Atmospheric Effects of Cooling Lakes

EPRI EA-1762
Project 578
Final Report
April 1981

Keywords:
Climatology
Cooling Lake
Fogging
Icing
Waste Heat
Weather Modification

MASTER

Prepared by
Illinois Institute of Natural Resources
Champaign, Illinois

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ELECTRIC POWER RESEARCH INSTITUTE

Atmospheric Effects of Cooling Lakes

EA-1762
Research Project 578

Final Report, April 1981

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ABSTRACT

The atmospheric effects of waste heat dissipation from cooling lakes operated in conjunction with power plants was assessed through a program of field measurements and analysis. An 890-hectare (2200-acre) cooling lake in southwestern Illinois was instrumented to provide necessary meteorological measurements. Analyses showed that steam fog and its downwind extent are the major atmospheric effects associated with cooling lakes, and that these effects maximize in winter and fall. However, the lake-induced fog is usually confined to the lake and short distances downwind. Consequently, cooling lakes with water-air temperature differences similar to those reported in Illinois and within a similar climatic regime can be located within 2 to 3 km of major highways, airports, or other centers of activity adversely affected by fog without any appreciable interference in the normal performance of such activities. Lake-related rime icing was either confined to the cooling lake or extended no more than 0.8 km downwind. Satellite and radar data showed no discernible increase of convective activity over or downwind of two cooling lakes in Illinois. For guidance in site planning and plant operations, a method is presented for determining the intensity and downwind extent of steam fog from known water-air temperature differences and ambient saturation deficits.

EPRI PERSPECTIVE

PROJECT DESCRIPTION

Natural and man-made impoundments (commonly called "cooling lakes" and "cooling ponds") have been used in recent years by electric utilities as alternatives to once-through cooling for heat rejection from power plants. This report, under RP578, describes a field measurement and climatological modeling program that addresses the potential atmospheric effects of heat dissipation from such cooling systems.

PROJECT OBJECTIVES

The specific aims of this study were to measure the frequency and magnitude of cooling-lake-induced effects on the atmosphere and to develop a method for predicting these effects based on readily available climate data. As part of this study, the contractor made extensive measurements of wind, temperature, humidity, visibility, and other meteorological parameters at an 890-hectare (2200 acre) cooling lake in southern Illinois during 1976-1978. Less extensive data were collected for comparison purposes from a nearby unheated "control" lake. Observed effects (principally fogging and icing) were stratified by synoptic weather type for climatological analysis.

PROJECT RESULTS

Steam fog was found to be the most frequently observed atmospheric effect of the cooling lake, with a maximum occurring in fall and winter. Natural fogs also occur most often in these periods. In only rare instances did fog, sufficiently thick to impair visibility, extend more than a few hundred meters from the lake shore. Light icing of structures near the lake was observed immediately near the lake when air temperatures were below -7^{o}C (19^{o}F). No changes in precipitation amount or intensity could be attributed to enhanced evaporation or convection from the cooling lake.

Using a synoptic stratification scheme, the contractor developed a simple method for predicting the probability of steam-fog initiation or enhancement, given information on the occurrence of cold air masses and cold fronts in a region.

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ACKNOWLEDGMENTS

This research was supported by the Electric Power Research Institute under grant RP578 and by the State of Illinois. The research was done under the general guidance of S. A. Changnon, Jr., Head of the Atmospheric Sciences Section of the Illinois State Water Survey. The field portions of the work were supervised by G. R. Boyd and P. Lamb, and the observations were taken by S. Langrehr and W. Petri. E. A. Mueller and D. A. Brunkow are appreciated for their engineering assistance. G. Dzurisin helped with the installation of equipment. Analysis assistance was given by M. Johnson, E. Schlessman, and A. Pfieffer and their many student assistants. Programming was performed by H. Yuen and C. Huang. The final typing was ably done by R. A. Runge. J. Brother and his staff drafted all figures.

Special recognition must go to: Illinois Power Company for allowing us to use Baldwin Lake as a field site, and for providing lake-related data; the staff of the Baldwin power plant, especially J. Kane, Manager, and his assistants D. Munini and D. Mason; Commonwealth Edison Company and Murray and Trettle, Inc. for supplying data from the earlier field program at Dresden power plant; the Department of Conservation at the Baldwin Lake Conservation Area for advice and use of their boat from time to time; and, most importantly, the many local residents who allowed us to place equipment on their land and who faithfully supplied rainfall observations.

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SUMMARY

The increasing demand for more energy throughout the world into the twenty-first century will require the construction of many electric power plants. These plants will dispense large amounts of waste heat into the atmosphere through auxiliary cooling systems such as cooling lakes and cooling towers. The atmospheric effects of waste heat dissipation from cooling lakes was evaluated using data from two field programs conducted in Illinois during 1971-1973 and 1976-1978.

Measurements of wind, temperature, humidity, visibility, and other meteorological parameters necessary for analyses of lake-induced effects on the atmosphere were made from February 1976 to March 1978 at Baldwin Lake. This is a large, man-made cooling lake operated in southwestern Illinois by Illinois Power Company. Waste heat from the 1800 MWe coal-fired power plant is dissipated in a 890-hectare (2200-acre) cooling lake. This field operation and analysis program constituted the main thrust of the research. Additional meteorological field data for the period December 1971 to March 1973 for the Dresden plant in northern Illinois were obtained from Commonwealth Edison and analyzed. The Dresden nuclear power station has a capacity of 1500 MWe, and waste heat during the field observations was dissipated by a combination of a spray canal system and a 445-hectare (1100-acre) cooling lake. Both Baldwin and Dresden are embedded in a temperate climate, typical of the Midwest.

STEAM FOG

A major atmospheric effect, and one of the most visible associated with cooling lakes, is the initiation and/or enhancement of steam fog. These fogs form when water vapor is added to the air and the source of the water vapor is much warmer than the air. Steam fog observations were made at both Baldwin and Dresden. The intensity of steam fog at Baldwin was defined by the visibility restriction. In evaluating the fog problem, steam fog with visibilities of 0.4 km (0.25 mi) or less was considered intense enough to impose restriction on driving conditions if the steam fog were to move across a road. At Dresden, the steam fog intensity was available only in qualitative terms, such as very light, light, moderate, and heavy. Visibility restrictions were ascribed to these intensities after obtaining further information from the primary field observer.

Steam fogs at Baldwin were stratified into initiation and enhancement days. Initiation days were defined as those when steam fog formed without any natural fog present near the cooling lake. Enhancement days were days when natural fog

was present and the visibility over the cooling lake was less than the visibility of the natural fog due to augmentation by steam fog. The Dresden observations were not sufficiently detailed to stratify the data in a similar way.

Steam fog observations were made on 40% of all days at Baldwin and on 49% of all days at Dresden. All intensities were most frequent during winter with a secondary maximum during fall, and minimums during spring and summer. The Baldwin data showed that only 25% of all steam fogs were accompanied by natural fog, that is, most steam fogs were strictly lake phenomena.

Cold air dominated the occurrence of all intensities of steam fog. Over 80% of the Baldwin and 92% of the Dresden steam fogs were embedded within cold air at the surface. On fog enhancement days, frontal and low pressure activity were more frequent. This would be expected because natural fog is often associated with these weather types.

The relatively small number of enhancement days at Baldwin produced an erratic temporal pattern with the greatest number of enhancement fogs occurring during summer. However, in Illinois the enhancement of natural fog by steam fog will maximize most frequently, on the average, during winter and fall when the greatest number of natural fogs normally occur. The enhancement effect will vary from year to year depending on the occurrences of natural fog and concomitant temperatures sufficiently cold to maintain the high water-air temperature difference needed to generate steam fog.

Dense steam fog (visibility of 0.4 km or less) was observed most often during winter. At Dresden 60 of 69 moderate-to-heavy or heavy fogs and at Baldwin 60% of all dense steam fogs occurred during winter. Furthermore, at Baldwin 80% of the dense initiation fogs (lake induced) occurred during winter and none in summer. Dense enhancement fogs maximized during winter also. Most dense cooling lake fogs in other seasons were associated with natural fogs rather than lake initiations.

Relatively cold air temperatures were associated with the occurrence of many dense steam fogs, but little dependence between temperature and fog intensity was noted. A useful indicator of steam fog intensity is the magnitude of the water-air temperature difference and the ambient saturation deficit. Steam fog intensity tends to vary directly with water-air temperature difference and inversely with saturation deficit.

Most dense steam fogs initiated at Baldwin (visibilities of 0.4 km or less) had water-air temperature differences of 19°C (34°F) or greater and saturation deficits of 0.5 g/kg or less. Initiation fogs were not observed over the cooling lake until the water-air temperature difference was at least 6 to 7°C (11 to 13°F). Water-air temperature differences in enhancement fogs of equivalent intensity were less. On enhancement days, the steam fog intensity was similar to that on initiation days, but when steam fog combined with natural fog, the ambient visibility was lowered by as much as 1 km (0.6 mi).

Downwind movement of steam fog farther than 6 m (20 ft) was observed in only 38% of all events at Baldwin, and only 22 steam fogs at Dresden moved more than 30 m (100 ft) beyond the confines of the lake. At Baldwin less than 10% of the fogs extended more than 0.2 km (0.1 mi), and fewer than 2% had horizontal extents greater than 1.6 km (1 mi). Significant downwind extent was observed in all seasons at Baldwin, but occurrences were most frequent in winter and fall. Over 67% of all fogs with some horizontal extent were initiation fogs. In all but two events at Baldwin, the visibility in steam fogs with horizontal extent rapidly approached the prevailing visibility as the fog mixed with the ambient air. A greater potential for intense fog and movement off the lake exists if the over-lake trajectory of air is from the cooler to warmer side of the lake.

Overall, the occurrence of steam fog at cooling lakes such as Baldwin and Dresden presents only minor problems. Most steam fogs at these locations were confined within 1.6 km (1 mi) of the lake. Only with winds less than 2 km/h (1.5 mi/h) and with very stable atmospheric conditions did steam fog with appreciably lowered visibilities travel more than 1.6 km (1 mi). On two occasions when this was observed, the steam fog drifted downwind along an old creek bed. Cooling lakes with water-air temperature differences similar to those reported at Dresden and Baldwin and within a similar climatic type regime can be located within 2 to 3 km (1.25 to 2.0 mi) of major highways, airports, or other centers of activity adversely affected by fog without appreciable interference in normal activities. It is concluded that the horizontal movement of most steam fogs will be less than 3 km (2mi), provided no unusual features, such as major valleys, are present. This, of course, applies to the Midwest and other regions with a similar climate.

Results of this study can be used in conjunction with hourly weather data from a nearby weather station (climatically similar to the proposed site) and water-air temperatures estimated from preliminary engineering studies to calculate the expected frequency of occurrence and intensity distributions of steam fog at proposed cooling lake installations. These computations can then be used in conjunction with other results to obtain estimates of the frequency distribution of the downwind extent of cooling lake fogs at the proposed site.

ICING

During the colder part of the year, steam fog which moves beyond the lake can coat structures and vegetation with ice. The ice can take two forms, glaze or rime. Only rime icing was observed during the four winters of observations at Dresden and Baldwin cooling lakes. Rime, because of its low density and friable nature, poses little or no danger to structures or vegetation.

Rime icing was not observed unless the air temperature was -7°C (19°F) or less. Thus, in Illinois and most of the Midwest, rime is primarily a winter phenomenon. However, the icing season will be extended in other regions where the temperature drops to -7°C and below earlier in the fall and continues at such temperatures later in the spring.

At Baldwin, the greatest horizontal extent of icing was 0.8 km (0.5 mi). Most of the icing events (90%) were observed within 200 m (650 ft) of the cooling lake. The greatest accumulation of rime at Baldwin was 7.6 cm (3 in), and 90% of the rime accumulations were 2.5 cm (1 in) or less.

For rime icing to occur beyond the confines of a cooling lake, it was determined that the following atmospheric conditions must be present: 1) an air temperature of -7°C (19°F) or less, 2) a saturation deficit of 0.5 g/kg or less, 3) a water-air temperature difference of 19°C (34°F) or greater, and 4) winds of at least 1 to 3 km/h (1 to 2 mi/h). These criteria are similar to the atmospheric conditions required for the more intense steam fog events at Baldwin.

CONVECTIVE PRECIPITATION

Cooling lakes, because of their elevated surface water temperatures and greater evaporation rates, have the potential of initiating and/or enhancing convection. To investigate the possible cooling lake effects on convective clouds, satellite, radar, and raingage data were used.

Visible photographs from the two SMS-GOES satellites during the summer of 1975 were employed to investigate cooling lake effects upon the time-space distribution of cloudiness. Analyses were made for two cooling lakes in southern Illinois, Baldwin and Coffeen, and a much larger, control lake, Carlyle. No evidence was found that the cooling lakes or control lake had a significant effect upon the summer cloud frequencies. However, local terrain features in the study region, such as ridges and river valleys, do influence the spatial distribution of clouds, primarily cumulus and cumulonimbus.

Researchers from the University of Chicago routinely collected data using a 3-cm, TPS-10 radar during the summers of 1972 to 1975. The area sampled included Baldwin Lake and the region within the satellite analysis. Plots of radar first echoes were examined, and they indicated that Baldwin and Coffeen cooling lakes have no significant effect on the first-echo distributions. However, the large control lake (Carlyle) appeared to have some influence on the initiation of convective precipitation when atmospheric motions were parallel to the major axis of this elongated lake.

A dense raingage network was operated in the Baldwin area during July to November 1976 and March to November 1977. The objective was to investigate potential effects upon the regional rainfall pattern resulting from waste heat discharges into the cooling lake associated with the Baldwin power plant. Results of the two-year study were inconclusive. A persistent rainfall maximum was located in the Baldwin Network 10 to 15 km (6 to 9 mi) east to east-northeast of the center of the lake when rainfall for the two years was combined. This apparent anomaly was especially prominent with storms moving from the southwest quadrant, which place the lake directly upwind of the observed maximum. However, the rainfall maxima in the eastern part of the network were in agreement with the natural rainfall distribution for southern Illinois during the sampling periods, as shown by the National Weather Service records.

It is concluded that cooling lakes the size of Baldwin and Coffeen have little or no effect upon the initiation of convective cloudiness or precipitation. However, much larger cooling lakes, as indicated by the Carlyle findings, could enhance convective activity when the low-level air and clouds have a relatively long travel time over the lake. Otherwise, most cooling lakes have a minimal impact upon the initiation and enhancement of convective cloudiness and should produce no environmental problems of significance.

TEMPERATURE AND MOISTURE PLUMES

Cooling lakes are warmer than natural lakes in the same climatic region and latitude, and the average water temperatures are warmer than the average air temperatures during all seasons. The evaporation rate from such a lake will be greater than from a natural lake. Air with an over-lake trajectory can be heated, and water can be evaporated from the lake surface, adding moisture. Thus, the near-surface air has the potential of advecting warmer and moister air downwind. Temperature and dew point data were stratified by prevailing winds at 0600 and 1500 CST to determine the magnitude of temperature and dew-point increases from the upwind to downwind shore and the downwind horizontal extent of the elevated temperatures. The largest increases in monthly averages and the greatest horizontal extent of the elevated temperatures downwind from the cooling lake were realized during winter and spring.

Increases from the upwind to downwind shore based on monthly averages ranged from near zero to 3°C (5.5°F) at 0600 CST, near the time of normal daily minimum temperatures. The largest departures from the upwind to downwind shores were noted with southwest and northwest winds. Downwind extent was usually detectable only in the first 0.8 to 1.6 km (0.5 to 1 mi). At 1500 CST, near the time of the maximum daily temperature, increases in air temperature from the upwind to downwind shore were minimal, but increases in dew-point temperature ranged from 0.5 to 3.0°C (1.0 to 6.0°F). However, the downwind extent of these elevated temperatures was only 0.4 to 0.8 km (0.25 to 0.5 mi) with southwest and northwest winds, or approximately 50% of the downwind extent experienced at 0600 CST.

On individual mornings (0600 CST), air temperature increases of as much as 4.4°C (8°F) and dew-point increases of 5.6°C (10°F) were noted from the downwind to the upwind shores. The horizontal extent of the elevated temperatures changes rapidly with increasing distance from the downwind shore. However, some minor elevated air temperatures and/or dew points (0.6°C or 1°F) were noted at Baldwin as far as 2 km (1.25 mi) downwind on some mornings. By mid afternoon the air temperature increases were not as pronounced, but the dew-point temperature changes were similar to the mornings. The horizontal extent of the elevated temperature was reduced to 1 km (0.6 mi) or less.

TRACER EXPERIMENTS

Three tracer experiments using sulfur hexafluoride (SF_6) were made to simulate the advection of moisture and heat, both important to the formation of steam fog and to the downwind extent of the visible fog plume. These tracer releases indicate that significant concentrations of moisture and heat are most likely to occur with a neutral or stable atmosphere near the surface. However, large amounts of dispersion were observed within relatively short distances. The rapid downwind dispersion experienced in these tracer releases helps to explain the relatively small downwind areal extent of lake-generated steam fog observed at Baldwin.

Section 1
INTRODUCTION

Significant increases in electric energy production are predicted to occur throughout the world into the twenty-first century to meet industrial and domestic requirements (1-3). As the power industry strives to meet these increased capacities, consideration must be given to demands upon society, the economy, and the environment.

A major environmental consideration is the impact of the huge amounts of waste heat released from each power plant. Nuclear and fossil-fueled power plants have efficiencies of approximately 33% and 40 to 45%, respectively; thus, the amount of waste heat to be dissipated into the atmosphere ranges from 1.2 to 2 times the plant capacity. For example, a nuclear power plant with a capacity of 2000 MWe will dispose of 4000 MW of thermal energy, whereas a similar fossil-fueled power plant will release 2400 to 3000 MW. Most new power plants being built or planned have capacities between 2000 and 5000 MWe, and it is conceivable that a number of such plants could be consolidated at one site to form a power park or energy center with a total capacity of over 30,000 MWe (4). Generally, the waste heat from such installations will be dispersed into the atmosphere by auxiliary cooling systems, such as cooling lakes or cooling towers. The impacts of such large concentrated releases of energy upon the atmosphere are to a great extent unknown (5-10).

A two-year field measurement program was initiated in Illinois to evaluate the atmospheric effects of waste heat dissipation from cooling lakes operated in conjunction with power plants. Baldwin Lake, a large, man-made cooling lake operated in Southwest Illinois by Illinois Power Company, was instrumented to provide measurements of wind, temperature, humidity, and other meteorological parameters necessary for analyses of lake-induced effects on the atmosphere. Additional cooling lake data from northern Illinois, obtained in an independent survey conducted by Commonwealth Edison (11) at Dresden power plant, were utilized to help delineate variations in atmospheric effects from cooling lakes under colder climatic conditions than those experienced at Baldwin.

Analyses were made of the possible effects of cooling lakes on the initiation of steam fog and icing, the enhancement of convective clouds and precipitation, the downwind extent of temperature and humidity plumes. Detailed discussions of these potential atmospheric impacts will be presented in the sections to follow. The remainder of this section will be devoted to a general description of the climate, terrain, and instrumentation at Baldwin and Dresden cooling lakes. Also, terms used frequently throughout this report will be defined.

DEFINITIONS

Reference to seasons is frequently made throughout this report. Winter is composed of December, January, and February; Spring is made up of March, April, and May; Summer is defined as June, July, and August; and Fall consists of September, October, and November.

Dense fog is defined as a fog intense enough to reduce visibility to 0.4 km (0.25 mi) or less; this term will be used when referring to natural and steam fog occurrences. All fog when used with reference to natural fog will refer to those conditions in which the visibility is restricted to 6 miles or less. However, when reference is made to fog during steam fog events, it will refer to all instances when steam fog was observed to form over a body of water, and no visibility restriction will apply.

Steam fog is formed when water vapor is added to air which is much colder than the source of the vapor (such as a cooling lake in winter).

Icing is the freezing of supercooled water droplets onto surfaces resulting in a coat of ice.

DESCRIPTION OF BALDWIN COOLING LAKE

The Baldwin power plant of the Illinois Power Company is located in southwestern Illinois, approximately 62 km (39 mi) southeast of St. Louis, as indicated in Figure 1-1. This is a coal-fired plant which has a capacity of 1800 MWe. The waste heat from the plant is dissipated through a man-made cooling lake having an area of 890 hectares (2200 acres). Also, this lake is used as a state conservation area and is one of the prime fishing lakes in Illinois. Approximately 60% of the waste heat is dissipated into the atmosphere through the cooling lake, and the remaining 40% is released through stack and implant losses. The lake, power

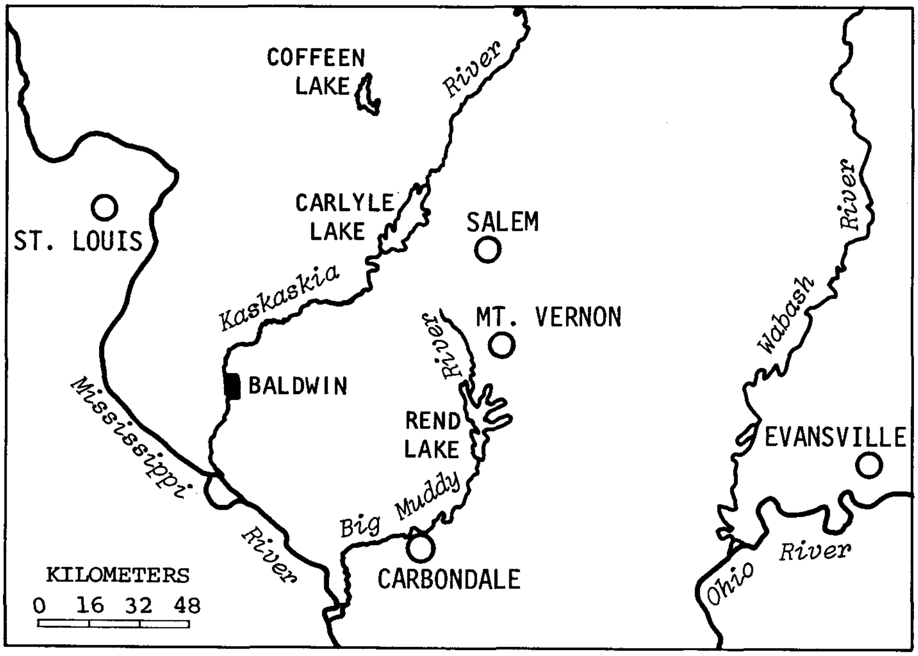

Figure 1-1. Baldwin cooling lake and surrounding climatic stations

plant, and meteorological instrument network are shown in Figure 1-2. The lake is oriented north-south in the form of a rectangle. Warm water from the power plant flows to the northeast corner of the lake along a channel on the east side. The water then flows south around the west end of a dike in the middle of the lake, and the cooled water returns to the power plant near the southeast corner of the lake. The warmest water is usually in the northern part of the lake, and the coolest in the southern part.

Relatively flat terrain surrounds the cooling lake, as indicated in Figure 1-2. The major topographical feature is the Kaskaskia River to the west. The even terrain and relatively unforested areas in the Baldwin area, especially to the east and south, were instrumental in selection of the experimental site for the project. These features minimize the possibility of confusing potential lake effects with other localized weather effects. Furthermore, the terrain features permit valid visibility measurements in all directions, and this is a virtual necessity in evaluating lake-induced fog effects. The flat terrain to the north, east, and south facilitates detection of lake-induced effects of all types, since these effects (if any) would be most pronounced in these directions from the lake, in view of the prevailing winds and storm movements in this region.

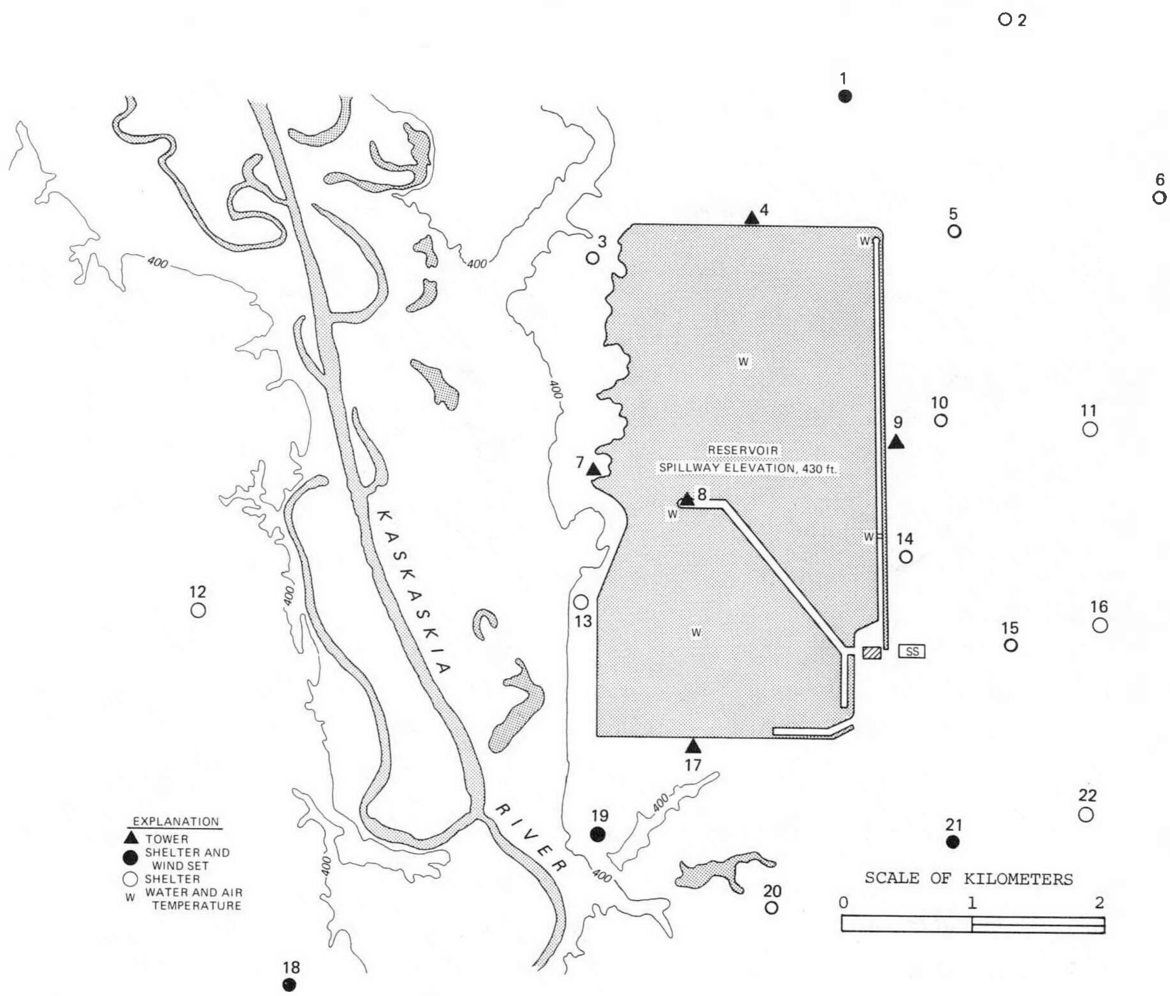

Figure 1-2. Baldwin instrument network

General Climate of Baldwin Area

The Baldwin area has the typical temperate climate of the Midwest. Annual precipitation averages 102 cm (40.30 in). Monthly precipitation ranges from an average maximum of 11 cm (4.35 in) in May to a minimum of 6.5 cm (2.55 in) in December. The number of days with precipitation of 2.5 mm (0.10 in) or more averages 68 annually and ranges from an average of 4 days in January to 9 days in May. Days with relatively heavy rainfall (12.5 mm or more) average 26 per year with a range from 1 in January to 3-4 in the April-July period. Snowfall averages 38 cm (15 in) per year, and over 90% of this falls in the December-March period.

The mean annual temperature is 13.9°C (57°F) with a range from 0.6°C (33°F) in January to 26.1°C (79°F) in July. The mean maximum daily temperature ranges from 6.1°C (43°F) in January to 32.8°C (91°F) in July. The mean minimum varies from -3.9°C (25°F) in January to 19.3°C (67°F) in July. The number of days on which temperatures exceed 32°C (90°F) occurs most frequently in July and August with an average of 18 each month. The average number per year is 60. The coldest days, defined as those on which temperatures are equal to or less than 0°C (32°F), reach a maximum in January with an average of 25 days. The average number of coldest days per year is 97.

Fog is a climatic variable of major importance in evaluating potential cooling lake effects on localized weather conditions. Therefore, an understanding of natural fog occurrences is basic to the Baldwin study. Investigation of the natural fog distribution in the Baldwin area shows that, on the average, natural fog occurs approximately 700 hours annually. This varies from an average of about 315 hours in winter (December-February) to 150 hours in spring (March-May) and fall (September-November), and less than 100 hours in summer (June-August). Fog has been recorded on an average of 115 days per year. The winter average is 35 days, compared with 30 days in fall and 25 days in spring and summer. Dense fog occurs on an average of 38 hours and 9 days annually. Seasonally, these occurrences range from averages of 20 hours and 4 days in winter to 5 hours and 2 days in spring, 3 hours and 1 day in summer, and 10 hours and 2 days in fall.

Baldwin Instrument Network

Plan views of instrumentation employed in the Baldwin study are shown in Figures 1-2 and 1-3. Within the network, temperature and humidity were measured at a single level at 16 locations indicated by the open circles in Figure 1-2. These measurements were made with hygrothermographs installed in standard weather shelters. At five of these sites, indicated by the filled circles in Figure 1-2, winds were measured at a single level of 6 m (20 ft). Five towers installed at sites indicated by triangles in Figure 1-2 had transducers to measure temperature and humidity at three levels (3, 6, and 9 m) and wind at two levels (3 and 9 m). The tower measurements were recorded electronically on data loggers.

The water temperature of the lake was measured at several points. The intake and outlet water temperatures were obtained from the Illinois Power Company. Additionally, water temperature was measured at six other sites shown in Figure 1-2.

Two net radiometers were installed near stations 6 and 14 (Figure 1-2). An evaporimeter, transmissometer, recording raingage, and microbarograph were also installed near station 14, adjacent to the hot water canal on the east bank of the lake. A soil thermograph was located near station 6, and measurements were made at the 10- and 20-cm levels. A large number of visibility markers were located at various distances around the lake. These were used, along with the transmissometer, to make measurements of visibility. They also served for making icing measurements. Evaporation was measured with the evaporimeter. The net radiometers and soil thermographs provided data needed to estimate the net radiation budget over the lake and the ground and the net energy flux of the air over lake and land.

In addition to the recording raingage at station 14 (Figure 1-2), a network of 47 non recording raingages was installed in 1976 and increased to 52 gages in 1977. The 1977 network is shown in Figure 1-3. Raingages were located at each of the instrument sites and the remainder at private residences. These raingages are a plastic, wedge-type gage of low cost, which is post-mounted for measuring total storm or daily rainfall. Their accuracy was established by Huff (12). The project observer serviced the gages at the instrument sites, and the others were serviced by cooperative observers at the residences.

Other equipment included a boat to service the buoys used at two of the water temperature stations. Cameras were employed to supplement the visibility measurements and to photograph cloud conditions that might be related to the power plant operations.

Sampling Procedures

A weather observer was employed to service the various field instruments on a routine basis and to make visual observations of weather conditions, particularly visibility and cloudiness. The network was serviced on a schedule of six days per week throughout the field observational program.

Air Temperature and Humidity. Data were digitized using an Autotrol and stored on magnetic tape. Temperature and humidity readings, extracted every 15 minutes, were averaged to determine hourly averages of both parameters. Charts were changed daily.

Wind. Data were recorded on data loggers, which have the capability of providing a sample every 15 seconds. These readings were averaged to obtain the 5-minute

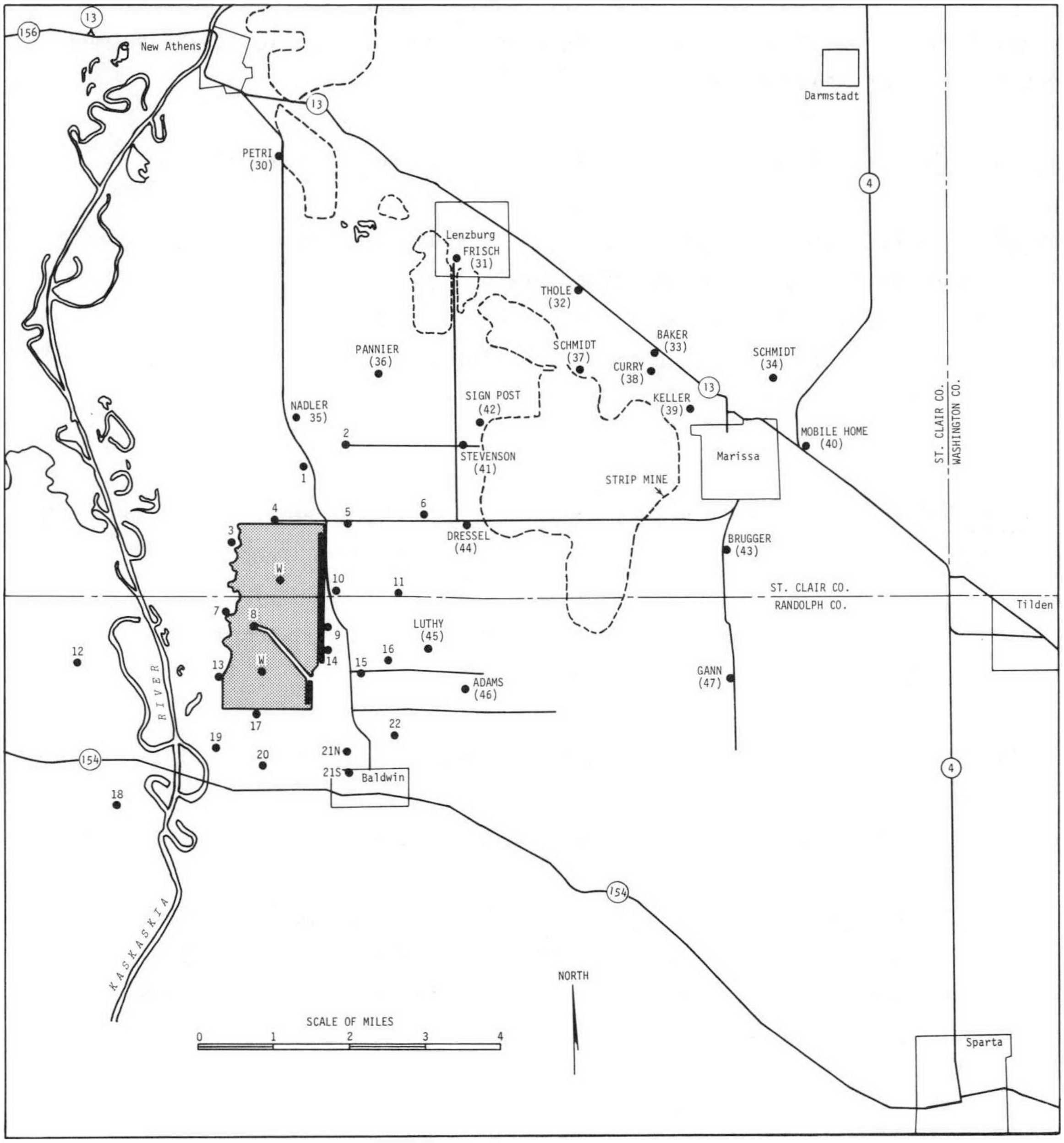

Figure 1-3. Baldwin raingage network

average wind. The 5-minute samples were then summed to obtain hourly average winds.

Water Temperature. Hourly values of the intake and outlet water temperatures were obtained from Illinois Power Company, and water temperatures were recorded at six additional sites. These charts were changed weekly, and hourly water temperatures were extracted.

Radiation. Net radiation data at the two locations were recorded on charts in Langleys/minute. The radiation was integrated over hourly periods, and summed to obtain daily or other values needed.

Soil Temperature. Hourly values of soil temperature were tabulated.

Rainfall. The recording raingage at station 14 provided information on rainfall intensity and the time distribution of the rainfall, in addition to measuring total rainfall adjacent to the lake. The network of 52 non recording, wedge-type gages (described earlier) was used to provide total storm and daily rainfall amounts for assessing potential lake effects on the regional precipitation distribution.

Recording Evaporimeter. This instrument was operated from April 1 to October 30 in 1976 and 1977, and hourly evaporation amounts were determined.

Pressure. Hourly station pressure was recorded from a microbarograph located in the Illinois Power building near station 14.

Visibility. A continuous record of visibility was made during part of the project period just east of Baldwin Lake with a transmissometer. The visibility data have been reduced at various time intervals depending upon their rate of change.

Visibility Markers and Icing Measurements. A number of visibility markers were placed around and in the near vicinity of the lake. These were used by the on-site observer to determine the variations in visibility with distance from the lake. Observations were recorded on a routine basis on forms supplied for this purpose.

Steam Fog. The vertical extent of steam fog over Baldwin Lake was estimated by two methods. The vertical extent of local fogs in the immediate vicinity of the power plant was recorded at 30-minute or hourly intervals, depending on the persistence of the fog and its time variation. The vertical extent of these fogs was estimated as a function of three 184-m (605-ft) stacks which are located on the southeast corner of the lake. When the vertical extent of fog was greater than 184 m (605 ft), or if fog measurements were required at considerable distances from the power plant, a second type of measurement was used. At these times, the observer measured the elevation angle using a Brunton compass. Fog events were also recorded with a camera.

Cloud Measurements. Photogrammetric methods were employed in a general evaluation of the stack effluent and cooling lake effects on the initiation and enhancement of clouds. On occasions when cloud effects appeared to be possible, the observer took numerous photographs from various positions and locations to provide data for computing the areal extent of clouds initiated or modified by the lake and stack effluent.

Control Lake Measurements. Observations of air temperature, humidity, wind, and water temperature were obtained at Rend Lake (Figure 1-1), which served as a control for assisting in the evaluation of cooling lake effects on local weather conditions.

DESCRIPTION OF DRESDEN COOLING LAKE

The Dresden nuclear power station, with a capacity of 1500 MWe, is situated 110 km (68 mi) southwest of Chicago, near the confluence of the Kankakee and Des Plaines rivers which marks the beginning of the Illinois River (Figure 1-4). The waste

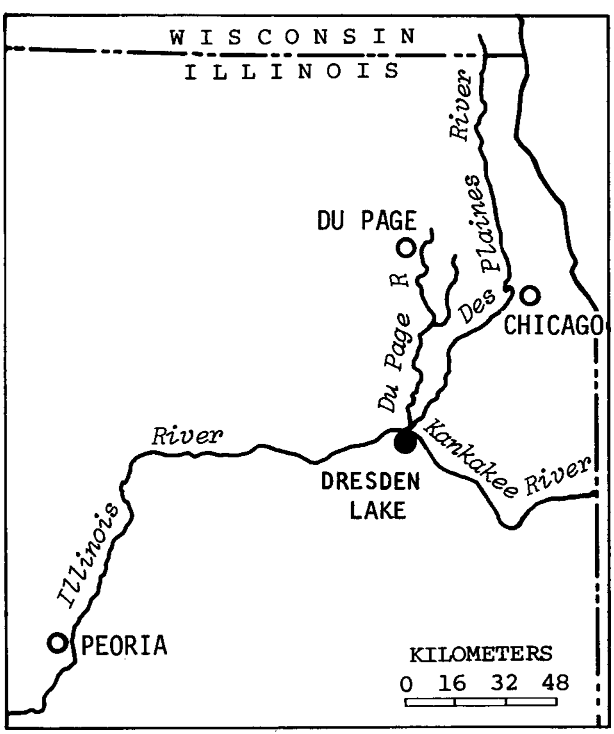

Figure 1-4. Dresden cooling lake and surrounding climatic stations

heat from this electric generating plant for the observational period of December 1971 to March 1973 was dissipated by means of a spray canal system and a 445-hectare (1100-acre) cooling lake. The cooling lake is located at an elevation of 158 m (520 ft) above sea level, approximately 3 m (10 ft) above the Kankakee River which provides make-up water. The terrain surrounding the lake is relatively flat with minor bluffs along the rivers and some small hills.

The data were collected by Murray and Trettel (11) for Commonwealth Edison Company to determine the meteorological aspects of the cooling lake and the spray canal system used for dissipation of the waste heat. During this period, spray canals and the cooling lake were used to cool the water before its release into the Illinois River. Water was pumped from the Kankakee River and circulated through the plant condenser system. This heated effluent was released into the spray canal and was then pumped to the cooling lake.

The cooling lake was divided into a series of subponds by a dike system which ensured that the whole lake was used for cooling (Figure 1-5). Initially, the heated water was released into the north part of pond 1; because of the dike

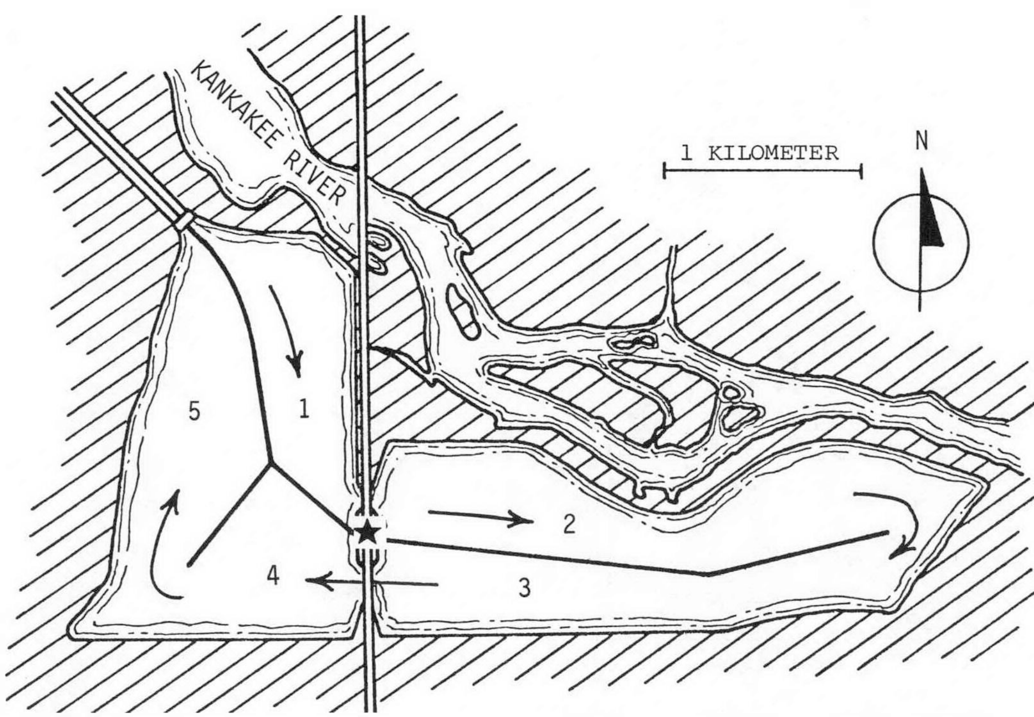

Figure 1-5. Dresden cooling lake--star indicates observation point

system, the water circulated in a clockwise manner to pond 5. Thus, the warmest water was in pond 1 and the coolest in pond 5. The water flowed from the lake into another spray canal and then into the Illinois River. The water temperature during the period of observations ranged from 9°C (48°F) in winter to 35°C (95°F) in summer.

An observer recorded steam fog, icing, and other weather-related events which occurred over the cooling lake on a daily basis. Generally these observations were taken between sunrise and midafternoon on a bridge which crosses the cooling lake (indicated by a star on Figure 1-5). These observations were supplemented by temperature and humidity readings taken with a sling psychrometer and water temperatures taken near the surface of the water at the same location. Wind information was available from a meteorological tower 4 km (2.5 mi) northwest.

General Climate of Dresden Area

Similar to Baldwin, the Dresden cooling lake is situated within a temperate climatic zone. The annual precipitation averages 89.4 cm (35.2 in). The heaviest precipitation, on the average, occurs in June with a normal of 10.9 cm (4.3 in). February is the driest month with an average of 4.3 cm (1.7 in). On the average, 63 days a year record 2.5 mm (0.10 in) or more of rain, with a range from 7 days each in April and May to only 2 days in January. Heavier rains, in excess of 12.5 mm (0.5 in), occur on 23 days each year, on the average, with a maximum of 4 days in June, and a minimum of 1 day each during the fall and winter months. The annual snowfall is 63.5 cm (25 in) with 90% of this occurring from December through March. The snow season usually begins in November and ends by early April.

The mean annual temperature is 10.6°C (51°F), and ranges from 23.3°C (74°F) in July to -3.8°C (25°F) in January. Monthly mean maximum temperatures range from 30°C (86°F) in July to 1.1°C (34°F) in January. The monthly mean minimum temperature varies from -8.3°C (17°F) in January to 17°C (63°F) in July. On the average, only 28 days per year have a temperature of 32.2°C (90°F) or more, and 8 of these days normally occur in July. During a normal year, 135 days experience a minimum temperature of 0°C (32°F) or less, and the maximum monthly occurrence is in January with 28 days.

According to fog statistics compiled by Murray and Trettel (11) from hourly observations at the Joliet Municipal Airport, nearly 1100 hours of fog are observed on an annual basis about 19 km (12 mi) north-northeast of the cooling lake. This varies from an average of 322 hours in winter to a minimum of 194 hours in summer. The month with the highest average frequency of natural fog is March with 135 hours. The spring and fall seasons have nearly equal occurrences of fog with 290 and 275 hours, respectively. On the average, fog is recorded 140 days each year with about 35 days in each season. Dense fog averages 99 hours each year on 25 days. Seasonally, such occurrences can be expected during 36 hours on 12 days in winter; 21 hours on 4 days in spring; 15 hours on 4 days in summer; and 27 hours on 5 days in fall.

COMPARISON OF DRESDEN AND BALDWIN CLIMATES

Baldwin and Dresden cooling lakes are both embedded in the same temperate climate, but Dresden is 375 km (233 mi) north-northeast of Baldwin, and there are some differences in temperature, precipitation, and fog. Dresden is colder than Baldwin and this difference is most pronounced during winter. For example, the January monthly temperature at Dresden is 4.4^{o}C (7.9^{o}F) colder. Another measure of the colder temperatures is provided by the fact that there are 38 more days with temperatures at 0^{o}C (32^{o}F) or below at Dresden.

Another difference between the two sites is the natural frequency of fog. Dresden during an average year can expect to receive 400 more hours of natural fog than Baldwin. The total number of hours of fog in winter is similar at both sites, but Dresden averages nearly twice as many fog hours in the other seasons. In addition, Dresden averages over 2.5 times more dense fog occurrences than Baldwin, and this difference is evident in all seasons.

On the average, Dresden receives 12 cm (5.1 in) less precipitation annually than Baldwin. Most of the difference occurs during the colder part of the year from October to March. During the warm part of the year (April to September) the average monthly rainfall at each site is similar, as is the number of days with rainfall of 2.5 mm (0.1 in) or more and 12.5 mm (0.5 in) or more. However, during winter Dresden receives 26 cm (10.2 in) more snow than Baldwin. Thus, during the colder parts of the year Dresden realizes more of its precipitation in the form of snow than does Baldwin.

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Section 2

STEAM FOG

INTRODUCTION

A major atmospheric effect -- one of the most visible associated with cooling lakes -- is the initiation and/or enhancement of steam fog (1-5). Steam fog is formed when water vapor added to air issues from a source that is much warmer than the air. A similar phenomenon is observed during winter when a person exhales and condensation forms. Steam fog is most often observed over natural water bodies, lakes and rivers, during fall and early winter, while the temperature of the air is dropping and the water is unfrozen and still relatively warm. Usually, steam fog is relatively shallow, resembling small columns or tufts of smoke rising from the water surface. Over the oceans it is often referred to as sea smoke and has been observed in arctic, temperate, and tropical waters (6). Over large natural bodies of water such as the Great Lakes and oceans, steam fog can reduce visibilities over vast portions of the water surface and present a hazard to navigation.

The frequency and intensities of steam fog over cooling lakes is largely unknown. This section presents results from two field studies in Illinois during which the formation of steam fog over cooling lakes was investigated. The first results are from Baldwin cooling lake in southern Illinois, and the second are based on observations made by Murray and Trettel (3) at Dresden cooling lake in the northeastern part of the state.

BALDWIN LAKE

Detailed weather observations were taken by an observer from Monday through Saturday at Baldwin. Observations were taken upon first reaching the lake and were continued for the remainder of the day whenever fog or other weather phenomena were present in the network. The first observations were made during the first few hours after sunrise, when both natural and steam fog most frequently maximize over Illinois (2, 4). The observational practices followed established National Weather Service (NWS) procedures (7), except for visibility measurements. Normally, the NWS uses prevailing visibility to define surface visibility, while detailed quadrant visibilities are reserved for special circumstances. Prevailing visibility provides only the greatest visibility over one-half or more of the horizon, whereas quadrant visibilities provide detailed observations of the intensity of any obscuring weather phenomena and are more stringent. For this study, the quadrant reporting procedure was used to provide more detailed information for evaluating the lake effect.

The nearest NWS cooperative weather station with a long period of records is Sparta, 18 km (11 mi) to the southeast of Baldwin. The average monthly and seasonal maximum, minimum, and daily temperatures for the study period (September 1976-March 1978) are given in Table 2-1. Other nearby stations showed similar temperatures and departures from the mean. These included St. Louis plus Nashville and Belleville, Illinois. The warmest month for the period of observation was July 1977 with an average daily temperature of 26.7°C (80.1°F), which was 1.3°C (2.3°F) above normal. The coldest month was January 1977 with an average daily temperature of -8.0°C (17.6°F), some 8.7°C (15.7°F) below normal. This was not only the greatest monthly negative departure from normal during the period, but was the coldest January observed at St. Louis, Missouri since 1940. The largest monthly positive departure from normal was 3.6°C (6.5°F) in March 1977. Seasonally, the winter of 1977-1978 was the coldest with an average temperature of -3.2°C (26.2°F), which was 5.1°C (9.2°F) below the seasonal normal. The average maximum during this winter was only 1.2°C (34.2°F), and the average minimum was -7.7°C (18.1°F). The next coldest period was the winter of 1976-1977 with an average temperature of -1.9°C (28.5°F), or 3.6°C (6.5°F) below normal. Only 7 of 19 months had above normal temperatures, and the only seasons with above normal conditions were spring and summer 1977. The remainder of the period was characterized by below normal to much below normal temperatures.

The monthly average water temperatures and the maximum and minimum water temperatures recorded at Baldwin for site 14 along the cooling canal are shown in Figure 2-1. These data represent the warmest water temperatures in Baldwin cooling lake; they were used as the water temperature in many of the steam fog analyses. Water temperatures are a function of the air temperature and the amount of waste heat input. The highest monthly average temperature (38.3°C or 101°F) was registered in July 1977, and the coldest (9.4°C or 49°F) was recorded in February 1978.

Frequency of Steam Fog Events

During the 19-month period from September 1976 to March 1978, 185 days with steam

Table 2-1

AVERAGE TEMPERATURES BY MONTHS AND SEASONS FOR SPARTA, ILLINOIS (°C)

Month	Maximum	Minimum	Average	Departure From Normal
September 1976	27.3	12.8	20.1	-1.3
October 1976	17.8	5.3	11.6	-4.1
November 1976	10.1	-2.4	3.9	-4.1
December 1976	5.6	-6.0	-0.2	-2.6
January 1977	-2.9	-13.1	-8.0	-8.7
February 1977	8.0	-3.3	2.3	-0.5
March 1977	16.8	4.8	10.8	3.6
April 1977	23.6	9.9	16.8	2.4
May 1977	29.4	15.2	22.3	3.2
June 1977	31.1	18.1	24.6	0.6
July 1977	33.2	21.2	26.7	1.3
August 1977	30.7	19.4	25.1	-0.1
September 1977	28.2	16.8	22.5	1.2
October 1977	19.9	7.4	13.7	-1.9
November 1977	11.9	4.2	8.1	0.2
December 1977	5.3	-4.1	0.6	-1.8
January 1978	-0.8	-9.9	-5.3	-5.6
February 1978	-0.8	-9.1	-4.9	-7.8
March 1978	9.8	-0.4	4.7	-2.6
Season				
Fall 1976	18.4	5.2	11.8	-3.1
Winter 1976-1977	3.6	-7.5	-1.9	-3.9
Spring 1977	22.8	10.0	16.7	3.1
Summer 1977	31.7	19.6	25.5	0.6
Fall 1977	20.1	9.4	14.8	-0.2
Winter 1977-1978	1.2	-7.7	-3.2	-5.1
March 1978	9.8	-0.4	4.7	-2.6

fog were observed over the Baldwin cooling lake. Observations were made on 464 days during this period. Thus, steam fog of some intensity was observed on nearly

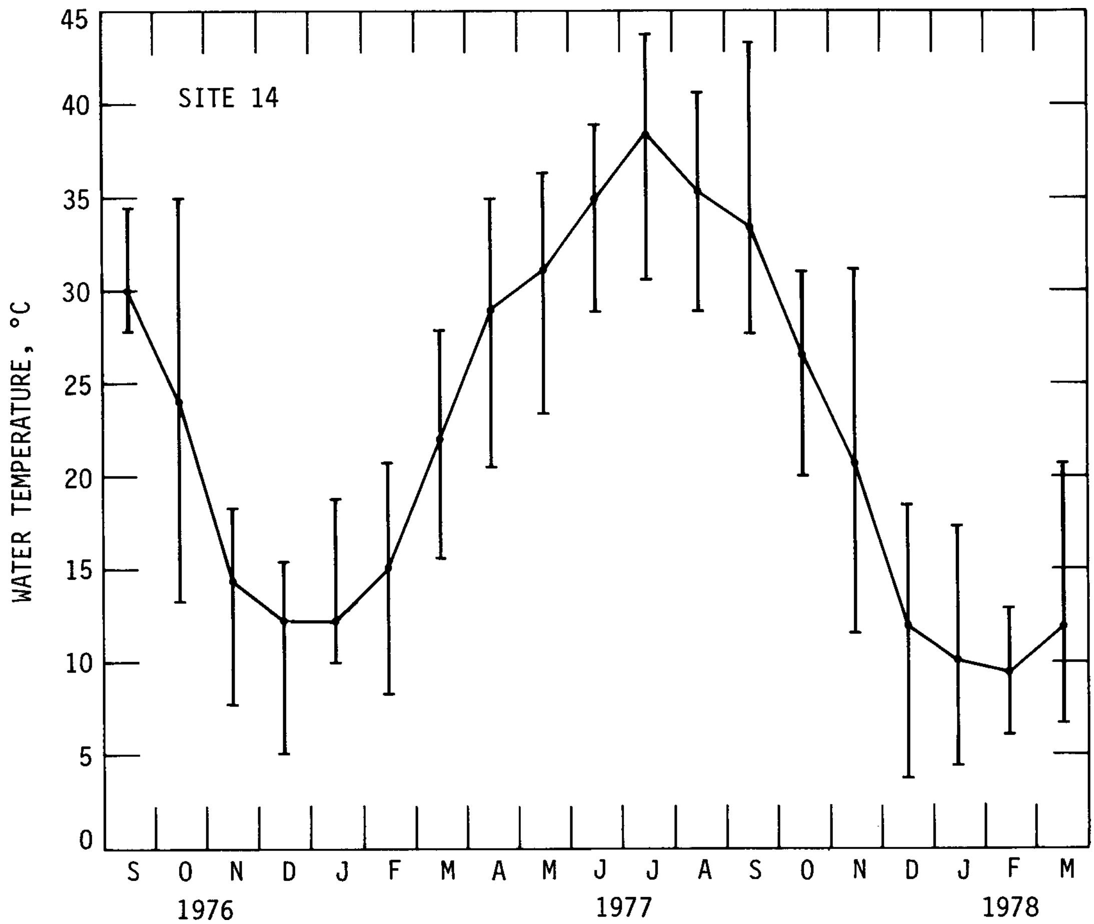

Figure 2-1. Monthly average water temperature and monthly maximum and minimum water temperatures at Baldwin site 14

40% of the days. During the same period natural fog was observed at St. Louis International Airport (Figure 1-1) 36% of all days between 0600 to 1000 CST, the maximum period of natural fog. St. Louis is the closest 24-hour, first-order weather station operated by the NWS.

The intensity of steam fog at Baldwin was defined by the visibility restriction. The lower the visibility the more intense the steam fog. Steam fog with visibilities of 0.4 km (0.25 mi) or less were considered to be intense enough to impose restriction on driving conditions if the steam fog were to move across a road. The Transportation Research Board of the National Research Council (8) indicates that during the daylight hours automobile traffic is not affected adversely by fog until the visibility is reduced to 600 ft (0.2 km). Thus, the visibility restriction of 0.4 km imposed in this analysis is a conservative estimate of the frequency of fogs which might reduce the visibility to dangerous limits for driving.

Steam fog days were stratified further by initiation and enhancement days. Initiation days were defined as those days when the steam fog formed without any natural fog present near the cooling lake. Enhancement days were days when natural fog was present and the visibility over the cooling lake was less than the visibility of the natural fog due to the formation of steam fog.

Table 2-2 shows the frequency of steam fog days over Baldwin cooling lake by intensity and season. The primary maximum occurred during winter, with 49 occurrences in the winter of 1977-1978 and 30 events in 1976-1977. The secondary maximums were recorded during fall, which had 32 occurrences in 1977 and 29 in 1976. Twice as many days with dense steam fog (visibilities less than 0.4 km) occurred during winter than in any other season. Fall was second in frequency of dense fogs. Steam fog occurred in all seasons, but no dense steam fog was observed during the spring of 1977, while three such events were observed during March 1978 alone. March 1978 was, on the average, 6.2°C (11.2°F) colder than March 1977.

There were 137 days with steam fog only and 48 days when natural fog was enhanced by steam fog. Thus, nearly 75% of all steam fog events were initiation days. As indicated in Table 2-2, the primary season for steam fog initiations was winter with a secondary maximum in fall. During the summer of 1977 steam fog was initiated on only five days, and the visibility was greater than 1.6 km (1 mi) on all these days. Nearly 80% of all dense initiations occurred during winter, and none were recorded during summer. During seasons other than winter, initiation fogs seldom reduced the visibility below 1.6 km (1 mi).

The enhancement of natural fog by steam fog depends upon the prevailing weather patterns. The temporal variability of steam fog enhancement is exhibited in Table 2-2. Only two days of steam fog enhancement were observed during the winter of 1976-1977 and the spring of 1977, whereas 14 days with enhancement occurred in the summer of 1977. No enhancement days were noted with a natural fog visibility greater than 8 km (5 mi). During the winter of 1976-1977 little natural fog formed because of the extremely cold, dry weather, even though climatically fog tends to maximize during this season (2). However, in the winter of 1977-1978 more natural fog formed, and 10 days of steam fog enhancement were observed. Normally, the enhancement effect would be expected to maximize during fall and winter, when climatologically the maximum of all fog and dense fog days occurs over Illinois (2). The enhancement effect will vary from year to year depending on the frequency and intensity of natural fog observed within the vicinity of the cooling lake.

Visibilities less than 0.4 km (0.25 mi) were noted in nearly 45% of all enhancement events. The lowest visibility associated with steam fog enhancement was 1.6 km (1 mi) or less over 80% of the time. In 7 of the 21 dense enhancement events, the natural fog visibility was less than 0.4 km; the

Table 2-2

FREQUENCY OF STEAM FOGS AT BALDWIN

Season	≤0.4	>0.4≤1.6	>1.6≤8	>8	Total
		All Fogs Visibility (km)			
Fall 1976	5	8	8	8	29
Winter 1976-1977	11	5	4	10	30
Spring 1977	0	2	6	9	17
Summer 1977	4	6	8	1	19
Fall 1977	6	6	4	16	32
Winter 1977-1978	16	3	9	21	49
March 1978	3	2	3	1	9
Total	45	32	42	66	185
Percent of Total	24	17	23	36	100
		Initiation			
Fall 1976	2	5	7	8	22
Winter 1976-1977	10	5	4	10	29
Spring 1977	0	1	6	9	16
Summer 1977	0	0	4	1	5
Fall 1977	2	1	4	16	23
Winter 1977-1978	9	1	8	21	39
March 1978	1	0	1	1	3
Total	24	13	34	66	137
Percent of Total	18	9	25	48	100
		Enhancement			
Fall 1976	3	3	1	0	7
Winter 1976-1977	1	0	0	0	1
Spring 1977	0	1	0	0	1
Summer 1977	4	6	4	0	14
Fall 1977	4	5	0	0	9
Winter 1977-1978	7	2	1	0	10
March 1978	2	2	2	0	6
Total	21	19	8	0	48
Percent of Total	44	39	17	0	100

steam fog lowered the visibility to zero four times and to 33 m (100 ft), or nearly zero, in the other three. Only three of these events occurred during winter. The winter of 1977-1978 had the greatest number (7) of dense enhancement fogs. Dense fog over the cooling lake in seasons other than winter, was associated usually with steam fog enhancement rather than initiation.

Overall, steam fog was observed over the lake on 40% of the days on which visual observations were made. In general, steam fogs occurred most frequently over Baldwin in winter, followed by fall. Twice as many dense fogs occurred in winter than in any other season. Nearly 75% of all steam fogs were lake initiation events. Nearly 80% of all initiations of dense fog occurred in winter and none in summer. Days with natural fog enhancement by the cooling lake showed an erratic temporal trend during the sampling period; however, lake-enhanced dense fog events were most common in winter, in agreement with the findings regarding lake-related initiations.

Synoptic Typing

A simple weather typing method was developed to determine the general weather conditions which initiated or enhanced steam fog. The seven basic synoptic weather stratifications are: 1) cold front, 2) warm front, 3) static front, 4) occluded front, 5) low pressure area, 6) warm air mass, and 7) cold air mass. All weather types were determined from the Daily Weather Map for 0600 CST published by the NWS (9). This time was chosen because steam fog events can be expected to maximize in the morning near the time of the daily minimum temperature (2, 4).

A fog event was considered to be frontal if a front was within 250 km (150 mi) of either side of the lake. If flow from a major cyclone dominated the circulation pattern over the cooling lake, the event was designated as a low pressure; usually, the center of the cyclone was within 150 km (90 mi) of the cooling lake. If a particular day was not classed as frontal or a low pressure, it was designated as a warm or cold air mass. A warm air mass was typified by general southerly flow and air temperatures above the seasonal normals. Otherwise, the air mass was considered to be cold, and these situations were often accompanied by cold air advection.

The most frequent weather type associated with the formation of steam fog over the Baldwin cooling lake was the cold air mass (Table 2-3). This weather type accounted for 68% of all weather types. The next most frequent types were warm air masses and cold fronts which were associated with 20% of all steam fog events. There were 41 steam fogs associated with frontal activity or low pressure areas,

Table 2-3

RELATION BETWEEN STEAM FOG FREQUENCY AND WEATHER TYPES AT BALDWIN

All Fogs

	Cold Air Mass	Warm Air Mass	Cold Front	Warm Front	Static Front	Low	Total
Fall 1976	19	7	2	0	0	1	29
Winter 1976-1977	23	0	6	1	0	0	30
Spring 1977	8	3	2	1	1	2	17
Summer 1977	4	3	2	2	8	0	19
Fall 1977	24	3	5	0	0	0	32
Winter 1977-1978	42	3	1	0	1	2	49
March 1978	5	0	1	1	0	2	9
Total	125	19	19	5	10	7	185
Percent of Total	68	10	10	3	5	4	100

Initiation Days

	Cold Air Mass	Warm Air Mass	Cold Front	Warm Front	Static Front	Low	Total
Fall 1976	14	6	1	0	0	1	22
Winter 1976-1977	22	0	6	1	0	0	29
Spring 1977	8	3	2	1	1	1	16
Summer 1977	1	1	0	0	3	0	5
Fall 1977	18	2	3	0	0	0	23
Winter 1977-1978	37	1	0	0	0	1	39
March 1978	2	0	0	0	0	0	2
Total	102	13	12	3	4	3	137
Percent of Total	75	9	9	2	3	2	100

Enhancement Days

	Cold Air Mass	Warm Air Mass	Cold Front	Warm Front	Static Front	Low	Total
Fall 1976	5	1	1	0	0	0	7
Winter 1976-1977	1	0	0	0	0	0	1
Spring 1977	0	0	0	0	0	1	1
Summer 1977	3	2	2	2	5	0	14
Fall 1977	6	1	2	0	0	0	9
Winter 1977-1978	5	2	1	0	1	1	10
March 1978	3	0	1	0	0	2	6
Total	23	6	7	2	6	4	48
Percent of Total	48	13	15	4	12	8	100

and 25 of these were embedded in the cold air sector. Thus, 150 or over 80% of all steam fogs occurred when cold air was lying over the cooling lake. No occluded fronts were identified with steam fog events at Baldwin.

Cold air mass situations were the dominant weather type in fall and winter. During spring, cold air mass types were associated with about 50% of all occurrences, but during the summer static fronts were the dominant weather type. A climatology of surface weather features (10) indicated that static fronts stagnate across central Missouri and southern Illinois during summer. In other seasons the maximum frequency of these fronts occurs over the Rockies. Thus, climatically the more frequent occurrence of static fronts with steam fog in summer is realistic.

On initiation days cold air masses accounted for 75% of all steam fog occurrences; except for summer, it was the dominant weather type in all seasons. When steam fog enhanced the occurrence of natural fog, 48% of the weather types were associated with cold air mass situations. Frontal activity and low pressure areas were more frequent on enhancement days, especially during summer. The greater frequency of fronts and lows on enhancement days can be expected, because natural fog is often associated with such large-scale weather events, especially in fall and winter.

Table 2-4 presents the frequency of weather types and steam fog visibilities. On initiation days with visibilities of 1.6 km (1 mi) or less, cold air mass accounted for 34 of the 37 cases (92%). Enhancement days exhibited more variability with respect to weather types in all visibility categories, and there was no preference of one weather type as a function of visibility. This could be expected since, as stated earlier, fog is often associated with frontal or cyclonic activity.

Briefly summarizing, steam fog is most frequently associated with cold air mass weather at Baldwin, particularly on initiation days, when 75% of all cases fell into this category. Although cold air mass weather was still the dominant type on enhancement days, the distribution was more variable since natural fog is not uncommon in the presence of fronts and lows. Relatively dense fog was more prevalent on enhancement days, when over 80% of the cases had visibilities of less than 1.6 km (1 mi), compared with 37% on initiation days when no natural fog was present. The foregoing analyses of steam fog distribution at Baldwin suggest that interference with activities that are fog related is most likely to occur in the vicinity of large power plants when the cooling lake is acting to intensify natural fog. Conversely, severe restrictions of visibility are unlikely to occur on most days when the lake is the sole fog-generating source.

Table 2-4

RELATIONS BETWEEN FREQUENCY OF WEATHER TYPES AND STEAM FOG VISIBILITIES AT BALDWIN

All Fogs

Visibility (km)	Cold Air Mass	Warm Air Mass	Cold Front	Warm Front	Static Front	Low	Total	Percent
≤0.4	34	2	4	0	3	2	45	24
>0.4≤1.6	21	3	3	2	2	1	32	17
>1.6≤8.0	22	6	5	2	5	2	42	23
>8.0	48	8	7	1	0	2	66	36
Total	125	19	19	5	10	7	185	100

Initiation Days

Visibility (km)	Cold Air Mass	Warm Air Mass	Cold Front	Warm Front	Static Front	Low	Total	Percent
≤0.4	22	0	2	0	0	0	24	18
>0.4≤1.6	12	1	0	0	0	0	13	9
>1.6≤8.0	20	4	3	2	4	1	34	25
>8.0	48	8	7	1	0	2	66	48
Total	102	13	12	3	4	3	137	100

Enhancement Days

Visibility (km)	Cold Air Mass	Warm Air Mass	Cold Front	Warm Front	Static Front	Low	Total	Percent
≤0.4	12	2	2	0	3	2	21	44
>0.4≤1.6	9	2	3	2	2	1	19	39
>1.6≤8.0	2	2	2	0	1	1	8	17
>8.0	0	0	0	0	0	0	0	0
Total	23	6	7	2	6	4	48	100

Wind

Table 2-5 presents the frequency of steam fog events stratified by wind direction. For all steam fog events, 27% of the time the dominant wind direction was northwest to north-northwest (NW-NNW). The next most frequent wind direction was from the southeast to south-southeast (SE-SSE) with 13 of the occurrences. Only 3% of all the events were associated with calm winds. Winds from northerly directions (west through north to east-northeast) accounted for 58% of all steam fog events, while southerly winds were associated with 39%. The annual wind rose for the

St. Louis International Airport (11) indicates that winds normally come from the west through east-northeast 44% of the time. This suggests an above normal frequency of winds from the north occurred during the Baldwin experiment. Such winds

Table 2-5

FREQUENCY OF WINDS AND ALL STEAM FOG EVENTS AT BALDWIN

Wind Direction	≤0.4	>0.4 ≤1.6	>1.6 ≤8.0	>8.0	Total	Percent
	Visibility (km)					
N-NNE	5	2	6	8	21	11
NE-ENE	4	4	7	3	18	10
E-ESE	4	7	1	2	14	7
SE-SSE	5	3	7	9	24	13
S-SSW	4	1	6	9	20	11
SW-WSW	4	4	3	3	14	8
W-WNW	2	3	2	11	18	10
NW-NNW	15	8	8	19	50	27
Calm	2	0	2	2	6	3
Total	45	32	42	66	185	100
	Winter 1976-1977 and 1977-1978					
N-NNE	2	0	3	3	8	10
NE-ENE	2	0	2	2	6	8
E-ESE	2	1	0	0	3	4
SE-SSE	2	1	2	3	8	10
S-SSW	2	0	1	3	6	8
SW-WSW	1	1	0	1	3	4
W-WNW	2	2	1	7	12	15
NW-NNW	12	3	3	12	30	37
Calm	2	0	2	0	3	4
Total	27	8	13	31	79	100
	Spring, Summer and Fall					
N-NNE	3	2	3	5	13	12
NE-ENE	2	4	5	1	12	11
E-ESE	2	6	1	2	11	10
SE-SSE	3	2	5	6	16	16
S-SSW	2	1	5	6	14	13
SW-WSW	3	3	3	2	11	10
W-WNW	0	1	1	4	6	6
NW-NNW	3	5	5	7	20	19
Calm	0	0	1	2	3	3
Total	18	24	29	35	106	100

are often associated with cold air advection and colder than normal temperatures. However, only minor differences were noted between wind directions and the intensity of the steam fog during the Baldwin study.

Since the primary season for steam fog was winter, the data were further stratified to group the two winter seasons (1976-1977 and 1977-1978). Winds from the northwest and north-northwest were associated with more steam fogs in winter than any other wind directions (Table 2-5). The frequency of steam fog with this direction was double the normal expected frequency during the winter, based on St. Louis normals. Winds from the north occurred 71% of the time with winter steam fog. Most of this difference was associated with wind from the northwest and north-northwest. South winds were associated with steam fog events only 27% of the time. Thus, during winter steam fog is much more likely to occur with winds from the north.

During spring, summer, and fall, the occurrence of steam fog and wind direction from the north and south were about equal (Table 2-5), with 48% of the winds from the north and 49% from the south. During these seasons, according to data from St. Louis, winds come from the north 42% of the time on the average; thus, a slight preference for steam fog to occur with northerly winds was observed.

The percent distribution of steam fog initiations with wind direction for all fog intensities and seasons was similar to that for all steam fog days in Table 2-5. However, for days with enhancement there were differences. For all enhancement days, winds from the northwest to north-northwest and northeast to east-northeast were the most frequent (Table 2-6) compared with northwest dominance in Table 2-5. Northerly winds were observed 50% of the time, and southerly winds occurred 46% of the time. Winds from the north through south-southeast accounted for 65% of all the enhancement days. Normally, only 39% of all winds at St. Louis come from the north through south-southeast, but in fogs a slight preference for easterly winds has been found (2). The sample size during winter was too small to make any comparisons. Little difference was noted between wind direction and steam fog intensity for enhancement days.

The frequency of wind speeds for all steam fog events is given in Table 2-7. As expected, these results indicate a general decrease in the frequency of steam fog events as wind speed increases. Over 85% of all steam fogs occurred with wind speeds of 16 km/h (10 mi/h) or less. Previous studies of Illinois fog (2) indicate that the occurrence of natural fog with wind speeds of 16 km/h or less ranges from

59% in spring to 86% in summer. Thus, many steam fogs were associated with lighter winds than normally occur with natural fogs. However, 9% of the dense steam fogs did occur with winds in excess of 24 km/h (15 mi/h), which is three times greater than the climatic average for natural fog. For steam fogs of other intensities, the distribution with wind speeds greater than 24 km/h (15 mi/h) was similar to the climatic average.

Table 2-6

FREQUENCY OF STEAM FOG ENHANCEMENTS AND WIND AT BALDWIN

Wind Direction	Visibility (km) ≤0.4	>0.4 ≤1.6	>1.6 ≤8.0	Total
N-NNE	3	1	0	4
NE-ENE	3	4	3	10
E-ESE	4	5	0	9
SE-SSE	3	2	3	8
S-SSW	0	1	1	2
SW-WSW	1	2	0	3
W-WNW	0	0	0	0
NW-NNW	5	4	1	10
Calm	2	0	0	2
Total	21	19	8	48

On initiation days the distribution of wind speeds was similar to the total distribution of all steam fogs. Over 70% of the enhancement days had wind speeds of less than 9 km/h (5 mi/h). Winds in excess of 24 km/h (15 mi/h) were not observed. Only on six days (13% of the time) were winds in excess of 16 km/h observed. Thus, all high wind speed events (greater than 24 km/h) were associated with initiation days. Wind speeds on enhancement days were similar to the long-term climatic average for natural fog days.

All but one of the initiation days with wind speeds in excess of 24 km/h occurred in winter and these accounted for 20% of all winter dense initiation days. On one occasion dense steam fog was observed with winds in excess of 65 km/h (40 mi/h). During spring, summer, and fall over 85% of all initiation days occurred with wind speeds of less than 16 km/h. Except for winter, steam fog tended to

Table 2-7

FREQUENCY OF STEAM FOG AND WIND SPEED AT BALDWIN

Wind Speed (km/h)	≤0.4	>0.4≤1.6	>1.6≤8	>8	Total
		Visibility (km) All Seasons			
0- 8	26	16	26	31	99
9-16	11	12	13	23	59
17-24	4	3	1	5	13
25-32	3	0	1	5	9
>32	1	1	1	2	5
Total	45	32	42	66	185
		Winter			
0- 8	12	2	7	11	32
9-16	9	3	4	10	26
17-24	2	2	0	4	8
25-32	3	0	1	4	8
>32	1	1	1	2	5
Total	27	8	13	31	79
		Spring, Summer, and Fall			
0- 8	14	14	19	20	67
9-16	2	9	9	13	33
17-24	2	1	1	1	5
25-32	0	0	0	1	1
>32	0	0	0	0	0
Total	18	24	29	35	106

occur with wind speeds of less than 16 km/h (10 mi/h) on both initiation and enhancement days.

In summary, combining all fog events and seasons, steam fog occurred most frequently at Baldwin with winds from the northwest to north-northwest. No significant relation was found between wind direction and fog intensity. Winter fogs showed the strongest bias toward association with northwest to north-northwest winds. No direction was really dominant in the other seasons. With respect to wind direction, the distribution on initiation days was similar to that for all events combined. However, fog enhancements were most frequently associated with winds having an easterly component, that is, from northeast through east to south-southeast. Over 85% of the steam fogs occurred with winds of 16 km/h (10 mi/h) or less. All steam fogs with strong surface winds (greater than 24 km/h) occurred on initiation days. On enhancement days the speed distribution was similar to that found from long-term climatic averages of natural fog events. This is not surprising in that enhancement involves reinforcement of natural fog by lake-induced steam fog.

Temperature and Humidity

The dependence of steam fog upon air temperature was investigated for Baldwin. Some dependency was found, but no strong relations were evident. As an example, the frequency distribution of upwind air temperature, the ambient temperature of the air mass, and the intensity of steam fog on winter initiation days is presented in Table 2-8. The absolute range of temperatures associated with dense steam fog events (visibilities $\leq$0.4 km) was from -23°C (-10°F) to -7°C (19°F), and the median temperature was -15°C (5°F). For light steam fog events, visibilities greater than 8 km (5 mi), the temperatures ranged from -15.5°C (4°F) to 4°C (39°F), and the median temperature was -7°C (19°F). For fog intensities between light and dense fogs, the temperature distribution was similar to light fogs. The coldest temperatures were associated with dense steam fogs, but over 50% of the light steam fog events had temperatures as cold as the dense steam fog events. The median temperatures were colder for the more intense events, but overall little dependence could be found with temperature and the formation or intensity of steam fog.

In other seasons, as in winter, the more intense steam fog events occurred with relatively cold temperatures, but temperatures associated with the various steam fog intensities did not indicate any direct relation between the initiation, enhancement, or intensity of steam fog. However, since intense steam fog events were associated with the colder temperatures in all seasons, the occurrence of the relatively cold weather events would indicate a higher probability of intense steam fog. These results are similar to those of Church (12) and Saunders (6), who found no direct relation between temperature and steam fog.

Table 2-8

FREQUENCY DISTRIBUTION OF AIR TEMPERATURES (°C) FOR WINTER INITIATION DAYS AT BALDWIN

Cumulative Percent Equalled or Exceeded	Visibility (km) ≤0.4	>0.4≤8.0	>8
	Temperature (°C)		
5	-22	-17	-14
10	-20	-14	-13
20	-18.5	-12	-11
25	-18	-11	-10
30	-17	-10	-9
40	-16	-9	-8
50	-15	-8	-7
60	-14	-7	-5
70	-13	-6	-4
75	-12	-5	-3
80	-11	-4	-2
90	-10	-2	1
95	-8	2	3
N	19	18	31

Other research has indicated that the differential temperature between the water and the ambient air is more indicative of the potential for steam fog (2, 6, 13, 14). The frequency of steam fog formations over Baldwin Lake associated with water-air temperature differences were determined for various fog intensities. The three-point running means for all steam fog events are shown in Figure 2-2.

Steam fogs at Baldwin maximized with water-air temperature differences of 18 to 19°C (32 to 34°F) with a secondary maximum of 11 to 12°C (20 to 22°F). Another minor maximum was indicated at 32 to 33°C (58 to 60°F). The frequency of fogs with visibilities in excess of 1.6 km (1 mi) is similar to the curve for all fogs; such fogs accounted for 57% of all steam fogs. For steam fogs with visibilities between 0.4 km (0.25 mi) and 1.6 km (1 mi), water-air temperature differences maximized between 15.5 and 16.5°C (28 and 30°F). A tendency for dense steam fog (<0.4 km, or 0.25 mi, visibility) to be associated with the larger temperature

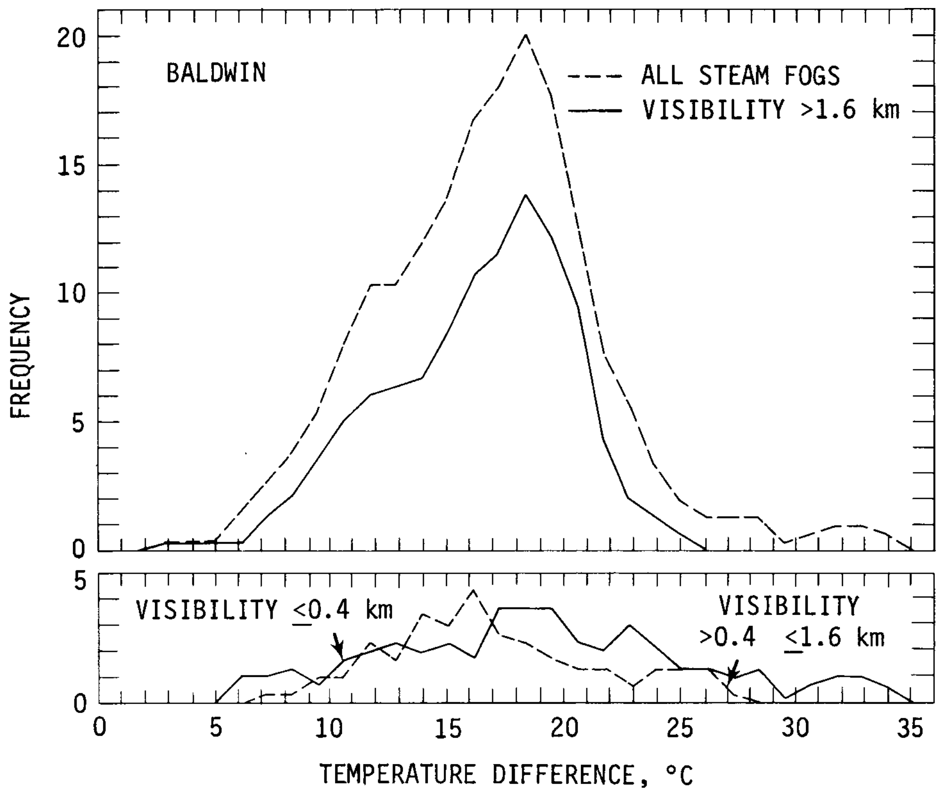

Figure 2-2. Frequency of water-air temperature differences for all steam fogs and various intensities at Baldwin

differentials is evident. In fact, only dense steam fogs were associated with temperature differentials in excess of 27°C (49°F).

Similar analyses were performed for initiation and enhancement days (Figures 2-3 and 2-4). The overall tendency for all initiation days and for initiation fogs with visibilities in excess of 1.6 km (1 mi) is similar to that of all steam fogs. However, no fog events were initiated until a water-air temperature differential of at least 6 to 7°C (12 to 14°F) was attained, and the secondary maximum which occurred on all fog days between 11 and 12°C (20 and 22°F) was not as prominent. On initiation days no dense fogs were formed until the temperature differential was at least 14.5 to 15.5°C (26 to 28°F). Only one fog with a visibility between 0.4 and 1.6 km (0.25 and 1 mi) occurred with a water-air temperature difference of less than 14.5°C (26°F).

On days with enhancement no temperature differential in excess of 19.5°C (35°F) was observed. The primary maximum on such days was 13.5 to 14.5°C (24 to 26°F); this peak accounted for the secondary maximum of all steam fog days (Figure 2-2). Very few enhancement days had visibilities in excess of 1.6 km (1 mi). The frequency curves for enhancement fogs of 0.4 km (0.25 mi) or less and between 0.4 and 1.6 km (0.25 and 1 mi) are similar.

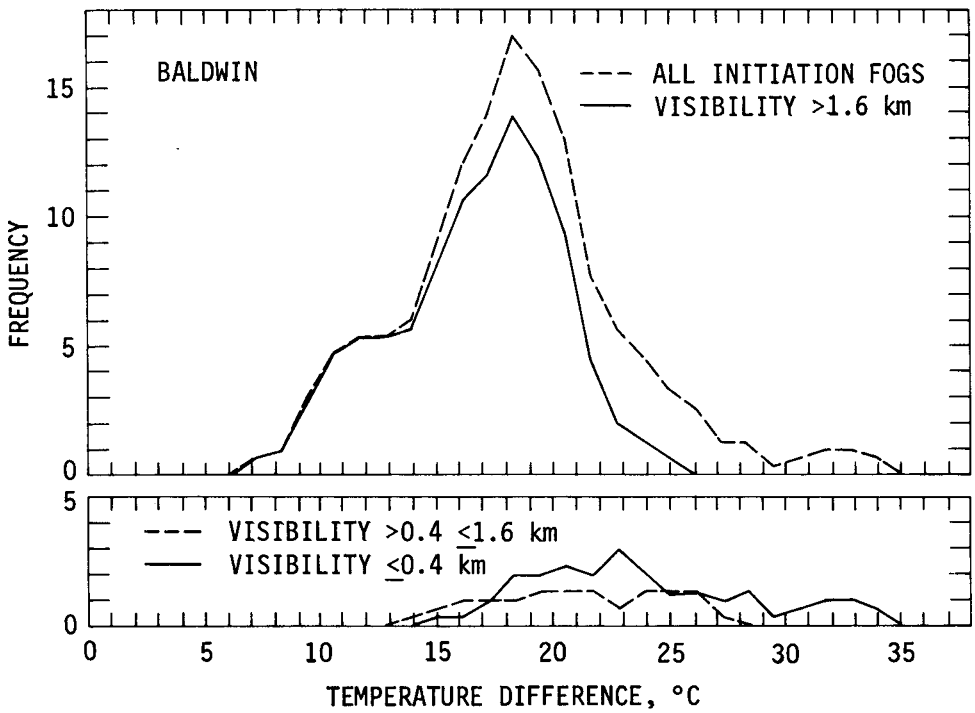

Figure 2-3. Frequency of water-air temperature differences for all initiation fogs and various intensities at Baldwin

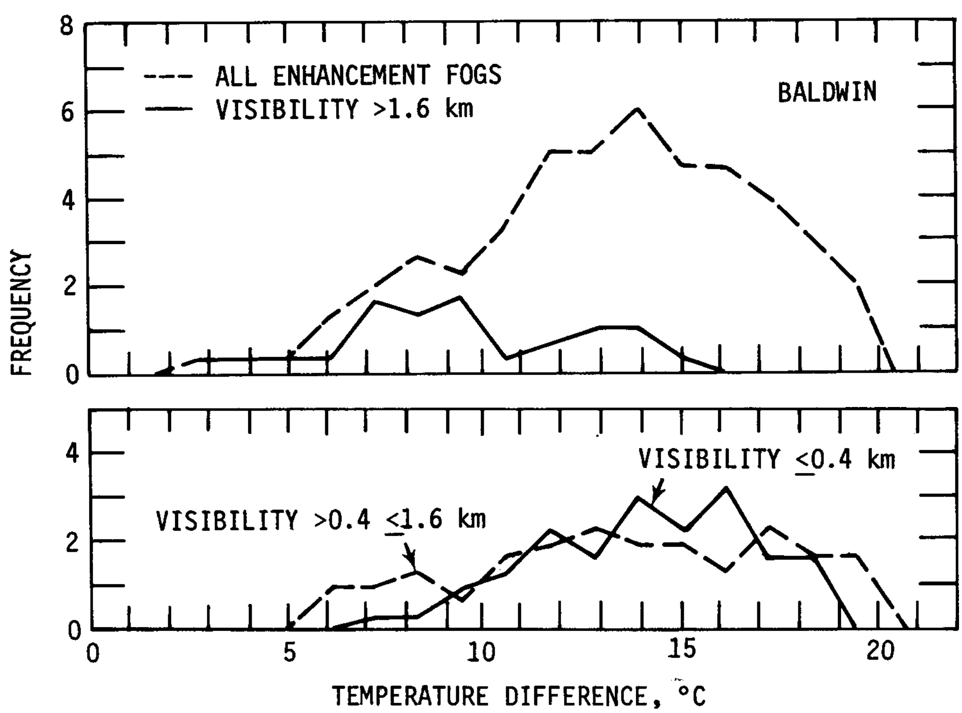

Figure 2-4. Frequency of water-air temperature differences for all enhancement fogs and various intensities at Baldwin

The frequency distribution of water-air temperature differences for initiation and enhancement days (Table 2-9) shows, in general, the more intense the fog event the greater the temperature differential. On initiation days the median water-air temperature difference for dense fogs is 23°C (41°F), while for fogs with visibilities in excess of 8 km the temperature differential is 16°C (29°F). On initiation days, 70% of all dense fogs occur with temperature differences in excess of 20°C (36°F), while only 20% of the light fogs (visibilities greater than 8 km) occur with such a temperature differential.

Table 2-9

FREQUENCY DISTRIBUTION OF WATER-AIR TEMPERATURE DIFFERENCES FOR BALDWIN FOGS (°C)

Cumulative Percent Equalled or Exceeded	Water-Air Temperature Difference (°C) Initiation Fogs Visibility (km) All	≤0.4	>0.4 ≤8.0	>8	Enhancement Fogs Visibility (km) All	≤0.4	>0.4 ≤8.0
5	27	32.0	24.5	22.5	19.0	19.0	18.0
10	24	30.0	22.5	22.0	18.0	18.5	17.0
20	22	27.0	21.0	20.0	16.5	17.5	16.0
25	21	26.5	20.0	19.5	16.0	17.0	15.5
30	20	26.0	19.5	19.0	15.5	16.0	15.0
40	19	24.0	18.5	17.5	14.5	15.0	14.0
50	18	23.0	18.0	16.0	13.5	13.5	13.0
60	17	21.0	17.0	15.0	13.0	12.5	12.0
70	16	20.0	16.0	14.0	11.5	11.0	11.0
75	15	19.5	15.5	13.0	10.5	10.5	10.5
80	14	19.0	15.0	12.5	10.0	10.0	9.5
90	12	18.0	13.0	11.0	7.5	8.0	7.5
95	11	16.0	12.0	10.0	5.5	6.5	5.5
N	137	24	47	66	48	21	27

Water-air temperature differences on enhancement days were not as large for corresponding initiation fog intensities. Only minor differences are indicated among the three visibility groups. The fog intensity as measured over or near the lake on enhancement days is dependent to a large extent upon the natural fog visibility. Visibilities in natural fog were less than 1.6 km (1 mi) on 24 of the 48 enhancement days. As pointed out previously, this results in a strong tendency for fog intensity to be greater on enhancement than on initiation days.

Comparisons between the frequency distribution of water-air temperature differences by seasons on initiation and enhancement days showed little or no difference. Smaller water-air temperature differences were most dominant during the summer months when enhancement fogs dominated. Higher water-air temperature differences were associated with initiation day fogs, but these higher temperature differences were distributed similarly in all seasons and dominated the winter months.

Church (12) suspected a correspondence between water-air temperature differences and the height of steam fog. Table 2-10 present the frequency of water-air temperature differences and the height of steam fog over Baldwin for initiation days. The height of steam fog on enhancement days was also estimated. However, the merging of steam fog and natural fog with height made the vertical estimates difficult, and little confidence was placed in their values. Most steam fogs had little vertical extent. Nearly 60% of all initiation fogs did not extend higher than 3 m (10 ft), and only 12 times (9%) did the vertical extent equal or exceed 30 m (100 ft). A tendency for larger water-air temperature differences to be associated with steam fogs of greater heights was observed, but no clear relation exists either for all initiation fogs or for those steam fogs stratified by season.

The water temperature in a cooling lake is generally elevated with respect to the water temperature of natural or man-made lakes of comparable size because of the addition of waste heat. For example, the Baldwin cooling lake was never frozen during the winters of 1976-1977 and 1977-1978, even though the temperatures were much below normal and natural bodies of water such as rivers and lakes were observed to freeze. Rend Lake, located 80 km (50 mi) east of Baldwin, did freeze. Thus, the chances of steam fog over a cooling lake are much greater than over a natural body of water.

Table 2-10

FREQUENCY OF WATER-AIR TEMPERATURE DIFFERENCE AND VERTICAL EXTENT OF INITIATION STEAM FOGS AT BALDWIN

Water-Air Temperature Difference (^{o}C)	Frequency for Given Vertical Height (m)				
	0-3	4-10	11-29	≥30	Total
8 - 9	3	0	0	0	3
10 -11	13	0	0	0	13
12 -15	8	1	0	0	9
15.5-16	16	3	1	1	21
17 -18	18	10	2	0	30
19 -20	19	9	3	1	32
21 -22	2	5	1	4	12
23 -25	1	5	0	2	9
25.5-27	1	3	0	1	4
28 -29	0	1	0	0	1
≥30	0	0	0	3	3
Total	81	37	7	12	137

Average monthly water temperatures from Baldwin and Rend Lake are presented in Table 2-11. The water temperatures at site 14 (Figure 1-2), measured just downstream from the power plant water outlet, are representative of the warmest water temperatures in the cooling lake (Figure 2-1). The intake water temperatures, taken near the plant water intake, were the coolest water temperatures. The water temperatures from Rend Lake were assumed to be 0^{o}C (32^{o}F) when the lake was frozen for most of a month, as it was during January 1977 and 1978 and February 1978. The average temperature difference between the warmest and coldest part of Baldwin Lake for the 19-month period was 5.9^{o}C (10.6^{o}F), and the coolest part of Baldwin Lake averaged 3.4^{o}C (6.1^{o}F) warmer than Rend Lake, the control lake. The measurements from site 14 averaged 9.3^{o}C (16.7^{o}F) warmer than Rend Lake.

The largest water temperature differences between the two lakes were noted during spring. Apparently, the cooling lake warmed faster than the control lake. Baldwin Lake is shallower than Rend Lake, and the water is mixed more with depth. In addition, the heat load from the waste heat would promote a more rapid warming. Since steam fog forms when the water temperature is much warmer than the air temperature, a greater chance for the formation of steam fog exists over a cooling lake because of its elevated water temperature, than over a natural water body in the same climatic zone. No steam fog could form over the natural lake when it was frozen, and only minor steam fog incidents were observed before freezing during fall and the early winter months over Rend Lake. These incidents usually occurred after the passage of a cold front, when minimum temperatures were colder than normal.

Table 2-11

MONTHLY AVERAGE LAKE TEMPERATURES (^{o}C)

	Baldwin Lake Site 14	Baldwin Lake Intake	Rend Lake
September 1976	30.0	27.2	21.7
October 1976	23.9	18.9	15.6
November 1976	14.4	10.6	9.4
December 1976	12.2	7.8	3.9
January 1977	12.2	5.0	0.0
February 1977	15.0	8.3	4.5
March 1977	22.2	15.0	10.6
April 1977	28.9	20.6	16.1
May 1977	31.1	25.0	21.1
June 1977	35.0	28.9	25.0
July 1977	38.3	32.8	27.2
August 1977	35.0	29.4	26.1
September 1977	33.3	28.3	25.0
October 1977	26.1	19.4	17.2
November 1977	20.6	13.3	12.8
December 1977	11.7	5.6	3.9
January 1978	10.0	3.3	0.0
February 1978	9.4	3.3	0.0
March 1978	11.7	6.7	5.6

The water-air temperature difference is a measure of sensible heat differences between the water and the air. Even though it is an indicator of the potential of steam fog and its possible intensity, if the air above the lake surface is dry and not enough water vapor is evaporated from the lake surface to cause condensation, either no steam fog or only wisps of steam fog will form. Thus, another important parameter to be considered in steam fog initiation is the amount of water vapor necessary for condensation in the lowest layer of the atmosphere. A measure of this parameter is supplied by the saturation deficit, which is the difference between the potential amount of water vapor which can be held and the actual amount of water vapor in the atmosphere. This difference represents a measure of the amount of water vapor needed in the lower layer of the atmosphere to attain condensation. Table 2-12 presents the saturation deficit for all steam fogs by intensity. The saturation deficit is expressed as a mixing ratio in grams of water vapor per kilogram of dry air.

Table 2-12

FREQUENCY OF SATURATION DEFICITS AND STEAM FOG INTENSITY

Visibility (km)	Saturation Deficit (g/kg) ≤.25	>.25 ≤.5	>.5 ≤.75	>.75 ≤ 1	>1	Total
	All Fogs, All Seasons					
≤.4	29	13	1	1	1	45
>0.4≤1.6	8	7	10	5	2	32
>1.6≤8.0	9	17	6	5	5	42
>8	5	19	18	13	11	66
Total	51	56	35	24	19	185
	Winter					
≤.4	16	11	0	0	0	27
>0.4≤1.6	1	3	4	0	0	8
>1.6≤8.0	3	7	3	0	0	13
>8	5	11	11	3	1	31
Total	25	32	18	3	1	79
	Spring, Summer, and Fall					
≤.4	13	2	1	1	1	18
>0.4≤1.6	7	4	6	5	2	24
>1.6≤8.0	6	10	3	5	5	29
>8	0	8	7	10	10	35
Total	26	24	17	21	18	106

All but three dense steam fog events had saturation deficits of 0.5 g/kg or less. During winter all steam fog events had saturation deficits of 0.5 g/kg or less. Over 60% of the dense steam fogs were associated with saturation deficits of 0.25 g/kg or less. Similarly, over 60% of the light steam fogs (visibilities greater than 8 km or 5 mi) had saturation deficits greater than 0.5 g/kg, and 90% of all events had saturation deficits of 1 g/kg or less. Thus, fog intensity appears to be strongly related to saturation deficit.

Climatically for all seasons at Baldwin, saturation deficits of 1 g/kg or less can be expected to occur about 25% of the time, including both fog and no-fog days, with a maximum of 50% during the winter (2). Table 2-12 shows that 90% of all steam fogs (99% in winter) at Baldwin occurred with a deficit of 1 g/kg or less. Smaller saturation deficits during winter are more frequent because as the air temperature becomes colder the atmosphere potentially can hold less water vapor, and for the same relative humidity the saturation deficit is lowered. For example, with a surface pressure of 1000 mb, a relative humidity of 90%, and an air temperature of 18^{o}C (64^{o}F), (a typical summer minimum temperature), the saturation deficit is 1.3 g/kg. Similarly, for a relative humidity of 90% and an air temperature of -7^{o}C (19^{o}F), (a typical winter minimum), the saturation deficit is 0.2 g/kg. Thus, there is a greater chance for small saturation deficits in winter; it is during this season that the occurrence of steam fog maximizes.

The saturation deficit for initiation and enhancement days (Table 2-13) shows that no dense fogs were initiated with saturation deficits in excess of 0.5 g/kg, and all dense steam fogs with saturation deficits in excess of 0.5 g/kg were associated with summer enhancement fogs. On enhancement days 76% of the dense fogs were associated with saturation deficits of 0.25 g/kg or less, and they accounted for 80% of all enhancement days with saturation deficits of 0.25 g/kg or less. On initiation days, saturation deficits of 0.25 g/kg or less were associated with only 42% of the dense steam fog events. In general, the lower saturation deficits are associated with the more intense steam fog events, especially on enhancement days.

The dependence of steam fog on water-air temperature differences, especially for days with initiation, and a similar dependence of the intensity of steam fog upon the saturation deficit in the atmosphere indicate that these two parameters when combined may provide a measure of the intensity of steam fog. Table 2-14 presents

Table 2-13

FREQUENCY OF SATURATION DEFICITS AND STEAM FOG INTENSITY FOR ENHANCEMENT AND INITIATION DAYS

	Enhancement Days						Initiation Days					
	Saturation Deficit (g/kg)											
Visibility (km)	≤.25	>.25 ≤.5	>.5 ≤.75	>.75 ≤ 1	>1	Total	≤.25	>.25 ≤.5	>.5 ≤.75	>.75 ≤ 1	>1	Total
All Seasons												
≤.4	16	2	1	1	1	21	13	11	0	0	0	24
>0.4≤1.6	2	4	6	5	2	19	6	3	4	0	0	13
>1.6≤8.0	2	2	1	1	2	8	7	15	5	4	3	34
>8	0	0	0	0	0	0	5	19	18	13	11	66
Total	20	8	8	7	5	48	31	48	27	17	14	137
Winter												
≤.4	8	0	0	0	0	8	8	11	0	0	0	19
>0.4≤1.6	0	1	1	0	0	2	1	2	3	0	0	6
>1.6≤8.0	1	0	0	0	0	1	2	7	3	0	0	12
>8	0	0	0	0	0	0	5	11	11	3	1	31
Total	9	1	1	0	0	11	16	31	17	3	1	68
Spring, Summer, and Fall												
≤.4	8	2	1	1	1	13	5	0	0	0	0	5
>0.4≤1.6	2	3	5	5	2	17	5	1	1	0	0	7
>1.6≤8.0	1	2	1	1	2	7	5	8	2	4	3	22
>8	0	0	0	0	0	0	0	8	7	10	10	35
Total	11	7	7	7	5	37	15	17	10	14	13	69

Table 2-14

FREQUENCY OF WATER-AIR TEMPERATURE DIFFERENCES AND SATURATION DEFICITS ON INITIATION DAYS

Water-Air Temperature Difference (°C)	Saturation Deficit (g/kg) ≤.25	>.25 ≤.5	>.5 ≤.75	>.75	Total	≤.25	>.25 ≤.5	>.5 ≤.75	>.75	Total
	VSBY ≤0.4 km					VSBY >0.4 ≤1.6 km				
15.5-16	1	0	0	0	1	1	1	0	0	2
17 -18	3	0	0	0	3	2	0	0	0	2
19 -20	1	2	0	0	3	2	0	1	0	3
21 -22	5	1	0	0	6	1	0	1	0	2
23 -25	0	4	0	0	4	0	2	1	0	3
25.5-27	1	2	0	0	3	0	0	1	0	1
28 -29	0	1	0	0	1	0	0	0	0	0
≥30	2	1	0	0	3	0	0	0	0	0
Total	13	11	0	0	24	6	3	4	0	13
	VSBY >1.6 ≤8 km					VSBY >8 km				
8 - 9	1	1	0	0	2	1	0	0	0	1
10 -11	0	1	0	0	1	1	3	4	4	12
12 -15	0	1	0	2	3	0	3	1	2	6
15.5-16	0	1	3	1	5	1	2	5	5	13
17 -18	4	6	1	3	14	2	3	3	3	11
19 -20	2	4	1	1	8	0	6	4	8	18
21 -22	0	1	0	0	1	0	2	1	0	3
23 -25	0	0	0	0	0	0	0	0	2	2
Total	7	15	5	7	34	5	19	18	24	66

the frequency of various steam fogs and their corresponding water-air temperature differences and saturation deficits. This table illustrates that the denser the fog, the less the saturation deficit and the greater the water-air temperature differential. For light fog (visibility greater than 8 km or 5 mi), no temperature differentials in excess of 19°C (34°F) and saturation deficits less than 0.25 g/kg were observed. Only 5 of the 14 cases with temperature differentials in excess of 19°C (34°F) and saturation deficits of 0.25 g/kg or less were observed to have visibilities greater than 0.4 km (0.25 mi). None of the 5 events had visibilities in excess of 3.2 km (2 mi). Over 60% of all the days with temperature differentials in excess of 19°C (34°F) and saturation deficits of 0.25 g/kg or less were observed to have visibilities of 0.4 km (0.25 mi) or less. No dense steam fogs were initiated over the lake with a saturation deficit greater than 0.25 g/kg, unless the water-air temperature differential was greater than 19°C (34°F). Only one steam fog with a visibility of 1.6 km (1 mi) or less was initiated with water-air temperature differentials of less than 19°C (34°F) and a saturation deficit greater than 0.25 g/kg. For those steam fogs which were initiated with saturation deficits in excess of 0.75 g/kg, only 20% of the events had visibilities of 8 km (5 mi) or less, and only 10% had visibilities of less than 5 km. Overall, the combination of water-air temperature differences and saturation deficits appears to be an excellent indicator of the intensity of steam fog.

Summarizing the analyses of temperature and humidity parameters, it is concluded that the combination of water-air temperature differences and saturation deficits provides the best indicator of steam fog intensity. Both parameters have a strong influence on the frequency and intensity of steam fog. There appears to be an especially strong relation between saturation deficit and steam fog intensity. No significant relation was found between air temperature and steam fog frequency or intensity. With regard to water-air temperature differences, steam fog generally occurred most frequently with differences of 18 to 19°C (33 to 34°F). Initiation over the lake was not observed until the water-air temperature differences reached at least 6 to 7°C (11 to 13°F). Enhancement occurred most frequently with differences of about 14°C (25°F). The differences tended to be smaller on enhancement days than on initiation days.

Downwind Movement of Steam Fog

When steam fog initiated or enhanced over the cooling lake remains confined to the lake boundaries, there will be a minimal impact upon vehicular traffic nearby, especially if no roads are built over or immediately adjacent to the cooling lake. However, if the steam fog moves off the lake it can reduce the visibility over nearby roads significantly. Thus, horizontal extent becomes an important factor in evaluating the atmospheric effects of steam fog.

The horizontal extent of cooling lake fogs on initiation days was determined by recording the downwind extent of the visible fog plume. It was more difficult to measure the horizontal extent on enhancement days, but was done using visibility observations. It was assumed that steam fog would decrease the visibility of natural fog; such a phenomenon was observed over the cooling lake. Thus, the downwind distance of decreased visibilities from the cooling lake was used to define the horizontal extent of steam fogs on days with natural fog.

From September 1976 to March 1978, only 38% (71 of 185) of the fogs were observed to move 6 m (20 ft) beyond the confines of the cooling lake (Table 2-15), and only 17 events, or less than 10% of all steam fogs, were observed to travel farther than 0.2 km (0.1 mi). Thus, most steam fog events remained over or within 0.2 km of the cooling lake.

As shown by Table 2-15 of those fogs which moved beyond the confines of the lake, 48 occured on initiation days, and 23 were associated with enhancement. On both enhancement and initiation days the downwind extent of the steam fog was observed to travel more than 0.2 km (0.1 mi) only when the lowest visibility due to steam fog or the enhancement of steam fog was less than 1.6 km (1 mi). Only three fog plumes were observed 1.6 km or more downwind, and they occurred on initiation days. On enhancement days no visibility reductions due to steam fog were noted beyond 0.8 km (0.5 mi). However, it is possible that steam fog on enhancement days could reduce the visibility farther downwind given the right conditions. The relation between the intensity of steam fog and the horizontal extent is quite strong. Of the 24 steam fog events which initiated over the cooling lake with a visibility of 0.4 km (0.25 mi) or less, 22 experienced some horizontal movement. Similarly, 13 of the 21 dense fogs with enhancement experienced some horizontal movement from the lake when the visibility was 0.4 km or less.

The visibilities in the downwind plume of the steam fog tended to rapidly approach the visibility within the natural fog or the visibility of the ambient atmosphere. Two exceptions occurred during October 1977, when dense steam fog formed with light winds (less than 3 km/h) from the west and the steam fog traveled 3.2 km (2 mi) and 6.5 km (4 mi) downwind along dry creek beds with much reduced visibilities.

Stratification of days with horizontal extent (movement off the lake) by synoptic type showed that over 90% (44 of 48) of the initiation days were cold air mass days compared to 75% for all initiation fogs. The distribution of synoptic types on enhancement days with horizontal extent was similar to the overall distribution for enhancement fogs.

The variation in the frequency of wind directions associated with fogs with horizontal extent is shown in Table 2-16. On initiation days, 60% of all events were associated with winds from the west through north-northwest, compared to less than 45% on all initiation days. On days with enhancement, 12 events had winds from the west. Thus, on days with horizontal extent at Baldwin winds from the west dominated.

It would appear that the horizontal movement of steam fog from the cooling lake into adjacent regions is highly dependent upon wind direction and the location of the warmest water in the lake. The maximum intensity of the steam fog is situated over the warmest water, so that there is a greater chance for this fog to move beyond the lake boundaries. Conversely, when steam fog is advected over the cooler part of the lake, the intensity of the fog diminishes. By the time it reaches the cooler side of the lake, there is little or no fog which can be advected from the lake. Air which travels from the cooler part of the lake to the warmer part entrains increased amounts of moisture and fog; as a result, fog intensity increases as it advects over the lake. Conversely, air which is advected from the warmer part of the lake to the cooler part of the lake will be continually entraining drier air, and the intensity of the steam fog will become less severe.

No apparent relation existed between the wind speeds and the horizontal movement of steam fog. The speeds varied from near calm to greater than 65 km/h (40 mi/h). Fogs with horizontal extent greater than 0.2 km (0.1 mi) were all associated with dense steam fogs, in which the water-air temperature differences are relatively large and saturation deficits are relatively small.

Most steam fogs were confined to the cooling lake during the Baldwin study. Less than 40% of all steam fogs moved more than 6 m (20 ft) off the lake. Of these, less than 10% moved more than 0.2 km (0.1 mi), and less than 2% had horizontal extent exceeding 1.6 km (1 mi). Of the 38% that exhibited some movement, approximately 2/3 were initiation fogs. Only moderate to dense fogs (visibility less than 1.6 km or 1 mi) ever moved more than 0.2 km (0.1 mi) off the lake before dissipating.

Table 2-15

FREQUENCY OF BALDWIN COOLING LAKE FOGS WITH HORIZONTAL EXTENT

	Initiation Days					Enhancement Days				
	Horizontal Extent (km)									
Visibility (km)	≤0.2	>0.2 ≤0.8	>0.8 ≤1.6	>1.6	Total	≤0.2	>0.2 ≤0.8	>0.8 ≤1.6	>1.6	Total
≤0.4	11	6	2	3	22	10	3	0	0	13
>0.4≤1.6	4	2	0	0	6	8	1	0	0	9
>1.6≤8.0	8	0	0	0	8	1	0	0	0	1
>8	12	0	0	0	12	0	0	0	0	0
Total	35	8	2	3	48	19	4	0	0	23

Table 2-16

FREQUENCY OF WIND DIRECTION FOR FOGS WITH HORIZONTAL EXTENT AT BALDWIN

	N-NNE	NE-ENE	E-ESE	SE-SSE	S-SSW	SW-WSW	W-WNW	NW-NNW	CALM
Initiation Days	3	2	0	4	6	3	9	20	1
Enhancement Days	2	3	3	3	2	3	0	7	0

Fogs that drifted downwind occurred most often with westerly winds which advected the fog across the warmer portions of the lake. The extent of horizontal movement is strongly dependent upon the wind direction and location of the warmest water in the lake.

Fog Enhancement

The amount of enhancement of natural fog by steam fog varied not only according to the temperature and saturation deficit, but also with the visibility of the natural fog. Table 2-17 shows the visibility within the natural fog and visibility of the natural fog plus steam fog. On enhancement days the greatest visibility observed within the steam fog region was 4.8 km (3 mi). Seven of the 21 dense enhancement fogs had natural-fog visibilities of less than 0.4 km (0.25 mi). Of the remaining 14 days, 12 had natural visibilities of 1.6 km (1 mi) or less. On all days with natural visibilities of 0.8 km (0.5 mi) or less, the steam fog acted to decrease the visibility to 0.4 km or less. Generally, the greater the visibility in the natural fog, the greater the visibility in the regions enhanced by steam fog.

Table 2-17

INTENSITY OF NATURAL FOG AND ENHANCED FOGS AT BALDWIN

Natural Fog Visibilities (km)	Enhancement Visibilities (km)				
	≤0.4	>0.4≤0.8	>0.8≤1.6	>1.6≤5	Total
≤0.4	7	0	0	0	7
>0.4≤0.8	3	0	0	0	3
>0.8≤1.6	9	4	1	0	14
>1.6≤5.0	2	6	8	8	24
Total	21	10	9	8	48

The water-air temperature differential and the saturation deficit for various enhancement fog intensities (Table 2-18) show that the more intense enhancement fogs occurred with saturation deficits of 0.25 g/kg or less. Relatively small saturation deficits and some of the higher water-air temperature differences were associated with the more intense steam fogs, whereas the less intense enhancement events had larger saturation deficits, lower water-air temperature differences, and greater natural visibilities. Most water-air temperature differences and saturation deficits observed on enhancement days were similar to those observed on initiation days with visibilities of 1.6 km (1 mi) or greater. Apparently, the intensity of the steam fog alone on enhancement days was similar to that of initiation days, but when combined with the natural fog, the total visibility can be lowered by more than 1 km (0.6 mi). The greatest enhancement effect by steam fog occurred when the natural fog visibility was less than 1.6 km (1 mi).

Table 2-18

FREQUENCY OF WATER-AIR TEMPERATURE DIFFERENCES AND SATURATION DEFICITS FOR BALDWIN ENHANCEMENT FOGS

Water-Air Temperature Difference (°C)	Saturation Deficits (g/kg)			
	≤.25	>.25≤.5	>.5	Total
	Visibility ≤0.4 km			
6 - 8	3	0	0	3
8 -10	1	0	0	1
10 -12	1	2	1	4
12 -12.5	4	1	0	5
15.5-17	3	0	1	4
17 -19	4	0	1	5
Total	16	3	3	22
	Visibility >0.4≤1.6 km			
6 - 8	0	0	0	0
8 -10	0	0	1	1
10 -12	1	1	2	4
12 -15.5	0	1	2	3
15.5-17	1	1	5	7
17 -19	0	1	3	4
Total	2	4	13	19
	Visibility >1.6 km			
2 - 4	0	1	0	1
4 - 6	0	0	0	0
6 - 8	0	1	1	2
8 -10	1	0	0	1
10 -12	0	0	0	0
12 -15.5	1	0	2	3
15.5-17	0	0	0	0
17 -19	0	0	1	1
Total	2	2	4	8

DRESDEN COOLING LAKE

The steam fog observations over the Dresden cooling lake were described in qualitative terms, such as very light, light, moderate, and heavy to describe the fog intensity over the cooling lake, rather than visibility measurements as done at Baldwin cooling lake. Supplementary information regarding the use of these qualitative terms was obtained from the primary field observer (Nickels, private communication, 1976). He indicated that very light fog was characterized by wisps or small patches over the cooling lake, with no visibility restriction and only a small amount of vertical extent. With light fog conditions over the cooling lake, the visibility was 1.6 km (1 mi) or greater and the fog had a vertical extent of 3 to 9 m (10 to 30 ft). The visibility in moderate fog ranged from 0.4 to 1.6 km (0.25 to 1 mi) and the fog extended vertically from 9 to 21 m (30 to 70 ft), while in heavy fog the visibility was less than 0.4 km (0.25 mi) and the fog extended higher than 21 m (70 ft).

Monthly average water temperatures and the minimum and maximum water temperature recorded during each month from the bridge at pond 1 are shown in Figure 2-5. The

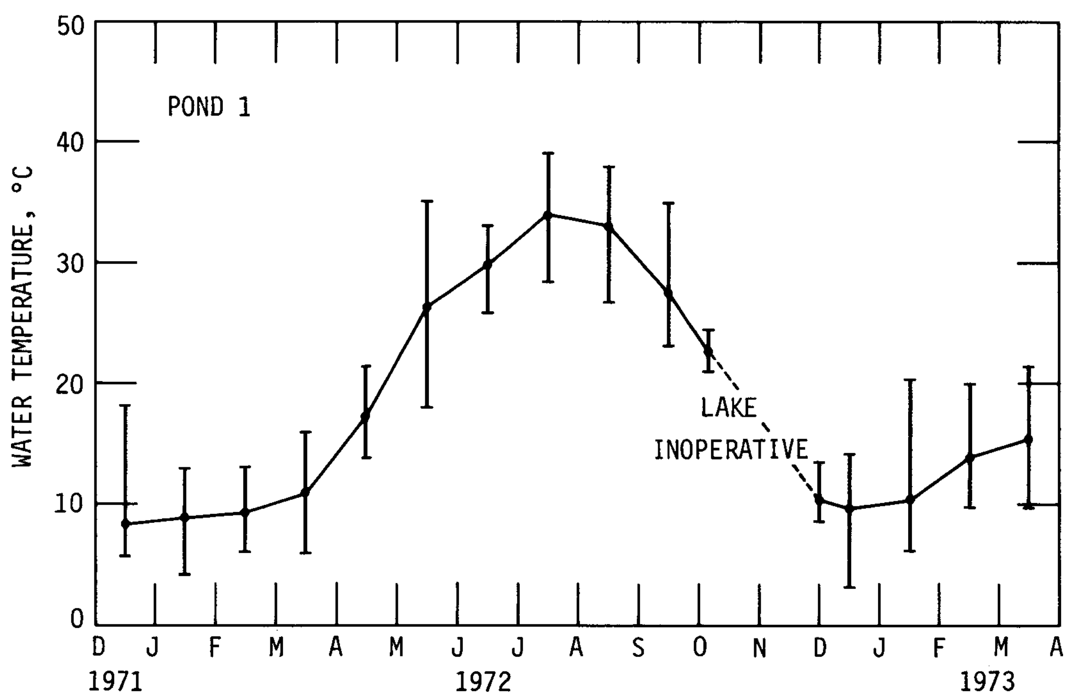

Figure 2-5. Monthly average water temperature and monthly maximum and minimum water temperatures at Dresden

measurements were taken with a temperature probe submerged near the water surface. The annual cycle of water temperatures shows a monthly maximum of 34°C (93°F) during July and a minimum of 8.5°C (47°F) during December 1971. These temperatures are a function of the waste heat input into the cooling lake and of the air temperatures. The water temperatures followed the expected annual curve for the northern hemisphere with summer maximums and winter minimums. From 13 October 1972 to 26 November 1972 the cooling lake was inoperative due to a break in the dike, and there was no water in pond 1. No steam fog or water temperature measurements were made during this period. Consequently, the temperatures shown on Figure 2-5 for these months are for those periods when the cooling lake was operational.

Table 2-19 gives the average monthly and seasonal maximum, minimum, and average temperatures, and the departure from the normal temperature at O'Hare International Airport for the observational periods at Dresden. The coldest month was January 1972 (-6.9°C or 19.6°F), and the warmest was August 1972 (23.2°C or 73.8°F). The largest positive departure from normal was 5.2°C (9.4°F) during March 1973, and the largest negative departure from normal was 2.6°C (4.7°F) in January 1972. Seasonally, the winters of 1971-1972 and 1972-1973 were near-normal winters, with departures from normal of -0.1°C (-0.2°F) and 0.6°C (1.1°F), respectively. The spring of 1972 registered the greatest departure from normal with 1.8°C (3.2°F). Thus, the period from December 1971 to March 1973 was characterized by relatively normal temperatures for northern Illinois.

Temperature and humidity readings were taken by the observer at the bridge over the lake (Figure 1-5). The humidity readings were not always representative of the amount of moisture within the ambient atmosphere. Moisture measurements representative of the air mass in which the steam fog was forming were obtained from a nearby surface hourly reporting station, O'Hare International Airport (Figure 1-4). On several occasions it was necessary to use the measurements at Dresden because the readings at O'Hare were not representative of the air mass in which the steam fog was forming.

Frequency of Steam Fog Events

From December 1971 to March 1973 a total of 236 steam fogs were recorded over pond 1 at the Dresden cooling lake. Thus, some steam fog was observed on 49% of all days over the cooling lake. These observations were made over the warmest

Table 2-19

AVERAGE TEMPERATURES BY MONTHS AND SEASONS FOR O'HARE (°C)

Month	Maximum	Minimum	Temperature	Departure from Normal
December 1971	5.0	-2.6	1.2	3.8
January 1972	-2.3	-11.6	-6.9	-2.6
February 1972	-0.1	-9.3	-4.7	-1.4
March 1972	5.6	-3.4	1.1	-0.4
April 1972	12.2	1.9	7.1	4.2
May 1972	22.3	9.8	16.1	1.8
June 1972	24.9	12.5	18.7	-1.3
July 1972	28.1	18.2	23.1	0.5
August 1972	27.8	18.6	23.2	1.4
September 1972	22.1	12.9	17.5	-0.1
October 1972	14.2	5.0	9.6	-2.1
November 1972	5.6	0.7	3.2	-0.2
December 1972	-0.6	-8.4	-4.5	-1.9
January 1973	1.8	-6.1	-2.1	2.2
February 1973	1.8	-5.5	-1.8	1.4
March 1973	11.0	2.3	6.7	5.2
Season				
Winter 1971-1972	0.9	-7.8	-3.4	-0.1
Spring 1972	13.4	2.8	8.1	1.8
Summer 1972	26.9	16.4	21.7	0.2
Fall 1972	14.0	6.2	10.1	-0.8
Winter 1972-1973	1.0	-6.7	-2.8	0.6
March 1973	11.0	2.3	6.7	5.2

pond, and represent the most intense steam fogs formed over the cooling lake. All steam fogs were recorded at 0800 CST, near the time when such events are expected to maximize (2). The distribution of these steam fog events according to intensity and season is given in Table 2-20.

Very light and light fog intensities occurred most frequently, accounting for over 55% of all events. The next most frequently occurring fog intensity was moderate-to-heavy and heavy fogs which were noted 69 times (29% of all occurrences). Light-to-moderate and moderate fogs occurred the least, only 33 times.

Nearly two to three times more steam fog was observed during winter than any other season. Steam fog was noted over the cooling lake on 60% of all days during the winter of 1971-1972 and on over 90% of all days in the winter of 1972-1973. Natural fog was recorded at O'Hare International Airport at 0800 CST on 12.1% of the steam fog days in the winter of 1971-1972 and on 20% of the days during 1972-1973. Thus, the frequency of fog over the cooling lake was greater than the occurrence of natural fog. In the remaining seasons the number of fogs ranged from 27 to 33 occurrences, or about one-third of the days in spring, summer, and fall. Less than 15% of the steam fogs in spring, summer, and fall had an intensity greater than light, emphasizing that the dominant season for the more intense steam fogs was winter.

Of the 69 moderate-to-heavy and heavy steam fogs, 60 (87%) occurred during the winter. These heavier events constituted nearly 45% of all the steam fogs during the winter. Thus, the primary season of intense steam fogs was winter. The frequency of occurrence of the more intense fogs fell off dramatically after winter, with only one or two occurrences in any other month. No intense steam fogs were observed during June and July 1972. The two intense steam fogs during the summer occurred in middle to late August (16 and 23).

The primary season for light-to-moderate and moderate fogs was winter, with a secondary maximum in fall. These lighter fogs followed closely the annual trend of the more intense fogs. Only two events with this intensity were recorded during spring, and none during summer.

Very light and light steam fogs were prevalent in all seasons but maximized in the winter of 1972-1973 and the summer of 1972. The 31 light or very light fogs

Table 2-20

FREQUENCY OF STEAM FOGS AT DRESDEN

	Very Light	Light	Light to Moderate	Moderate	Moderate to Heavy	Heavy	Total
Winter 1971-1972	7	15	9	4	8	13	56
Spring 1972	9	16	1	1	1	2	30
Summer 1972	17	14	0	0	1	1	33
Fall 1972	11	4	5	3	1	3	27
Winter 1972-1973	17	17	8	1	22	17	82
March 1973	4	3	0	1	0	0	8
Total	65	69	23	10	33	36	236

during the summer of 1972 accounted for 94% of all the fogs during that season. Very light and light steam fogs were recorded in all seasons, but they dominated during the summer. However, such events did not cause any visibility restrictions.

Synoptic Types

The weather typing scheme used at Baldwin and described previously was used to classify steam fogs at Dresden. Table 2-21 gives the frequency of weather types associated with steam fogs. Cold air mass situations occurred most frequently with steam fog over the Dresden cooling lake, accounting for 80% of all steam fog events. The distribution of cold air mass situations varied somewhat with season, but this weather type dominated in all seasons, ranging from 61% of all occurrences in summer to over 85% of all steam fogs in winter. All frontal and low pressure classes combined were associated with 35 steam fogs or less than 15%. Of these 35 events, 28 were embedded in the cold air behind the front or the low pressure area. Thus, 92% of all steam fogs occurred within the cold air sectors. Generally, little variation in the distribution of weather type from one season to another was found.

The distribution of the various weather classifications by steam fog intensity and season is similar to Table 2-3. The cold air mass situation dominated the occurrence of steam fog for all intensities. The only exceptions were warm air mass and occluded front situations which were associated with very light and light steam fog intensities. Usually, both of these weather types were characterized by relatively mild temperatures for the season and only minor variations in temperatures from one air mass to the other. This emphasizes the need for the air over the cooling lake to be much colder than the water temperatures before a steam fog capable of significantly lowering the visibility can be expected.

Wind

Wind information for Dresden was obtained by the observer from the meteorological tower north of the cooling lake. Wind direction to 16 points of the compass was recorded. The frequencies of wind directions observed at Dresden with steam fogs are given in Table 2-22. Considerable scatter of wind directions was observed at Dresden. More than half (55%) of all winds were from the west through east-northeast, 40% of the winds were from the east through west-southwest, and only 5% of the winds were calm. About 50% of the time during a year west through east-northeast winds are experienced in Chicago. Thus, no dominant wind direction was associated with the steam fogs.

Table 2-21

RELATION BETWEEN STEAM FOG FREQUENCY AND WEATHER TYPES AT DRESDEN

	Winter	Spring	Summer	Fall	Total
Cold Air Mass	118	30	20	21	189
Warm Air Mass	2	2	7	1	12
Cold Front	7	2	2	3	14
Warm Front	2	0	2	2	6
Static Front	5	1	2	0	8
Occluded Front	2	0	0	0	2
Low	2	3	0	0	5
Total	138	38	33	27	236

Table 2-22

FREQUENCY OF WINDS AND FOGS AT BALDWIN

	Steam Fog Intensities			
Wind Directions	Moderate to Heavy and Heavy	Light to Moderate and Moderate	Very Light and Light	Total
N-NNE	5	6	20	31
NE-ENE	8	2	13	23
E-ESE	8	5	20	33
SE-SSE	1	1	7	9
S-SSW	7	3	19	29
SW-WSW	5	2	16	23
W-WNW	18	7	15	40
NW-NNW	11	6	19	36
Calm	6	1	5	12
Total	69	33	134	236

Previously it was noted that almost 80% of all the steam fogs were classified as cold air mass situations, indicating that high pressure regions dominated the weather. The wind directions indicate that the center of many of the highs were west of Dresden when the steam fog occurred and there was active cold air advection. Thus, it would appear that steam fog is less likely to form when the cooling lake is west of the center of the high pressure area and is embedded in the warm return air.

Over 40% of all moderate-to-heavy and heavy fogs were associated with winds from the northwest quadrant. These were the only steam fogs which showed any preferred wind direction. Such wind directions are often associated with sudden temperature falls which occur after a cold frontal passage and when a strong anticyclonic circulation dominates the regional weather pattern. Only minor variation of wind direction by seasons was noted, except for spring, when nearly 75% of all steam fogs occurred when winds had a northerly component. Overall, little dependence of steam fog upon wind direction was found, in agreement with earlier steam fog analyses by Church (12).

The wind speeds observed with various steam fog intensities over Dresden cooling lake are shown in Table 2-23. Most steam fogs were associated with wind speeds of less than 16 km/h (10 mi/h). Only 23% of all the steam fogs occurred with wind speeds greater than 16 km/h (10 mi/h). This distribution of wind speeds is similar to the annual climatic distribution of wind speeds at Chicago (15). Little difference in the distribution of wind speed and steam fog between winter and the other seasons was evident. All but one of the steam fogs with wind speed greater than 24 km/h (15 mi/h) were associated with winds which came from the west through north to east-northeast. Thus, a tendency for steam fogs with strong winds (greater than 24 km/h) to be associated with strong cold air advection was noted. No other preferential wind speeds or directions were associated with the occurrence of steam fog.

Temperature and Humidity

To determine if temperature and the intensity of steam fog were related during winter, the season of maximum frequency and intensity, frequency distributions of air temperatures representative of the air mass overlying the Dresden cooling pond were obtained (Table 2-24). The temperatures indicate a tendency for the occurrence of more intense steam fog with colder temperatures. For example, the median

Table 2-23

FREQUENCY OF STEAM FOG AND WIND SPEED AT DRESDEN

Speed (km/h)	Moderate to Heavy and Heavy	Light to Moderate and Moderate	Very Light and Light	Total
		All Seasons		
0- 8	29	14	48	91
9-16	23	13	55	91
17-24	13	1	25	39
>24	4	5	6	15
Total	69	33	134	236
		Winter		
0- 8	25	9	17	51
9-16	21	10	20	51
17-24	11	0	17	28
>24	3	3	2	8
Total	60	22	56	138
		Spring, Summer, and Fall		
0- 8	4	5	31	40
9-16	2	3	35	40
17-24	2	1	8	11
>24	1	2	4	7
Total	9	11	78	98

temperature for very light and light steam fog was -1.7°C (29°F), for light-to-moderate and moderate events -5.6°C (22°F), and for the more intense events -8.9°C (16°F). Many of the more intense steam fogs tended to be associated with colder air temperatures. During winter 75% of all Illinois natural fog forms with air temperatures of -1°C (30°F) or greater (2). Thus, the potential of enhancing natural fog with steam fog is high, especially for moderate or lesser intensity steam fog. Although related to steam fog intensity, air temperature cannot be considered a reliable indicator of the initiation or intensity. This conclusion agrees with measurements made by Church (12) over Lake Michigan in the early 1940's.

Table 2-24

FREQUENCY DISTRIBUTION OF AIR TEMPERATURES (°C) FROM O'HARE ASSOCIATED WITH WINTER DRESDEN STEAM FOGS

Cumulative Percent Equalled or Exceeded	Very Light to Light	Light to Moderate and Moderate	Moderate to Heavy and Heavy
5	-9.4	-17.2	-23.3
10	-7.8	-15.6	-20.6
20	-5.6	-12.2	-16.1
25	-5.0	-11.1	-14.4
30	-4.4	-10.0	-13.3
40	-2.8	-7.2	-10.6
50	-1.7	-5.6	-8.9
60	-0.6	-3.9	-6.7
70	0.6	-2.2	-4.4
75	1.7	-1.1	-2.8
80	2.2	0.0	-1.7
90	4.4	1.7	1.1
95	6.1	2.8	2.8
N	56	22	60

The difference in temperature between the water and air, a measure of the strength of the convection, has been shown by several investigators to influence significantly the formation and intensity of steam fog (2, 12, 13, 14, 16). The frequency distribution of water-air temperature differences associated with steam fogs during the winter and the combined seasons of spring, summer, and fall at the Dresden cooling lake (Table 2-25) indicated that the more intense steam fog events were associated with higher water-air temperature differences in both winter and other seasons. For example, during winter 70% of all moderate-to-heavy and heavy steam fogs were associated with water-air temperature differences of 19.4°C (35°F) or greater, only 45% of the light-to-moderate and moderate events had water-air temperature differences in excess of 19.4°C, and less than 20% of the light and very light fogs had water-air temperature differences in excess of 19.4°C.

Table 2-25

FREQUENCY DISTRIBUTION OF WATER-AIR TEMPERATURE DIFFERENCE (°C) FOR DRESDEN FOGS

Cumulative Percent Equalled or Exceeded	Water-Air Temperature Difference (°C)					
	Moderate to Heavy and Heavy		Light to Moderate and Moderate		Very Light and Light	
	Winter	Spring, Summer & Fall	Winter	Spring, Summer & Fall	Winter	Spring, Summer & Fall
5	34	23	31	24	23	19
10	32.5	22	27	22	21	18
20	30.5	20.5	24	19	19	17
25	29	20	22.5	18	18	17
30	28	19	22	17	17	17
40	27	18	20	15.5	16	16
50	24	18	19	13	15	15
60	22	17	17.5	12	14	14
75	17	15	15	11	12	12
80	15.5	14	14	11	10	11
90	14	13	13	10.5	9	10
95	13	12	12	10	8	8
N	60	9	22	11	56	78

The water-air temperature difference distribution for the other seasons indicates that water-air temperature differences for steam fog over the cooling lake are not nearly as great, though the larger differences are usually associated with the more intense fog events. The frequency of light-to-moderate and more intense fogs was relatively minor during these periods. An examination of these events indicates that many of the more intense events during spring, summer, and fall were associated with natural fog or other weather phenomena, such as rain, drizzle, or sleet. Thus, the initiation and intensity of steam fog without any natural enhancement was dependent upon the magnitude of the water-air temperature difference, especially in winter.

The relation between the initiation of steam fog and water-air temperature differences is further illustrated by Figure 2-6. A primary maximum of water-air

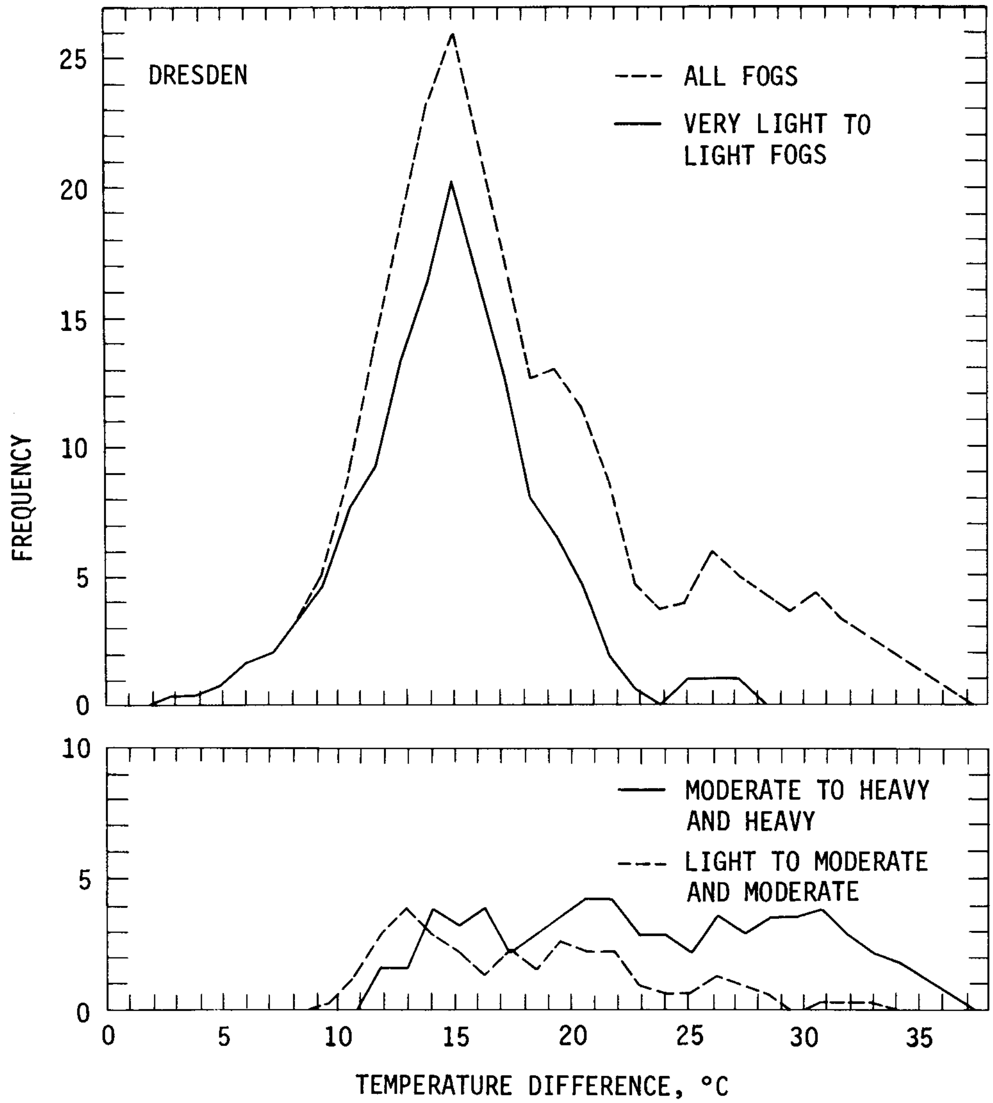

Figure 2-6. Frequency of water-air temperature differences for all steam fogs and various intensities at Dresden

temperature difference from 16 to 17°C (28 to 30°F), and secondary maximums between 19 to 20°C (34 to 36°F) and 26 to 27°C (46 to 48°F) were associated with the occurrence of steam fog at Dresden. Figure 2-6 shows the frequency of water-air temperature difference as a function of steam fog intensity. The very light and light steam fogs account for all steam fogs with a water-air temperature difference of less than 28°C (50°F). The more intense steam fogs account for almost all of those events with water-air temperature differences of 21°C (38°F) or more. Thus, a relation between the initiation and intensity of steam fog is revealed. However, this relation is not as definitive at Dresden as it was at Baldwin, because the observations at Dresden were not sufficiently detailed to differentiate between initiation and enhancement days.

The dependence of the saturation deficit (g/kg) of the air upon the intensity of steam fog is shown by Table 2-26. The saturation deficits given in this table are from O'Hare International Airport; they represent the moisture content of the air mass in which steam fog occurred at Dresden cooling lake. It is acknowledged that some of these moisture deficits will not be completely representative of the moisture deficits at Dresden. However, the moisture values obtained at Dresden often were taken within the steam fog and indicated more moisture than was available within the ambient atmosphere. Earlier work indicated that the moisture values available from the DuPage County Airport, which is closer than O'Hare, were not reliable, especially during winter. Those measurements, taken with a psychrometer, depended on the reliability of the weather observer; if he was in a hurry, an accurate measurement was not made.

Table 2-26

FREQUENCY DISTRIBUTION OF SATURATION DEPRESSIONS (g/kg)
AT O'HARE FOR DRESDEN STEAM FOG EVENTS

Cumulative Percent Equalled or Exceeded	Very Light and Light		Light to Moderate and Moderate		Moderate to Heavy and Heavy	
	Winter	Spring, Summer & Fall	Winter	Spring, Summer & Fall	Winter	Spring, Summer & Fall
5	0.28	0.30	0.16	0.10	0.03	0.17
10	0.36	0.50	0.23	0.25	0.09	0.25
20	0.47	0.80	0.32	0.30	0.16	0.40
25	0.51	1.00	0.36	0.35	0.19	0.45
30	0.55	1.15	0.40	0.50	0.21	0.50
40	0.64	1.85	0.46	0.60	0.27	0.60
50	0.72	2.30	0.53	0.70	0.33	0.70
60	0.80	2.90	0.59	0.75	0.40	0.75
70	0.90	3.25	0.66	0.80	0.48	0.85
75	0.97	3.70	0.70	0.90	0.53	0.90
80	1.03	4.90	0.75	1.10	0.58	0.95
90	1.20	6.00	0.88	1.20	0.74	1.10
95	1.36	7.25	0.98	1.30	0.88	1.25

Saturation deficit represents the difference of water vapor between the amount the air can hold at saturation and the actual amount of water vapor present in the air. This is a direct measure of the amount of water vapor necessary to achieve saturation in the ambient atmosphere. Generally, the more intense steam fogs during winter were associated with the lowest saturation deficits. For example, over 70% of the moderate-to-heavy and heavy steam fogs had saturation deficits of 0.5 g/kg or less and less than 25% of the very light and light events had similar saturation deficits. Only one steam fog of moderate-to-heavy or greater intensity occurred with a saturation deficit greater than 1 g/kg, and it is possible that this value was erroneously high.

Higher saturation deficits were associated with steam fogs in seasons other than winter. These differences reflect the change of the amount of water vapor air can hold at higher temperatures. For example, the saturation deficit is 0.64 g/kg with a 2.5°C (4.5°F) dew-point departure at 0°C (32°F), while the same dew point departure at 21°C (69.8°F) gives a saturation deficit of 2.23 g/kg. Thus, less water vapor is needed to achieve condensation in winter than in summer for the same dew point departure.

Downwind Movement of Steam Fog

The summary report of Murray and Trettel (3) indicated that most steam fog over Dresden cooling lake from January 1972 to February 1973 remained within the confines of the cooling lake. On 22 occasions steam fog ranged beyond the lake boundaries from 30 m (100 ft) to 2.4 km (1.5 mi). Most of the fog observed dissipated before it extended more than 1.6 km (1 mi). On the two days that the steam fog extended 2.4 km downwind, natural ground fog was observed near the cooling lake.

In only one case did the steam fog extend beyond the lake in a season other than winter. The one exception occurred in late November. However, the cooling lake was not operational during most of October and November of 1972, and it is probable, considering results from the Baldwin observational program, that other steam fogs would have moved beyond the confines of the lake during fall.

The water-air temperature differences for all these cases were in excess of 16.7°C (30°F), and 16 of the 22 cases had water-air temperature differences of 22°C (40°F) or greater. Heavy steam fog intensities were observed in 17 cases, and only two of these cases had water-air temperature differences of less than 22°C (40°F).

The dominant surface wind direction associated with the downwind movement of steam fog was from the southeast (18 of 22 cases). Only in five instances were the wind speeds in excess of 16 km/h (10 mi/h). In those cases, where adequate visibility data are available, the steam fog was observed to dissipate rapidly or to have no effect upon visibility downwind of the lake. On only one occasion were the winds calm, and 10 of the wind speeds ranged from 10 to 16 km/h (6 to 10 mi/h).

Thus, steam fogs which moved beyond the lake were associated with the more intense events and with water-air temperature differences of 16.7°C (30°F) or greater. Generally, the winds at Dresden were from the southeast. In most cases, the downwind extent of the steam fog was less than 1.6 km (1 mi), and dissipated rapidly with distance.

SUMMARY AND CONCLUSIONS

Steam fog observations were made at Baldwin cooling lake in southwestern Illinois from September 1976 to March 1978 and at Dresden cooling lake in northeastern Illinois from December 1971 to March 1973. During these periods steam fog occurred on 49% of all days at Dresden and on 40% of all days at Baldwin. All intensities were most frequent during winter, with a secondary maximum during fall and minimums during spring and summer. The data at Baldwin were stratified also by initiation and enhancement days. These data show that only 25% of all steam fog events at Baldwin were accompanied by natural fog, that is, most steam fogs were strictly lake phenomena.

Enhancement days at Baldwin showed an erratic temporal pattern during the sampling period. The greatest number occurred during summer. However, in Illinois the enhancement of natural fog by steam fog maximizes most frequently during winter and fall, when the greatest number of natural fogs normally occurs. The enhancement effect will vary from year to year, depending on the occurrences of natural fog and concomitant temperatures sufficiently cold to maintain the high water-air temperature difference needed to generate steam fog.

Dense steam fog (visibility of 0.4 km, or 0.25 mi, or less) was observed most often during winter. At Dresden 60 of 69 moderate-to-heavy or heavy fogs and at Baldwin 60% of all dense steam fogs occurred during winter. Furthermore, at Baldwin 80% of the dense initiation fogs (lake induced) occurred during winter and none in summer. Dense enhancement fogs maximized during winter also. Most dense cooling lake fogs in other seasons were associated with natural fogs rather than lake initiations.

Cold air mass weather patterns dominated the occurrence of all intensities of steam fog, accounting for 67% of all Baldwin occurrences and 80% of all Dresden events. Over 80% of the Baldwin and 92% of the Dresden steam fogs were embedded within cold air at the surface. On steam fog enhancement days frontal and low pressure activity were more frequent, as was expected since natural fog is often associated with these weather types. Almost 50% of all enhancement steam fogs were associated with cold air mass patterns.

Overall, no significant relation between wind direction and steam fogs was noted. The most frequent wind direction at both Dresden and Baldwin was west through north-northwest. At Baldwin, winds from an easterly direction were most often associated with enhancement fogs, which is similar to the distribution of wind directions associated with natural fogs. Most steam fogs at Dresden and Baldwin occurred with speeds of 16 km/h (10 mi/h) or less. Only initiation steam fogs at Baldwin occurred with speeds in excess of 24 km/h (15 mi/h). These occurrences were associated with winds from west through north to northeast, indicative of strong cold air advection. On Baldwin enhancement days, the wind speeds were similar to the long-term climatic average of natural fog events.

Relatively cold air temperatures were associated with the occurrence of many dense steam fogs, but little dependence between temperature and fog intensity was noted. More than 50% of the light steam fogs had temperatures as cold as the more intense events at both Dresden and Baldwin. A better indicator of the intensity of steam fog is the magnitude of the water-air temperature difference and the ambient saturation deficit. Steam fog intensity tends to vary directly with water-air temperature difference and inversely with saturation deficit.

Most dense initiation steam fogs at Baldwin (visibility 0.4 km, or 0.25 mi, or less) had water-air temperature differences of 19°C (34°F) or greater and saturation deficits of 0.5 g/kg or less. Initiation fogs were not observed over the cooling lake until the water-air temperature difference was at least 6 to 7°C (11 to 13°F). Water-air temperature differences in enhancement fogs of equivalent intensity were less. On enhancement days the steam fog intensity was similar to that on initiation days, but when steam fog combined with natural fog, the ambient visibility was lowered by as much as 1 km (0.6 mi).

Downwind movement of steam fog farther than 6 m (20 ft) was observed in only 71 of 185 events (38%) at Baldwin. At Dresden, only 22 steam fogs were observed to move more than 30 m (100 ft) beyond the confines of the lake. Significant downwind extent was observed in all seasons at Baldwin, but occurrences were most frequent in winter and fall. Primarily, winter occurrences were noted at Dresden. Data from both observation sites indicated that most fogs with a horizontal extent of 0.2 km (0.1 mi) or greater were associated with steam fog visibilities of 1.6 km (1 mi) or less. Of those with some horizontal extent at Baldwin, less than 10% extended more than 0.2 km (0.1 mi), and fewer than 2% had horizontal extents greater than 1.6 km (1 mi). Over 67% of all fogs with some horizontal extent were initiation fogs. In all but two events at Baldwin, the visibility in steam fogs with horizontal extent rapidly approached the prevailing visibility as the fog mixed with the ambient air.

At Baldwin northwest winds were most often associated with horizontal movement from the lake, whereas at Dresden over 80% of the fogs with horizontal movement had winds from the southeast. The extent and frequency of horizontal movement was strongly linked with wind direction and the location of the warmest lake water. At Baldwin the warmest water was on the east side of the lake, whereas at Dresden the northwest part of the lake was warmest. Steam fog intensity increased as it moved from the colder to the warmer part of the lake by entrainment of more moisture-laden air, whereas air advected from the warmer to the cooler part of the lake entrained drier air, and the fog intensity did not continue to increase. Thus, a greater potential for more intense fog and for fog to move off the lake existed if the over-lake trajectory of air was from the cooler to warmer side of the lake.

Overall, the occurrence of steam fog at cooling lakes presents only minor problems. Most steam fogs at Baldwin and Dresden were confined to within 1.6 km (1 mi) of the lake. Only with winds of less than 2 km/h (1.5 mi/h) and with very stable conditions did steam fog with appreciably lowered visibilities travel more than 1.6 km (1 mi). On two occasions when this was observed, the steam fog drifted downwind along an old creek bed. Cooling lakes with water-air temperature differences similar to those reported at Dresden and Baldwin and within a similar climatic regime can be located within 2 to 3 km (1.25 to 2.0 mi) of major highways, airports, or other centers of activity adversely affected by fog without appreciable interference in normal activities. If the water temperatures of a cooling lake are greater than those at Baldwin and Dresden, it is possible that the horizontal extent of steam fog will be greater than observed in Illinois. However, it is concluded that the horizontal movement of most steam fogs will be less than 3 km (2 mi) providing no unusual topographic features, such as major valleys, are present. This conclusion applies to the Midwest and other regions with a similar climate.

Results of this study can be used in conjunction with hourly weather data from a nearby weather station (climatically similar to the proposed site) and water-air temperatures estimated from preliminary engineering studies to calculate the expected frequency of occurrence and intensity distributions of steam fog at proposed cooling lake installations. For example, dense steam fog (visibilities of 0.4 km, or 0.25 mi, or less) can be determined from the frequency of days and hours with water-air temperature differences of 19°C (34°F) or greater and saturation deficits of less than 0.5 g/kg. This will provide a conservative estimate of the frequency distribution of dense steam fog initiations. The frequency distribution of the initiation of moderate steam fog (visibilities between 0.4 and 1.6 km or 0.25 and 1 mi) can be estimated by determining how often water-air temperature differences are between 15.5 and 19°C (28 and 34°F) and saturation deficits are 0.5 g/kg or less. The occurrence of light steam fog (visibility greater than 1.6 km) can be determined by water-air temperature differences greater than 8°C (14°F) and saturation deficits between 0.5 and 1 g/kg. When natural fog is occurring and the water-air temperature difference is greater than 6°C (11°F), the over-lake visibility can be estimated by lowering the natural fog visibility by 1 km (0.6 mi), or to zero if the natural fog visibility is already 1 km (0.6 mi) or less. This will provide a conservative estimate of the intensity distribution on enhancement days. The above method will generate estimates of both frequency and intensity of steam fog over a cooling lake.

These computations can then be used in conjunction with the results summarized in Table 2-27 to obtain estimates of the frequency distribution of the downwind extent of cooling lake fogs at the proposed site. The technique outlined above should provide satisfactory estimates for evaluation of the problems associated with lake-induced steam fogs at proposed power plant sites in much of the Midwest and other regions with similar climate and topography.

Table 2-27

PERCENTAGE DISTRIBUTION OF HORIZONTAL EXTENT OF BALDWIN COOLING LAKE FOGS

	Horizontal Extent (km)							
	Initiation Days					Enhancement Days		
Visibility (km)	≤0.006	>0.006 ≤0.2	>0.2 ≤0.8	>0.8 ≤1.6	>1.6	≤0.006	>0.006 ≤0.2	>0.2 ≤0.8
	Percent of Events							
≤0.4	8.3	45.9	25.0	8.3	12.5	38.1	47.6	14.3
>0.4≤1.6	53.8	30.8	15.4	0	0	52.6	42.1	5.3
>1.6≤8.0	76.5	23.5	0	0	0	87.5	12.5	0
>8.0	81.8	18.2	0	0	0	0	0	0

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Section 3

ICING

INTRODUCTION

During the colder part of the year, when steam fog forms and moves away from the lake, ice may coat structures and vegetation. The icing can take two forms, glaze or rime. According to the Glossary of Meteorology (1), glaze is "a coating of ice, generally clear and smooth but usually containing some air pockets, formed on exposed objects by the freezing of a film of supercooled water deposited by rain, drizzle, fog, or possibly condensed from supercooled water vapor." Such icing is formed by large water droplets, has a density of 0.8 to 0.9 g/cm^3, and occurs with the air temperature between -7^{o}C (19^{o}F) to -1^{o}C (30^{o}F). Glaze forms a hard, continuous sheet and can cause structural damage if the accumulation is great enough. Rime is defined in reference (1) as "a white or milky and opaque granular deposit of ice formed by the rapid freezing of supercooled water drops as they impinge upon an exposed object." Rime is favored by the formation of small water droplets, has a density between 0.3 to 0.8 g/cm^3, and usually occurs when the air temperature is less than -7^{o}C (19^{o}F). Rime icing is friable (easily crumbled), poses little or no problems to vegetation or structures, and is less dense than glaze.

The average diameter of droplets formed by steam fog was determined to be 7.5 to 15 microns at the Four Corners power plant in New Mexico(2). Such droplets are considerably smaller than drizzle drops, the smallest precipitation-sized drop. Thus, rime rather than glaze icing can be expected to occur around a cooling lake.

BALDWIN COOLING LAKE

Icing observations at Baldwin Lake were made by the observer with the same routine used for steam fog observations. Generally, observations were made in the first few hours after sunrise and were continued until the icing stopped or darkness approached. Vegetation, visibility posts, instrumentation, and a trailer situated at site 14 (Figure 1-2) were used to estimate the accumulation of rime. The horizontal extent of the icing was estimated by the observer. The primary periods for such observations were the winters of 1976-1977 and 1977-1978.

Frequency of Icing and Synoptic Types

During the observational period at Baldwin, 33 icing events were noted. The earliest date was 26 November and the latest was 4 March. Thus, icing is primarily a winter phenomenon. Only one icing observation was made on a day with natural fog. That is, icing was almost exclusively restricted to initiation days. However, only 45% of all winter initiation days had icing associated with them. In only 20 of the 33 events was icing occurring at the time of the observation, and only those observations will be discussed. Because the sun was usually shining after the other 13 events, any icing deposition could have been partially dissipated and not be representative. In addition, since the exact timing of the icing is unknown, the weather observations at the time of these observations may not be truly representative of the condition during which rime formed. In only two events where icing was not actively occurring was an accumulation of 0.65 cm (0.25 in) or greater observed.

Rime accumulations in excess of 2.5 cm (1 in) were observed twice, and the greatest accumulation was 7.6 cm (3 in). Most icing events (65%) had accumulations between 1.3 and 2.5 cm (0.5 to 1 in) and were confined to within 100 m (300 ft) of the cooling lake (Table 3-1). Only two events were observed to extend more than 200 m (0.1 mi). During each of the two winter periods, about 1.2 cm (0.5 in) of icing accumulated on the east berm road immediately adjacent to the cooling lake. The largest rime depositions were observed to occur adjacent to the cooling lake, and the accumulation decreased rapidly with distance from the lake.

Table 3-1

FREQUENCY OF BALDWIN RIME ICE ACCUMULATION AND HORIZONTAL EXTENT

Horizontal Extent (m)	Accumulation (cm)				
	<.65	.65-1.2	1.3-2.5	>2.5	Total
<15	0	2	4	0	6
15-100	1	1	6	0	8
101-200	0	1	2	1	4
>200	0	0	1	1	2
Total	1	4	13	2	20

All but one of the 33 events were synoptically classed as cold air mass weather types. The sole exception was classed as a cold front that passed Baldwin 24 hours prior to the icing incident. Thus, Baldwin was essentially embedded in the cold air during all icing events.

Wind

Before rime can form, steam fog must be blown beyond the confines of the cooling lake. The horizontal extent of rime icing depends upon wind speed and the horizontal extent of the steam fog. The frequency of wind speeds and icing is given in Table 3-2. Wind speeds from calm to greater than 24 km/h (15 mi/h) were noted. The horizontal extent of all events with winds of 5 km/h (3 mi/h) or less did not exceed 15 m (50 ft). Half of the icing events had wind speeds of 6 to 15 km/h (4 to 9 mi/h). No apparent relation between wind speed and the horizontal extent of the rime existed, nor was there a significant relation between the horizontal wind speed and the icing accumulation.

Table 3-2

FREQUENCY OF WIND SPEED AND HORIZONTAL EXTENT OF ICING AT BALDWIN

Horizontal Extent (m)	Wind Speed (km/h)				
	0-5	6-15	16-24	>24	Total
<15	3	2	1	0	6
15-100	0	5	1	2	8
101-200	0	1	1	2	4
>200	0	2	0	0	2
Total	3	10	3	4	20

Most of the icing events (65%) were associated with winds from the west-southwest through northwest (Table 3-3). Of the five riming events with horizontal extent greater than 150 m (500 ft), two were associated with winds from the north-northwest to northeast. Only three icing occurrences were observed with winds from an east or south component. Thus, most icing was associated with active cold air advection.

Most of the area around the lake is typified by relatively flat land. The region immediately south of the cooling lake is about the same elevation as the lake

Table 3-3

FREQUENCY OF WIND DIRECTION AND HORIZONTAL EXTENT OF ICING AT BALDWIN

Horizontal Extent (m)	Wind Direction					
	NNW-NE	ENE-SE	SSE-SW	WSW-NW	Calm	Total
<15	0	0	1	4	1	6
15-100	1	1	1	5	0	8
101-200	1	0	0	3	0	4
>200	1	0	0	1	0	2
Total	3	1	2	13	1	20

itself, but the region east of the lake is 3 to 6 m (10 to 20 ft) below the top of the dike. Thus, steam fog advected south (north-northwest to northeast winds) flowed directly from the lake, and would be deposited as rime directly on surface vegetation. Steam fog which moved eastward was elevated to a certain extent; although it restricted visibility at eye level, surface vegetation and other features were not readily coated with rime because of the increased mixing with the ambient atmosphere. All three icing events with north-northwest to northeast winds extended at least 60 m (200 ft) inland, whereas only 3 of the 13 events with winds from the west-southwest to northwest had similar horizontal extents. The wind speeds and other meteorological parameters for these icings were similar. Thus, it appears that minor differences in terrain immediately around the lake influenced the horizontal extent of icing at Baldwin.

Temperature and Humidity

The air temperature is critical to the formation of rime on surfaces (1-4). All Baldwin icing events were observed to occur with air temperatures of -7°C (19°F) or below (Table 3-4). Most riming (85%) was observed with temperatures below -10°C (14°F), and the heavier accumulations were associated with the colder temperatures.

Table 3-5 presents the frequency of rime with the associated saturation deficits and water-air temperature differences. All but one of the icing events had water-

Table 3-4

FREQUENCY OF OCCURRENCE OF RIME ICING AND TEMPERATURE

Air Temperature (°C)	Accumulation (cm) <.65	.65-1.2	1.3-2.5	>2.5	Total
-19 to -15	0	2	4	1	7
-14 to -10	0	1	8	1	10
-9 to -7	1	1	1	0	3
Total	1	4	13	2	20

Table 3-5

FREQUENCY OF RIME ICING AND WATER-AIR TEMPERATURE DIFFERENCE AND SATURATION DEFICIT

Water-Air Temperature Difference (°C)	Saturation Deficit (g/kg) ≤.25	.26-.50	.51-.75	Total
15-19	1	0	0	1
20-24	4	5	1	10
25-29	1	3	2	6
≥30	1	2	0	3
Total	7	10	3	20

air temperature differences in excess of 19°C (34°F), and 17 of the 20 events had saturation deficits of 0.5 g/kg or less. This distribution suggests that icing is associated with dense steam fog events. Indeed, all but three of the active icing events were associated with dense steam fog events, and all occurred with visibilities of 1.6 km (1 mi) or less. During the winters of 1976-1977 and 1977-1978, 25 initiation fogs with visibilities of 1.6 km or less were observed; 16 or 64% of these were associated with icing. Of the nine remaining events, five exhibited no horizontal movement off the cooling lake and no rime was deposited. Two had winds of less than 5 km/h (3 mi/h), and the remaining two had temperatures near the -7°C (19°F) cutoff. Thus, the Baldwin study indicates that there is a potential for icing in any steam fog with a visibility of less than 1.6 km (1 mi) and an air temperature of -7°C (19°F) or less. Although three rimes had wind speeds of less than 4 km/h (2.5 mi/h), analyses indicate some air movement is necessary for the deposition of rime.

OTHER ICING MEASUREMENTS

Other icing observations have been made by Murray and Trettel, Inc. (5) and Currier et al. (2, 3) in Illinois and at the Four Corners power plant in New Mexico. Observations over two winter periods (1971-1972 and 1972-1973) at Dresden cooling lake by Murray and Trettel showed only 12 rime icing observations having horizontal extents of 30 m (100 ft) or greater, and only three were detected at 60 m (200 ft) or more from the lake. Only two of the rime icing events had accumulations in excess of 2.5 cm (1 in). Most occurrences were east of the cooling lake, which indicates that the winds were from the west for most icing events at Dresden.

Many other rime events with accumulations of up to 10 cm (4 in) were noted on the bridge which bisects the cooling lake just east of the warmest section. All icing events were observed during winter. No glaze icing due to steam fog was observed at Dresden.

Currier et al. (2, 3) made several observations of icing near Coffeen cooling lake in west central Illinois and at Four Corners cooling lake near Fruitland, New Mexico. Little or no horizontal extent was noted. They obtained some measurements of the accretion rate of rime, and, in general, they determined that the colder the ambient air temperatures, the more rapid the ice accumulation. All icing situations at Coffeen and Four Corners occurred with air temperature of -5.5^{o}C (21^{o}F) or less, water-air temperature differences of 22^{o}C (40^{o}F) or more, and saturation deficits of 0.6 g/km or less.

Other rime icing observations were reported at Dresden cooling lake during the winter of 1976-1977 (6). The general operation of Dresden cooling lake and spray canals changed from supplementary cooling in 1973 to a closed water system in the winter of 1976-1977. Previously, the water in the cooling lake was pumped from the Kankakee River and released into the Illinois River after cooling. At the present time, only make-up water is added from the Kankakee River and the water is continuously cycled. As a result, water temperatures during the winter of 1976-1977 seldom dipped below 20 to 25^{o}C (68 to 77^{o}F) (6). These water temperatures were at least 10 to 15^{o}C (18 to 27^{o}F) warmer than the winters of 1971-1972 and 1972-1973. During these two winters the average temperature at O'Hare Airport, 75 km (47 mi) north, was -3.4 and -2.8^{o}C (25.8 and 26.9^{o}F), respectively. During the winter of 1976-1977 the average air temperature at O'Hare Airport was -7.2^{o}C (19^{o}F), at least 3.8^{o}C (6.8^{o}F) cooler than the two earlier winters which were near normal. These cooler temperatures coupled with the warmer water temperatures should have produced more dense steam fog than in the earlier years. The dramatic rime ice accumulations, observed in 1976-1977 by Shannon and Everett (6) on instrument shelters and on instrumentation located on a raft in the center of pond 1 (Figure 1-4), were produced by the extreme differences in water and air temperatures. Such icing accumulations were not observed at Dresden or Baldwin cooling lakes during the four winter observational periods reported here. The horizontal extent of icing with the 1976-1977 extreme water-air temperature differences should be greater than those reported either at Dresden earlier or at Baldwin. However, no measurements were reported of the horizontal extent and accumulation of these riming events.

SUMMARY AND CONCLUSIONS

Only rime icing was observed during each of two winters of observations at Dresden and Baldwin cooling lakes in Illinois. Rime has a low density, is friable (easily crumbled), and poses little danger to structures or vegetation. No glaze icing due to steam fog was noted during these four winters. The absence of glaze icing (formed by large water droplets) supports the droplet diameter measurements of 7.5 to 15 microns made in steam fog by Currier et al. (2, 3).

Rime icing in Illinois (and most of the Midwest) is primarily a winter phenomenon, as shown by the observations at Baldwin and Dresden. Air temperatures of -7°C (19°F) or less are required for rime ice formation. Riming occurred at Baldwin as early as 26 November and as late as 4 March; however, these occurrences were associated with unusually cold air masses for southern Illinois on these dates. The icing season will be extended in other regions where the temperature drops to -7°C (19°F) and below earlier in the fall and continues at such temperatures later in the spring.

Only limited observations of the horizontal extent of icing were available from the Dresden observations. However, on 12 occasions rime with accumulations of up to 9 cm (3.5 in) was observed 40 m (125 ft) or more from the boundaries of the cooling lake. Of the 20 active rime events at Baldwin, the greatest horizontal extent was 0.8 km (0.5 mi). Most of the icing events (90%) were observed within 200 m (650 ft) of the cooling lake. The greatest accumulation of rime at Baldwin was 7.6 cm (3 in), and most (90%) of the rime accumulations were 2.5 cm (1 in) or less. Also, it was noted that the horizontal extent of icing was greater south rather than east of Baldwin, even though there were more icing events to the east.

However, the area south of the cooling lake is flat and nearly level with the lake surface, whereas the area east of the lake is 3 to 6 m (10 to 20 ft) lower than the lake surface. This would indicate that rime is not as readily deposited at ground level if the region beyond the lake boundary is depressed even slightly relative to the lake level.

For rime icing to occur beyond the confines of a cooling lake, the Baldwin, Coffeen, and Four Corners observations indicate that the following atmospheric conditions must be present: 1) an air temperature of -7°C (19°F) or less, 2) a saturation deficit of 0.5 g/kg or less, 3) a water-air temperature difference of 19°C (34°F) or greater, and 4) winds of at least 1 to 3 km/h (1 to 2 mi/h). These criteria are similar to the atmospheric conditions required for the more intense steam fog events at Baldwin. All of the active icing events observed at Baldwin were associated with steam fogs with visibilities of 1.6 km (1 mi) or less.

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Section 4

ENHANCEMENT OF CONVECTIVE CLOUDS

INTRODUCTION

Cooling lakes have a greater potential than natural lakes to initiate and/or enhance cumulus clouds due to their elevated surface water temperatures and greater evaporation rates. Parcels of air crossing a cooling lake near the surface take on added moisture and become more unstable than parcels of air traversing a comparable natural lake. This effect would be most apparent over relatively large cooling lakes and during times of low wind speeds because of the increased travel time in crossing the lake.

To investigate this possible cooling lake effect on clouds, visible photographs were obtained from two SMS-GOES meteorological satellites for the summer of 1975 at 0900, 1200, and 1500, and 1800 CST when possible. These photographs were required to be taken within 30 minutes of the scheduled time. Two areas of approximately 4550 km^2 (1750 mi^2) were chosen for this study. The first area was concentrated around Baldwin Lake. The other contained a large control lake, Carlyle, and another cooling lake, Coffeen. These areas and their surface features are shown in Figure 4-1.

Changnon and Huff (1) have shown that the occurrence of cumulus and cumulonimbus clouds maximizes during June, July, and August in the Midwest. Also, they determined that cumulus clouds at 0900 CST occur only 45% as frequently as during the afternoon maximum at 1400 CST. However, the occurrence of cumulus clouds increases dramatically from 0900 to 1200 CST to 95% of the afternoon maximum. Between 1200 and 1500 CST there is little change in their frequency. By 1800 CST the frequency decreases to 35% of the afternoon maximum. The diurnal maximum of cumulonimbus clouds occurs at 1800 CST in June and July. Thus, the hours between 0900 and 1800 CST during June, July, and August present a favorable opportunity to observe whether cumulus or cumulonimbus clouds are enhanced or occur more frequently in the vicinity of cooling lakes. Other clouds that maximize during this period are altocumulus and cirroform clouds; however, they exhibit only small variations in their diurnal distribution.

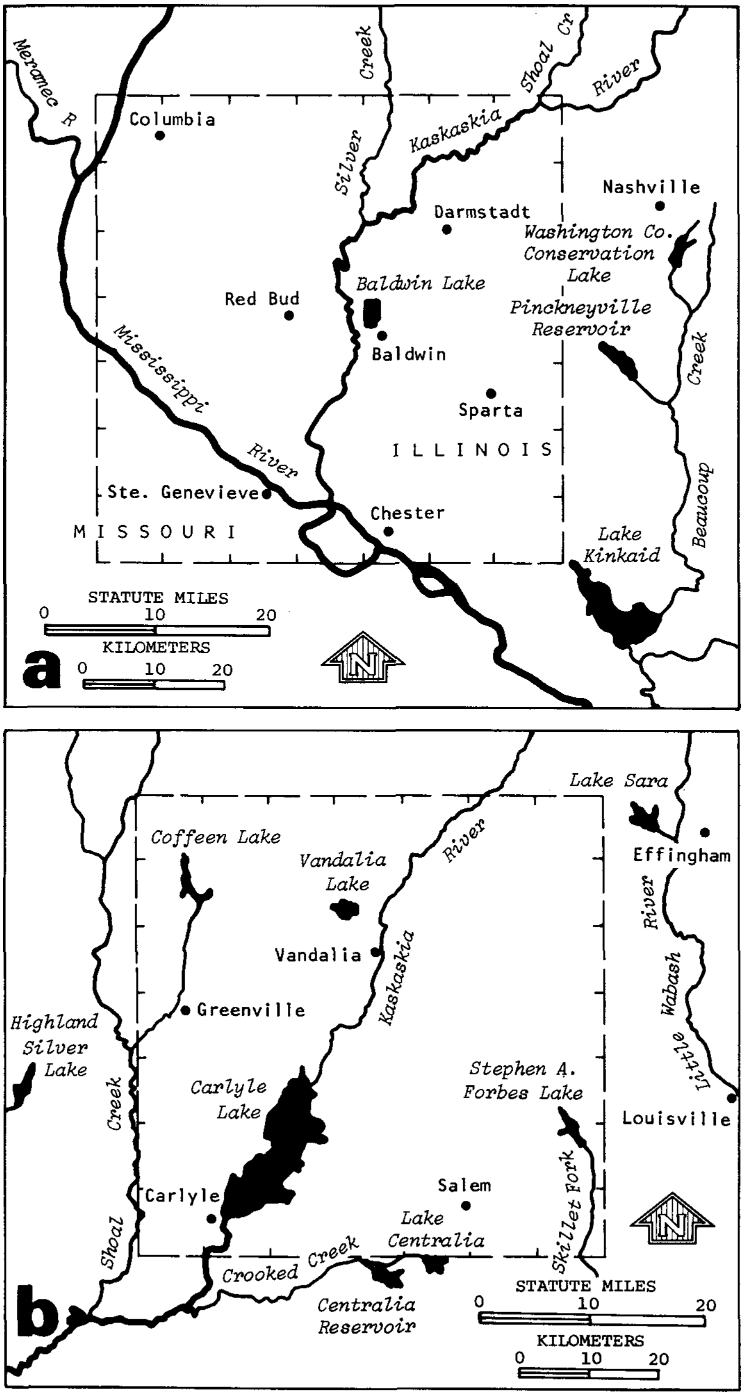

Figure 4-1. Satellite study areas a) Baldwin and b) Control region

The occurrence of clouds within each study area was determined subjectively with a Zoom Transfer Scope. This is an optical device which magnifies the satellite image and allows the photograph to be rectified for more positive alignment. A grid of 49 squares, each with an area of 93 km^2 (36 mi^2), was superimposed over each study area, and the occurrence of any cloud types within a grid square was counted. The frequency of all cloud occurrences was determined for all photographs for which suitable landmarks were available for the accurate delineation of the two study areas. Due to excessive cloud cover over the Midwest and/or oncoming darkness at 1800 CST, there was not the same number of low cloud photographs for each of the four time periods. For comparing observations from one time period to another, the data were normalized by dividing the frequency of cloud occurrences by the total number of photographs for each period to obtain a percentage frequency. This is the same procedure followed by Grosh (2) for satellite analysis over small regions.

Other large-scale satellite observations (3, 4) have established that topography exerts an effect upon the occurrence of clouds. Clouds were often observed to form and move downwind from surface ridges. Grosh (2) studied the cloud distribution over and downwind of an urban-industrial complex (St. Louis) with the same spatial resolution utilized in this study. He indicated that clouds were observed in the vicinity of surface ridges. In addition, apparent urban-industrial effects upon the distribution of clouds were noted, especially in middle to late afternoon. Grosh's results indicate that the scale employed in the satellite analyses is sufficient for the study of small-scale features, such as urban regions and smaller terrain features.

If a natural or cooling lake has an appreciable effect upon the distribution of clouds, the frequency of cloudiness should be noticeably greater over and/or downwind of the lake. Possible downwind effects were determined by stratifying the cloud frequency data by the steering level winds of cumuloform clouds. Hiser and Bigler (5) determined that the average winds in the layer from 850 to 500 mb (approximately 1500 to 5800 m or 5000 to 18,000 ft) describe the motion of convective clouds over Illinois. Byers and Braham (6) used similar layer-average winds to describe the cloud motion of cumulonimbus clouds. The satellite data were stratified by 45° sectors of winds. Table 4-1 gives the total number of photographs used for each time period and each of the 45° wind sectors, which show the direction from which the wind was blowing.

Table 4-1

NUMBER OF PHOTOS FOR EACH TIME PERIOD AND 45° WIND SECTOR

	NNE	ENE	ESE	SSE	SSW	WSW	WNW	NNW	Wind Missing	Total
0900 CST	2	5	5	4	8	22	24	11	1	82
1200 CST	2	4	5	3	7	22	21	9	1	74
1500 CST	5	4	2	4	3	20	17	12	0	67
1800 CST	3	3	1	3	4	5	13	6	0	38

DESCRIPTION OF TWO AREAS

Baldwin Area

The west side of the Mississippi River is lined by bluffs and the terrain is hilly and rugged, forming the eastern boundary of the Ozark Mountains (Figure 4-1a), Heights in excess of 305 m (1000 ft) are found near Farmington, Missouri, and heights in excess of 245 m (800 ft) are situated in the southwest corner of the study area. East of the Mississippi River there are two ridge lines. Heights in excess of 185 m (600 ft) occur from Dupo, Illinois, south to the Mississippi. A second ridge with heights between 150 m (500 ft) to 185 m (600 ft) is situated from Lake Kinkaid north to near the mouth of Shoal Creek. The eastern boundary of the study region is almost coincident with this ridge. The Kaskaskia and Mississippi river valleys are less than 120 m (400 ft) in elevation. Most of the area east of the Mississippi is characterized by gently sloping terrain. The region in the vicinity of Baldwin is open and characterized by relatively flat land. The only major changes in the terrain are imposed by the Kaskaskia, which has an average elevation of about 115 m (370 ft) near Baldwin Lake.

Control Region

Figure 4-1b shows the major features of the control region, which is centered 105 km (65 mi) northeast of Baldwin Lake. Lake Carlyle, situated near the southwest corner, is a relatively shallow lake 28 km (17 mi) long. Coffeen Lake is an 445-hectare (1100-acre) cooling lake for a coal-fired power plant operated by Central Illinois Public Service and producing 869 MWe. This lake is located in small natural valleys and is lined by trees. The terrain in the control region generally rises from south to north with only minor changes from west to east. The only prominent ridge is near the eastern boundary of the area of investigation and extends from near Lake Centralia to the northeast corner.

TOTAL DISTRIBUTION OF CLOUDS IN STUDY REGIONS

Baldwin Lake

The total distribution of cloud frequencies at 0900, 1200, 1500, and 1800 CST within the experimental region is shown in Figure 4-2. Cloud frequency maximums were situated near Ste. Genevieve and generally along the eastern boundary of the study area in all four time periods. Both of these maximums correspond to high points within the study region.

Minimums near the mouth of the Meramec River and Columbia, Illinois, and just east of the Mississippi River were observed in all time periods. The maximum

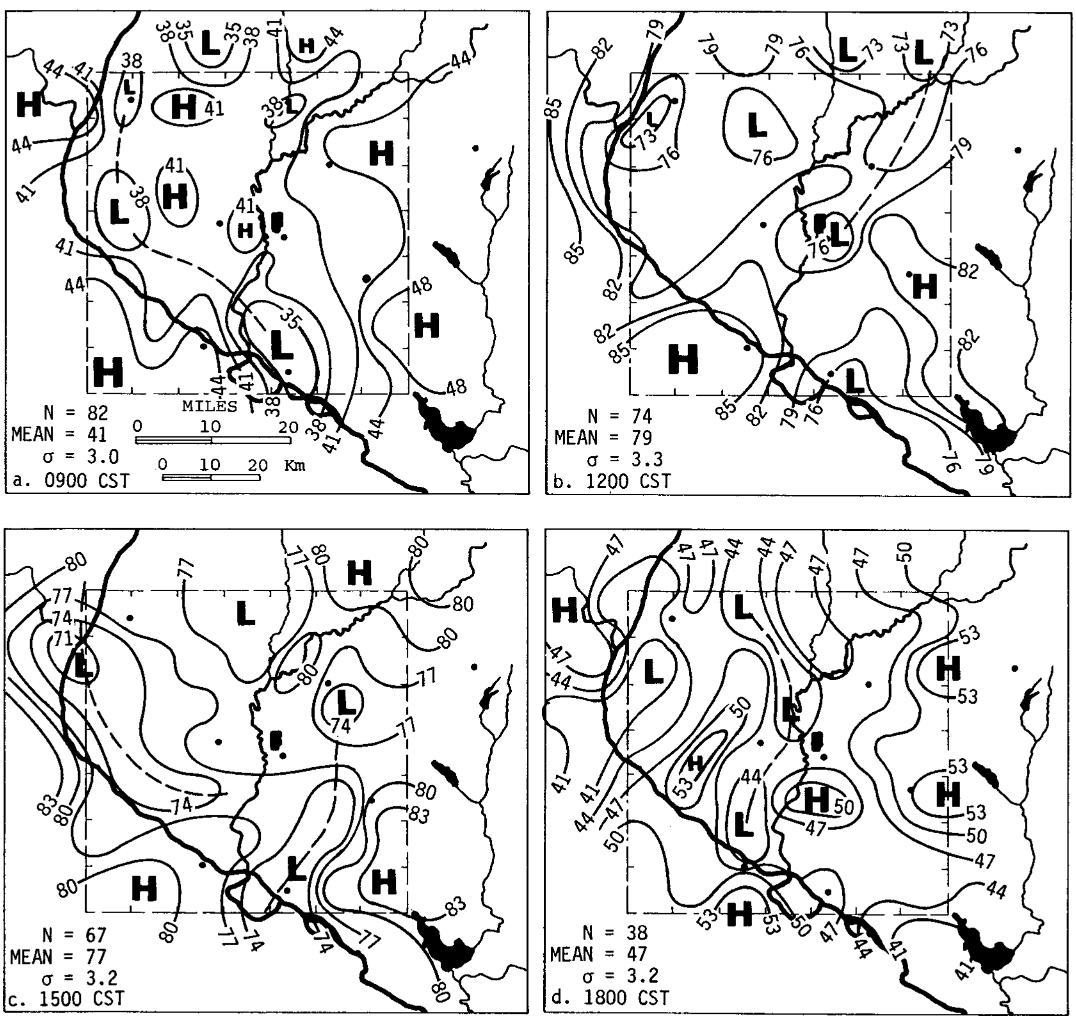

Figure 4-2. Baldwin percent frequency of clouds at a) 0900, b) 1200, c) 1500, and d) 1800 CST.

near Ste. Genevieve appears to be strong enough to interrupt the minimum along the Mississippi at both 1200 and 1500 CST (Figures 4-2b and c). Minimums or near-average cloud frequencies were experienced also along or just east of the Kaskaskia River. The water temperature during the day is less than the surrounding land temperatures, and it would appear that air over and near the rivers is more stable and less conducive to the production of low-level clouds.

In the vicinity of Baldwin Lake no unusually high frequency of clouds was noted. Generally, the values in the region bounded by Red Bud, Darmstadt, and Sparta were characterized by frequencies near or below the mean. From this sampling, there is no evidence of the initiation or enhancement of cumulus-type clouds from this cooling lake.

Control Region

The minimums and maximums of cloud occurrences within the control study regions (Figure 4-3) are more scattered than within the Baldwin region. The most persistent features of this area are the minimum southwest of Carlyle Lake and the maximum southeast of Salem which were evident at all four times. In addition, a minimum was observed in the vicinity of the Kaskaskia River at 0900, 1200, and 1500 CST. Maximums within the control region were not as persistent. The most prominent maximums were situated northwest of Carlyle Lake at 1200 CST, and over the northwest and northeast portions of the region at 1800 CST. None of these maximums appeared to be associated with either Carlyle or Coffeen Lakes. The generally higher values over the north half of the study area at 1800 CST appear to be associated with the higher terrain, ridges, and abrupt changes in surface elevation.

In summary, no evidence was found of a lake effect upon the frequency of clouds. There was some evidence of an enhancement by the natural terrain features, such as ridges and the Kaskaskia River Valley.

DISTRIBUTION OF CLOUDS BY STEERING-LEVEL WINDS

Steering-level wind directions for cumulus-type clouds near Baldwin Lake and the control region were obtained from the Salem radiosonde station. Salem is situated within the control region and is 90 km (56 mi) northeast of Baldwin Lake. The steering winds were found by vector averaging the winds at the 850-, 700-, and 500-mb levels. For a typical summer day these pressure levels range from approximately 1500 to 5800 m. Hiser and Bigler (5) and Byers and Braham (6) have determined

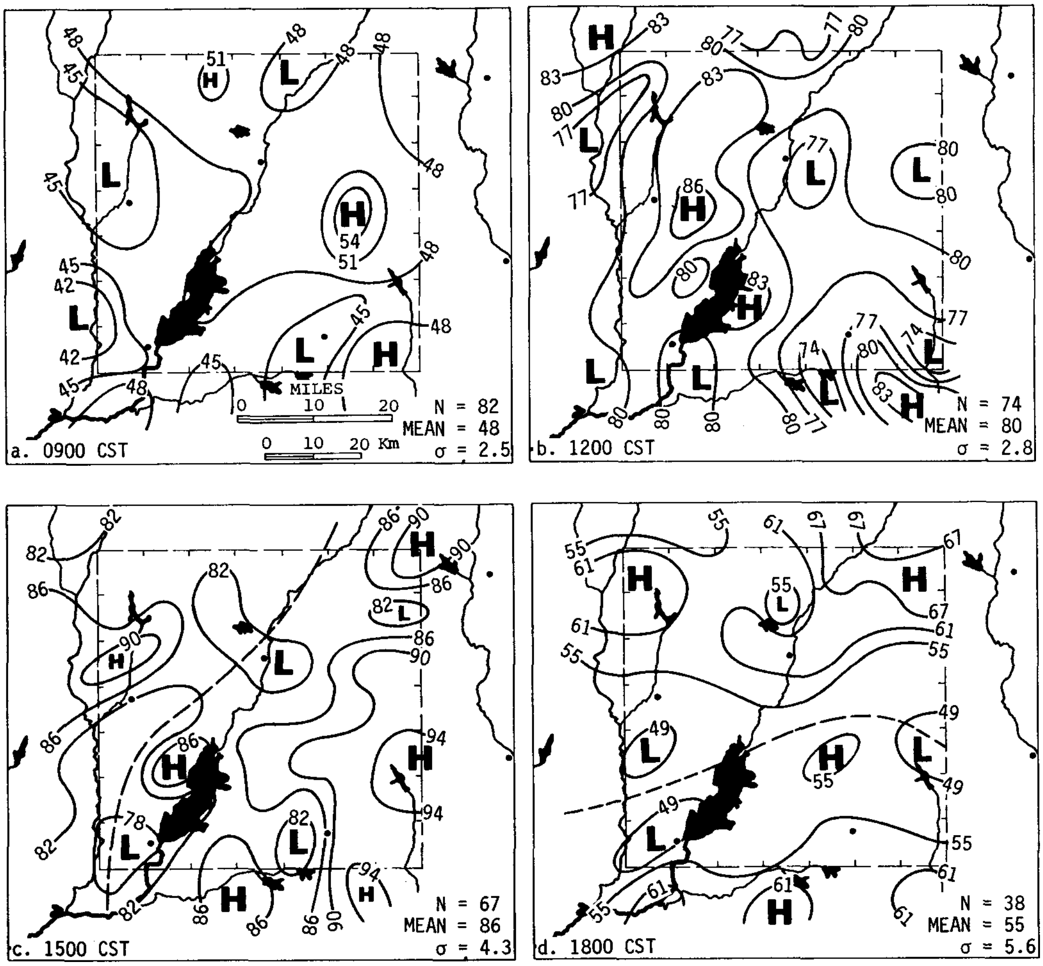

Figure 4-3. Control region percent frequency of clouds at a) 0900, b) 1200, c) 1500, and d) 1800 CST.

that the winds in this layer of the atmosphere are good indicators of the movement of cumulus-type clouds. The winds were again stratified into 45^{o} sectors.

The steering-level winds for satellite photographs at 0900 and 1200 CST were determined from the upper-air sounding at 0600 CST. The sounding at 1800 CST was used to determine the steering-level winds for the photographs at 1500 and 1800 CST. Analysis was made for all eight 45^{o} sectors. The sector with winds from the west-southwest is shown as an example (Figure 4-4), and results from the other sectors summarized. This sector is especially important because with steering-level winds from this direction more moisture from the Gulf of Mexico is available through a deep layer of the lower atmosphere. In addition, climatologically an upper-air trough would be situated west of the region, giving rise to convective instability and a greater likelihood of cumulus-type clouds. Thus, more cloudiness, especially cumuloform clouds, would be expected. Indeed, more cloudiness was observed near Baldwin Lake and in the control region than in the total cloud sample. This is confirmed further by the fact that there were more rain days associated with this particular steering-level wind direction than any other sector wind.

Baldwin Lake

Figure 4-4 shows the percent of cloud occurrences in the Baldwin Lake region when

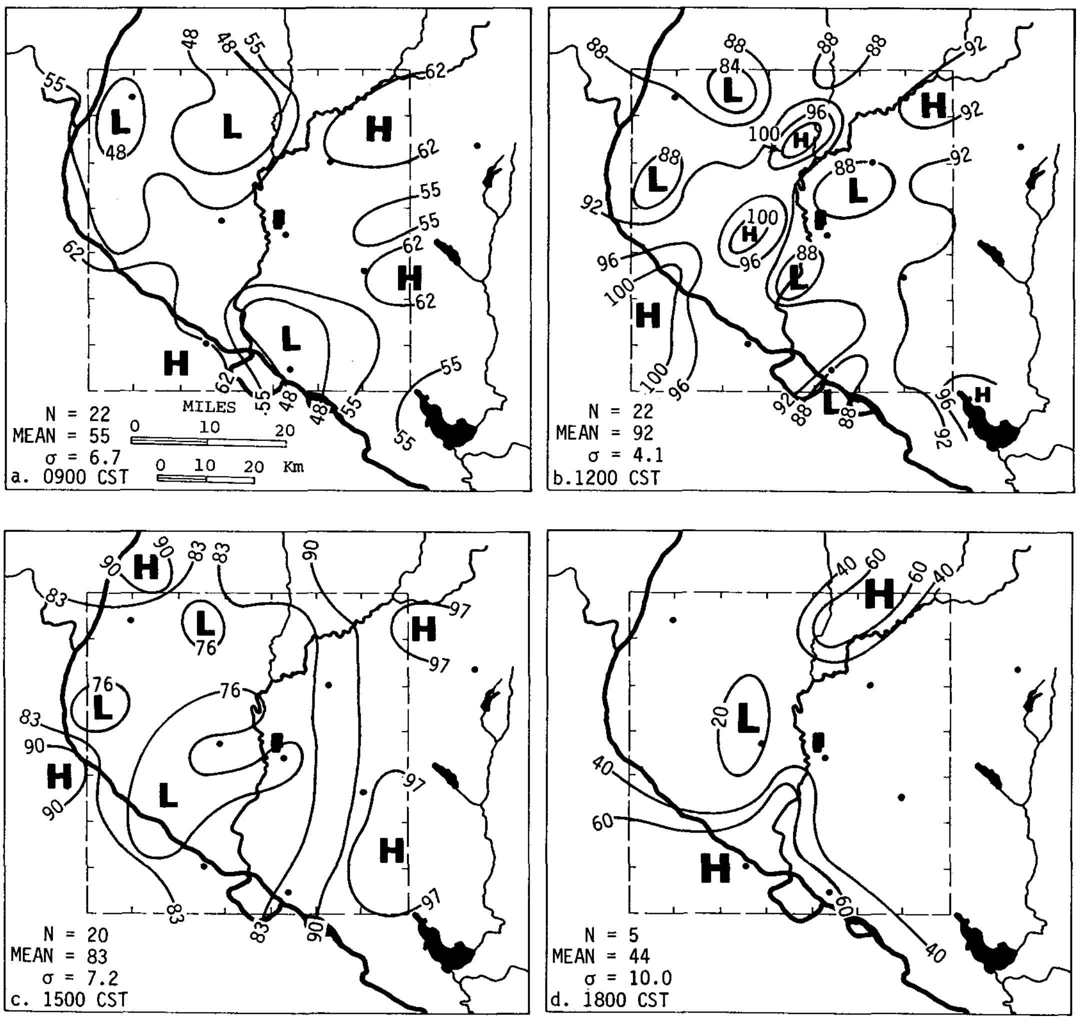

Figure 4-4. Baldwin percent frequency of clouds with west-southwest winds at a) 0900, b) 1200, c) 1500, and d) 1800 CST

the steering level-winds were from the west-southwest. At 0900, 1200, and 1500 CST, 50% of the days had rain in the vicinity of Baldwin Lake during the daylight hours, and at 1800 CST rain was recorded during two of the five days. Thus, the data presented in Figure 4-4 provide a good sampling of both rain and nonrain days.

The charts for 0900, 1200, and 1500 CST are similar to the total sample presented in Figure 4-2. Minimums in cloud observations were observed in the vicinity of the Mississippi and Kaskaskia rivers. Maximums occurred near Ste. Genevieve, Missouri, and over the eastern edge of the analysis region. The maximums over the southwest and eastern portions of the region appear to be related to the underlying surface ridges and agree with other satellite observations of cloudiness over or downwind of ridge lines (2, 3, 4, 7). The pattern at 1800 CST is similar to the overall pattern, but the limited data sample at this hour for west-southwest winds is not sufficient for any firm conclusions.

If clouds were enhanced or initiated by the cooling lake in a significant manner, a maximum of cloud observations would be expected over or northeast of Baldwin Lake. However, no such maximums were observed. Analysis of the remaining data by 45^{o} sectors gave similar results. The area near or upwind of Baldwin Lake usually exhibited cloud frequencies near the mean for the region. However, the major terrain features of the region, the river valleys and the ridge lines, do appear to affect the occurrence of clouds during the summer.

Control Region

The distribution of cloud occurrences with west-southwest winds for the control region is shown in Figure 4-5. The distribution at 0900 CST has a flat gradient, with a general maximum from Carlyle Lake to the northeast. The distribution of clouds at 1200 CST shows a general maximum over the west part of the region. At 1500 CST, a minimum of occurrences was observed in the vicinity of the Kaskaskia River. The cloud distributions at 1200 and 1500 CST were similar to the total data sample (Figure 4-5). The pattern at 1800 CST with steering-level winds from the west-southwest was similar to the total cloud sample at 1800 CST, but the sample size was too small to be definitive.

No prominent increase in cloud occurrences was observed over or northeast of Carlyle and Coffeen Lakes. Generally, the observed maximums were situated on or near ridges or just upwind of the peaks. Similar results were obtained from

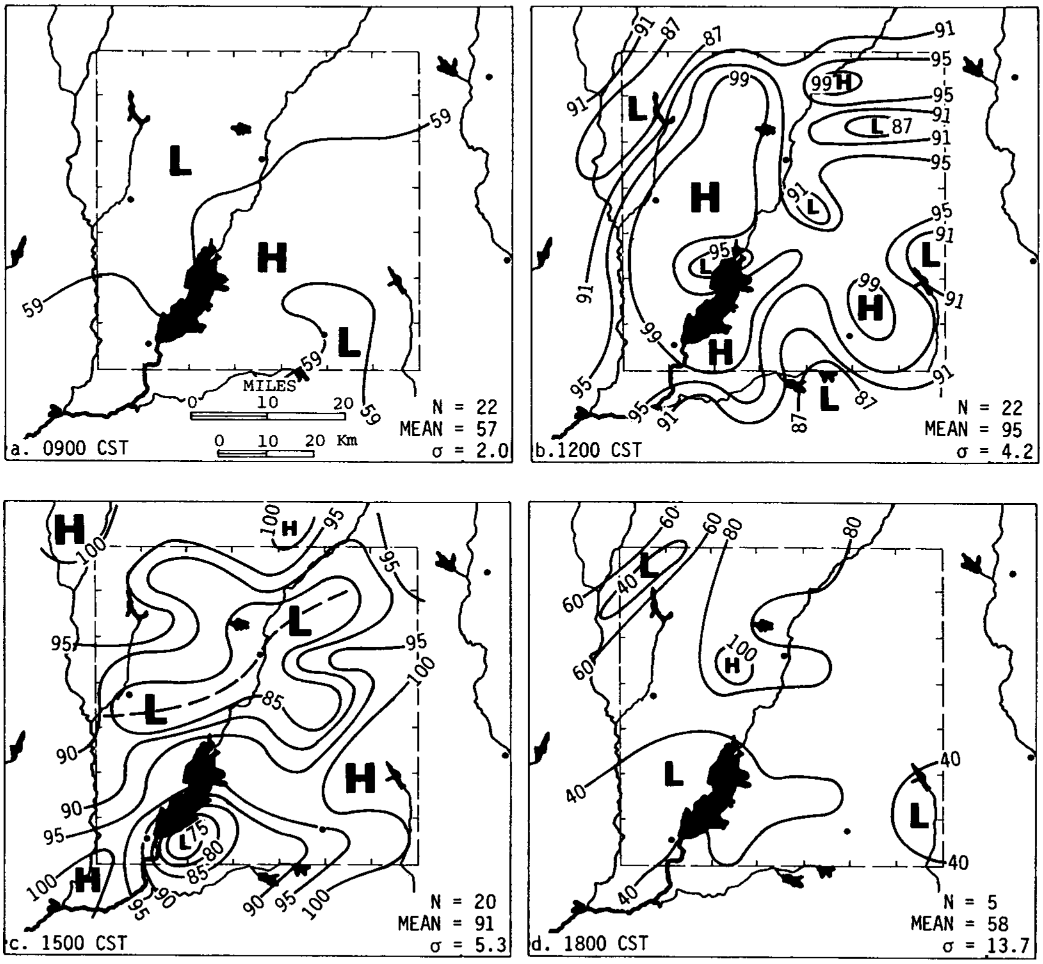

Figure 4-5. Control region percent frequency of clouds with west-southwest winds at a) 0900, b) 1200, c) 1500, and d) 1800 CST

other stratifications of the steering-level winds. Thus, no evidence was found to support any significant change in cloud distributions caused by Carlyle or Coffeen Lakes, when the data were stratified by steering-level winds. The distribution of clouds observed within the vicinity of Carlyle and Coffeen Lakes by satellite does not suggest that either lake is acting to initiate or enhance the distribution of clouds.

DIURNAL VARIABILITY

Diurnally, the percent cloud cover within the Baldwin and control region compares favorably with the normal diurnal distribution of cumulus and cumulonimbus clouds in Illinois. Cumulus and cumulonimbus clouds experience a mid-afternoon peak, and their occurrence decreases considerably by 1800 CST (1). It would appear that these clouds are the dominating characteristics of the distributions found in the satellite photographs, since the other cloud types have a more uniform diurnal distribution during the daylight hours (1).

Table 4-2 presents the means and standard deviations of the percent cloud occurrences for Baldwin, the control region, and the data obtained by Grosh (2) in the vicinity of St. Louis. The diurnal variabilities in the three data sets are similar, with sharp increases in the occurrences of cloud cover from 0900 to 1200 CST. Between 1200 and 1500 CST there is little change in the average frequency. This period is followed by a decrease in the percent cloud coverage at 1800 CST. The Baldwin and St. Louis data agree especially well. Since there was more cloud cover within the control region than near Baldwin, there is no support for a cooling lake effect in the diurnal distribution characteristics.

Table 4-2

DIURNAL CHARACTERISTIC OF THE MEAN AND STANDARD DEVIATION OF PERCENT CLOUD COVER

	Percent Mean			Standard Deviation		
	Baldwin	Control	St. Louis	Baldwin	Control	St. Louis
0900 CST	41	48	43	3.0	2.5	2.8
1200 CST	79	80	76	3.3	2.8	5.2
1500 CST	77	86	78	3.2	4.3	3.5
1800 CST	47	55	49	3.2	5.6	5.2

USE OF RADAR DATA IN EVALUATING POTENTIAL COOLING LAKE EFFECTS

Radar data can help to determine if a cooling lake has an impact upon the initiation of convective precipitation over or downwind of the lake. Such a data set was gathered by the University of Chicago during the months of June, July, and August from 1972 to 1975 (8). A 3-cm, TPS-10 radar routinely collected information about convective clouds within a 97-km (60-mi) radius of Greenville, Illinois. Included within this region were Baldwin Lake and the control region used for the satellite analyses. First echoes from the radar were used to look for possible urban-industrial effects from St. Louis on the initiation of precipitation in convective clouds. They determined that convective clouds over and immediately downwind of St. Louis were initiating precipitation preferentially by the coalescence process.

A total of 4553 first echoes were found and plotted. An examination of the plot of these first echoes (9, 10) indicates that Baldwin and Coffeen Lakes had no apparent effect on the distribution of first echoes over or in the vicinity of these cooling lakes.

To determine possible downwind effects, the first radar echoes were stratified by motion in two ways. Echo motions were determined by 1) steering-level winds, and 2) the motion of three or more widely separated echoes. The cooling lakes at Baldwin and Coffeen did not appear to have any effect upon the distribution of first echoes either over or downwind of the cooling lakes within any of the motion stratifications. However, there was an indication of a minor maximum of first echoes downwind of Carlyle Lake on those days when both the steering-level winds and the mean echo motions were from 202 to 249°. It would appear that the moisture content of the air was increased by lake evaporation as it moved across the long axis of Carlyle Lake. The results from Braham and Dungey (9) indicate that this effect is confined to the area immediately downwind of the lake. Cooling lakes such as Baldwin or Coffeen do not appear to be large enough to have a sufficiently large evaporative output to significantly effect the initiation of convective clouds.

SUMMARY AND CONCLUSIONS

Satellite photographs taken during the summer of 1975 were employed to investigate cooling lake effects upon the time-space distribution of cloudiness. Analyses were made for two cooling lakes in southern Illinois, Baldwin and Coffeen, and a much larger control lake, Carlyle. No evidence was found that the cooling lakes or control lake had any significant effect upon the summer cloud frequencies, and, consequently, upon precipitation. There was some evidence, however, that local terrain features in the study region, ridges and river valleys, do influence the spatial distribution of clouds, primarily cumulus and cumulonimbus.

The potential cooling lake effect was investigated further through use of available radar data for the summers 1972 to 1975. Results supported the satellite findings with respect to the two cooling lakes. However, the larger control lake (Carlyle) appeared to have some influence on the initiation of convective precipitation when atmospheric motions were parallel to the major axis of this elongated lake.

Thus, it is concluded that cooling lakes the size of Baldwin and Coffeen have little or no effect upon the initiation of convective cloudiness or precipitation.

However, much larger cooling lakes, as indicated by the Carlyle findings, could enhance convective activity when the low-level air and clouds have a relatively long travel time over the lake. Otherwise, most cooling lakes have a minimal impact upon the initiation and enhancement of convective cloudiness and should produce no environmental problems of significance in this direction. These field results agree with numerical modeling experiments by Koenig et al. (11). They found that all auxiliary systems have potential for the initiation of convective cloudiness. However, systems which primarily release waste energy as latent heat, such as cooling lakes, have the least effect upon the initiation and enhancement of convective clouds.

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Section 5

RAINFALL DISTRIBUTION IN BALDWIN NETWORK

INTRODUCTION

A dense raingage network was operated in the Baldwin area from July through November 1976 and from March through November 1977. The purpose was to search for evidence of a cooling lake effect upon the regional precipitation. In view of prevailing winds and storm movements in the area, any effect would be expected to be most pronounced northeast, east, and southeast of the lake with maximum effect in the northeasterly quadrant. Residents in the area have indicated that warm-season convective storms tend to split over the lake and reform downwind.

The precipitation measurements were made with a plastic, wedge-type gage. This is a low-cost, post-mounted gage for obtaining total storm or daily rainfall measurements. Their accuracy was established by Huff (1), and they have been used in several past field projects of the Illinois State Water Survey. These gages are damaged by freezing weather, so the network was not operated in winter (December-February).

In 1976, a wedge gage was placed at each of the Baldwin instrument sites and at additional sites farther downwind. A total of 47 gages were operated in 1976, and the network was increased to 53 gages in 1977. Measurements were taken at the instrument sites by the field technician, and the others were made and recorded by cooperative observers where the gages were located. The 1977 network is shown in Figure 1-3. It would have been desirable to have extended the network farther westward. This region is usually upwind of the lake and, therefore, would have provided a larger "control" area for comparing upwind and downwind rainfall distributions. However, the lack of residences, and, consequently, cooperative observers prevented a greater westward extension.

SEASONAL RAINFALL DISTRIBUTIONS IN 1976-1977

The first step in the analysis was to investigate monthly rainfall distributions during the two-year sampling period. Observations were recorded from July through

November 1976 and from March 15 through November 1977. The natural sampling variability was so great in individual months that no potential effect from the cooling lake would have been detectable, unless it was a very large change. Therefore, monthly totals were combined to obtain seasonal totals to reduce the natural variability interference somewhat.

<u>July-August 1976</u>

Examination of the July-August rainfall totals for 1976 in the dense sampling network indicated areas of relatively heavy rainfall immediately west and southwest of the lake, regions usually upwind of the lake during rainstorms. A high was also located a few kilometers north of the lake, and a low extended eastward from Baldwin. Examination of the rainfall pattern in the surrounding regions of southern Illinois derived from the climatic network of the National Weather Service (NWS) indicated the low east (downwind) of the lake was part of a larger natural rainfall low in the large-scale pattern. Thus, it was concluded that no evidence of a lake effect was discernible during this two-month period.

<u>September-November 1976</u>

The fall pattern for 1976 was reversed from the July-August distribution in that relatively light rainfall occurred west and north of the lake, whereas rainfall became gradually heavier east and northeast of Baldwin. This network pattern agrees with the larger-scale pattern shown by the NWS climatic network, which indicated a region of relatively heavy rainfall extending many kilometers eastward from Baldwin and, similarly, relatively light rainfall extending over the area west of the lake.

The NWS climatic network is not satisfactory for detailed rainfall studies since it averages only 1 gage per 600 km^2 (230 mi^2) in Illinois. However, it can be used as a means of approximating macroscale patterns for periods of a month or longer, and that is how it has been used in the Baldwin study. That is, it is used as a guide in judging the reality of any apparent lake effects on the rainfall distribution in its immediate vicinity.

<u>July-November 1976</u>

When all months for July through November 1976 were combined, the network rainfall pattern became very flat with relatively heavy amounts indicated southwest, west, and north of the lake and relatively light rainfall extending eastward from

Baldwin. However, the pattern suggests no lake effect. Reference to the larger-scale pattern of the NWS climatic network showed the Baldwin area was part of a relatively large area with no substantial rainfall gradients for the five-month sampling period. Thus, there was no evidence in the 1976 sampling that the cooling lake had any significant effect on the intensity or spatial distribution characteristics of rainfall in the surrounding region.

March-May 1977

Baldwin Lake was part of a north-south trough in the spring rainfall pattern. Rainfall was heaviest in the extreme eastern part of the network and was relatively light in the northern and southern extremes. Comparison with the NWS climatic network pattern over southern Illinois indicated the trough through the lake was part of a macroscale trough in the spring rainfall distribution. The heaviest rainfall occurred at a point about 12 km (7 mi) east-northeast of the lake, where the spring total was 20% greater than the network mean of 22 cm (8.7 in). However, at Sparta, about 18 (11 mi) southeast of the lake and not in the path of most storms crossing the lake, the spring rainfall was 42% greater than the network mean.

June-August 1977

The summer pattern also showed a north-south trough of relatively light rainfall over Baldwin Lake with a high to the east and southeast. This lake low in both spring and summer suggests the possibility of a lake effect. However, inspection of the climatic network pattern in southern Illinois again indicates the Baldwin low was part of a large trough in the regional rainfall pattern that extended far beyond any potential lake effect. Furthermore, any lake effect would be expected to occur most distinctly northeast, east, or southeast of the lake, since there would be a time lag in realizing the lake effect in the surface rainfall pattern. However, there is some possibility that the lake trough is related to downslope motion off a slight ridge located west of the lake. The network high was also part of a macroscale high centered well to the southeast of the lake beyond any potential lake effect.

September-November 1977

A north-south trough occurred in the network pattern and this low, which extended from the northern to southern boundaries of the network, intersected the eastern part of the lake and dominated the network pattern. Again, this was part of a larger-scale trough extending through the central to southwestern portions of southern Illinois. The heaviest network rainfall occurred approximately 10-12 km (6-7 mi) east-northeast of the lake, where one station recorded 27 cm (10.6 in), whereas the network mean was 22 cm (8.7 in).

March-November 1977

Total rainfall for spring, summer, and fall of 1977 reflected the consistencies of the seasonal patterns. Thus, relatively light rainfall dominated the central two-thirds of the network with relatively heavy rainfall on the western and eastern extremities of the gaged area. Again this pattern is in general agreement with the macroscale pattern for southern Illinois indicated by the NWS climatic network. The heaviest rainfall occurred 10-12 km (6-7 mi) east-northeast of the lake, where amounts exceeded the network mean of 72 cm (28.3 in) by 20%.

Two-Year Totals

The final step in the seasonal analysis was to combine the 1976-1977 data for summer, fall, and all months. The two-summer pattern (Figure 5-1a) showed relatively light rainfall over the central and northern part of the network, with highs on the western, southern, and eastern extremities of the network. The only suggestion of a possible lake effect was the existence of the heaviest rainfall about 10 km (6 mi) east of the lake, where the maximum rainfall was approximately 15% greater than the network mean. The two-fall pattern (Figure 5-1b) showed relatively light rainfall dominant over most of the network, with highs on the eastern and western extremities. This pattern is in agreement with the macroscale pattern of the climatic network, and, from this standpoint, is not indicative of a lake effect. However, the heaviest network rainfall was in the extreme eastern part of the network which is generally downwind of the lake during rainstorms. Maximum rainfall was approximately 20% greater than the network mean at a raingage located 12 km (7 mi) east-northeast of the center of the lake.

The total rainfall for all months combined in 1976-1977 is shown for the network area in Figure 5-1c. This pattern shows a low extending from the lake northward, with relatively light rainfall dominating the northern portions of the network. The heaviest rainfall occurred in the eastern extremity of the network approximately 10-12 km (6-7 mi) east-northeast of the center of the lake. In this region, the total rainfall was approximately 15% greater than the network mean. However, the rainfall was no greater in this area than at Sparta, in the southeast corner of the network, which is considered too far southeast of the lake to exhibit any substantial lake effect, particularly since only about 1/4 of the storms move from the northwest (discussed later).

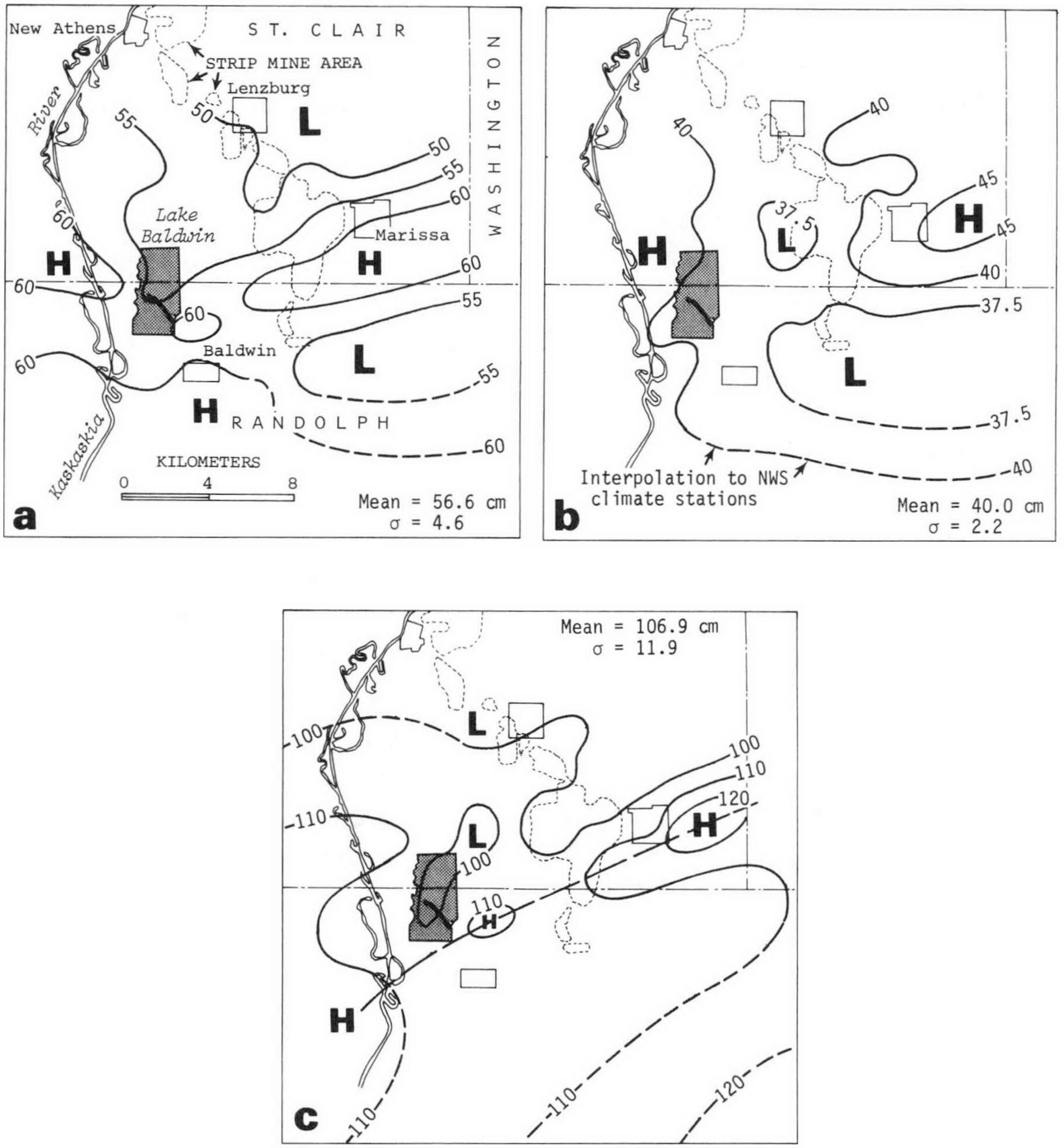

Figure 5-1. Rainfall pattern (mm) for a) summers 1976 and 1977, b) falls 1976 and 1977, and c) total rainfall 1976 and 1977

Summary and Conclusions

The rainfall pattern in the Baldwin Network provides some evidence for a lake-induced increase in rainfall at distances of 10-12 km (6-7 mi) east to east-northeast of the lake. In this region the two-year total rainfall (July-November 1976 plus March-November 1977) was approximately 15% above the network mean at distances of 10-12 km (6-7 mi) east-northeast of the lake. This rainfall surplus resulted primarily from 1977 events. The potential lake-induced increase was present in both summer and fall rainfall distribution and in the one spring pattern for the Baldwin Network. However, this evidence must be considered weak in view of the relatively short sampling period and because the network pattern in most cases was in agreement with the large-scale patterns exhibited for southern Illinois by the NWS climatic network. The only real evidence for a possible lake effect is the consistency in location and relative intensity of the network high with respect to the network mean rainfall.

Assuming the network patterns do reflect a localized anomaly, it could be related to other topographic features in the general area rather than the cooling lake. It was shown in the previous section on enhancement of convective clouds in the Baldwin region that the topography west (upwind) of the lake is characterized by small ridges and bluffs, and these were found to stimulate convective cloud development. Also, no evidence was found of cloud stimulation downwind of the lake. In view of these findings, which are admittedly based on limited data, it appears unlikely that rainfall is being stimulated by the relatively small heat-moisture source provided by the 890-hectare (2200-acre) lake. Furthermore, Huff et al. (2) have shown that small-scale topographic features can lead to the enhancement of precipitation in southern Illinois. Unfortunately, it was not possible to investigate the potential topographic effects further within the limitations of personnel, budget, and objectives of the Baldwin project. Our tentative conclusion, based upon available information at this time, is that cooling lakes of the size of Baldwin will not exert a significant effect upon the precipitation in the region surrounding the power plant.

FREQUENCY DISTRIBUTION OF RAINFALL EVENTS IN BALDWIN AREA

An investigation of the frequency distribution of rain occurrences on the Baldwin network was made to investigate further whether the lake may affect the initiation of rainstorms. This was done for the two summers and two falls combined. Further division by month and year was not feasible because of the sample size. The rainfall events were subdivided according to total storm amounts, and the number of occurrences in each category tabulated and plotted on a base map. The rainfall groups included rain amounts of 0.25-6.24 mm (0.01-0.24 in) (light rains), 6.25-24.99 mm (0.25-0.99 in) (moderate rains), and 25 mm (1 in) or more (heavy rains).

The pattern for light rains in summer showed a gradual decrease in frequencies from west to east across the network. There was no real evidence of a lake effect in this pattern. The distribution for moderate rains showed a banded structure of frequencies with maximum number of occurrences across the north-central and southern parts of the network and fewer occurrences in the northern and south-central portions of the network. The area immediately east of the lake was in a relatively low frequency band, but it appeared to be a part of the natural variability rather than a lake effect. The frequency of heavy rains in summer (25 mm or 1 in, or more) showed a maximum in the extreme eastern portion of the network where rainfall was heaviest during the two-summer period. As pointed out in earlier discussions of the total rainfall patterns, this could be the reflection of a lake effect, but the eastern high is also part of the natural rainfall distribution in southern Illinois as shown by the NWS climatic network.

The light rainfall occurrences in fall displayed a rather random distribution on the network and provided no evidence of a lake effect. Moderate rain occurrences in fall had maxima extending along a north-northeast-south-southwest line through the lake and off the network, and in the extreme eastern part of the network. A north-south low dominated the network area east of the lake. This pattern is in general agreement with the total rainfall pattern for fall discussed in a previous section. The heavy rainfall frequencies for fall maximized in the extreme eastern and northwestern parts of the network, with a low extending approximately north-south through the lake area and off the northern and southern ends of the network.

Overall, the analysis of the frequency of rain events provided no further clarification of the lake effect beyond that obtained in the total rainfall analysis. There was a tendency for the heavy rainfalls to be most frequent in the eastern part of the network which is frequently downwind of the lake, but, as pointed out in the total rainfall discussions, there is some question as to whether this is a lake anomaly or merely a reflection of the natural rainfall distribution during the two-year sampling period.

DISTRIBUTION OF RAINFALL ACCORDING TO STORM MOVEMENT

In view of the weak evidence for a possible lake effect, it was decided to undertake more detailed analyses of the rainfall data to search for supporting evidence. The next step consisted of stratifying the data according to storm movements and deriving rainfall patterns for storms which moved out of each of the four quadrants (southwest, northwest, southeast, and northeast). Storm movements were determined from surface and upper air synoptic maps and from radar summaries prepared and published by NWS. Although analyses were performed initially for each sampling month in each year, they were later combined into a single two-year sample because of the relatively small sample sizes when the storms were subdivided into four groups by quadrant from which they moved.

The distribution of total rainfall in the network during the two-year sampling (July-November 1976, April-November 1977) is shown in Table 5-1. Typical of Illinois and the Midwest was the preponderance of storm movements out of the southwest quadrant. Since over 71% of the storms moved from the southwest quadrant, any lake-induced effect would be expected to be most prominent in the northeast quadrant of the network. If the effect was strong, some indication might be evident in the southeast quadrant, since 22% of the storms moved out of the northwest quadrant. Since less than 7% of all storms moved from the southeast and northeast quadrants, no measurable effect would be expected southwest, west, and northwest of the lake.

Table 5-1

DISTRIBUTION OF RAINFALL BY STORM MOVEMENTS IN 1976-1977

Quadrant	Network Mean (cm)	Percent of Total Rainfall
SW	76.0	71.2
NW	23.5	22.0
SE	6.6	6.2
NE	0.6	0.6

Figure 5-2a shows the rainfall pattern for storms moving out of the southwest. The major region of relatively heavy rainfall occurred 10-12 km (6-7 mi) east-northeast of the lake center where amounts were 15% to 20% greater than the network mean. Since these storms produced over 71% of the two-year rainfall, the downwind high tends to be located in the same region as that for total rainfall during the entire sampling period. However, the anomaly was not quite as large for all storms combined, since it ranged from approximately 13% to 17% in the same area.

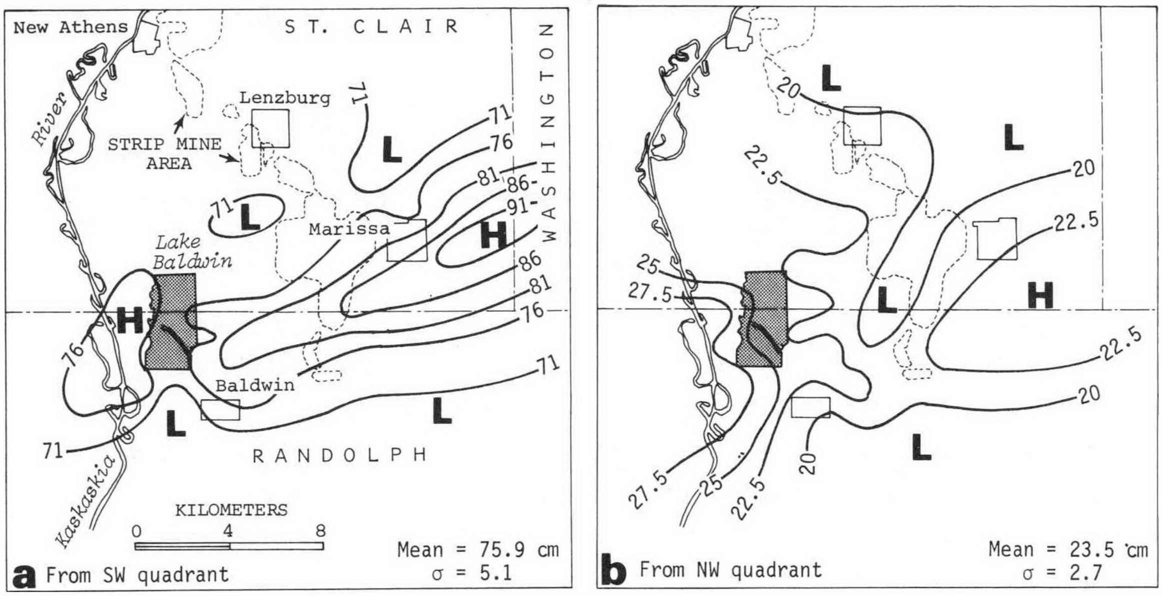

Figure 5-2. Rainfall pattern (mm) for storms from a) southwest and b) northwest

Figure 5-2b shows the rainfall distribution for storms moving from the northwest quadrant. In such storms, any lake effect would be expected to occur in the southeast quadrant of the network. However, this did not occur. The heaviest rainfall was in the western and southwestern parts of the network. The most prominent feature of the southeast quadrant is a region of relatively light rainfall. A secondary high was located in the eastern part of the network. There is no solid support for a lake-induced high in this pattern; if anything, it would suggest a lake-induced low. However, this low is part of a trough extending northward east of the lake and apparently continues off the network to the north and northeast.

The pattern for storms moving from the southeast, which was associated with only 6% of the rainfall, showed the heaviest rainfall on the eastern extremity of the network, where the maximum rainfall was 22% greater than the network mean. Thus, a primary or secondary high existed in this general region with storms moving from the southwest, northwest, and southeast. This suggests that the relatively heavy rainfall may have no relationship to the lake. In analysis of the climatic network data of NWS, a high extending east and southeast of Baldwin was found in the large-scale pattern. This high was centered near Sparta in the southeast corner of the network. The high east-northeast of the lake in the eastern part of the Baldwin network may very well be only a northward extension of the Sparta high. This hypothesis is supported by the patterns for the northwest and southeast quadrants.

Overall, it is concluded from analyses performed on the rainfall network data that support is weak for a lake-induced increase (or decrease) in the rainfall distribution during the convective storms that dominate spring, summer, and fall rainfall in the Baldwin region. In view of the pronounced high in the eastern part of the network, particularly with storms moving from the southwest quadrant, the possibility of a lake effect can not be eliminated, even though there is other evidence that this apparent anomaly may only be a ramification of the natural distribution during the sampling period. Unless the lake effect was very pronounced, it would be very difficult to verify in a two-year period. Experience with METROMEX (3) and other rainfall projects at the Illinois State Water Survey indicates that five years is a minimum observational period for defining localized effects with a high degree of reliability.

DISTRIBUTION OF RAINFALL ACCORDING TO SYNOPTIC WEATHER TYPES

In a further effort to evaluate the rainfall pattern on the Baldwin network, the storms were stratified according to six general synoptic weather types used in METROMEX (3) and other Water Survey studies. These are cold fronts, warm fronts, static fronts, occluded fronts, air mass storms, and low center passages. Analysis showed that cold fronts were most frequently associated with the Baldwin rainfall. The distribution of cold front rainfall is shown in Figure 5-3a. Approximately 55% of the total rainfall during the two-year sampling period occurred with these storms. Two high areas are indicated, with one of these again in the eastern extremity of the network and east-northeast of the lake. The maximum rainfall was about 10% above the network mean of 61.6 cm (24.3 in).

The second largest contributor to the Baldwin rainfall was air mass storms which were associated with 27% of the total rainfall. The pattern in Figure 5-3b shows relatively heavy rainfall in the southwest, northeast, and extreme eastern parts of the network with a low immediately east and southeast of the lake. The most prominent high was in the southwest part of the network. The maximum rainfall in this high was 15% greater than the network mean of 30.3 cm (11.9 in). There is no substantial support for a lake-induced anomaly in the air mass pattern.

The network pattern for static fronts is shown in Figure 5-3c. These storms accounted for about 9% of the network total rainfall. The familiar pattern of a high in the eastern part of the network with a low oriented nearly north-south through the lake is shown. However, the network mean rainfall was only 9.8 cm (3.9 in).

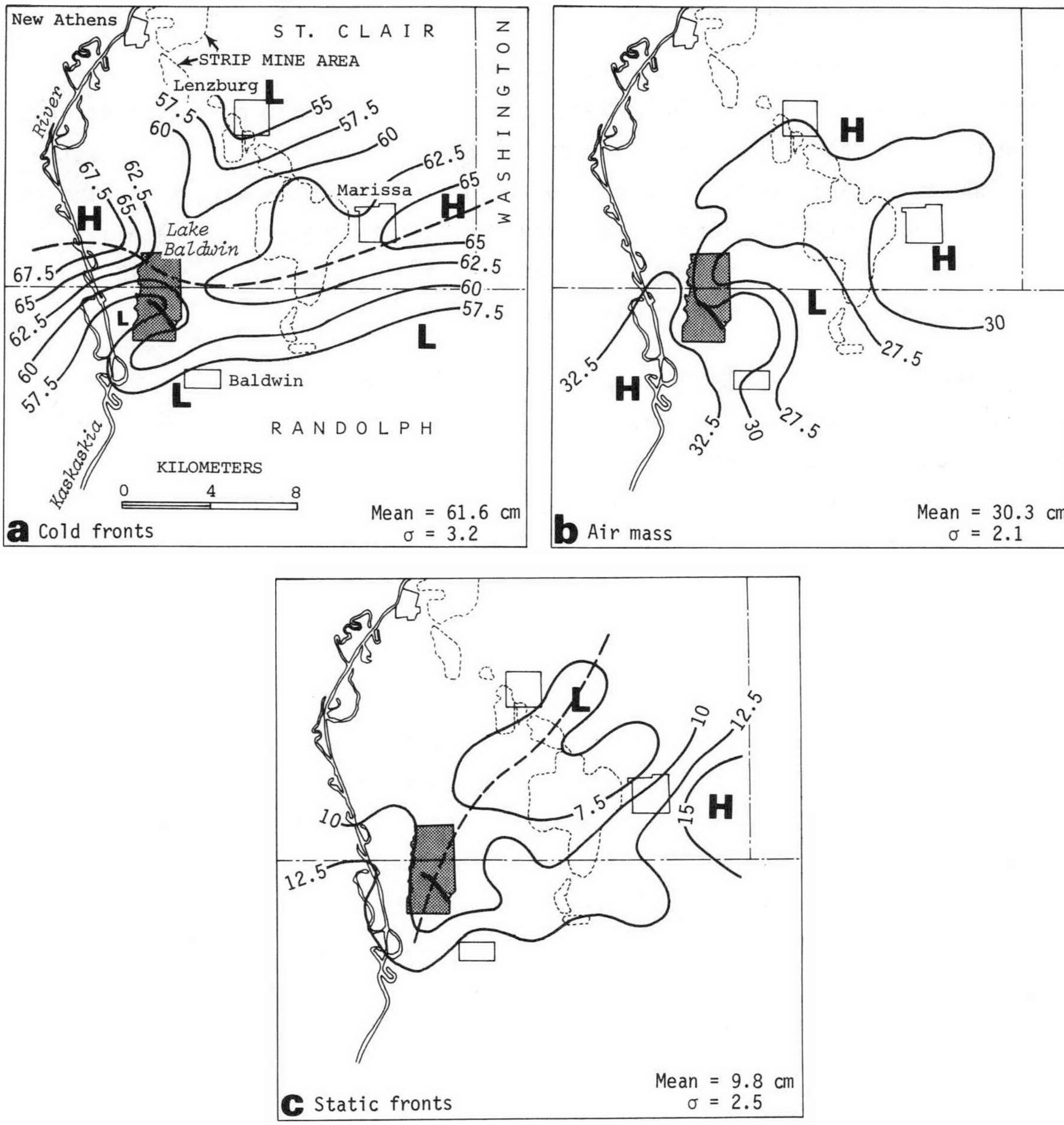

Figure 5-3. Rainfall pattern (mm) for a) cold front storms, b) air mass storms, and c) static front storms

Cold fronts, air mass storms, and static fronts were associated with 91% of the total rainfall. Another 7% occurred with warm fronts and low center passages. Both rainfall patterns had the familiar high in the eastern part of the network.

Overall, the synoptic patterns suggest the possibility of a lake-induced anomaly in the rainfall distribution, but the evidence can not be considered strong in view of the natural distribution pattern displayed for southern Illinois by the NWS climatic network which was discussed earlier.

GENERAL SUMMARY AND CONCLUSIONS

A dense raingage network was operated in the Baldwin area during July-November 1976 and March-November 1977. The objective was to investigate potential effects upon the regional rainfall pattern resulting from waste heat discharges into the cooling lake associated with the Baldwin power plant. Analyses were performed to determine seasonal distributions of total rainfall, the frequency of rainfall events, the effect of storm movements on network rainfall patterns, and the relation between rainfall and synoptic weather types.

Results of the two-year study were inconclusive. When rainfall for the two years was combined, there was a persistent high in the Baldwin network located 10-15 km (6-9 mi) east to east-northeast of the center of the lake. This apparent anomaly was especially prominent with storms moving from the southwest quadrant, placing the lake directly upwind of the observed maximum. However, the rainfall maxima in the eastern part of the network were in agreement with the natural rainfall distribution for southern Illinois during the sampling periods, as revealed by the NWS climatic network data.

The most positive evidence of a localized anomaly was its persistence in location during the sampling period. If this is a localized anomaly, it could also be related to topographic features to the west (upwind) of the network where ridges and bluffs apparently stimulate the development of cumulus and cumulonimbus, as shown in the previous section on enhancement of convective clouds. Since no evidence was found of convective cloud stimulation downwind of the lake, it appears unlikely that the relatively high rainfall in the eastern part of the Baldwin network in 1976-1977 can be attributed to a cooling lake effect on the environment. On the basis of presently available information, it is concluded that cooling lakes of the size of Baldwin (890 hectares, or 2200 acres) will not significantly modify the precipitation regime in the surrounding area.

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3. S. A. Changnon, F. A. Huff, P. T. Schickedanz, and J. L. Vogel. Summary of METROMEX, Volume 1: Weather Anomalies and Impacts. Urbana, IL: Illinois State Water Survey, 1977, Bulletin 62.

Section 6

TEMPERATURE AND MOISTURE PLUMES

INTRODUCTION

Cooling lakes are warmer than natural lakes in the same climatic region and latitude, and the average water temperatures are warmer than the average air temperatures during all seasons. The evaporation rate from such a lake will be greater than a natural lake (1). The air with an over-lake trajectory can be heated, and water evaporated from the lake surface will add moisture. Thus, the near-surface air has the potential of advecting warmer and moister air downwind. The hygrothermograph network around Baldwin Lake was used to investigate the magnitude of the temperature and moisture increase from the upwind to downwind shore and the downwind horizontal extent of these elevated values.

ANALYSIS

Temperature and dew-point data were stratified by prevailing winds at 0600 and 1500 CST and averaged for the month to determine possible climatic differences in the region surrounding Baldwin cooling lake. The winds were stratified into four quadrants: northeast (10^o to 90^o), southeast (100^o to 180^o), southwest (190^o to 270^o), and northwest (280^o to 360^o). On the average, the daily minimum temperature is experienced at 0600 CST near the time of maximum steam fog occurrence. As a result, the humidity plume should be best developed at that time. Normally, the maximum air temperature is recorded about 1500 CST and the cooling lake will normally have the least effect on air temperature at that time; however, the evaporative process will continue adding some moisture to the air. In addition to the monthly analyses presented in this section, temperature and dew-point data are shown for four days at 0600 and 1500 CST to illustrate the magnitude of the relatively large diurnal variations observed at Baldwin.

Monthly Averages

Figures 6-1 and 6-2 show average temperatures and dew points (^oC) stratified by prevailing surface winds at 0600 and 1500 CST for January 1977. This was the coldest month during the observational period from September 1976 to March 1978.

The average monthly temperature was -8.0°C (17.6°F) which was 8.7°C (15.7°F) below normal. The average maximum temperature for January 1977 was -2.9°C (26.8°F) and the average minimum was -13.1°C (8.4°F). The average water-air temperature difference in the warmest part of the lake was 20.2°C (36.4°F), and in the coolest part it was 13°C (23.4°F).

At 0600 CST (Figure 6-1a and b) temperature and dew-point increases from near zero to 2°C (4°F) were observed over the lake with northeast and southeast winds. Due to network design and the topography of the area, the downwind extent of these elevated air and dew-point temperatures could not be delineated. Air crossing the

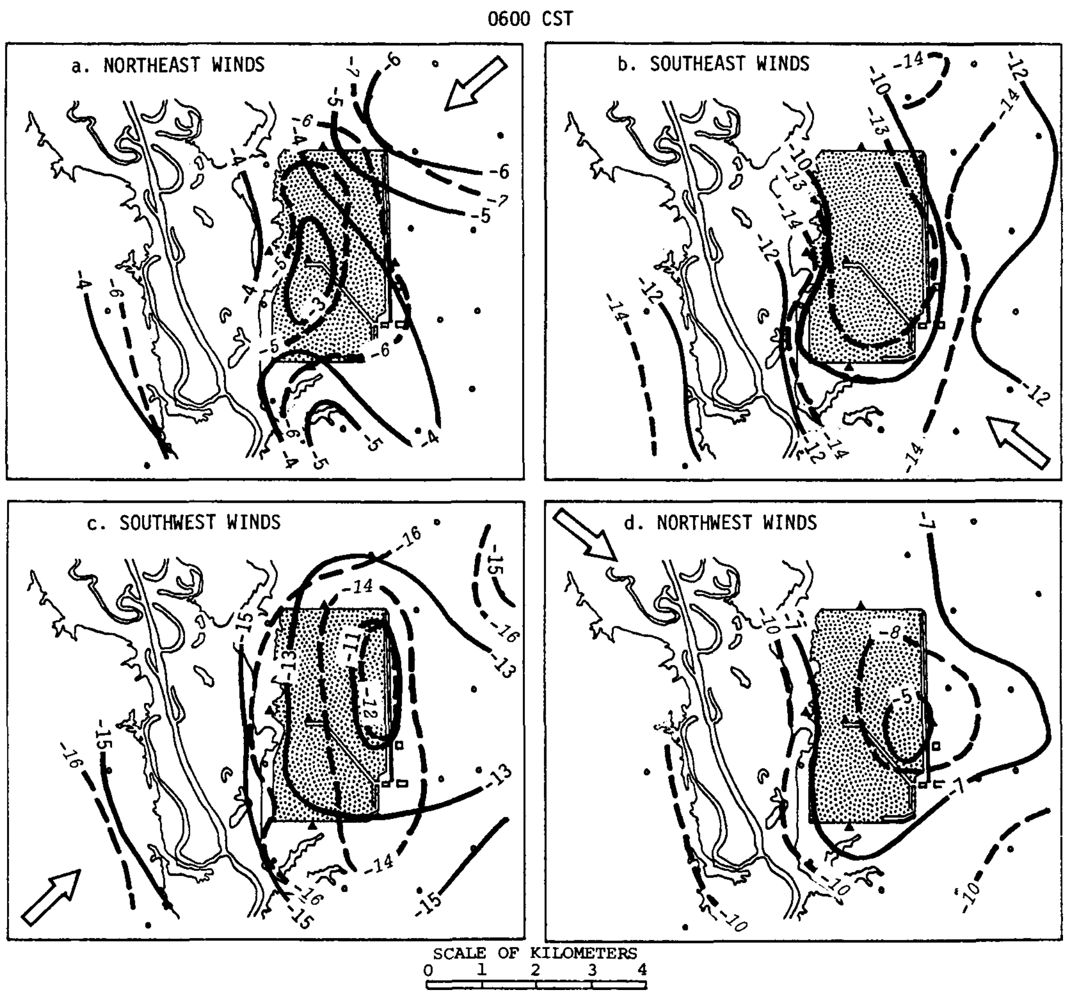

Figure 6-1. Air and dew-point temperature patterns for January 1977 at 0600 CST for a) northeast, b) southeast, c) southwest, and d) northwest winds

cooling lake with southwest or northwest winds (Figure 6-1c and d) showed temperature and dew-point increases of 2 to 3°C (3.5 to 5.5°F) from the upwind to downwind shore. The air and dew-point temperature maximums extended more easterly than northeasterly or southeasterly, with winds from both the southwest and northwest quadrant. This occurred because winds on most of the days were closer to west than south or north. The temperature and dew-point gradients were most pronounced within 0.8 km (0.5 mi) of the cooling lake with a decrease of about 1°C (2°F). Within 1.6 km (1 mi) the temperatures and dew points were again at or near the upwind values.

The air and dew-point temperatures maximized over or on the downwind lake shore for all wind directions. With southwest and northwest winds the over-lake trajectory was from cooler to warmer water, and the temperature and dew-point increases were greater than those with northeast and southeast winds, when the air moves from the warmer to cooler water. Thus, temperature and dew-point increases can be expected to maximize on days when the over-lake trajectory of the air is from cooler to warmer water.

The temperature and dew-point effects over the lake and on its downwind shore were less at 1500 CST than at 0600 CST for all wind stratifications (Figure 6-2). The largest dew-point increases, 2 to 2.5°C, occurred on days with northwest winds (Figure 6-2d). The upwind to downwind temperatures on these days only showed an increase of approximately 1°C (2°F). The temperature and dew-point gradients near the downwind shore were relatively strong, with most temperatures and dew points returning to or near upwind background values within 0.8 km (0.5 mi). For other wind stratifications, the temperature and dew-point increases between the upwind and downwind shores were 1°F (2°F) or less with only minor downwind plumes. In general, air and dew-point temperature changed from the upwind to downwind shore, and the temperature and moisture plumes at 1500 CST were not as large as at 0600 CST. The decreased extent of the temperature and dew-point plumes is related to increased vertical mixing in the lower layers of the atmosphere which diffuses the added heat and moisture through a greater depth of the atmosphere at 1500 CST, when the air tends to become more unstable from solar radiational effects.

The largest air temperature and dew-point increases from the upwind to downwind shore and the maximum plume extents were noted during January 1977. Similar temperature and dew-point increases were noted during early spring, but the downwind horizontal extent was not as great. In summer and fall, the temperature and dew-point increases at 0600 CST were about half those experienced during winter, and the plumes dissipated within 0.8 to 1.2 km (0.5 to 0.75 mi). Monthly temperature and dew-point increases (0.6^{o}C) were noted up to 1.6 km (1 mi) downwind during winter.

At 1500 CST, little temperature change from the upwind shore to the downwind shore was noted during any season other than winter. However, dew-point increases of 1 to 2^{o}C (2 to 4^{o}F) were noted in all seasons. Usually, these dew-point increases dissipated within 0.4 to 0.8 km (0.25 to 0.5 mi) of the downwind shore, which was similar to the winter observations.

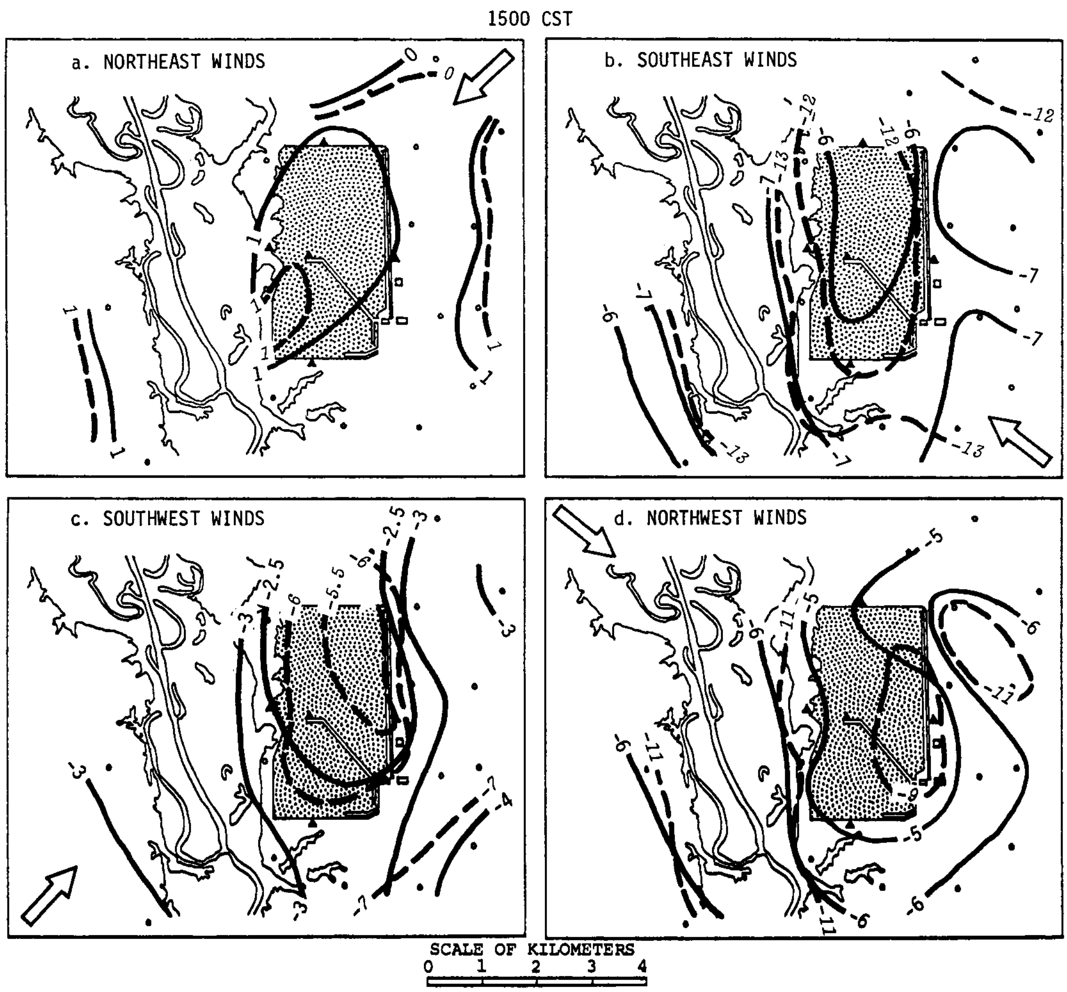

Figure 6-2. Air (T) and dew-point (T_d) temperature patterns for January 1977 at 1500 CST for a)northeast, b) southeast, c)southwest, and d)northwest winds

Hourly Values

Temperature and dew-point patterns at 0600 and 1500 CST are shown for four days (Figures 6-3 to 6-6). They show air temperature and dew-point changes ranging from no discernible increase to 4.4°C (8°F), plus elevated temperatures and dew points extending more than 2 km (1.25 mi) downwind. These cases were chosen to show some of the larger upwind to downwind air and dew-point temperature changes and downwind horizontal extents of these elevated temperatures. Winds were from the southwest or northwest in each case. On days with winds from the northeast and southeast, the increases from the upwind to downwind shore usually were not as large. No attempt to determine the downwind horizontal extent of the elevated temperatures could be made because of the network configuration and the surface topography around the lake.

13 October 1976. Figure 6-3 presents the air and dew-point temperature patterns for 13 October 1976 at 0600 and 1500 CST. The winds at 0600 CST on this day were from the west (280°) at 8 km/h (5 mi/h), and the water temperature varied from 15 to 22°C (59 to 72°F). The greatest air temperature difference between the upwind and downwind shores was 3.3°C (6°F), but it then decreased 1.7°C (3°F) in 0.4 km (0.25 mi) as the lake-exposed air moved downwind. A dew-point increase of 2.2°C (4°F) was observed from the upwind to downwind shore. Elevated air temperatures and dew points (0.6°C or 1°F) were observed 2 km (1.2 mi) downwind of the lake.

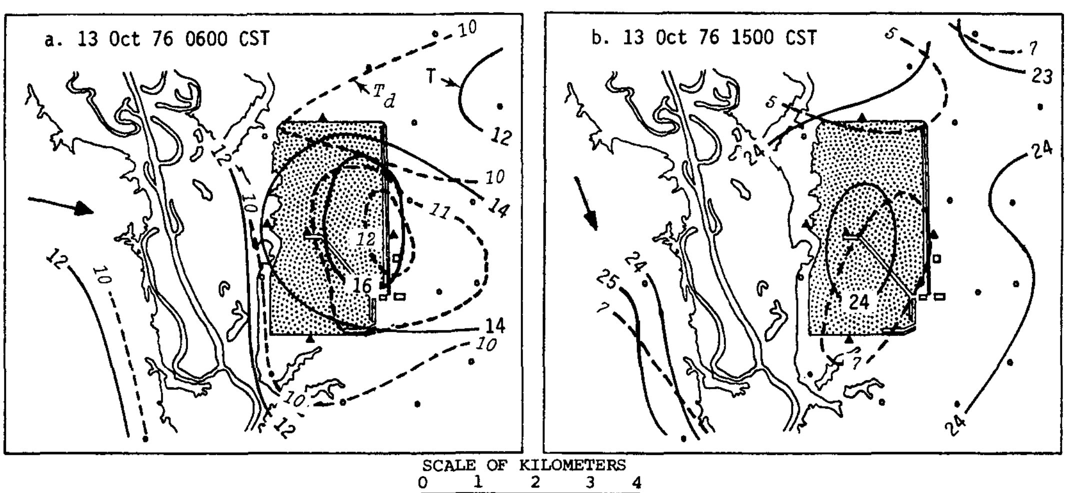

Figure 6-3. Air (T) and dew-point (T_d) temperature patterns for 13 October 1976 at a) 0600 CST and b) 1500 CST

By mid afternoon (1500 CST) the air temperature rose about 10°C (18°F), and winds were from the north-northwest (340°) at 18 km/h (11 mi/h). The water temperature varied from 17 to 26°C (62 to 79°F). The temperature pattern over the network showed little or no change due to the cooling lake, but the dew point increased as much as 3.0°C (5.4°F) from the upwind to downwind shore. The dew point approached the background value within 1.25 km (0.75 mi) of the downwind shore.

21 October 1976. The 0600 CST patterns on 21 October 1976 are shown in Figure 6-4a. On this morning, the winds were from the southwest (235°) at 11 km/h (7 mi/h), and the water temperatures varied from 10 to 21°C (50 to 69°F). The average air temperature was 1.1°C (34°F), and the dew point was -0.3°C (31.4°F). From the upwind to downwind shore the maximum temperature increase was 4.4°C (8°F), and the maximum dew-point rise was 1.7°C (3°F). Dew points approached the background values within 2 km (1.25 mi) of the cooling lake. Within the first 0.6 km (0.4 mi) downwind of the lake the temperature decreased 1.7°C (3°F), but some increase relative to the upwind background was detected more than 2 km (1.25 mi) downwind.

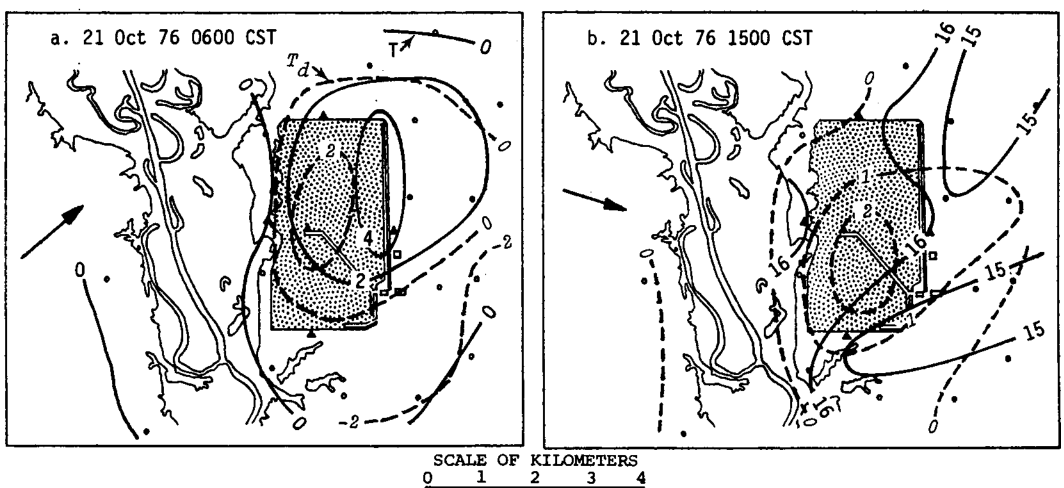

Figure 6-4. Air (T) and dew-point (T_d) temperature patterns for 21 October 1976 at a) 0600 CST and b) 1500 CST

Between 0600 to 1500 CST on 21 October the winds shifted from the southwest to the west-northwest (285°) at 19 km/h (12 mi/h). The water temperatures ranged from 10.5 to 22°C (51 to 72°F). The average air temperature on the sampling network was 15.6°C (60°F), and the dew point was 0.6°C (33°F). Only a minor air temperature rise (0.6^{o}C) was observed from the upwind to downwind shore, and no downwind temperature increases were detectable within 0.4 km (0.25 mi) of the downwind shore. A dew-point temperature increase of 2.2^{o}C (4^{o}F) on the downwind shore was noted, and an increase of 1.6^{o}C (1^{o}F) was observed 1.6 km (1 mi) from the downwind shore.

<u>18 January 1977</u>. On 18 January 1977 at 0600 CST the average air temperature was -18.3^{o}C (-1.0^{o}F), the average dew-point temperature was -21.7^{o}C (-7^{o}F), and the upwind relative humidity was 70 to 75%. West-northwest (300^{o}) winds at 21 km/h (13 mi/h) prevailed. The water temperature varied from 1.7 to 9^{o}C (35 to 48^{o}F). The water-air temperature difference was 26^{o}C (47^{o}F), and the upwind saturation deficit was 0.25 g/kg. Dense steam fog (zero visibility) was observed along the east side of the cooling lake and it extended about 0.8 km (0.5 mi) downwind. A maximum increase of 3.3^{o}C (6.0^{o}F) in air temperature was recorded, and a 5.6^{o}C (10^{o}F) dew-point difference was measured from the upwind to downwind shore (Figure 6-5a). The saturation deficit decreased from 0.25 to 0.1 g/kg from the upwind to downwind shore. Elevated air temperatures and dew points were observed within 0.8 km (0.5 mi) downwind of the cooling lake and these coincided with the visible steam fog plume.

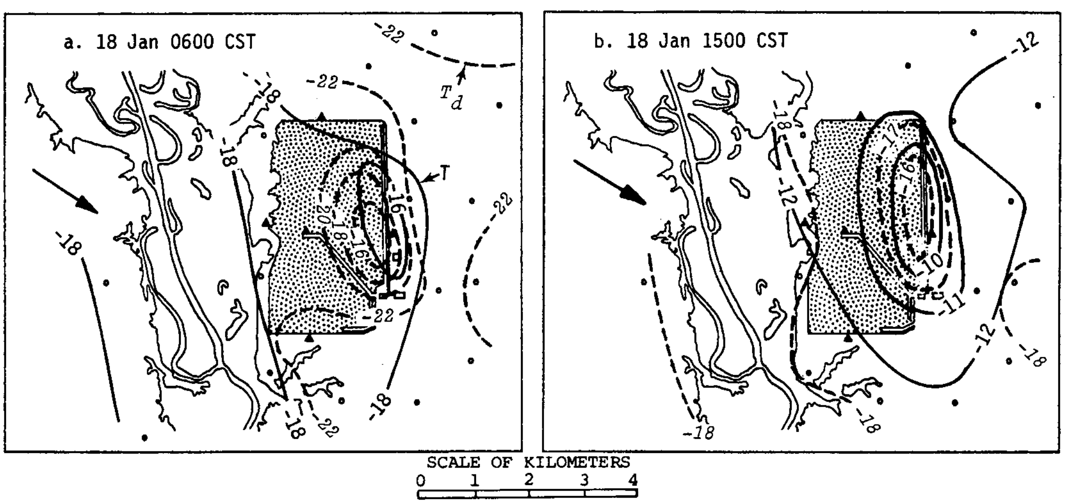

Figure 6-5. Air (T) and dew-point (T_d) temperature patterns for 18 January 1977 at a) 0600 CST and b) 1500 CST

By 1500 CST on 18 January the average air temperature on the network warmed to -12.2^{o}C (10^{o}F), and the average dew point was -17.8^{o}C (0^{o}F). The water temperature remained between 1.7 and 9°C (35 and 48°F), and the winds continued from the west-northwest at 20 km/h (12.5 mi/h). The air and dew-point temperatures increased 1.7°C (3°F) and 6.7°C (12°F), respectively, from the upwind to downwind shore (Figure 6-5b). The only downwind effect was an increase of 0.6°C (1°F) in air temperature recorded 1 km (0.6 mi) east of the lake. The upwind relative humidity ranged between 60 and 65%, but the relative humidity immediately adjacent to the east side of the cooling lake was 96%. The saturation deficit changed from 0.6 g/kg upwind to 0.1 g/kg on the downwind shore. Although there were relatively large increases in air and dew-point temperatures over the lake, the downwind effect was minimal. Steam fog continued over the warmer portions of the cooling lake, but the visibility was 1.6 km (1 mi) or greater, and little or no horizontal extent of the visible plume was evident. The air and dew-point temperature changes on this day were typical of the largest changes measured during the observational period.

<u>13 March 1977</u>. The patterns at 0600 and 1500 CST for 13 March 1977 are shown in Figure 6-6. At 0600 CST the average air temperature was 7.8°C (46.0°F), and the water temperature varied from 13.3 to 20°C (58 to 68°F). The winds were from the south-southwest (205°) at 14 km/h (8.5 mi/h). The network average dew point was 3.9°C (39°F). Both the air and dew-point temperature increased approximately 2°C (3.6°F) from the upwind to the downwind shore. Air and dew-point temperature increases of only 0.6°C (1.1°F) could be detected 2 km (1.25 mi) downwind.

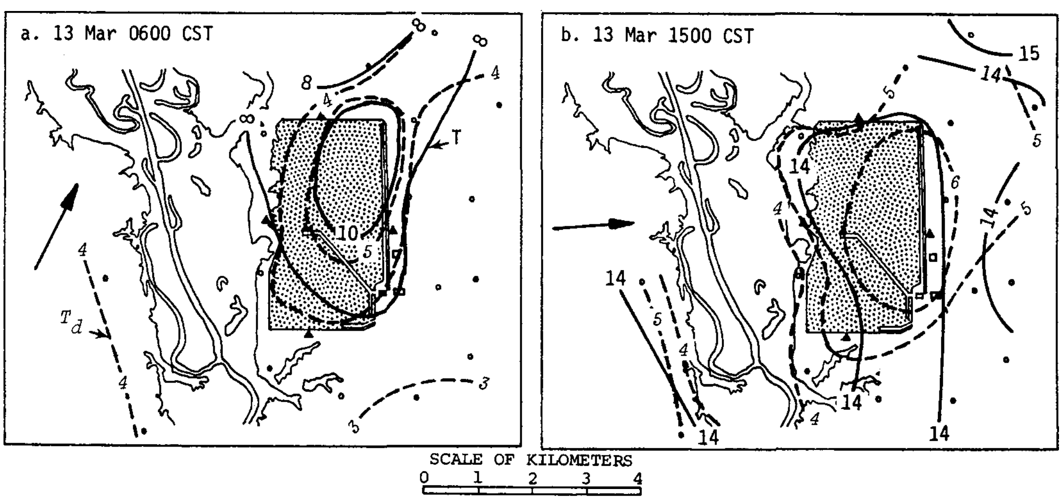

Figure 6-6. Air (T) and dew-point (T_d) temperature patterns for 13 March 1977 at a) 0600 CST and b) 1500 CST

The average air temperature on 13 March increased to 14.2°C (57.5°F) by 1500 CST. The dew point was 5°C (41°F). The winds shifted from the south-southwest to west (265°) at 15 km/h (9 mi/h). The water temperature varied from 15 to 22°C (59 to 72°F). From the upwind to downwind shore the air temperature increased about 1°C (2°F) and the dew-point by 1.7°C (3°F). The horizontal extent of these increases could be detected only within 0.4 to 0.8 km (0.25 to 0.5 mi) of the lake.

Summary. The four cases illustrated in Figures 6-3 to 6-6 represent some of the extreme increases in air and dew-point temperatures between the upwind and downwind shores, as well as the larger horizontal extents of the temperature and moisture plumes measured at Baldwin. In general, most temperature increases from the upwind to downwind shore did not exceed 1 to 2°C (2 to 4°F), and the horizontal extent of most elevated air and dew-point temperatures was confined to 0.8 km (0.5 mi) of the downwind shore. It was anticipated that the largest upwind to downwind air temperature and dew-point changes would be experienced with low wind speeds, because of the greater exposure time of the air over the lake. However, relatively large air temperature and dew-point changes occurred not only with light wind speeds of 5 km/h (3 mi/h) or less, but with speeds in excess of 20 km/h (12 mi/h) as well.

SUMMARY AND CONCLUSIONS

Prevailing surface winds at 0600 and 1500 CST were used to stratify air and dew-point temperatures to determine the magnitude of their increase from the upwind to downwind shore and the downwind horizontal extent of the elevated temperatures. The largest increases in monthly averages and the greatest horizontal extent of the elevated temperatures downwind from the cooling lake were realized during winter and spring.

Increases from the upwind to downwind shore, based on monthly averages, ranged from near zero to 3°C (5.5°F) at 0600 CST. Horizontal extents, on the average, were detectable only in the first 0.8 to 1.6 km (0.5 to 1 mi). The largest departures from the upwind to downwind shore were noted with southwest and northwest winds. In these instances, the trajectory of the surface air was from the cooler to the warmer water, so that the surface air was heated continually during its passage over the lake. With northeast and southeast winds, the surface air moved from warmer to cooler water, and the temperature and dew-point increases were not as large. It was not possible to determine the horizontal extents of the elevated temperatures with northeast and southeast winds, because of topography and network configuration. At 1500 CST, near the time of the maximum daily temperature, increases in air temperature from the upwind to downwind shore were minimal.

Increases in dew-point temperature from the upwind to downwind shore ranged between 0.5 and 3.0°C (1.0 and 6.0°F). However, the downwind extent of these elevated temperatures was only 0.4 to 0.8 km (0.25 to 0.5 mi) with southwest and northwest winds, or approximately 50% of the downwind extent experienced at 0600 CST.

Usually the air temperature in the morning is lower than the water temperature; more heat can be transferred from the water to the air passing over the lake surface. By midafternoon the air temperature approaches (or occasionally surpasses) the water temperature, and the amount of heat transferred is minimized. As a result, the air temperature pattern by midafternoon shows little or no effect from the cooling lake.

The dew point is normally lower than the air temperature. It equals the air temperature only when the air is saturated (relative humidity of 100%). The dew point is a more conservative quantity than the air temperature, i.e., the dew point, assuming there is no moisture advection, changes little during the day. As a result, in midafternoon water vapor due to evaporation from the lake surface can still produce considerable moisture input to the surface air. Thus, upwind to downwind dew-point increases can be anticipated in both the morning and afternoon. However, the atmosphere is usually less stable in the vertical during the afternoon. Thus, more mixing through a greater depth of the lower atmosphere occurs. This diffuses the added water vapor into the atmosphere more rapidly than in the morning and the added moisture is no longer detectable as far downwind.

On individual mornings (0600 CST), air temperature increases of as much as 4.4°C (8°F) and dew-point increases of 5.6°C (10°F) were noted from the downwind to upwind shores. These extremes are most likely during winter, when the air temperature and dew-point temperature are often substantially lower than the water temperature throughout the day. The horizontal extent of the elevated temperatures changes rapidly with increasing distance from the downwind shore. However, some minor elevated air temperatures and/or dew points (0.6°C or 1°F) were noted at Baldwin as far as 2 km (1.25 mi) downwind on some mornings. Usually, by midafternoon the air temperature increases were not as pronounced, and the horizontal extent was reduced to 0.8 km (0.5 mi) or not detectable. In general, most individual temperature increases from the upwind to downwind shore at 0600 CST varied from near zero to about 2°C (4°F). In the afternoon, air temperature increases ranged between zero to 1°C (2°F), and the dew-point increases were similar to the morning increases. The horizontal extent of most elevated air and dew-point temperatures was confined to within 1 km (0.6 mi) of the cooling lake during both morning and afternoon. Often, only minor or no temperature changes due to the cooling lake could be detected during the afternoon hours.

REFERENCE

1. R. L. Drake. A Review and Evaluation of Information on the Thermal Performance of Ultimate Heat Sinks: Spray Ponds and Cooling Ponds. Richland, WA: Battelle, Pacific Northwest Laboratories, September 1975, BNWL-B-446.

Section 7

TRACER EXPERIMENTS

INTRODUCTION

Several tracer releases were conducted at Baldwin to supplement the information yielded by the temperature and humidity data concerning lake-induced effects on the local weather. Data from such experiments provide useful information on 1) the dynamics of cooling-lake plumes, 2) the diffusion of water vapor and heat downstream from the cooling lake, 3) the effect of cooling lakes on the stability of the ambient atmosphere, and 4) the potential extent and diffusion characteristics of cooling-lake-induced fog.

The tracer used in the releases was sulfur hexafluoride (SF_6), a gas which is inert, nontoxic, colorless, tasteless, nonflammable, noncorrosive, and highly insoluble in cold water (1). It is readily detectable to as little as a few parts in 10^{13} parts of air by electron capture gas chromatographs (2, 3). Additionally, the background concentration of this gas in the atmosphere is extremely low, approximately 0.24 pp 10^{12} (4), making it ideal for use as a tracer. The primary commercial use of SF_6 is as an insulator for high-voltage transformers and switches. Thus, the natural background of this gas can be expected to be somewhat higher in the presence of a power plant and near high-voltage lines. Indeed, background studies near the Savannah River power plant at Aiken, South Carolina, showed the background level to be two times greater than the expected concentration (4). However, these concentrations are still extremely low and do not interfere significantly with tracer experiments.

In the Baldwin experiments, the tracer was released with near neutral-to-stable weather conditions and surface winds of 22 km/h (14 mi/h) or less. The releases were made for these prevailing weather conditions because these are the conditions during which the humidity, heat, and fog plumes should have their greatest impact upon the local environment (5, 6). Furthermore, the winds had a westerly component to minimize the effects of topography and to ensure that a reasonable distribution of samples was obtained downwind from Baldwin Lake.

To determine the weather situation most likely to prevail at Baldwin with the above weather restriction, 20 days with light winds having a westerly component were selected for synoptic analysis during the four winters of 1972-1973 to 1975-1976. As expected, the surface weather maps on these days were dominated by a high pressure area or ridge east of the Baldwin region with anticyclonic flow over the region. At 500 mb, zonal flow generally dominated the United States with a series of short-wave troughs moving from west to east.

The SF_6 tracer was released from a point source on the berm road leading to the center of the lake (Figure 7-1). Samplers were deployed at 1, 3, and 6 km (0.6, 1.8, and 3.6 mi) in arcs of 120^0 centered on the wind direction. In each arc there were 10 evacuated steel flasks with a volume of 900 cm^3 (54.9 in^3) equipped with critical orifices to sample the air at a controlled flow rate. The samplers were mounted on fence posts about 1.2 m (4 ft) above the ground and were opened for approximately 35 minutes. Two or three samplers during each release were placed upwind of the release point to provide background samples of SF_6.

Background samples were obtained on 28 October 1976 upwind and downwind of the Baldwin power plant. The average SF_6 background measurement for all 10 samples was 0.51 ± 0.02 pp 10^{12}. The concentrations ranged from 0.47 to 0.52 pp 10^{12} with no discernible maximums either downwind or upwind of the power plant. These concentrations agree well with the background measurements collected at the Savannah River power plant in South Carolina which measured 0.52 ± 0.03 pp 10^{12} (4).

The releases were made in cooperation with Dr. R. Dietz of Brookhaven National Laboratories. The Water Survey assumed the responsibility for the release of the SF_6, the required meteorological recordings, and the deployment, operation, and collection of the SF_6 bottle samplers. Brookhaven National Laboratories prepared and provided the sampler bottles and the chemical analysis.

CALCULATIONS

Calculations of the concentration of SF_6 along the centerline of the horizontal extent of SF_6 were made using the Gaussian plume equations. These calculations were made to determine if these equations can be used to calculate dispersion downwind from a cooling lake. The equations have been used extensively and are considered by some regulatory agencies to be the standard of comparison (7). According to Turner (8), the concentration of gas, χ, at some distance (x, y, z), from a continuous source at an effective release height, H, is

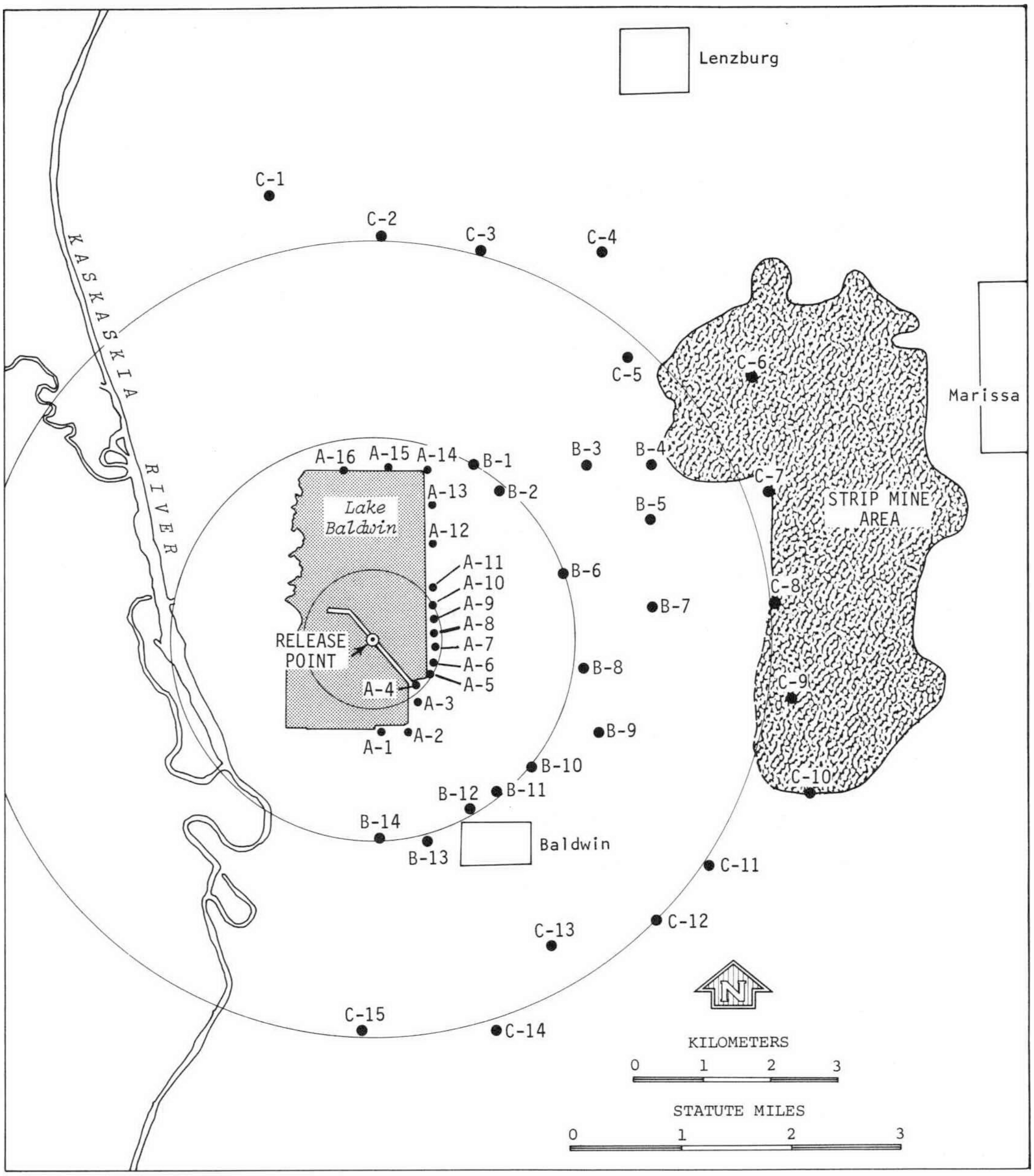

Figure 7-1. Baldwin tracer network

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

where Q is a uniform emission rate, σ_y and σ_z are the standard deviations of the plume concentrations in the horizontal and the vertical, respectively, and u is the average wind speed. This equation assumes 1) the vertical and horizontal spread of the gas will have a Gaussian distribution, 2) the wind speed affecting the plume can be expressed by a mean value, 3) there is a uniform emission rate, and 4) no deposition or reaction of the substance takes place.

For these tracer releases, the SF_6 was released at ground level, and no convective rise was associated with its release, reducing H to zero. All calculations were made for ground level, with z also reduced to zero. Thus, concentrations for this experiment could be calculated using the following form of the equation:

$$\chi\ (x,y,0,0) = \frac{Q}{\Pi \sigma_y \sigma_z u} \exp\ [-\frac{1}{2}(\frac{y}{\sigma_y})^2]$$

Estimations of σ_y and σ_z were made initially from Pasquill-Gifford-type curves as given by Turner (8). Such curves were established to describe the effects of mechanical and thermal diffusion over relatively flat terrain from ground-level sources, and should reasonably approximate the diffusion characteristics in the vicinity of Baldwin Lake.

As the sampling time increases beyond 10 minutes, the actual concentration will decrease downwind because of increasing meander of winds in the horizontal. As a consequence, to obtain downwind concentrations of SF_6 for the 35-minute sampling period, the calculated centerline concentration was modified by the following equation (8)

$$\chi_m = \chi(\frac{t_m}{t})^p$$

where χ_m is the modified concentration, t_m is the sampling time, t is the shorter sampling time, and p is a constant. For a 35-minute sampling period the centerline concentrations can be approximated by

$$\chi_m = 0.8_\chi$$

A similar reduction has been suggested by Gifford (7), and similar results were obtained.

It has been recommended (9) that σ_y should be modified by the downwind distance and the standard deviation of the horizontal wind angle. Also, the σ_z values should never exceed 0.8 of the mixing layer. Such modifications were made when possible.

The stability classification during the tracer releases was defined by the Pasquill stability categories (10), which are a combination of wind speed, cloud cover, and incoming solar radiation. The solar effect was determined in the manner suggested by Turner (8). Strong insolation corresponded to a solar altitude greater than 60° with clear skies; moderate incoming solar radiation occurred when the solar altitude ranged from 35 to 60° under clear skies; and slight incoming solar radiation was defined under clear skies by a solar altitude between 15 and 35°.

An alternate to the Pasquill definition of stability, the standard deviation of the horizontal wind direction, was used. The criteria for the various stability categories were as follows: extremely unstable (A), greater than 22.5°; moderately unstable (B), 17.5 to 22.5°; slightly unstable (C), 12.5 to 17.5°; neutral (D), 7.5 to 12.5°; slightly stable (E), 3.8 to 7.5°; and moderately stable (F), 1.6 to 3.8°.

TRACER RELEASES

Three tracer experiments were carried out during the winter and early spring of 1978. One experiment was attempted during the winter of 1977, but extremely cold weather during January caused the seals around the samplers to crack, and no data were collected.

22 February 1978

The first tracer release was on 22 February 1978. The National Weather Service surface map showed no frontal activity within 800 km (500 mi) of Baldwin. The major surface feature was a high pressure area centered in the Gulf of Mexico off the east coast of Texas, with a ridge extending north-northeast across southwestern Illinois to Lake Superior.

The SF_6 release began at 0645 CST, and the last sample was collected at 1045 CST. The winds from 0700 to 0800 CST, when the samples for the 1-km (0.6-m) arc were collected, varied from the south-southwest to west-southwest at 12.5 km/h (7.5 mi/h), with a wind shift from the west-southwest to south-southwest occurring between 0700 to 0715 CST. As the samples for the 3-km (1.8-mi) arc were being collected (0800 to 0900 CST), a gradual wind shift from the south-southwest to the south occurred. The winds between 0900 to 1100 CST were from the south (170 to 180°) at 11 to 19 km/h (7 to 12 mi/h).

The sky at 0700 CST was clear. Some thin cirrus clouds moved onto the western horizon at 0900 CST, but by 1100 CST they covered less than 0.4 of the sky. Some light steam fog was noted between 0600 to 0730 CST. The steam fog did not restrict the visibility, had a vertical extent of 3 m (10 ft), and remained confined to the lake.

The Pasquill stability classes varied from slightly stable (E) to slightly unstable (C) during the collection of samples from the 1-km (0.6-mi) arc (0715 to 0800 CST). From 0800 to 1100 CST slightly unstable (C) conditions prevailed. The standard deviation of the wind direction indicated a neutral (D) stability class from 0700 to 0300 CST, and slightly unstable (C) for the remainder of the tracer sampling period.

For the 1-km (0.6-mi) arc (Table 7-1) the calculated centerline concentration was considerably higher than the measured concentration, and the crosswind extent of the SF_6 was greater than the calculated values. As indicated, the wind direction shifted from the west-southwest to south-southwest between 0700 to 0715 CST. As a result, the measured downwind concentrations were lower and the crosswind extent was greater than indicated by the equation computations. The lower measured values appeared to have been caused by the wind shift, which spread the SF_6 over a wider path.

The gradual wind shift from south-southwest to south between 0800 and 0900 CST dispersed the SF_6 over a wider area, and SF_6 concentrations of 0.3 to 0.4 $\mu g/m^3$ were measured over a width of 1.6 km (1 mi) in the 3-km (1.8-mi) arc. Consequently, the calculated concentrations were larger than the measured values. The winds during the sampling period for the 6-km (3.6-mi) arc remained from the south, and the calculated centerline concentrations were within 15 to 30% of the measured values. The calculated crosswind extent of the SF_6 from the centerline to the background value of SF_6 was 650 to 900 m (1970 to 2950 ft) low. Overall, the calculations and measurements for the 6-km (3.6 mi) arc were in reasonable agreement. Note the relatively large changes in concentrations and crosswind extent produced by relatively fast horizontal and vertical dispersion of the SF_6.

Table 7-1

CALCULATED AND MEASURED RESULTS FROM SF_6 RELEASE ON 22 FEBRUARY 1978

	Downwind Distance (km)		
	1	3	6
Pasquill Stability	E to C	C	C
Calculated Centerline Concentration ($\mu g/m^3$)	17.3 to 104	2.9	0.9
Calculated Crosswind Extent (m)	220-415	1000	1650
Stability from Standard Deviations of Winds	D	C	C
Calculated Centerline Concentration ($\mu g/m^3$)	52.3	2.9	0.9
Calculated Crosswind Extent (m)	300	1000	1650
Pasquill Stability	E to C	C	C
Calculated Centerline Concentration* ($\mu g/m^3$)	57 to 161	3.4	0.8
Calculated Crosswind Extent* (m)	140	720	1400
Measured Centerline Concentration ($\mu g/m^3$)	5.1	0.4	0.7
Measured Crosswind Extent (m)	700-1000	1300	2300

* σ_y and σ_z modified as recommended by Hanna *et al*. (9)

16 March 1978

The second tracer experiment began at 1446 CST and was terminated at 1813 CST on 16 March 1978. The surface features at 1500 CST showed a low off the coast of Virginia and a high-pressure ridge from the Dakotas to Texas. The pressure field across southern Illinois was flat with only a 0.7-mb gradient from St. Louis, Missouri, to Evansville, Indiana (Figure 1-1), a distance of 270 km (168 mi).

Cumulus and stratocumulus clouds with 0.6 to 0.8 sky cover were observed at 750 to 900 m (2500 to 3000 ft) from 1400 to 1730 CST. The clouds became scattered (0.5 sky cover) by 1800 CST. The wind speeds throughout the tracer release averaged 22 km/h (13.5 mi/h) at the 10-m (30-ft) level. From 1400 to 1600 CST the winds were from 315^{o}, shifting to 330^{o} from 1600 to 1800.

The incoming solar radiation was slight throughout the period, and the stability classification according to Pasquill was neutral (D). The standard deviation of the wind direction indicated that the stability in the lower levels was moderately unstable (B) from 1500 to 1600 CST when the 1-km (0.6-mi) samples were taken. During the remainder of the sampling period neutral (D) stability was indicated.

For the 1-km (0.6-mi) arc (Table 7-2) the calculations using the indicated Pasquill stability class (D) were about 3.5 to 4 times the measured values. The moderate instability indicated by the standard deviation of the winds provided the closest approximation to the actual centerline concentrations. When this stability classification (B) was used to calculate the centerline concentration and the crosswind extent with the modified form of σ_y, a value of 7.9 $\mu g/m^3$ along the centerline and a crosswind extent of 300 m were obtained. These values are good approximations of the actual measured values. In general, the calculations for the 3- (1.8-) and 6-km (3.6-mi) arc were higher than the measured amounts by two to six times.

The presence of stratocumulus clouds indicated that there was some slight instability in the lower levels. Therefore, the stability classification was modified from neutral (D) to slightly unstable (C), and the calculations repeated. The centerline concentrations using the σ_y and σ_z from Turner (8) for the 1- (0.6-), 3- (1.8-), and 6-km (3.6-mi) arc were then 8.7, 1.6, and 0.4 $\mu g/m^3$, respectively. These values are all within 15 to 50% of the measured centerline concentrations. Thus, when the original stability classification was modified according to the synoptic conditions observed during the tracer release, the Gaussian equations provided good approximations of the actual measured centerline concentrations and their associated crosswind extents.

Table 7-2

CALCULATED AND MEASURED RESULTS FROM SF_6 RELEASE ON 16 MARCH 1978

	Downwind Distance (km)		
	1	3	6
Pasquill Stability	D	D	D
Calculated Centerline Concentration ($\mu g/m^3$)	26.5	6.3	2.2
Calculated Crosswind Extent (m)	340	720	1220
Stability from Standard Deviations of Winds	B	D	D
Calculated Centerline Concentration ($\mu g/m^3$)	3.1	6.3	2.2
Calculated Crosswind Extent (m)	660	720	1220
Pasquill Stability	D	D	D
Calculated Centerline Concentration* ($\mu g/m^3$)	29.7	7.6	1.3
Calculated Crosswind Extent* (m)	300	600	2100
Measured Centerline Concentration ($\mu g/m^3$)	7.7	1.1	0.5
Measured Crosswind Extent (m)	400 to 500	500 to 900	1700 to 2200

* σ_y and σ_z modified as recommended by Hanna *et al*. (9)

31 March 1978

The tracer release began at 0536 CST on 31 March 1978, but due to mechanical difficulties the first sampler was not opened until 0630 CST. The last sampler was closed at 0910 CST, and the tracer release was terminated at 0920 CST. The surface map at 0600 CST showed a sprawling high pressure ridge from the Gulf of Mexico to Virginia, and a warm front which stretched across northeast Illinois to Virignia from a low pressure area over the Dakotas. The warm front moved slowly north during the tracer release, and the sky was clear.

The average wind direction between 0500 to 0800 CST at the 10-m (30-ft) level was 190 to 200^o at 9 to 12 km/h (6 to 7.5 mi/h). From 0800 to 1000 CST, the winds ranged from 200 to 210^o at 13 to 16 km/h (8.5 to 10 mi/h).

During the sampling period, the stability categories according to the Pasquill scheme ranged from slightly stable (E) at 0600 CST to slightly unstable (C) between 0800 and 0900 CST. According to the standard deviation of the wind direction, the stability classes ranged from neutral (D) at 0600 CST to slightly unstable (C) between 0800 and 0900 CST. Both stability classes were in substantial agreement.

The calculated and measured centerline concentrations and crosswind extents are given in Table 7-3. No centerline measurements could be made in the 1-km (0.6-mi) arc because the SF_6 plume was over the lake and samplers could not be deployed. According to the Pasquill stability categories, the stability for the 3-km (1.8-mi) arc varied during the sampling period from slightly stable (E) to neutral (D) conditions. The actual centerline concentration of SF_6 was about midway between the two calculated values, which is excellent agreement. Similarly, the measured and calculated crosswind values obtained by varying the σ_y value, as recommended by Hanna et al. (9), and by determining the stability from the standard deviation of the wind also agreed well with the measured values.

The stability according to both classification systems during the sampling of the 6-km (3.6-mi) arc was slightly unstable (C). All of the calculated centerline concentrations were the same, but they were lower than the measured concentration (0.5 $\mu g/m^3$ compared to 2.1 $\mu g/m^3$). The calculated crosswind extent of SF_6 for all three computations agreed well with the measured value. The standard deviation of wind direction was almost in the neutral (D) stability class. The calculated centerline concentration for the neutral stability class was 2.7 $\mu g/m^3$, substantially in agreement with the measured centerline concentration. The calculated crosswind extent was 1330 m (4363 ft), comparable to the measured crosswind extent.

Table 7-3

CALCULATED AND MEASURED RESULTS FROM SF_6 RELEASE ON 31 MARCH 1978

	Downwind Distance (km)	
	3	6
Pasquill Stability	D to E	C
Calculated Centerline Concentration ($\mu g/m^3$)	12.6 to 25.9	0.5
Calculated Crosswind Extent (m)	500 to 650	1725
Stability from Standard Deviations of Winds	D	C
Calculated Centerline Concentration ($\mu g/m^3$)	12.6	0.5
Calculated Crosswind Extent (m)	650	1725
Pasquill Stability	D to E	C
Calculated Centerline Concentration* ($\mu g/m^3$)	12.4 to 19.2	0.5
Calculated Crosswind Extent* (m)	665 to 690	2370
Measured Centerline Concentration ($\mu g/m^3$)	18.2	2.1
Measured Crosswind Extent (m)	600	1400 to 1900

* σ_y and σ_z modified as recommended by Hanna _et al_. (_9_)

SUMMARY AND CONCLUSIONS

Estimates of the dispersion rate of water vapor and heat downwind from a cooling lake were obtained from three tracer releases of SF_6 from a point source over the lake. Preliminary measurements of the SF_6 background indicated a concentration of 0.51 pp x 10^{12}. This is in agreement with other background measurements by Dietz et al. (5).

The transport of heat and water vapor downwind from a cooling lake is most likely to be detectable at ground level when the lower levels of the atmosphere are in a stable to near-stable state. As reported in Section 6, the greatest downwind extents of temperature and moisture plumes occurred during the winter and spring months. Consequently, the three SF_6 releases were made during these seasons. No attempt was made to test the dispersion rate under moderately or extremely unstable (A or B) conditions, since the primary atmospheric effect, steam fog, does not occur normally with such conditions.

SF_6 was used to simulate the advection of moisture and heat, both of which are important to the formation of steam fog and to the downwind extent of the visible fog plume moving off the lake. As expected, the results of the tracer releases indicate that significant concentrations of moisture and/or heat are most likely to occur with a neutral or stable atmosphere near the surface. However, the dispersion under these relatively favorable stability conditions will usually be large, as indicated in Tables 7-1 to 7-3 by the measurements of centerline concentrations and crosswind extent from 1 (0.6) to 6 km (3.6 mi) downwind.

The three tracer experiments show mixed results with respect to the prediction accuracy of the Gaussian plume equations. In one experiment the computations agreed satisfactorily with the measured values of centerline concentration and crosswind extent. In another case, most measurements and equation computations disagreed by relatively large amounts. In the third experiment, the crosswind extents computed from the equations were in satisfactory agreement with the measured values, but the centerline concentrations were in considerable disagreement. In the second experiment (16 March 1978), it was found that the equation predictions and measured values were in good agreement, if the stability class dictated by the computation method was modified to take into account the synoptic weather conditions observed during the experiment.

Thus, from the three experiments, indications are that accurate estimates of the downwind concentrations and crosswind extent of fog plumes off a cooling lake are not provided consistently by the equation predictions. One cause of the inconsistency in the predictions appears to be shifting winds during the period of interest. Another likely source of computational error is the selection of the proper stability class for the calculations, as suggested by the case of 16 March 1978.

It has been suggested (11) that the stability of the air near the surface of the cooling lake is more unstable than indicated by the Pasquill stability classes or other stability classification methods because of the heated water causing increased convection. The smaller than calculated concentrations of SF_6 in two of the tracer releases support this contention, that is, instability appears to be enhanced substantially over the cooling lake. The above finding provides support for modifying the stability criteria used in the Gaussian equations, if they are to be applied to cooling lake plumes. Perhaps adjustment of the indicated Pasquill stability by one class would be more appropriate in these situations. For example, an indicated E would be changed to D, D to C, etc. Tracer data were insufficient to pursue this problem further.

Measurements made in the three tracer experiments clearly illustrate the large amount of dispersion of aerosols that occurs within relatively short distances of the source. For example, the centerline concentration of SF_6 decreased by 80 to 90% as the gas moved from 1 to 6 km (0.6 to 3.6 mi) downwind. Similarly, the crosswind extent of the plume increased by 3 to 4 times in the same distance. This rapid dispersion helps explain why the downwind areal extent of lake-generated steam fog was so limited in the Baldwin region during the study period, as discussed in Section 2.

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