Reprinted from JOURNAL OF APPLIED METEOROLOGY, Vol. 8, No. 5, October, 1969, pp. 747–753
American Meteorological Society
Printed in U. S. A.

Frequency, Duration, Commencement Time and Intensity of Temperature Inversions at St. Paul-Minneapolis[1]

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(Manuscript received 10 March 1969, in revised form 11 July 1969)

ABSTRACT

This study is based upon temperatures for the period June 1961 through July 1968, obtained from thermistors installed on a television tower at heights of 70, 170 and 500 ft. The tower was located in the heart of the metropolitan area but well outside of the main business district of either city. Only inversions ≥ 2 hr in duration were counted.

On an annual basis only 2.5 inversions per 100 days occurred in the lower level (70–170 ft) compared to 26.3 inversions per 100 days in the upper level (170–500 ft). The total frequency, including the two levels and the deeper inversions that extended over both levels, equalled 45.5 per 100 days.

The average duration of inversions within both levels was 6.8 hr, the 8.2-hr average in October being the longest of any month. Midnight was the single most common hour for inversion formation. Inversion intensity (defined as the temperature difference between levels) varied directly with duration of the inversions. The average intensity of all inversions within both levels was 3.6F.

An inversion rating index was developed that takes into account frequency, duration and intensity of inversions so that either time periods or sites may be quantitatively compared. The index indicated that the major inversion months were October, August and September, the minor months being April, March and May.

A decrease in inversion intensity and frequency over the record period was assumed to indicate an increasingly urban influence on the temperature of the region.

1. Introduction

In light of increased interest and importance of urban climatology, temperature data from sensors mounted at three levels within 500 ft of the ground were analyzed in detail. The portion of the data pertaining to inversions for the period June 1961–July 1968 is presented herein.

2. Instrumentation and site description

The data used in this study were obtained from an air pollution project initiated by Cowan and Paulus (1964). Temperatures were measured by aspirated and shielded resistance thermometers mounted at 70, 170 and 500 ft above the ground on a television tower. The data were recorded automatically with Leeds and Northrup model G strip chart recorders housed in a special instrument shelter at the foot of the tower. The sensors were calibrated periodically and at no time was a correction >0.1F required.

[1] Scientific Journal Series No. 6790, Minnesota Agricultural Experiment Station.

The television tower is located on the boundary between the Twin Cities of St. Paul and Minneapolis. This location is nearly in the geographical center of the Twin Cities metropolitan area. The tower is on a small hill that stands at 910 ft MSL. With the exception of a 980 ft MSL hill that is 0.2 mi due west, the land slopes rather gently away in all directions for 0.5 mi and more. While there are a few hills in the Twin City area that are higher, the combination of the hill and television tower are such that the tower is the highest structure in the region. The immediate area is one of older private homes and light industry. As a result, the area is not entirely concrete and asphalt but one of scattered lawns and deciduous trees. The trees are about 40 ft tall and are as tall or taller than most nearby structures. A heavily traveled intercity street is at the foot of the tower and a large railroad switch yard and grain elevators are located 0.2 mi north. The St. Paul business district is about 5.5 miles ESE at a general elevation of around 760 ft MSL. The Minneapolis business district has an elevation of about 850 ft MSL and is approximately 3 mi WNW of the tower. Details of the area are shown in Fig. 1.

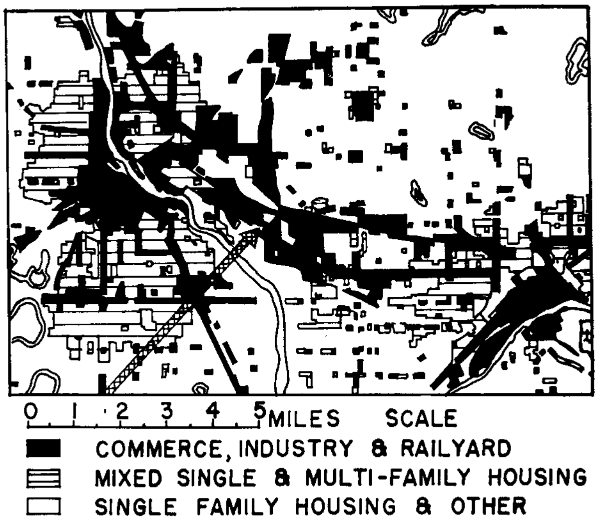

FIG. 1. A generalized map (north is at the top) of the Twin Cities of St. Paul-Minneapolis, Minn. The arrow points to the television tower site.

While the temperatures at the three levels were automatically recorded at 2-min intervals, hourly averages were tabulated and analyzed for 2-hr intervals. The inversions were tabulated for the levels 70–170 ft, 170–500 ft and 70–500 ft. Inversions that occurred simultaneously at the lower and upper levels or extended over the entire depth were counted as a single inversion and only in the total layer.

Equipment failure did occur; however, Table 1 shows that ~87% of the days were available for analysis, and only in March and June was the equipment in operation less than 80% of the days.

The total number of inversions was counted rather than the number of inversion days. Since many of the inversions were nocturnal in character and frequently extended from late one day to the early hours of the next (only one inversion in the entire period lasted more than 20 hr), a deceiving count and frequency could result if inversion days were used. Because the operational days in each month were not equal (Table 1), the inversion frequencies are expressed on a basis of number of inversions per 100 operational days.

TABLE 1. Number of days in which the temperature sensing and recording equipment were in operation, St. Paul-Minneapolis, June 1961–July 1968.

Month	Operational days	Potential days	Percentage of days in operation
January	179	217	82.5
February	168	198	84.8
March	153	217	70.5
April	173	210	82.4
May	191	217	88.0
June	176	221	79.6
July	215	248	86.7
August	188	217	86.6
September	207	210	98.6
October	209	217	96.3
November	177	210	84.3
December	210	217	96.8
Total	2,246	2,599	86.4

3. Inversion frequency

The occurrence of inversions at the 70–170 ft leve was far less frequent than at the 170–500 ft interval (Fig. 2). On an annual basis inversions at the lower level averaged only 2.5 per 100 operational days compared to a frequency of 26.3 for the upper level. This differs from what De Marrais (1961) observed in Louisville, Ky. He found, within nearly identical height intervals (60–170 and 170–524 ft), that the upper level inversions were twice as frequent as those in the lower level. The most probable reason for the higher upper level than lower level inversion frequency in our study is the urban heating in the vicinity of the television tower.

There was a gradual and more or less stepwise increase in the low level inversions from none in January to a maximum in September. A much more rapid buildup in inversion frequency occurred in the upper level between April and August. The total number of inversions, which included those in the upper and lower levels and the deep ones which extended over both levels, showed regular increases only in April, May and June.

Fig. 2 shows that August was the month of maximum inversion frequency when there occurred almost 60 per 100 operational days. During five months, June–October, the frequency was greater than 50. April and December were months of lowest frequency with 32.9

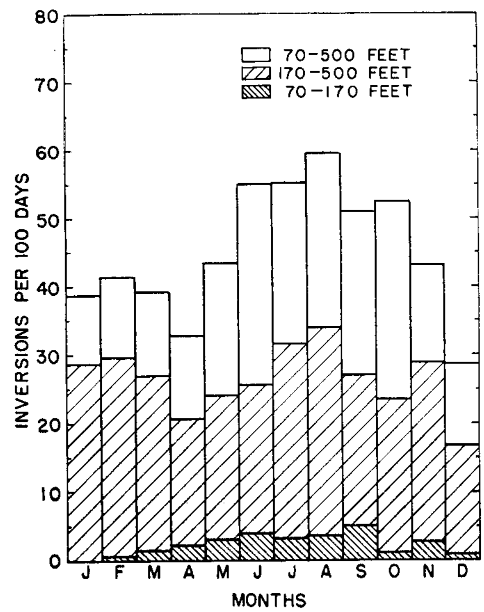

FIG. 2. Average monthly inversion frequency per 100 operational days, St. Paul-Minneapolis, June 1961–July 1968.

Table 2. Average monthly cumulative frequency distribution (per cent) of the duration of inversions, St. Paul-Minneapolis, June 1961–July 1968.

Duration (hr)	Jan	Feb	Mar	Apr	May	Jun	Month Jul	Aug	Sep	Oct	Nov	Dec	Annual
2	25.7*	24.6*	19.7	22.8*	32.5*	24.7*	26.0*	15.2	20.5	18.6*	21.3*	23.9*	22.7*
4	40.0	40.0	37.7	42.1	51.8	43.2	47.0	28.6	35.0	34.5	41.3	31.4	39.2
6	51.4	58.5	54.1	56.1	66.3	57.6	66.3	46.5	43.5	43.3	56.0	49.3	53.7
8	62.8	66.2	78.7*	78.9*	84.4	78.2	91.5	69.7*	54.6	52.1	65.3	62.7	70.2
10	75.7	80.0	91.8	92.9	97.7	95.7	98.2	92.0	76.0*	68.0	80.0	73.1	85.3
12	85.7	90.8	98.3	98.2	98.9	98.8	99.1	99.1	94.8	78.6	85.3	82.0	92.8
14	98.6	95.4	100.0		100.0	100.0	100.0	99.1	99.1	94.5	90.6	92.4	97.6
16	100.0	100.0						100.0	100.0	100.0	93.3	98.4	99.3
18											97.3	98.4	99.6
20											100.0	100.0	99.9
—													
—													
30				100.0									100.0
Average daily dark hours	14.9	13.6	12.1	10.5	9.1	8.4	8.7	9.9	11.5	13.0	14.4	15.2	

* The most frequently occurring duration.

and 28.6, respectively. The average annual frequency of the inversions equalled 45.5 per 100 days.

On a seasonal basis it was summer and fall in which the greatest number occurred with a frequency of 56.6 and 49.3, respectively. A late summer and early fall inversion frequency maximum was also found to be the case in Louisville, Ky., by De Marrais, with winter and spring being lowest with frequencies of 35.3% and 38.7%, respectively.

Using radiosonde data, Hosler (1961) determined the frequencies of inversion and isothermal conditions within the first 500 ft for selected Weather Bureau stations. The maximum occurrence of inversions at any one of the four daily radiosonde observation times was determined and the results shown as maps of seasonal and annual maximum inversion frequency in per cent. In each season the frequencies obtained by Hosler were higher than obtained in this study by a minimum of about 7% in the fall and a maximum of about 31% in the winter. These differences may be accounted for by the fact that Hosler included isothermal conditions and surface measurements, and his sources of data were more often than not rural sites. The only agreement between the two studies was that both showed summer to be the season of highest inversion frequency. (St. Paul-Minneapolis was estimated at 77% from Hosler's Fig. 2 as compared to 57 per 100 days in this study.) Hosler found spring to be the second highest season (St. Paul-Minneapolis estimated at 70%), whereas in this study fall was second highest.

It is apparent from Fig. 2 that for the total inversions there were, in effect, two inversion frequency seasons. There was a five-month high-frequency period averaging 54.8 per 100 days that extended from June–October and a five-month December–April low-frequency (35.4) season. The transition months of May and November averaged 43.3 per 100 days.

4. Inversion duration

As might be expected, inversions of 2 hr duration were generally the most frequently occurring, averaging about 23% of the cases as shown in Table 2. Notable exceptions were March, April, August and September when 8–10 hr inversions were most frequent. On the average about 46% of the inversions during the year lasted more than 6 hr.

Beginning in June and ending in October, the five-month period when more than 50 inversions occurred per 100 operational days (Fig. 2), there was a change in the frequency distribution of the duration of inversions. The distributions tended to flatten out such that by October there was nearly a 48% chance of an inversion ≥10 hrs (Table 2).

At the bottom of Table 2 is shown the average daily hours of darkness for each month. As expected, there is a marked similarity between the hours of darkness and the longer lasting inversions. This direct relationship between hours of darkness and the inversion duration indirectly demonstrates the influence of solar heating upon the dissipation of inversions.

The inversion that lasted 30 hr beginning at 1800 CST on 13 April 1962 was the longest one encountered in this study. Oddly enough, the temperature differential within that inversion never exceeded 1F. Some patches of snow were still to be found on the ground in the local area with the general meteorological situation during the 30-hr period one of a strong cP high over south-central Canada that extended southward to a relatively weak and small high over Mississippi and Alabama. The high pressure over Minnesota was weak and of narrow east-to-west extent due to two strong lows just off both the Atlantic and Pacific coasts at about 45 and 50N, respectively.

TABLE 3. Average duration (hr) of inversions, St. Paul-Minneapolis, June 1961–July 1968.

Month												
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
7.2	6.9	6.4	6.5	5.4	6.0	5.4	7.0	7.5	8.2	7.4	7.8	6.8

The average duration of the inversions was greatest in October with 8.2 hr, and least in May and July with only 5.4 hr per inversion (Table 3). If the single 30-hr inversion in April is not counted, since it was apparently both a rare and a random event, the average duration of April inversions decreased to 6.1 hr. The data in Table 3 then present a smoother picture; that is, there was a period of relatively short-duration inversions from March–July and a period of longer duration inversions in September–December. January and February plus August serve as transition months between the periods of longer and shorter duration inversions.

Longer duration inversions occurred with greater frequency in fall and winter than in spring and summer (Fig. 3). The similarity in frequencies of the seasons of spring and summer and of fall and winter is quite remarkable. It is perhaps noteworthy that this pairing of the seasons is different from the inversion occurrence frequencies, where it was found that summer and fall had the higher frequencies and winter and spring the lower frequencies.

Based upon radiosonde data for the first 500 ft above a station, Hosler (1961) showed seasonal isopleths of inversion frequency expressed as per cent of total hours (Fig. 1 in his paper). Estimates for St. Paul-Minneapolis from this figure are shown in Table 4 for comparison with the per cent of time that inversions actually occured based on the present study. Both data sources indicate that winter and fall are seasons of maximum duration. It should be noted, however, that in reality Hosler determined the "per cent frequency of total

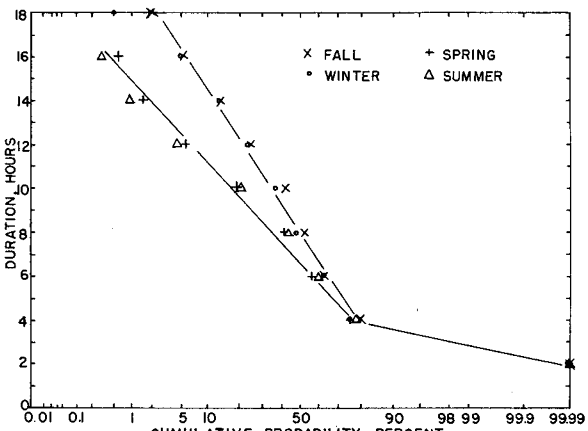

FIG. 3. Cumulative probability of the duration of inversions by seasons, St. Paul-Minneapolis, June 1961–July 1968.

TABLE 4. Inversion frequency expressed as a per cent of total hours. Data from Hosler's 1961 study are based upon estimates from his Fig. 1.

	Fall	Winter	Spring	Summer	Annual
Hosler's data	35	37	30	29	32
St. Paul-Minneapolis data*	32	30	25	25	28
St. Paul-Minneapolis data using Hosler's method**	27	21	17	21	22

* Expressed as a per cent of the 24-hr day, based on the average duration of inversions per 24-hr day.
** Expressed as a per cent of the nighttime period, based on the product of seasonal per cent frequency and the per cent of 24-hr day that is the nocturnal period.

seasonal hours" not upon a 24-hr day but rather upon the nocturnal period or hours of darkness. If Hosler's method (whose data sources were essentially rural in character) is then used on our data the results vary significantly. The fall frequency remains as the maximum, while the summer frequency increases largely because of the short dark period (Table 4).

5. Inversion commencement hour

The frequency with which a temperature differential was first recorded within the two levels at the indicated 2-hr intervals is shown in Table 5. It is evident in this table that the daytime formation of inversions was a relatively rare event, although the only hour of the day not represented by inversion formation was 1400. The highest percentage of the inversions formed on the average at 0000. On the average this is about 7 hr after low-level inversions measured between 4 and 128 inches commence in a semi-rural environment that is 2 mi distant from the television tower.[2]

It is noteworthy that in September and October, months when long-duration inversions were most frequent, that almost 60% and 55%, respectively, of the inversions formed before midnight. In sharp contrast were May–August when less than 20% of the inversions formed before midnight. This last is the result of two factors: 1) the later sunset hour during these months; and 2) the larger reservoir of heat released after sunset, which is due to both the longer days and the more intense radiation. The high frequency of September and October pre-midnight inversion formation is due at least in part to the relatively high frequency of clear days and nights.

Only in January did less than 85% of the inversions form during the nocturnal hours (Table 5), while in April, August and September over 95% of the inversions commenced in the dark hours.

6. Inversion intensity

The inversion intensity as used here refers to the maximum positive temperature differential observed

[2] Enz, J. W., 1969: Unpublished data.

Table 5. Commencement hour frequency of inversions in per cent, St. Paul-Minneapolis, June 1961–July 1968.

Hour of commencement	Jan	Feb	Mar	Apr	May	Jun	Month Jul	Aug	Sep	Oct	Nov	Dec	Annual
0000	15.7	23.1	34.4	33.3	38.6	37.1	21.0	39.3	19.7	10.6	17.3	7.5	24.7
0200	7.1	13.8	19.7	17.5	15.7	27.8	39.5	25.0	11.1	8.0	13.3	3.0	17.9
0400	18.6	16.9	11.5	12.3	16.9	14.4	14.3	10.7	6.0	11.5	10.7	19.4	13.1
0600	4.3	9.2	1.6	5.3	8.4	5.1	5.9	7.1	0.9	10.6	6.7	4.5	5.9
0800	8.6	7.7	4.9	0.0	2.4	0.0	3.4	0.9	3.4	4.4	4.0	6.0	3.6
1000	7.1	0.0	0.0	0.0	0.0	0.0	0.0	0.9	0.0	0.0	5.3	4.5	1.3
1200	0.0	0.0	0.0	1.7	1.2	0.0	0.0	0.0	0.0	0.9	1.3	1.5	0.5
1400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1600	1.4	1.5	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	2.7	1.5	0.6
1800	10.0	3.1	6.5	1.7	0.0	2.1	3.4	0.9	0.9	4.4	6.7	7.5	3.6
2000	12.9	7.7	4.9	10.5	3.6	2.1	1.7	1.8	21.4	38.1	18.7	17.9	12.2
2200	14.3	16.9	16.4	17.5	13.3	11.3	10.1	13.4	37.6	11.5	13.3	26.9	16.9
Total (1200–0000)	38.6	29.2	27.8	31.4	18.1	15.5	16.0	16.1	59.9	54.9	42.7	55.3	33.8
Total (nocturnal hours)	82.9	90.7	88.5	96.4	88.1	92.7	86.6	97.3	97.6	94.7	86.7	86.7	90.7
Average sunrise time	0748	0715	0626	0529	0445	0426	0440	0514	0551	0628	0710	0744	
Average sunset time	1658	1741	1819	1858	1935	2001	1957	1920	1825	1792	1645	1632	

between the measurement levels (70–170, 70–500 or 170–500 ft) in which the inversion was found.

Table 6 shows that the intensity of an inversion almost invariably increased as the duration increased. Unfortunately, the data were analyzed in such a way that it cannot be stated whether the intensity actually increased with time or if an originally intense inversion was simply able to persist longer. The former would probably be the more frequent event, however.

Fig. 4 shows that on the average the intensity of inversions increased at a rate of about 0.5F hr^{-1} as the inversion duration increased from 2 to 12 hr. For those inversions >12 hr the intensity increased at a curvilinear and less predictable rate.

The range in the monthly values shown in Table 6 indicates that Fig. 4 is a useful predictor only for inversions up to 10 hr in duration. For longer duration inversions the range is such that the average is of little value in prediction.

The relationship between the average inversion intensity and the time when the inversion began to form is shown in Table 7. (The table does *not* show the average intensity at the indicated hour). Inversions that formed between 1800 and 0200 all showed an intensity greater than 3F. However, the maximum intensity occurred on the average with inversions that began to form at 2200 and at 0000. For inversions that formed after midnight

Table 6. Average monthly intensity (°F) of inversions for indicated durations, St. Paul-Minneapolis, June 1961–July 1968.

Duration (hr)	Jan	Feb	Mar	Apr	May	Jun	Month Jul	Aug	Sep	Oct	Nov	Dec	Annual*
2	1.7	1.5	1.3	1.5	1.1	1.4	1.6	1.0	1.0	1.2	1.1	1.6	1.3
4	2.2	2.1	1.9	1.6	1.9	1.8	2.2	2.1	1.7	2.4	1.8	2.4	2.0
6	3.1	2.7	2.0	2.9	3.0	3.1	3.3	3.1	2.9	4.0	3.0	2.5	3.0
8	5.6	3.6	3.7	3.9	4.9	3.9	4.1	4.4	3.6	4.6	4.3	4.8	4.3
10	4.7	4.6	5.5	5.0	6.3	5.6	6.0	5.7	5.2	4.7	4.4	3.6	5.1
12	7.0	5.4	5.0	2.7	11.0	2.0	5.0	7.0	6.7	5.0	5.3	5.8	5.7
14	7.5	8.0	6.0		9.0	6.0	3.0		5.6	7.1	7.7	5.3	6.5
16	4.0	9.0						21.0	11.0	9.7	9.5	7.5	10.2
18											8.7		8.7
20											10.0	17.0	13.5
—													—
—													—
30				1.0									1.0

* The annual figure is based only upon the months with inversions and is not an average for the 12 months.

TABLE 7. Average maximum temperature difference (°F) within the inversions formed at the indicated 2-hr intervals, St. Paul-Minneaplis, June 1961–July 1968.

Hour of commencement	Jan	Feb	Mar	Apr	May	Jun	Month Jul	Aug	Sep	Oct	Nov	Dec	Annual
0000	5.5	3.7	3.2	3.6	4.3	3.5	4.1	4.2	3.7	5.3	3.2	2.6	3.9
0200	3.2	3.9	3.6	2.9	2.6	3.4	3.5	4.2	1.9	3.2	3.2	3.5	3.3
0400	3.8	2.5	1.6	2.3	2.4	2.2	2.3	3.4	1.4	3.1	2.9	2.9	2.6
0600	1.3	2.2	1.0	1.7	1.1	1.6	1.6	1.5	1.0	1.7	3.2	4.3	1.9
0800	2.2	1.6	1.7	0.0	1.5	0.0	1.3	1.0	1.0	1.4	1.0	1.7	1.2
1000	3.1	0.0	0.0	0.0	0.0	0.0	0.0	21.0	0.0	0.0	2.5	3.0	2.5*
1200	0.0	0.0	0.0	2.0	1.0	0.0	0.0	0.0	0.0	4.0	2.0	1.0	0.8
1400	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1600	4.0	2.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	5.5	2.0	1.4
1800	3.2	6.5	3.8	1.0	0.0	2.5	1.2	1.5	1.0	6.0	6.6	3.8	3.1
2000	4.3	4.6	1.7	2.0	1.7	1.5	4.0	1.5	4.0	5.3	4.6	5.3	3.4
2200	4.6	4.7	3.5	3.0	3.9	1.8	2.7	3.9	5.2	5.0	4.0	5.0	3.9

* 0.7F if the single 21F inversion is not counted.

the intensity was found to decrease as the inversion formation hour approached the time of sunrise.

The most intense inversion observed during the seven-year period was recorded on 30 August 1962. It formed at 1000 and lasted 16 hr, the average hourly temperature differential was 11F, and the maximum differential was 21F. The inversion was limited to the lower level. For the duration of this inversion there was a stationary front south of the Twin Cities oriented NE-SW through southeastern Minnesota. The skies remained overcast and precipitation had fallen in the last 24 hr.

A point of interest is whether the intensity of the inversions varied appreciably during the course of a year. Table 8 shows that there was a definite seasonal variation with October having the maximum of 4.3F per inversion and April the minimum of 2.9F. There was a seven-month period, August–February, when the intensity was ~3.9F per inversion. The least intense inversions occurred during March–July and averaged but 3.1F per inversion.

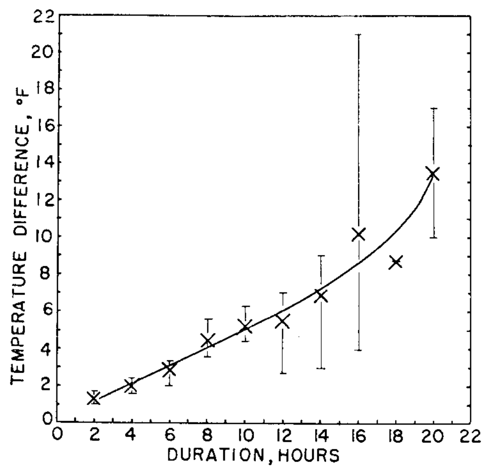

FIG. 4. Annual inversion intensity for all levels for inversions of given duration, St. Paul-Minneapolis, June 1961–July 1968. The crosses and vertical lines indicate the mean values and the range in values, respectively.

7. Inversion index

Even though inversions were more frequent in August there seems to be no doubt that October was the major month for inversions when the three elements of frequency, duration and intensity are considered together. However, it is not at all obvious how the other months rank. It might be of value if some scale could be developed which would permit a numerical ranking so that months or even sites could be quantitatively compared.

A simple product of the three elements, that is, frequency×duration×intensity, provides an elementary rating system. Each of the elements is weighted equally, and, since the product has no physical significance, dimensions are omitted. Fig. 5 shows what might be termed an inversion index. The three highest months are October, August and September, the three lowest April, March and May. Turning to atmospheric pollution potentialities for demonstration purposes, the first three months represent periods of maximum hazard and the last three periods of minimum pollution hazard insofar as inversions may be a factor.

8. Temporal changes

The urbanization and industrialization of the Twin Cities' area continued unabated throughout the investigation period. If the urbanization and industrialization were sufficient to modify the immediate area of the television tower, the effect upon inversions would most

TABLE 8. Average monthly inversion intensity (°F per inversion) within the upper level, 170–500 ft, St. Paul-Minneapolis, June 1961–July 1968.

Jan	Feb	Mar	Apr	May	Jun	Month Jul	Aug	Sep	Oct	Nov	Dec	Annual
3.9	3.6	3.0	2.9	3.3	3.2	3.1	3.6	3.8	4.3	3.8	3.9	3.6

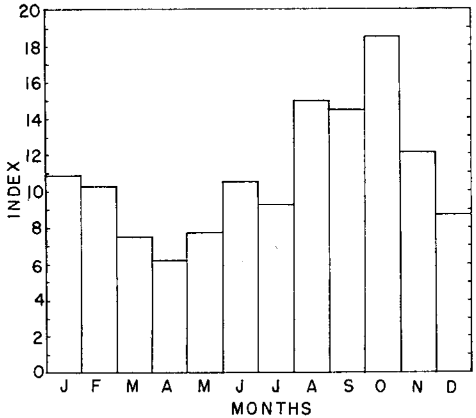

FIG. 5. Monthly inversion index, St. Paul-Minneapolis, June 1961–July 1968.

likely appear as a reduction in both their intensity and frequency. Table 9 indicates that there has been some reduction in both, particularly if the years are considered as two distinct periods, 1961–1964 and 1965–1968. Further evidence will be required to substantiate the environmental change indicated before it can be termed a fact. There was no change in the instrumentation nor has there been a drastic change in the local environment evident to the authors which would explain the apparently radical difference between the two periods.

9. Conclusion

There were three conditions considered in this study which have a great bearing upon pollution, insofar as inversions are a factor in atmospheric pollution. (Wind movement was not considered.) All three point to the month of October as having the conditions most conducive to maximum pollution potential. These conditions were:

TABLE 9. Average annual inversion intensity and frequency, St. Paul-Minneapolis, June 1961–July 1968.

	Year							
	1961	1962	1963	1964	1965	1966	1967	1968
Intensity (°F per inversion)	3.6	3.8	3.6	3.9	3.0	3.9	3.0	3.4
Frequency (inversions per 100 operational days)	49.1	47.6	52.0	44.6	36.8	40.4	40.9	36.5

1) Frequency; October was one of five months of maximum inversion frequency.

2) Duration; nearly 48% of the October inversions were ≥10 hr. The average duration of an October inversion was 8.2 hr, a maximum for any month of the year.

3) Intensity; the maximum intensity of an average upper level inversion was greatest in October and equalled 4.3F.

The minimum pollution potential, based upon the "inversion index," was in April, March and May.

The last four years of the study period (1961–1968) showed a reduction in both the intensity and frequency of inversions. This is an effect typical of urban sites and is assumed to be a manifestation of the increasingly urban character of the Twin Cities.

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