring sites in Anchorage than is the case in Fairbanks. Anchorage has not only a heat island, but a major heat source in the tidal waters of Cook Inlet as well. Although ice pans cover the water surface to a variable extent, they are thin compared with pack ice farther north and there is normally at least some open water between the pans. The result is that when winds speeds are low enough that turbulent mixing is minor, the CO measuring sites are generally colder -- by as much as 10°C -- than the airport, which is nearer the coast. This is true even though the Anchorage heat island is strong enough to be visible on some NOAA satellite images, e.g., Figure 4-2.

If temperatures inland at some fixed elevation were the same as those measured at the aiport, the ground temperatures at the measuring sites could be used to estimate the lapse rates at the same points. Heat island effects would undoubtedly give some near-surface mixing -- probably more than in Fairbanks (next chapter) -- but the overall inversion strength would be correct. Figure 4-13a shows the resulting sounding for Dec. 25, 1982 at Benson and Spenard if the 100-m temperature above the surface is assumed to be the same as at the airport.

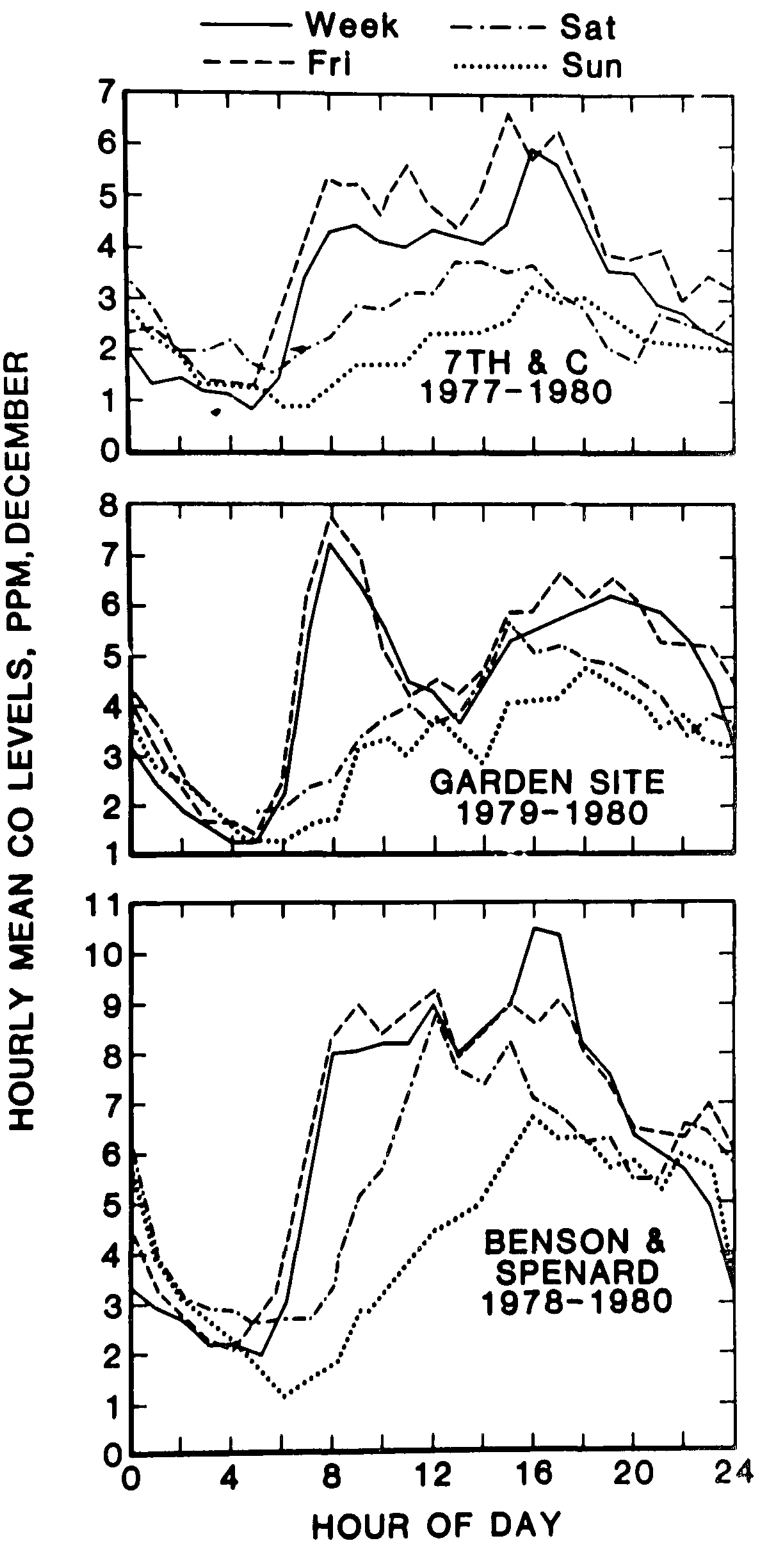

Figure 4-11. December mean hourly values of CO for the same three stations as Figure 4-10.

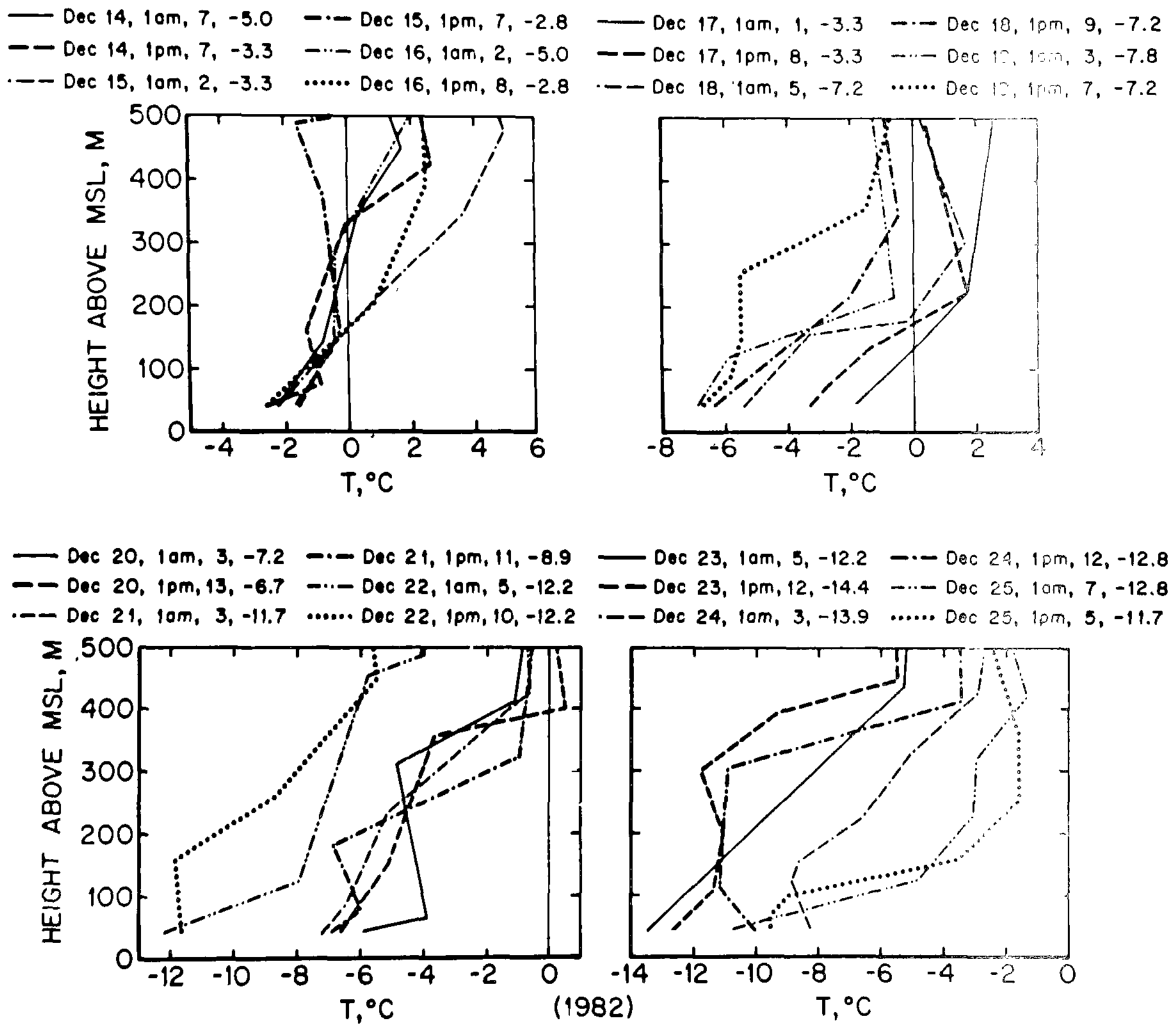

Figure 4-12. Airport soundings for a high CO episode in December 1982. Heavy lines are 1 pm soundings. The first number after each day and time is the corresponding hourly mean CO (ppm) at Benson and Spenard; the second is the surface temperature at Benson and Spenard.

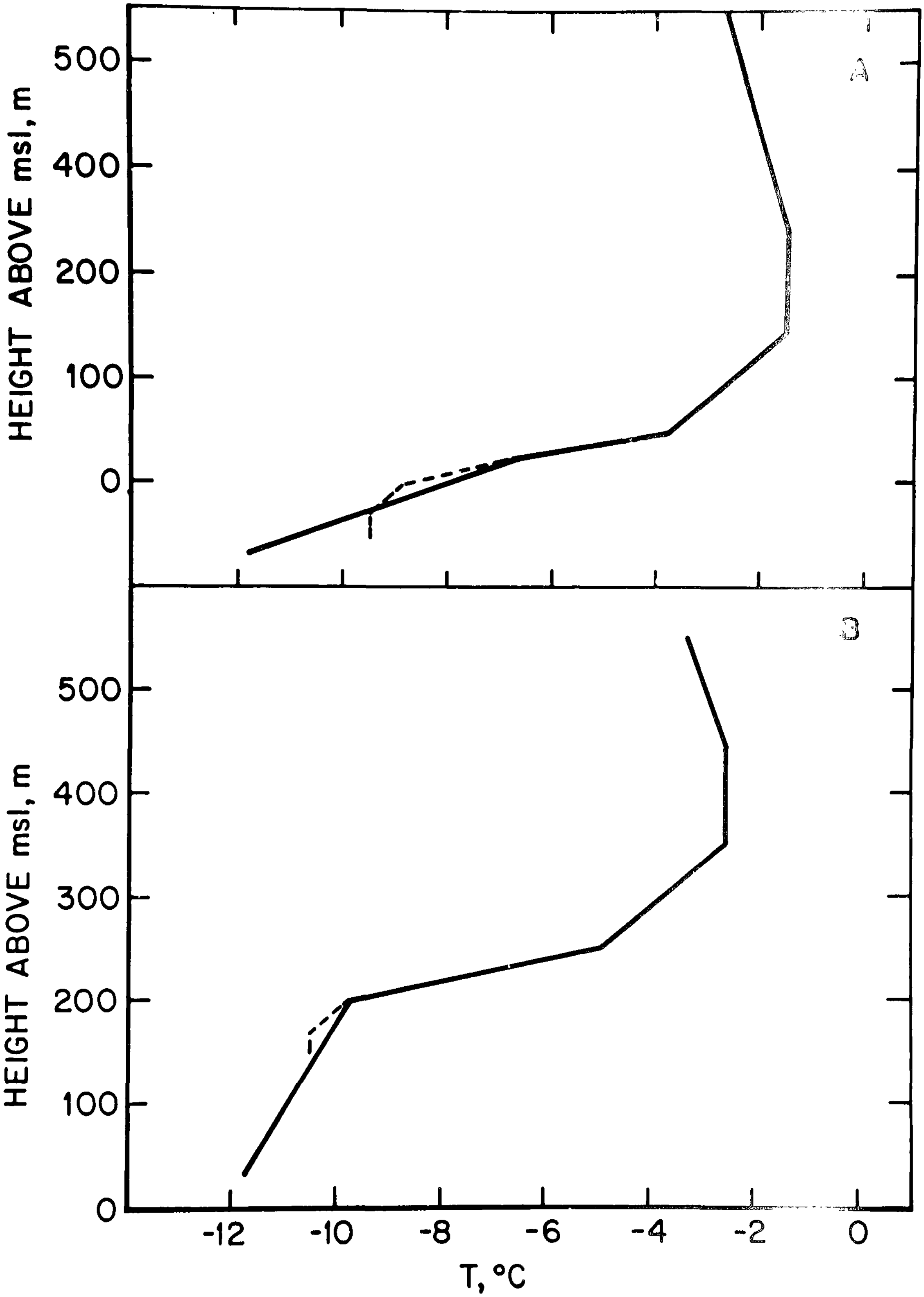

Figure 4-13. Possible soundings at Benson and Spenard for 1 pm Dec. 25, 1982. See text for explanation.

However, air coming from across the Chugach range -- the normal direction during a pollution episode -- will be moving downward as well as westward. The exact path followed will vary with the episode (Figure 4-14), but the uppermost path -- a straight line from the range westward to the ground at the airport -- will give the maximum vertical air motion between the measuring sites and the airport. Air at the airport will have subsided about 100 m (Wz) since Benson and Spenard, and 200 m relative to that over the Garden Site. If the air subsides as a uniform layer, and has a lapse rate (- dT/dz) of q, the temperature difference at a given height more than 145 m above sea level between Benson and Spenard and the airport will be Wz(q Q), where Q is the adiabatic lapse rate of 1°C/100m. Figure 4-13b shows the resulting December 25 sounding at Benson and Spenard. The real case is probably somewhere between the extremes.

In an effort to resolve the problem, we attempted to use the Tethersonde system to obtain a chain of low-level soundings along Tudor Road. By the time problems which had shown up while using the system in Fairbanks were resolved, it was too late to use the system in Anchorage in the late winter of 1982. When we attempted to try the same experiment the following year, the signal acquisition circuits on the ground station went out, requiring continual manual reaquisition of the instrument package signal. By the time the instrument was sent to Colorado for repairs and returned, the season was again over.

We did obtain one good ascent at the Bus Barn (See Figure 2-2) on January 14, 1983. This ascent, together with the flanking airport soundings, is shown in Figure 4-15. Although it confirms our suggestion that inversions become

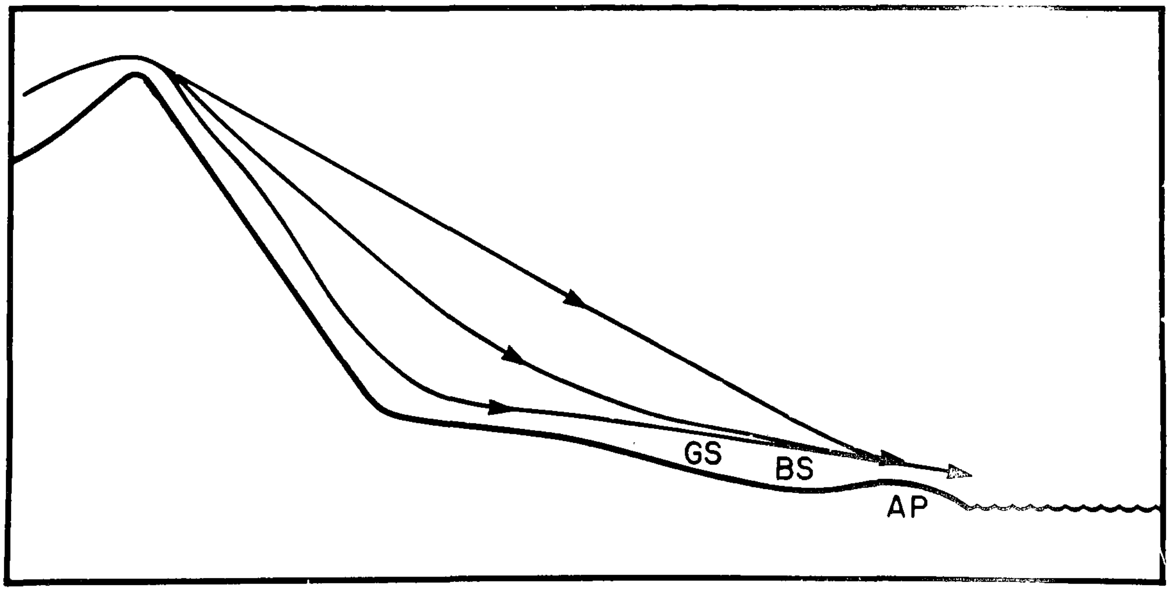

Figure 4-14. Possible paths for air flow over the Chugach Range.

stronger away from the coast, the warmth of the temperatures above 25 m is not easily explained. These measurements urgently need repetition.

THE WIND FIELD

The wind field in Anchorage, like that in Fairbanks, is complex and variable. Figure 4-16 shows wind directions for three stations -- the airport, 7th and C,

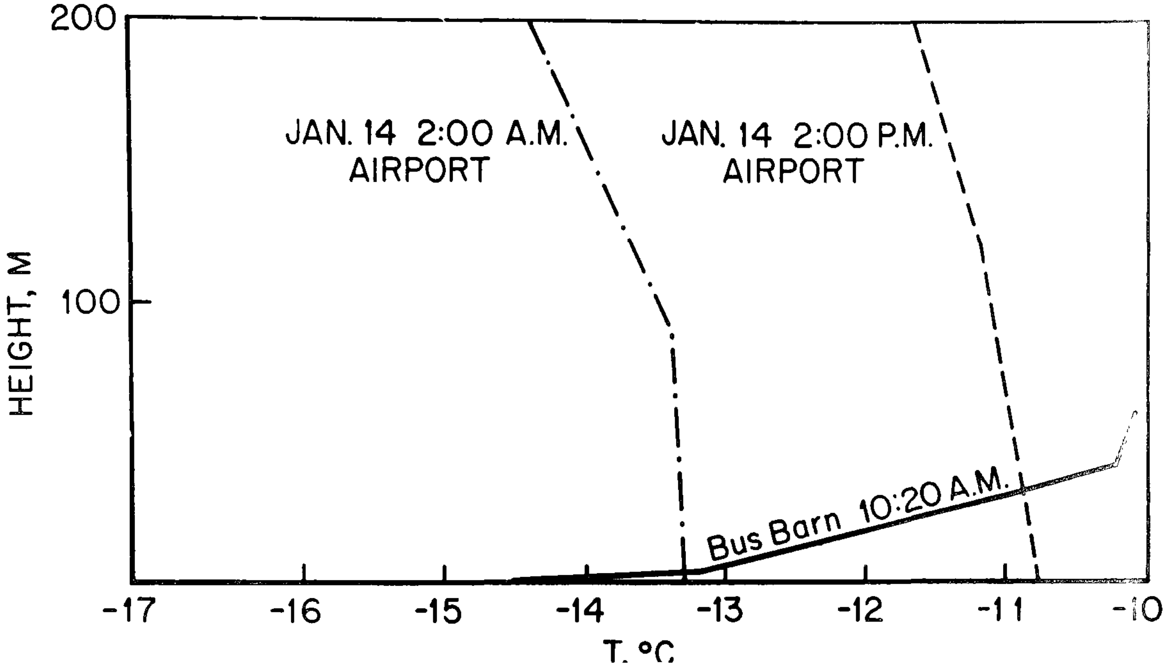

Figure 4-15. Comparison of an inland Tethersonde sounding made at the Bus Barn (B on Figure 2-2) with flanking soundings from the airport.

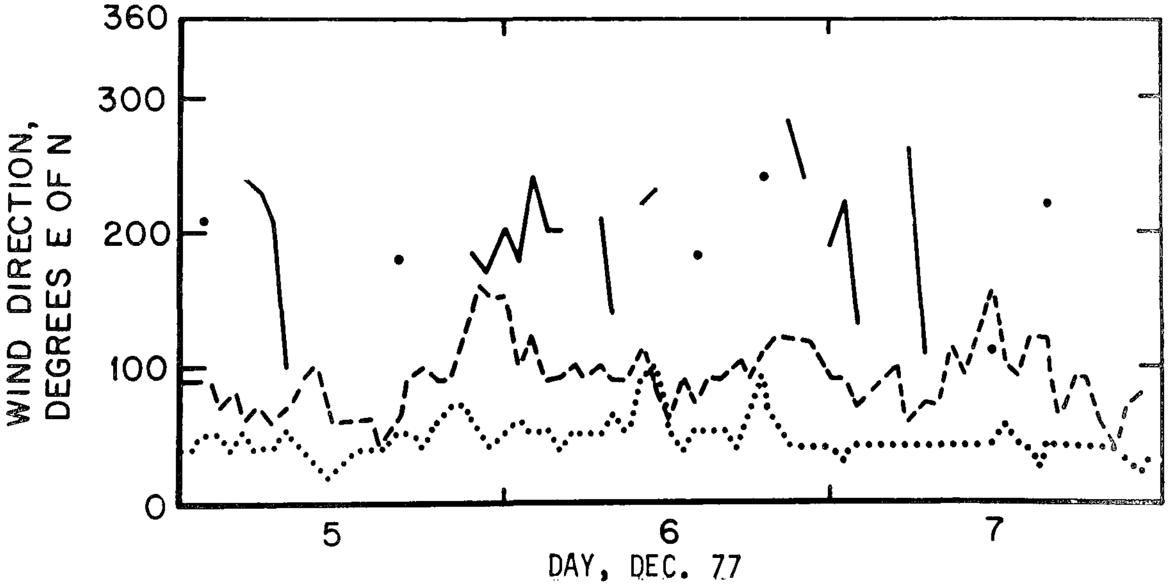

Figure 4-16. Comparison of wind directions measured simultaneously at the airport (solid line), 7th and C (dashed line) and Tudor and Lake Otis (dotted line).

and an early site at Tudor and Lake Otis -- over a 3-day period with high CO levels at 7th and C. The airport anemometer had a starting speed around 3 mph, compared with 1 mph for the other two stations, so there are considerably more missing data at the airport. Nevertheless, the general tendency is clear -- northeast winds at the station nearest the mountains swinging through southeast winds downtown to southwest winds at the airport. According to Anchorage residents the opposite situation, with south winds near the mountains and north winds at the airport, also occurs; and we have observed situations with fairly uniform wind directions, and with brisk winds in the western part of town while calm conditions prevailed near the mountains. Additional complications are introduced by topography. Fairbanks is on a depositional river plain with very minor relief. Anchorage, however, is on an originally smooth sedimentary plain which was uplifted by glacial rebound and then dissected, and the local relief, even away from the mountain front, is far greater than observed in Fairbanks. Gravity drainage is correspondingly more complex.

In view of the uncertainties regarding the spatial variability of both inversion strength and winds across Anchorage, we strongly recommend a measurement program aimed at obtaining and interpreting data on both. A reasonable system would involve a 15-m tower at each CO monitoring site plus at least four additional towers along an east-west transect -- probably along Tudor Road -- and one or two towers in topographically interesting areas. Wind and temperature measurements should be made at 2, 8 and 15 meters. A modern data logging system would allow direct readout of hourly mean wind directions and speeds, standard deviation of direction and possibly periodic variations induced by gravity waves. This is particularly important as the existing micrometeorological stations at the monitoring sites are being removed.

THE LARGER BASIN: INNER COOK INLET

The CO problem appears to be local and confined to the immediate vicinity of Anchorage. However, the larger basin is subject to inversions, as seen in Figures 4-2 and 4-6, and both shores of the inner half of Cook Inlet, as well as large portions of the lower Matanuska and Susitna valleys, must all be considered part of the same air drainage. An unplanned demonstration of that fact occurred in the spring of 1983, when moderate clearing operations (500 acres) were carried out near Point Woronzoff, across Cook Inlet from Anchorage. Slash burning from the clearing resulted in a very substantial smoke problem in Anchorage (Anonymous, 1983; Ryan, 1983). According to my own observations, at around 5 pm 20 May 1983, the plume was crossing the Parks Highway as a well defined layer near the Knik River bridge, at the head of the arm of Cook Inlet north of Anchorage. In the valleys inland of the bridge the smoke was eddying visibly down to the ground in what appeared to be a fumigation type episode. The lower atmospheric layers had in all probability remained stable and inhibited mixing while crossing the cold waters of Cook Inlet, then been destabilized by heating as they moved over the land.

Superadiabatic lapse rates near the ground with strong capping inversions starting at 50-300 m have been observed at Anchorage in midwinter. These episodes are associated with northerly to westerly surface winds and are almost certainly due to heating of the lowest layers of cold continental air flowing over the incompletely frozen waters of Cook Inlet. Of two such episodes in January 1980, one was associated with severe CO pollution (1-hour levels above 15 ppm at Benson and Spenard and Garden Site) and the other with 0-1 ppm. The major difference appears to be that in the first episode, skies were clear and the temperatures at the monitoring stations were almost 10°C cooler than at the airport -- i.e., it appears that a ground inversion was developing very rapidly as the air moved inland or that inland stations were not influenced by Inlet-modified air. The capping inversion was relatively weak. In the second case, skies were cloudy, the CO monitoring sites were only 2-3°C cooler than the airport, and the capping inversion was quite strong--4.8°/100 m from 280 m to 400 m. The extreme superadiabatic lapse rate on 17 Feb. 1980, which was capped at less than 50 m and accompanied by average CO levels, has already been mentioned. Thus the elevated inversion appears to have a negligible influence on CO concentrations. However, this situation could cause an elevated plume from across the Inlet to mix down to the ground at Anchorage.

These two cases suggest that potential dispersion problems may exist throughout the year for the larger basin. Emissions on the west shore of Cook Inlet must be considered in terms of their influence on the entire basin. This should certainly be taken into consideration in any discussion of industrial development, as well as more extensive clearing planned for Point Woronzoff.

CONCLUSIONS

The major meteorological situation associated with high CO levels in Anchorage, Alaska is a ground-based radiative inversion with wind speeds low enough that turbulence is minor. Surface temperature data and very limited sounding data both suggest that inversions become more intense and winds become lower away from the coastal areas and toward the mountain front. Conditions probably improve in the foothills, but no measurements are available. The very high CO levels observed at Garden Site, with far less source intensity than Benson and Spenard, tend to verify this: Garden Site is the only CO monitoring site between the Chugach Range and A Street. The tendency for pollution episodes to occur with geostrophic flow from the direction of the mountains strongly suggests that the shielding effect of the mountains may be very important in the development of the low wind speeds observed with high CO levels.

On the basis of this study the area most vulnerable to pollution from local sources (though not necessarily with the highest present levels) is that between the Seward Highway and the foothills of the Chugach Mountains. Particular care needs to be taken that source levels do not increase in this area, especially in the vicinity of Providence Hospital.

Forecasting of CO in Anchorage might be possible in a very limited way -- e.g., very low, moderate or moderately high probability of violation or alert levels. Such forecasting would be based on Weather Service capability and willingness to forecast wind and cloud cover for the entire peninsular area, rather than just the airport, when forecast geostrophic winds were easterly. An additional requirement would be access at the forecasting location to real-time CO data from a good monitoring station. Although our own forecasting attempts as part of the 1983 field season did not pick up any violations at the established sites, we did manage to identify in advance the day which provided the Tethersonde ascent with a substantial inversion, as well as get the principal investigator to Anchorage during a period with several high spikes of CO.

It is also worth pointing out that Anchorage, like Fairbanks, has a period in midwinter when ground-based "nocturnal" inversions can form regardless of time of day. As a result, the mixing volume available for daytime automotive emissions is far less than it would be 20° further south.

Details of both the vertical temperature structure and the wind field through the city are still unclear and need further study. However, the fundamental cause of the Anchorage problem, like that of Fairbanks, appears to be the short days and low sun angle in winter.

SECTION 5

MIXING HEIGHTS AND MODELING

INTRODUCTION

Modeling of air pollution levels is important both for estimating the effect of changing the pattern of sources and for determining critical meteorological factors. Most existing dispersion models were designed for situations where high pollution levels are due to high emissions with only moderately poor dispersion, and cannot be applied if wind speed or vertical dispersion is extremely low. Unfortunately the high-latitude pollution situation is generally one in which moderate quantities of pollutants are emitted into an atmosphere in which dispersion is extremely poor. In particular, vertical dispersion is normally much worse than the models can cope with. (Low wind speeds and the complexity of wind directions in the horizontal can also cause problems with standard models, but this is too large a problem to address in detail here.)

As it is still necessary to estimate the effects of new sources or changes intended to alleviate the effects of existing sources, standard models are, however, applied. Since the worst cases the models can handle are generally or the order of inversions around 1 to 2°C/100 m or mixing heights around 100 m, while observed inversion strengths in Fairbanks may easily be 10 to 30°C/100 m, it is hardly surprising that the predicted pollution levels do not agree with those observed. This is usually handled by "tuning" the models - adjusting parameters until the model gives the observed pollution level. Unfortunately this procedure cannot be used to obtain a model which responds correctly to a major change in source distribution.

The remainder of this chapter is concerned with measurements aimed at obtaining the physical parameters affecting vertical dispersion in the Fairbanks and Anchorage areas, and suggestions of ways in which existing models might be modified to allow more accurate computations of pollutant levels in high latitudes.

EFFECTS OF "TUNING" MODELS

Two simple cases should suffice to show some of the pitfalls of using heavily tuned models to evaluate the results of changing source fields. First, consider an area with good mixing up to 50 m, with an intense inversion at 50-m and an initial source which is primarily an area source. A model which can handle a 100-m mixing height as a worst case can be tuned to handle this situation fairly well by using a 100-m mixing height and doubling the emission rate. But what happens if the tuned model is used to evaluate the impact of a proposed point source with an effective stack height of 75-m? In reality, the strong inversion at 50-m would allow very little mixing to ground level. The modeled 100-m inversion, however, would give complete trapping of a doubled pollutant input.

A second tuning problem has to do with the practice of linking horizontal and vertical dispersion parameters in most models. This is examined in some detail in Appendix 1, and will be considered here only briefly. Going back to our area-source city, suppose we now have a model with horizontal and vertical dispersion parameters linked so that very low vertical dispersion implied a very uniform wind direction. In our real city, however, the variability of wind direction begins to increase as vertical dispersion becomes very poor. If measurements are made within the area covered by the area source, wind direction and its variability are not important, and the model can be tuned to handle the area source even though the variability of the wind direction is totally unrealistic. However, an elevated point source cannot be correctly handled in this case. If realistic vertical dispersion is used, the horizontal spread of the modeled average plume will be a few degrees, while the horizontal spread of the physical plume (averaged over several hours) will more likely be tens of degrees. This in turn will produce an order of magnitude error in the plume concentration. If the actual horizontal variability is used to set the dispersion and the source strength is increased to compensate for the unrealistic high vertical dispersion this produces, the degree to which the plume mixes down to the ground will be incorrectly modeled.

Given that most air pollution episodes at high latitudes do in fact occur when vertical dispersion is very poor (F or G stability or worse) while winds are light and very variable in direction, it is absolutely essential that any model used to evaluate the effects of a change in source distribution be capable of handling separate horizontal and vertical dispersion parameters. Furthermore, both horizontal and vertical dispersion used in such models should correspond as closely as possible to those actually occurring. Finally it must be recognized that the meteorology corresponding to that of the worst case with a change in sources may differ from that for the worst case with existing sources.

MEASUREMENTS OF FAIRBANKS MIXING HEIGHTS

It has been known for many years that Fairbanks ground-based inversions, measured outside the downtown area, are among the strongest in the world (Benson, 1965). However, there has been little or no information on the details of how the near-surface lapse rate is modified by the city heat island, although Bowling and Benson (1978) speculated that the mixing height in the core area was around 60 m. The State of Alaska made a Tethersonde system available to us for this study, and several pairs of ascents were made at Creamer's Field, upwind of Fairbanks, and at 5th and Lacy, a block south of the CO monitoring station (Figure 5-1). The three best sets of ascents were carried out in December 1981, covering three of the five days that month with 8-hour CO levels over 12 ppm, including both days over 13 ppm.

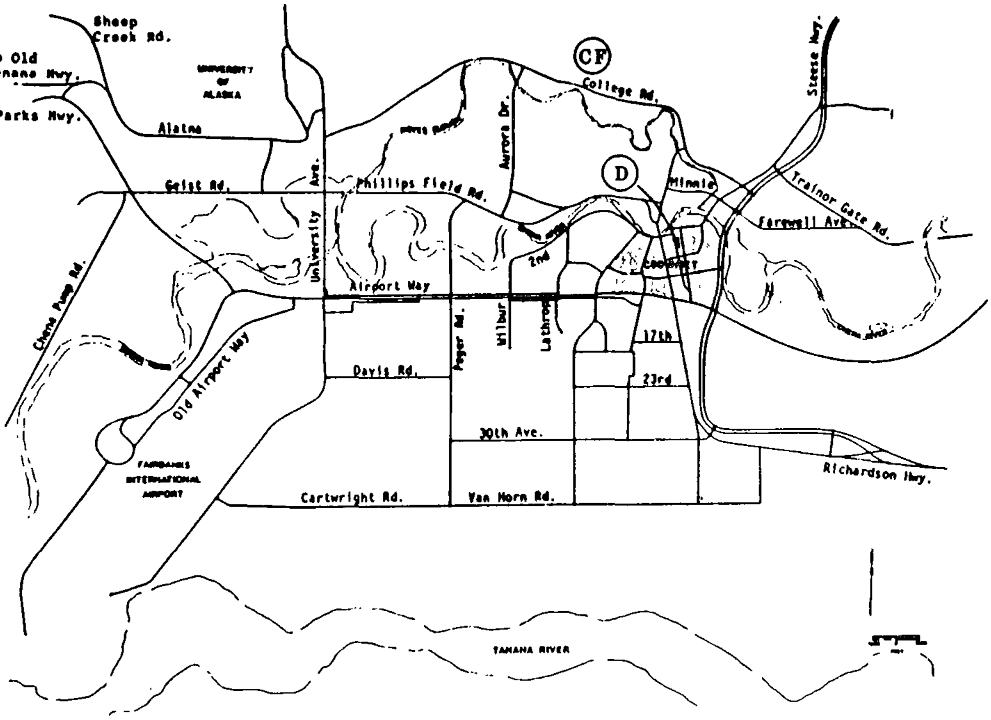

Figure 5-1. Main road net in Fairbanks. CF (Creamer's Field) is site of background ascent; D (downtown) is the city ascent location.

Hourly CO data around the time of the ascents are shown in Figure 5-2, and the ascents themselves are shown in Figures 5-3 through 5-5. If the isothermal part of the city sounding is taken to indicate the mixing height, then the measured mixing heights were 30 m on 15 December, 10 m on 22 December and 6 m on 23 December. While these values do not correlate well with the CO levels observed at the time of ascent, they do agree with the direction of change in the CO level observed at that time. The 30-m mixing height was measured as hourly mean CO dropped from 13.5 to 6.5, the 10-m height had CO holding nearly steady from 15 to 14 ppm, and the 6-m height corresponded to an increase from 8 to 12.5 ppm.

The mixing heights on the ascents for 22 and 23 December could also be defined as the heights where the city and background soundings meet, in which case the mixing heights are somewhere between 15 and 30 m for 22 December and close to 50-m for 23 December. However, these portions of the soundings include substantial inversions - up to 15°C/100 m. One explanation for these warmed but still inverted segments of the city soundings is that they represent partial mixing due to warm polluted air rising in contact with building walls coupled with slow sinking of the intervening relatively clear air. However, the upper part of the warming on 23 December, as well as the cooling from 45 - 95 m on 22 December, could be due to gravity waves in a strong inversion. In both cases, the observed temperature difference from background to city could be accounted for by 15-m vertical motion. Gravity waves of at least this amplitude have been documented in the Fairbanks area (Holmgren et al., 1975). The apparent warming between 30 and 50 m on 23 December could also represent a power plant plume, as the city power plant would have been upwind at that time and place. There are few buildings in Fairbanks exceeding 10 to 15 m in height, and the few taller buildings (up to 35 m) are clustered northwest of the measurement site.

Another method of estimating mixing height under very stable conditions is to identify the height of the low-level wind maximum (Arya, 1981). Again, the data suggest 30 m or less. In particular, there is a definite maximum of 1.4 m s^{-1} at 29 m on 23 December. December 22 shows a maximum wind speed of .4 m s^{-1} between 3 and 6 m, with wind speeds from 13 to 25 m being below the instrument threshold, again suggesting very little mixing above 6 m on this ascent.

The explanation offered here is that complete turnover and mixing, even in the city heat island, extended only to 6 to 30 m, the exact depth depending on the detailed structure of the lowest portion of the background inversion and on the time the air had spent in the city. Partial mixing due to warm air rising along building sides and wind-generated turbulence probably moved some pollutants up to 30 to 40 m, regardless of the overall mixing depth. It is unlikely that any substantial vertical mixing of pollutants above that level occurred.

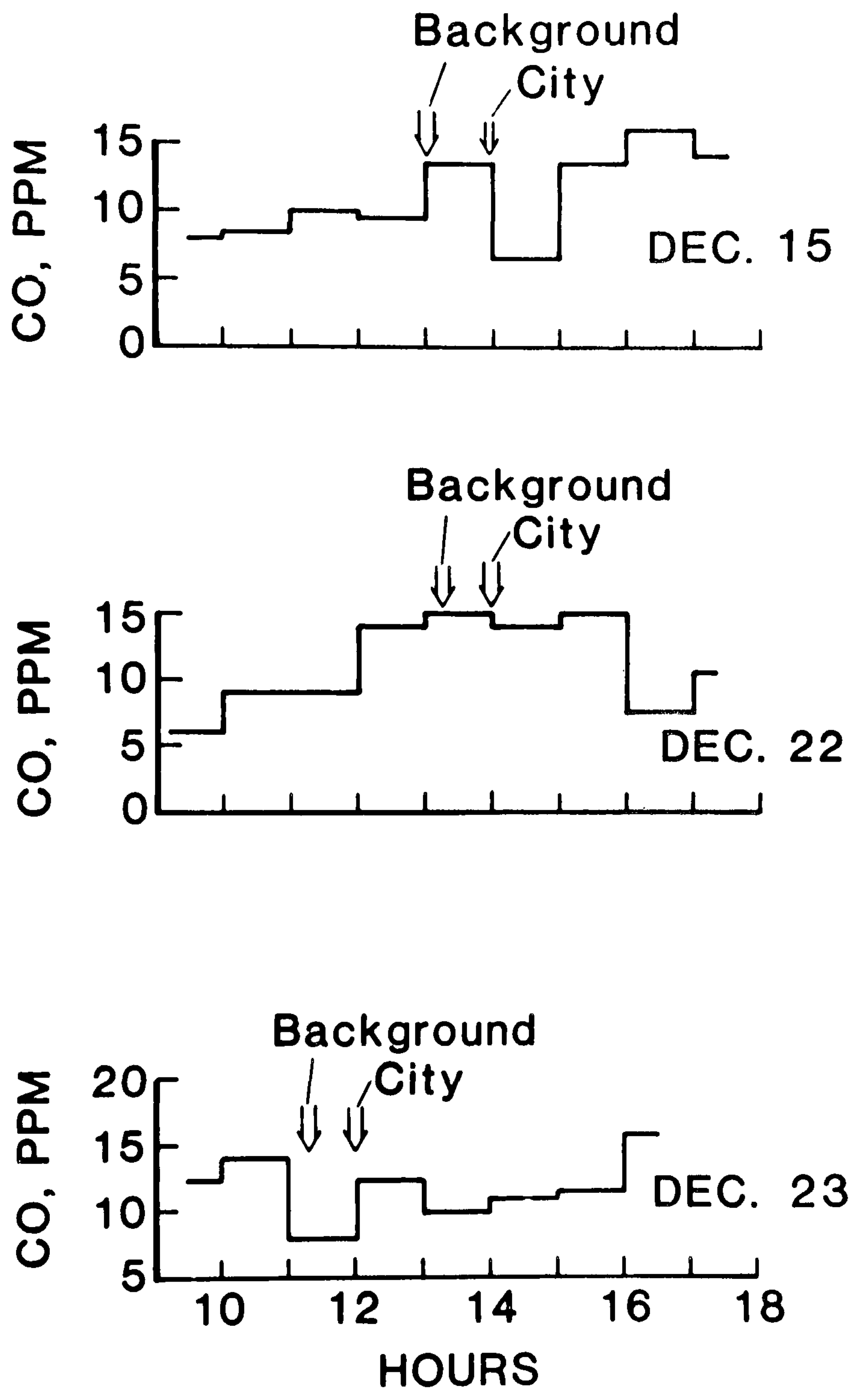

Figure 5-2. CO levels near the times of the three sets of ascents.

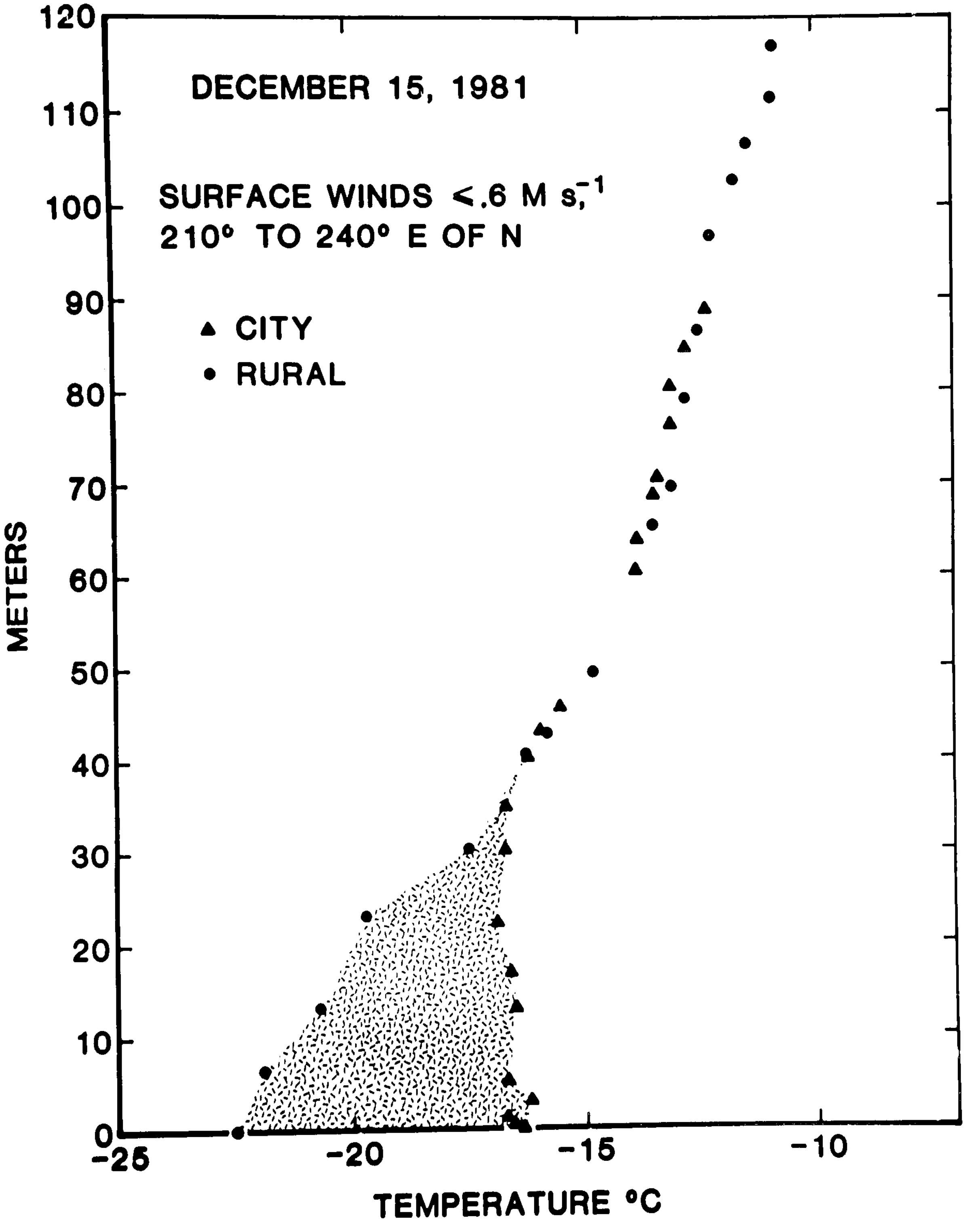

Figure 5-3. Background and downtown soundings, 15 December 1981.

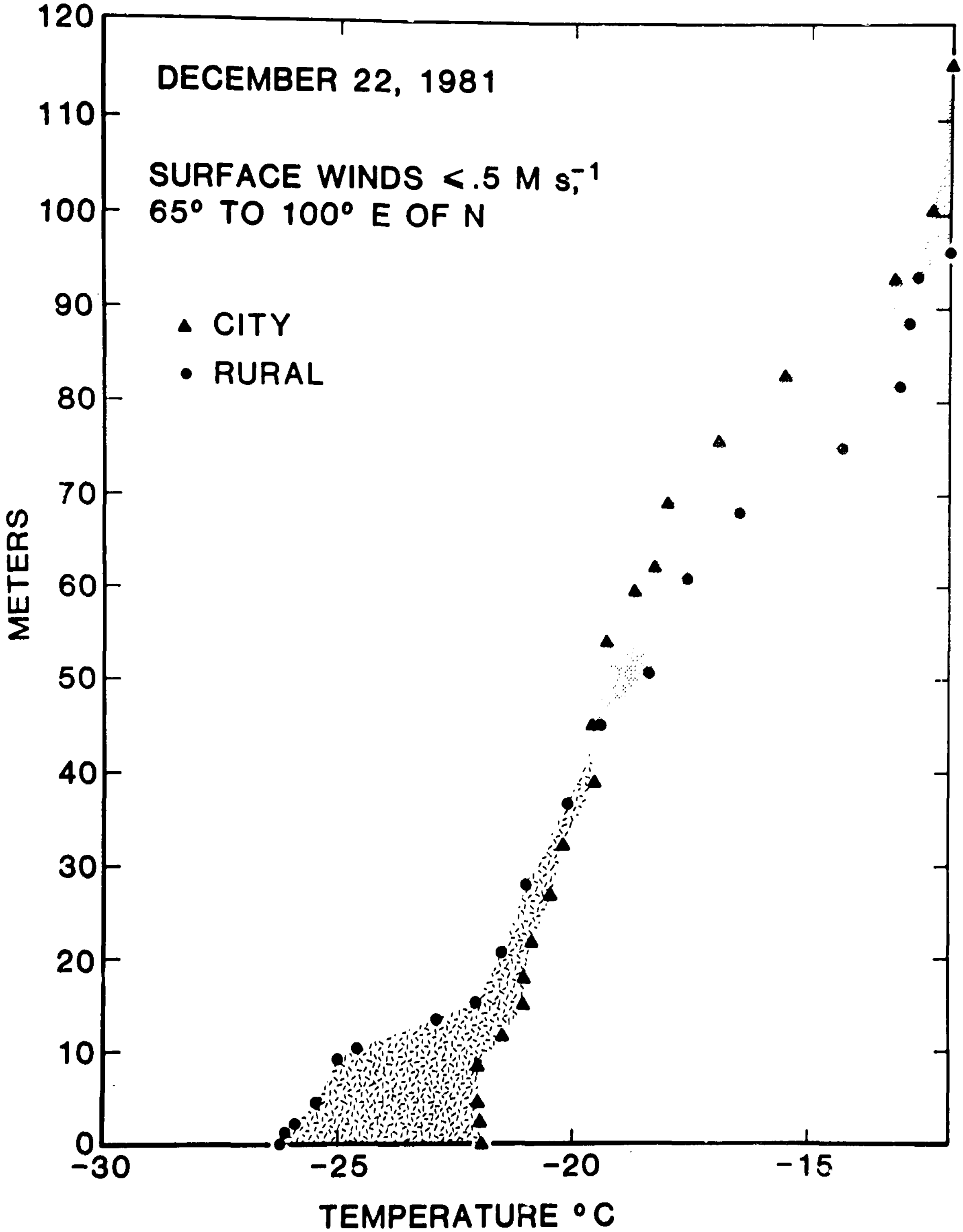

Figure 5-4. Background and downtown soundings, 22 December 1981. Different shade patterns show city site warmer or colder than rural site.

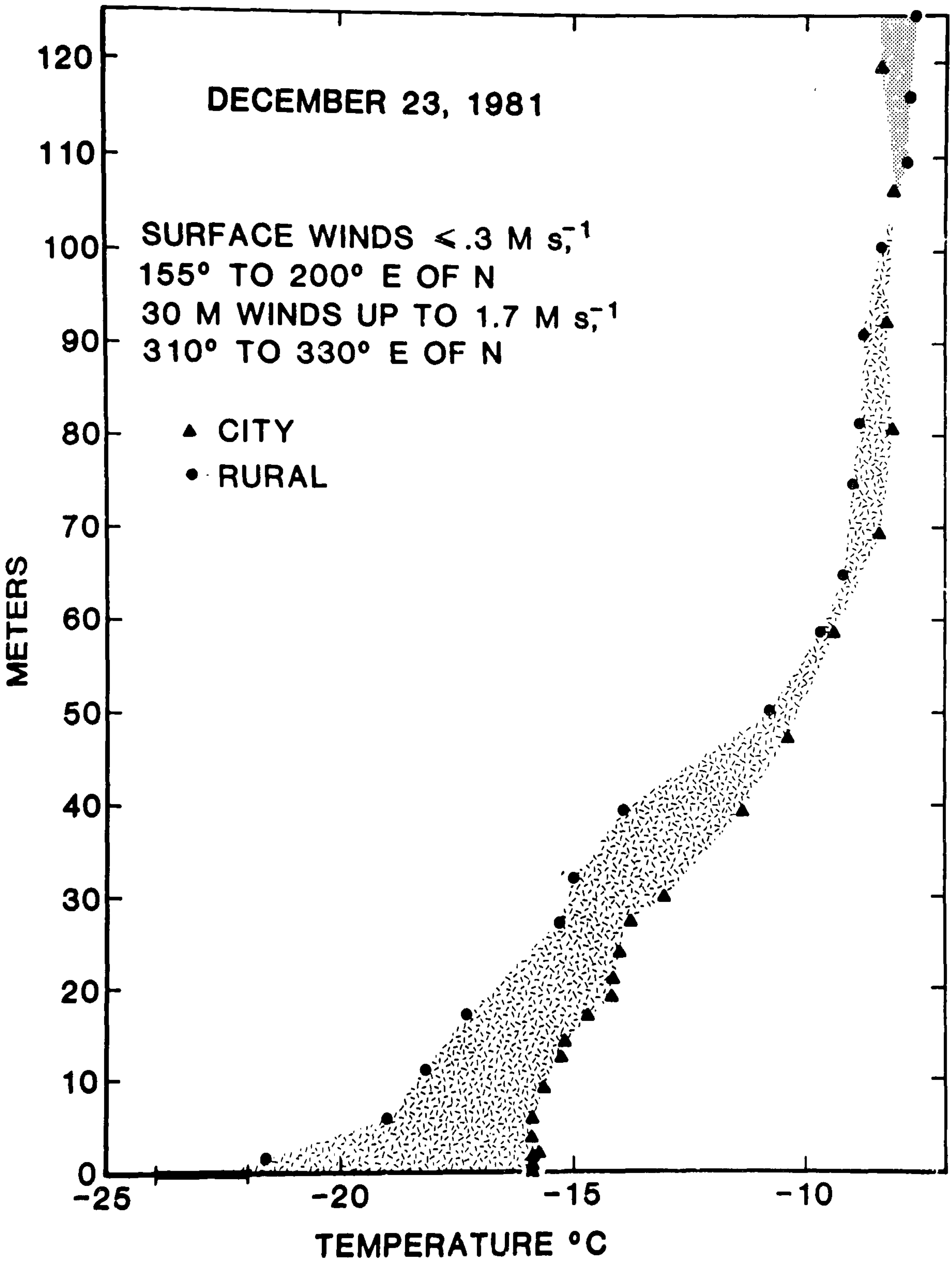

Figure 5-5. Background and downtown soundings, 23 December 1981.

These measurements do not represent worst-case conditions. All of the three cases had background inversions of 5°C or more in the first 35 m (15°C/100 m) and fairly high CO levels, but stronger background inversions (Bowling, 1967), and higher CO levels are known to occur in the Fairbanks area. Observations along the Steese Expressway in the southeast part of Fairbanks show clear layering of smoke at heights of 10-12 m to be common in winter. All things considered, 10 meters should probably be considered a maximum mixing height for a worst-case simulation of pollution from near-surface sources in the Fairbanks area, and worst-case wind speeds should be modeled at .5 m s^{-1} or less. The variability of surface wind directions is well illustrated in Figures 5-3 through 5-5 - the range of values in each figure occurred within about 5 minutes. Worst case analyses for elevated sources should assume a mixing height just above the effective stack height.

Further discussion of the effect of city heating on mixing height is found in Appendix 2.

ANCHORAGE MIXING HEIGHTS

Understanding of the appropriate parameters for modeling the Anchorage situation is not as satisfactory as is the case for Fairbanks. This is in part due to the fact that much more was known about Fairbanks than Anchorage at the beginning of the study, in part due to equipment problems, and in part due to the contribution of local topography, including Cook Inlet, to the complexity of the Anchorage situation. The tower measurements of winds and inversions recommended in Section 4 are badly needed as input for modeling. Interim worst case values should be based on the Fairbanks situation - partial mixing to building heights (much higher in Anchorage than Fairbanks), complete mixing to 10 m, wind speeds .5 to 1 m sec^{-1}. Further Tethersonde measurements are urgently needed in Anchorage.

CONCLUSIONS

Input values for modeling worst-case dispersion in either Fairbanks or Anchorage should not exceed 10-m mixing height or .5 to 1 m sec^{-1} winds. Horizontal and vertical dispersion must be separated, as the worst-case situation generally involves A horizontal and G vertical dispersion classes. The wind fields in both cities are complex, and modeling over the full area should be done with models capable of handling differences in wind vectors of 180° over distances of as little as 20 m vertically or a few hundred meters horizontally.

SECTION 6

SUMMARY AND CONCLUSIONS

CONCLUSIONS

The Anchorage CO problem, like that in Fairbanks, is due to nocturnal inversion conditions persisting through the hours of maximum automotive emissions. The high CO emissions characteristic of cold starts undoubtedly add to the problem, and encouraging the preheating of engines at temperatures above -20°C could have beneficial effects in reducing emissions. Emission control strategies in use at lower latitudes would also help by reducing emissions from warm vehicles and possibly reducing the number of cars operating. In contrast to the common correlation of nocturnal inversions with anticyclonic conditions (as is the case in Fairbanks), Anchorage CO episodes occur due to shielding of the city by the adjacent mountain front. All but two CO episodes were found to occur with a substantial pressure gradient between an anticyclone to the north and a cyclone to the south. Blockage of the resulting easterly geostrophic winds by the Chugach Range (which forms an abrupt front east-southeast of Anchorage) can lead to stagnation conditions over the city. There is good evidence that inversions are better developed near the mountain front than along the coast, and that winds are often lighter near the mountains as well. Thus the potential for high CO levels, if not the actual current levels, may be worst just west of the mountain front.

The two exceptional cases occurred with dissipating low pressure systems located directly over Anchorage. Thin or high clouds with essentially zero pressure gradients seem to be responsible for the poor dispersion in these cases.

Coupling of horizontal and vertical dispersion within the model is known to cause problems with the use of Gaussian plume-based models in nocturnal inversion conditions, and this problem extends to any use of such models at high latitudes. The "split-sigma" approach of Sagendorf and Dickson (1974) is essential for model applications in Anchorage and Fairbanks. In addition, vertical stability categories must be based on solar elevation angle rather than time after sunrise. There is good evidence that nocturnal conditions may persist as much as 3 hours after sunrise at high latitudes.

Mixing heights were measured directly in downtown Fairbanks, and found to be as low as 6 meters. Ten meters is probably a generous estimate for a worst-case mixing height in Fairbanks, and should be used in Anchorage until better measurements can be made.

Any serious modeling of the effect of changing source distributions in the Anchorage area must take account of the complex and, at this point, very poorly understood wind field. A program of meteorological tower measurements, in conjunction with further tethered balloon observations, is urgently needed in Anchorage.

There is evidence that fumigation-type conditions can occur summer or winter within the larger upper Cook Inlet basin. This needs to be considered if development of the north and west shores of Cook Inlet is contemplated, as the entire inner basin may act as a single airshed.

The Fairbanks forecasting scheme, although showing some skill and offering a definite improvement over either pure meteorological dispersion or pure persistence-based forecasts, is not forecasting the most severe CO episodes. Meteorological features associated with 8-hour CO levels in excess of 15 ppm include relatively high winds at the airport with calm conditions in downtown Fairbanks, low-level warm air advection, and detailed coincidence of poor dispersion conditions with emission peaks. Several striking examples of the last condition occurred in February, when the nocturnal inversion, although broken during midday, was re-established by the time of the 5 pm emissions peak. The single factor which would probably do most to improve forecasts is better communication between the Fairbanks North Star Borough CO forecaster and the local office of the NOAA Weather Service (which prepares the dispersion forecasts). At present the dispersion forecasts are prepared without benefit of CO data, and the Weather Service is not getting CO feedback to validate these forecasts. The Borough forecaster, on the other hand, receives dispersion forecasts which vary enormously in completeness - ranging from a one-word dispersion forecast and a copy of the latest airport sounding to a detailed discussion of how weather and dispersion are expected to change through the next 24 hours. Both parties would benefit by closer interaction.

A probability-based forecasting scheme for Anchorage could probably be set up with existing data. Such forecasting would require real-time access to CO data (not presently available in Anchorage) and full cooperation from the local NOAA Weather Service Forecasting Center.

RECOMMENDATIONS

1. An observational micrometeorological program should be carried out in Anchorage to clarify the wind field and the local variation in inversion strengths. The program should include 15-m towers at each CO monitoring site, along an east-west traverse across the city, and at least one tower each in a drainage channel and on a local ridge. Measurements should include wind and temperature at 2, 8 and 15 m, and modern data-logging techniques should be used.

2. Any attempt to develop an adequate air pollution model for Anchorage would require the data from 1, above. As an interim recommendation, a 10-m mixing layer and wind speed of 0.5 m sec^{-1} should be used for worst-case modeling of surface sources. Models used should separate horizontal and vertical dispersion, and solar elevation angle rather than

time relative to sunrise or sunset should be used to estimate vertical dispersion.

3. Communications between the Fairbanks North Star Borough and the NOAA Weather Service must be strengthened if alert levels of CO are to be forecast for Fairbanks with any degree of accuracy. Similar communication lines in Anchorage should be assured as an initial condition of any possible forecasting effort there.

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APPENDIX 1

MODIFICATIONS NECESSARY TO USE STANDARD DISPERSION MODELS AT HIGH LATITUDES*

It has long been recognized that Gaussian-plume models with plume spreads based on semi-empirical stability categories do not apply to conditions of very low wind speeds (< 1 m sec^{-1}). Nevertheless, regulatory agencies may require application of such models, even in areas such as Alaska where it is recognized that many, if not most, violations occur under conditions which the models cannot handle. It is the purpose of this contribution to examine the approximations behind these models and their associated dispersion criteria, to point out those that conflict with observed meteorological conditions and to suggest modifications to these assumptions which would improve the utility of these models under conditions of strong inversions and very light winds.

The fundamental physical assumptions behind Gaussian models can be illustrated by the release at a point x=0, y=0, $z=z_0$ of successive puffs of a pollutant into a wind field $\vec{V}(x, y, z, t)$. For the moment we assume that the puff density matches that of the surrounding air, and the vertical velocity at release = 0. A single puff will follow a trajectory of the $\vec{V}$ field, with some spreading due both to molecular diffusion and the fact that if the initial puff has non-zero dimensions its component subregions will follow slightly different trajectories. If the concentration as a function of x, y, z at a time t after each puff is calculated for a very large number of puffs and the results averaged, the general appearance will be that of a puff traveling with the mean wind $\overline{\vec{V}}$ and spreading in the x, y, and z directions with the turbulent fluctuations of $\overline{\vec{V}}$; $\vec{v}' = \vec{V}-\overline{\vec{V}}$. If the coordinate system is oriented so that the mean wind direction is along the x axis, the mean position of the center of the puff at time t will be

*to be published in Atmospheric Environment given by ($\bar{v}_x t$, 0, z_0) and the magnitude of the spread in the x, y and z directions will be determined by the distribution of magnitudes of v'_x, v_y' and v_z'. The distribution of pollutant concentration along any axis from the point ($\bar{v}_x t$, 0, z_0) is normally assumed to be proportional to the Gaussian distribution, $\sqrt{2\pi\sigma_i} \exp [-\frac{1}{2} \frac{x_i - x_i}{\sigma}^2]$. Thus far, there is no obvious reason why the theory should not apply to very small values of $\bar{v}_x$.

If the release of a pollutant is continuous, the time-averaged concentration at a given point is the integrated total of contributions of puffs released at all times from $t = -\infty$ to $t = 0$. At this point an approximation is normally made which implicitly assumes that $v_x' < \bar{v}_x$: mixing in the x direction is ignored on the assumption that the variation in pollutant concentrations between parcels which might be exchanged along the x axis is negligible. However, this assumption does not always hold under clear-night, radiative-inversion conditions, as indicated by measured extreme-to-extreme variations in wind direction in excess of 180° (Fahl, 1969). In this case $v_x' > \bar{v}_x$, and non-negligible pollutant concentrations may occur "upwind" of the source. This particular assumption is too deeply rooted in conventional Gaussian-plume models to be removed without completely redoing the models and will cause problems with upwind concentration modeling whenever the mean amplitude of v_x' equals or exceeds $\bar{v}_x$.

Widely-used Gaussian-plume models such as the HIWAY and CALINE models make another assumption which can be expected to cause significant errors under conditions of low wind speed: horizontal and vertical dispersion are assumed to be under the control of the same dispersion parameters. The σ_i in the Gaussian distribution above is a measure of how far the plume has spread horizontally (σ_y) or vertically (σ_z) and is a function of the v_y' (or v_z') values and the time since the plume element left the stack: effectively, $t = x/\bar{v}_x$. If the σ's are tabulated as functions of distance, then the σ_i for a particular distance is effectively a function of $v_i'/\bar{v}_x$. For small $\bar{v}_x$ and high stability, $v_y'/\bar{v}_x$ may become large (approaching or exceeding 1) while v_z'/v_x remains small due to the suppression of vertical motion by strong inversions. Thus the horizontal dispersion which is indicated by σ_y, as defined by the variation of wind direction, may be quite large, while vertical dispersion, measured by σ_z, is very small. In theory, a significant improvement in the performance of Gaussian-plume models under conditions of low wind speed and high static stability could be obtained with minimal effort simply by changing the routine for obtaining σ_y and σ_z to allow input of separate dispersion classifications for horizontal and vertical diffusion. This "split sigma" approach has been tested under inversion conditions by Sagendorf and Dickson (1975) and found to produce a significant improvement in predicted concentrations from a point source.

Attempts have been made in the past to get around these problems by "tuning" existing models: i.e., by adjusting input parameters until the predicted and observed pollutant concentrations agree. It cannot be over-emphasized that tuning cannot substitute for the split sigma approach if both point and area sources, or line sources both parallel and perpendicular to the mean wind, are present (Bowling, 1984b). Diffusion from point sources or line sources parallel to the wind is strongly affected by horizontal meander - in fact, since σ_y normally exceeds σ_z when dispersion is poor, (Sagendorf and Dickson, 1975) the horizontal dispersion is the dominant control on concentration. Diffusion from area sources or line sources perpendicular to the wind, however, is negligibly affected by horizontal diffusion if the target point is located within the area or substantially closer to the line source than the line source length. The effect of vertical stability is roughly the same for area and point sources. If a real situation has a horizontal dispersion corresponding to category A (extremely unstable - $\sigma_\theta > 25°$) and a vertical dispersion corresponding to category G (extremely stable - $\Delta T/\Delta z > 4°C/100$ m) any attempt to apply a single stability class in modeling will over-estimate the importance of point sources relative to area sources. Such data as are available for Fairbanks, Alaska suggest that the A-G combination above is by no means an exaggeration, and in fact area sources appear to dominate the air pollution distribution in Fairbanks. Recent paired urban and rural measurements there have documented rural inversions of 10°C/100 m with urban mixing heights of 10 m and urban wind speeds of 0.5 m sec^{-1}, with directional fluctuations over a range of 40° (Bowling, 1984a).

An additional assumption in Gaussian models in that the dispersion categories and $\overline{v}_x$ are independent of the space and time coordinates. This is certainly not true in the vertical: 180° wind shears over heights of a few hundred or even tens of meters are common in Fairbanks (e.g. Holmgren et al., 1975), and long-term shears of similar magnitude can occur over a horizontal distance of less than a kilometer (Bowling and Benson, 1978). The effect of such variation with z is partially offset by the fact that the lack of momentum transfer necessary for the development of large vertical wind shear implies also the lack of vertical pollutant transfer through the shear, but the horizontal variability remains a serious problem in modeling.

The actual assignment of horizontal and vertical dispersion criteria at high latitudes is also subject to some problems. Table 1 summarizes several criteria for Pasquill and Turner stabilities and their relationships and is based on Sagendorf and Dickson (1975) and Gifford (1976).

TABLE 1

DEFINITION OF STABILITY CATEGORIES

Classification	Pasquill	Turner	Slade: σ_Θ (degrees)	$\Delta T/\Delta z$ (°C/100 m)
Extremely unstable	A	1	25	-1.9
Moderately unstable	B	2	20	-1.9 to -1.7
Slightly unstable	C	3	15	-1.7 to -1.5
Neutral	D	4	10	-1.5 to -0.5
Slightly stable	E	5*	5	-0.5 to 1.5
Moderately stable	F	6*	2.5	1.5 to 4
Extremely stable	G	7*	1.7	>4

*The relationship between these categories and the Pasquill categories is in some doubt; this relationship is the one used implicitly by Doty and Holzworth (1976).

The standard deviation of wind direction (σ_Θ) should be used to obtain σ_y. Unfortunately, σ_Θ is not generally available from standard meteorological data, although Doppler radar wind printouts may include σ_Θ as a derived number. Such data as are available from Fairbanks suggest that σ_Θ values may significantly exceed 25° under near-calm conditions. It is possible that horizontal dispersion at specific sites might prove to be closely related to a combination of vertical stability and wind speed, but this has not yet been investigated and any relationship would probably be site specific.

Actual lapse rates are rarely available at the times and places where they are most needed for pollutant modeling, so the vertical stability category is normally estimated from a combination of sky cover and cloud height, wind speed, and solar elevation angle. Standard schemes (e.g., Doty and Holzworth, 1976) also involve a distinction between day and night based on time (one hour after sunrise and one hour before sunset). Physically, the distinction between day-unstable and night-stable conditions lies in whether the absorbed solar radiation is greater than or less than the net outgoing longwave radiation. Ignoring long-wave differences, this means the physical dependence is on albedo, solar elevation and cloud conditions. As shown by Figure 1, one hour after sunrise corresponds to greatly differing solar elevations at different latitudes, especially as the latitude exceeds 50°. Consequently, use of the standard tables can assign C or even B stability to cases with lapse rates typical of G stability - at Fairbanks, for instance, the sun at winter solstice is less than 2° above the horizon at solar noon, almost 2 hours after sunrise, and the daily temperature maximum is most likely to occur at midnight.

In an attempt to correct this problem, we drew up the following modification of vertical stability calculation based on the instructions given in Doty and Holzworth (1976):

(1) If the total cloud cover is 10/10 and the ceiling is less than 2000 m (7000 ft) set the net radiation index = 0 if the solar elevation angle is greater than 6° and equal to - $^1/_2$ if the solar elevation angle is less than 6°. Go to step 5.

(2) Use Table 2 to determine the insolation class. (Solar elevation > 60° gives class number 4). For any particular latitude and longitude, a chart can be drawn up giving the solar elevation angle as a function of time of day and date, as has been done for Anchorage (150°W, 61° 10'N) in Figure 2.

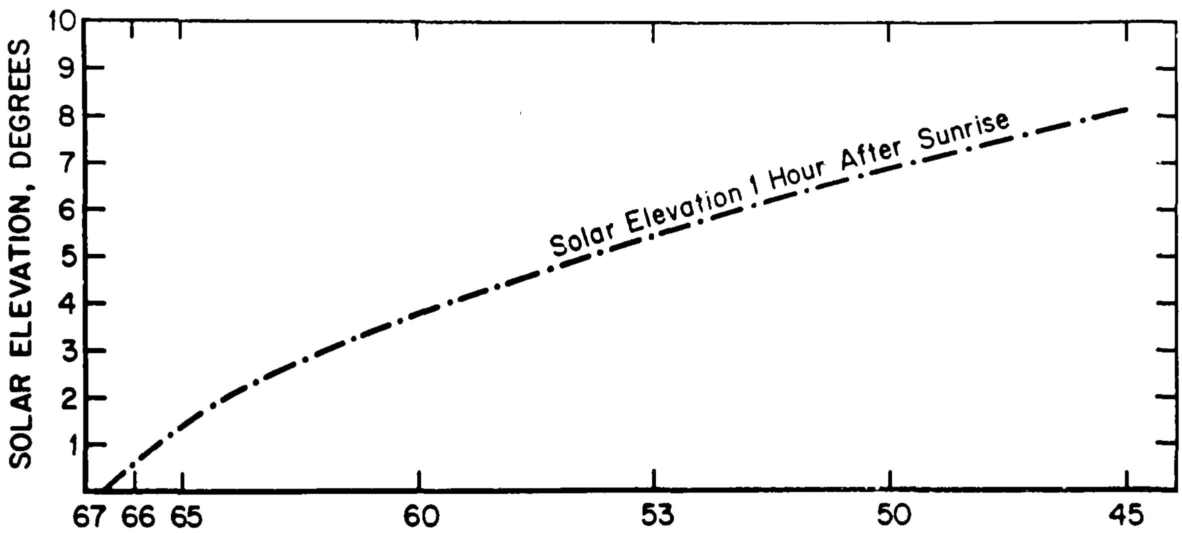

Figure 1. Dependence on latitude of solar elevation one hour after sunrise at the winter solstice for high latitudes. The equinox value at Los Angeles is about 12°, which is also the value assumed in the practical definition of civil twilight (1/2 hour after sunset or solar depression of 6°).

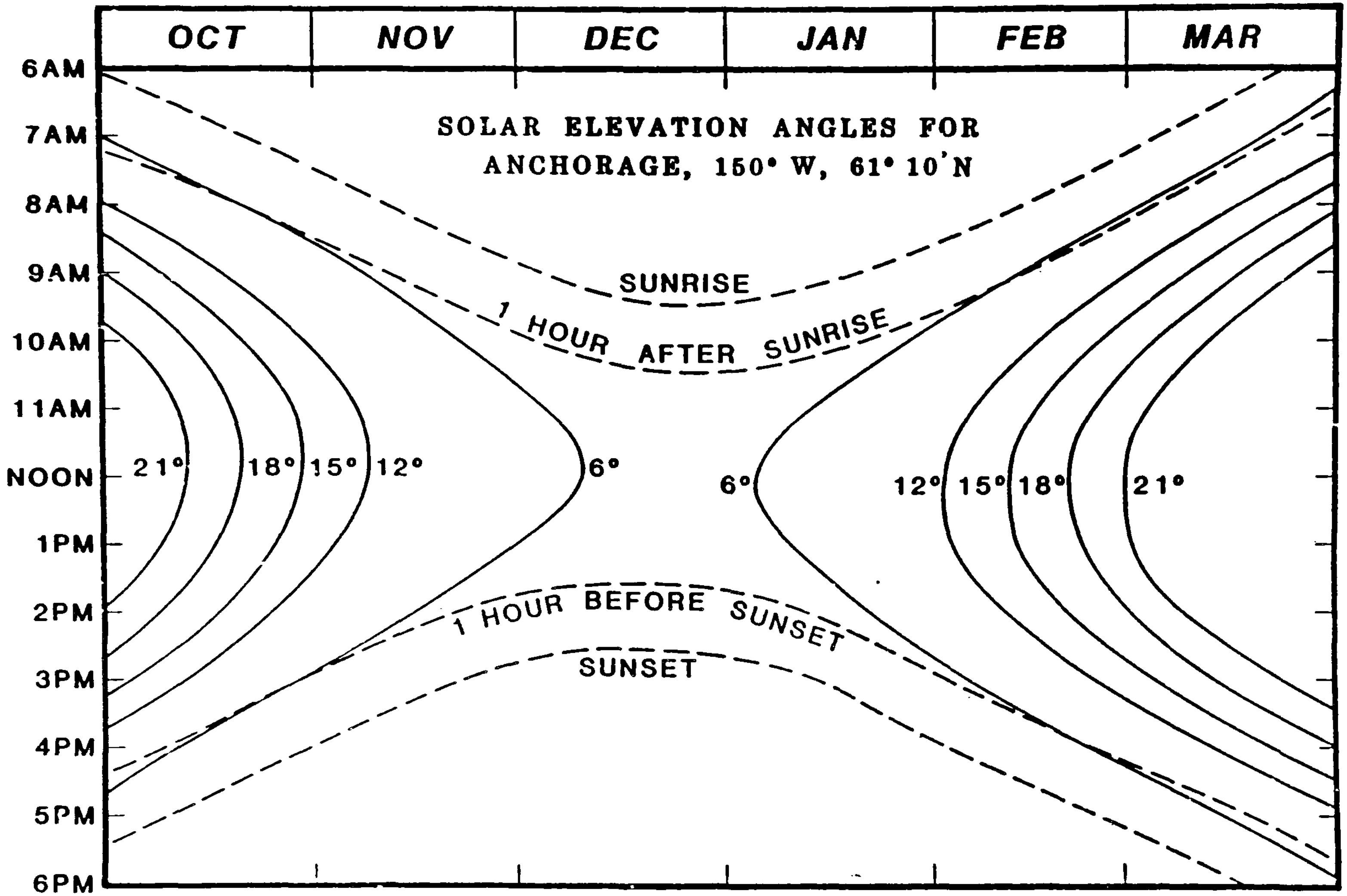

Figure 2. Solar elevation angles, sunrise and sunset for Anchorage, Alaska, as a function of time and date. The conventional day-night boundary for dispersion classification is shown, dashed, for comparison; a working chart would have only the solid lines.

TABLE 2

INSOLATION CLASS DETERMINATION

Solar Elevation Angle	> 35°	35	21	18	15	12	6	< 6
Bare ground	+3		+2	+2	+2	+1	N/2	night
Snow patchy or < 6" deep	+3		+2	+2	+1	N/2	night	night
Snow cover 6" or more	+2		+2	+1	N/2	night	night	night

(3) If the category is "night", use a net radiation index of -3 if skies are clear, -2 if the cloud cover is between 0.1 and 0.4, and -1 if the cloud cover is 0.5 or more. Divide these values by 2 for "N/2". Go to step 5.

(4) For daytime:

a. If the cloud cover is less than .5, the net radiation index equals the insolation class. Go to step 5.

b. If the cloud cover is greater than .5, modify the insolation class number by following the steps below:

(1) Ceiling < 2000 m (7000 ft) subtract 2.

(2) Ceiling between 2000 m and 5000 m (16,000 ft) subtract 1.

(3) Cloud cover = 1, subtract 1.

(4) The net radiation index is equal to the modified insolation class number or to 1, whichever is greater.

(5) Use Table 3 to find the vertical stability class.

TABLE 3

DETERMINATION OF STABILITY CATEGORY

Wind Speed m sec^{-1}	mph	Knots	Net Radiation Index 4	3	2	1	0	$-^1/2$	-1	$-1^1/2$	-2	-3
0 - .5	0, 1	0, 1	A	A	B	C	D	E	F	F	G	H
1	2, 3	2, 3	A	B	B	C	D	E	F	F	G	G
2	4, 5	4, 5	A	B	C	D	D	D	E	F	F	G
3	6, 7	6	B	B	C	D	D	D	E	E	F	F
3.5	8	7	B	B	C	D	D	D	D	E	E	E
4	9,10	8, 9	B	C	C	D	D	D	D	D	E	E
5	11	10	C	C	D	D	D	D	D	D	E	E
5.5	12	11	C	C	D	D	D	D	D	D	D	D
6	>13	>12	C	D	D	D	D	D	D	D	D	D

This scheme is essentially identical to the Doty and Holzworth (1976) scheme (hereinafter referred to as DH) for the contiguous U.S. in summer and all but the northern tier of states in winter. The only differences are the addition of a brief transition period between night-stable and day-unstable regimes, allowance for the effect of snow cover on solar heating, and addition of one more stability category, "H", tentatively equated to $\Delta T/\Delta z$ of more than 10°C/100m. At high latitudes in winter, however, the present scheme and DH differ spectacularly. DH predicts that the time interval between the lines labeled "1 hour after sunrise" and "1 hour before unset" in Figure 2 will have neutral to unstable stability. Plowed streets and general grime put Anchorage into the patchy snow category, so the modified procedure allows <u>no</u> unstable conditions in November, December or January. Average hourly CO values in these months do not show a midday decline beyond the traffic-related dropoff between 8 am and 10 am, while February hourly means show a definite mid-day minimum in CO concentration (Bowling, 1984b).

Additional comparisons of both schemes have been made with individual Anchorage hourly CO levels. The results are:

(1) When observed CO concentrations were normalized to January hourly values for a 2 1/2 month period in 1979-80, all three periods with CO levels six standard deviations or more above normal were associated with "H" stability, as were well over half of the periods with CO concentrations 3σ or more above normal.

(2) No tendency toward a mid-day minimum of CO was observed before February 13, although DH predicted several hours a day of "B" stability. On February 13 the modified scheme for the first time predicted "B" stability ("H" stability overnight) and a midday drop in CO became apparent and persisted through the rest of February.

(3) During a 1-day period from 14 through 24 December 1982, inversions persisted at the airport with no systematic difference in stability between 2 am and 2 pm soundings. Thus far, no case in which the DH and modified schemes predict significantly different dispersion conditions has been found in which the modified scheme has not been more accurate. Further testing is needed, especially for the deep-snow case, but the superiority to DH at high latitudes in winter seems clearly established. "H" stability, tentatively equated to $\Delta T/_{\Delta z}$ of more than 10°C/100 m, does not appear in most tables; but, with the separation of horizontal and vertical dispersion, it should be possible to incorporate G and H stabilities into existing models.

In closing, we wish to reemphasize the importance of separating horizontal and vertical dispersion parameters rather than tuning a coupled model against observed conditions. Tuning can be expected to work only if the geometrical properties of the sources remain unchanged. A model tuned with area sources dominating which is based on linked horizontal and vertical dispersion parameters cannot predict the result of a source change which involves expansion of an area source to surround a measurement point or the addition of one or more major point sources or line sources parallel to the mean wind. Use of models for such purposes at high latitudes requires split-sigma models.

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APPENDIX 2

THE INFLUENCE OF THE FORM OF THE TEMPERATURE SOUNDING ON THE DEPTH OF THE MIXING LAYER PRODUCED OVER A CITY *

I. Introduction

Waste heat (which ultimately includes almost all of the energy used by mankind) is in the long term a major limiting factor to energy growth. In the short term, middle to high latitude cities in winter already release as waste heat amounts of energy comparable to or even greater than that received by these cities from the sun. The result is a noticeable disturbance of the natural lapse rate in the vicinity of a city - a disturbance which may profoundly influence both local temperatures and the mixing of pollutants when the natural lapse rate is stable.

When stable air flows over a warm surface, such as a city whose roughness is comparable with that of its surroundings, the resultant heating can be described in two ways: the temperature near the ground rises, and a mixing layer develops in the otherwise stable air. The first effect has been expressed in an empirical heat island formula by Ludwig (1970) and in the theoretical treatment by Summers (1965). The second effect is important for dispersion of air pollution and has been studied by Leahey and Friend (1971), among others. The purpose of this paper is to point out the importance of the nature of the background inversion on the depth of the mixing layer and the strength of the heat island developed. (See also Bowling and Benson, 1978).

2. Development of the Model

Assume that air which initially has a potential temperature $\theta(z,0)$ which increases with height (z) is flowing with speed v(y) independent of height over a uniform surface. As we are considering only a shallow layer

*submitted to Atmosphere-Ocean

of air (< 1 km) we will use the approximate equation

$\frac{d\theta}{dz} = \frac{dT}{dz} + \Gamma$, where Γ is the adiabatic lapse rate, 1°C (100 m)$^{-1}$, the lapse rate being defined as $-\frac{dT}{dz}$. The coordinate along a trajectory is y. Over some part of the surface, sensible heat is transferred to the air from the surface at a rate q(y) expressed in energy per unit area per unit time. The total energy which will have been added to a column with a unit basal area by the time it reaches the coordinate y' is

$$Q(y') = \int_0^{y'} \frac{q(y)}{|v(y)|} dy. \tag{1}$$

This energy is assumed to heat the air column by development of an adiabatic lapse rate working up from the base of the sounding (Summers, 1965). The potential temperature profile at point y' is then assumed to be

$$\begin{aligned} \theta(z,y') &= \theta(Z,0) \qquad (0 < z < Z) \\ \theta(z,y') &= \theta(z,0) \qquad (z > Z) \end{aligned} \tag{2}$$

where Z = Z(y') is the depth of the mixing layer, and $\Delta T = \theta(Z,0) - \theta(0,0)$ is the intensity of the heat island (the amount of rise in surface temperature) at point y'.

Sensible heating of a unit volume of the air is given by $c_p \rho \Delta\theta$, where ρ is the air density and c_p is the specific heat of air, so the total energy required to develop an adiabatic layer of depth Z by adding an amount of heat Q(y') is

$$Q(y') = \int_0^Z c_p \, \rho \left[\theta(Z,0) - \theta(z,o) \right] dz \qquad (3a)$$

or, provided Z is small enough that the variation in ρ with height may be neglected,

$$\frac{Q(y')}{c_p\rho} = G\,(y') = \int_0^Z \left[\theta(Z,0) - \theta(z,0) \right] dz \qquad (3b)$$

Once $\theta(z,0)$ is specified, (3b) may be solved analytically or numerically to obtain $Z(y')$ and thence $\Delta T(y')$ as functions of $G(y')$ and $\theta(z,0)$.

Note that G, which is the change in temperature integrated over height, is proportional to the total heat energy transferred through the base of the air column. The maximum value of G, which has units of length temperature, will vary with city size, energy use patterns, wind speed and air density. For Fairbanks, Alaska with population 45,000 and wind speeds of the order of 1 m sec^{-1} or less, G at the city center is believed to be of the order of 200 to 250 m K (meters-degrees Kelvin) (Bowling and Benson, 1978). Three sets of low-level soundings outside of Fairbanks and near (but not at) the city center gave values from 45 m K to 120 m K (Bowling, 1984).

To demonstrate the effect of the form of $\theta(z,0)$ on both Z and ΔT, three initial soundings with the same potential temperature θ_0 at ground level and the same value of $\theta(100,0)$, differing from θ_0, at 100 m will be considered: a constant lapse rate profile, a capping inversion and a logarithmic inversion.

The temperature-height equations for the three cases and their approximate potential temperature equivalents are: for the constant lapse rate

$$T(z,0) = T_0 - \gamma z \;(\gamma = \text{lapse rate} = \frac{-dT}{dz}) \qquad (4a)$$

or

$$\theta(z,0) = \theta_0 + \beta z \ (\beta = \Gamma - \gamma; \ \ \Gamma = \text{adiabatic lapse rate}); \qquad (4b)$$

for the capping inversion

$$T(z,0) = T_0 - \gamma_1 z \qquad (0 \leq z \leq z_1)$$

$$T(z,0) = T_0 - \gamma_1 z_1 - \gamma_2(z-z_1) \qquad (z_1 \leq z \leq z_2) \qquad (5a)$$

where γ_1 is the lapse rate in the weakly stable or neutral air below the capping inversion, γ_2 is the lapse rate in the capping inversion, and z_1 and z_2 are the heights of the base and top of the capping inversion. The sounding is not defined here for $z > z_2$. The potential temperature form is

$$\theta(z,0) = \theta_0 + \beta_1 z \qquad (0 \leq z \leq z_2)$$

$$\theta(z,0) = \theta_0 + \beta_1 z_1 + \beta_2 (z-z_1) \qquad (z_1 \leq z \leq z_2) \qquad (5b)$$

the β's being defined as in (4b).

Finally, the logarithmic inversion is given by

$$T(z,0) = T_0 - \Gamma z + ab \ \ell n \ (1 + \frac{z}{b}) \qquad (6a)$$

or

$$\theta(z,0) = \theta_0 + ab \ \ell n \ (1 + \frac{z}{b}). \qquad (6b)$$

Here $a = \frac{d\theta}{dz} = \frac{dT}{dz} + \Gamma$ at $z = 0$, and b is the height at which $\frac{d\theta}{dz} = \frac{a}{2}$. This particular form approaches an adiabatic lapse rate as z becomes large.

If a defined amount of heat is added at the base of an air column with a known initial temperature distribution, the resultant mixing height is well defined, i.e., there is a functional relationship between G and Z. To obtain this relationship for the temperature distributions given by (4), (5) and (6), substitute each in turn into (3b). The results are, for the linear case:

$$G = \beta \frac{Z^2}{2} \tag{7}$$

or

$$Z = \sqrt{2G/\beta} \quad ; \qquad \Delta T = \sqrt{2\beta G} \tag{8a, 8b}$$

For the capping inversion

$$G = \beta_1 \frac{Z^2}{2} \qquad (0 \le Z \le z_1)$$

$$G = \beta_2 \frac{Z^2}{2} + (\beta_1 - \beta_2) \frac{z_1^2}{2} \qquad (z_1 \le Z \le z_2). \tag{9}$$

For $Z < z_1$, (8a) amd (8b) apply with β replaced by β_1; for $z_1 \le Z \le z_2$

$$Z = \sqrt{\left[2G + (\beta_2 - \beta_1) \; z_1^2\right] / \; \beta_2}$$

$$\Delta T = z_1 \; (\beta_1 - \beta_2) + \sqrt{\beta_2 \left[2G + z_1^2 \; (\beta_2 - \beta_1)\right]} \tag{10}$$

Finally, for the logarithmic case:

$$G = ab \; \{Z - b \; \ln \; (1 + \frac{Z}{b})\} \tag{11}$$

3. Numerical results

Z has been calculated as a function of G for the three types of profiles discussed above, using two different inversion strengths in the altitude range from 0 to 100 m. The soundings are shown in Fig. 1 and

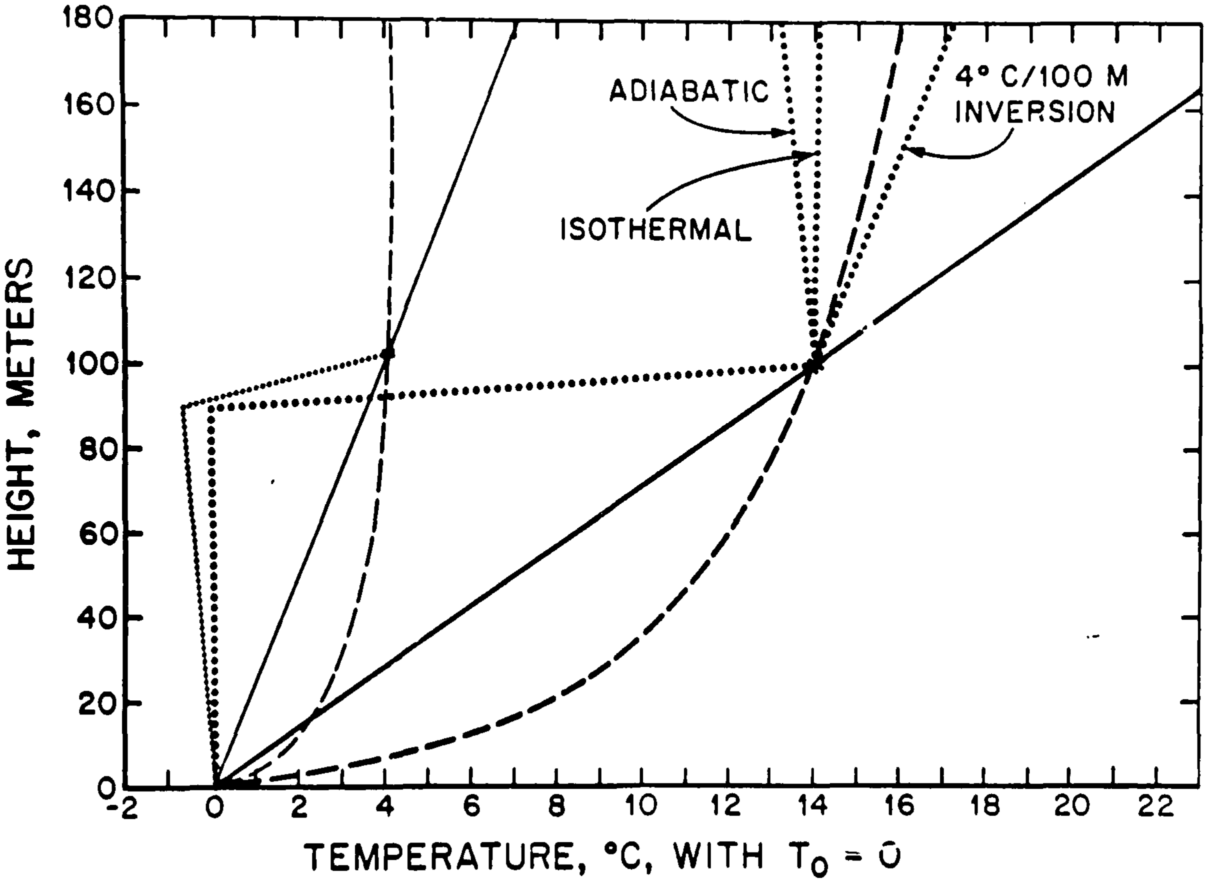

Figure 1. Temperature soundings for which the mixing heights and pollution potentials in Figures 2 and 3 were calculated. Heavy lines - overall inversion 14°C/100 m; light lines - overall inversion 4°C/100 m. Solid lines - constant lapse rate; dashed lines - logarithmic sounding; dotted lines - capping inversion. 4°C capping inversion is terminated at 100 m; 14°C capping inversion has 3 possible extensions indicated.

the numerical values of the coefficients are in Table 1. It is apparent from the values of Z as a function of G shown in Fig. 2 that the different forms of these soundings (which are within observed limits for Fairbanks, Alaska) are sufficient at times to produce more change in Z than a three-fold change in the temperature difference between 0 and 100 m - the type of parameter most often used to represent the inversion strength.

4. Implications for air pollution potential

If pollutants are added at the ground in direct proportion to the heat added, and are then mixed uniformly through the adiabatic layer, the concentration of pollutants in the mixed layer at any point y' should be proportional to G(y')/Z(y'). This quantity, which we will call the pollution potential index (PPI) is plotted against G in Fig. 3 for each of the soundings considered. It must be kept in mind that this PPI completely neglects variation of a number of factors that may differ among cities or even with season (e.g., wind speed, or ratio of pollutant output to heat output, or air density). Nor does it consider effects of radiative energy losses (which have the effect of reducing the energy transferred to the air and thus increasing the pollution/heat ratio) or the impact of elevated pollution sources. To the extent that G increases with city size (with the square root of the population if geometrical similarity is maintained) Fig. 3 does provide an estimate of how pollution would be expected to increase as a city grows. This assumes predominantly low-level pollution sources and does not allow for major industrialization, which could change the ratio of heat input to pollution input.

The logarithmic sounding is typical of regions with very low wind speeds and clear skies, with radiative cooling dominating outside the city. Such conditions are common in sheltered locations at high latitudes.

TABLE 1

Values of coefficients in equations (4) through (6) corresponding to overall 0 to 100 m inversion of 14°C and 4°C

Sounding	Parameters
14° constant inversion	β = .15 K/m
14° capping inversion γ_1 = 0°C/m γ_2 = 1.40°C/m	β_1 = 90 m z_1 = 90 m β_2 = 1.41 K/m z_2 = 100 m β_3 (above z_2) = 0 K/m (adiabatic) = .01 K/m (isothermal) = .05 K/m (4°/100 m inversior
14° logarithmic inversion	a = .985 K/m b = 5 m
4° constant inversion	β_1 = .05 K/m
4° capping inversion, γ_1 = .007°C/m γ_2 = .463°C/m	β_1 = .003 K/m z_1 = 90 m β_2 = .473 K/m z_2 = 100 m Calculations terminated at 100 m
4° logarithmic inversion	a = .328° K/m b = 5 m

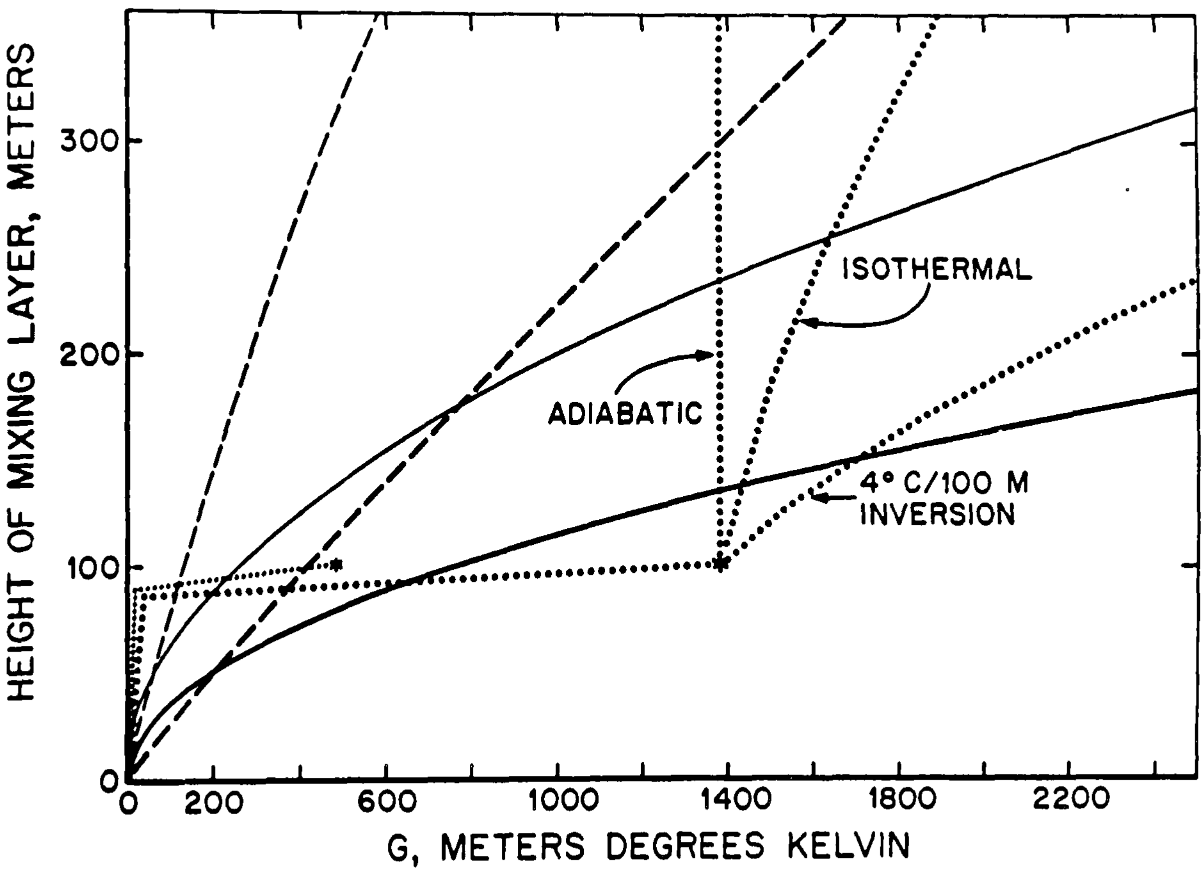

Figure 2. Mixing heights calculated for various values of G, the change in temperature integrated over height, for the soundings in Figure 1. Line code is the same as Figure 1.

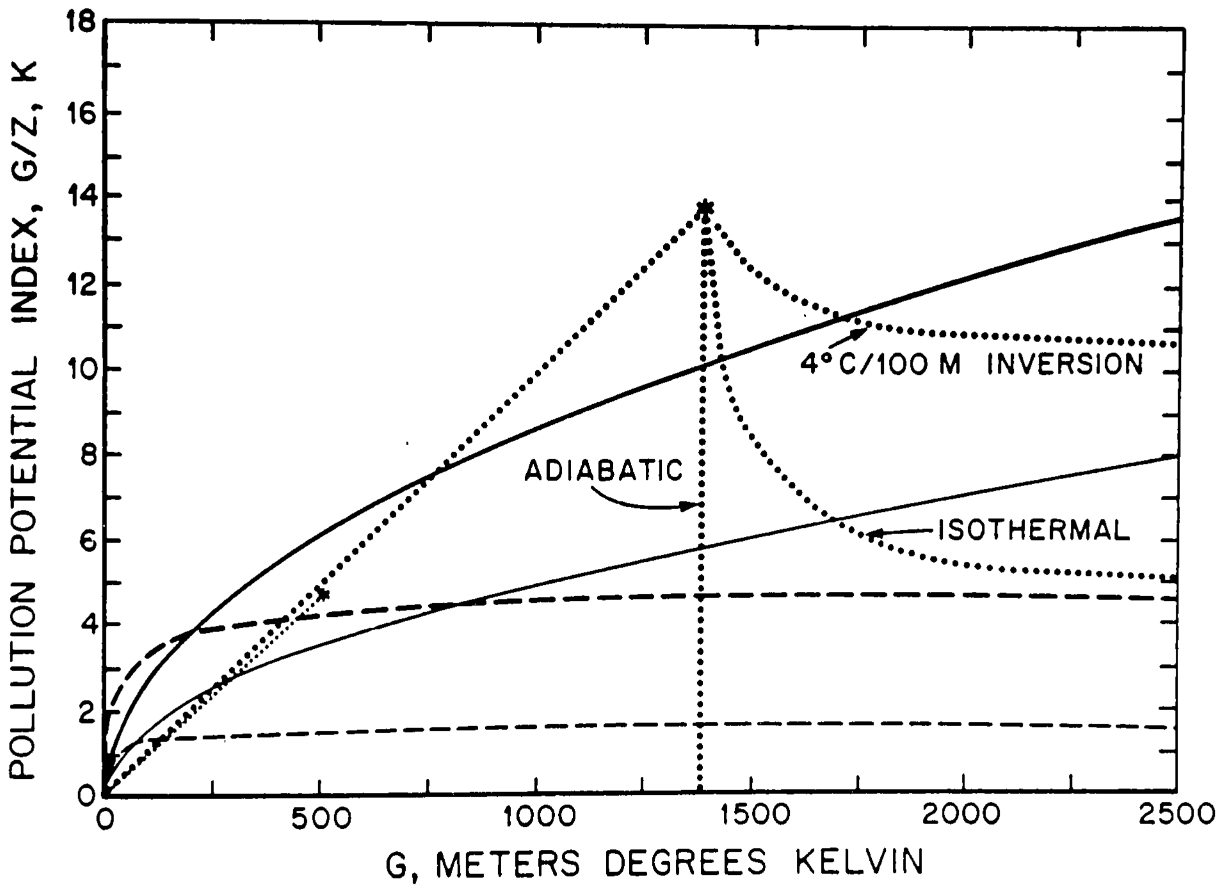

Figure 3. Pollution Potential Index (PPI) as a function of G for the soundings in Figure 1 and 2. Line code is the same as in Figure 1.

For this type of sounding, the equations predict a very fast growth of the PPI with heat input, so that even a small settlement may have a substantial pollution problem, in agreement with observed conditions at high latitudes. However, the PPI then levels off rapidly, becoming asymptotic to the constant value ab. Some values of Z and G giving various fractions of the maximum PPI are given in Table 2.

It should be emphasized that the PPI approaches a constant value only in the case where the logarithmic sounding approaches the adiabatic sounding with height. A more realistic case would be an approach to a stable constant lapse rate. Mathematically, this would correspond to

$$\theta(z,0) = \theta_0 + \beta z + ab \; \ell n \; (1 + \frac{z}{b}) \tag{12}$$

from which

$$G = \frac{\beta Z^2}{2} + ab \left[Z - b \; \ell n \; (1 + \frac{Z}{b}) \right] \tag{13}$$

Figure 4 compares the PPI's corresponding to (12) and (6b) when β is set equal to .005 (a normal lapse rate at half the adiabatic strength), b is kept at 5 meters, and a is adjusted to maintain a 14° inversion between 0 and 100 m. The PPI for $\theta(z,0) = \theta_0 + .005\,z$ is plotted for reference. The very rapid initial rise in pollution potential with city size is maintained, but the PPI continues to increase for large values of G. The values of β, a and b used in Fig. 4 are reasonable winter values at Fairbanks, Alaska. This sounding has a maximum temperature 20°C warmer than the surface at an altitude of about a kilometer.

The constant lapse rate case is the easiest to handle analytically, with PPI $=\sqrt{\beta G/2}$. Physically, it may be considered a special form of the logarithmic case in which $b \to \infty$ while $a = \beta$. Theoretically, there is no upper limit on pollution intensity. In practice, the constant

TABLE 2

Non-dimensional values of G and Z corresponding to various ratios of the pollution potential index to its maximum value, ab

PPI/ab	G/ab^2	Z/b
.25	.18	.73
.50	1.25	2.5
.75	7.06	9.4
.90	32.4	36
1.00	∞	∞

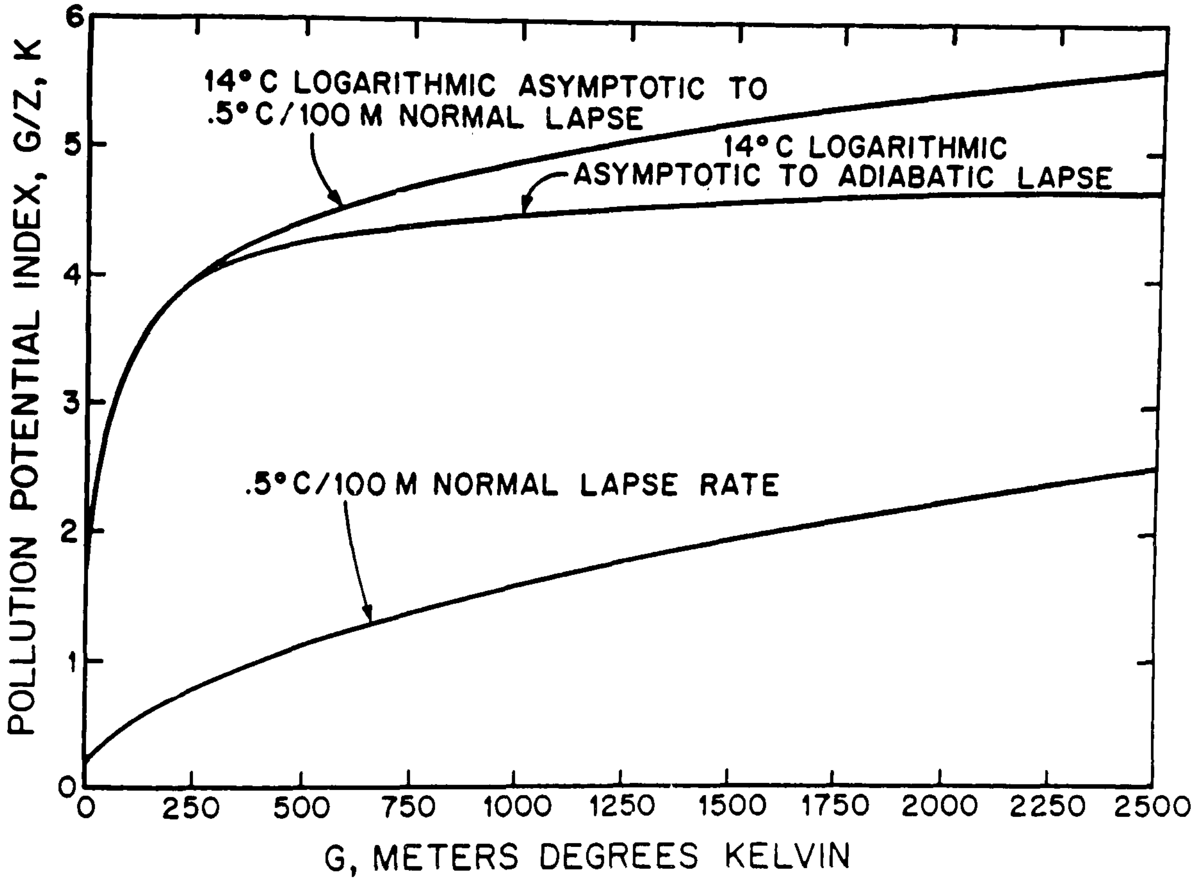

Figure 4. Effect on the Pollution Potential Index of having a logarithmic sounding approach a stable lapse rate rather than an adiabatic one. Note Vertical scale change from Figure 3.

lapse rate is normally limited in vertical extent, and the situation for very large values of G will approach either the logarithmic or the capping case.

The capping inversion is generally due to large-scale motion rather than to radiative processes. Advection of warm air over cooler air is one possible causative mechanism. Subsidence over a mixed layer or heating of a stable air mass from below are other possible formative mechanisms. (Inversions of this type are typical of L s Angeles). With this type of inversion, the potential for pollution is low for small settlements but continues to increase rapidly for large values of G. It is not difficult to demonstrate that, to a good approximation, the rate at which the PPI increases with G is inversely proportional to the height of the base of the capping inversion. The capping inversion case is unique in that a large enough city may be able to "break" the inversion, at which point ground level pollution will fall off sharply. Manipulation of (9) and (10) shows that for an idealized "square" capping inversion ($\beta_1 = 0$, $(z_2 - z_1) \ll z_1$, and $(z_2 - z_1)\ \beta_2 = I$ = inversion strength), the PPI at the point of breakthrough is directly proportional to I, while the value of G necessary to reach this breakthrough point is equal to Iz_2.

5. Conclusions

As a general rule, in areas in which inversions are normally steepest near the ground and stability decreases with height, air pollution will be a problem even in small towns but its severity will increase only slightly with increased city size. In areas where stability increases with height, small settlements will have fewer problems with air pollution, but the severity of pollution will increase relatively rapidly with city size.

Thus, if climatological summaries of inversion frequencies are to be used as input for making decisions related to pollution, they should whenever possible be organized to indicate the predominant inversion forms as well as inversion strengths.

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