Low-Level Stability and Pollutant-Trapping Potential for a Rural Area[1]

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ABSTRACT

Temperature and wind speed measurements over a 6-year period from a 32 m tower located in a primarily rural area are used to assess the pollutant-dispersive characteristics of a rural site. A monthly comparison of a crude pollution-trapping index shows July through September the most favorable, and December through February the least favorable, months for the trapping of contaminants emitted from ground-based sources in rural areas.

1. Introduction

Considerable research has been carried out in the last few years to characterize atmospheric stability in and around urban areas to assist in interpreting the results of air-quality monitoring and numerical modeling programs. The inversion characteristics of rural areas also have been documented; rural sites, however, have not received as much consideration for pollutant trapping because large-scale sources of atmospheric contaminants usually are associated with urban areas. The widening scope of environmental concern, however, is bringing into consideration agriculturally generated pollutants (Heck *et al.*, 1973), e.g., pesticides and other chemicals, smoke and gases from agricultural burning, allergens such as pollens and dust, odor from large-scale feedlots, and field and road dust. Major highway systems are sources of carbon monoxide and lead (Aschbacher, 1973), and concentrations along roads traversing rural areas are, like concentrations from agricultural sources, governed by rural dispersion characteristics. Therefore, the pollutant-trapping potential for a rural area should be determined.

Summaries of temperature profiles for other rural areas have been given by Geiger (1965) who lists several studies in England, and De Marrais (1961) who compares rural data from Idaho Falls and Sussex, England, with urban Louisville data. Moses and Bogner (1967) have presented a 15-year climatological summary for the Argonne National Laboratory site, which is primarily rural with some urban influence. Studies of shorter duration such as the Prairie Grass Experiment (Barad, 1958) and the Wangara Experiment (Clarke *et al.*, 1971) have provided extensive data for case studies. Hosler (1961) gives an overview of inversion frequency across the United States.

The depth of mixing in the atmosphere shows a strong diurnal cycle and on the average (Holzworth, 1967) varies from an early morning minimum of 300–400 m to an afternoon maximum of 700 m in winter or 1700 m in summer for stations in areas climatologically similar to Iowa. Acoustic echo-sounders recently have provided graphical displays of mixing characteristics as a function of time. The sounder facsimile records (McAllister *et al.*, 1969; Wyckoff *et al.*, 1973) often show two distinct types of inversions: those developing upward from the ground closely following the diurnal cycle, and elevated inversions which are related to synoptic conditions. Both types of inversions may be important in pollutant dispersal estimates, depending on how and at what elevation the pollutant is injected. Although the heat-island effect of large metropolitan areas may prohibit the establishment of ground-based inversions (Duckworth and Sandberg, 1954; De Marrais, 1961; Baker *et al.*, 1969; Ewing, 1972), ground-based inversions may play a primary role in the control of pollutant dispersal in rural areas or smaller cities with less nocturnal heating and lower-level pollutant sources.

The Ames Laboratory of the Energy Research and Development Administration has maintained a 32 m meteorological tower in operation near Ames since 1962. The climatic characteristics of the site would be reasonably close to those given for Des Moines (U. S. Dept. of Commerce, 1968) which is 63 km

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south of Ames. The period between July 1964 and June 1970 provided a set of data relatively free of equipment failure and other down times. We believe these data are sufficient for at least a preliminary attempt to characterize low-level stability conditions and pollutant trapping potential in this region of the United States. Although the limited tower height will seldom indicate the vertical extent of the inversion, the data will indicate the presence and magnitude of a ground-based temperature inversion. These factors are important considerations in the horizontal and vertical spread of atmospheric contaminants from ground-based sources.

2. Equipment

The data for this study were collected from a 32 m instrumented tower operated in conjunction with the Ames Laboratory Research Reactor located at the northwestern edge of Ames. The terrain is gently rolling, with variations of less than 10 m for 0.9 km in all directions except the northwest where, at about 0.4 km, there is a 25 m drop to Onion Creek. The fetch consists of short grass for at least 60 m in all directions. Beyond 60 m to the south is agricultural land, to the west and east beyond 185 m is woodland, and to the north, at about 150 m, are the reactor building and offices with a maximum height of 16 m.

Temperature was measured at 2 m with a copper-constantan thermocouple, and temperature differences between this and the 4, 8, 16 and 32 m levels were measured with iron-constantan thermocouples. The thermocouples were soldered into cylindrical gold-plated copper slugs approximately 1 cm in diameter and 3 cm long. These were housed in gold-plated coaxial radiation shields and were ventilated by a small blower for 15 min before and also during the hourly measurement period. Airways 339A counting-type anemometers were located at all five levels. The wind and temperature measurements recorded for a given hour represent averages over the period beginning on the hour and ending 11½ min after the hour.

3. Data

This study uses data from the period 1900 LST 27 July 1964 to 0100 LST 21 May 1970 with interruptions totaling only 0.82% of the period. Temperature differences between 2 and 32 m were used to identify inversions. The lower intervals showed inversion characteristics proportionately similar to those of the 2 to 32 m interval. The inversion commencement times for lower intervals were, in general, 1–3 h earlier than for the 2 to 32 m interval, indicating a slow nocturnal boundary layer growth. Inversions were observed to break up almost simultaneously for all intervals based at 2 m, presumably due to rapid warming of the air near the 2 m sensor.

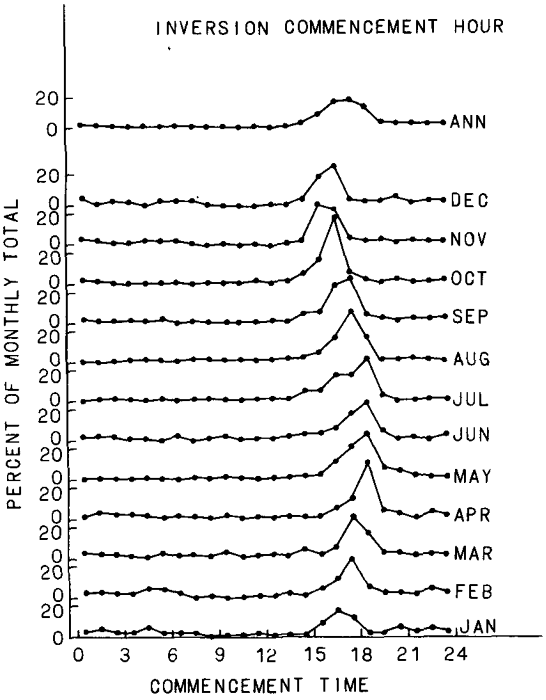

FIG. 1. Monthly distribution of commencement time for ground-based inversions.

During the period studied, there were 2645 occurrences of inversion conditions between the 2 and 32 m levels. The data period was not an integral number of years, nor was the equipment down time uniformly distributed. The number of inversions recorded in any one month ranged from a low of 194 in December to a maximum of 250 in August; thus, we believe there are adequate numbers of inversions each month to give meaningful statistical results.

Fig. 1 displays the onset time of ground-based inversions for each month as a percentage of the monthly total. Because the inversion is already established at the hour designated as the commencement hour, the corresponding point is plotted midway between this and the previous hour. Thus, maximum error is ½ h. The solar influence is quite strong, with nearly all inversions beginning near sunset. This aspect was examined in more detail by compensating for varying sunset times. Each inversion onset time was divided by time of sunset for Ames to obtain a "normalized" inversion commencement time. The results, given in Fig. 2, show more clearly the relationship of inversion commencement time to sunset time rather than to clock time, which was shown in Fig. 1. If every inversion began exactly at sunset, each month would have a spike at 1.0. From late spring to mid-fall, however, inversions most frequently set in at 0.9 of the sunset hour. In August, for example, which has an average sunset time of 1923 LST, inversions tend to begin at 0.9×19.23=1731 LST, which is almost 2 h before sunset.

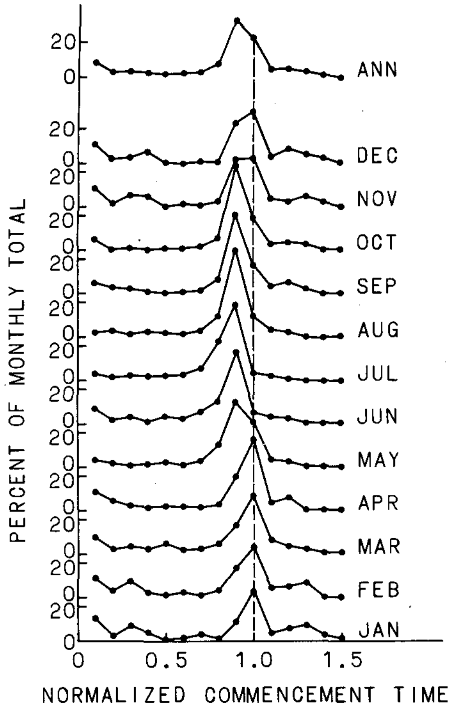

FIG. 2. Monthly distribution of normalized commencement time for inversions.

This summer pattern differs from the winter regime extending from December through April, which has a preponderance of inversions beginning very near sunset. Comparing times of the peaks of Fig. 1 with the solar altitude as calculated from equations given in the *Smithsonian Tables* (List, 1968), it is found that summertime inversions tend to become established when the sun altitude is still 10°–20°, whereas in the wintertime, an altitude of 0°–4° is a more optimum commencement time over a 30 m depth.

The shift to earlier commencement times during the summer and fall could be attributed to decreased cloudiness and surface moisture during this period. Also, deeper convective mixing carries warm air to higher elevations. Encouraged by a dry surface and clear sky, radiational cooling then quickly inverts the temperature profile.

Fig. 3 gives the monthly distribution of inversion duration. All months show a significant percentage of short inversions (1–3 h), although this is somewhat more prevalent in the winter and spring than in the summer and fall. There is a relatively low percentage of long inversions (>3 h) from early winter to early spring. The maximum percentage of the monthly total of long inversions gradually increases from January through October and then quickly resumes the winter characteristics. By dividing each inversion duration by the period of darkness (to be nearest minute) for that day, we get the results shown in Fig. 4. A comparison of Fig. 4 with Fig. 3 shows that from January through June the duration of inversions gets shorter as the nights get shorter; however, relative to the number of hours of darkness, the inversions get longer. The rapid shift to longer normalized duration between April and June can perhaps be explained by decrease

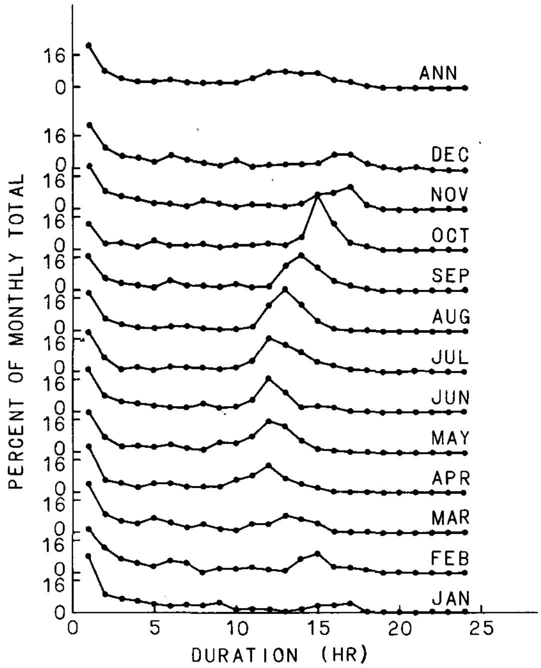

FIG. 3. Monthly distribution of duration for ground-based inversions.

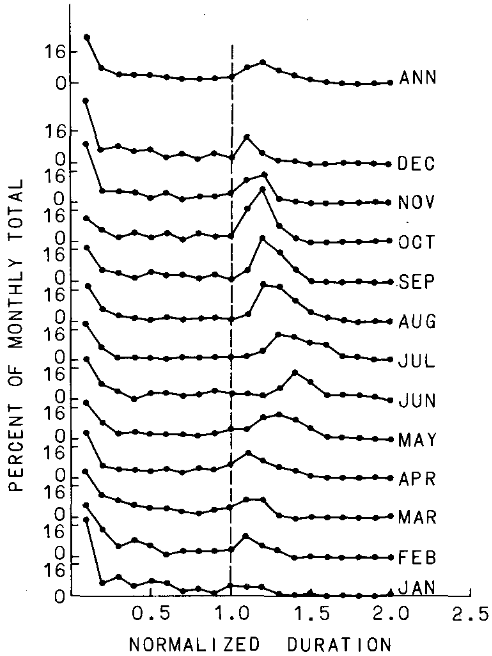

FIG. 4. Monthly distribution of normalized duration of inversions.

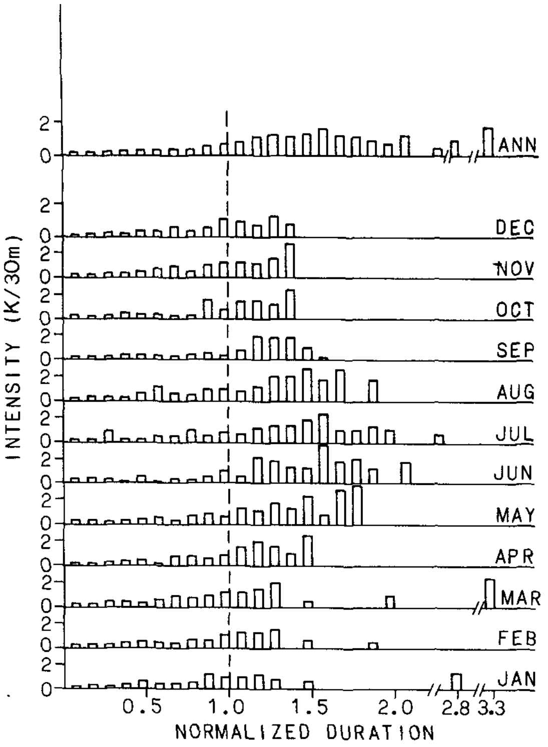

FIG. 5. Monthly distribution of average intensity of ground-based inversions as a function of normalized duration.

in cloudiness, wind speed and surface moisture that begin during these months. There is a relatively low percentage of long inversions in the winter months.

The intensity of inversions is important in characterizing dispersive capabilities of the lower levels of the boundary layer. The data of Moses and Bogner (1967) for Argonne and De Marrais (1961) for Idaho Falls show the average maximum-intensity inversion to occur from July to October. These results agree well with our observations for Ames. Fig. 5 shows the temperature difference (K per 30 m) as a function of normalized duration for each month. For all months, the longest inversions are also the strongest, as would be expected. Fig. 5 also shows all monthly distributions to be quite similar for times corresponding to ordinate values less than 1.4. From 1.4 and beyond, winter inversions are quite rare, whereas summertime inversions continue to intensify out to about 1.5 or 1.6 before diminishing.

Slade (1968) discusses the Idaho Falls data of De Marrais and Islitzer (1960) and states that the individual inversion maxima occur in winter for that desert site. However, the influence of these isolated events on monthly averages is obscured by a greater number of inversions of lower intensity during the winter months. In contrast to this, both the Ames and Argonne data show very intense inversions to occur most frequently during the summer months. This difference might be attributed to orographic details of the Ames and Argonne sites, since a very stable surface layer would be highly susceptible to drainage, thus limiting the maximum observable inversion intensity.

Fig. 6 may be useful in forecasting pollution episodes. Note that, from May through December, if an inversion extends through 30 m by 0.8 of the 24 h sunset time (3.5–4.0 h before sunset), it is likely to be more intense than inversions beginning earlier or later. September and November are exceptions to this and follow the January through April pattern of having maximum intensity for a commencement time of 0.9 ×sunset time. In general, an inversion that gets a "running start" will be much more intense (by a factor of 2–5) than an inversion beginning after sunset, regardless of month.

The data of Moses and Bogner (1967) show seasonal and diurnal variations of inversion intensity very similar to those presented here. Their data show a broad peak centered in July and August, which agrees with the Ames intensity data of Fig. 7. The Idaho Falls data (De Marrais, 1961) also resemble ours although the intensity peaks in September. The inversion commencement time and duration for both Argonne and Idaho Falls also show good agreement with the Ames data. From these independent studies we may conclude that the diurnal and seasonal inversion characteristics of rural areas are fairly predictable.

Detailed comparison of the dispersive capability of a rural environment with that of an urban area is difficult because each city modifies its climate in a unique manner, and only a few urban temperature

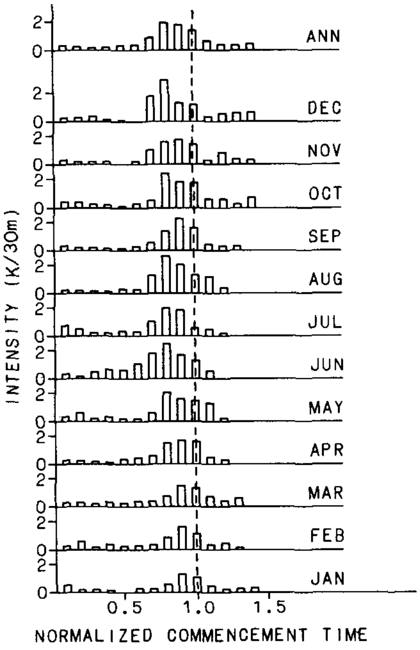

FIG. 6. Monthly distribution of average inversion maximum intensity as a function of normalized commencement time.

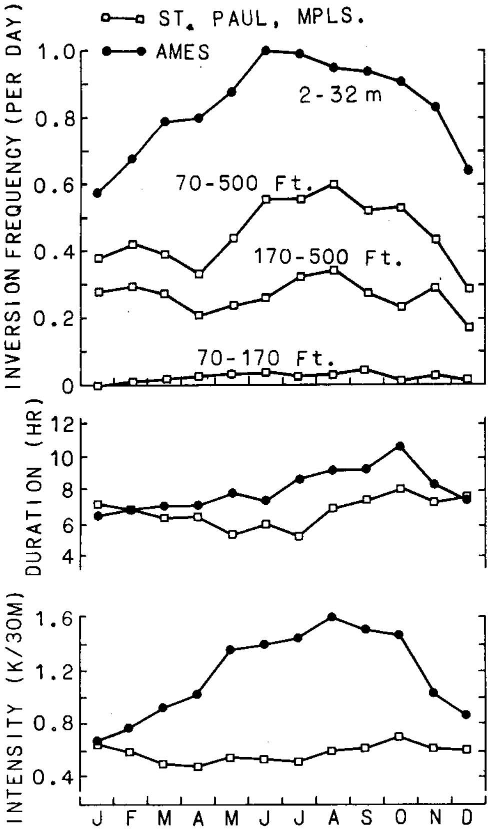

FIG. 7. Monthly comparison of occurrence, duration and intensity of inversions.

profile climatologies are available. Baker *et al.* (1969) have presented stability data for St. Paul–Minneapolis from a 500 ft tower. The differences in tower height, surface features and latitude preclude a close comparison, although some general comparisons can be made of month-to-month pollutant-dispersing tendencies. Fig. 7 shows the occurrence of long (>3 h) inversions, in addition to the average duration and average intensity of inversions throughout the year. Baker *et al.* provide inversion frequency information for three intervals on the tower, all of which are plotted in Fig. 7. Comparison of the 70–170 ft interval from urban St. Paul–Minneapolis with the rural Ames data shows the capability of the urban area to prevent establishment of the nocturnal inversion. The Ames data do not show the secondary maximum of inversion frequency during the winter that appears in the upper level in St. Paul–Minneapolis. The limited height of the Ames tower may account for this difference.

The inversion duration for Ames shown in Fig. 7 shows a peak in October, as does the St. Paul–Minneapolis plot. The winter maximum of the urban area again is missing in the low-level rural data. The curves for inversion intensity shown in Fig. 7 reveal a marked departure during the summer months. The differences in heat-holding and re-emitting characteristics of the urban and rural (vegetated) areas would account for this departure. These intense summertime rural inversions will strongly suppress vertical mixing. For comparison, it might be noted that these summertime intensities are 50% stronger than the estimated inversion strength during the devastating air pollution episode in Donora, Pa., in 1948 (Williamson, 1973).

De Marrais (1961) has presented urban Louisville data for an 11-month period. The height intervals for the Louisville data are almost identical to those of the St. Paul–Minneapolis study. The results of the two studies are quite similar except for the lower incidence of inversions in the 60–170 ft interval in Louisville.

Following Baker *et al.*, we can specify a crude index of pollutant-trapping potential by multiplying the duration of an inversion by its intensity and summing over all inversions for a given month. This is divided by the number of operating hours for each respective month, which eliminates distortions due to unequal distribution of equipment down time and number of days per month:

$$\text{INDEX}=\frac{\Sigma\ (\text{DURATION}\times\text{INTENSITY})}{\text{MONTHLY OPERATIONAL HOURS}}.$$

The result is represented by the INDEX curve in Fig. 8.

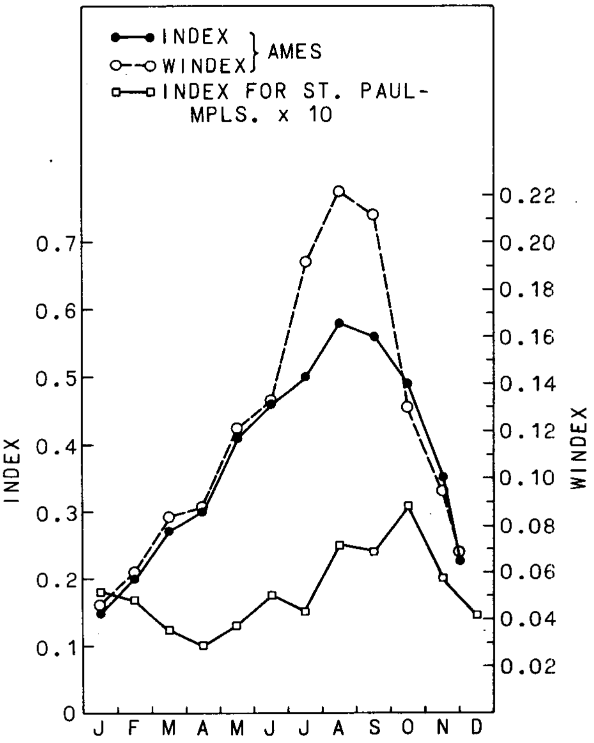

FIG. 8. Monthly comparison of two indices of pollutant-trapping potential for Ames with a comparable index for St. Paul-Minneapolis.

The wind speed for the inversions studied decreased with increasing inversion average intensity as shown in Fig. 9. The general trend is similar to that observed by Frankenberger as displayed by Geiger (1965, p. 124). The limited number of very intense (>3 K per 30 m) inversions we observed showed a wide range of wind speeds, but the number of events is too low to draw definite conclusions.

To incorporate the effect of wind speed into this index, it may be recalled that the Gaussian distribution of a gaseous effluent concentration from a continuous point source in a mean wind u has a $1/u$ dependence (Turner, 1969). Thus, a crude extension of Baker's index for comparing months when the effect of mass transport is included would be

$$\text{WINDEX} = \frac{\Sigma\,(\text{DURATION} \times \text{INTENSITY/WIND SPEED})}{\text{MONTHLY OPERATIONAL HOURS}},$$

where both the intensity and 32 m wind speed are obtained by averaging hourly values over the duration of the inversion. For both these indices, the units are meaningless and have been omitted. Fig. 8 shows a marked enhancement of WINDEX over INDEX during the period when conditions are already most favorable for a ground-level pollutant trapping.

On the basis of temperature measurements alone, Baker *et al.* (1969) find October to be the month of maximum pollution potential, with a secondary maximum in January–February for the lowest 500 ft for St. Paul–Minneapolis. The data presented here describing the lowest 30 m (98 ft) for rural Ames show August as the peak month, whether or not wind speed is considered, and the winter months of December through February forming the minimum of the curve. Note the effect of wind speed on the July and October values of INDEX: the July WINDEX is substantially enhanced, whereas the October WINDEX is somewhat suppressed when compared with INDEX. The sharp decline in WINDEX between September and October compared with the modest decline of INDEX for the same period points out the greater sensitivity of WINDEX in assessing pollutant-trapping potential. It would be most interesting to have wind data incorporated into the St. Paul–Minneapolis (or other urban) data to compare with the temperature-derived index to make a more complete month-to-month comparison of stagnation potential.

4. Conclusions

Low-level wind speed and temperature data for a rural environment have been presented to show the dispersive capabilities of the atmosphere for ground-based pollutant sources. The results agree with other rural sites but differ substantially from urban sites, as would be expected, and show July through September to be months of maximum pollution potential, with December through February being minimum.

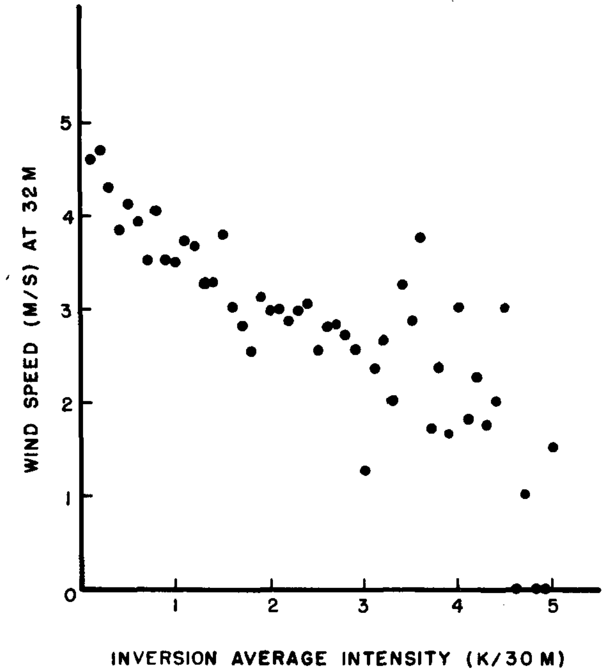

FIG. 9. Variation of 32 m wind speed with inversion average intensity.

The agreement of the Ames data with those of two other rural sites and the expected wind speed vs inversion intensity relationship allow us to conclude that the seasonal variation of INDEX and WINDEX would generally apply to rural sites in climates similar to that of the Midwest.

As an example of the use of these data, the potential is relatively low during the period of spring herbicide and insecticide application in the Corn Belt. Mid-to-late-summer herbicide applications are more likely to lead to higher concentrations, especially at night, at or downwind from the source.

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