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ADVECTION–RADIATION FOG NEAR LAKE MICHIGAN*

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Abstract—Two years of visibility measurements made about 1 and 19 km from Lake Michigan are analyzed to determine occurrences of advection–radiation fog. Occurrences at both stations are most frequent in the summer months, and the 1-km station has about twice as many hours of fog as the 19-km station. The reason is that a combination of onshore gradient winds and lake breezes acts to maintain higher average relative humidities at the 1-km station, with terrain differences of secondary importance.

1. INTRODUCTION

A study has been underway since 1972 to determine and evaluate meteorological effects of mechanical-draft cooling towers at the Palisades Nuclear Plant. The nuclear plant is located on the southeast shoreline of Lake Michigan about 10 km south of South Haven, Michigan, and is capable of producing about 700 MW(e). It uses 36 cells of mechanical-draft cooling towers arranged in two parallel blocks, each of which is 200 m long, 16 m wide and 23 m high. The cooling towers may evaporate as many as 12,000 gal (600 kg) of water per minute. (USAEC, 1972).

The plan of the study is to obtain four years of measurements of those variables likely to be affected by operation of the cooling towers. Effects of the plume on temperature, humidity, precipitation, fog and icing inland from the cooling towers are of main interest. In keeping with a construction schedule for the cooling towers, the plan provides for about two years (1973–1974) of measurements prior to their operation and for two years during it. The final evaluation of their impact will be based on an analysis and comparison of preoperational and operational data, case studies and observations and photographs of the cooling tower plume. Thus far, operational data have been obtained from 4 April to 20 December 1975 and since 11 May 1976.

Because of the importance of fog, it has been measured in terms of a sensor-equivalent visibility at two locations since 1973. The purpose of this paper is to describe an analysis of advection–radiation fog measured prior to the operation of the cooling towers and to summarize briefly some preliminary results obtained during their operation.

2. METEOROLOGICAL NETWORK

In 1972–1973, a network of 13 stations was established and equipped to measure the variables given above except for icing, which was to be observed by plant personnel. A map showing station locations is given in Fig. 1. They extend inland from the cooling towers in general SE, E and NE directions. Measurements of temperature, relative humidity and precipitation are made at all stations. Stations 3 and 7 are principal stations because, in addition to measurements of the above variables, they have equipment to measure wind velocity at 3 m, total solar radiation and visibility. As shown in Fig. 1, station 3 is 0.9 km from the cooling towers and station 7 is 19 km inland. Because station 7 is out of range of direct influence of the cooling towers, it is considered to be a control station.

3. VISIBILITY MEASUREMENTS

Sensor-equivalent visibility at stations 3 and 7 is measured with Model 1580 Fog Visiometer systems manufactured by Meteorology Research Incorporated, Altadena, CA. It is recorded on a strip chart recorder as an analog voltage which is proportional to the atmospheric scattering coefficient. The analog signal is digitized manually with a sonic digitizer and processed by computer in terms of meteorological range, which is a measure of the clearness of the atmosphere and serves as an upper limit to other definitions of visibility (Middleton, 1952).

Visibility data are sorted into episodes during which a meteorological obstruction to visibility occurred and reduced it to 3 km or less. The reasons for choosing 3 km are that (1) the visiometer did not appear to respond accurately to changes in visibility which occurred at greater distances and (2) the operational significance of changes for visibilities greater than 3 km is small. Each episode was assigned a beginning and ending time and was further broken down into time periods, to the nearest minute, that the visibility remained below 3, 1 and 0.5 km at each station.

The type of obstruction was determined on the basis of (1) hourly weather observations made 19 km

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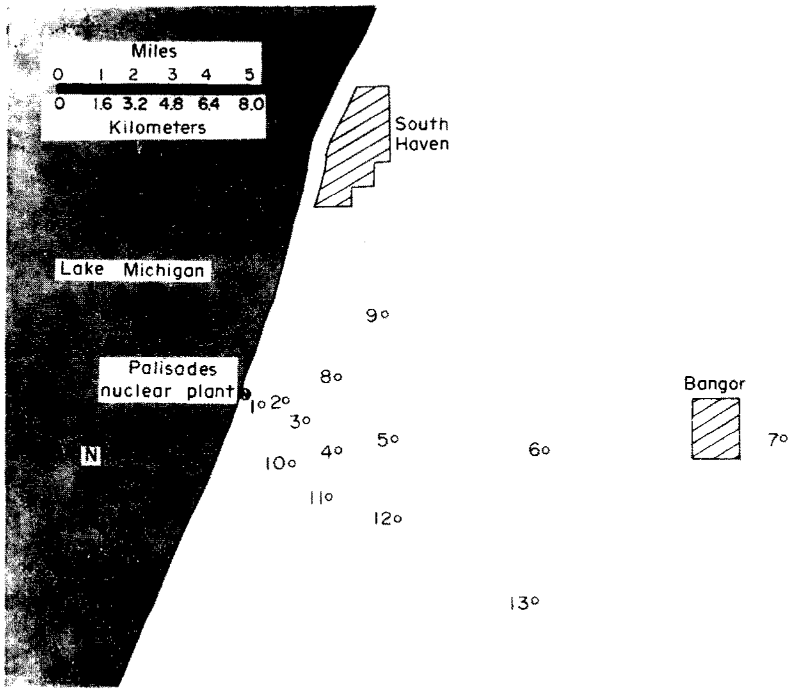

Fig. 1. Locations of stations in Palisades meteorological network.

away at the Federal Aviation Administration station at Benton Harbor Airport between about 05:00 and 21:00 h local time and at National Weather Service stations farther away on a 24-h basis and (2) measurements of precipitation, relative humidity and other variables within the meteorological network. If fog caused the obstruction, the above information plus that obtained from surface weather maps were used to decide if it were classifiable as advection–radiation type fog.

4. FOG CLASSIFICATION AND CLIMATOLOGY

In the classification system proposed by George (1951), advection–radiation fog is defined as the type occurring in an air mass which has moved over an extensive water surface during the daylight hours preceding the night before its formation due to radiative cooling. The proximity of the stations to Lake Michigan plus the high frequency of onshore gradient winds which are frequently enhanced by lake breezes in spring and summer cause advection–radiation fog to be the most frequent type in the warm seasons.

Climatological information on fog occurrences in the coastal region near the cooling towers was obtained to supplement the measurements made at each station. The nearest representative observations made on a 24-h basis are those for the National Weather Service station at Muskegon, Michigan, located 112 km north of the network and 6 km inland. A study of all types of fog was made by Koss and Altomare (1971) using 4.5 y of Muskegon data. Their results indicate that: (1) During the summer months fog occurs on about 19% of the total observations made at 05:00 h local time and that; (2) About 37% of all hours of fog occur during the winter quarter of the year, a finding they attribute to the increased vertical flux of moisture from Lake Michigan and to frequent passages of frontal systems.

Their results and other climatological information for Muskegon provide a basis for comparison in assessing the effects of the cooling towers not only on producing and/or enhancing fog but also on other meteorological variables.

5. OCCURRENCES AT STATIONS 3 AND 7

The number of hours of advection–radiation fog which reduced the visibility to 3, 1 and 0.5 km in 1973 and 1974 at stations 3 and 7 is listed in Table 1. The significance of the 0.5-km distance is that if fog reduces the visibility to this distance it is classified by the National Weather Service as heavy fog. Also given in Table 1 is the number of hours of data used in the computations each month. It can be noted that significant portions or even all data for some months are missing because of failures of a visiometer or a recorder. Even though several months have incomplete data, however, significant differences in the number of hours of fog at the two stations are evident as well as variations at each station throughout the year. Some features of Table 1, e.g. are the following: (1) For months with at least 90% data recovery at both stations the number of hours of fog at station 3 is significantly greater than at station 7; (2) The months of July, August and September have the most hours of fog and December, January and February have the fewest.

Table 1. Hours of advection–radiation fog by month for stations 3 and 7

	Station 3				Station 7			
Month	Hours of data	Visibility (km) ≤3	≤1	≤0.5	Hours of data	Visibility (km) ≤3	≤1	≤0.5
1973								
May	532	34.4	18.6	7.9	379	13.1	9.2	7.4
June*	720	59.2	41.8	17.1	652	18.5	0.9	0.8
July	744	75.7	29.5	14.3	727	38.2	9.8	4.8
Aug.	718	103.5	47.1	28.1	455	26.7	3.4	0.9
Sep.	720	61.9	29.3	12.3	439	13.6	4.9	2.1
Oct.*	737	87.5	44.6	21.5	744	25.3	8.8	4.9
Nov.	720	5.7	3.9	3.8	420	5.4	4.4	1.9
Dec.*	725		None		744		None	
1974								
Jan.	0				718		None	
Feb.	371		None		633	10.7	9.2	8.9
Mar.	444	5.5	3.9	3.2	493	5.9	4.7	4.3
Apr.	0				0			
May	319	6.6	5.8	2.9	561	13.8	4.1	0.1
June*	720	51.5	33.6	20.2	718	25.9	9.5	1.9
July*	744	78.1	30.	13.3	744	20.6	7.6	5.4
Aug.	642	93.8	29,6	6.7	504	23.9	2.8	0.8
Sep.	672	119.2	75.4	49.9		Data unreliable		
Oct.	744	14.3	0.9	0		Data unreliable		
Nov.	720	31.9		8.8		Data unreliable		
Dec.			None			Data unreliable		

* Greater than 90% data recovery at both stations.

The hours of fog given in Table 1 were analyzed to determine how often fog occurs at both stations together or at one and not the other. Such information is operationally more significant than only the total hours of fog each month because if the cooling towers increase fog, the increase will more likely occur at station 3 than at station 7. If a significant increase in fog occurs at station 3 and not at 7 during cooling tower operation, for example, it may be possible to quantify the increase with a 2 by 2 contingency table similar to that shown in Table 2.

The numbers comprising Table 2 are hours of fog which reduced the visibility to 3 km or less at either or both stations. Beginning and ending times of fog episodes were used. The table is called tetrachoric because four possibilities are considered. They are: (1) the number of hours when both stations had fog at the same time, (2) the number of hours when station 3 did but 7 did not, (3) the number of hours when station 7 did but 3 did not and (4) the number of hours when neither station did. For the data used, fog occurred at one or both stations on 130 different days, so there could have been as many as 3120 h with fog on those days.

Table 2. Tetrachoric table of hours of advection–radiation fog at stations 3 and 7 for visibility ≤3 km

		Station 3 Fog	No fog	Total
Station 7	Fog	158.9	44.3	203.2
	No fog	337.8	2579	2916.8
	Total	496.7	2623.3	3120

One of the most significant features of the results shown in Table 2 is that there are only about 44 h when fog occurred at station 7 but not at 3, yet there are about 338 h when fog occurred at station 3 but not at 7. In addition, station 3 had over twice (496.7/203.2) as many hours with fog as station 7.

6. LAKE AND TERRAIN EFFECTS

It is well known that the formation of radiation fog on a given night is favored by the simultaneous occurrence of several general meteorological conditions, the most important of which are the following: (1) High relative humidity; (2) Cloudless sky or high scattered clouds to allow rapid radiative heat loss; and (3) Light surface winds to distribute the cooling vertically.

The condition probably most effective in causing more frequent and longer lasting fog at station 3 is a higher average relative humidity nearer Lake Michigan, especially in summer. Observations in the network indicate that the other two conditions are less important. For example, significant differences in the frequency of cloudless skies or light surface winds for the two stations, in relation to their effects on the results given in Table 2, were not observed.

The fact that relative humidity can be increased by decreasing the temperature and/or increasing the dew point is of major importance in explaining the observed results. Cool and relatively moist lake air moves inland past station 3 on most days in the warm seasons due to onshore gradient winds and/or lake breezes. As instability of the air increases inland, turbulent mixing is enhanced, the air warms and relative humidity decreases in a vertically increasing layer. Evidence for this type of boundary layer development as it affects diffusion processes near coastlines is given by Van der Hoven (1967) and by Lyons and Olsson (1972). Warming of the lake air with distance inland in itself lowers the relative humidity even though dew point may change very little. In spite of the fact that both stations may be in lake air, therefore, measurements show that the relative humidity at station 7 is about 10% lower than at station 3 on afternoons preceding fog formation. As a result, less radiative cooling on such days is required for the air at station 3 to reach saturation, so fogs characteristically form sooner.

Also having a significant effect on conditions leading to fog formation at station 3 but not at station 7 is the true lake breeze, defined here as lake air which moves inland either directly against an offshore gradient wind or against some component of it. How far inland the lake breeze front penetrates and remains through sunset determines about how far inland fog will form, since it separates warm and dry land air from the comparatively cool and moist lake air.

A total of 80 true lake breezes was observed and analyzed using measurements from the meteorological network for March–September of 1973, 1974, and 1975 (Ryznar and Weber, 1976). Of these, 30 moved inland at least as far as station 7. Another 33 were forced by the offshore gradient wind to retreat lakeward after having reached various distances inland. The remainder became quasi-stationary.

In general, a lake breeze front either became quasi-stationary or retreated if the offshore wind or a component of it, as measured at a height of 3 m, exceeded about $6\ m\ s^{-1}$. If the front became quasi-stationary, the lake air behind it gradually lost its measurable identity as general cooling took place in late afternoon. Although true lake breezes are infrequent, occurring on about 13% of the days in the months considered, those which passed station 3 but not station 7 undoubtedly increased the likelihood of fog at the former location.

There is also an effect of terrain variations which may result in greater cold air drainage at station 3, but it is considered to be of secondary importance. The elevation of station 3 is about 27 m less than station 7, and there are higher elevations in the 18-km distance between the two stations. The elevation of each station, in addition, is about 30 m less than elevations of nearby hills and/or dunes. As a result, effects of cold air drainage on fog formation are probably quite similar at both locations. Compared to the influence of the lake with onshore winds on causing the observed differences in fog frequency at the two stations, the influence of cold air drainage is quite minor.

7. COOLING TOWER EFFECTS

A preliminary analysis of network meteorological data, time-lapse photographs and plume observations for several months in summer and autumn with the cooling towers operating has not shown increases in either fog occurrences or durations of fog episodes at either station. The main effects of the cooling tower plume on fog observed thus far have been fogs caused by plume downwash, which occurs with wind speeds exceeding about $4\ m\ s^{-1}$. None on the downwashed plumes, however, has been observed to extend farther downwind than about 300 m from the tower structures. Except for cases of downwash, during onshore winds the natural buoyancy of the plume is enhanced by orographic lifting caused by sand dunes paralleling the shoreline, causing the plume to remain aloft as it moves inland.

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