Climatology of Transport and Diffusion Conditions along the United States Atlantic and Gulf Coasts

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(Manuscript received 22 April 1980, in final form 11 May 1981)

ABSTRACT

A study of the atmospheric transport and diffusion climatology of the United States east and Gulf coasts was conducted to aid in planning and site selection for potentially polluting installations. This paper presents selected results from an extensive statistical study. Regular hourly observational data were obtained from 30 coastal stations from Maine to Texas and analyzed in terms of conditions important to emission transport and diffusion. The 30 stations included four pairs with one of each pair at a greater distance from the coast than the other but near the same latitude.

For each station, wind directions were classified into eight groups with reference to orientation of the local coastline. For some studies, fewer classes were desirable and these were combined into three groups—onshore, alongshore and offshore. Wind speeds were divided into four classes. A stability class for each observation was computed by a modified Pasquill method. This gave eight classes which were combined into three—unstable, neutral and stable—for some studies. Diffusion ratings ranging from very good to very poor were derived from combinations of wind speed and stability classes. Finally, the joint frequency distributions of wind direction and diffusion rating were calculated for each station. Data were then classified by season, time of day, wind direction, wind speed, stability class and combinations of these variables, and the percent of hours in each subgroup determined.

Onshore winds were least frequent along the New England and Mid-Atlantic coasts except from Cape Cod to New York City and along the west coast of Florida. Onshore winds were most frequent along the east coast of Florida and the Texas coast. Poor diffusion conditions occurred most frequently from the Carolinas to the Florida east coast and along the northern Gulf Coast. At all stations, diffusion conditions were better during the day than at night. Among the paired stations, the more inland had a greater frequency of poor diffusion hours than the one nearer the coast.

1. Introduction

Coastal locations are used for a variety of installations and activities which are actual or potential sources of atmospheric pollutants. Additional facilities and activities are continually being proposed. Among the current and proposed installations are both floating and shore-based nuclear power plants, fossil-fueled power plants, industries and refineries. Activities include oil drilling, shipment of fuel, and transport of hazardous material. Such facilities and activities are commonly concentrated in coastal locations because of proximity to population centers, access to transportation and availability of cooling water.

In the past, sites for such facilities and activities have generally been selected on the basis of economic or political considerations with little effort to select locations which would minimize the effects of airborne emissions. In recent years, environmental impact studies are often required after a site has been selected, but usually these merely document existing conditions, more or less adequately. In a few cases, particularly for nuclear installations, impact studies may affect the design or operating requirements of the plant, but seldom the location. Thus, studies of diffusion are normally made after a site has been selected and are rarely influential in the site selection process. It is hoped that this study will be useful as an evaluation of diffusion conditions before site selection.

This study is part of a larger program of studies of coastal meteorology and diffusion (Raynor *et al.*, 1975, 1978, 1979) and was planned to assist in site selection by describing the transport and diffusion climatology of the United States east and Gulf coasts in as much detail as can be extracted from readily available meteorological data. Site specific studies may still be necessary for particular locations especially if the site is not representative of the coastline in the region, but such studies could be based on and guided by the information presented here. In other cases, the information below may be adequate to guide a choice between potential sites with respect to air pollution transport and diffusion. No consideration was given in this study to other environmental, economic, or political

0021-8952/81/080882-08$06.00

conditions that may also be important in site selection although a planned extension of this study will rate each section of coastline for severe weather potential. The effects on atmospheric diffusion of meteorological processes in coastal zones were discussed earlier (Raynor, 1978). Complete results of this study were given in a report by Raynor and Hayes (1979).[1]

2. Area

The area covered in this study is the United States east and Gulf coasts from Maine to Texas. The inland extent of the coastal zone is considered to be that distance to which sea breezes normally penetrate, about 30 km in the north and 60 km in the south. However, boundaries are somewhat indefinite due to the irregular configuration of the coast and the presence of partially or completely enclosed bodies of water such as bays, sounds, harbors, and estuaries. The seaward extent of the coastal zone is even more indefinite, but conditions measured on land should probably not be extrapolated more than 10 km offshore without appropriate adjustments, particularly in wind speed and stability.

The region studied is all within the coastal plain and is generally characterized by flat beaches and very gentle slopes inland except in New England where the coast is more rugged and the terrain hilly close to the sea. Local geography should be considered in applying or extrapolating results presented below.

3. Variables

Meteorological variables of primary concern in this study are those which govern or influence transport and diffusion of airborne gases and particles. The most important are wind direction and speed and some measure of diffusive capacity such as turbulence, gustiness or lapse rate. Other pertinent meteorological parameters include amount, type and height of clouds, solar radiation, air, land and water temperatures, humidity, and precipitation. Other important variables are time of year, time of day, latitude, local geography, topography and surface roughness. Not all of these variables were included in the data available and some that were available were used indirectly, to determine a stability category, for instance.

4. Data

Data for the portion of the study reported here were obtained from the National Climatic Center

[1] Raynor, G. S., and J. V. Hayes, 1979: Data summary for evaluation of the transport and diffusion climatology of the United States east and Gulf coasts. BNL 51098, Brookhaven National Laboratory, Upton, NY, 461 pp.

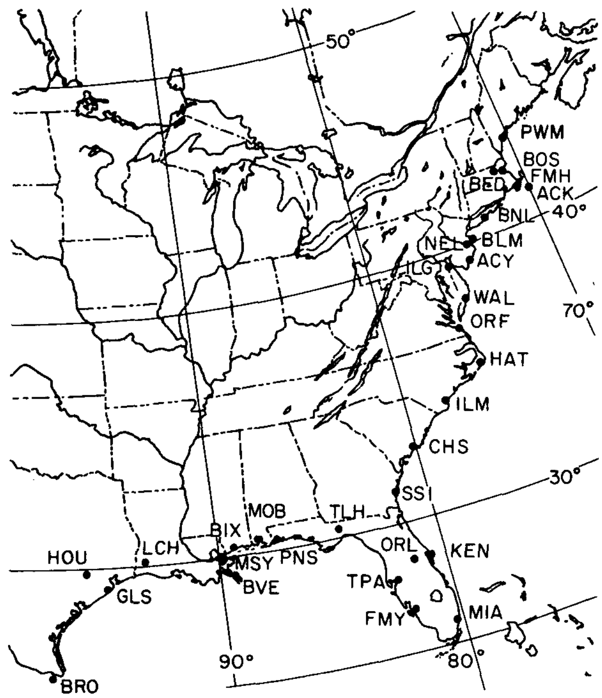

Fig. 1. Map of the study area showing Brookhaven National Laboratory (BNL) and the stations from which data were used. Stations are identified in Table 1.

and consist of hourly or three-hourly synoptic observations usually for consecutive 2-year periods from 30 stations. It was not possible to obtain the same two-year period for all stations since all were not operative at the same time and not all data taken at the stations were available on tape. The years 1970–71 were obtained for most stations.

The stations selected are shown in Fig. 1 and listed in Table 1 with their designation, latitude, longitude, elevation, angle of nearest coastline and period of data. Since these weather stations are at varying distances from the coast, the distance to the nearest large body of water (usually a bay) and the distance to the open ocean or gulf also are tabulated.

Stations were selected to give a reasonably continuous and evenly spaced distribution along the coast while avoiding geographically non-representative locations as much as possible. Moreover, selection was limited to those stations for which data on tape were available.

Eight stations were chosen to give four pairs for comparison between a coastal station and another somewhat further inland. The pairs are Boston and Bedford, Massachusetts; Belmar and Lakehurst, New Jersey; Cape Kennedy and Orlando, Florida; and Galveston and Houston, Texas. The same years of data were obtained for both stations in each pair.

The synoptic data normally include station designation, date and time, type, height and amount

TABLE 1. Description of stations.

Station	Designation	Latitude (N)	Longitude (W)	Elevation (m)	Distance (km) to Nearest water	Distance (km) to Open coast	Direction of coast (deg)	Period of data	
Portland, ME	PWM	43°39′	70°19′	19.0	1.3	8.8	028–208	1970	1971
Boston, MA	BOS	42°22′	71°02′	4.6	3.8	10.2	354–174	1969	1970
Bedford, MA	BED	42°28′	71°17′	43.6	25.4	31.8	354–174	1969*	1970*
Falmouth, MA	FMH	41°39′	70°31′	41.8	8.3	11.4	076–256	1968*	1969*
Nantucket, MA	ACK	41°15′	70°04′	3.7	0.4	0.4	271–091	1968	1969
Belmar, NJ	BLM	40°11′	74°04′	25.6	1.3	5.1	012–192	1960*	1970
Lakehurst, NJ	NEL	40°02′	74°20′	36.9	16.6	24.1	010–190	1960*	1970
Atlantic City, NJ	ACY	39°27′	74°35′	20.4	8.8	16.6	040–220	1970	1971
Wilmington, DE	ILG	39°40′	75°36′	24.1	2.6	96.5	037–217	1970	1971
Wallops Island, VA	WAL	37°51′	75°29′	2.1	0.2	0.2	032–212	1970	1971
Norfolk, VA	ORF	36°53′	76°12′	9.1	6.4	17.8	000–180	1970	1971
Cape Hatteras, NC	HAT	35°16′	75°33′	7.6	0.0	2.6	046–226	1970	1971
Wilmington, NC	ILM	34°14′	77°57′	14.0	11.4	13.4	033–213	1970	1971
Charleston, SC	CHS	32°54′	80°02′	14.0	17.8	25.4	056–236	1970	1971
Brunswick, GA	SSI	31°15′	81°28′	9.5	6.3	8.7	016–196	1970	1971
Cape Kennedy, FL	KEN	28°29′	80°33′	4.9	1.0	1.0	340–160	1970	1971
Orlando, FL	ORL	28°33′	81°20′	33.5	50.8	63.6	340–160	1970	1971
Miami, FL	MIA	25°49′	80°17′	7.3	2.4	15.8	027–207	1970	1971
Ft. Myers, FL	FMY	26°34′	81°52′	6.1	12.7	16.6	329–149	1970	1971
Tampa, FL	TPA	27°58′	82°32′	11.0	1.3	29.3	350–170	1970	1971
Tallahassee, FL	TLH	30°26′	84°20′	20.7	42.0	42.0	084–264	1970	1971
Pensacola, FL	PNS	30°28′	87°12′	35.4	2.6	16.6	080–260	1970	1971
Mobile, AL	MOB	30°41′	88°14′	66.1	17.9	48.3	092–272	1970	1971
Biloxi, MS	BIX	30°24′	88°55′	7.9	0.6	19.1	083–263	1969**	1970**
New Orleans, LA	MSY	29°59′	90°15′	2.1	6.4	76.3	084–264	1972	1973
Boothville, LA	BVE	29°20′	89°24′	0.9	2.5	15.3	095–275	1972	1973
Lake Charles, LA	LCH	30°07′	93°13′	4.3	10.1	36.8	090–270	1970	1971
Galveston, TX	GLS	29°16′	94°51′	2.7	1.3	1.3	051–231	1961*	1962*
Houston, TX	HOU	29°39′	95°17′	18.9	25.4	59.7	051–231	1961*	1962*
Brownsville, TX	BRO	25°55′	97°28′	6.1	21.6	31.9	000–180	1970	1971

* 24 observations per day.
** 16–18 observations per day.

of clouds in as many as four layers, total sky cover, ceiling height, visibility, weather and/or obstructions to vision, sea level and station barometric pressure, dry-bulb and wet-bulb air temperature, dew point, relative humidity, wind direction and wind speed. Wind measurements were taken at the standard National Weather Service anemometer height, ~10 m. Most data were three-hourly observations. Table 1 footnotes those years with 24 or 16–18 hourly observations per day. In the latter case observations were not taken during nighttime hours.

5. Analytical methods

Synoptic data were converted to forms most useful for the purposes of this study. Wind directions were divided into eight numbered classes relative to the coastline nearest to the station (Fig. 2). For some analyses, these eight classes were combined into three: onshore, alongshore and offshore. In some cases [e.g., FMH, ACK, ORF, HAT, BVE and MSY (see Fig. 1)] coastal waters were present in two directions from the station due to a location on an island, on a peninsula, or near a bend in the coast. In these cases, the nearest coast representative of the open ocean or Gulf was chosen. The coastal orientation chosen is listed in Table 1.

Wind speeds were converted from knots to meters per second and grouped into five classes—calm, 0.5–2.4, 2.5–4.9, 5.0–9.9 and ≥10.0 m s^{-1}. A stability class was calculated for each observation using a modification of the Pasquill-Gifford method described by Turner (1964) by modifying the STAR computer program obtained from the National Weather Service. The original program uses date, time of day, geographic location, total sky cover, ceiling height, and wind speed to compute a stability class. Modifications used here were described earlier.[2] Briefly, it was found that not all low overcast hours had neutral lapse rates or corre-

[2] Raynor, G. S. and Hayes, J. V., 1978: A comparative study of diffusion classification by lapse rate, gustiness and a modified Pasquill method. *Proc. NATO/CCMS 9th Int. Tech. Meeting on Air Pollution Modeling and its Application*, 28–31 August 1978, Toronto, Canada. [Available from Brookhaven National Laboratory, Upton, NY, Rep. BNL-24844.]

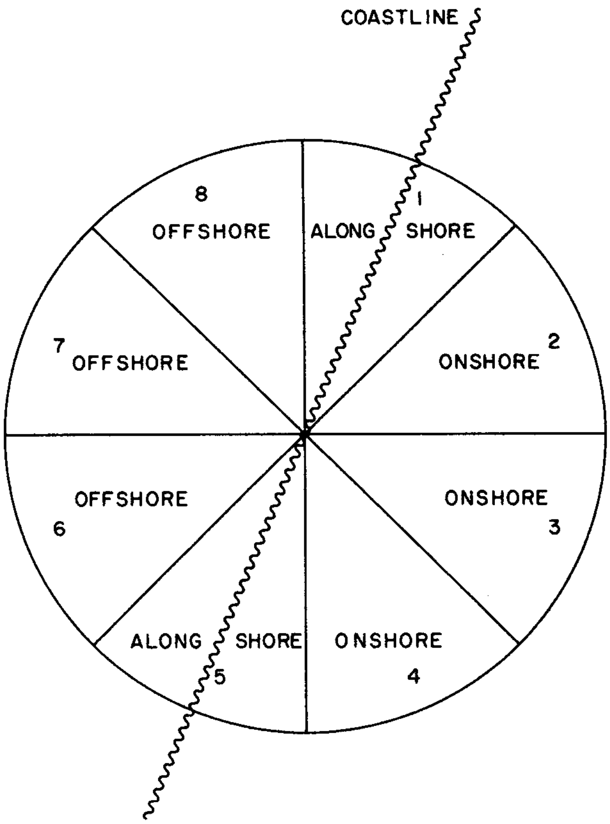

FIG. 2. Number and designation of wind direction sectors relative to the coastline.

sponding gustiness classes but could be unstable during the day or stable during the night. Therefore, the mandatory inclusion of all low overcast cases in the neutral class was eliminated except for precipitation hours. Daytime low overcast cases were assigned the minimum daytime radiation index of 1 and allowed to be either slightly unstable or neutral depending on the wind speed. Night cases were placed by wind speed into either the neutral or the stable class. Examination of non-overcast nighttime hours suggested that the original separation of cases into only two groups with no consideration of cloud height was too coarse and did not account for the variability in outgoing longwave radiation and subsequent amount of surface cooling and degree of inversion. Accordingly, the nighttime cases were further subdivided by cloud amount and ceiling height into five rather than two groups with final choice of stability class within each group determined by wind speed. Other minor changes were also made.

The eight stability classes computed are designated extremely unstable, unstable, slightly unstable, neutral day, neutral night, slightly stable, stable, and extremely stable. To reduce the number

TABLE 2a. Diffusion rating by wind speed and stability classes.

Stability	Calm	Wind speed (m s^{-1}) 0.5–2.4	2.5–4.9	5.0–9.9	≥10.0
Very unstable	3	2	1	1	1
Unstable	4	3	2	2	1
Slightly unstable	4	3	3	2	2
Neutral	5	4	3	3	3
Slightly stable	5	4	4	3	3
Stable	5	5	4	4	4
Very stable	5	5	5	4	4

of classes in some analyses, the eight classes were combined into three: unstable, neutral, and stable.

For classifying the data by season, four classes were formed: spring, March–May; summer, June–August; fall, September–November; winter, December–February. For classifying data by time of day, two classes were formed, day and night. In order to obtain the best agreement between these classes and atmospheric stability, day is considered the period from 1 h after sunrise to 1 h before sunset as used in the STAR program. Day-night comparisons are not given for the one station with some nighttime observations systematically missing (Table 1).

A diffusion rating classification was derived from a combination of the wind speed and stability classes as shown in Table 2a. It should be noted that wind speed is used both directly and indirectly through the stability class in forming the diffusion rating. Diffusion rating classes were determined from ranges of dilution factors ($\bar{u}\sigma_y\sigma_z$) at 1 km as shown in Table 2b. The three parameters comprising the dilution factor occur in the denominator of the Gaussian plume diffusion equation. Relative ground-level concentrations (χ/Q) at receptor locations from a ground-level source, for instance, are inversely proportional to the value of each. These divisions agreed well with the subjective determinations of several meteorologists experienced in diffusion studies. Values of σ_y and σ_z at 1 km were taken from Turner (1964). Some combinations of wind speed and stability may rarely or never occur, but all are given a rating for completeness. The dif-

TABLE 2b. Dilution factor ($\bar{u}\sigma_y\sigma_z$) ranges for diffusion rating classes.

Diffusion rating	Dilution factor at 1 km (m^3 s^{-1})
1 Very good	$>2 \times 10^5$
2 Good	$4.5 \times 10^4 – 2 \times 10^5$
3 Fair	$8 \times 10^3 – 4.5 \times 10^4$
4 Poor	$1 \times 10^3 – 8 \times 10^3$
5 Very poor	$<10^3$

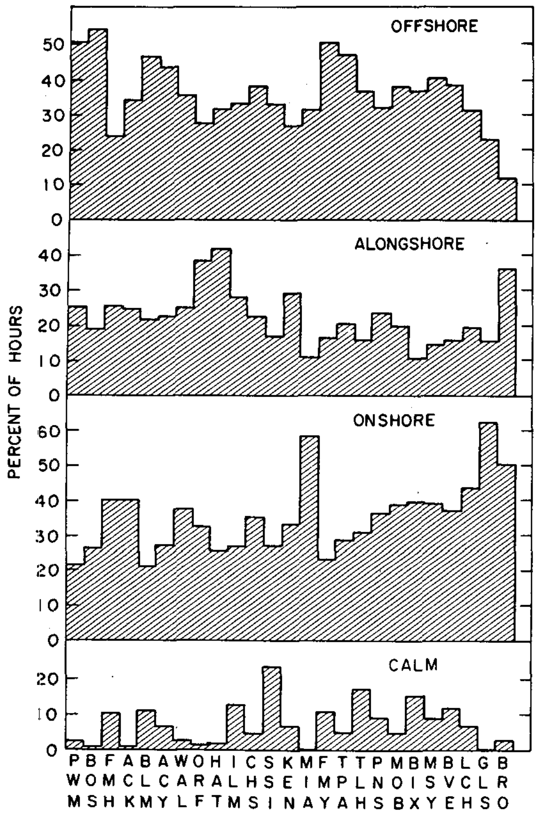

FIG. 3. Percent of hours in each wind direction class at 25 coastal stations. Read station designations vertically.

fusion rating was used as a new variable. The joint frequency of the wind direction classes and the diffusion rating classes was computed for each station.

Finally, for each station, percentage frequency distributions were computed for selected variables or combinations of variables including the following: the percent of hours in each of the three combined wind direction classes and the percent with calm winds were determined by season and time of day. The percent of hours in each of the three combined stability classes by the combined wind direction classes and wind speed was computed for all hours with non-calm wind speeds. The percent of hours in each of the eight stability classes by the combined wind direction classes, season and time of day was calculated for all non-calm hours. The percent of hours in each wind speed class by the combined wind direction classes, season and time of day was determined for all non-calm hours. The percent of hours in each diffusion rating class by combined wind direction class, season and time of day and the joint percentage frequency of hours in each combination of wind direction class and diffusion rating class was also computed. Tabular results of all computations were reported by Raynor and Hayes (1979).[1] Only selected results are presented and discussed here.

6. Results

The frequency of calms and of winds in the three direction sectors relative to the coastline are shown in Fig. 3 for the 25 coastal stations from Portland, Maine (PWM) to Brownsville, Texas (BRO). Onshore winds are most frequent at Miami and the Texas coast and least frequent at several New England and Mid-Atlantic coast sites, and the west coast of Florida. The percents of onshore hours at Portland, Belmar and Fort Meyers were less than one standard deviation below the mean of the 25 stations and the percents at Miami, Galveston and Brownsville were more than one standard deviation greater. Calms occur over 10% of the time at eight stations but very seldom at Miami and Galveston. The same information was computed as a function of season and was reported by Raynor and Hayes (1979).[1]

Inland stations have a greater frequency of calm hours than nearby coastal stations (Fig. 4). In Massachusetts and Texas, the percentage of onshore winds is greater at the coastal station but in New Jersey and Florida, the differences are not significant.

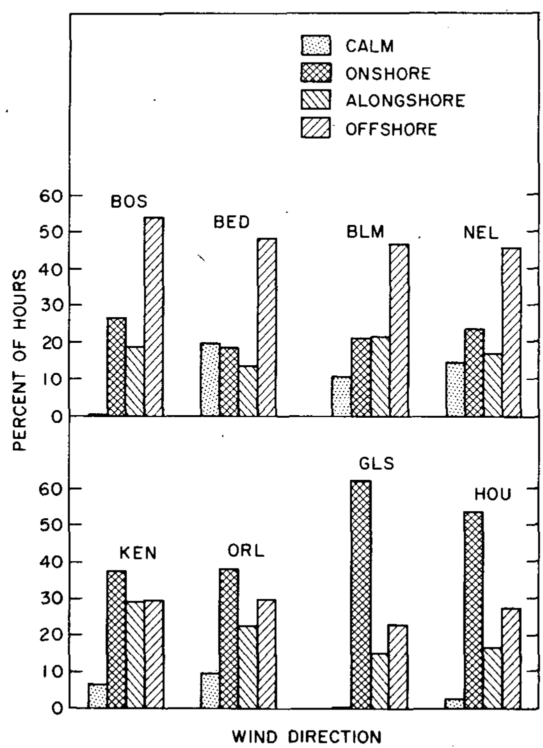

FIG. 4. Percent of hours in each wind direction class at four coastal-inland pairs of stations.

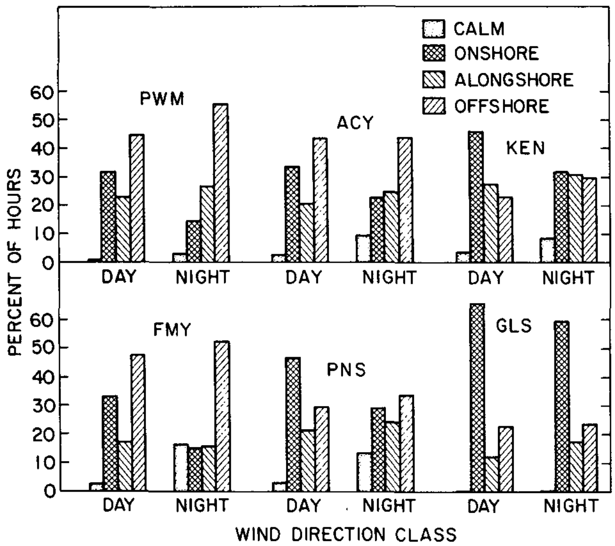

Fig. 5. Percent of hours in each wind direction class at six stations by day and night.

Differences between day and night in wind direction distribution are shown in Fig. 5 for six selected stations. At each, onshore winds are more frequent in the daytime, largely due to the occurrence of sea breezes. Offshore winds and calms are more common at night. Similar differences were found for the other stations.

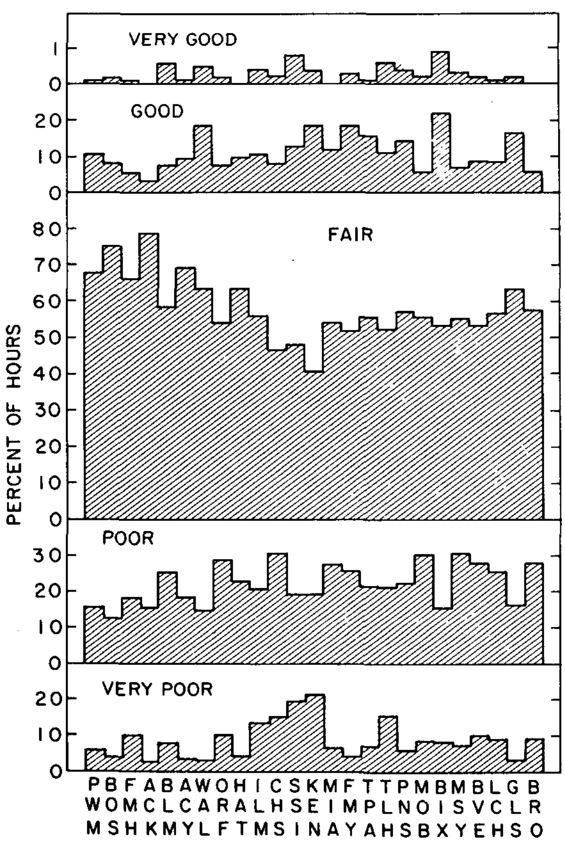

Fig. 6. Percent of hours in each diffusion rating class at 25 coastal stations during onshore winds. Read station designations vertically.

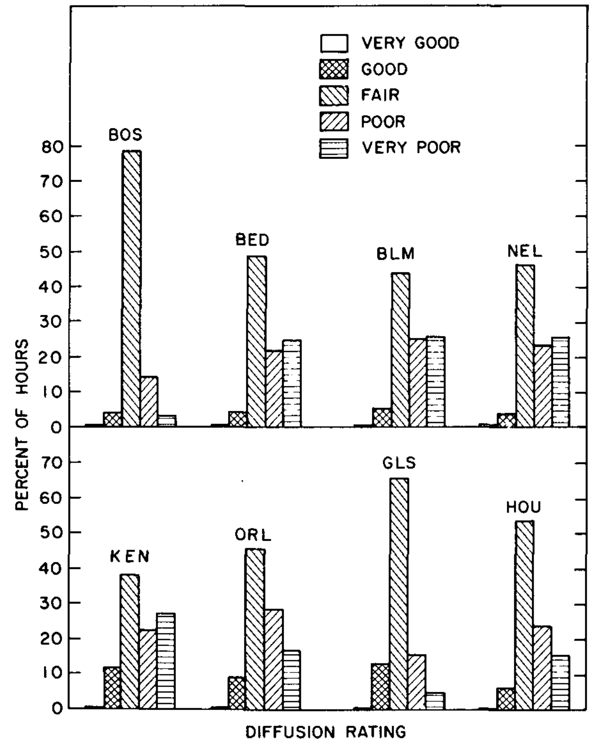

Fig. 7. Percent of hours in each diffusion rating class at four coastal-inland pairs of stations.

The frequency of the five diffusion rating classes at the 25 coastal stations during onshore winds is shown in Fig. 6. Poor and very poor diffusion conditions as computed from dilution factors occur more frequently than good or very good conditions at most stations. Among the stations with the highest frequency of good and very good conditions are Wallops Island, Biloxi, and Galveston. Poor conditions predominate at Norfolk, Charleston, and Brownsville. The percentages of hours in the very good and good classes were less than one standard deviation below the mean at Falmouth, Nantucket, Mobile and Brownsville and more than one standard deviation above the mean at Wallops Island, Cape Kennedy, Fort Myers and Galveston. The percentages of hours in the poor and very poor classes were less than one standard deviation below the mean at Portland, Boston, Nantucket, Atlantic City, Wallops Island and Galveston and more than one standard deviation above the mean at Charleston and Cape Kennedy. Similar information was previously reported for other wind direction sectors and for all directions combined (Raynor and Hayes, 1979).[1]

As shown in Fig. 7, the frequency of poor

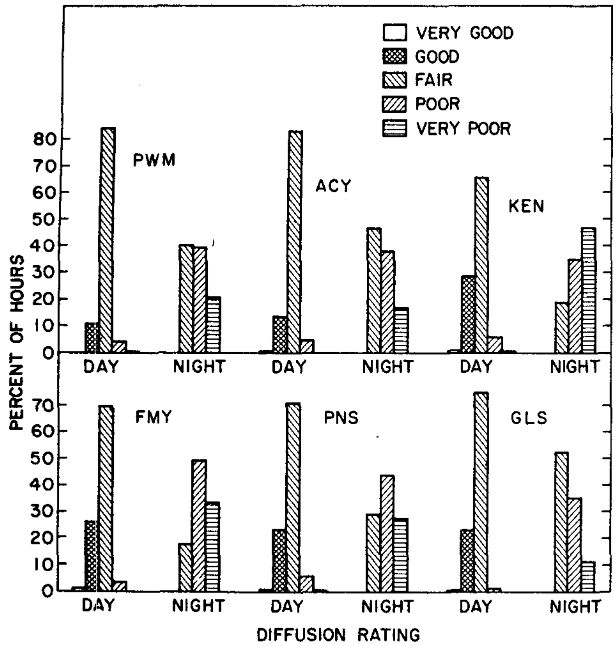

FIG. 8. Percent of hours in each diffusion rating class at six stations by day and night.

and very poor diffusion rating is appreciably greater at the inland station in Massachusetts and Texas than at the coastal station. However, differences are small in New Jersey and Florida.

Differences in diffusion conditions between day and night at six selected stations are shown in Fig. 8. Good conditions are more frequent during the day and poor conditions during the night. These differences are representative of the other stations not shown (Raynor and Hayes, 1979).[1]

Conditions under which effluents could be released with little expectation of high concentrations at onshore receptor locations include 1) offshore winds, 2) onshore winds with good to very good diffusion, and 3) alongshore winds with fair to very good diffusion. The percent of hours in these three categories were added together to give the percent of time these combinations of circumstances occurred at each of the coastal stations (Fig. 9). Such conditions are most frequent in New England, at Cape Hatteras and along the west coast of Florida and least frequent along the Georgia and east Florida coast and along the lower Texas coast.

The percentages of hours with acceptable diffusion conditions were less than one standard deviation below the mean at Brunswick, Miami, Lake Charles, Galveston and Brownsville and more than one standard deviation above the mean at Portland, Boston, Cape Hatteras, Fort Myers and Tampa.

Data from the four coastal-inland pairs show that calms and poor diffusion conditions are more frequent inland but onshore winds are less frequent. Considering wind directions and diffusion conditions jointly, however, favorable release conditions are somewhat more frequent at the coast (Raynor and Hayes, 1979).[1]

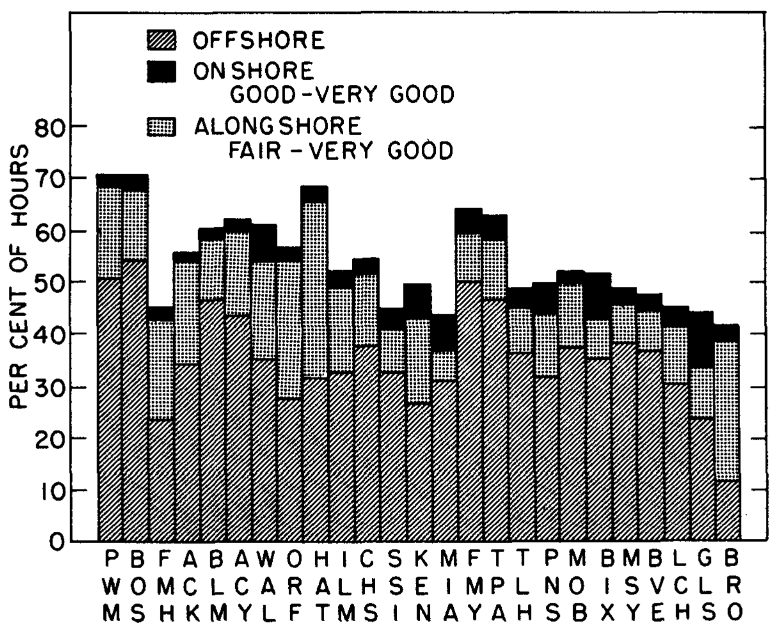

FIG. 9. Percent of hours in favorable wind direction and diffusion rating classes at 25 coastal stations. Read station designations vertically.

7. Application

The results obtained were arranged for easy use with diffusion models in which the primary meteorological inputs are wind speed and measures of lateral and vertical diffusion. The latter can readily be derived from the stability classes by established relationships. Presentation of data by season, time of day and wind direction classes permits ready selection of the other meteorological parameters for any desired combination of conditions. Interpolation can be employed for locations between stations but local geographic and topographic features should be considered. Use of the information in the detailed report may permit preliminary site evaluation without diffusion modeling.

Acknowledgments. This research was conducted under the auspices of the U.S. Department of Energy Contract DE-AC02-76CH00016.

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