ILLINOIS STATE WATER SURVEY
at the
University of Illinois
Urbana, Illinois

ATMOSPHERIC EFFECTS FROM WASTE HEAT TRANSFER ASSOCIATED WITH COOLING LAKES

by

Floyd A. Huff and John L. Vogel

FINAL REPORT

National Science Foundation
NSF GI-35841

Principal Investigator: Floyd A. Huff

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Our special appreciation is expressed to Mr. Orville Tranby and Mr. Michael Groppi, both with Commonwealth Edison Company, and Mr. Wendell E. Miller, Illinois Power Company, for their cooperation in providing us with available data and reports on Illinois cooling lakes that were useful in our research.

INTRODUCTION

The generation of electric power in the United States is forecast to increase some 7 times from 1970 to 2000 (Hauser, 1969), and during this time it will be necessary for power companies to build massive plants to accomodate this growing power need. In addition to developing new technology for the generation of this power from nuclear and fast breeder reactor plants, the power industry will also be faced with the problem of dissipation of waste heat from these plants. Hauser predicted that the industry will have to dispose of 10 times as much waste heat in 2000 than in 1970. To solve this problem it will be necessary to utilize such ancillary methods as cooling towers, spray canals, and cooling ponds. To evaluate the potential effects that cooling lakes and ponds have on weather conditions in the vicinity of large plants, a 1-year pilot study was undertaken.

The major localized change to be expected is an increase in fog, especially during the period from late fall to early spring when weather conditions are most frequently favorable for the development of natural fog. Potentially, the heated lake water and its associated evaporation of water vapor could significantly increase the intensity, frequency, and areal extent of fog beyond that occurring under natural conditions. The possibility also exists that cooling lakes could stimulate the development of convective clouds on a localized scale, especially during summer, and subsequently alter the cloudiness and rainfall distribution in the vicinity of large cooling lakes. However, this effect appears much less likely to be of significance than the fog effect.

The 1-year study has involved two major phases. The first was concerned with detailed climatological analyses of the natural distribution of fog and related atmospheric elements whose modification by cooling lakes might conceivably lead to significant mesoscale changes in the distribution of fog, icing, clouds, and rainfall. The second phase involved preliminary atmospheric modeling to obtain estimates of the potential changes in fog and clouds that could be induced from heat and moisture exchanges between the cooling sources and the atmosphere during various seasons and under different weather conditions. Emphasis was placed upon the fog problem in both phases of the study, since it appears to be the most important environmental effect that could be produced by cooling lakes and ponds (Ackermann, 1971).

From the results obtained in this pilot study, recommendations have been made concerning future research needs to evaluate more precisely cooling lake effects on local weather conditions. Although based primarily upon Illinois data, the study results are considered generally representative of the Midwest and other areas with similar climate.

Data Used

The primary source of data used in developing the natural fog climatology was climatological records published by the Environmental Data Service of NOAA (formerly U. S. Weather Bureau). They provided data on occurrences of fog days and fog hours, wind, air temperature, dew point temperatures, and relative humidity, all of which were used in defining the natural fog distributi and its relationship to various meteorological parameters. In addition to the data obtained from NOAA publications, data were obtained from U. S. Air Force and FAA weather records at Rantoul and Joliet, Illinois. Radiosonde data from Peoria (NOAA) were used in developing a low-level mixing ratio climatology and in the cloud modeling aspects of the study.

Definitions

Reference is frequently made to seasonal relations in this report. Winter is defined as the months of December through February, spring includes March-May, summer denotes the June-August period, and fall refers to the September-November period. In the tables, standard meteorological abbreviations are often used for the cities. These are Chicago (CHI), Moline (MLI), Peoria (PIA), Springfield (SPI), St. Louis (STL), Evansville (EW), and Indianapolis (IND).

Dense Fog is defined as a fog intensity that reduces visibility to 0.25 mile or less. All fog combined includes those conditions in which visibility is restricted to 6 miles or less.

Waste Heat is that heat which is discharged as a consequence of the generation of electrical power.

Icing is the freezing of supercooled water droplets on surfaces with a coat of ice resulting.

Mixing Ratio is a ratio of the mass of water vapor to the mass of dry air and is usually expressed as the number of grams of water vapor per kilogram of dry air (g/kg).

AVERAGE SEASONAL AND ANNUAL DISTRIBUTION OF FOG

Determination of the distribution of natural fog is basic to evaluation of the fogging potential associated with cooling lakes. Lake-induced fog and intensification of existing natural fog are most likely to occur in those regions with the highest frequency of natural fog. Figures 1 to 5 show the average distribution pattern of natural fog in each season and annually, based upon 1) all days with fog, 2) days with dense fog, 3) total number of hours with fog, and 4) total number of hours with dense fog.

Winter is of primary importance since weather conditions are more frequently favorable for the formation of fog. Figures 1 to 4 show that natural fog occurs most frequently in the east central part of the state in winter, so that environmental effects from cooling sources are most likely to be a major problem in this region. Conversely, fog occurrences in winter minimize in the extreme southern part of the state where warmer air temperatures prevail. However, a distinct area of low frequency also occurs in the relatively cold northeastern part of the state.

In general, the natural fog frequency reaches a minimum in summer in Illinois with intermediate values in spring and fall. The seasonal differences are more pronounced in the fog-hour than in the fog-day patterns of Figs. 1-4. The hourly patterns provide a more precise index of the fog problem, since average fog duration enters into the derivation of these distributions.

An interesting comparison is that between all fog occurrences and dense fog frequencies. Thus, comparing Figs. 1 and 2 in winter, it is apparent that dense fog occurs on only about 25% of the fog days in the low frequency areas of southern and northeastern Illinois. This percentage increases to approximately 35% in the maximum frequency region in the east central part of the state. In summer, only 5%-8% of the fog days have dense fog in southern Illinois, and this increases to approximately 12% in the maximum occurrence region in the east central part of the state. The potential for significant increases in dense fog from intensification of natural fog during air passage over relatively warm water bodies is evident from the above comparisons.

Figure 5 shows the mean annual distribution of fog by days and hours. The annual patterns resemble the winter distributions in most respects with low frequencies in the southern and northeastern parts of the state and maximum frequency in the east central to central regions of the state.

Figures 1-5 have shown seasonal and annual occurrences of fog on a daily and hourly basis. Further insight into the fogging problem can be obtained by expressing the fog occurrences in terms of percent of possible

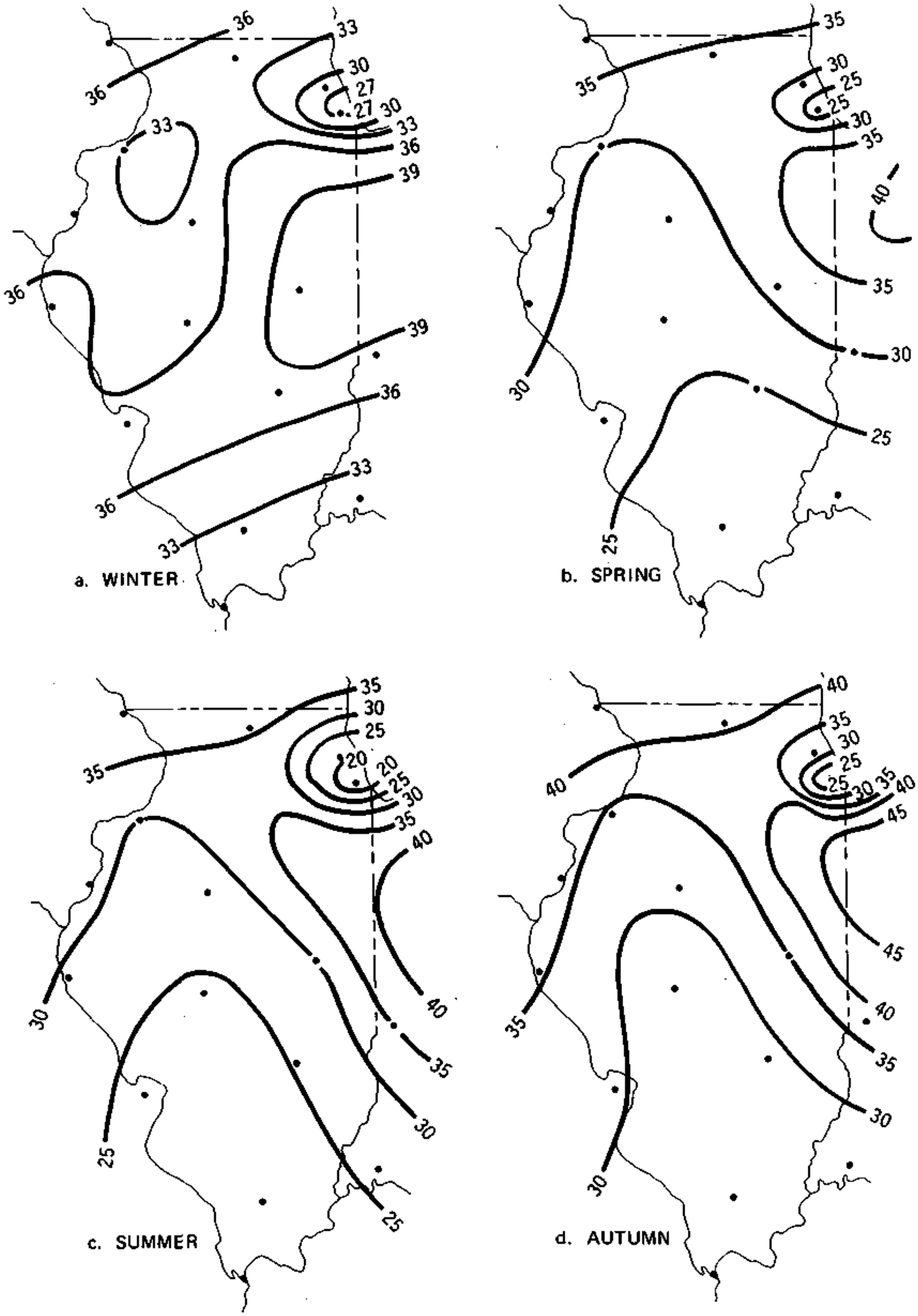


Figure 1. Average Number of Days with. Fog of any Type.

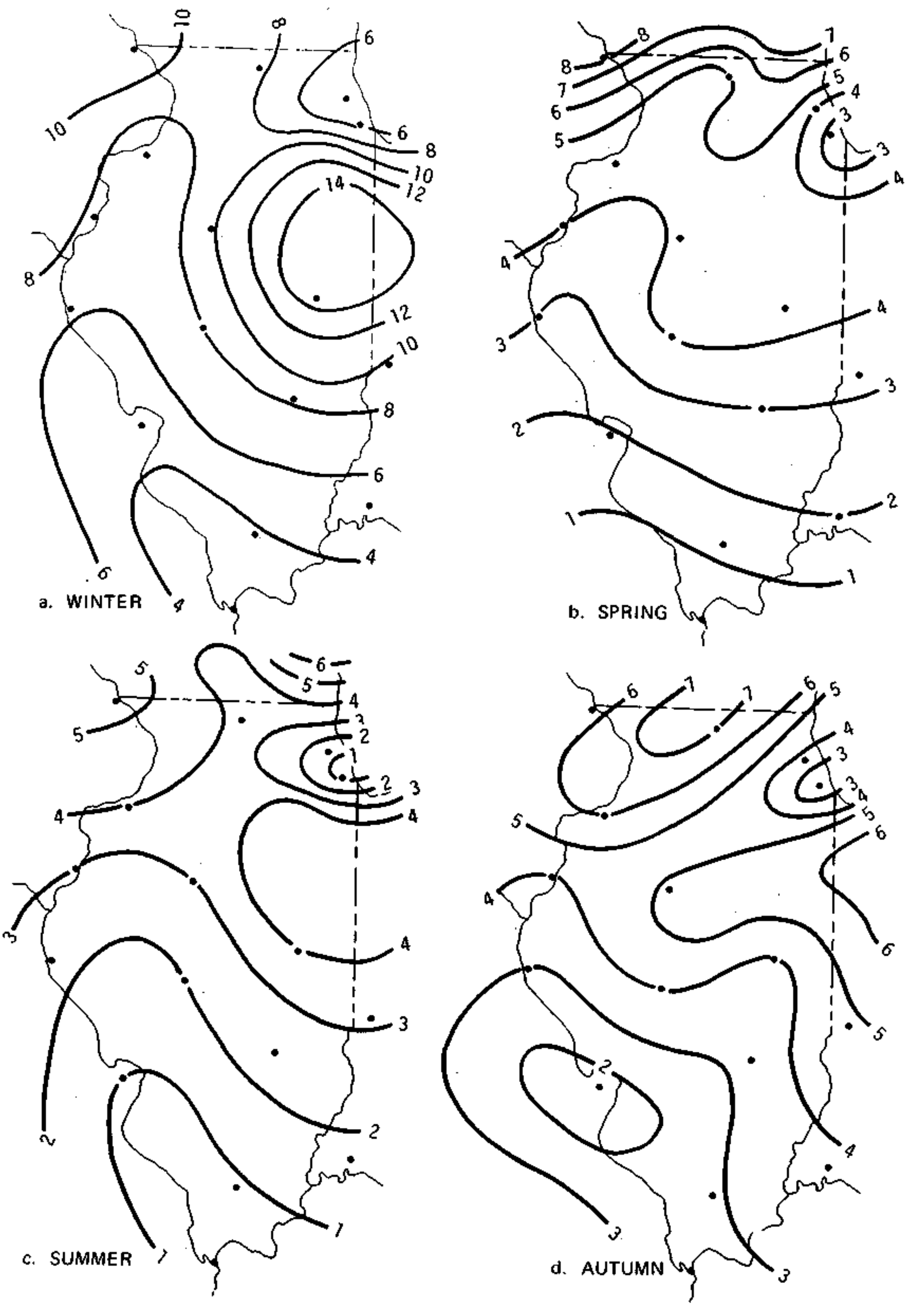


Figure 2. Average Number of Days with Dense Fog.

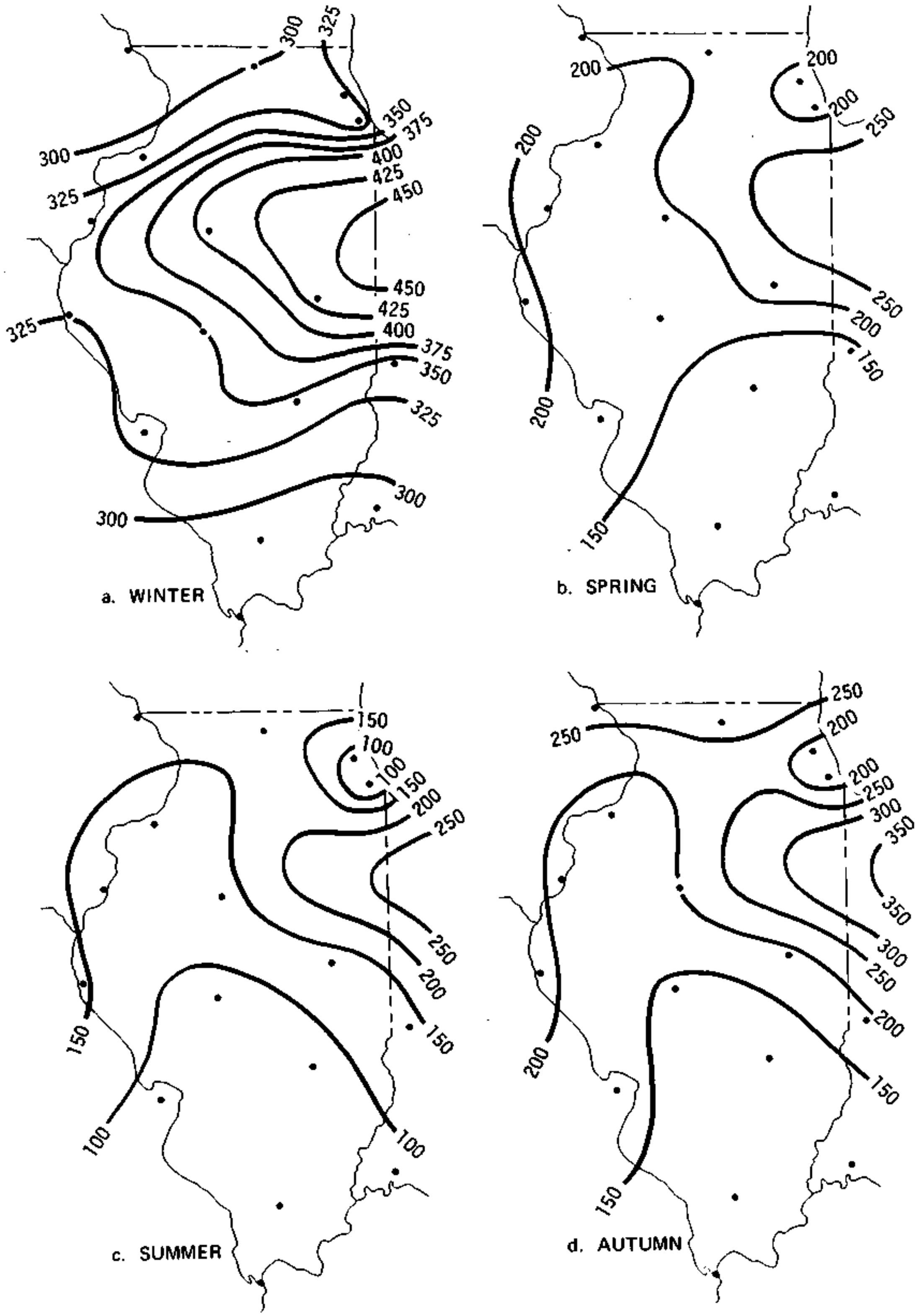


Figure 3. Average Number of Hours with Fog of any Type.

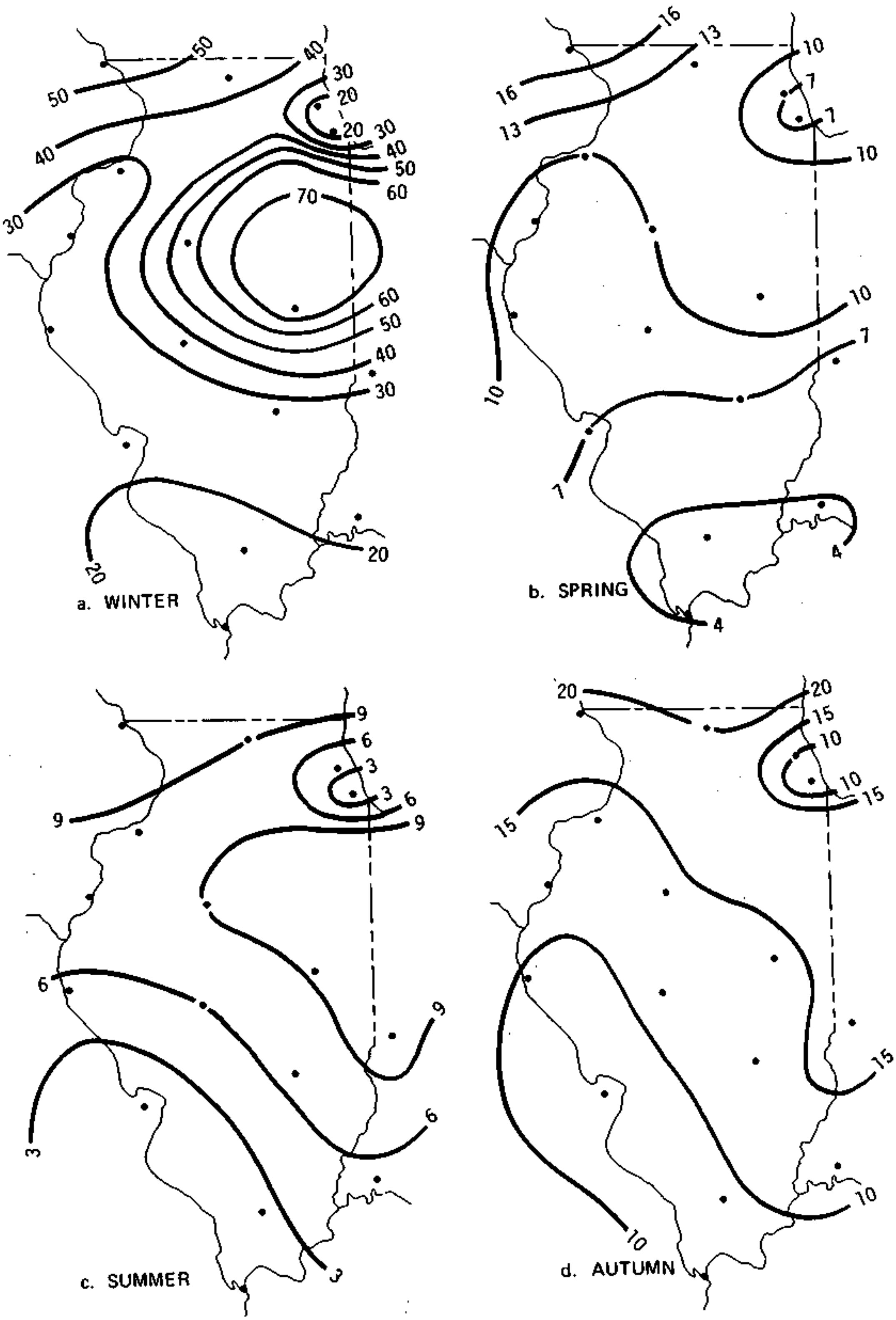


Figure 4. Average Number of Hours with Dense Fog.

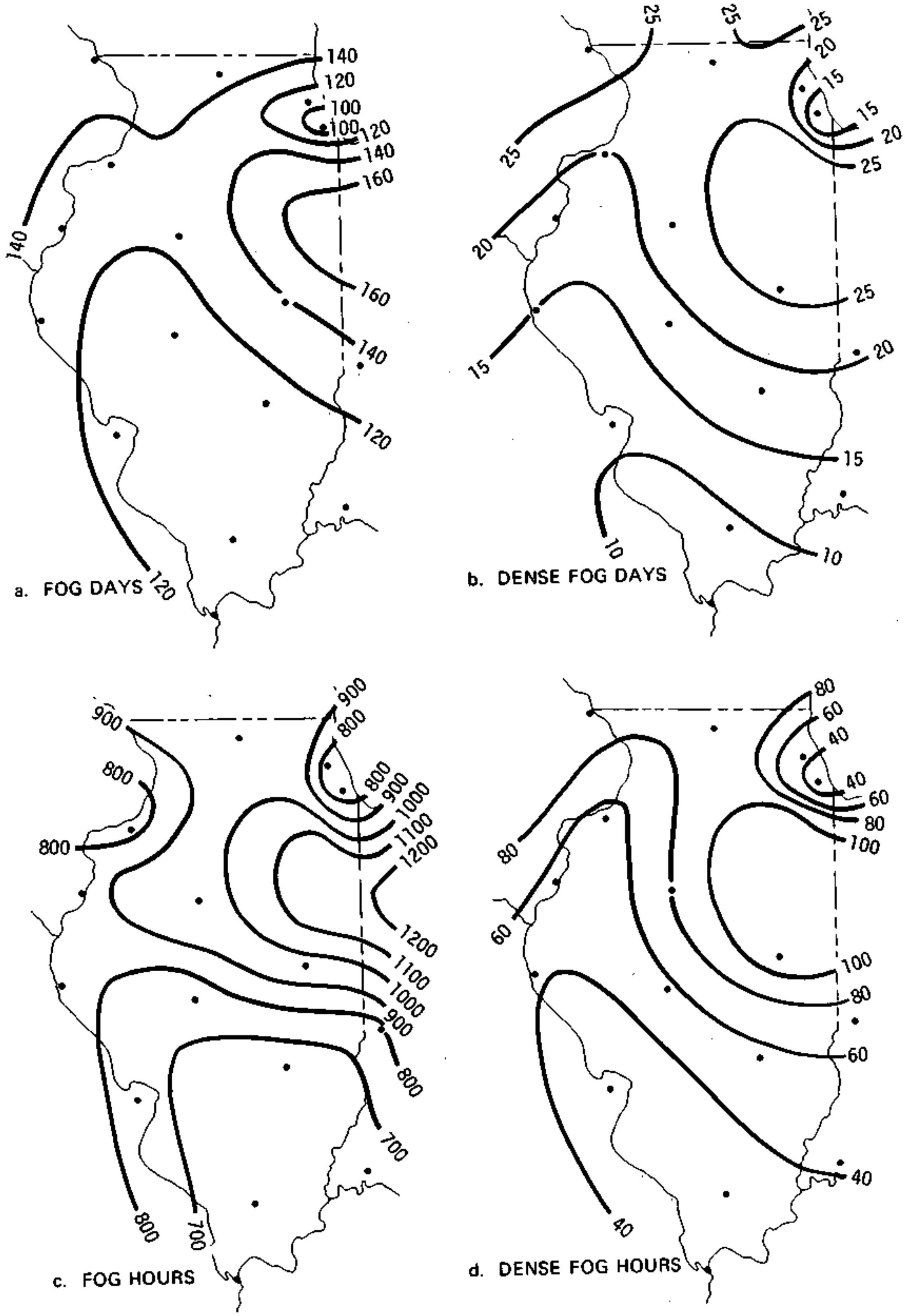


Figure 5. *Average Annual Distribution of Fog Days and Fog Hours.*

occurrences, that is, the percent of the total days and total hours which experience fog in each season and annually. This has been done in Tables 1 and 2 in which the distributions in Figs. 1-5 have been converted to the percent of possible occurrences for the seven stations with most complete records.

Table 1. Percent of Total Days with Fog at Selected Locations on a Seasonal and Annual Basis.

Average Percent of Total Days with Light, Moderate, or Dense Fog

Location	Winter	Spring	Summer	Fall	Annual
Chicago	30	26	19	24	25
Moline	37	33	33	37	35
Peoria	38	30	30	34	33
Springfield	39	30	26	31	32
St. Louis	40	30	26	34	33
Evansvilie	36	25	28	31	30
Indianapolis	43	35	47	46	43
Median	38	30	28	34	33
Range	30-1+3	26-35	19-47	24-46	25-43

Average Percent of Total Days with Dense Fog

Location	Winter	Spring	Summer	Fall	Annual
Chicago	6	3	1	2	3
Moline	8	4	4	7	6
Peoria	11	4	3	6	6
Springfield	9	4	2	4	5
St. Louis	6	2	1	2	3
Evansville	6	2	2	4	4
Indianapolis	9	3	3	6	5
Median	8	3	2	4	5
Range	6-11	3-4	1-4	2-7	3-6

Table 1 shows a winter median of 38% with a range of 30% to 43% among the seven stations for all fog types combined. The median decreases to 30% and 28%, respectively in spring and summer, then increases to 34% in fall. An annual median of 33% with a range from 25% to 43% is indicated. Thus , a substantial portion of the days do record fog sometime during the 24-hour period. However, Table 2 shows that a much smaller percentage of the total hours per season and annually are affected by fog.

Comparison of the dense fog values in Table 1 and 2 shows that it is not a major problem in Illinois even in winter which is the season of most frequent occurrence. Thus, winter medians of 8% of the total days and slightly more than 1% of the total hours are indicated. In summer these medians decrease to 2% and 0.3%, respectively, and on an annual basis are only 5% and 0.6%.

Table 2. Percent of Total Hours with Fog at Selected Locations on a Seasonal and Annual Basis.

	Average Percent of Total Hours with Light, Moderate, or Dense Fog				
Location	Winter	Spring	Summer	Fall	Annual
Chicago	14	8	4	7	8
Moline	14	8	6	8	9
Peoria	19	9	7	9	11
Springfield	16	8	4	7	9
St. Louis	1 5	9	4	8	9
Evansvilie	14	5	5	6	7
Indianapolis	19	12	13	13	14
Median	15	8	5	8	9
Range	14-19	5-12	4-13	6-13	7-14

	Average Percent of Total Hours with Dense Fog				
Location	Winter	Spring	Summer	Fall	Annual
Chicago	0.7	0.3	0.1	0.3	0.4
Moline	1.3	0.5	0.4	0.6	0.6
Peoria	2.7	0.2	0.4	0.6	0.9
Springfield	1.4	0.4	0.3	0.5	0.7
St. Louis	1.0	0.3	0.1	0.3	0.4
Evansville	1.0	0.2	0.2	0.5	0.5
Indianapolis	1.6	0.3	0.4	0.7	0.7
Median	1.3	0.3	0.3	0.5	0.6
Range	0.7-2.7	0.2-0.5	0.1-0.4	0.3-0.7	0.4-0.9

PERSISTENCE OF FOG

All Fog Combined

To evaluate the environmental effects of cooling ponds and lakes, the persistence of fog is an important consideration. Thus, if a cooling lake is enhancing the formation and/or intensity of natural fog, both the time of day and duration of the fog determine the magnitude of adverse effects to a large extent. Three stations were used in an analysis of the persistence of natural fog events in order to obtain estimates of the distribution of fog duration in hours in the northern, central, and southern parts of Illinois. Moline, Springfield, and Evansville were selected for this purpose.

For each station, data for the 1948-1964 period were tabulated to show the time of initiation of each fog event and its duration in hours. Separate analyses were made for each of the four seasons. The persistence of fog in hours for each location and each season is summarized in Table 3. In this table, the cumulative percent of all fog occurrences having durations of one hour or more are presented. Also shown are the total hours of fog upon which the percentages are based.

Table 3 shows that approximately 50% of all fog events in Illinois during winter will have durations of 6 hours or less. Less than 30% of the fogs last more than 12 hours. During this season when the occurrence of fog maximizes, fog begins most frequently in the period from 0500-0800 CST (Table 4). During 1948-1964, 26%, 22%, and 29% of all fog events began in this time period at Moline, Springfield, and Evansville, respectively. Thus, the early forenoon hours when traffic is relatively heavy with people going to work experience fog most frequently. This emphasizes the need to locate cooling ponds and lakes at sufficient distances from highways, so that the natural fog problem is not intensified.

Little difference is indicated in the winter distribution of fog durations throughout the state in Table 3. That is, the percentage of total fog events in the various duration categories is very similar. However, as shown in Fig. 3, the total hours of fog varies considerably within Illinois, so that the winter fog problem is more severe in central Illinois than in the southern part of the state, even though the percentage distribution of fog duration is similar.

The spring, summer, and fall distributions in Table 3 show greater percentages of short-duration fog than winter. During this period, over 50% of the fog events have durations of 4 hours or less. In summer, all three stations show over 50% of the occurrences persisting for 3 hours or less, less than 25% of the occurrences lasting more than 6 hours, and less than 5% persisting for more than 12 hours. In general, the persistence of fog minimizes in summer in all regions of the state.

Table 3. Percentage Distribution of Fog Duration by Seasons During 1948-1964 Period.

Cumulative Percent of All Fog Occurrences

Fog Duration (Hours)	Winter MLI	Winter SPI	Winter EVV	Spring MLI	Spring SPI	Spring EVV	Summer MLI	Summer SPI	Summer EVV	Fall MLI	Fall SPI	Fall EVV
1	11.1	13.3	11.1	17.2	32.0	15.8	18.3	22.4	15.1	16.5	24.3	18.2
2	21.3	24.4	21.2	35.6	51.4	33.0	38.9	43.3	33.4	33.9	45.4	35.0
3	30.2	31.3	29.5	45.6	61.6	44.8	50.5	59.0	51.9	44.7	58.3	47.8
4	39.1	37.3	38.8	54.9	68.3	54.9	60.9	70.0	63.7	54.3	65.0	56.4
5	47.3	42.5	44.5	61.9	72.8	62.1	69.5	76.9	73.6	62.6	70.1	63.1
6	52.8	47.9	50.0	67.3	77.4	69.3	75.7	82.1	80.0	68.1	73.5	68.7
6-12	72.8	71.1	72.5	84.1	90.1	91.1	94.9	97.6	97.5	87.8	89.3	92.5
12-18	83.3	81.6	85.0	93.2	95.4	95.4	97.9	99.4	99.4	94.4	95.4	97.2
18-24	89.2	88.7	90.1	96.4	97.8	98.6	98.2	99.6	99.7	97.2	97.9	99.1
>24	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total Cases	474	496	506	441	582	348	432	446	372	436	474	429

Table 4. Percentage Distribution of Fog Initiation by Season During 1948-1964 Period.

Percent of All Fog Occurrences Starting at Given Time

Time	Winter			Spring			Summer			Fall		
(CST)	MLI	SPI	EVV	MLI	SPI	EVV	MLI	SPI	EVV	MLI	SPI	EVV
2300-0200	12	15	13	13	14	15	22	21	19	16	14	15
0200-0500	15	16	13	22	22	20	43	48	50	20	23	22
0500-0800	26	22	29	21	17	22	11	12	13	28	25	29
0800-1100	8	8	9	9	11	9	4	4	4	6	7	6
1100-1400	8	8	9	8	8	8	4	2	2	5	6	5
1400-1700	8	10	10	8	10	7	2	2	2	8	9	5
1700-2000	10	9	7	10	8	8	6	3	3	8	6	4
2000-2300	13	12	10	9	10	11	8	7	8	9	10	12

Greater differences in the percentage distributions occur among the three stations during spring to fall than in winter, with Springfield showing the greatest percentage of short-duration fogs of 1 to 3 hours. A valid explanation of this difference cannot be given at this time. Fog frequency and duration can be affected considerably by local features of the terrain. Springfield does have the greatest number of fog hours in the spring-fall period among the three stations, and the differences appear to be the result primarily of more occurrences of fog of short duration in the Springfield area.

As a check on the Springfield statistics, data for St. Louis and Indianapolis were also processed for each season. In spring, the St. Louis percentage distributions were closer to those for Evansville and Moline, but they were very similar to Springfield in summer and fall. Indianapolis, as expected, showed percentage distributions closer to those for Moline and Evansville in all seasons. Thus, it was concluded that the Springfield statistics are valid and approximately representative of the west central and southwestern parts of the state.

Analyses indicated close agreement among the three stations in the time of day when fog is most likely to begin (Table 4). Fall is similar to winter, since the most frequent period of initiation in the 1948-1964 period was 0500-0800 when 28%, 25%, and 29% of the fog events started at Moline, Springfield, and Evansville, respectively. The strongest bias toward a particular starting time occurs in summer. At Moline, Springfield, and Evansville, respectively, 43%, 48%, and 50% of the fog occurrences started in the 0200-0500 period during 1948-1964. The most frequent starting time in spring was nearly equally divided between the 0200-0500 and 0500-0800 periods. Early spring follows the winter pattern and late spring is similar to summer.

Analyses were made to determine whether long-duration fogs tend to initiate at a different time than indicated for all fog events combined in

Table 5. Percentage Distribution of Dense Fog Durations by Seasons During 1948-1964 Period.

Fog Duration (Hours)	Cumulative Percent of All Dense Fog Occurrences											
	Winter			Spring			Summer			Fall		
	MLI	SPI	EVV	MLI	SPI	EVV	MLI	SPI	EVV	MLI	SPI	EVV
1	44.8	26.4	21.0	35.9	44.0	30.8	54.3	50.0	35.8	58.7	27.2	26.5
2	56.7	47.1	42.0	66.6	52.0	30.8	62.8	66.7	67.9	71.4	56.7	64.8
3	61.2	66.6	63.0	76.9	80.0	54.0	82.8	83.4	85.7	79.4	65.8	82.4
4	76.1	77.0	69.4	76.9	84.0	69.3	94.2	95.9	96.4	82.6	77.2	82.4
5	86.5	86.2	82.3	84.6	96.0	77.0	97.1	95.9	100.0	87.4	88.6	82.4
6	91.0	87.3	90.4	89.7	96.0	84.7	97.1	95.9	100.0	93.7	88.6	85.3
6-12	98.5	96.5	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
12-18	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total Cases	67	87	62	39	25	13	35	24	28	63	44	34

the previous discussion of initiation. Since the largest portion of long-duration fogs was in the category of 6 to 12 hours, calculations of the most frequent starting times were made for this group of fog events. Results showed that the most frequent starting time for these fogs was 2300-0200 CST in all seasons. During winter, 22% to 26% of these fog events initiated in this time period. In spring, the percentage varied from 29% to 35% among the three stations, and in summer they ranged from 47% to 69%. In fall, all three stations had 33% of the 6-hr to 12-hr fogs starting in the 2300-0200 period. Thus, these fogs tended to initiate near midnight and end between early forenoon and mid-day. They account for approximately 22%, 17%, 17%, and 20%, respectively, of all winter, spring, summer, and fall fog events.

Dense Fog

Tables 5 and 6 present summaries for dense fog occurrences similar to those prepared for all fogs combined in Tables 3 and 4. The dense fog variations between stations and their seasonal trends are more erratic than for all fogs combined, and this results partly, at least, from the much smaller sample of dense fogs. Only 12-18% of all fog hours were classified dense in winter, and this reduced to 4-9% in the spring-summer period, and to 8-14% in fall at the three stations.

Table 5 shows that dense fogs in all regions of the state tend to have short durations in the majority of the occurrences. Thus, in winter all three stations show over 60% of the dense fogs lasting 3 hours or less. In summer, over 80% of the relatively few dense fogs have durations less than 3 hours, and over 60% last 2 hours or less.

Table 6. Percentage Distribution of Dense Fog Initiation by Season During 1948-1964 Period.

Percent of All Dense Fog Occurrences Starting at Given Time

Time	Winter			Spring			Summer			Fall		
(CST)	MLI	SPI	EVV	MLI	SPI	EVV	MLI	SPI	EVV	MLI	SPI	EVV
2300-0200	8	10	18	13	16	31	17	17	18	16	9	12
0200-0500	22	15	15	36	56	31	49	54	64	30	37	38
0500-0800	24	18	29	26	20	15	31	29	14	35	25	41
0800-1100	7	8	3	10	4	8	0	0	0	5	7	0
1100-1400	3	4	6	0	0	7	0	0	0	0	0	3
1400-1700	8	10	8	0	0	0	0	0	0	2	0	0
1700-2000	10	15	13	5	4	0	0	0	0	3	2	3
2000-2300	18	20	8	10	0	8	3	0	4	9	20	3

Table 6 shows that dense fog in spring and summer is initiated most often in the 0200-0500 period, in general agreement with the preferred starting time for all fog occurrences combined in Table 4. Except for Springfield, dense fog during winter started most often in the 0500-0800 period during 1948-1964, again similar to findings for all fogs combined. At Springfield, the winter maximum shifted to 2000-2300 followed closely by 0500-0800. During fall, the Springfield maximum was 0200-0500, the same as for the spring-summer period. With dense fogs tending to start most frequently during the 0500-0800 period in winter and over 60% lasting 3 hours or less, this adverse weather is most likely to occur in the early morning to mid-forenoon period when traffic has one of its diurnal peaks (people going to work), and this finding is in agreement with that found for all fogs combined (discussed earlier).

DIURNAL DISTRIBUTION OF FOG

As a logical follow-up of information presented in the last section, the diurnal distribution of fog was investigated to determine those hours when the probability of fog would be greatest during the day in each of the four seasons. Time of most frequent initiation was discussed in the previous section. Complete and partial records for the period, 1948-1964, were available for this phase of our studies. Stations included: Moline, Chicago, Springfield, Peoria, Rockford, and Rantoul in Illinois; Evansville, Indianapolis, and Terre Haute, Indiana; St. Louis, Missouri; and, Burlington, Iowa. Records used were hourly surface observations obtained from the National Climatic of the National Oceanic and Atmospheric Administration at Asheville, North Carolina and the published Local Climatological Data for the stations.

Diurnal distributions were determined in terms of actual fog hours and in percentages of the total hours of fog. The percentage distributions showed only small variations in Illinois, so average distributions were determined for the state in each season. The results are presented in Fig. 6.

Some shifting in the time of maximum fog frequency is indicated in Fig. 6. The maximum occurs latest in the day (0800 CST) during the winter when sunrise is latest. The earliest maximum is at 0500 CST in summer, whereas spring and fall are intermediate with their maxima at 0600 and 0700 CST, respectively. Minimum frequencies occur in mid-afternoon in all seasons with some slight shifting between them. The 3-hour period of maximum frequency varies from 0600-0900 in winter to 0500-0800 in spring, 0400-0700 in summer, and 0500-0800 in fall. Thus, the problem of lake-induced and lake-enhanced fog would normally be greatest in the early part of the day when natural fog formation is most common. During winter when the fogging problem maximizes, the most critical period is early to mid-forenoon.

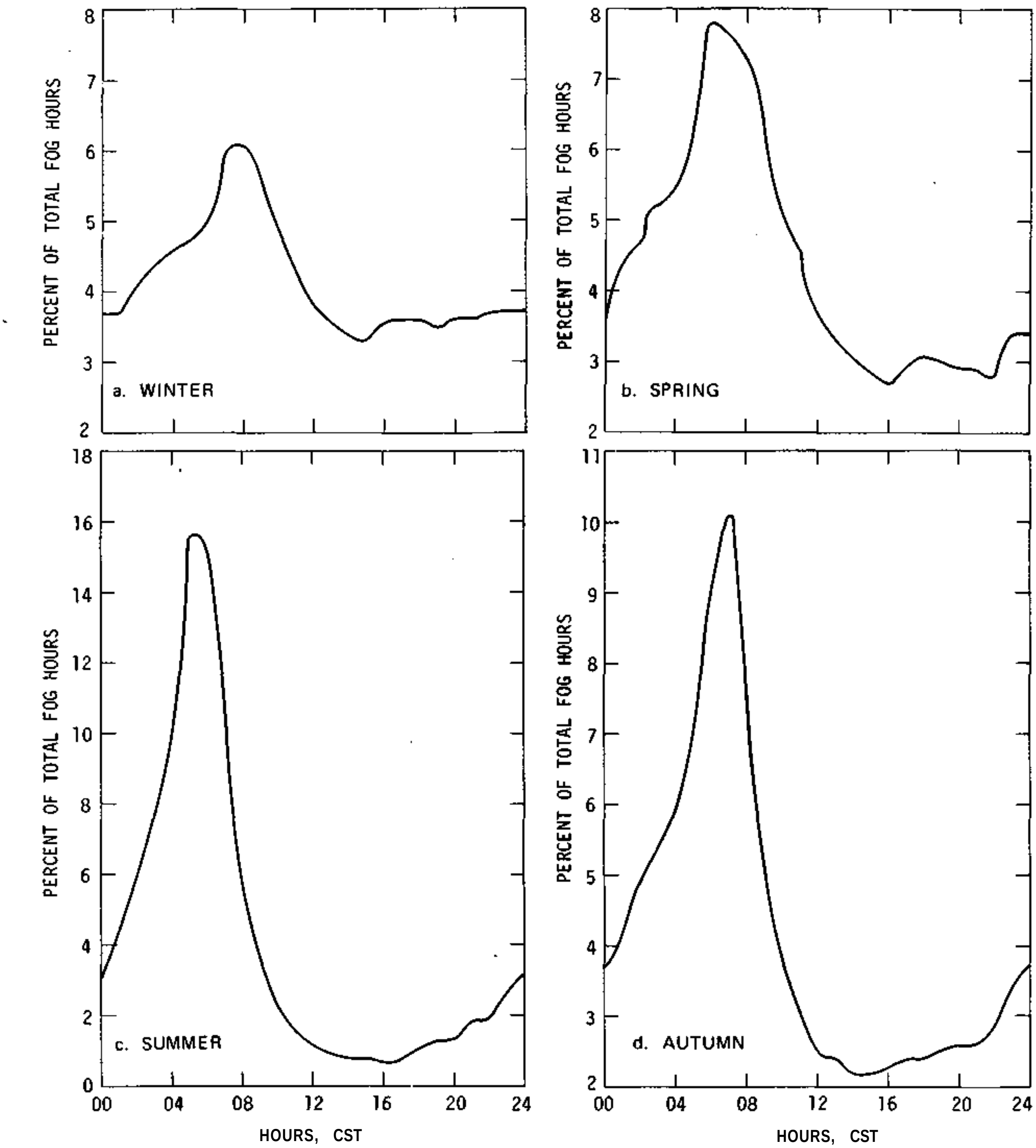


Figure 6. Diurnal Distribution of Fog Hours Grouped by Season.

TIME TRENDS IN FOG OCCURRENCES

Annual 5-Year Moving Averages

Figure 7 shows 5-year moving averages of the annual number of fog days for six locations that represent various regions of the state. These were calculated to search for trends in the fog climatology that might result from alteration of the environment from man's activities. For example, certain types of particulates that are discharged into the atmosphere from industrial stacks can serve as condensation nuclei upon which fog droplets can form. If such emissions have increased substantially in recent years, the result could be an increase in fog frequency in and near urban areas, such as those represented by the curves in Fig. 7. Conversely, efforts have been made to reduce the concentration of stack pollutants in some industries in recent years, and this reduction could conceivably lead to a reduction in fog frequency if the reduction in condensation nuclei was substantial. In any case, trends should be recognized and accounted for in evaluating the effects of cooling lakes and other potential sources of inadvertent weather modification.

Figure 7 shows a pronounced decrease in fog frequency from the start of the sampling period in 1944 to a minimum in the early to mid 1950's, followed by a rapid increase for a few years , another period of decrease, and finally a second period of increase in recent years. The minima in the early 1950's and early 1960's are the result of drought conditions. The extreme minimum in fog frequency in the early 1950's was associated with one of the worst droughts on record in Illinois. The low humidities accompanying drought conditions suppresses fog formation, and consequently, results in the excellent correlation between drought and fog shown by Fig. 7.

Examination of the individual curves in Fig. 7 shows large time variability, but only slight indications of a time trend in the fog frequency. Peoria does show evidence of an overall trend for increasing fog occurrences from the start of the sampling period (1944) to 1973. However, Chicago and Moline which are also in the northern half of the state do not exhibit this trend. Both stations show annual occurrences at present similar to those at the start of the sampling period. Springfield, St. Louis, and Evansville, which are representative of the southern part of the state, do show evidence of an overall increase in fog frequency. In general, the conclusion is that there has been an increase in fog frequency in most areas since World War II and this increase has been most evident in and near highly industrialized urban areas. However, the increasing trend apparently has not been strong in Illinois and surrounding regions, so that statistics compiled for the 1944-1973 sampling period can be used in deriving first approximations of cooling lake effects on fog frequency now and in the near future.

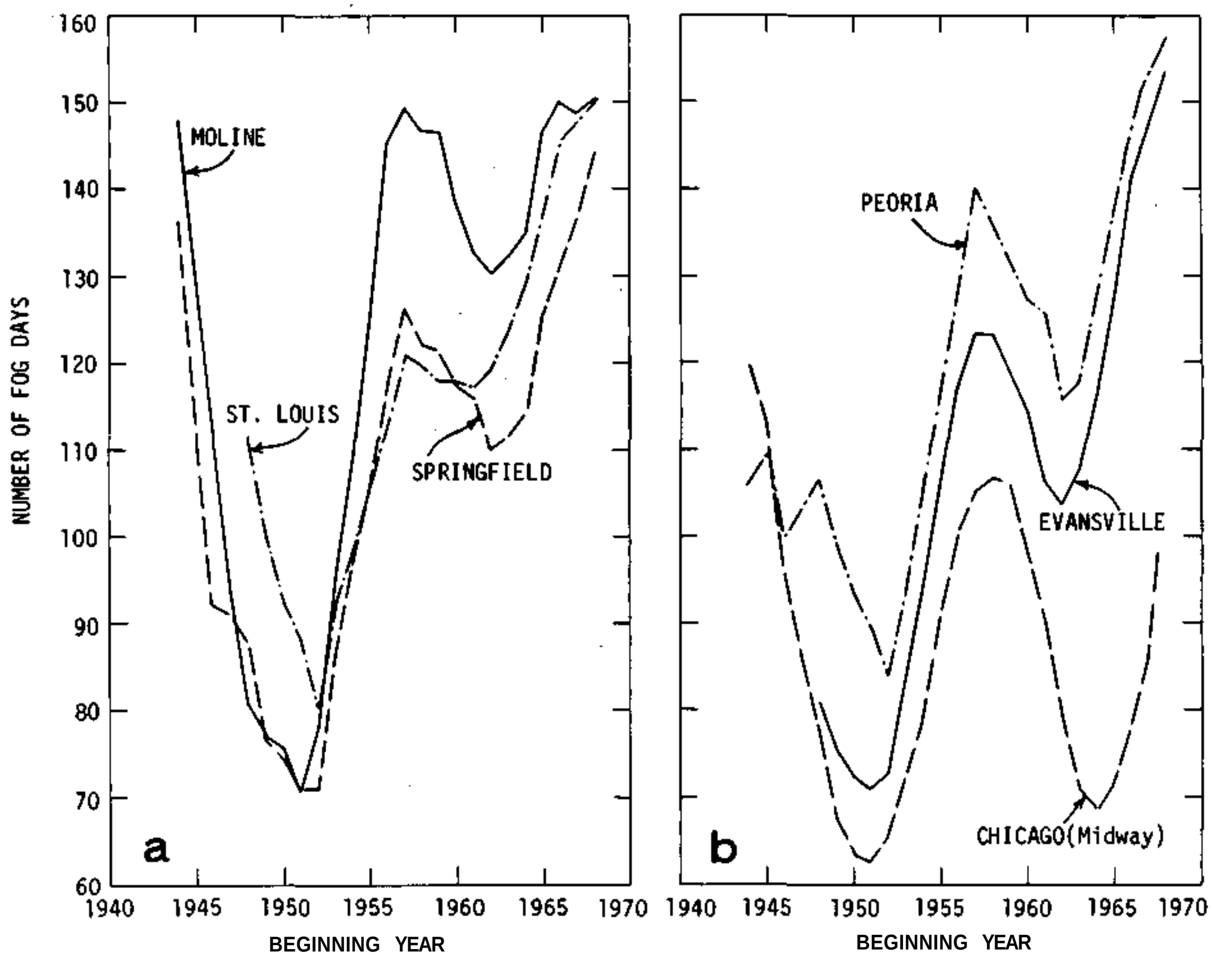


Figure 7. 5-Year Moving Averages of Annual Number of Fog Days.

Seasonal 5-Year Moving Averages

In addition to the 5-year moving averages of annual fog frequencies discussed earlier, similar curves were constructed for each season at each station having sufficient length of records. During winter, the period of most frequent fog occurrences, no significant evidence of a trend was observed in the 1944-1973 sampling period at Moline or Chicago. A very weak upward trend was indicated at Springfield, Peoria, and Evansville. At St. Louis, a substantial upward trend was noted with the number of fog days in the 25-35 range in the early years and a general upward trend to 40-42 occurrences in the most recent years. In general, the foregoing analyses lead to the conclusion that most areas have not experienced a significant increase in the average frequency of winter fogs since World War II.

Spring data showed evidence of an upward trend at St. Louis, Evansville, and Peoria. Moline exhibited no trend. Chicago and Springfield had a very weak downward trend. Thus, there is no real agreement among stations and the observed trends cannot be accepted with a high degree of reliability.

Moline and Chicago showed no real evidence of a summer trend. Springfield and St. Louis indicated a slight upward trend, whereas Peoria and Evansville indicated quite pronounced upward trends. For example, summer fog frequencies have varied from 20-22 at Peoria near the beginning of the sampling period (1944) to 35-40 in the past several years. With a variation from none to weak to pronounced, there is, again, no stable trend exhibited between stations.

Fall data again showed no evidence of a trend at Chicago and Moline. Springfield exhibited a slight upward trend. Again, Peoria, St. Louis, and Evansville showed upward trends.

Summarizing, Peoria, St. Louis, and Evansville showed evidence of upward trends during the 1944-1973 period for each of the four seasons. No trends were indicated at Chicago and Moline except possibly for a very weak downward trend in spring. Thus, as indicated in the discussion of the annual trend analysis earlier, there is evidence of a modest upward trend in fog frequency in central and southern Illinois since World War II, but this trend is not evident in the northern part of the state, based upon Chicago and Moline data. The upward trends are probably the result of relatively rapid expansion of industrial activities in those urban areas. No reliable explanation for the differences between the northern cities and the central and southern cities can be provided at this time.

PROBABILITY DISTRIBUTION OF FOG HOURS

All Fog Combined

Figures 3 and 5 show the distribution of average number of hours with fog on a seasonal and annual basis. However, information is frequently

Table 7. Distribution of Total Fog Hours at Selected Stations.

Probability (%)	Chicago	Moline	Springfield	St. Louis	Evansvilie	Indianapolis
	Number of Hours Equalled or Exceeded					
	ANNUAL					
5	880	1260	1080	1010	935	1205
10	810	1160	1000	963	905	1160
20	735	1060	910	890	860	1090
30	680	985	845	835	820	1030
40	640	925	802	780	785	980
50	605	880	760	740	755	935
	WINTER					
5	435	530	590	545	525	455
10	398	483	540	512	465	447
20	342	430	557	419	405	428
30	301	390	405	360	365	410
40	266	360	365	320	335	390
50	235	327	330	285	310	370
	SPRING					
5	292	310	242	290	207	280
10	254	282	230	270	192	269
20	213	251	212	229	171	243
30	188	228	198	203	155	223
40	169	208	183	182	141	206
50	15 3	191	175	169	132	189
	SUMMER					
5	132	278	161	152	183	290
10	128	250	157	142	177	280
20	115	217	148	130	162	257
30	103	194	138	120	151	230
40	93	177	128	110	140	204
50	83	161	115	98	128	180
	FALL					
5	231	382	300	291	309	332
10	208	350	271	275	280	317
20	178	303	219	240	241	283
30	159	271	184	210	210	255
40	142	243	160	182	185	228
50	128	218	140	160	161	202

needed on the probability of abnormal occurrences of fog. Therefore, probability distributions were developed from data for six stations having complete records for the 1948-1964 period. Results are summarized in Table 7 for these stations, which are representative of various areas of the state and the immediate surrounding region.

In this table, the number of fog hours that will be equalled or exceeded at selected probability levels is given. Thus, at Springfield, which is a central Illinois station, there is a 5% probability or 1 chance in 20 that a year selected at random will experience 1080 or more hours with fog. Similarly, on the average, there will be 5% of the winters that will have 590 or more fog hours. At Springfield, the number of hours at the 5% level decreases to 242 in spring, 161 in summer, and then increases to 300 in fall.

Data at any probability level from Table 7 can be plotted on base maps and used to draw fog-hour patterns for interpolation purposes when information is needed for sites at considerable distances from any of the analyzed stations. In doing this, the patterns of average number of fog hours in Figs. 3 and 5, which were developed with the assistance of data from several other stations in addition to those in Table 7, should be used as a guide in drawing the statewide patterns. Other probability-level estimates can be obtained by interpolation in Table 7.

Dense Fog

The probability distribution of hours with dense fog (visibility ≤ 1/4 mi) was determined for the 6 stations shown in Table 8. This was done for the most critical season, winter, and on an annual basis. The number of hours equalled or exceeded at each probability level is consistent with the mean frequencies shown in early maps for the state. That is, the stations with the greatest average number of fog hours also tend to have the greatest number at the various probability levels. Thus, at the 5-percent probability level (1 year in 20), Table 8 indicates that Chicago will have 62 or more dense fog hours and this number decreases gradually to 33 hours at the 50-percent level (1 chance in 2). Springfield, which normally experiences more fog than Chicago, shows 86 hours at the 5-percent level and 59 hours at the 50-percent level on an annual basis.

RELATION BETWEEN AIR TEMPERATURE AND FOG

The seasonal distribution of fog hours according to air temperature was determined for six stations (CHI, MLI, SPI, STL, EVV, and IND), based upon data for the 1948-1964 period. The relation between air temperature and fog occurrences under natural conditions provides useful background information in assessing the weather conditions under which cooling lake initiation and enhancement may be stimulated most frequently. When cumulative percent of fog hours was related to air temperature, no distinct trend between stations was obtained. Therefore, all station data were combined to obtain an average relation between cumulative percent of fog hours and temperature for the Illinois (Midwest) region. Seasonal curves for all fog hours combined and dense fog hours are shown in Fig. 8.

Table 8. Probability of Dense Fog Occurrences.

Probability (%)	Number of Hours Equalled or Exceeded					
	Chicago	Moline	Springfield	St. Louis	Evansville	Indianapolis
	ANNUAL					
5	62	88	86	77	79	96
10	56	82	81	71	70	90
20	48	74	74	60	60	81
30	43	68	68	51	53	75
40	37	62	64	43	48	69
50	33	58	59	36	43	64
	WINTER					
5	53	59	64	58	56	67
10	42	51	57	48	44	61
20	29	41	47	37	32	54
30	22	34	39	29	27	47
40	17	29	33	23	25	41
50	13	24	28	18	20	33

In winter, 40% of all fog hours were found to occur with temperatures in the range from 30°F to 40°F. Over 50% of the dense fog hours occurred within this range of winter temperatures.

Examination of the curves for summer, the season when the fog problem minimizes, shows nearly 60% of all fog hours associated with temperatures from 60°F to 70°F. Nearly 70% of the dense fog hours occur with these temperatures. Air temperatures that favor the formation of natural fog should be closely related to air temperatures favorable for cooling lake initiation and enhancement of fog. Therefore Fig. 8 can be used as a guide in assessing the temperature ranges in which the cooling lake problem is most likely to maximize.

Table 9 shows the cumulative percent of hourly temperatures for various ranges of temperature for Moline (MLI), representative of northern Illinois, and Evansville (EVV), which experiences temperatures typical of the southern

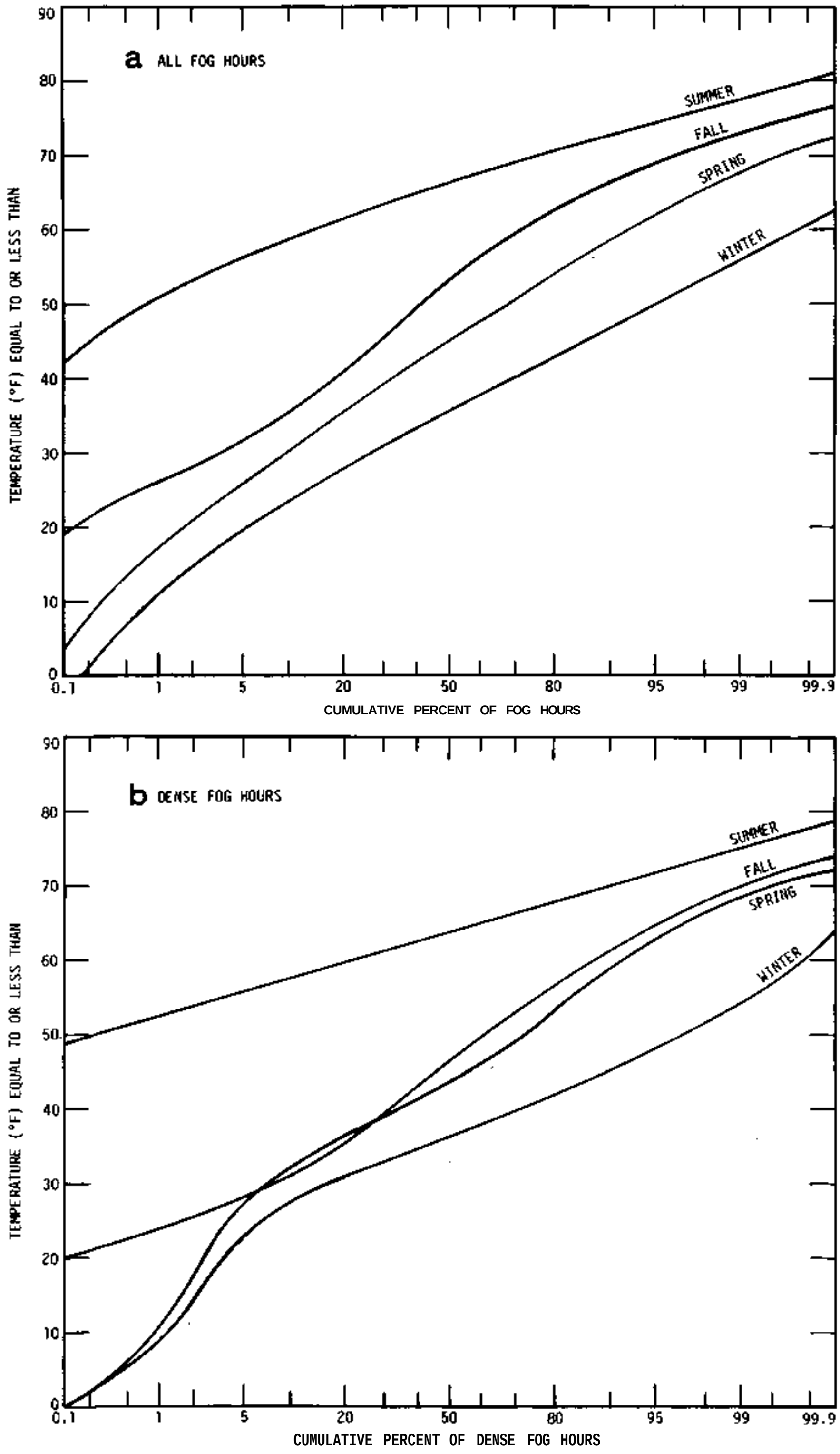


Figure 8. Seasonal Distribution of Fog Hours Grouped by Air Temperature.

part of the state. Values are shown for the middle month of each season, based upon 1951-1960 data-

Table 9. Percentage Distribution of Hourly Temperatures, 1951-1960.

Temperature Equalled or Exceeded (°F)	Cumulative Percent of Hourly Temperatures							
	January		April		July		October	
	MLI	EVV	MLI	EVV	MLI	EVV	MLI	EVV
90					5	10		
80			2	4	31	44	2	4
70			9	17	73	88	11	18
60			26	43	97	99	31	43
50	1	11	51	69	100-	100-	60	69
40	5	28	79	92			86	92
30	30	67	98	98			99-	99+
20	63	90	99+	100-			100-	100-
10	84	98						
0	96	100-						

Table 9 provides estimates of the temperatures occurring most frequently in the four seasons. Thus, 25% of all hours in January had temperatures in the 30° to 40° range at Moline during the 1951-1960 period, compared with 39% at Evansville. As indicated earlier, this temperature range accounts for approximately 40% of all fog hours in Illinois. The most frequent range of hourly temperatures is 20° to 30° at MLI and 30° to 40° at EW. Thus, Table 9 indicates that the highest percentage of fog hours occurs with those temperature having the greatest frequency in southern Illinois in winter, but not in the northern part of the state where the most frequent temperature range is 20° to 30°.

In summer, the greatest frequency of fog hours occurs at 60°-70°, relatively cool temperatures according to Table 9. The most frequent range of July temperatures, 70°-80°, accounted for 44% and 42% of the hourly temperatures, respectively, at EVV and MLI, but the highest percentage of summer fog hours (nearly 60%) were found to occur at 60° to 70°. In general, fog is favored by relatively mild temperatures in winter (especially in the northern part of the state) and by relatively cool temperatures in summer.

RELATION BETWEEN DEWP0INT TEMPERATURE AND FOG

In the previous section, results of an investigation of the relationship between air temperature and the distribution of fog hours were summarized. In this section, results of a similar analysis of the frequency distribution of fog hours according to dewpoint temperature depressions are briefly summarized. Since the dewpoint depression (difference between air and dewpoint temperature) is a measure of the proximity of the air to saturation, a definite relationship between this atmospheric parameter and fog is to be expected. The dewpoint depression provides a moisture index which can be useful in evaluating the potential of cooling ponds for initiating and enhancing fog, and determination of its distribution with respect to fog occurrences provides information on the temperature-moisture conditions most amenable to fog formation.

Table 10 shows the percentage distribution of all fog hours grouped by dewpoint depression, based upon 1948-1964 data for six key stations representative of climatic conditions in various areas of Illinois and adjacent regions. Data are presented for winter and summer, the seasons normally experiencing maximum and minimum fog frequencies. The dewpoint depressions for winter show that a majority of the fog hours occur with depressions of 2°F or less at all stations, with a median value of 74% for the six stations. A similar relation is indicated for summer with a slightly lower median value of 69% for fog occurrences with depressions of 2° or less.

Table 10 indicates a distribution of dewpoint depression with considerable similarity to the fog hour distributions in Figs. 3 and 4. Thus, the fog-hour low for winter in the Chicago urban area in Fig. 3 and the fog-hour peak extending westward into east central Illinois from Indianapolis are indicated by the CHI and IND-SPI values in Table 10.

Table 11 presents percentage distributions for dewpoint depressions associated with dense fog occurrences. This table shows that dense fog occurs only occasionally with dewpoint depressions exceeding 1°F in either winter or summer. In fact, approximately 2/3 of the dense fog occurrences are associated with completely saturated air (0°F depression), as indicated by the median values for the six stations. Chicago is apparently an exception with dense fog occurring frequently with 1-degree depressions. This urban anomaly is supported by data for both the Midway and O'Hare stations, and is apparently related to weather conditions affected by the unusual combination of an urban-affected and lake-affected climate.

From this section and the preceding section on air temperatures, it is apparent that winter fog is most likely to occur with relatively warm air temperatures in the range from 30° to 40° and dewpoint depressions of 0° to 2°. In summer, fog is most likely to form with relatively cool temperatures in the range from 60° to 70° and dewpoint depressions of 0° to 2°. With dense fogs, the dewpoint depressions are seldom more than 2°F in either winter or summer.

Table 10. Percentage Distribution of All Fog Hours Grouped by Dewpoint Depression, 191+8-1964.

Winter

Percent of Fog Hours Equal to or Less than Given Dewpoint Depression (°F)

Station	0°	1°	2°	3°	4°	5°	≥6°
CHI	11	37	72	89	97	99	100
MLI	20	45	72	88	95	98	100
IND	26	56	80	92	97	99	100
SPI	21	50	76	90	97	99	100
EVV	24	48	76	88	95	98	100
STL	21	46	71	84	93	97	100
Median	21	47	74	89	96	99	100

Summer

	0°	1°	2°	3°	4°	5°	≥6°
CHI	5	27	57	84	94	97	100
MLI	11	39	70	89	95	98	100
IND	20	55	80	92	96	98	100
SPI	13	38	68	88	97	99	100
EVV	11	45	74	90	96	98	100
STL	10	36	58	81	90	95	100
Median	11	39	69	89	96	98	100

Table 11. Percentage Distribution of Dense Fog Hours Grouped by Dewpoint Depression, 1948-1964.

Winter

Percent of Fog Hours Equal to or Less than Given Dewpoint Depression (°F)

Station	0°	1°	2°	3°	4°	5°	≥6°
CHI	40	82	97	100	--	--	--
MLI	77	88	92	97	99	100-	100
IND	73	95	97	99	99+	100-	100
SPI	63	93	99	100-	100	--	--
EVV	60	84	96	98	100	--	--
STL	74	93	98	100-	100	--	--
Median	68	91	97	99	100	--	--

Summer

	0°	1°	2°	3°	4°	5°	≥6°
CHI	47	87	90	93	98	98	100
MLI	62	93	100	100	--	--	--
IND	67	90	99	100	--	--	--
SPI	63	83	95	100	--	--	--
EVV	52	89	99	100	--	--	--
STL	67	92	95	98	98	98	100
Median	63	90	97	100	--	--	--

RELATION BETWEEN SURFACE WINDS AND FOG

The intensity of fog is strongly related to surface wind speeds, since mechanical turbulence which increases with increasing wind speed exerts a dissipating force on any fog initiated over an area. Thus, fog is less likely to occur and persist with high wind speeds than with light speeds. The distribution of wind directions is partly determined from synoptic weather conditions, but can be modified considerably by local terrain features, such as hills, valleys, and large water bodies. The direction distribution of surface wind flow is highly important in locating cooling lakes and assessing their environmental effects, since this distribution could have a major effect upon where the lake contribution to fog enhancement maximizes.

Data for six key stations (CHI, MLI, SPI, STL, EVV, IND) were used to derive the frequency distribution of all fog hours combined and dense fog hours, according to wind speed and wind direction. The wind speed-fog hour relations are summarized in Table 12 in which the cumulative percentage distribution is shown for all fog hours and dense fog hours in each season, based upon averages for the six stations. Wind speed may be affected considerably by exposure of the wind instruments. Therefore, the station data were combined after it was determined that no distinct areal trend in wind speeds was present. The average distribution is considered to be the most representative statistic to evaluate the typical fog-wind speed relation in Illinois and surrounding regions.

Table 12 shows that nearly all dense fogs during summer and fall occur with winds less than 10 mph, especially in summer when these winds accounted for 99% of the dense fog hours. In winter and spring, most dense fogs also occur with wind speeds under 10 mph, but approximately 15% of the 1948-1964 cases did occur with stronger winds; however, only 3% of the dense fog hours were recorded with winds of 15 mph or greater in these two seasons.

Table 12. Average Relation Between Fog Occurrence, Wind Speed, and Season During 191+8-1964.

	Cumulative Percent of Fog Hours for Given Seasonal Fog Type							
Hourly Wind	Winter		Spring		Summer		Fall	
Speed (mph)	All	Dense	All	Dense	All	Dense	All	Dense
0 - 4	20	41	19	54	49	77	37	68
5 - 9	58	84	52	87	86	99	73	96
10 - 14	87	97	83	97	98	100	92	99
≥15	100	100	100	100	100	100	100	100

Considering all types of fog combined, Table 12 shows that over 40% of the fog hours occur with winds of 10 mph or greater in winter and spring, indicating that light to moderately dense fogs survive frequently in windy conditions during these two seasons. However, in summer only a small portion (14%) of all fogs were recorded with winds of 10 mph or greater. Combining the information in Table 12 with that from the previous two sections, we find that dense winter fogs tend to form most commonly with relatively warm temperatures of 30° to 40°F, dewpoint depressions of 1°F or less, and wind speeds less than 10 mph. In summer, dense fogs occur most frequently with relatively cool temperatures of 60° to 70°, dewpoint depressions of 1° or less, and wind speeds less than 5 mph.

Table 13 shows the percentage distribution of fog hours stratified by wind direction for each season. Averages for the six stations were again used, since there was no distinct regional trend in preferential wind directions for fog occurrences. The averages in Table 13 show no outstanding trends with respect to direction with either all fog hours combined or dense fog hours. The calm wind condition becomes more pronounced in dense fogs in all seasons, particularly in the summer-fall period.

No generalization can be made with regard to wind directions associated with fog, except that a very weak trend does exist for the maximum fog occurrence with wind directions having an easterly component.

Table 13. Average Relation Between Fog Occurrence, Wind Direction, and Season During 1948-1964.

	Percent of All Fog Hours for Given Season and Fog Type							
Wind	Winter		Spring		Summer		Fall	
Direction	All	Dense	All	Dense	All	Dense	All	Dense
NNE - NE	12	8	16	12	14	8	10	7
ENE - E	12	15	20	20	15	6	10	10
ESE - SE	11	18	15	13	10	8	12	13
SSE - S	14	14	9	9	9	6	16	12
SSW - SW	11	10	6	7	9	14	12	8
WSW - W	9	8	7	8	8	14	9	8
WNW - NW	12	10	10	6	9	10	11	11
NNW - N	14	6	13	8	11	7	11	5
Calm	5	11	4	17	15	27	9	26

The preceding discussions have dealt with the relations between fog occurrences and both wind speed and wind direction separately. A third analysis was made in which the joint probabilities of fog occurrence with various combinations of wind speed and direction were determined, based upon data for the 1948-1964 period. This was done for the six key stations used in the separate wind analyses. The purpose was to determine whether certain combinations of wind speed and direction were associated with a major portion of the fog occurrences at the various stations and whether there might be a trend for these combinations to be consistent within a given region but perhaps vary between regions.

No strong evidence was found to indicate stability in the various fog-wind combinations within or between regions. The nature of the findings is illustrated in Table 14 where results are summarized for dense fog occurrences in winter at three stations representative of the northern, central, and southern parts of Illinois. Thus, at Moline in northwestern

Illinois the majority of the dense fogs with light winds are associated with calm conditions. Fog occurrences with moderate to strong winds occur most frequently with winds from ENE to E. However, at Evansville, the most southerly station, fogs with moderate to strong winds occur most frequently with southerly winds.

At Springfield in central Illinois an unexpected number of dense fog hours have occurred with strong winds (10 mph or more). Similarly, the calm percentage is unexpectedly low. Reference to similar analyses for other stations (not shown) indicates that the Springfield distribution probably is not typical of central Illinois relations between dense fog occurrences and wind speed. This could be an anomaly associated with the wind instrument exposure or the station's exposure to local conditions that produce an abnormal fog density in moderate to strong winds. In any case, the Springfield anomaly stresses the importance of local conditions on fog distribution characteristics.

Table 14. Relation Between Dense Fog, Wind Speed, and Wind Direction for Winter in Percent.

Wind Speed (mph)	NNE-NE	ENE-E	ESE-SE	SSE-S	SSW-SW	WSW-W	WNW-NW	NNW-N	Calm	Number of Fog Hours
					MOLINE					
0-4	1	12	5	4	4	9	3	3	59	219
5-9	14	35	12	4	7	17	9	2	-	158
≥10	15	46	15	8	2	8	2	4	-	48
					SPRINGFIELD					
0-4	9	15	15	11	14	14	5	6	11	170
5-9	11	17	14	12	15	12	11	8	-	182
≥10	13	21	7	20	19	5	7	8	-	119
					EVANSVILLE					
0-4	9	10	17	5	7	4	12	9	27	184
5-9	4	9	24	31	5	2	14	11	-	138
≥10	0	8	8	12	28	12	28	4	-	25

DISTRIBUTION OF MOISTURE DEFICITS AT SURFACE LEVEL

Distribution of Average Hourly Deficits by Season

The frequency with which a cooling lake will initiate or intensify fog and the density of the lake-related fog are strongly dependent upon the nearness to saturation of the air passing over the lake. Therefore, in our studies considerable effort has been devoted to determination of the moisture deficit of the air under natural conditions, that is, its nearness to saturation as it approaches the lake. As part of this effort, the climatology of surface moisture deficits was determined for stations representative of various areas of the state and which had data records in a form usable for this type of analysis. The distribution of moisture deficits were determined first on a seasonal basis. The diurnal distributions of moisture deficits were then calculated for the middle month of each season. Moisture deficit was expressed as grams of water vapor per kilogram of dry air (g/kg). Meteorologically, this represents the difference between the actual and saturation mixing ratios of the surface-layer air (mixing ratio deficit).

In determining the seasonal distribution of hourly moisture deficits, station data were grouped according to wind speed. Groups included 0-4, 5-14, 15-24, and ≥ 25 mph. Calculations were made also for all wind observations combined. Suitable data were available for Chicago, Moline, Springfield, St. Louis, Evansville, and Indianapolis. Average moisture deficits were calculated for each month of the sampling period, based upon data for the period, 1951-1960, published by the National Weather Service in station pamphlets entitled, "Summary of Hourly Observations".

In the above publication, the distribution of the surface temperatures are listed by the number of hours of occurrence for temperature and relative humidity classes. In calculating the moisture deficits, the central temperature and relative humidity of each group were used. Using the average relative humidity, a dewpoint temperature was calculated for each central air temperature. Using the central air temperature and the assumed mean dewpoint temperature, moisture deficits were calculated for each pair of temperatures and dewpoints within each wind speed class.

Moisture deficits were calculated for each month of the year for each station. These deficits were then combined by season for each of the four wind speed classes and for all wind speeds combined. From these, frequency distributions of moisture deficit were computed and results summarized in Tables 15-18. In the final analysis it was found that the 15-24 mph and greater than 24 mph classes were so much alike that these two groups were combined into a class of wind speed equal to or greater than 15 mph for several of the stations as indicated by (*) in the tables.

Since deficits of 2 g/kg and less are potentially susceptible to the formations of fog from relatively small additions of evaporated water into the air, it was decided to prepare a table giving a probability measure of some of the critical values. Table 19 shows the probability of moisture deficits not exceeding 2 g/kg, 1 g/kg-, and 0.5 g/kg during each season at the six stations used in this part of the investigation. To obtain this table the probability readings were made from the curves for all wind speeds combined.

Maps were plotted for each season showing the probability of not exceeding each of the values selected at each of the six stations. In all seasons, the northwest part of the state shows the highest probability of . being susceptible to the formation of fog with the addition of moisture; however, the entire state has high probabilities during the winter months. Patterns for 0.5 and 1 g/kg are shown in Fig. 9 for winter and summer. Obviously, the probability of lake-induced fog is much greater in winter than summer. The probability in the critical winter season increases northward and northwestward from minima of near 50% and 25% for 1 and 0.5 g/kg, respectively, in southern Illinois to 80% and 4-0% in the northwestern part of the state.

The probability distributions in Tables 15-18 provide a more precise and detailed definition of the natural distribution of moisture deficits than provided by the maps of Fig. 9. Interpretation of these tables is illustrated by reference to the values for winter at Moline. Thus, with wind speeds in the range of 0-4 mph, the probability of an hour with a moisture deficit of 0.10 g/kg is 5%. This increases gradually to 0.35 g/kg at the 50% probability level. For a given probability, the deficit gradually increases with wind speed. Thus, the 5% probability at Moline increases from 0.10 g/kg at 0-4 mph to 0.19 at speeds of 25 mph or more. Combining all wind speeds, the 5% probability is for a deficit of 0.12 or less.

Comparing a northern station (Moline) with a southern station (Evansville), it is apparent that the probability of lake-induced variations in fog frequency are more likely to occur in the northern part of the state in winter than in the southern region. For convenience, the interested reader can plot state maps of the areal distribution of moisture deficit for any probability level and season from Tables 15-18.

Table 19 shows a seasonal summary of the probability of moisture deficits equal to or less than 2, 1, and 0.5 g/kg at each station for each season, combining all wind data. For the most critical deficit group, 0.5 g/kg, the most likely occurrence is at Moline in the most critical season, winter. Moline also ranks first or second in the other three seasons. The least likely occurrence of 0.5 g/kg or less was found at St. Louis in winter, and this station also ranked first or second in the other three seasons for minimum likelihood of near-saturation conditions. Thus, as indicated earlier, the probability of near-saturation conditions of the surface-layer air under natural conditions is greatest in the northwestern part of the state and gradually decreases to a minimum in the southern 1/3 of the state.

Table 15. Probability Distribution of Average Surface Moisture Deficits in Winter.

Probability %	Deficit (g/kg) not Exceeded with Given Wind Speed (mph) 0-4	5-14	15-24	≥25	ALL	0-4	5-14	15-24	≥25	ALL
	MOLINE					CHICAGO				
2	<0.10	0.11	0.12	0.15	0.10	0.11	0.12	0.14	0.10	0.12
5	0.10	0.12	0.15	0.19	0.12	0.13	0.15	0.17	0.14	0.15
10	0.11	0.15	0.20	0.31	0.14	0.15	0.18	0.25	0.31	0.18
20	0.14	0.21	0.39	0.53	0.20	0.21	0.33	0.47	0.54	0.36
30	0.18	0.37	0.53	0.70	0.36	0.41	0.52	0.60	0.68	0.53
40	0.25	0.50	0.65	0.86	0.50	0.55	0.62	0.73	0.83	0.64
50	0.35	0.59	0.80	1.06	0.60	0.64	0.75	0.86	0.98	0.76
	SPRINGFIELD					INDIANAPOLIS				
2	0.11	0.12	0.13	0.13	0.12	0.11	0.12	0.13	0.14	0.12
5	0.12	0.13	0.15	0.16	0.14	0.12	0.14	0.15	0.17	0.14
10	0.13	0.16	0.19	0.22	0.16	0.14	0.17	0.19	0.26	0.17
20	0.17	0.23	0.40	0.44	0.28	0.19	0.24	0.38	0.45	0.27
30	0.24	0.40	0.57	0.61	0.46	0.26	0.46	0.54	0.65	0.47
40	0.36	0.53	0.71	0.80	0.59	0.43	0.59	0.67	0.87	0.59
50	0.48	0.66	0.88	1.01	0.73	0.58	0.72	0.82	1.16	0.73
	ST. LOUIS					EVANSVILLE				
2	0.12	0.13	0.14	0.17	0.13	0.11	0.13	0.14	0.15	0.12
5	0.14	0.15	0.17	0.21	0.16	0.12	0.15	0.16	0.18	0.15
10	0.17	0.20	0.25	0.33	0.20	0.14	0.19	0.26	0.35	0.18
20	0.24	0.44	0.54	0.65	0.46	0.19	0.44	0.54	0.67	0.37
30	0.49	0.62	0.75	0.90	0.62	0.32	0.62	0.73	0.91	0.58
40	0.66	0.79	0.97	1.19	0.80	0.46	0.77	0.93	1.18	0.75
50	0.81	0.99	1.22	1.54	1.00	0.57	0.95	1.18	1.50	0.94

Table 16. Probability Distribution of Average Surface Moisture Deficits in Spring.

Probability %	Deficit (g/kg) not Exceeded with Given Wind Speed (mph) 0-4	5-14	15-24	≥25	ALL	0-4	5-14	15-24	≥25	ALL
	MOLINE					CHICAGO				
2	0.12	0.16	0.14	0.17	0.15	0.17	0.18	0.18	*	0.18
5	0.15	0.22	0.21	0.35	0.20	0.25	0.29	0.29	*	0.27
10	0.21	0.39	0.51	0.58	0.46	0.44	0.57	0.65	*	0.59
20	0.37	0.72	0.89	0.98	0.72	0.76	0.95	1.00	*	0.94
30	0.62	1.09	1.31	1.41	1.08	1.01	1.29	1.41	*	1.30
40	0.86	1.56	1.81	1.95	1.50	1.30	1.71	1.86	*	1.71
50	1.18	2.12	2.45	2.60	2.06	1.64	2.22	2.42	*	2.20
	SPRINGFIELD					INDIANAPOLIS				
2	0.11	0.15	0.16	*	0.15	0.14	0.15	0.17	0.18	0.15
5	0.18	0.24	0.27	*	0.22	0.20	0.23	0.22	0.24	0.23
10	0.29	0.42	0.51	*	0.41	0.34	0.37	0.40	0.53	0.38
20	0.53	0.72	0.91	*	0.78	0.55	0.64	0.79	0.91	0.66
30	0.80	1.08	1.32	*	1.15	0.81	0.96	1.13	1.33	1.00
40	1.13	1.50	1.83	*	1.60	1.12	1.32	1.61	1.87	1.41
50	1.60	2.06	2.52	*	2.17	1.53	1.82	2.23	2.52	1.99
	ST. LOUIS					EVANSVILLE				
2	0.20	0.17	0.16	0.18	0.17	0.15	0.21	0.19	0.20	0.17
5	0.34	0.26	0.22	0.29	0.25	0.18	0.33	0.30	0.48	0.27
10	0.49	0.59	0.60	0.85	0.58	0.26	0.58	0.67	0.83	0.46
20	0.84	1.01	1.12	1.42	1.01	0.44	0.98	1.12	1.39	0.81
30	1.22	1.50	1.79	2.08	1.50	0.62	1.41	1.71	2.05	1.27
40	1.71	2.07	2.60	2.88	2.10	0.90	1.93	2.40	2.80	1.81
50	2.35	2.86	3.70	3.88	2.89	1.21	2.60	3.30	3.80	2.53

* 15-24 mph and >25 mph combined into one class because of the similarity in values of probability for the individual classes.

Table 17. Probability Distribution of Average Surface Moisture Deficits in Summer.

Probability %	Deficit (g/kg) not Exceeded with Given Wind Speed (mph)							
	0-4	5-14	≥15	ALL	0-4	5-14	≥15	ALL
	MOLINE				CHICAGO			
2	0.41	0.59	0.66	0.49	0.60	0.69	0.67	0.67
5	0.50	0.72	1.25	0.62	0.73	0.82	0.90	0.80
10	0.60	0.88	2.32	0.75	0.82	1.90	2.10	1.65
20	0.73	2.08	3.65	1.55	1.80	2.85	>4.00	2.56
30	0.95	2.88	>4.00	2.52	2.32	3.85	>4.00	3.45
40	1.83	3.60	>4.00	3.50	2.88	>4.00	>4.00	>4.00
	SPRINGFIELD				INDIANAPOLIS			
2	0.48	0.63	0.70	0.59	0.53	0.58	0.62	0.57
5	0.63	0.76	0.82	0.74	0.66	0.71	0.80	0.70
10	0.74	0.84	1.90	0.84	0.76	0.82	1.40	0.80
20	0.86	2.09	3.51	1.90	0.85	1.50	3.07	1.50
30	1.70	3.10	>4.00	2.95	1.40	2.60	>4.00	2.45
40	2.46	>4.00	>4.00	3.91	2.30	3.61	>4.00	3.32
	ST. LOUIS				EVANSVILLE			
2	0.72	0.74	0.71	0.74	0.48	0.72	0.70	0.59
5	0.81	0.84	0.89	0.82	0.60	0.82	1.00	0.73
10	1.00	1.75	2.08	1.55	0.71	1.10	2.72	0.84
20	2.47	3.30	4.00	2.97	0.83	2.90	>4.00	1.50
30	3.26	>4.00	>4.00	>4.00	0.98	4.00	>4.00	2.80
40	3.92	>4.00	>4.00	>4.00	1.87	>4.00	>4.00	3.95

Table 18. Probability Distribution of Average Surface Moisture Deficits in Fall.

Probability %	Deficit (g/kg) not Exceeded with Given Wind Speed (mph) 0-4	5-14	15-24	≥25	ALL	0-4	5-14	15-24	≥25	ALL
	MOLINE					CHICAGO				
2	0.13	0.18	0.21	0.22	0.15	0.19	0.24	0.21	*	0.22
5	0.16	0.30	0.41	0.38	0.25	0.29	0.48	0.42	*	0.42
10	0.22	0.47	0.66	0.53	0.39	0.51	0.75	0.66	*	0.69
20	0.38	0.81	1.15	0.70	0.69	0.89	1.17	1.03	*	1.08
30	0.57	1.21	1.76	0.93	1.03	1.23	1.61	1.43	*	1.50
40	0.81	1.70	2.45	1.28	1.49	1.56	2.13	1.89	*	2.00
50	1.11	2.35	3.44	1.74	2.03	1.95	2.78	2.43	*	2.58
	SPRINGFIELD					INDIANAPOLIS				
2	0.12	0.19	0.21	*	0.19	0.15	0.17	0.18	0.15	0,17
5	0.20	0.33	0.43	*	0.32	0.20	0.25	0.27	0.19	0.25
10	0.32	0.52	0.69	*	0.51	0.31	0.41	0.44	0.32	0.40
20	0.57	0.91	1.12	*	0.89	0.56	0.72	0.80	0.61	0.70
30	0.86	1.37	1.60	*	1.32	0.86	1.10	1.22	0.91	1.03
40	1.22	1.94	2.17	*	1.88	1.22	1.53	1.27	1.21	1.50
50	1.71	2.65	2.87	*	2.58	1.71	2.18	2.50	1.60	2.09
	ST. LOUIS					EVANSVILLE				
2	0.25	0.23	0.23	*	0.24	0.15	0.21	0.24	0.26	0.17
5	0.39	0.51	0.47	*	0.45	0.18	0.34	0.47	0.42	0.24
10	0.58	0.80	0.73	*	0.71	0.23	0.63	0.74	0.60	0.39
20	0.94	1.32	1.21	*	1.19	0.39	1.07	1.24	0.97	0.72
30	1.32	1.91	1.76	*	1.71	0.59	1.56	1.81	1.38	1.10
40	1.80	2.61	2.42	*	2.37	0.84	2.14	2.53	1.88	1.60
50	2.38	3.54	3.23	*	3.18	1.16	2.90	3.43	2.48	2.27

* 15-24 mph and ≥25 mph combined into one class of ≥15 mph because of small sample size in ≥25 mph group.

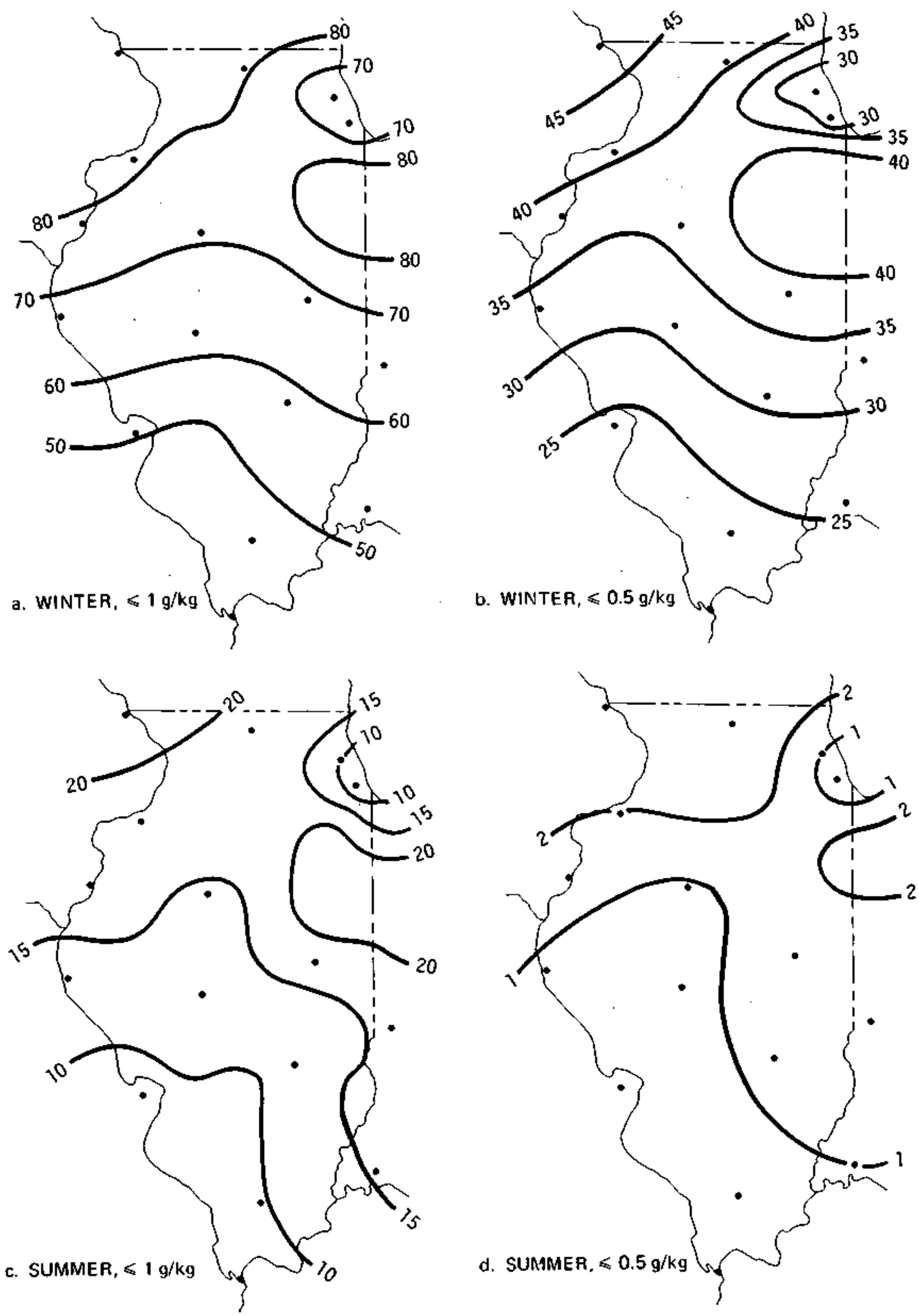


Figure 9. Seasonal Probabilities (%) of Average Moisture Deficit, Based Upon All Hourly Observations.

Table 19. Probability of Moisture Deficits Equal to or Less Than Given Amounts During Each Season.

	Probability (%) of Not Exceeding Given Deficit (g/kg)											
	Winter			Spring			Summer			Fall		
Station	2	1	0.5	2	1	0.5	2	1	0.5	2	1	0.5
Chicago	92	66	28	46	22	8	13	7	<1	40	18	6
Moline	97	82	41	49	28	13	24	16	2	49	19	14
Springfield	88	64	33	47	26	12	20	14	1	42	23	10
Indianapolis	88	65	32	50	30	14	25	19	1	48	28	13
St. Louis	78	50	23	38	20	9	12	8	<1	34	16	6
Evansville	81	53	26	43	24	11	24	16	1	46	27	13

Diurnal Distribution of Deficits

In the previous section, analyses of the seasonal distribution of moisture deficits were presented in terms of probability distributions for total hours of occurrence per season. However, the probability of fog varies greatly depending upon the time of the day. Therefore, we selected the middle month of each season (January, April, July, and October) and carried out an analysis of the diurnal distribution of moisture deficits at 3-hourly intervals throughout the day. The analysis was made for the 5-year period, 1960-1964, for which suitable data were available at seven key stations. These stations were Chicago, Moline, Peoria, Springfield, St. Louis, Evansville, and Indianapolis. Calculations involved use of air temperatures and dewpoint temperatures listed in the hourly observations published by the National Weather Service in their Local Climatological Data, commonly referred to as LCD's.

From the temperature and the dewpoints their respective vapor pressures were obtained using the following formula,

$$E = \exp^{(19.079T - 4782.9)/(T - 35.9)},$$

where E is the vapor pressure in mb and T is the temperature in °K. The vapor pressure and the saturation vapor pressure were then converted to mixing ratios using

$$X = \frac{623\ E}{P-E}$$

where X is the mixing ratio in g/kg and P is the pressure.

The mixing ratio deficits were tabulated by frequency for the number of times selected class intervals of moisture deficits occurred. Cumulative percent probabilities were calculated using (N_n + 1) as the divisor of N_1, N_2, . . . N_n , for each of the 3-hourly tabulations. The cumulative probabilities were then plotted on log-probability paper and lines of best fit were drawn.

The best-fit lines were used to prepare two sets of tables. The first set (Tables 20-22) show the moisture deficits that will not be exceeded at selected frequencies (probability levels). Results are shown for MLI, SPI, and EVV to illustrate variations from north to south. Results for all seven stations have been included in the second set (Tables 23-29) which show the probability of not exceeding deficits of 2, 1, and 0.5 g/kg at each of the 3-hour intervals.

Maps were prepared, Fig. 10, to show the statewide probability of moisture deficits equal to or less than 1.0 g/kg and 0.5 g/kg for the months of January and July (winter and summer) at the 0600-hour observation. The 0600 observations show the greatest probability of small moisture deficit for each of the months used in the analysis.

The winter months represented by January are the most likely months in which fog forms due to small moisture deficits. All stations show that the early morning hour of 0600 has the smaller deficits during winter. Spring and fall also show that the lowest deficits are observed around 0600 with the lowest deficits for summer at 0300 or, perhaps, between 0300 and 0600. The 1500 observations have the largest moisture deficits during all seasons used here as would be expected from the normal diurnal distribution of relative humidity.

The statewide patterns for summer and winter at 0600 CST in Fig. 10 show quite similar basic patterns to those obtained in the fog distribution maps. That is, the least probability of near saturation in atmosphere moisture content at the surface is in the southern part of the state, and in the Chicago area of northeastern Illinois, whereas the most likely occurrences are in the east central, central, and northwestern regions of the state. One exception to this is the high probability of 1 g/kg or less deficit at 0600 CST when the highest probability (95%) reaches close to Chicago. Thus, as expected, there is a relatively strong correlation in the distribution of natural fog occurrences and the natural moisture deficit of the atmosphere. This leads to the obvious conclusion that where the probabilities are relatively large for small moisture deficits the probability of lake-induced fog is also greatest. In general, this indicates that southern and northeastern Illinois, around the Chicago area, are least likely to have problems with fog related to cooling lake discharges of evaporated water and the east central and northwestern regions are likely to experience the most frequent problems in this direction.

Table 20. Frequency Distribution of Surface Moisture Deficits for Given Hour During Selected Months at Moline.

Frequency %	Deficit (g/kg) not Exceeded at Given Hour							
	00	03	06	09	12	15	18	21
	JANUARY							
1	<0.10	<0.10	<0.10	<0.10	<0.10	0.14	<0.10	<0.10
5	0.13	0.14	0.12	0.15	0.25	0.32	0.20	0.16
10	0.20	0.19	0.17	0.22	0.35	0.42	0.32	0.25
20	0.28	0.25	0.23	0.31	0.45	0.53	0.41	0.34
50	0.51	0.44	0.40	0.48	0.78	0.89	0.68	0.58
	APRIL							
1	<0.10	<0.10	<0.10	<0.10	<0.30	0.13	<0.10	<0.10
5	0.30	0.15	<0.10	0.30	0.61	0.61	0.48	0.27
10	0.42	0.18	0.17	0.58	1.03	1.04	0.87	0.49
20	0.63	0.44	0.39	1.02	1.81	2.00	1.56	0.93
50	1.37	1.03	0.88	2.48	>4.00	>4.00	>4.00	2.17
	JULY							
1	<0.10	<0.10	<0.10	<0.10	<0.10	1.21	0.96	<0.50
5	<0.10	<0.10	<0.10	1.02	1.74	2.40	1.64	0.63
10	0.50	0.24	0.40	1.93	3.35	>4.00	2.50	1.21
20	0.94	0.69	0.85	3.50	>4.00	>4.00	>4.00	1.85
50	1.91	1.37	1.57	>4.00	>4.00	>4.00	>4.00	3.60
	OCTOBER							
1	<0.10	<0.10	<0.10	<0.10	0.44	0.46	0.22	<0.10
5	<0.10	<0.10	<0.10	0.20	0.90	1.00	0.67	0.21
10	0.24	0.21	<0.10	0.63	1.98	2.00	1.07	0.39
20	0.43	0.37	0.29	1.12	3.20	3.68	1.81	0.67
50	1.22	0.91	0.73	2.45	>4.00	>4.00	>4.00	1.82

Table 21. Frequency Distribution of Surface Moisture Deficits for Given Hour During Selected Months at Springfield.

Frequency %	Deficit (g/kg) not Exceeded at Given Hour							
	00	03	06	09	12	15	18	21
				JANUARY				
1	<0.10	<0.10	<0.10	<0.10	<0.10	0.15	<0.10	<0.10
5	0.16	0.15	0.12	0.14	0.23	0.25	0.18	0.19
10	0.22	0.20	0.17	0.21	0.32	0.32	0.25	0.25
20	0.30	0.27	0.24	0.32	0.46	0.47	0.38	0.33
50	0.54	0.48	0.44	0.56	0.89	0.94	0.75	0.60
				APRIL				
1	0.43	0.23	0.24	<0.40	0.34	0.49	0.59	0.36
5	0.63	0.46	0.40	0.69	0.87	1.10	1.16	0.81
10	0.80	0.60	0.54	1.01	1.41	1.60	1.66	1.13
20	1.08	0.85	0.76	1.55	2.45	2.85	2.57	1.61
50	2.00	1.62	1.44	3.20	>4.00	>4.00	>4.00	2.90
				JULY				
1	<0.50	0.45	<0.50	1.00	1.82	1.80	<1.50	1.01
5	0.94	0.63	0.78	1.77	3.30	3.61	2.52	1.39
10	1.27	0.86	0.97	2.56	>4.00	>4.00	3.95	1.70
20	1.74	1.13	1.23	3.80	>4.00	>4.00	>4.00	2.24
50	2.87	1.91	1.97	>4.00	>4.00	>4.00	>4.00	>4.00
				OCTOBER				
1	0.21	<0.10	<0.10	<0.10	0.48	0.55	0.39	<0.10
5	0.50	0.32	0.16	0.56	1.23	1.22	1.02	0.58
10	0.71	0.55	0.42	1.01	2.07	2.20	1.55	0.89
20	1.06	0.88	0.70	1.71	3.85	>4.00	2.47	1.38
50	2.07	1.73	1.28	>4.00	>4.00	>4.00	>4.00	2.90

Table 22. Frequency Distribution of Surface Moisture Deficits for Given Hour During Selected Months at Evansville.

Deficit (g/kg) not Exceeded at Given Hour

Frequency %	00	03	06	09	12	15	18	21
				JANUARY				
1	<0.10	<0.10	<0.10	<0.10	<0.10	0.14	<0.10	<0.10
5	0.13	<0.10	<0.10	<0.10	0.27	0.28	0.19	0.15
10	0.20	0.16	.0.12	0.17	0.38	0.42	0.29	0.22
20	0.30	0.27	0.23	0.33	0.57	0.66	0.46	0.34
50	0.62	0.54	0.48	0.65	1.27	1.59	0.99	0.72
				APRIL				
1	0.20	0.15	0.32	0.75	0.81	0.82	0.99	0.63
5	0.68	0.57	0.54	1.26	1.51	2.18	1.73	1.00
10	0.90	0.76	0.71	1.66	1.95	3.20	2.34	1.28
20	1.27	1.08	0.99	2.30	>4.00	>4.00	3.40	1.73
50	2.45	2.10	1.89	>4.00	>4.00	>4.00	>4.00	3.11
				JULY				
1	<0.10	<0.10	<0.10	0.80	<1.25	1.71	1.65	<0.60
5	0.44	0.33	0.39	1.59	2.65	>4.00	3.50	1.29
10	0.81	0.58	0.69	2.55	>4.00	>4.00	>4.00	1.57
20	1.09	0.61	0.98	>4.00	>4.00	>4.00	>4.00	2.00
50	1.93	1.43	1.64	>4.00	>4.00	>4.00	>4.00	3.13
				OCTOBER				
1	<0.10	<0.10	<0.10	<0.10	0.74	0.31	0.52	0.22
5	0.18	0.19	0.16	0.67	1.60	1.28	1.25	0.41
10	0.29	0.28	0.23	1.15	2.90	2.70	1.81	0.58
20	0.49	0.44	0.36	1.92	>4.00	>4.00	2.67	0.87
50	1.25	1.00	0.84	3.90	>4.00	>4.00	>4.00	1.90

Table 23. Probability Distribution of Moisture Deficits at 3-Hour Intervals during Mid-Season Months at Chicago (Midway),

Moisture Deficit (g/kg)	Probability (%) of not Exceeding Certain Moisture Deficits at a Given Hour							
	00	03	06	09	12	15	18	21
				JANUARY				
2.00	99	>99	>99	98	91	86	96	98
1.00	85	86	90	88	60	52	72	85
0.50	48	53	59	51	21	16	28	43
				APRIL				
2.00	50	63	71	36	16	18	25	38
1.00	20	29	33	13	6	7	10	15
0.50	6	9	7	3	2	3	4	6
				JULY				
2.00	13	22	22	6	4	3	6	9
1.00	2	5	4	1	<1	<1	1	2
0.50	<1	1	1	<1	<1	<1	<1	<1
				OCTOBER				
2.00	45	60	69	23	10	8	16	31
1.00	15	29	36	8	4	4	4	8
0.50	4	8	12	2	<1	<1	2	2

Table 24. Probability Distribution of Moisture Deficits at 3-Hour Intervals during Mid-Season Months at Moline.

Moisture Deficit (g/kg)	Probability (%) of not Exceeding Certain Moisture Deficits at a Given Hour							
	00	03	06	09	12	15	18	21
				JANUARY				
2.00	97	98	98	98	90	86	96	97
1.00	84	89	93	90	64	57	74	79
0.50	49	58	64	54	24	17	30	40
				APRIL				
2.00	66	74	80	41	22	20	26	46
1.00	37	48	55	19	9	9	12	22
0.50	14	23	28	8	4	4	5	10
				JULY				
2.00	52	69	64	11	6	3	7	22
1.00	22	34	26	5	3	1	1	7
0.50	10	15	12	3	2	<1	<1	2
				OCTOBER				
2.00	66	78	84	40	10	10	22	53
1.00	43	55	62	17	5	5	9	31
0.50	23	29	36	8	2	1	3	14

Table 25. Probability Distribution of Moisture Deficits at 3-Hour Intervals during Mid-Season Months at Peoria.

Moisture Deficit (g/kg)	00	03	06	09	12	15	18	21
	Probability (%) of not Exceeding Certain Moisture Deficits at a Given Hour							
	JANUARY							
2.00	99	99	99	99	91	83	95	98
1.00	87	92	96	93	66	54	71	85
0.50	51	61	63	57	31	22	31	45
	APRIL							
2.00	60	73	80	44	21	16	19	32
1.00	30	41	47	20	8	6	8	20
0.50	13	17	20	8	3	3	4	8
	JULY							
2.00	44	70	73	12	4	2	4	15
1.00	19	27	32	5	2	<1	1	6
0.50	8	9	10	3	<1	<1	<1	2
	OCTOBER							
2.00	62	81	88	38	13	11	17	43
1.00	32	51	64	16	7	6	9	17
0.50	16	25	34	9	4	3	5	7

Table 26. Probability Distribution of Moisture Deficits at 3-Hour Intervals during Mid-Season Months at Springfield,

Moisture Deficit (g/kg)	00	03	06	09	12	15	18	21
	Probability (%) of not Exceeding Certain Moisture Deficits at a Given Hour							
	JANUARY							
2.00	97	98	99	98	84	80	92	96
1.00	81	86	91	85	56	53	66	77
0.50	46	52	58	42	23	22	30	40
	APRIL							
2.00	50	62	68	28	15	13	14	30
1.00	17	26	32	10	6	4	3	8
0.50	2	6	8	3	2	1	<1	2
	JULY							
2.00	27	53	51	6	1	3	7	33
1.00	6	15	11	1	<1	<1	<1	16
0.50	1	2	2	<1	<1	<1	<1	1
	OCTOBER							
2.00	48	58	73	23	10	9	15	33
1.00	18	24	36	10	3	4	5	12
0.50	5	9	12	4	1	<1	1	4

Table 27. Probability Distribution of Moisture Deficits at 3-Hour Intervals during Mid-Season Months at St. Louis.

Moisture Deficit (g/kg)	Probability (%) of not Exceeding Certain Moisture Deficits at a Given Hour							
	00	03	06	09	12	15	18	21
	JANUARY							
2.00	88	92	94	91	68	60	76	85
1.00	66	75	80	72	42	36	50	62
0.50	36	48	54	44	19	18	24	32
	APRIL							
2.00	33	46	56	18	12	13	12	23
1.00	9	16	21	5	3	2	2	4
0.50	2	3	4	<1	<1	<1	<1	<1
	JULY							
2.00	18	35	47	7	2	1	2	7
1.00	6	13	18	2	<1	<1	1	3
0.50	3	5	7	1	<1	<1	<1	2
	OCTOBER							
2.00	39	45	63	25	11	8	12	23
1.00	13	27	34	10	4	2	3	7
0.50	2	12	18	3	1	1	<1	3

Table 28. Probability Distribution of Moisture Deficits at 3-Hour Intervals during Mid-Season Months at Evansville.

Moisture Deficit (g/kg)	Probability (%) of not Exceeding Certain Moisture Deficits at a Given Hour							
	00	03	06	09	12	15	18	21
	JANUARY							
2.00	91	95	96	93	69	59	80	90
1.00	71	78	81	71	40	33	50	65
0.50	40	47	52	36	17	13	22	34
	APRIL							
2.00	40	47	53	15	5	4	7	26
1.00	12	17	21	3	1	1	1	5
0.50	3	6	7	<1	<1	<1	<1	<1
	JULY							
2.00	42	70	62	7	3	2	2	20
1.00	16	30	21	2	<1	<1	<1	2
0.50	3	8	6	<1	<1	<1	<1	<1
	OCTOBER							
2.00	68	77	82	21	7	8	12	52
1.00	42	50	58	8	2	4	3	24
0.50	20	24	30	3	<1	2	1	8

Table 29. Probability Distribution of Moisture Deficits at 3-Hour Intervals during Mid-Season Months at Indianapolis.

Moisture Deficit (g/kg)	Probability (%) of not Exceeding Certain Moisture Deficits at a Given Hour							
	00	03	06	09	12	15		21
	JANUARY							
2.00	97	98	99	97	84	76	91	95
1.00	79	84	88	82	51	44	64	77
0.50	44	50	55	47	18	16	27	41
	APRIL							
2.00	57	69	75	38	23	18	21	39
1.00	28	39	45	15	9	6	8	15
0.50	11	16	19	5	3	2	3	6
	JULY							
2.00	64	85	84	11	2	3	6	23
1.00	20	48	44	6	1	1	1	8
0.50	9	19	16	2	<1	<1	<1	2
	OCTOBER							
2.00	59	78	86	31	11	11	19	39
1.00	30	49	61	15	4	5	8	16
0.50	12	26	33	8	2	<1	3	7

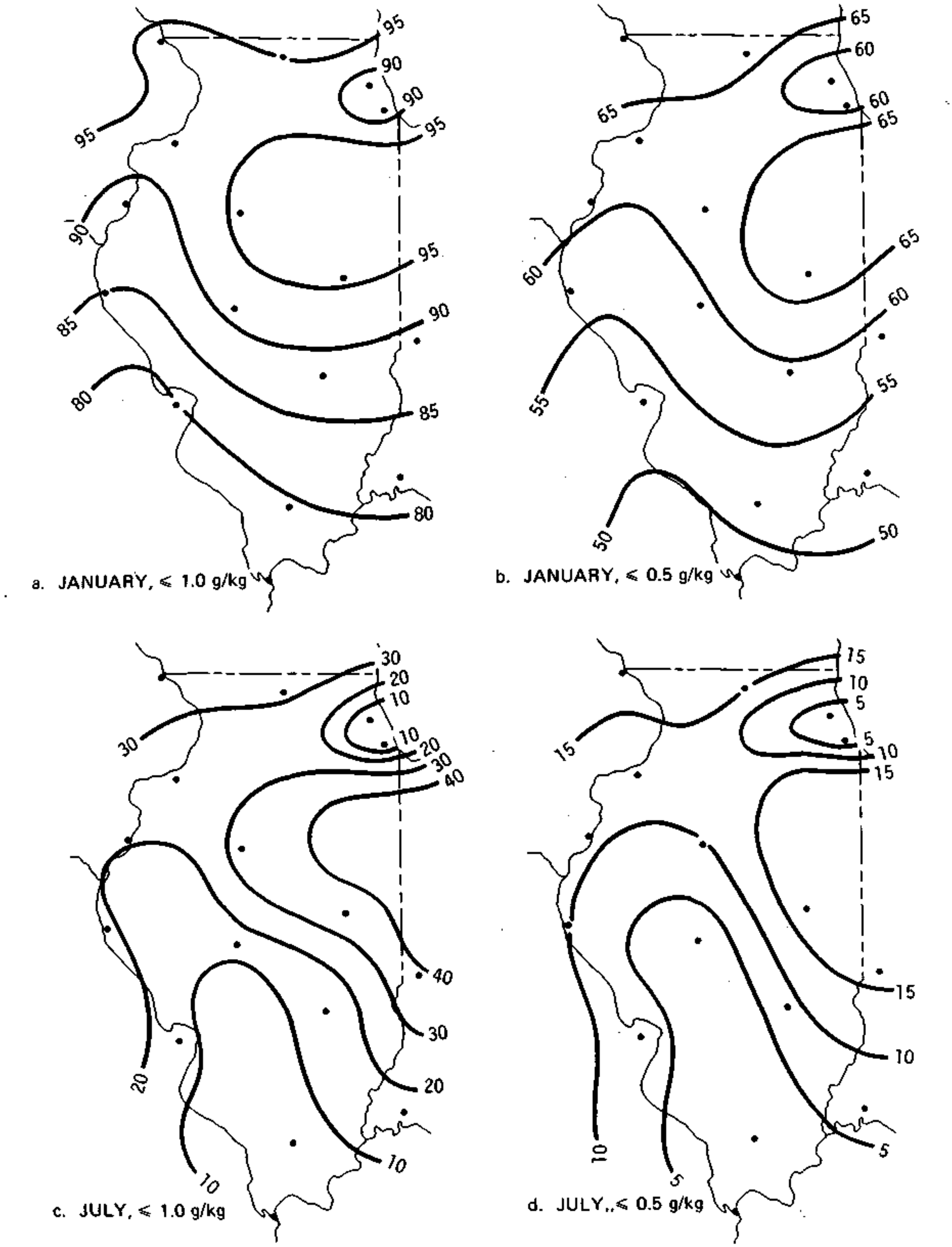


Figure 10. Probability (%) That Moisture Deficits at 0600 CST Will Not Exceed Given Values in January and July.

RELATION BETWEEN FOG AND SATURATION DEFICIT

The frequency and density of fog is strongly related to the distribution of saturation deficits in the air near the surface. Therefore, analyses were performed to ascertain the percentage of fog events of various density occurring with saturation deficits of various magnitude. This was done on a seasonal basis for six key stations having continuous records in the 1948-1964 period. These included Chicago, Moline, Springfield, St. Louis, Evansville, and Indianapolis. Substantial differences occur in the number of hours of fog between the northern and southern parts of Illinois, as shown in Figs. 1 to 5. However, in this analysis where the percentage of fog hours was related to saturation deficit, no stable trend was noted from north to south; that is, the percentages of total fog occurrences in the various visibility ranges (fog density) appeared to be quite persistent between stations except for differences due to sampling variations in the 1948-1964 period. Therefore, data for the six stations were averaged to obtain mean values for the state.

Results for each season are summarized in Table 30, which shows the percent of total fog hours for six visibility ranges and several classes of saturation deficit. Thus, the winter summary in Table 30 shows that dense fog (visibility of 1/4 mile or less) occurs almost exclusively with saturation deficits of 0.5 g/kg or less. As the density of fog decreases (visibility increases), the percentage of fog occurrences with the air at or close to saturation decreases gradually from a 6-station mean of 99.1% for dense fog to 68.7% for very light fog with visibilities of 3.1 to 6.0 miles.

Thus, the initiation of relatively dense fog by a cooling lake is unlikely unless the air above the lake is approaching saturation from natural causes, or possibly, it could occur in the case of a relatively large, hot lake in which evaporation was occurring at an extremely high rate. The rate of evaporation from relatively hot, moderate, and cool lakes will be discussed in a later section. In general, intensification of existing fog from moderate to dense would most likely occur with the air having saturation deficits of 1.0 g/kg or less and visibilities of 1 mile or less when the existing fog reached the upwind edge of a lake. Of course, intensification among the moderate to light intensities could also occur, but the major lake-related problem is dense fog.

MEAN SOLAR RADIATION

An important parameter in the determination of evaporation rates from any water body is solar radiation. This information is pertinent in the development of numerical models for predicting the initiation and/or enhancement of fog from cooling lakes and the potential effects of such water bodies on

Table 30. Average Percentage Frequency of Fog Hours Grouped by Visibility and Moisture Deficit.

Deficit (g/kg)	Percent of Total Fog Hours for Given Visibility (miles) ≤ 1/4	5/16-1/2	5/8-1.0	1.1-2.0	2.1-3.0	3.1-6.0
				Winter		
≤0.5	99.1	97.7	93.8	86.0	78.0	68.7
0.5-1.0	0.9	2.1	6.0	13.1	20.2	27.8
1.1-2.0	0.0	0.2	0.2	0.9	1.8	3.5
				Spring		
≤0.5	89.6	82.2	78.7	67.0	55.2	44.1
0.5-1.0	6.8	13.9	15.9	25.4	33.3	38.2
1.1-2.0	2.7	3.4	4.8	6.6	10.3	16.0
2.1-3.0	0.9	0.5	0.5	0.8	1.1	1.5
>3.0	0.0	0.0	0.1	0.2	0.1	0.2
				Summer		
<0.5	72.2	58.0	34.8	25.5	18.4	16.8
0.5-1.0	21.9	32.0	41.1	33.1	31.4	29.2
1.1-2.0	3.9	10.0	21.1	33.8	39.5	41.5
2.1-3.0	1.4	0.0	2.3	5.8	7.5	9.4
>3.0	0.6	0.0	0.7	1.8	3.2	3.1
				Fall		
<0.5	92.2	84.1	70.0	59.4	46.6	38.6
0.5-1.0	6.0	13.3	21.4	27.5	33.4	35.2
1.1-2.0	1.8	2.6	8.1	11.8	17.2	22.8
2.1-3.0	0.0	0.0	0.5	1.1	2.3	2.7
>3.0	0.0	0.0	0.0	0.2	0.5	0.7

clouds and precipitation. Other factors being equal, evaporation rates will tend to increase with increasing solar radiation.

Therefore, as part of the background climatological studies, monthly and annual maps of mean solar radiation were developed for Illinois and the immediate surrounding area. These were obtained from station data through 1962 appearing in the Climatic Atlas of the United States (Environmental Data Service, 1968), and from data for the 1963-1972 period published in the National Weather Summary of Climatic Data (National Weather Service, 1963-1972). Additional data for Urbana, Illinois were obtained from weather records of the Illinois State Water Survey.

Figure 11 shows the mean daily patterns of solar radiation in langleys on an annual basis, and for the months of maximum radiation (June) and minimum radiation (December). For most applications of such data in estimating means and extremes of evaporation rates, Fig. 11 is sufficient. Thus, other factors being equal, annual evaporation would increase gradually from north to south in Illinois. During the minimum month, December, there is a general increase in radiation from a minimum in the northeastern part of the state to the southwestern part. During the maximum month, June, there is a gradual increase from a minimum in the northwest to a maximum in the southwest.

LAKE EVAPORATION

Evaporation maps for the United States have been provided by Kohler et al., (1959), and a more detailed investigation of lake evaporation in Illinois has been provided by Roberts and Stall (1967). Evaporation in past investigations has normally been expressed in daily or monthly totals. For application to the cooling lake problem, evaporation rates for much shorter intervals are needed. Changnon (1959) has provided mean diurnal curves of evaporation for summer and winter applicable to central Illinois (Fig. 12).

The Changnon curves were used in conjunction with daily evaporation estimates, based upon the empirical method employing meteorological parameters developed by Kohler et al., (1959), to develop hourly estimates of lake evaporation for various conditions of wind, air temperature, dew point temperature, and solar radiation.

Our studies show that winter fog in Illinois occurs most frequently with air temperatures of 30°F to 40°F, dew point depressions of 2°F or less, and wind speeds less than 5 mph. Fig. 13a illustrates the average hourly lake evaporation for the above two temperatures, dew point depression of 2°F and wind speed of 5 mph. In summer, fog occurs most often with air temperatures of 60°F to 70°F and similar dew point depressions and weak winds. Figure 13b illustrates hourly evaporation on a typical summer day favorable for fog formation, based on the Kohler daily estimates of lake evaporation under the

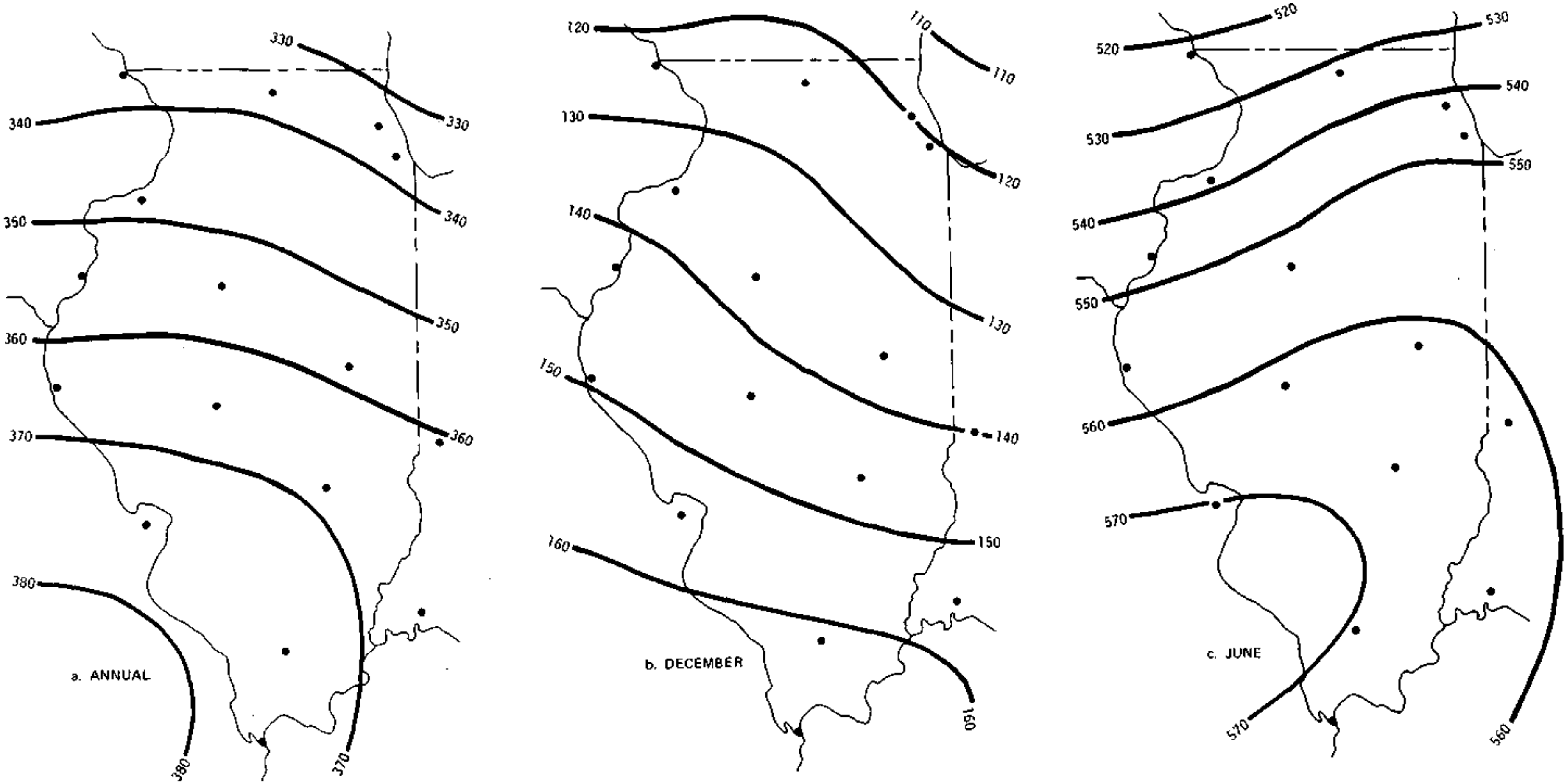


Figure 11. Mean Daily Patterns of Solar Radiation.

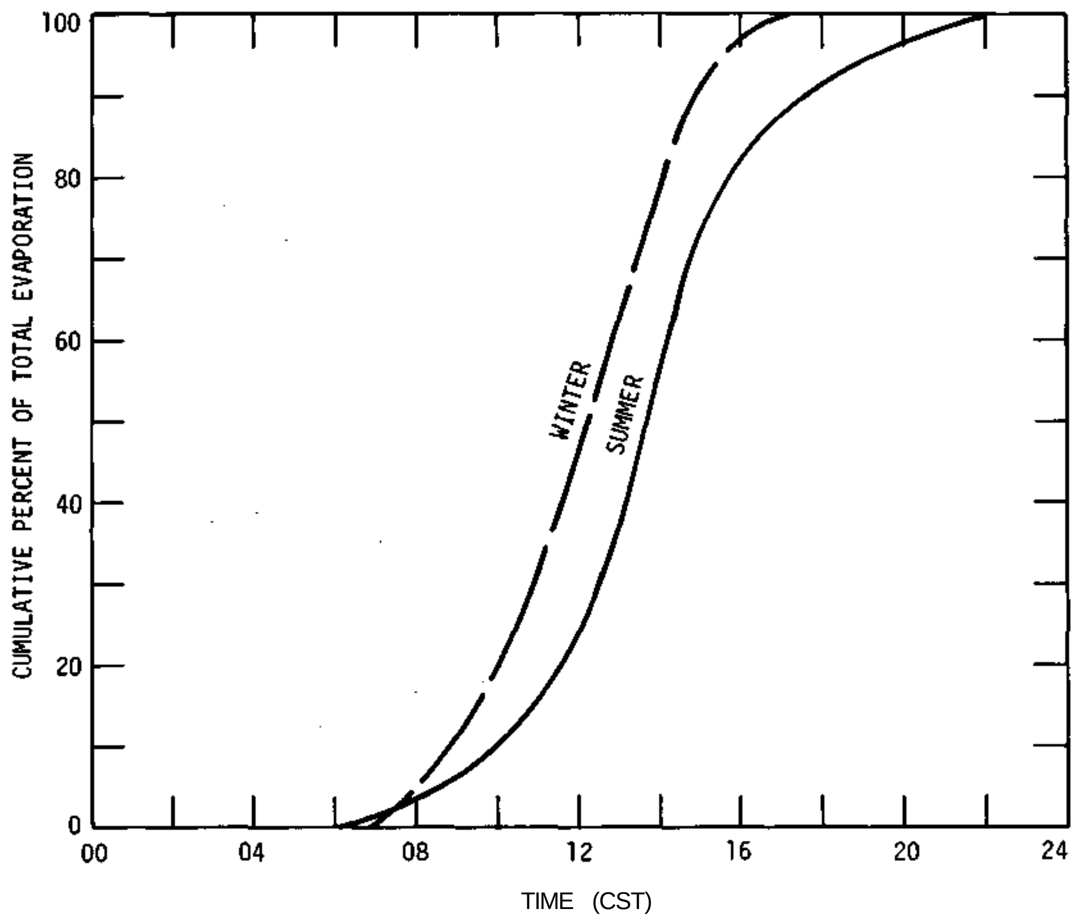


Figure 12. Diurnal Distribution of Lake Evaporation.

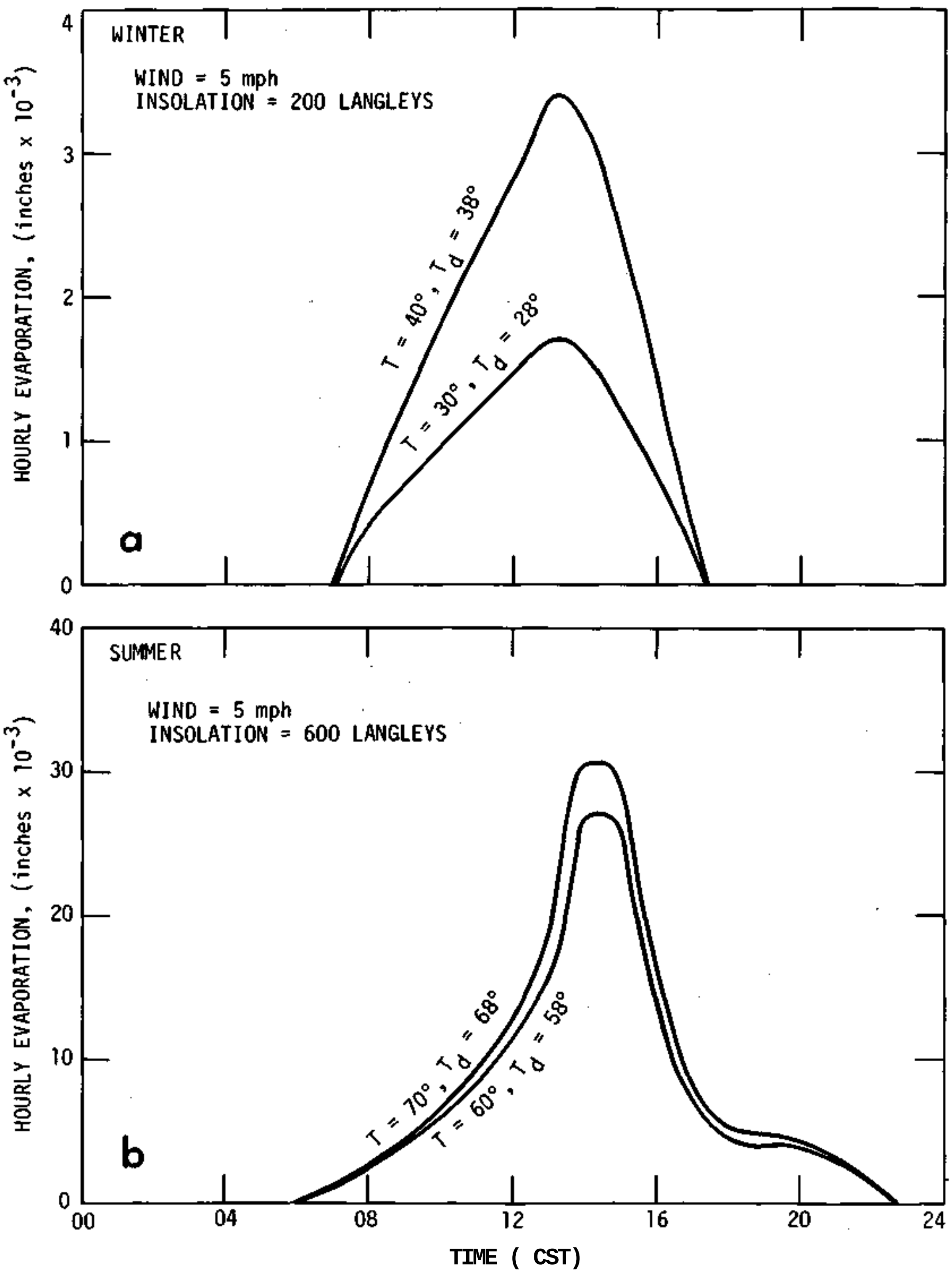


Figure 13. Average Hourly Lake Evaporation on Typical Winter and Simmer Days.

given conditions and the Changnon diurnal distribution. A cooling lake has surface water temperatures that would normally be much higher than a natural lake. Therefore, evaporation rates from a natural lake under typical winter or summer conditions would be much less than from the artificially heated cooling lake. However, the diurnal trend and percentage distributions under natural conditions should be quite similar to those for the hotter cooling lakes, and information of the type presented in Figs. 12 and 13 should provide useful background knowledge in evaluating the potential effects of cooling ponds on the environment over and immediately downwind of these heat-moisture sources.

COOLING POND FOG INITIATION

Currier, Knox, and Crawford (1972), using a series of measurements made at cooling pond sites near Hillsboro, Illinois (Coffeen Station) and Fruitland, New Mexico (4-Corners) during the winter, obtained critical values for the formation of steam fog over a cooling pond. They found a definite correlation between the water surface and air temperature difference and the saturation vapor pressure deficit of the air. In essence, this is a measure of the free convection over the cooling pond surface against the ability of the air to hold additional moisture. They indicate that it is necessary to have a temperature difference between the water surface and the air of 30°F or more and a vapor pressure deficit of 1 mb to form heavy fog. There were several instances where fog did not occur under these circumstances, but these were offset by other times when fog occurred outside of their critical limits. Murray and Trettel, Inc. (1972), in an interim report for Commonwealth Edison, published an independent set of data for the Dresden Nuclear Power Station in Illinois. Their observations confirmed the results of Currier, et al. for the month of January.

Three hypothetical cooling ponds (cold, moderate, and hot) were designed to describe the potential of heavy fog initiation that might be experienced over Illinois and other areas with similar climates. The design curves of mean surface temperature on an annual basis are illustrated in Fig. 14. The water surface temperature in the coldest month (January) was allowed to range from 34°F to 69°F, and in the hottest month of the year (July) the temperatures ranged from 74°F for the cold pond to 104°F for the hot pond.

Three weather stations which describe the temperature distribution across Illinois, Moline (northern), Springfield (central) and Evansville, Indiana (southern) were selected. For each station the distributions of temperature as a function of mixing ratio were determined, for the middle month of each season of the year (January, April, July, and October), from the Decinnal data for the period 1951-1960 (U. S. Weather Bureau, 1963). It was necessary to calculate the mean mixing ratio as a function of temperature and humidity.

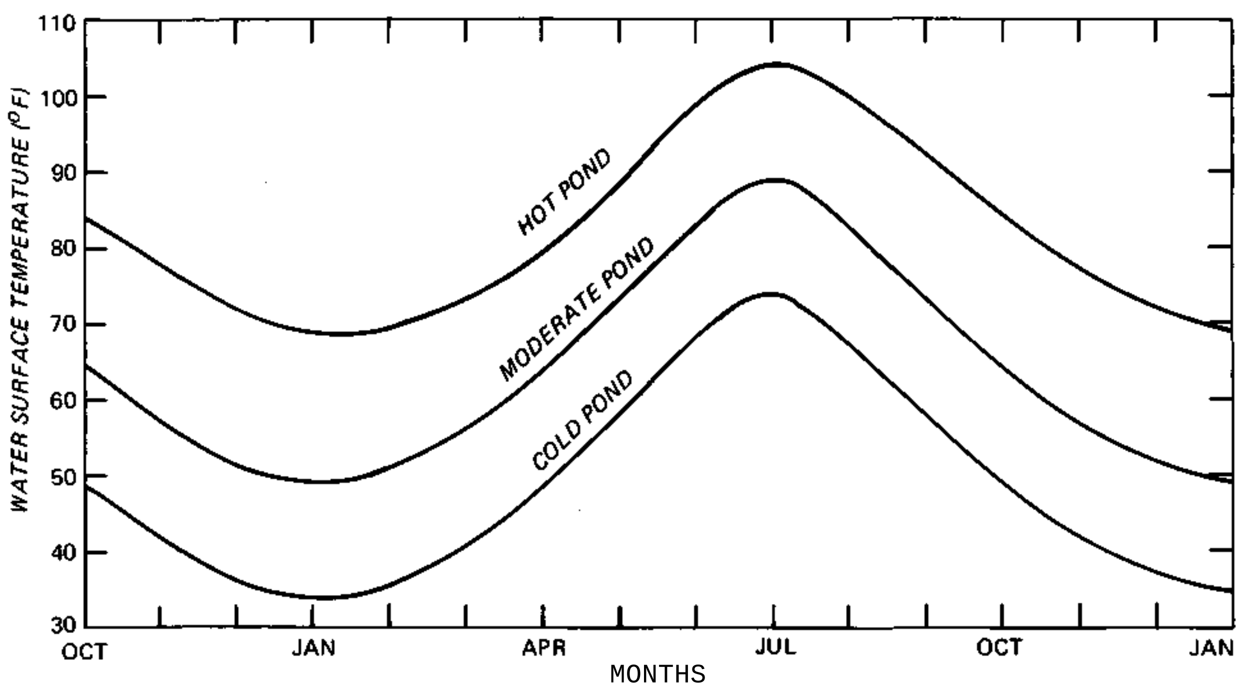


Figure 14. Mean Water Surface Temperature Design of Three Hypothetical Cooling Ponds.

The average amount of time during a month that a cooling pond can be expected to form heavy steam fog over the surface of the pond can be determined by multiplying the total number of hours per month by the percent of time that the temperature of the pond would exceed the air temperature by 30°F or more and the mixing ratio deficit was less than or equal to 1 g/kg in January and 2 g/kg in April, July, and October. This joint probability of temperature difference and mixing ratio deficit defines the amount of time the air over a cooling pond would have enough free convection coupled with a saturation deficit in the air small enough to absorb the evaporated water to become saturated. A mixing ratio deficit of 1 g/kg in winter and 2 g/kg for the other seasons was picked to ensure that a conservative estimate was being made. This saturation deficit is approximately 0.3 g/kg greater than was found by Currier, Knox and Crawford for the winter months, and it is believed that 2 g/kg would be an equally conservative value for the other seasons of the year. To obtain the percent possible initiation hours over a pond, the percent of time that fog formed under the above conditions must also be subtracted. Only the potential for heavy fog was analyzed because it was felt that these were the only times that a cooling pond had a significant chance of adversely affecting the visibility around such an installation.

Using the above method the percent possible initiation hours were found over northern, central and southern Illinois, and these results are shown in Fig. 15. The hot pond indicates that the percent of the total hours during which fog initiation is possible over northern Illinois is 67% in January and this decreases to 40% over southern Illinois. This difference of over 25% is a substantial reduction which reflects the differences of the winter climate from the northern to the southern sections of the state. The other seasons of the year indicate little variation-from the north to the south. In summer the percent possible initiation hours lowers to 12 to 13%.

The moderate pond has a maximum value of 38% in winter over the northern section of Illinois and drops to 10% over southern Illinois. Once again a winter difference of over 25% is noted between the northern and southern extremities of the state, which emphasizes the importance of the weather factor in siting power plants to achieve a minimum environmental effects. From the end of spring to early autumn, the percent of the total time that steam fog initiation may be expected to occur decreases to about 2% of the total hours. The cold pond maximizes to less than 15% during the cold season and shows little or no effect during the rest of the year for all sections of Illinois.

The estimates shown in Fig. 15 must be considered conservative. The mixing ratio deficits selected were higher than the critical values shown by other data, the pond temperatures were assumed to remain constant throughout a month, and it was assumed that the temperature of the pond would increase in a quantum manner from one month to another. All of these are conservative estimates. The hot cooling pond designed for the purposes of this experiment was deliberately chosen to be an extreme, as was the cold pond. It was felt that with such deliberately over-designed temperature characteristics a maximum range of possible initiation hours over the state of Illinois could be established.

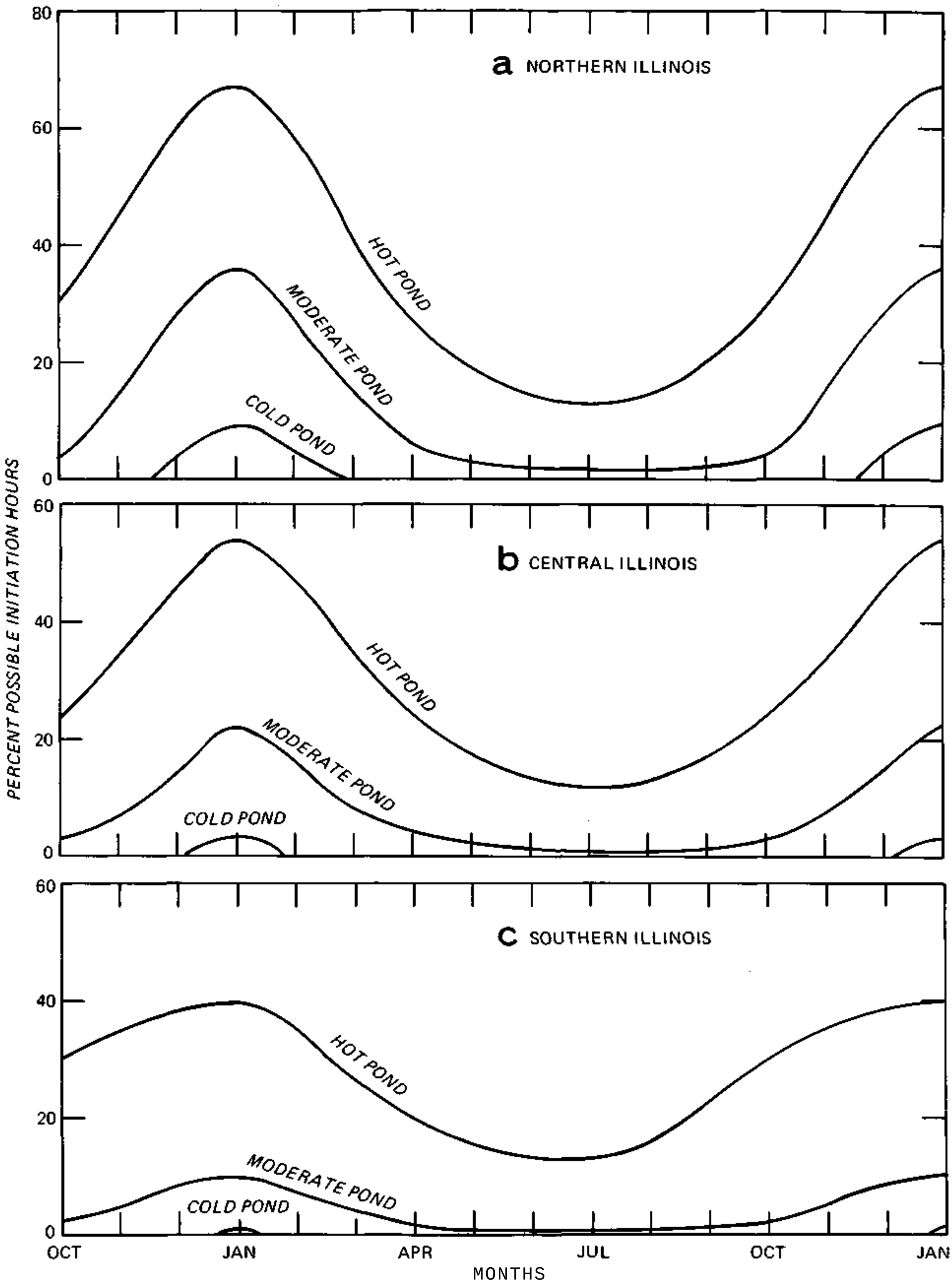


Figure 15. Possible Heavy Fog Initiation Hours.

For a conventional power plant of today (a fossil-fuel type plant) the water temperatures of the moderate pond would most probably apply, and even these may be a little high for the winter months. Most nuclear power plants of the future, and even those few which are operating today in Illinois, can be expected to fall somewhere in the range between the moderate and hot cooling ponds. Over northern Illinois this would probably reduce the possible initiation hours to less than 60% of the total possible hours in January, and the other sections of the state would also be somewhat reduced.

The above figures indicate the amount of time heavy steam fog may be initiated over the surface of a cooling pond. The above figures are not meant to imply that fog can be expected to travel a substantial distance downwind at all times under these circumstances. Indeed, in many instances the fog which does form over a cooling pond can be expected to travel only small distances beyond the edge of the pond, and at other times the fog will change to stratus clouds and will never really affect the surrounding countryside, unless the cooling pond is located in a fairly steep valley.

If a cooling pond site is being planned or designed, calculations of the type shown above should be carried out. However, these calculations should be taken further. In addition, a wind rose of the area as a function of the stability of the ambient air will provide a good estimate of what percent of the time a cooling pond would affect an area downwind. This was not done for the above example, since this type of procedure would require extensive data processing, and a knowledge of the wind rose for the potential site. However, we did determine what percent of time the fog initiated by the cooling pond could be expected to affect an area downstream from the designed cooling ponds over central Illinois. This analysis was performed for the hot, moderate and cold ponds in January using the Springfield wind rose. The results, shown in Table 31, indicate the most likely direction the wind will be blowing from is northwest through north. This means the area downwind which will be substantially affected by a cooling pond is the area southeast through south of the pond. For the hot pond the area from the south to the southeast of the pond will be affected about 25% of the time; in January, if one also considered the stability criteria, this percentage would be reduced further. However, it points out, as could be expected, that during January wind blowing from the northwest through north would cause the major problem, indicating that the most dangerous time synoptically would be the period after a cold front has swept through the area. At that time, relatively cold temperatures would be most likely and the greatest temperature differences between the air and water surface would be expected.

Table 31. Percent of Total January Hours having Fog Potential with a given Wind Direction at Springfield, Illinois.

	Wind Direction								
Pond Type	WNW-NW	NNW-N	NNE-NE	ENE-E	ESE-SE	SSE-S	SSW-SW	WSW-W	Calm
Hot	13.0	11.5	5.2	4.2	4.8	11.5	8.0	7.5	0.6
Moderate	4.5	4.0	1.8	1.5	1.6	4.0	2.8	2.6	0.2
Cold	0.6	0.5	0.2	0.2	0.2	0.5	0.3	0.3	<0.1

PLUME CALCULATIONS

A major question which needs to be asked at any present cooling pond site or at any potential site is, "How far downwind will the effluents from the pond be potent enough to substantially affect the atmosphere?" In other words, how far downwind can one expect fog to penetrate and, perhaps more important, how far downwind can we expect fog or icing to be severe enough to actually affect, in a detrimental way, normal activities.

It is quite obvious that the problem will be most acute within 200 to 300 feet of the pond. Within this region the major effects will be due to dense fog (visibility less than or equal to a 1/4 mile), and if the ambient temperature is cold enough icing will become a problem.

One possible approach to this question is the use of diffusion equations. Tsai and DeHarpporte (1971) used the turbulent diffusion equations to numerically calculate the diffusion of fog over and downwind of a cooling pond. Within their model they allowed the moisture to advect upward over the pond strictly by vertical diffusion and considered the combined effects of diffusion and buoyancy over the land. They tested their results over a cooling pond, but unfortunately did not define thoroughly the pond or climatic characteristics. Even so, their results indicated that only under extreme conditions would one expect fog to travel more than 2500 feet downwind from the pond.

Another approach is that of the Gaussian Plume form of the diffusion equations. This approach has been applied to the effluents from cooling towers by Septoff (1970) and McVehil (1970). Currier et al. (1972) applied this method to cooling ponds. This same type of approach has been used in our study.

This form of the diffusion equation has some limitation, the first of which is that the plume is considered to have a gaussian distribution downwind, and it is designed to give an average concentration of a gas or aerosol over several minutes downwind from its source. It is assumed that there is no deposition of particles and that no particle is more than about 20 microns in diameter. Turner (1970) indicates that the most general form of the equation for a continuously emitting point source is

$$\chi(x,y,z:H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left[-\frac{1}{2}\frac{y}{\sigma_y}\right]^2 \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \right\} \quad (A)$$

X(x,y,z:H) is the concentration of the plume in the x-direction (along the wind), y-direction (perpendicular to the wind), and z-direction (vertical distance) as a function of the effective emission height, H. Q is the rate of emission of the quantity, σ_y and σ_z are the standard deviations of the plume concentration in the horizontal and vertical, respectively, and u is the wind speed. This equation can be utilized only when one can assume that there is no diffusion of the substance along the direction of the wind.

For a cooling pond the effective height of the emission is ground level; thus, H can be set to zero. To evaluate whether or not there is the possibility of fog the calculations were made at the ground level and along the centerline of the plume. Hence, both y and z can also be set to zero. For a continuously emitting point source, Equation A then reduces to

$$\chi(x,o,o:o) = \frac{Q}{\pi\sigma_y\sigma_z u} \quad . \qquad (B)$$

Since there are very few cooling ponds less than 500 to 1000 acres, it is necessary to treat Equation B as an area source, rather than a point source. This technique is often referred to as a virtual point source. One assumes that the total effluent over the pond is concentrated over a fictitious point upwind. The fog which is emitted from the surface of the pond is a form of steam fog and the water vapor and sensible heat being released by the pond will be spread over the total area of the pond. This method spreads the effluents out along the y-axis, giving a more realistic value of the amount of water vapor or sensible heat which is being spread downwind from the pond. Turner has available in graph form the values for the standard deviations in the y and z direction for 6 stability classes ranging from very unstable to stable.

Fog is a ground-based cloud, and like a cloud, will form when the atmosphere nearly becomes or is saturated, provided there are sufficient condensation nuclei present. The type of fog initiated over a cooling pond is steam fog which forms only when the air overlying a water surface is much colder than the water. Under these circumstances the equilibrium vapor pressure of the water is much greater than the vapor pressure of the air, and as the excess water vapor from the water surface is added to the air it cools and condenses forming fog. Because of the extreme temperature differences between the water and the air, the surface layer of the air will become heated and since it will then be lighter than the air above, convection will set in carrying the warmer, moister air upward and the colder, drier air downward, allowing the formation of steam fog to continue.

To determine the emission rate of the water vapor from the surface of the pond, it is necessary to calculate the rate of evaporation. There are three basic methods used to determine the rate of evaporation; the water-budget method, the mass-transfer method, and the energy-budget method. The first of these methods has been applied to Lake Hefner in Oklahoma and Lake Mead in Nevada (U. S. Geological Survey, 1954 and 1958). In both instances, an extensive array of equipment was needed and though the results were accurate, in general, the method is impractical because of the possibility that small errors in measurements can result in unreliable estimates of evaporation.

The classical mass-transfer method attempts to measure the amount of evaporation as a function of the forced convection resulting from the flow of air across the surface of the lake. Many such formulas have been developed both from theoretical considerations and as the result of extensive field programs (U. S. Geological Survey, 1954 and 1958). Most of the formulas which were developed prior to 1960 were concerned with the evaporation rates from natural lakes or from cooling reservoirs with only limited thermal loading (U. S. Geological Survey, 1959). It is only recently that any attention has been given to evaporation from cooling ponds or water surfaces that have highly elevated water temperatures.

Shulyakovskiy (1969) and Ryan and Harleman (1973) have argued that over a cooling pond both forced and natural convection must be considered to effectively evaluate the evaporation rate. This only stands to reason since the lower layer of the atmosphere will be heated and natural convection will act at any time the water temperature is greater than the air temperature.

The last method, the energy-budget method, is based on the law of conservation of energy. By carefully measuring the amounts of energy into and out of a lake surface a very reliable estimate of the amount of water evaporated into the atmosphere can be made. This method is by far the superior method; however, because of a lack of radiation measurements and due to the fact that standard meteorological data provide the necessary input the mass-transfer method was utilized for these calculations.

Since the surface of a major cooling pond installation would have an elevated water temperature, it was decided to use the evaporation formula proposed by Ryan and Harleman (1973). This formula, when converted from heat units to an evaporation rate, becomes

$$E = 0.750\ [0.00494\ (\Delta\Theta_v)^{1/3} + 0.00566 w_2]\ (e_s - e_a)\ . \qquad (C)$$

The formula is in terms of ft/day and $\Delta\Theta_v$ is equal to the virtual temperature of the water surface minus the air virtual temperature at 2 meters (°C), w_2

is the wind speed at 2 meters (mps), and e_s and e_a are the vapor pressures of the water surface and air respectively (mb).

The cooling pond will also release a certain amount of sensible heat which will serve to warm the air over and downwind from the pond. A first approximation of the amount of sensible heat released by the pond can be obtained by determining the Bowen Ratio. The Bowen Ratio is the ratio of the sensible heat released, Q_H, to the. heat released by evaporation, Q_E,

$$\frac{Q_H}{Q_E} = \frac{c_p \, p \quad (T_w - T_a)}{0.621 \, L \, (e_w - e_a)} \tag{D}$$

where L is the latent heat of condensation, p is the atmospheric pressure, C_p is the specific heat of air at constant pressure, T_w and T_a are the temperatures of the water and air, and e_w and e_a are the vapor pressures of the water and air. The sensible heat released by the pond can be found by solving Equation D for Q_H.

The calculations were made on the assumption that there was a 1000-acre, (about 4 km^2) square-shaped cqoling pond, and the season was winter. The wind speed in all cases was to be 3 mps (6 mph). The air and water temperatures chosen are shown in Table 32. It was assumed that most major cooling ponds would be between the two water temperatures, and that a range of possible answers would be obtained. It was further assumed that the air was not quite saturated (a rather severe assumption). The concentrations of water vapor, X_E, and sensible heat, X_H, were calculated for distances of 1500 feet (0.5 km) and 5000 feet (1.5 km) downwind from the edge of the cooling pond.

Table 32. Initial Temperature Data for Plume Calculations.

Case	Air Temperature	Pond Temperature	Temperature Difference
1	10F (-12.2C)	70F (21.1C)	60F (33.3C)
2	40F (4.4C)	70F (21.1C)	30F (16.7C)
3	-10F (-23.3C)	40F (4.4C)	50F (27.7C)
4	10F (-12.2C)	40F (4.4C)	30F (16.7C)

The change in temperature, AT, caused by the addition of sensible heat was found using the formula

$$\Delta T = \frac{\chi_H}{\rho c_p} \quad \text{(E)}$$

where ρ is the density of the air.

The resulting increments of temperature and water vapor concentration were then added to the ambient value. If the resultant water vapor value was equal to or in excess of the saturation value at the new air temperature, it was concluded that fog had formed. However, the temperature increases which resulted from these calculations were completely unrealistic. Some of the temperature increases were in excess of 40°C.

Turner (1970) points out that the estimates of σ_z can be in error by more than 2 to 3 times for long distance travel with stable or unstable conditions. He also states that σ_y can be in error by 2 times for the same reason. In the above situation, where there is a large difference between the water and the air temperatures, and even though the air surrounding the pond is stable to very stable , the air over and downwind from the pond cannot be expected to remain stable. Due to the extreme air-water interaction which would be taking place under these circumstances, the air over and downwind from the pond should be expected to become highly modified, becoming unstable. Therefore, errors in the estimation of σ_y and σ_z of 2 to 4 times respectively can be expected.

Since the calculated changes in temperature due to the flux of sensible heat were so unrealistic, it was decided, on the basis of synoptic experience, to assume the following temperature changes at a distance of 1500 feet (0.5 km) downwind from the edge of the pond.

Case 1: ΔT = 8C (14.4F)

Case 2: ΔT = 4C (7.2F)

Case 3: ΔT = 7C (13.6F)

Case 4: ΔT = 3.5C (6.3F)

It is possible to solve for $\sigma_y\sigma_z$ by the following equation

$$\sigma_y\sigma_z = \frac{Q_H}{\pi \rho c_p u \Delta T} \quad \text{(F)}$$

These results were then compared with the original estimates of σ_y and σ_z. To stay within the temperature change estimates, it was necessary to divide our original answer by factors ranging from 3.2 to 7. The factors for the four cases are as follows:

Case 1	7
Case 2	6.3
Case 3	6.5
Case 4	3.2

The four cases chosen are admittedly extreme cases; the results show that in all cases with an almost saturated atmosphere, fog can be expected at both 1500 and 5000 ft downwind. These results are shown in Table 33. The calculations for all four cases were made assuming that the atmospheric stability classes, defined by Turner (1970) varied between unstable (class B), neutral (class D), slightly stable (class E), and stable (class F).

To reiterate, all calculations were made assuming that the atmosphere was very close to saturation. Table 33 also shows the excess liquid water within the plume; that is, if in the ambient atmosphere this water vapor deficit had existed no fog would have been in evidence downwind from the cooling pond. It can readily be seen that in most instances a water vapor deficit of 1 g/m^3 or less would have been sufficient to retard the occurrence of fog downwind from the pond. The only case that would require a water vapor deficit greater than 1 g/m^3 is Case 1. However, this is an extreme case and would occur very seldom. In all of the cases for stability classes B, D, and E, there is a strong likelihood that instead of fog a stratus plume at heights of several hundred to a 1000 feet may have formed downwind from the pond, especially at a downwind distance of 5000 ft. This is especially likely when one considers the highly active air-water interaction demanded by the extreme temperature differences between the air and the water.

These results can only be considered inconclusive and tentative at best. Considering the unrealistic answers from the original version of the equation and the highly speculative results shown above, it can only be concluded that this approach is highly unlikely to give realistic results. Furthermore, the above results quite definitely point out how little is really known about the air over and downwind of a cooling pond.

Some of the limitations of this type of diffusion equation and perhaps the biggest problem inherent in using this approach is that no allowance has been made for the deposition of droplets which have diameters of 20 microns or greater. The bigger droplets are the droplets which make the major contribution to the liquid water content of a natural fog (Eldridge, 1971). This type of mathematical modeling does not allow for the deposition of these droplets as the plume spreads downwind, and this may well account for some of the seemingly excessive liquid water concentrations which were found. Currier et al. (1972) have allowed for the deposition of droplets as a function of distance and they claim satisfactory results.

These are extreme cases and with the temperatures hypothesized the evaporation rate will become extremely high and will tend to cool the surface of the pond at a fairly rapid rate; hence, these extreme conditions cannot be expected to last longer than about 1 hour.

Table 33 also shows that the colder the water temperature, the less chance a cooling pond has of forming fog. Part of the reasoning behind this is that as the actual air and water temperatures become colder, sensible heat is released at a greater rate in comparison to the evaporative heat release. Since the air cannot hold as much water at these temperatures and more sensible heat is being released in the atmosphere there is less of a chance of fog forming.

Table 33. Plume Calculation Results.

		1500 ft		5000 ft	
Case	Stability Class		Excess Liquid Water (g/m^3)		Excess Liquid Water (g/m^3)
1	B	Fog	0.3	Fog	0.2
T_w = 70	D	Fog	1.4	Fog	1.0
T_a = 10	E	Fog	1.9	Fog	1.7
	F	Fog	2.8	Fog	2.6
2	B	Fog	0.4	Fog	0.3
T_w = 70	D	Fog	0.7	Fog	0.6
T_a = 40	E	Fog	1.2	Fog	0.8
	F	Fog	1.3	Fog	1.2
3	B	Fog	0.1	Fog	<0.1
T = 40	D	Fog	0.5	Fog	0.4
T_a = -10	E	Fog	0.6	Fog	0.5
	F	Fog	0.9	Fog	0.8
4	B	Fog	<0.1	Fog	<0.1
T_w = 40	D	Fog	0.2	Fog	0.1
T_a = 10	E	Fog	0.3	Fog	0.2
	F	Fog	0.4	Fog	0.4

COOLING POND ICING POTENTIAL

In addition to the fog problem, cooling ponds will also induce icing, which is divided into two categories, glaze and rime. Glaze, or clear icing, is formed by the impingement of large slightly supercooled water droplets and a consequent flattening upon the surface. Most of this type of icing forms when the air temperature ranges from 20-29°F, and its density is about 0.9 g/cm^3. Rime is the second type of icing and is the result of the collision of small highly supercooled water droplets and the resultant freezing upon a surface. The density of rime icing ranges from 0.3 to 0.8 g/cm^3, and it usually occurs with temperatures less than 20°F.

The data regarding icing around cooling ponds is scanty and no definite relation exists between the water surface and/or the air which would clearly define the occurrence of icing. However, from the data presented by Currier et al. , (1972), one can infer that it is necessary to have at least a 40°F temperature difference between the water and the air, and a saturation deficit in the ambient air of no more than about 0.6 g/kg saturation deficit. All of the icing that did occur, during the period of their observations, were at temperatures of 2 3°F or less. In view of the normal droplet spectrum of fog and the results from the two days of droplet size measurements made at 4-Corners, New Mexico (Currier et al., 1972), one can conclude that the droplet diameters of fog induced by cooling ponds are, in the mean, much less than 20 microns in diameter, and can be classified as small drops. Thus, rime icing is the most likely culprit and this analysis will be confined to rime icing that may possibly be induced by a cooling pond.

Wind is also an important factor to consider in any icing analysis. If the wind is less than 5 mph, some of the larger water droplets would fall out before they reached the edge of the pond and as a result most of the icing would be confined to the near edges; also with these light winds, the deposition efficiency of the icing would be at a minimum. Therefore, it was hypothesized that in order for any significant icing to form it would be necessary to have a wind speed of 5 mph or greater, a temperature difference between the water and the air of at least 40°F, and a saturation mixing deficit of 1 g/kg or less.

To determine that percent of the time that icing would be a critical factor in the vicinity of the pond, climatological data was again stratified for the northern, central and southern sections of Illinois, but only for the month of January, the worst possible month. The analysis was carried out using the same definitions of cold, moderate, and hot ponds presented in Fig. 14.

The results of this analysis are shown in Table 34. The hot pond has the potential of inducing icing 13 percent of the time or about 96 hours in the month of January, the worst possible winter month. Over central Illinois this value quickly falls off to 4 percent and over the southern reaches of the state it reduces to 1 percent. For a moderate pond, over northern Illinois, icing is a potential problem only 2 percent of the time or about 15 hours per January, and for central Illinois this value for a moderate pond is reduced by half, and over southern Illinois there is less than a 0.5 of one percent chance of any significant icing in the vicinity of a cooling pond.

The analysis for a cold pond is not reproduced in Table 34 since the potential icing effect of a cold pond for the whole state of Illinois was found to be negligible.

The above results must be considered to be conservative and may well represent an overestimate of the potential icing effect. As has been stated, data concerning the effect a cooling pond has on icing are slight, and that which is available hardly represents a good sample of this atmospheric phenomena. It is believed that most of the icing would generally be confined to the area within about 1000 feet of the edge of the cooling pond. There will be some rare occurrences of icing beyond this 1000 feet, but it is believed that such occurrences could be minimized to a large extent by the inclusion of pine stands within a half mile of the edge of the cooling pond in that area or areas where icing would present a definite public hazard (Murray and Trettel, Inc., 1973).

Table 34. Icing Potential Near a Cooling Pond in Illinois during January.

Pond Location	Percent of Hours Having Icing Potential for Hot and Moderate Ponds	
	Hot	Moderate
Northern	13	2
Central	4	1
Southern	1	<0.5

LOW-LEVEL MOISTURE AND TEMPERATURE DISTRIBUTIONS

The most probable atmospheric effects of cooling ponds , the formation of fog and the enhancement of cumulus clouds, are low-level phenomena. Hence, it was decided that a preliminary low-level climatology of the thermal and moisture structure was required to help assess the potential effects cooling ponds have on these two atmospheric elements. Upper air data available from Peoria, in north central Illinois, for the 5-year period 1958-62 were utilized to determine the merits of an approach of this type. Average temperatures, relative humidities, and the distribution of mixing ratios and saturation deficits were calculated for the four seasons, at the surface, 950 mb and 900 mb levels.

Figure 16 shows the average temperature and dew point curves for winter and summer at 0600 and 1800 from the surface to 900 mb at Peoria. The summer soundings for the two times are on the right and the two winter soundings on the left. For both seasons the 1800 sounding is indicated by solid lines and the 0600 sounding is shown by dashed lines. The temperatures are plotted as circles and the dew points as triangles. The thin solid lines, numbered at the top, indicate the saturation mixing ratio; i.e., the maximum amount of water vapor air can hold at that temperature and pressure. Spring and autumn are not presented since they only show the transition between summer and winter.

Characteristics of Winter Soundings

The morning sounding for the winter months shows that the temperature normally increases from the surface to 900 mb, which indicates that the atmosphere during the morning is, on the average, quite stable. At 0600, the saturation deficit for this average morning sounding ranges from 0.5 g/kg at the surface to 1.2 g/kg at 900 mb. By 1800, the inversion is usually well on its way to reforming, after daytime weakening or elimination, as is evidenced by the nearly isothermal temperature curve. For the most part, the lower levels of the atmosphere during winter are characterized by relatively stable conditions for a major portion of the day. Also, the saturation deficit through the low levels of the atmosphere changes little from the morning to the evening. At 1800, the average saturation deficit from the surface to 900 mb ranges from 0.6 g/kg to 1.2 g/kg.

The average soundings for the morning and the evening at Peoria do not reflect the diurnal temperature change, which is 15° to 20°F for winter. The maximum temperature can be generally expected in the early to mid-afternoon, corresponding to the time of the day when one would find the maximum saturation deficit. As a result, fog would have less of a tendency to form or to continue during these hours. This is borne out by Fig. 6, which shows that the minimum fog period during winter is in the early afternoon.

However, there will be times, especially in the winter, when the surface temperature will not heat to the point where the inversion disappears, and fog over cooling ponds will then have a greater propensity to remain. There will be more of a tendency for cooling ponds to generate fog during these stable periods, since pond evaporation will be confined to the lower levels and, consequently, will tend to condense as fog or stratus clouds. Because of the stable nature of the atmosphere during winter, longer-lived and more frequent fog can be expected.

Characteristics of Summer Soundings

During the summer, as indicated by Fig. 16, a shallow inversion can be expected during the morning hours; however, the low saturation deficit values are generally confined to the surface. The saturation deficits range from 1.7 g/kg at the surface to 4.5 g/kg at 900 mb. The air, in the

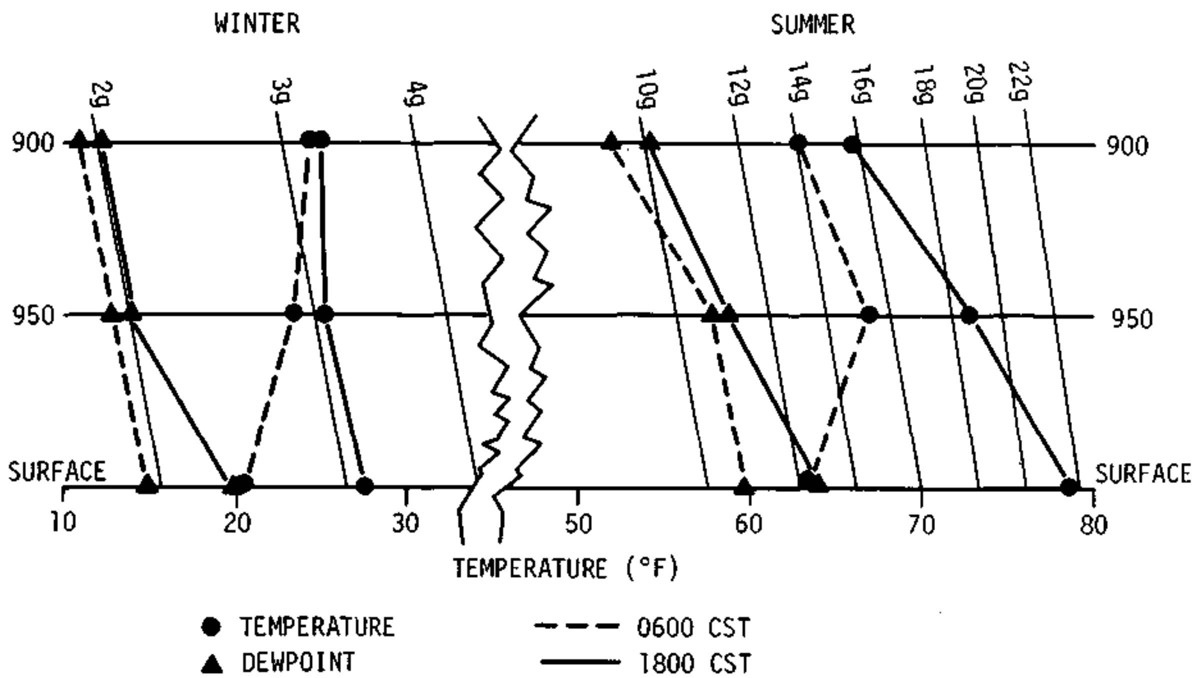


Figure 16. Average Temperature and Dew Point Curves at Peoria for Winter and Summer at 0600 and 1800 CST.

summer from 0600 onward, becomes heated rather rapidly at the surface, since there is more available solar energy, and the temperature normally reaches a maximum during mid-afternoon. Both of these effects are reflected in the 1800 summer sounding. The early evening summer sounding is characterized by an almost dry-adiabatic lapse rate from the surface to 900 mb, showing that the air in this layer is well mixed. This type of sounding is potentially unstable and is favorable for the formation of convective clouds, providing that enough moisture and lift is present. The average saturation deficit during the evening ranges from 8.9 g/kg at the surface to 5.4 g/kg at 900 mb.

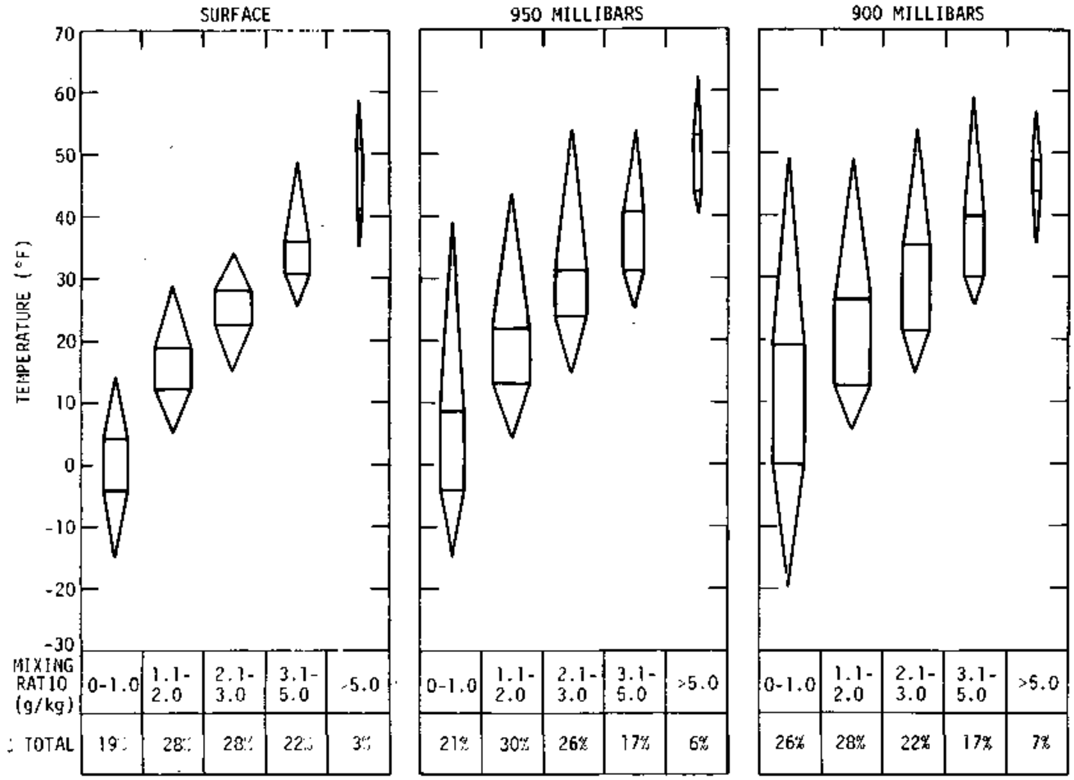
Most fogs which form during the summer would be confined to a very shallow layer and would burn off usually after several hours (see Fig. 6). Fog during the summer, except for the early morning period from 0400 to 0900, would be at a minimum and even then the occurrences of fog would seldom be dense. Because of the well mixed character of the air and the large amounts of evaporation which can be expected in the summer, it is quite conceivable that the main atmospheric effect of a cooling lake would be the generation or enhancement of cumulus clouds.

Winter-Summer Comparisons

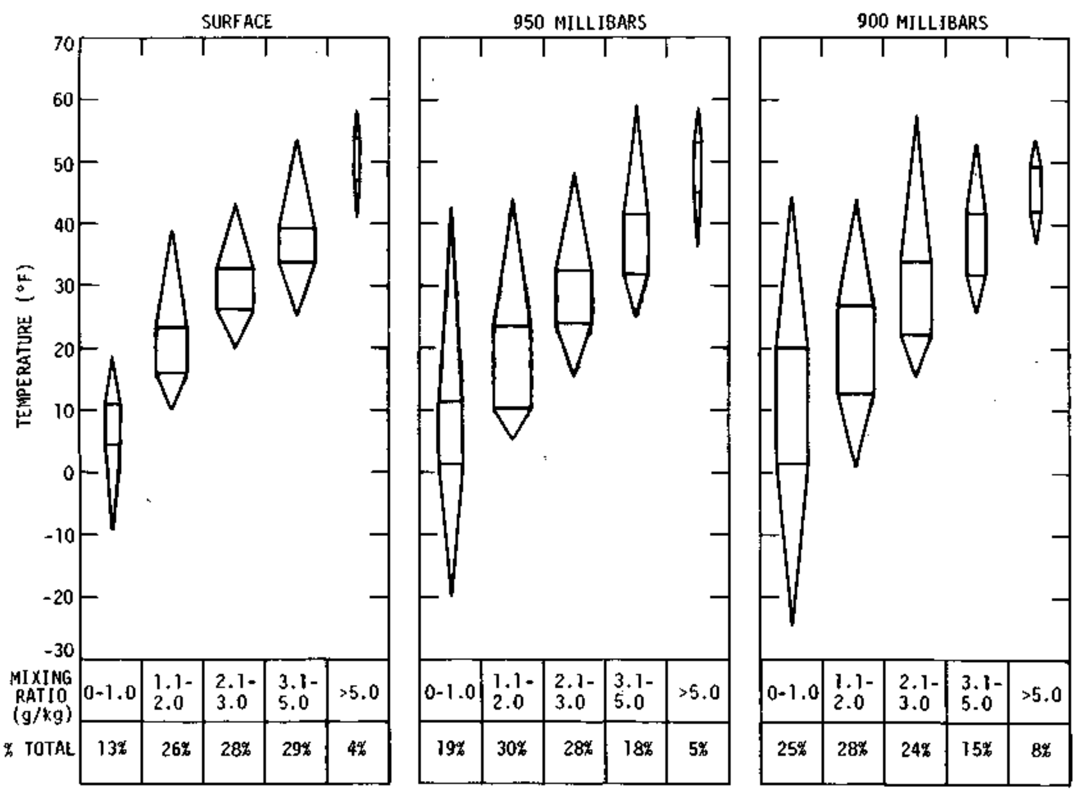
Figures 17 through 20 present the distributions of the saturation deficits and mixing ratios, as a function of temperature (°F), for winter and summer at 0600 and 1800. In these figures, the length of the hexagon represents the range of temperatures which are applicable; the rectangle in the center shows the 50-percentile grouping of the distribution; and the area enclosed by the hexagon is directly proportional to the percent of total occurrences for any one level.

Figure 17 indicates the distribution of the winter mixing ratio for Peoria at 0600 and 1800. At 0600 and 1800 there is a relatively smooth transition at all levels in all categories with the range of temperature increasing from the surface to 900 mb. There is little change in the distribution of mixing ratios from morning to evening. The central temperature values increase about 5°F from the morning to the evening, and there is a corresponding rise in the value of the mixing ratios.

The distribution of the winter saturation deficits at 0600 and 1800 are shown in Fig. 18. The major difference is evident near the surface. In the morning, saturation deficits of 1 g/kg or less can be expected 95% of the time; while at 1800, the saturation deficits are 1 g/kg or less only 65% of the time. This trend is evident to a somewhat lesser extent at 950 mb. In the morning, the percent of time that the saturation deficit is 1 g/kg or less ranges from 95% at the surface to 54% at 900 mb. At 1800, a saturation deficit of 1 g/kg or less was reported 65% of the time at the surface and 54% at 900 mb.

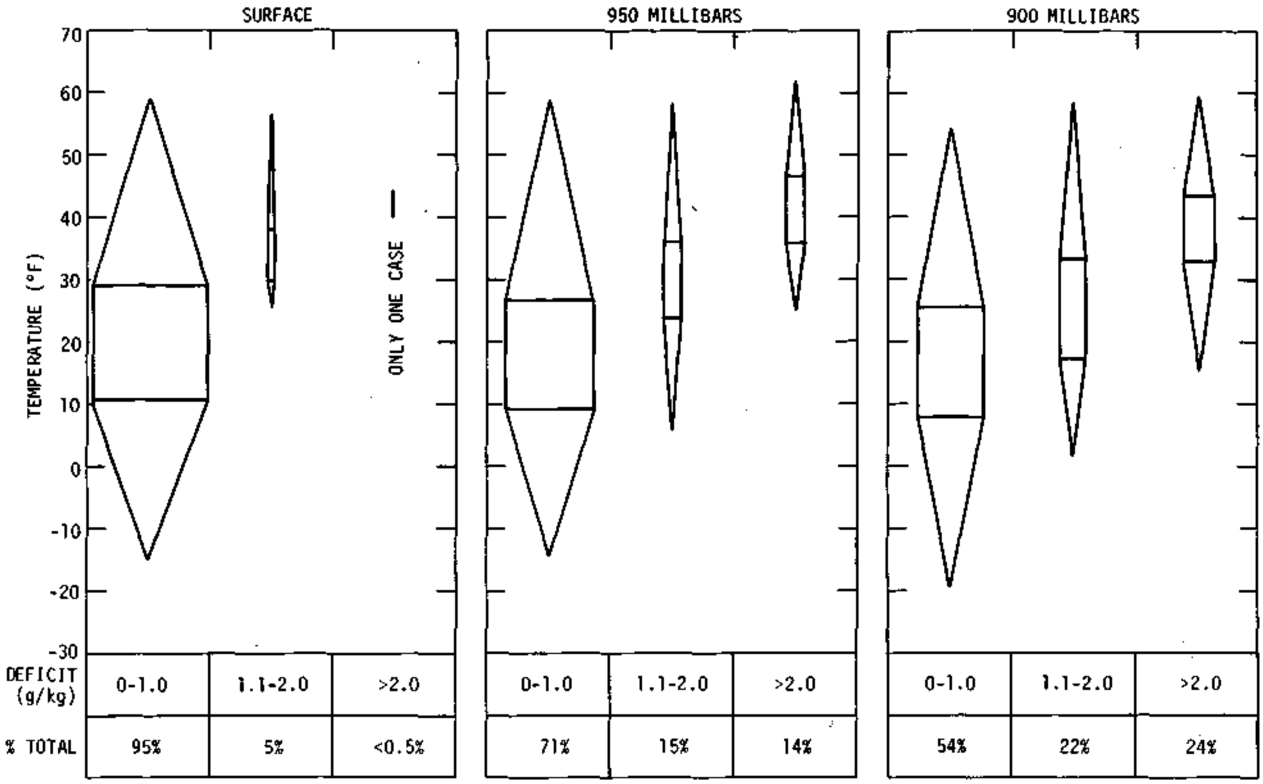


a. 0600 CST

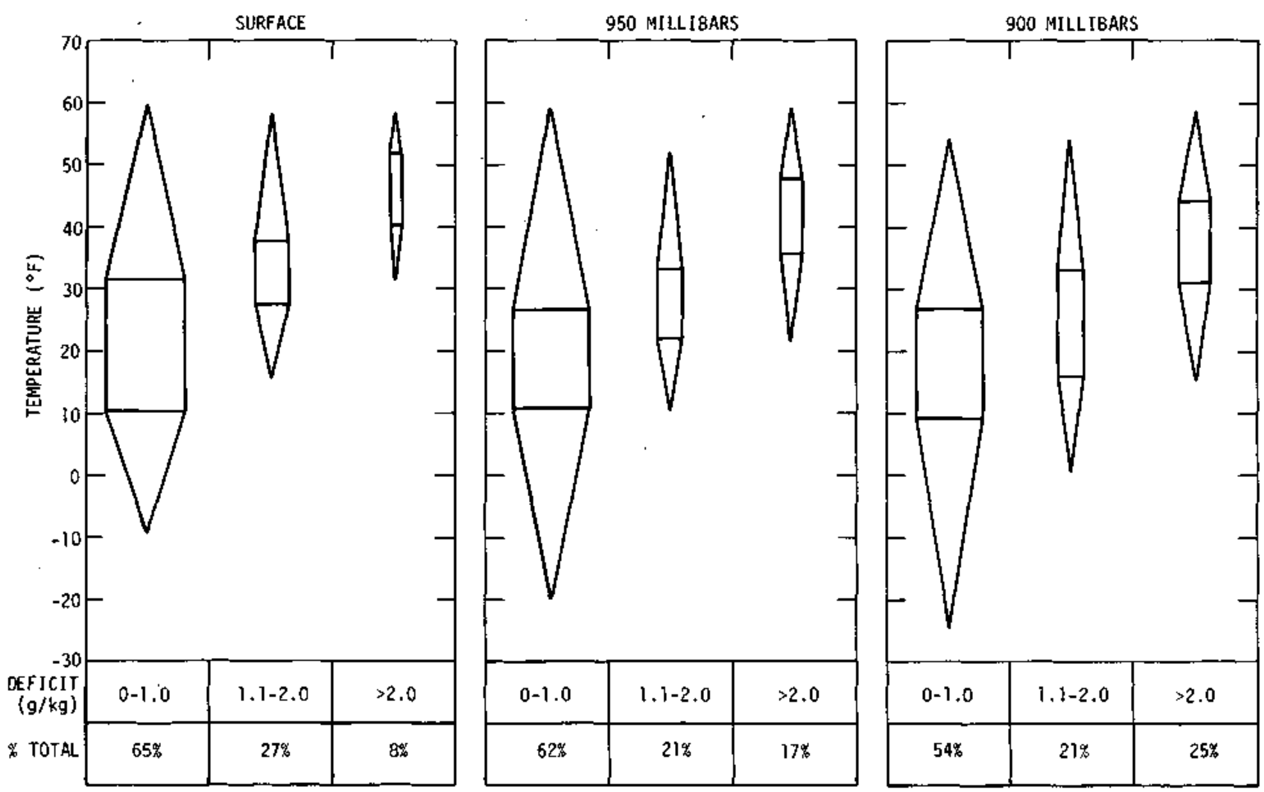


b. 1800 CST

Figure 17. Low-Level Distribution of Mixing Ratios at Peoria During Winter at 0600 and 1800 CST.



a. 0600 CST



b. 1800 CST

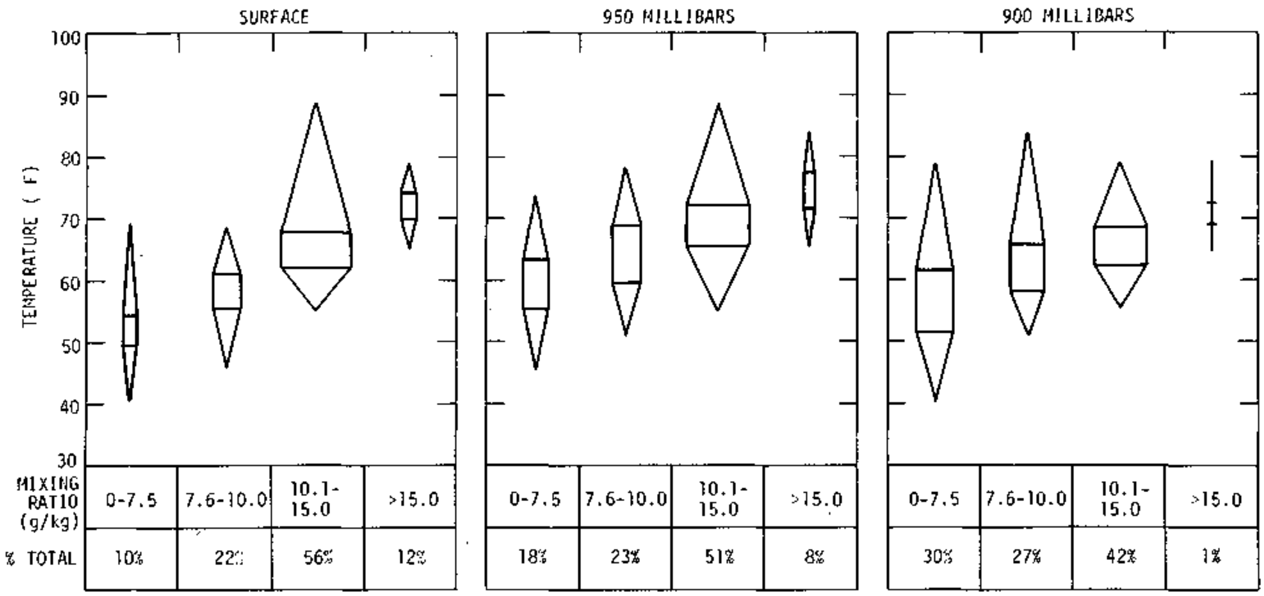
Figure 18. Low-Level Distribution of Saturation Deficits at Peoria During Winter at 0600 and 1800 CST.

Thus, the low levels of the atmosphere during the winter are generally characterized by low saturation deficits, which means that the atmosphere is not capable of taking much additional moisture from any other source without condensation occurring. At the surface, over 50% of the saturation deficits of 1 g/kg or less occur at 0600 and 1800 with temperatures less than 30°F. This means that the greatest potential for initiation and enhancement of fog and/or icing exists when the temperature is below 30°F. Figure 8 shows that over 70% of the time natural fog occurs with temperatures equal to or in excess of 30°F, and 80% of the time dense fog occurs with temperatures greater than or equal to 30°F. This means that the potential for the enhancement of all fog combined is less than 30%. This is a conservative figure. As has been stated earlier, it is necessary to have a saturation deficit of less than 1 g/kg and a visibility of 1 mile or less before fog can be expected to cause the visibility to fall below 1/4 mile. Thus, it can be concluded that during winter the major fog problem over a cooling pond is not that of enhancement, but rather one of initiation, which was indicated earlier in the study of cooling pond initiation potential. During winter, because of the stable air and the deep areas of small saturation deficit, fog which does form can be expected to be relatively deep and consequently there would be a greater chance for long-lived fog cases.

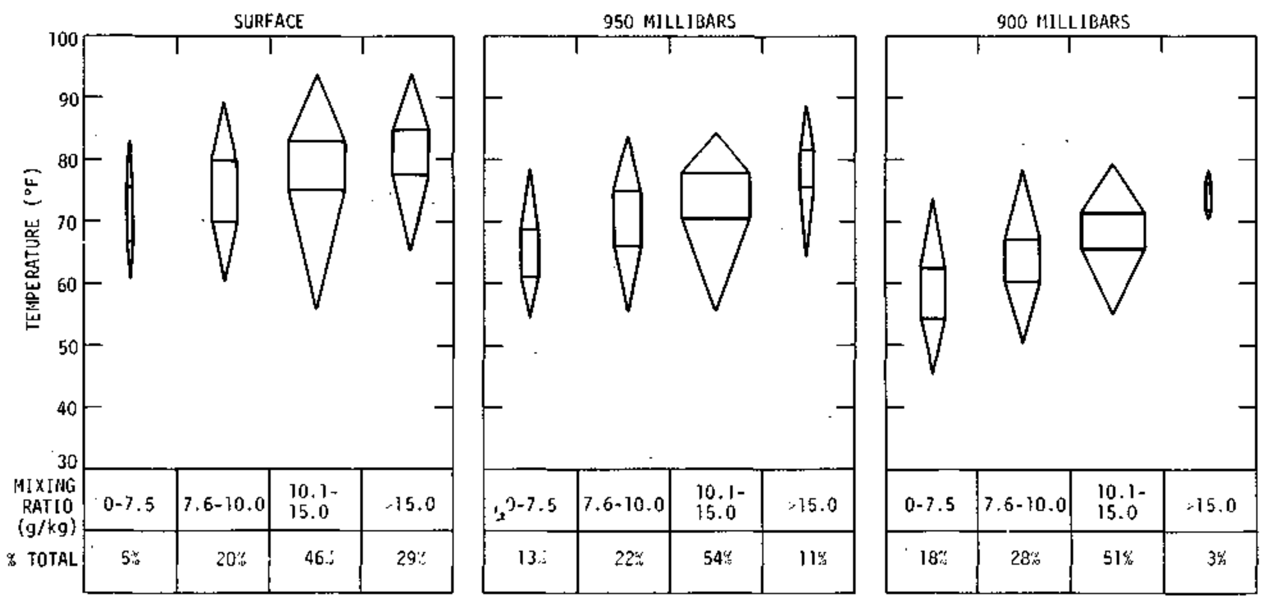
During the summer, most of the mixing ratios are between 10.1 to 15 g/kg, over a temperature range from 55 to 94°F, as indicated by Fig. 19. There is little change from 0600 to 1800 at any level except for slightly higher temperatures at 1800.

Figure 20 shows the summer moisture deficit distribution at 0600 and 1800, and they show that there is an appreciable diurnal change from the morning to the evening. The deficits are more varied in the summer, so that the saturation deficits are bracketed by different categories than in the winter. The most dramatic difference from morning to evening is found at the surface, where deficits of 2 g/kg or less occur 73% of the time in the morning and only 6% of the time in the afternoon, and occurrence of deficits of 5 g/kg or greater vary from 3% to 82% from the morning to the afternoon. During the summer, an increase of 15°F can mean a difference of about 11 g/kg in the amount of water vapor the air can hold, while in the winter a 15°F difference in' temperature may only mean a difference of 2 g/kg in the amount of water vapor the air can hold. The normal diurnal temperature change from minimum to maximum, in the summer, is on the order of 20° to 25°F, and the 1800 sounding is close to the time of maximum temperature. Thus, one would logically expect large changes in the values of the saturation deficits. These diurnal changes are clearly evident in Fig. 20 at the surface, and even though they damp somewhat with height, they are apparent up to 900 mb.

The average saturation deficits for summer indicate that any fog which does form during the summer will generally be confined to the low levels since the smaller saturation deficits are confined to the lower layers of the atmosphere. Climatologically, cumulus clouds are most likely

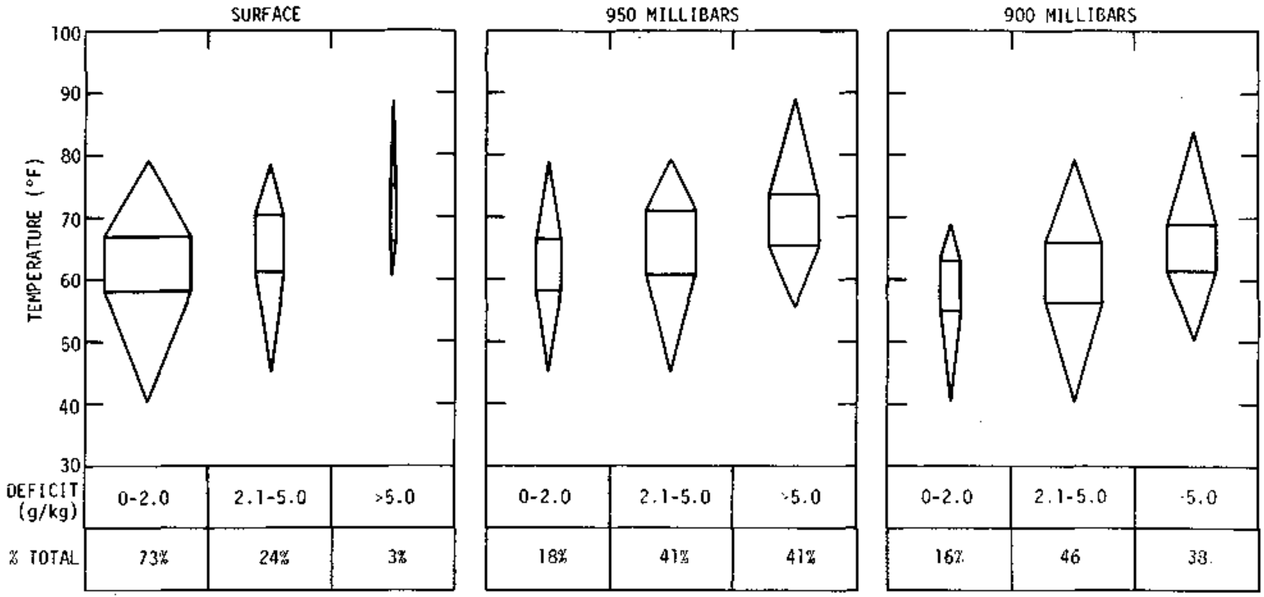


a. 0600 CST

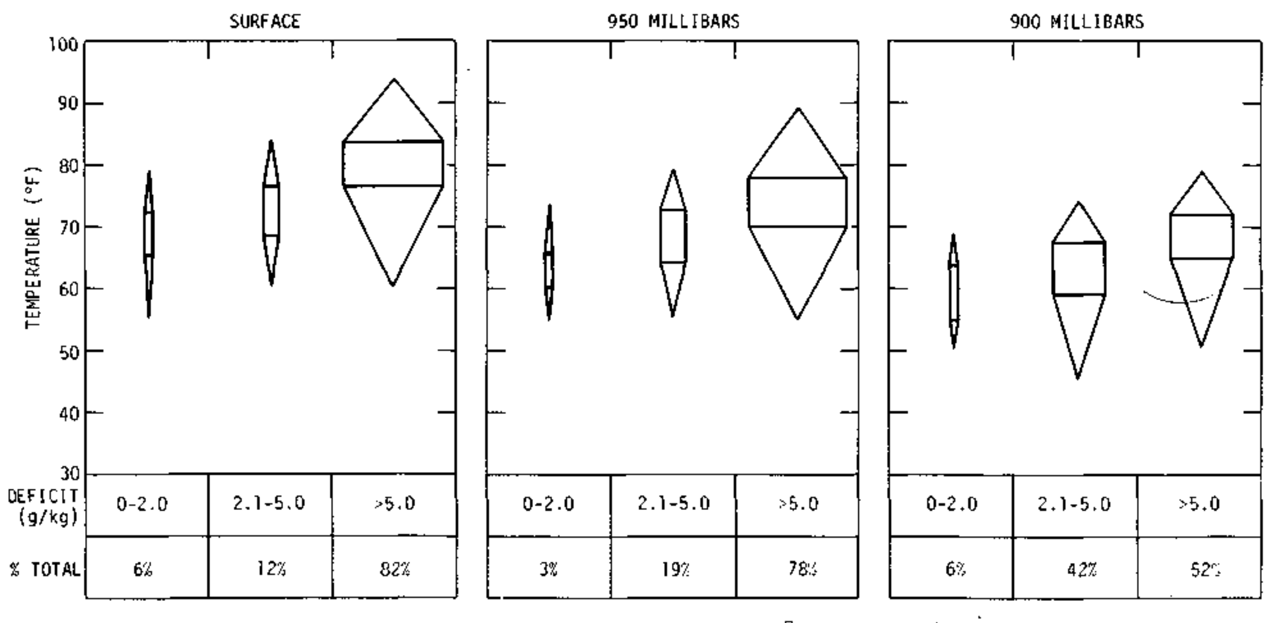


b. 1800 CST

Figure 19. Low-Level Distribution of Mixing Ratios at Peoria During Summer at 0600 and 1800 CST.



a. 0600 CST



b. 1800 CST

Figure 20. Low-Level Distribution of Saturation Deficits at Peoria During Summer at 0600 and 1800 CST.

to form in the early afternoon and continue through the maximum heating period, mid to late afternoon. The distribution of saturation deficits at 1800 are most representative of this time period, and they indicate, that on the average, the cooling pond would have to enhance the water vapor content in the lower 2000-3000 ft by some 5 g/kg or more. This is an unlikely prospect. The most synoptically favorable situation in which a cooling pond might be a significant factor, would be those times when the lower layers of the atmosphere have a saturation deficit of 2 g/kg or less, and this is not the norm. Figure 20 shows that saturation deficits of 2 g/kg or less at 1800 can be expected less than 6% of the time, so that cumulus cloud enhancement over cooling ponds cannot be considered to be a significant factor.

Conclusions

Overall, the mixing ratio climatology indicates (similar to our other analyses) a relatively high probability of fog initiation over ponds during winter mornings, but also that fog enhancement is not a major problem, except under extremely stable atmospheric conditions. The initiation and enhancement of fog seems to be only a minor factor in the summer, when cooling pond generated or enhanced fog would tend to be shallow and short-lived. Results of the summer saturation deficits indicate that the initiation or enhancement of cumulus clouds would only occur infrequently.

The results of this portion of our analysis must be considered preliminary and are conservative. They are biased to early morning and early evening, because these are the times the National Weather Service takes daily upper air observations. Somewhat more definite values could be obtained if a longer data base were utilized. In this preliminary study, we used only that data base which was readily available, but the results point out the utility of this type of climatological analysis.

INVESTIGATION OF CUMULUS DEVELOPMENT AND ENHANCEMENT

One of the potential effects a cooling pond might have on the atmosphere is the enhancement or development of cumulus clouds, and if this effect is sufficiently strong the precipitation pattern downstream from the ponds could be affected (Ackerman, 1971). Initially it was proposed that this effect be evaluated using a one-dimensional cloud model, but it soon became apparent that this type of model is not sufficiently sophisticated to evaluate these effects. Instead, a two-dimensional model being developed by Dr. Harry Ochs of our staff was employed (Ochs and Ceselski, 1973).

The model being developed by Ochs is similar to models previously developed by Orville (1965) and Takeda (1971). In order to model the convective clouds in an x-z plane the following equations were utilized:

A) the continuity equation,

$$\frac{\partial \rho_o u}{\partial x} + \frac{\partial \rho_o w}{\partial z} = 0$$

where ρ_o is the density of initial atmosphere, u is the horizontal velocity and w is the vertical velocity;

B) the vorticity equation,

$$\frac{\partial \eta}{\partial t} = - u\frac{\partial \eta}{\partial x} - w\frac{\partial \eta}{\partial z} + \frac{2w}{\rho_o}[\eta - u\frac{\partial \rho_o}{\partial z}]\frac{\partial \rho_o}{\partial z} + wu\frac{\partial^2 \rho_o}{\partial z^2}$$

$$+ \rho_o g\frac{\partial \ell}{\partial x} - .608\ \rho_o \frac{\partial r'}{\partial x} - \rho_o g\frac{\partial}{\partial x}\frac{\theta'}{\Theta_o} + \nabla \cdot K_m \nabla \eta$$

where n is the y-component of vorticity, g is the acceleration of gravity, ℓ is the cloud water content, r' is the perturbation water-vapor content, 9' is the perturbation of the potential temperature, θ_O is the reference potential temperature, and K_m is the eddy diffusion coefficient for vorticity;

C) the thermodynamic equation,

$$\frac{\partial}{\partial t}\frac{T'}{T_o} = - u\frac{\partial}{\partial x}\frac{T'}{T_o} - w\frac{\partial}{\partial z}\frac{T'}{T_o} - \frac{w}{T_o}\left(\frac{\partial T_o}{\partial z} + \frac{g}{c_p}\right)$$

$$+ \nabla \cdot K_T \nabla \frac{T'}{T_o}$$

where T' is the perturbation temperature, T_Q is the reference temperature, C_p is the specific heat of air at constant pressure and K_T is the eddy diffusion constant for temperature;

D) the equation for the water-vapor and cloud-water content of the atmosphere,

$$\frac{\partial r}{\partial t} = - u\frac{\partial r}{\partial x} - w\frac{\partial r}{\partial z} + \nabla \cdot K_r \nabla r$$

$$\frac{\partial \ell}{\partial t} = - u\frac{\partial \ell}{\partial x} - w\frac{\partial \ell}{\partial z} + \nabla \cdot K_\ell \nabla \ell$$

where K_r is the eddy diffusion coefficient for water vapor and K_ℓ is the eddy diffusion coefficient for cloud water content.

The advection terms in the above equations are evaluated by the Arakawa space differencing method, while all time intergration is done using the Adams-Bashforth scheme (Ochs and Ceselski, 1973).

The first horizontal grid level is considered to be 10 meters above the ground level. To simulate heating and evaporation from the ground Orville's time dependent functions were employed, and the model is designed so that the magnitudes of these parameters can be varied in order to simulate heat and moisture sources. Clouds are formed, at a grid point, whenever the water vapor of the air is in excess of the saturation mixing ratio, and if the water vapor content becomes less than the saturation mixing ratio any available cloud water is then evaporated into the air in an effort to maintain saturation.

Using a grid spacing of 100 meters, a calculation was made over a matrix of 65 points in the horizontal and 33 points in the vertical. It was assumed that the cooling pond was 900 meters wide and two different calculations were made. The first contained only a heat source, while the second simulated a situation where the heat source was upwind of the cooling pond. The cooling pond was simulated by allowing additional evaporation to take place over several of the grid points, and the additional water vapor was assumed to be diffused through the lower 500 meters over the pond.

The test data was a summer sounding during which cumulus clouds could be expected to develop. In the first calculation,with no pond assumed to be involved, cumulus clouds were initiated over the designated heat source and the cumuli continued to build and dissipate throughout the experiment. The pond was introduced in the second calculation; and even though the strongest vertical motions were observed over the heat source, the first cumulus cloud was initiated over the pond. The cumuli once again built and dissipated, but at a rate typical of a more stable environment. After an elapse of time the pond became more stable and the cumuli began to develop over the heat source. The cumulus formed, moved off and all but one dissipated before reaching the pond. The cumulus that did last long enough to advect over the pond grew as it moved over the area of the pond. The pond, as a result of the extra water being evaporated from its surface, seemed to provide the moisture needed to promote the continued growth of the cumulus.

One can. interpret the above results in the following manner:

1. the hot thermal source, upwind of the pond, tended to block the horizontal wind, and the pond then became a favorable site for the initiation of cumulus, and

2. a cooling pond may act to enhance the development of cumulus.

This model is still in the early stages of development, and no additional modeling experiments were attempted. However, this one simulation points out some of the deficiencies inherent in the application of any numerical model to a study of this type. No numerical model will be able to adequately describe the real physical condition over or downstream from a cooling pond without an adequate data base. There are very few reliable observations of the temperature and humidity profiles over or downwind of such a structure. There is only a very small data base from which one can make reasonable estimates of radiation processes around a cooling pond. Much work has been done to determine the rate of evaporation, but most of the formulas and data are concerned with evaporation rates over a day, a week, a 10-day period or a month. Most of the equations which have been developed and most of the data gathering have been concerned with natural lakes; an efficient cooling pond, on the other hand, will have temperatures much hotter than any natural lake, and as result the formulas which have been developed for these natural ponds and lakes are not directly applicable to a cooling pond.

For modeling purposes the evaporation rates must be almost instantaneous. To ensure an adequate description of the micro-physical process , one must be able to describe the rate of evaporation.

If one hopes to describe the total situation with a numerical model, in addition to the macro-scale processes, which can be described rather well numerically, one must be prepared to completely describe the micro-physics which exists over and downwind from a cooling pond. One of the more obvious micro-physical structures which must be accounted for is the radiation and heat balance, for the heat exchange between the air and the water surface is the major reason a cooling pond works.

AIRCRAFT OBSERVATIONS OVER LAKE BALDWIN

The water vapor which is released from the surface of a cooling pond, as a result of evaporative processes , cannot be expected to be confined only to those layers near the surface. Due to the large differences between the air and water temperatures, it is possible that the warm, moist effluent from the pond may be measurable to a considerable depth. To obtain data of this nature, it is necessary to utilize a well-instrumented research aircraft flying a series of low passes over and downwind of a cooling pond. Fortunately, the Precipitation Enhancement Project of the Water Survey (Ochs and Ceselski, 1973) was operating a research aircraft of this type over southern Illinois during the summer of 1973, and on three occasions they were able to make a flight over a cooling pond, without interferring with their own research mission.

The aircraft made several passes over Lake Baldwin, a cooling lake in southern Illinois, at either 500 or 1000 feet above the ground. During at least one of these missions, they observed that the bases of the cumulus clouds in the near vicinity of the cooling lake were somewhat lower than the surrounding clouds. Temperature and humidity were the primary parameters which were recorded. Unfortunately, these data have not been analyzed because the dynamic corrections for the temperature and humidity probes which were used in this experiment have not yet been obtained. These data will be analyzed in the near future.

SUMMARY AND CONCLUSIONS

An investigation was made of the potential effects of cooling lakes on weather conditions in the vicinity of large power plants. This 1-year pilot study involved two major phases. The first phase involved detailed climatological analyses of the natural distribution of fog and related atmospheric elements whose modification by cooling lakes could conceivably lead to significant local changes in the distribution of fog, clouds, and, possibly, precipitation. The second phase involved preliminary numerical modeling and development of techniques to obtain first approximations of the potential changes in the frequency, intensity, duration, and extent of fog and clouds that might be induced from heat and moisture changes between cooling lakes and the atmosphere. The second phase was concerned also with evaluating deficiencies in current technology and developing recommendations to overcome the deficiencies so as to provide more reliable calculations of cooling pond effects in the future. Major emphasis was placed upon the fog problem, since it appears to be the most important environmental effect that would be associated with cooling lakes. The study results are based primarily upon Illinois data. However, because of the large variability of climate within its borders, the results derived from Illinois data should be generally applicable to the Midwest and other areas of similar climate.

Climatology Studies

Determination of the distribution of natural fog is basic to the evaluation of the fogging potential associated with cooling lakes. Lake-induced fog and intensification of existing natural fog are most likely to occur in those regions with the highest frequency of natural fog. Furthermore, those atmospheric conditions, such as wind, temperature, and moisture deficit, which determine the distribution of natural fog will also strongly affect the characteristics of fog initiation or enhancement by cooling lakes.

Natural fog was found to occur most frequently in winter and least in summer under average midwestern conditions. For example, in Illinois the average number of hours with fog (all types combined) varied from less than

300 to 450 in various regions of the state during winter, compared with 100 to 250 hours in summer. Dense fog (visibility less than 0.25 mile), however, only averages 20 to 70 hours per winter, and only 3 to 10 hours in summer. In general, the winter fog problem decreases with increasing mean temperature, so that the problem minimizes in southern Illinois and maximizes in the central and northwestern parts of the state.

Fog is not a particularly common weather condition in the Midwest even in winter. On the average, only 14% of the total winter hours and 5% of the summer hours experience fog of any type in Illinois. Dense fog is recorded during only about 1% of the total winter hours.

The potential for enhancement of existing natural fog during air passage across relatively warm water bodies such as cooling lakes is very evident from comparison of all fog and dense fog statistics. Thus, only 25% to 35% of the Illinois winter fog days and 5% to 12% of the summer fog days normally record dense fog.

Fog persistence and its diurnal distribution are important considerations in evaluating potential environmental effects from cooling lakes. Both factors are important in defining the magnitude of the problem. Fog persistence , as expected, was found to be greatest in winter when approximately 50% of the Illinois fog occurrences, on the average, last six hours or longer. In summer, over 50% of the fogs last less than 3 hours. Diurnally, the most frequent period of occurrence is early morning. During winter when the fog problem maximizes, the period of greatest frequency is 0600-0900, which encompasses a diurnal peak in traffic associated with people going to work. This finding emphasizes the necessity of constructing cooling lakes away from major highways, and emphasizes the need to determine more accurately than is possible with available data and analytical techniques the initiation, enhancement, and downwind extent of lake-related fogs.

Analyses of air temperatures associated with fog indicated that winter fogs occur most frequently with relatively mild temperatures, whereas summer fogs are favored by relatively cool temperatures. Illinois mid-winter fogs occur most frequently with temperatures in the range from 30°F to 40°F and mid-summer fogs with temperatures in the 60°-70° range.

Dewpoint temperature depressions (difference between air and dewpoint temperature) provides a measure of how near to saturation the air is, and, therefore, has a definite relationship to fog occurrences. In both winter and summer, natural fog was found to occur the majority of the time with dewpoint depressions of 2°F or less. Dense fog occurs only occasionally with depressions exceeding 1°F. Dewpoint depression patterns for Illinois were found to be quite similar to the fog frequency patterns.

Analyses of wind conditions associated with fog indicated that most dense fogs occur with wind speeds less than 10 mph. However, in winter when the fog problem maximizes, over 40% of all fogs combined occurred with winds of 10 mph or more and about 13% with winds of 15 mph or greater. Only 15% of the dense fogs were associated with winter winds of 10 mph or more. Thus, light to moderate fog may occur quite often with moderate to relatively strong winds in winter. In summer, approximately 99% of the dense fogs occurred with winds of less than 10 mph, and only 14% of all fogs combined occurred with winds of 10 mph or greater. Summarizing with respect to air temperature, dewpoint depression, and winds, it appears that dense winter fogs, the major concern with the cooling lake problem, occur most frequently with relatively mild temperatures of 30° to 40°, dewpoint depressions of 1° or less, and wind speeds less than 10 mph.

An investigation of wind directions associated with fog showed no stable relation between locations, except for a weak trend for fog to be associated more frequently with easterly component winds. Wind directions are strongly affected by conditions of exDOsure and interference by natural barriers or man-made structures, so that wind direction climatic studies should be made wherever a cooling lake installation is anticipated. The other weather elements or factors involved in site selection can be generalized much better to permit interpolation with reasonable accuracy on pattern maps such as presented throughout this report.

A more thorough investigation of the relation between atmospheric moisture and fog was undertaken through analyses of atmospheric moisture deficits. Moisture or saturation deficit was expressed as grams of water vapor per kilogram of air needed to saturate the air under existing conditions. Results indicated that dense fog in winter occurs almost exclusively with moisture deficits of 0.5 g/kg or less. For light fog (visibilities - 3 to 6 miles), deficits of 0.5 g/kg or less occurred only 69% of the time. The smallest deficits in winter occurred in the early morning hours, as expected, since this is the time of maximum fog frequency. In general, the moisture deficit patterns for the state closely resemble the fog frequency patterns, indicating the expected close relationship. Thus, during the major problem period in winter, moisture deficits tend to be smaller (closer to saturation) in the central and northwestern parts of the state and to minimize in the extreme south.

A most important fact brought out by the various climatic studies is that the environmental danger potential from the installation of cooling lakes can vary within relatively short distances. Thus, in Illinois, the natural fog distribution indicates that the danger potential would minimize in the extreme southern part of the state with its relatively warm winter climate and would maximize in east central Illinois 200-250 miles from the optimum locations. In winter a natural fog hour occurs 50% more often in east central than in extreme southern Illinois. Dense fog, the most dangerous weather element subject to enhancement by cooling lakes, occurs 3.5 hours in the east central part of the state for every hour in southern Illinois.

Potential Fog and Cloud Effects from Cooling Ponds

The initiation of fog over cooling ponds is potentially one of the major atmospheric effects from waste heat dissipation. Typical cold, moderate, and hot cooling ponds were designed to assess the potential initiation of heavy fog. The surface temperatures of these ponds were then applied to three different climatic regimes in Illinois. It was found that the hot pond, with surface water temperatures ranging from 69° to 104°F, has the potential of producing heavy fog over 60% of the time over northern Illinois and about 40% of the time over southern Illinois during winter. During summer, when the variation of the natural air temperature is at a minimum, there is little difference across the state and the potential of fog initiation over a hot pond hovers between 15 to 20% of the time. A moderate pond, with temperatures ranging from 49° to 84°F, shows that the major effect season is winter, with a heavy fog potential almost 40% of the time over northern Illinois and only about 10% of the time over southern Illinois. In the remaining seasons, the potential for fog initiation over a moderate pond is less than 20% of the time over the state. The cold pond, as could be expected, also maximizes in winter, but during an average year heavy fog would be initiated less than 10% of the time in all seasons.

A similar analysis was performed to determine how often a cooling pond would have the potential of initiating icing. Based on icing data around other cooling ponds, and since the normal droplet size of fog is relatively small, it was decided to confine the investigation to the rime icing potential of a cooling pond. For January in northern Illinois, with a hot pond, the worst possible case, it was found that the potential for ice initiation around a cooling pond is only 13%, and this reduces to 1% over the southern extremities of the state. For a moderate pond, the potential for initiating icing is only 2% over northern Illinois reducing to less than 1% over the southern part. The icing potential of a cold pond was found to be insignificant.

A concern which is more applicable to the fog problem is how far downwind one can expect the effluent to travel and to be a hazard. Some preliminary plume calculations, using the Gaussian plume equations, were attempted but the results were discouraging. They pointed out in very vivid terms how little is really known about the atmosphere over and in the near vicinity of cooling ponds. Some of the more prominent variables which cannot be closely approximated are the evaporation rate, the effect that natural convection over the pond has upon the stability of the environment, the droplet distribution of the steam fog generated, and the temperature and humidity distributions over and downwind from the cooling pond. To assess realistically the validity of such parameter calculations, and to evaluate the potential hazard a cooling pond might exert downwind, it is necessary to have a firm idea of how much modification the air over and in the near environment of the cooling pond might experience.

A preliminary climatological study of the low-level thermal and humidity structure over Peoria, Illinois, helped to physically confirm several previous findings. The average sounding at 0600 and 1800 showed that during winter the lower 2,000-3,000 feet of the atmosphere, except for some time during the daylight hours, is characterized by stable air. Thus, this condition increases the likelihood of longer-lived as well as relatively deep fog layers. At 0600 during summer, there was normally only a shallow, moist, inversion layer near the surface, and by 1800 the average sounding was characterized by a potentially unstable layer through the lower levels. This would indicate that during the summer the chances of fog are most likely during the early morning hours (which is borne out by earlier climatological findings), and that those fogs which do form would be shallow. The early evening sounding, which was characterized by a dry-adiabatic lapse rate from the surface to 900 mb, indicates that the most likely atmospheric effect of a cooling pond during a summer afternoon would not be the formation of fog, but rather the formation or intensification of cumulus clouds.

During the winter, saturation deficit distributions showed that 95% of the time in the morning and 65% of the time in the evening the saturation deficit at the surface was 1 g/kg or less. This indicates that fog is likely to be enhanced or initiated from sunset to just after sunrise, reaching a maximum during the morning hours. These distributions also showed that over 50% of the time, in the early evening and early morning, surface saturation deficits of 1 g/kg or less are associated with temperatures below 30°F at Peoria at 0600 and 1800. Since over 70% of all natural fog in winter occurs with temperatures greater than 30°F, the potential for enhancement of existing fog occurs less than 30% of the time. This is a conservative estimate, which again emphasizes that the major fog problem is that of initiation not enhancement.

During the summer, the saturation deficits indicated that fog initiation or enhancement would normally be confined to the early morning hours and that fog which did form would tend to be shallow and short-lived. A saturation deficit of some 5 g/kg was noted throughout the lower layer during the early evening, which indicates that, on the average, a cooling pond would be unable to enrich the water vapor content enough to have a significant effect on the formation of cumulus clouds.

The modeling experiment indicated, under admittedly extreme conditions, that the cooling pond might act as an initiator of some cumulus during the early part of the convective periods. Because of the high evaporation rate during the summer, the cooling pond might act as a moisture source tending to enhance cumulus as they pass over, but preliminary modeling indicates that this effect would cease as soon as the cloud moved out of the pond's downwind plume. It appears that a cooling pond will have its major effect on the enhancement of cumulus clouds when the ambient conditions of the lower 3,000 ft of the atmosphere are near saturation; then the cooling pond would exert a maximum effect by adding moisture that might be sufficient to induce condensation or to lower the cloud base of existing cumulus.

RECOMMENDATIONS

Preliminary investigations were made of the initiation of fog and/or icing over and downwind of cooling ponds, the extent of fog and stratus plumes, and the utilization of numerical modeling in evaluating the potential of cooling ponds to alter the fog and cloud populations in their vicinity. These investigations revealed definite deficiencies in our knowledge with respect to many of the pertinent physical processes associated with the heat and moisture output to the atmosphere from cooling ponds. The extreme limitations of available methodology for calculating downwind diffusion of fog was very apparent.

Several specific areas in which more knowledge must be accumulated before the environmental effects of cooling ponds can be reliably evaluated are listed below.

1) Critical air and water temperature data must be collected in sufficient quantity to provide criteria for predicting the occurrence of heavy steam fog and/or icing over and downwind of cooling ponds.

2) Observations and analyses must be performed to establish pond evaporation rates under varying atmospheric conditions. This is necessary since evaporation from the relatively hot water of cooling ponds will differ substantially from evaporation over a natural pond or lake. Natural convection resulting from more extreme temperature differences between water and air in cooling ponds will play a much more prominent role in cooling pond evaporation than in that associated with natural water bodies.

3) Information must be assembled on the stability of the air over and downwind from cooling ponds and lakes, since the ambient air stability will be significantly altered because of the strong destabilizing effect of the hot pond on the relatively cold air passing over it, especially in winter.

4) A rather extensive measurement program of the temperature and humidity plume over and downwind of ponds is needed to permit reliable estimations of the extent and density of the fog plume under various weather conditions.

5) Similarly, comprehensive observational programs are required to define the distribution and extent of visibility restrictions imposed by fog resulting from enhancement or initiation over cooling ponds. Visibility should be examined in terms of distance from the initiation or enhancement source.

6) Much more information is needed regarding the downwind distribution of icing and snowfall induced by cooling ponds.

7) The droplet distribution of pond-associated fog should also be investigated to aid in establishing fog prediction models.

The acquisition of knowledge listed above is necessary if reliable estimates of cooling pond effects on local weather conditions are to be made consistently. Derivation and verification of suitable numerical models that could greatly advance our capabilities in this field of endeavor can not be achieved without comprehensive field programs to obtain the data and information outlined above.

Field programs undertaken to gather the necessary data and information would require deployment of a network of instruments around a given cooling lake or pond to record air temperature, humidity, and wind at two or more levels, water temperature, visibility, radiation, and precipitation. Field research programs should be established in several areas of varying climate to provide input data for computing cooling pond effects over a wide variety of climatic conditions. For example, Commonwealth Edison Company is presently making a rather extensive synoptic survey at their Dresden Power Plant in northeastern Illinois in order to define the magnitude of the fog problem in that area. Therefore, it would be most desirable to undertake a complimentary set of measurements in southern Illinois, such as the Baldwin Lake Plant of Illinois Power Company, where climatic conditions (especially temperature) are considerably different in winter when the fog problem maximizes. Data from these two field studies, used in conjunction with comparative climatic studies for standard weather stations in and surrounding these two cooling lakes , should then provide the basic input to assess the environmental effects of cooling ponds in various climatic conditions of the Midwest and other areas with similar climatic regimes.

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