ATMOSPHERIC DISPERSION OVER CHESAPEAKE BAY

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ABSTRACT

Horizontal wind speed and direction range data were obtained during 300 hours of westerly winds on both the east and west shores of the Chesapeake Bay during the period December 1960 through May 1961. Measurements of air and water temperature were made at each shore as well as from a bridge tower in the bay. Standard deviations of the horizontal direction fluctuations (σ_θ) were estimated from 5-minute direction range values for each shore. The east and west shore values of σ_θ were then used to estimate the relative overwater-overland dispersive capacity of the atmosphere.

It was found that, after the air had traveled for about 7 miles over the water, its direction fluctuations were always less than they had been before reaching the water. If the air was initially warmer than the water, and thus cooled from below during the overwater travel, the decrease in direction fluctuation was greater than occurred when the air was warmed from below.

The wind speed usually increased as the air crossed the water. The increase was largest for warming from below and smallest for cooling from below. It was noted that frequently, when the air was cooled from below, the wind speed decreased as the air crossed the Bay.

With the observed parameters it was possible to relate the overland to the overwater dispersive capacities of the atmosphere. The ratio of overland to overwater dispersive capacity, computed for a point 0.5 miles from a postulated source, varied from less than 5:1, for heating from below, to greater than 35:1 for cooling from below.

1. INTRODUCTION

The nature of the modification in the characteristics of an air mass as it passes from land out over water may be treated in a number of ways. Craig [1], Burke [2], and Vorontsov [3] studied the modification of thermal and humidity structures of the atmosphere in the first few tens to hundreds of kilometers offshore. Petterssen and Calabrese [4] investigated the heating effect of the Great Lakes on the dynamic and thermodynamic characteristics of cold air flow patterns. Hewson et al. [5] made airborne measurements of diffusion of a smoke plume at a water-land boundary. A comprehensive survey of many studies of transport and diffusion experiments over oceans and shore lines is given by Prophet [6].

This report deals with the changes in some of the small-scale turbulent characteristics of a flow of air passing from land over a body of water. These changes are of importance in assessing differences in the dispersive capacity of the atmosphere near and over bodies of water. The observed changes are used to make such an assessment.

In most continuous point-source diffusion models, the pollutant is assumed to be normally distributed both laterally and vertically about the plume axis. The fundamental entities of such models are the standard deviations of the lateral and vertical particle dispersion, σ_y and σ_z. Hay and Pasquill [7], in their studies of dispersion, have related both theoretically and experimentally the lateral spread of a cloud at a point downstream from the source to the fine-scale wind variations at the source. They have shown that the lateral particle standard deviation, σ_y at 100 meters from the source is proportional to the horizontal wind direction standard deviation, σ_θ, computed from wind direction data which have been subjected to a running averaging process. Islitzer [8], Cramer [9], and others have also presented data which relate σ_y to σ_θ.

The relationship which holds between σ_y and σ_θ can also be expected to apply to σ_z and σ_ϕ, the vertical standard deviations of the particle spread and wind fluctuation. There is however, much less corroborative data for this relationship than for the horizontal standard deviations. Evidence also exists that σ_θ may be related to σ_z as well as σ_y.

DeMarrais and Islitzer [10] and others have shown that a reasonably good relationship exists between σ_θ over a given time interval and the absolute horizontal range of wind direction, R, over that same interval. The computation of σ_θ is quite laborious when compared with the range determination which simply involves the difference between the extremes over the given time interval. The use of range offers a simple approach for estimating the standard deviation of large quantities of wind direction data.

2. OBSERVATIONAL SITES AND INSTRUMENTS

Wind and temperature data were collected in the vicinity of the Chesapeake Bay Bridge (fig. 1). Wind

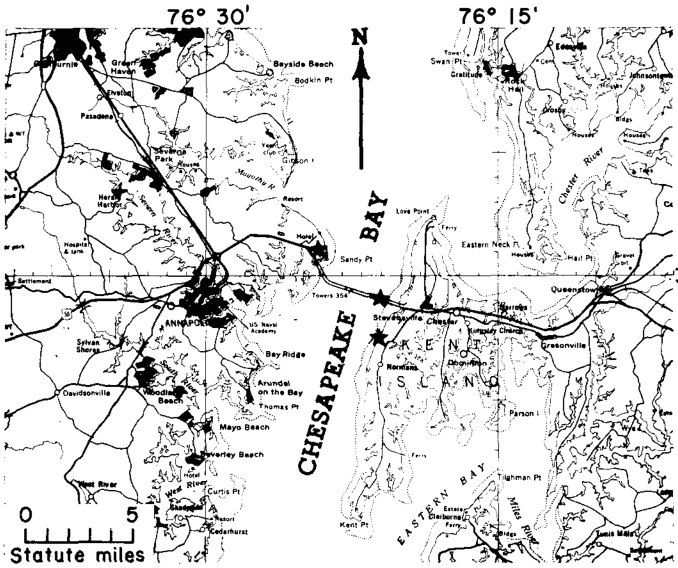

FIGURE 1.—Chesapeake Bay in the vicinity of the Chesapeake Bay Bridge. Observation sites on each shore and at bridge tower are indicated by stars.

and temperature measurements were made on both shores and temperature measurements in the vertical were made on one of the bridge towers. The exact locations of the shore based instruments were dictated by the security of the sites since the instruments were left unattended between servicing visits. Both shore sites chosen had exposures free of major upwind obstacles in the directions between approximately southwest and northwest. The study was thus limited to those periods when the wind on both shores was from between these directions.

Temperatures were measured with standard Weather Bureau thermographs equipped with one-week charts. Wind measurements were made with Beckman and Whitley K100A wind systems and recorded at 3 inches per hour on Esterline-Angus recorders.

At the west shore location, the thermograph was installed at a height of 4 feet in a weather shelter at a point about 1,000 feet west of the water and about 12 feet above the water level. The wind sensors were installed on a 10-foot tripod on the western edge of a 17-foot high building. Winds from any direction except southwest-northwest were not used because they had first to pass over the building giving unrealistic speed and direction characteristics. Thus, the data from the west shore installation represent overland flow.

A similar location was available on the east shore where an 11-foot cliff rose abruptly at the water's edge. The 10-foot tripod was mounted at the edge of this cliff. A dense forest extended to the east of the site. The thermograph on the east shore was also mounted in a weather shelter. All winds arriving at this site from between southwest through northwest had an overwater trajectory and thus, data from the east shore site represent overwater flow.

Since it was not practicable to mount wind instruments on the bridge, only temperature measurements were taken. Thermographs were mounted at 21 and 174 feet above the water on a bridge tower 1.2 miles from the east shore. Water temperatures were taken from the bridge tower and on both sides of the Bay.

3. DATA AND ASSUMPTIONS

The data used in this study were collected on all possible occasions during the 6-month interval December 1, 1960, through May 31, 1961, when the required wind directions occurred simultaneously on both shores. A data collection interval was defined as a continuous interval of at least 2 hours during which the average 5-minute wind direction on both shores remained between an indicated southwest and northwest direction. The intervals chosen on the basis of this definition were all longer than 2 hours.

The basic data extracted from the charts are:

S_w=wind speed, west shore (m.p.h.)
S_e=wind speed, east shore (m.p.h.)
R_w=wind direction range, west shore (degrees of azimuth)
R_e=wind direction range, east shore (degrees of azimuth)
T_w=air temperature, west shore (° F.)
T_e=air temperature, east shore (° F.)
T_b=Bay temperature (° F.)

The wind data were read off the charts as 5-minute average values of speed and 5-minute absolute direction ranges. These data were also averaged for 1-hour periods. The air temperature data were always 1-hour average values. Daily water temperatures were obtained by interpolation between the weekly measured temperatures at the three sites.

Comparisons of wind direction between the two shores were not made because of two possible sources of error in the data. First, the direction alignment procedure for the Beckman and Whitley wind system allows for errors of at least ±5° in azimuth. In addition, the direction trace showed a tendency to drift as much as 5° or 10° between the weekly servicing visits. It was felt that the magnitude of the possible error prohibited direction comparisons between the two relatively close sites. The possible error of 10° in wind direction did not interfere with the use of southwest and northwest as boundaries for accepting data since these limits were chosen to encompass only the central part of the total arcs of overland flow on the west shore and overwater flow on the east shore.

During the 6-month observational period, it was possible to obtain 286 hours of simultaneous wind speed and direction data and an additional 17 hours of direction data alone. A large volume of data could be lost each time one of the wind systems malfunctioned during the week between servicing. Although the thermographs

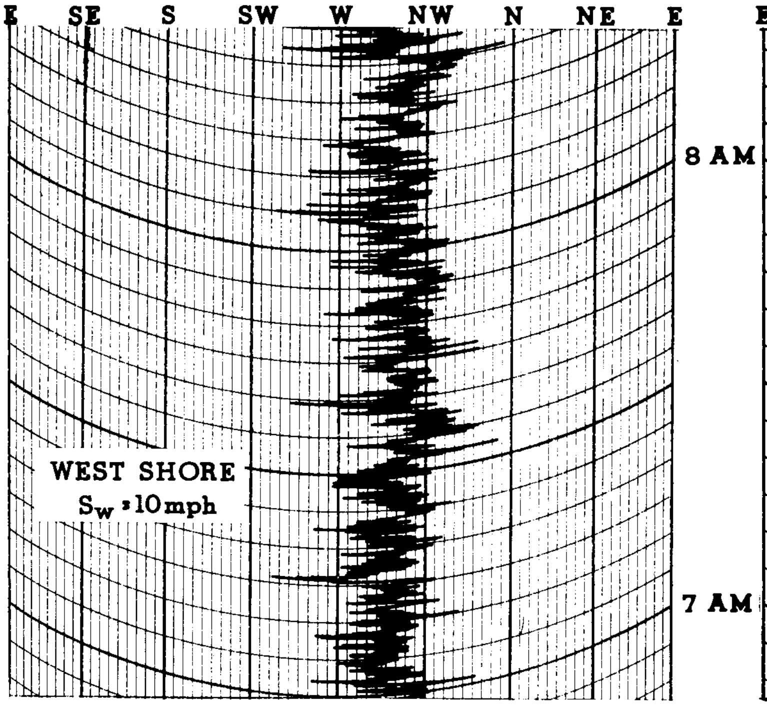

FIGURE 2.—Typical simultaneous wind direction traces at the Chesapeake Bay sites.

were relatively free of trouble, weather conditions were occasionally severe enough during the winter to prohibit climbing the bridge tower and servicing those two thermographs.

It was noted that many of the extremes of speed, direction range, or temperature occurred when wind directions were other than those chosen for the study or at times when instrumental difficulties precluded a complete data collection. Thus, some of the extreme conditions during the 6-month interval are not included in these data.

A number of assumptions were made in order to relate the east shore wind data to those of the west shore. The first assumption was that the station locations were representative of the conditions along each shore. Winds from westerly directions reaching the west shore installation had had a primarily overland travel, while westerly winds reaching the east shore arrived entirely from over the water. The land surface on the west shore is flat and perhaps one-half covered with small deciduous trees. Much of the west shore in this region of the Bay is similar. Therefore, it was expected that the west shore site would be representative of conditions over the land. The east shore site is representative of conditions over the water.

Another assumption that was made, based on the preceding, was that both sites were always along a given trajectory. If the first assumption is reasonable, then this follows.

It was decided, because of the first two simplifications, to compare observations taken simultaneously rather than to compare an observation taken at time t on the west shore with one taken at time $t+x/\bar{u}$ on the east shore (where x is the distance between stations and $\bar{u}$ an average wind speed).

Finally, no account was taken of the length of overwater travel experienced by the wind prior to reaching the east shore. This distance varied from 4.5 to 13.5 miles with the greater distances to the southwest or west-southwest of the east shore station (fig. 1). The average distance was about 7 miles.

4. WIND AND TEMPERATURE STATISTICS

A number of averages may be presented based on the entire sample of observations. Table 1 shows some of the wind speed parameters for the 286 hours of data collected. The Ft. Meade and Annapolis data were taken from the respective station records for the same hours. Ft. Meade is 18 miles west-northwest of the west end of the Chesapeake Bay Bridge. The Annapolis Naval Air Station is 4 miles southwest of the same point.

These wind speeds may be compared with the 5-year December through May average speeds for westerly

TABLE 1.—*Average wind speed values (m.p.h.)*

	West shore (S_w)	East shore (S_e)	Ft. Meade (anemometer at 10 ft.)	Annapolis NAS (anemometer at 180 ft.)
Average speed, all observations	11.0	16.7	8.2	12.8
Standard deviation of 286 1-hour averages	5.6	6.4		
Highest hourly average speed	25.0	33.0		

TABLE 2.—*Average wind direction range values (degrees of azimuth)*

	West (R_w)	East (R_e)
Average of 303 hourly averages of 5-minute range	61.4	31.0
Standard deviation of 303 hourly averages of 5-minute range	10.9	5.8
Greatest hourly average range	96.5	56.5
Least hourly average range	27.5	18.5

TABLE 3.—*Wind speed and direction range ratios*

Wind speed		Direction range	
Ratio of average wind speed S_w/S_e	0.66	Ratio of hourly averages of 5-minute direction range R_w/R_e	1.98
Standard deviation of hourly average wind speed ratio	0.20	Standard deviation of hourly average 5-minute direction range ratios	0.46
Extreme values of ratio	0.22; 1.50	Extreme values of ratio	0.97; 3.47

winds at Washington National Airport, 11.1 m.p.h. (anemometer at 115 ft.) and at Baltimore's Friendship Airport, 12.5 m.p.h. (anemometer at 133 ft.).

Wind direction range has been defined as the absolute range, in degrees of azimuth, of the horizontal wind direction over a 5-minute interval. Most of the direction range data in this report are in the form of hourly averages of the 5-minute range data. Table 2 presents various range statistics based on the entire population of observations of wind direction range. Two typical simultaneous wind direction traces are shown in figure 2. The upper limit of the range is bounded by the fact that all the 5-minute average directions were required to fall between SW and NW. The effect of this artificial boundary will be discussed later.

The ratios, derived from the first two tables, of speed and direction range on each shore are presented in table 3. The expected effects of overwater travel are apparent from any of the first three tables. On the average, the wind

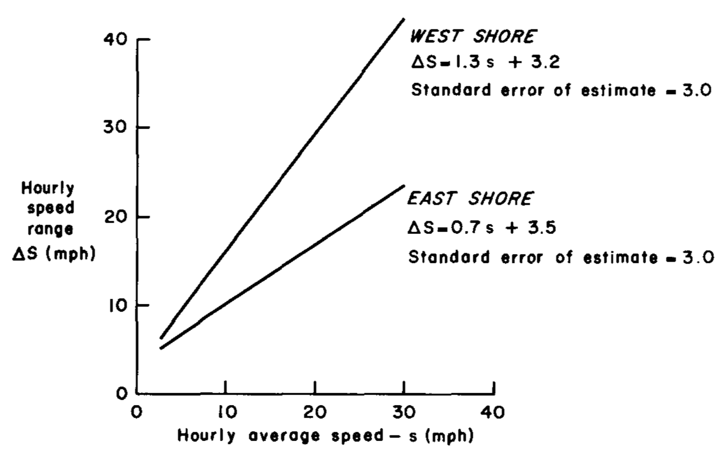

FIGURE 3.—Relationship between hourly average wind speed and hourly speed range for westerly winds at the Chesapeake Bay sites.

TABLE 4.—*Temperature difference data (°F.)*

	T_b-T_w	T_w-T_e
Average of 303 hourly average values	+2.8	−1.3
Standard deviation	8.3	2.0
Extreme values*	+19.5	−6.5
	−15.0	+7.5

*The extremes of T_b-T_w and T_w-T_e are not simultaneous.

speed increases and the direction variations decrease as the air moves over the water. The difference between the highest and lowest wind speed during each hour (speed range) was plotted against the average speed. The regression lines drawn for these data are presented for each shore in figure 3.

Two sets of temperature difference data were computed. The first set is composed of the differences between the daily average temperature of the Bay and the hourly average temperature of the air at the west shore (T_b-T_w). The second set is composed of the temperature differences between the air at the west and east shores (T_w-T_e). The values are shown in table 4.

No averaged data will be presented for the vertical temperature difference taken on the bridge tower. About 40 percent of the hourly observations were missed because of the inability to service the instruments on schedule in high winds and because of occasional instrument difficulty. However, a review of all the data obtained during the 6-month period showed extreme inversions of more than 11° F. and lapse conditions of 4° F. over the 153-foot vertical interval.

An example of the horizontal temperature gradients that may exist over the Bay during light winds is shown in figure 4. The rapid changes in horizontal gradient caused by changing wind direction seem, at least on the east shore, to be mostly confined to the first mile of overwater travel.

5. EFFECT OF HEATING AND COOLING

In order to investigate the effect on the wind of overwater passage and heating or cooling from below, it was decided to stratify the speed and range ratios by means of day-night difference and heating or cooling from below. The average times of sunrise and sunset for the 6-month period are close to 0600 and 1800 EST. These times were used as day-night boundaries. Warming or cooling from below was considered to occur if the temperature of the water was 2.5° F. or more above or below that of the air on the west shore. If the temperature of the water was within ±2.5° F. of the air at the west shore, a "neutral" condition was said to exist. The stratified values of speed and range ratios appear in table 5. The range ratios for hourly averages of 30-minute ranges were also computed and found to be similar to the hourly averages of the 5-minute range ratios.

On 23 occasions the values of the S_w/S_e ratio were 1.0

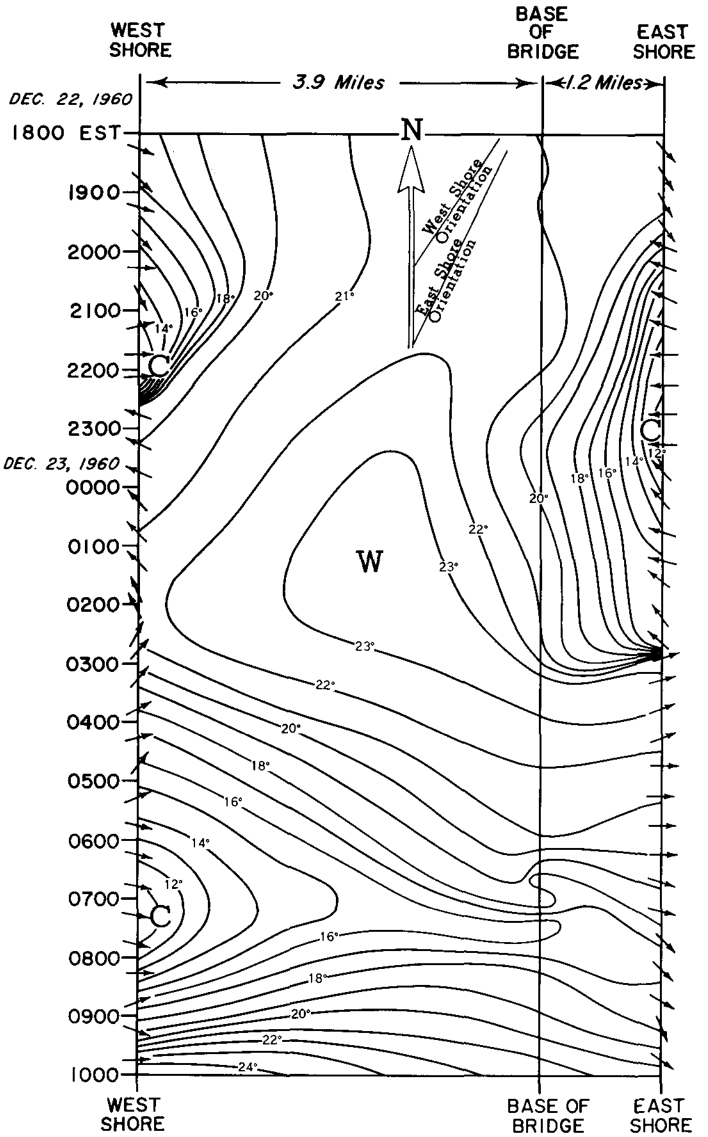

FIGURE 4.—Air temperature (°F.) and wind directions at the Chesapeake Bay sites December 22–23, 1960. Sky clear during entire period. Water temperature 35° F.

or greater, indicating an equal hourly average wind speed on each shore or a decrease in speed as the air crossed the Bay. Twenty-two of the values occurred during cooling-from-below conditions during both day and night and one during a neutral state. The largest ratio of S_w/S_e obtained during this experiment was 1.5. During a preliminary experiment, not included in the 6-month interval, values of the S_w/S_e ratio of over 2.0 were obtained on a day when the water was over 30° F. cooler than the air on the west shore. It is normally expected that a flow of air accelerates as it moves from over a rough to over a smooth surface and therefore the decrease in wind speed can be ascribed to the overwater inversion conditions as indicated by the bridge tower thermographs. Similar reductions in wind speed have been noted by Craig [1] and Hunt [11].

Values of the S_w/S_e ratio of less than 0.30 occurred six

TABLE 5.—*Ratios of speed and direction range*

	Average Wind Speed $\frac{S_w+S_e}{2}$	S_w/S_e	No. of cases	R_w/R_e	No. of cases
DAY	(*m. p. h.*)				
Warming from below	15.8	0.69	49	1.81	52
Neutral	17.1	0.75	23	2.18	25
Cooling from below	16.8	0.86	54	2.34	54
NIGHT					
Warming from below	11.9	0.50	110	1.79	118
Neutral	11.5	0.61	26	2.38	30
Cooling from below	12.1	0.83	24	2.39	24

times, all during conditions of heating from below at night. During these instances skies were clear or with scattered clouds in five cases and overcast in the other. Thus it is likely that at least five of these cases occurred during inversion conditions at the west shore site. It is postulated that, as the inversion layer moved over the water, it was destabilized by the heating of the water, allowing greater vertical mixing and consequent downward transport of momentum. This resulted in higher winds on the east shore than at the western site.

All except one of the 303 hourly averages of the 5-minute range ratios, R_w/R_e, were greater than 1.0. The one exception was a value of 0.97.

Limiting the data to intervals during which all 5-minute average directions were between southwest and northwest, for at least a few hours, caused a bias, as a result of which a true climatology of westerly wind fluctuations for the period of study was not obtained. Large, thermally induced direction fluctuations that would be expected with light wind speeds on the west shore by day rarely had 5-minute means that remained for any length of time within the prescribed bounds, and thus such data could not be used in the study. Similarly, the very small night wind fluctuations on the west shore occurring with low wind speeds would be associated with longer period meandering so that these data frequently could not be used. Therefore, a bias toward higher wind speed was introduced, and the measured wind ranges emphasized the effects of mechanically induced turbulence.

6. ESTIMATES OF DISPERSION

It is of practical interest to make estimates of dispersion over land and water corresponding to these observations. The technique used is due to Cramer [9], who presented a set of nomograms based on Project Prairie Grass measurements, in which σ_y and σ_z, the horizontal and vertical standard deviation of plume concentration distribution, are expressed as a function of x, the distance from the source, and σ_θ, the standard deviation of azimuthal direction fluctuations.

Approximate values of σ_θ were obtained by dividing the direction range values by 6.0. This value was determined experimentally by DeMarrais and Islitzer [10] for wind speeds of 14 m.p.h. using an Aerovane wind instrument. Values of approximately 6.0 were also found by Hosler, Pack, and Harris [12] for lapse, neutral, and inversion conditions using a Beckman and Whitley instrument. A number of actual standard deviation-range comparisons were determined from high-speed wind traces taken on both shores of the Bay during slightly unstable conditions. An average factor of 5.75 was determined from 2.0- to 30.0-second time-averaged data with a 1.0-second step ahead. Thus, while it is known that this factor shows some variation with meteorological conditions and height of measurement, there seems to be sufficient justification for the use of the value of 6.0 to determine an approximate value of σ_θ.

From σ_θ, it was possible, by means of Cramer's graphs, to find both σ_y and σ_z for overland and overwater flow for a given distance from the postulated source. This, of course, assumes that the relationship between σ_θ and σ_y and σ_z, derived from overland data, holds for an overwater flow. This assumption was made as a first approximation. The σ_y and σ_z could then be substituted into the Gaussian plume formula to find the axial concentration:

$$\chi=\frac{Q}{2\pi\bar{u}\sigma_y\sigma_z}$$

where χ =concentration, ML^{-3}
Q =source strength, MT^{-1}
σ_y=standard deviation of horizontal plume concentration distribution, L
σ_z=standard deviation of vertical plume concentration distribution, L
$\bar{u}$ =average wind speed along plume axis, LT^{-1}

Reflection from the ground plane was ignored.

Ratios of the concentrations were computed from:

$$\frac{\chi_e}{\chi_w}=\frac{S_w}{S_e}\cdot\frac{\sigma_{y,w}\sigma_{z,w}}{\sigma_{y,e}\sigma_{z,e}}$$

where the west shore data represent overland conditions and the east shore data, overwater. These ratios are given in table 6. The concentrations were determined for a distance of 0.5 mile from a postulated source. The χ_w values are assumed to be typical of land values in this area and the χ_e values are assumed to represent overwater conditions about 7 miles from shore, the average length of overwater trajectory for air reaching the eastern shore site. A ratio of greater than 1.0 indicates poorer diffusion conditions over the water than over the land.

It may be noted that for the average conditions, which correspond to the values in table 5, the relative diffusion over water was always less than over land. The one occasion in which the ratio of ranges was less than 1.0 provided the data for the extreme warming-from-below-at-night case used in table 6.

Since table 6 indicates that differences exist in the ratio of χ_e/χ_w for average overwater heating and cooling, the day and night wind direction ranges and wind speeds were stratified by 5° F. intervals of T_b-T_w and the χ_e/χ_w ratios were computed for the midpoint of each interval. The resulting graph is shown as figure 5. It was decided not to fit a curve to the points in figure 5 since it was not

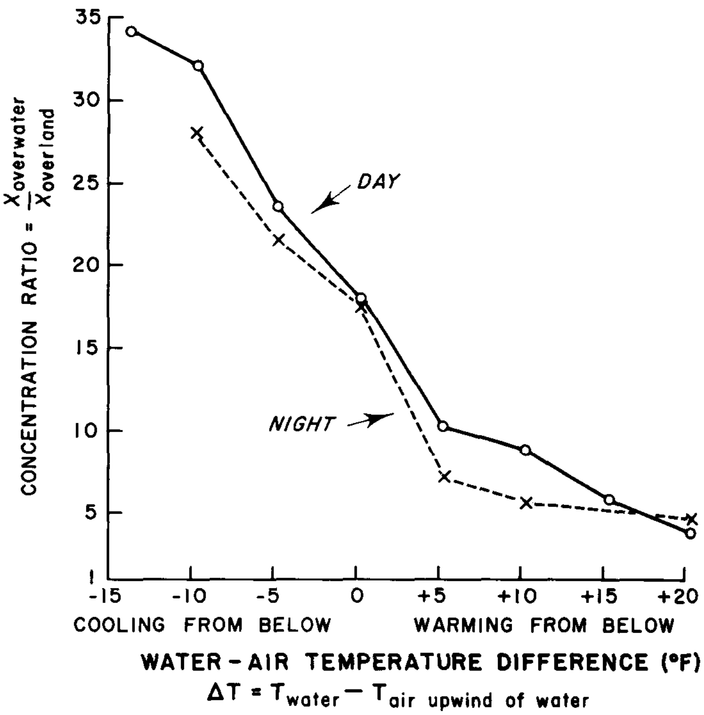

FIGURE 5.—Relationship between day and night concentration ratios and water-air temperature difference (°F.). Concentrations evaluated for a point 0.5 mile from source. Overwater concentration data based on overwater travel of 7 miles.

TABLE 6.—*Concentration ratios, χ_e/χ_w from data observed at Chesapeake Bay (Computed for a distance 0.5 miles from source after an overwater travel of 7 miles)*

	$\sigma_{\theta,w}$	$\sigma_{\theta,e}$	$\sigma_{y,w}$	$\sigma_{z,w}$	$\sigma_{y,e}$	$\sigma_{z,e}$	S_w/S_e	χ_e/χ_w
Average cooling by day	11.5	5.0	100	115	22.0	16.0	0.86	28
Average warming by day	10.4	5.8	84.0	82.0	30.0	20.0	0.69	8.0
Average cooling by night	10.1	4.3	80.0	76.0	16.0	13.0	0.83	24
Average warming at night	9.5	5.2	73.0	63.0	23.0	17.0	0.50	5.9
Extreme cooling by day*	13.2	3.8	113	158	13.0	12.0	1.50	171
Extreme warming at night*	6.6	6.8	38.0	24.0	42.0	26.0	0.22	0.18

*The observations of wind direction fluctuation and speed for the two extreme cases are not simultaneous. Rather, those observations giving extremes of the range and speed ratios were used.

TABLE 7.—*Concentration ratio compared to average water-air temperature difference*

χ_{water}/χ_{land} (Computed for a point 0.5 mile from a source after an overwater travel of 7 miles)	ΔT(° F.)$=T_{water}-T_{overland}$
<5	>+16
5 to 15	+16 to +2
15 to 25	+2 to −7
25 to 35	−7 to −15
>35	<−15

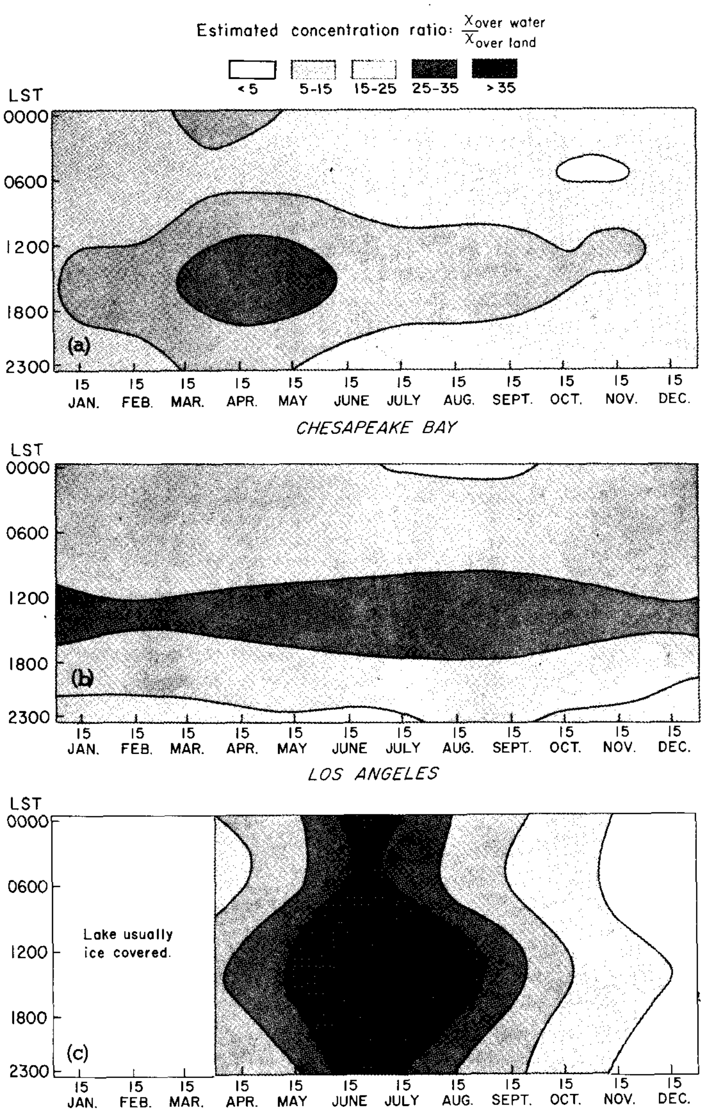

Figure 6.—Estimates of overwater-overland concentration ratio based on relationship in table 7: (a) Chesapeake Bay in vicinity of Chesapeake Bay Bridge, (b) Los Angeles-Long Beach, Calif., harbor area, (c) Duluth, Minn., harbor area.

evident whether some of the changes in slope are real or fortuitous. For instance, both the day and night curves show a decrease in slope for warming from below. It remains to be determined, from independent data, whether this relationship is real. Figure 5 is approximated by the values in table 7.

When the concentration ratio is computed for a point one mile from the postulated sources, a maximum value of 100 is obtained at an average temperature difference of $-15°$ F. From the extreme hourly values of the wind data observed, concentration ratios of 880 and 1/5 are found for the 1-mile interval.

The differences between the average monthly water temperatures for each hour of the day may be used with the data in table 7 to compute a relative diffusion climatology for offshore flows. Figure 6a is an example of such a climatology for the Chesapeake Bay. This method can be used in a gross way with data from other harbor areas. Figures 6b and 6c result from the application of the method to data from the Los Angeles-Long Beach, Calif., harbor and for Lake Superior in the vicinity of Duluth, Minn.

7. SUMMARY AND CONCLUDING REMARKS

Easily obtained meteorological data have been used to estimate diffusion over water relative to that over land during conditions of off-shore flow. These data indicate that diffusion is generally poorer over the water than over the land due primarily to the reduction of wind fluctuations over the comparatively smooth water surface. It has also been shown that the magnitude of the overwater diffusion is greatly influenced by the water-air temperature difference.

The actual concentration ratios that have been derived may be open to considerable argument because of the numerous simplifications that have been used. However, it is likely that diffusion over rather small inland water bodies is different enough from that over the adjoining land to indicate that this difference should be considered in environmental evaluations of the effects of important shoreline and overwater pollution sources.

It is well to recognize that a definitive study of the overwater dispersion problem would necessarily have to be based on overwater tracer diffusion experiments. In lieu of this, the values determined in this report should be used only as guides in assessing changes of diffusion potential between land and water.

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