

## Atmospheric Diffusion Studies Near a Lake Shore<sup>1,2,3</sup>

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### ABSTRACT

Experiments designed to measure atmospheric diffusion in transitional states have been carried out for several years over the western end of Lake Erie. The concept of diffusion in transitional states, both in general and for such a shoreline location, is described. The methods of data analysis which have been used are explained and their advantages and limitations outlined. Results of the experiments are presented in terms of Sutton's parameters  $n$ ,  $C_z$  and  $C_y$ . Values of  $C_y$  are generally larger than those which have been measured over more uniform sites. One experiment is described in detail to illustrate diffusion in a transitional state which was due to the advection of warm air aloft.

### 1. Introduction

Diffusion experiments using fluorescent particles (FP material) emitted from an elevated continuous point source have been carried on for several years along the western shore of Lake Erie. The experiments began as an integral part of a study of the natural environment at the site of the Enrico Fermi Atomic Power Plant. The plant is located halfway between Toledo, Ohio and Detroit, Michigan, as shown in Fig. 1. Early experiments were designed to measure diffusion in transitional states under stable atmospheric conditions when it was suspected that material in the atmosphere would diffuse slowly.

The phase "diffusion in transitional states" was first used by Hewson *et al.*<sup>4</sup> to describe the diffusion regimes near the shore of Lake Erie. It means simply that the field of atmospheric turbulence often exhibits marked variations in time or space or both. Diffusion under such conditions may be termed "diffusion in transitional states." This idea is not new, for the atmosphere is a dynamic entity whose characteristics can and do change radically within short intervals of time or space or both.

One of the earliest investigations of diffusion under radically changing atmospheric conditions was con-

ducted by Hewson and Gill<sup>5</sup> in the Columbia River valley near Trail, British Columbia. Two examples of diffusion in transitional states were investigated. One was a spatial variation of turbulent diffusion caused by a lapse condition in the lower layers capped by an inversion whose base was still within the valley walls. The second example was a temporal variation in atmospheric turbulence caused by solar heating during the mid-

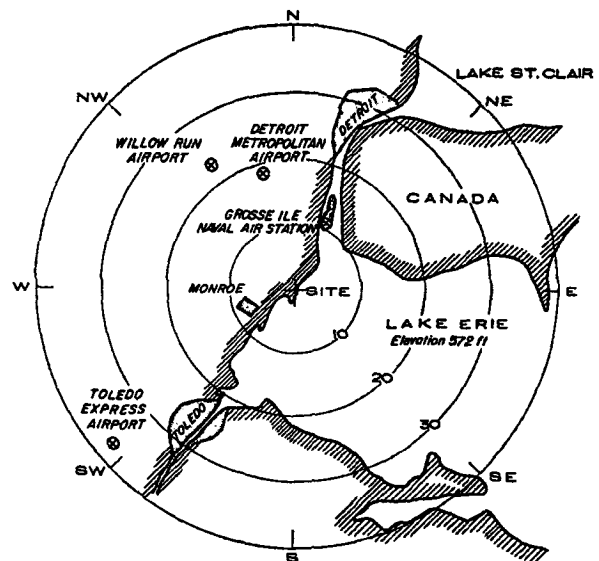


FIG. 1. Map of local area in the vicinity of the Enrico Fermi plant site. Radial distances shown in miles.

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<sup>4</sup> Hewson, E. W., G. C. Gill and E. W. Bierly, 1960: Atmospheric diffusion study at the Enrico Fermi nuclear reactor site, technical installation and preliminary analysis. The Univ. of Mich. Res. Inst. Rpt 2728-1-P., 66 pp.

<sup>5</sup> Hewson, E. W., and G. C. Gill, 1944: Report submitted to the Trail Smelter Arbitral Tribunal. U. S. Bureau of Mines Bull. No. 453, 23-225, 304 pp.

morning hours. The result of the mixing in the lower layers of the atmosphere due to the temporal variation in turbulence is the process termed fumigation (Hewson, 1946).

It is natural to extend the idea of transitional diffusion to other areas and regimes. The type to be discussed in this paper is transitional diffusion occurring near a shore line. The variation of turbulence in the horizontal plane along a line perpendicular to a shore line can be significant, but has received little attention. These horizontal variations can be due to temperature differences in the underlying surface, or they can be due to roughness differences in the underlying terrain. Both thermal and mechanical turbulence can be induced or suppressed depending upon whether the air flows over water or over land or over first one type of surface and then another. Such differences produce highly complex patterns of turbulence, and therefore highly complex patterns of diffusion. Details of the "floating grid" system used to obtain measurements of atmospheric diffusion under such conditions have been discussed by Bierly and Gill (1963).

This paper examines data obtained from measurements of diffusion in transitional states near a shore line using Sutton's parameters  $n$ ,  $C_z$ , and  $C_y$  as the basis of the analysis. The parameters  $C_z$  and  $C_y$  are computed from the measured concentrations using an assumed value of  $n$ . The methods of analysis are discussed and the results of two independent methods are compared. The paper concludes with an analysis of transient diffusion on a day with advection of warm air aloft.

**2. The value of Sutton's  $n$**

The empirical-mathematical model of Sutton (1947) was used as a basis for data analysis. The concentration from an elevated continuous point source at a point  $(x, y, z)$  is given by the following formula (Sutton, 1953):

$$\chi(x, y, z) = \frac{Q \exp(-y^2/C_y^2 x^{2-n})}{\pi C_y C_z \bar{u} x^{2-n}} \times \{ \exp[-(z-h)^2/C_z^2 x^{2-n}] + \exp[-(z+h)^2/C_z^2 x^{2-n}] \}, \quad (1)$$

where

- $Q$  = source strength, mass per unit time.
- $\bar{u}$  = mean wind speed at some selected level, usually midway between the highest and lowest sampling heights.
- $x$  = horizontal distance downwind from the source.
- $y$  = horizontal distance crosswind from the centerline of the plume.
- $z$  = vertical distance measured upward from the surface.
- $h$  = height of the source above the surface.

- $C_y$  = horizontal crosswind virtual diffusion coefficient.
- $C_z$  = vertical virtual diffusion coefficient.
- $n$  = a dimensionless number whose upper limit is 1 and which is related to the stability of the atmosphere.

Sutton (1953) suggests that the value of  $n$  can be computed from the wind profile using the following equation:

$$u/u_1 = (z/z_1)^{n/(2-n)}. \quad (2)$$

Attempts to evaluate  $n$  using Eq (2) did not produce reliable or reproducible values, so a value of  $n$  was assumed for each experimental day.

A problem is immediately evident when assuming a value of  $n$ . Using the "floating grid" system of sampling, the duration of each individual sample taken by the aircraft varies from 15-120 sec. A complete traverse through the plume at any one altitude varies from 2-16 min depending upon the distance from the source. The individual samples are of short time duration, the sampling time for a given radial distance is intermediate, while the sampling time for the entire plume may be of several hours duration. The problem then is, does one value of  $n$  adequately describe the atmosphere during the course of any one experiment? Barad and Haugen (1959) have shown in an analysis of Project Prairie Grass data that there is in reality not a single value of  $n$  which characterizes diffusion, but two values of  $n$ , one for lateral diffusion,  $n_y$ , and one for vertical diffusion,  $n_z$ . The present investigation, however, does not lend itself readily to a similar analysis.

The assumption was made, therefore, that the selected value of  $n$  was invariant in space and time and did describe the atmosphere during the entire experiment. Near a shoreline area where there are two very different regimes, one over land and another over water, the atmosphere is rarely found to be in an extreme condition of either stability or instability. Therefore, if the assumptions made relative to the value of  $n$  are valid anywhere, they are more likely to be valid in an area where the atmosphere is always near a condition of neutral stability.

The actual value of  $n$  was determined from the vertical temperature soundings obtained by the aircraft (see Bierly and Gill, 1963). The sounding was plotted and then compared with the dry adiabatic vertical temperature distribution. The degree of stability or instability was then used as the criterion for the determination of the value of  $n$ .

**3. Computation of  $C_z$**

The values of  $C_z$  and  $C_y$  were computed using two different methods. Method I was based directly on Sutton's equations. Method II utilized graphical techniques to obtain the standard deviation of the concentrations which was then related to Sutton's parameters  $C_z$  and  $C_y$ .

*Method I.* Several assumptions were made to simplify Eq (1) when computing  $C_z$  by the use of Method I. The first assumption was that there was no reflection from the earth's surface, thus allowing the third exponential term in Eq (1) to be neglected. A further assumption was that  $C_y$  was independent of  $y$ , thus permitting Eq (1) to be integrated across wind in the  $y$ -direction. The resulting equation for the integrated cross-wind concentration is

$$x_{ICC}(x,z) = \frac{Q \exp[-(z-h)^2 / (C_z^2 x^{2-n})]}{\pi^{1/2} \bar{u} C_z x^{(2-n)/2}} \quad (3)$$

Values of  $C_z$  were obtained by taking ratios of Eq (3) at two adjacent heights on the same radial arc. Eq (4) shows the form of this ratio:

$$C_z = \left[ \frac{(z_{ii}-h)^2 - (z_i-h)^2}{R x^{2-n}} \right]^{1/2} \quad (4)$$

where

$z_{ii}$  and  $z_i$  = the heights of two adjacent sampling levels above the surface

$R$  = natural logarithm of the ratio of the integrated crosswind concentrations at heights  $z_{ii}$  and  $z_i$ .

A mean value of  $C_z$  was obtained for each radial distance sampled during the experiment by averaging the values of  $C_z$  obtained from several layers. The  $C_z$  values for each radial distance were averaged to give a mean value of  $C_z$  which was assumed to be characteristic of  $C_z$  for the entire day's experiment. Mean values of  $C_z$  obtained by using Method I are given in Table 1 for 13 experimental days. The range of values of  $C_z$  obtained on each arc is also included in Table 1. Where there are no values given for the range, there were only enough data to compute one value for  $C_z$ .

*Method II.* Method II had fewer but perhaps more stringent assumptions. The basic assumptions underlying the use of the graphical technique of Method II are that of normality in the distribution of the fluorescent particle material and that the maximum counts lie in the same vertical plane. The procedure adopted was as follows: the maximum count for the lowest level sampled at a given radial distance was added to the maximum at the level above it until all maxima were totaled. Cumulative relative frequencies of these maxima were then computed and plotted on normal probability paper using cumulative relative frequency in per cent as the abscissa and height in feet as the ordinate. Fig. 2 shows a plot of data treated in this manner. A straight line was fitted to the points by eye. The standard deviation of the spread of the count was determined in the following way: the 50 per cent line on the abscissa scale represented the mean of the distribution, while the 84.1 per cent line represented the mean plus the standard deviation. Values were read on

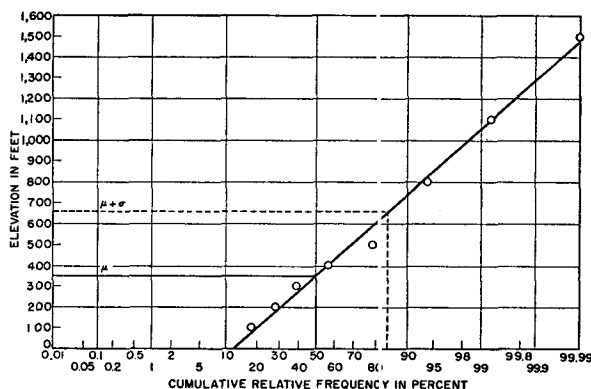


FIG. 2. Plot of the cumulative relative frequency in per cent of the maximum fluorescent particle count at each level at 4 km from the source vs. height in ft, used in calculating  $C_z$ , 6 September 1960.

TABLE 1. Values of Sutton's parameters from experiments conducted along a lake shore.

Experiment number	Date	Assumed value of $n$	$\bar{C}_z (m^{n/2})$		$\bar{C}_y (r_1^{n/2})$	
			Method I (range of values)	Method II (range of values)	Method I (range of values)	Method II (range of values)
1	8/ 5/59	0.25	0.10 (0.09-0.10)	0.06 (0.06-0.07)	0.42 (0.14-0.69)	0.69 (0.64-0.74)
3	8/ 6/59	0.25	0.15 (0.13-0.16)	0.07 (0.06-0.09)	0.38 (0.23-0.39)	0.67 (0.63-0.74)
5	11/27/59	0.20	0.14 (0.11-0.20)	0.07 (0.04-0.10)	0.64 (0.32-0.71)	0.74 (0.62-0.85)
7	2/ 4/60	0.30	0.08 (0.06-0.10)	0.03 (0.02-0.04)	0.54 (0.36-0.72)	0.69 (0.39-0.99)
9	4/ 3/60	0.30	0.09 (0.05-0.14)	0.07 (0.05-0.09)	0.61 (0.45-0.63)	0.49 (0.46-0.53)
13	5/ 8/60	0.20	0.13	0.16	0.44	0.37
14	6/25/60	0.23	0.14	0.08 (0.03-0.14)	0.37	0.56 (0.46-0.71)
16	8/30/60	0.25	0.14 (0.06-0.21)	0.06 (0.05-0.09)	0.44 (0.35-0.49)	0.61 (0.40-1.16)
18	9/ 6/60	0.23	0.12 (0.08-0.20)	0.08 (0.06-0.11)	0.56 (0.49-0.68)	0.78 (0.48-1.10)
19	11/25/60	0.25	0.12 (0.04-0.24)	0.06 (0.04-0.08)	0.46 (0.42-0.51)	0.61 (0.44-0.71)
20	11/26/60	0.25	0.11	0.06 (0.02-0.11)	0.45	0.34 (0.34-0.35)
23	12/27/60	0.23	0.17 (0.09-0.21)	0.13 (0.09-0.19)	0.50 (0.40-0.61)	0.65 (0.58-0.76)
24	12/28/60	0.23	0.14 (0.03-0.19)	0.07 (0.03-0.14)	0.50 (0.36-0.54)	0.72 (0.61-0.85)

the ordinate scale where the 50 and 84.1 per cent lines intersected the straight line representing the distribution. The difference between the ordinate values at 50 and 84.1 per cent represented the standard deviation of spread of the maximum particle count in terms of height. The standard deviation was converted to values of  $C_z$  by use of the following formula (Sutton, 1953):

$$C_z = \sqrt{2} \frac{\sigma_z}{x^{(2-n)/2}}, \tag{5}$$

where

$\sigma_z$  = the standard deviation of the spread of the maximum particle count

and the other parameters are as defined above.

A straight line could also be fitted to the data using least squares methods, but the data have to be replotted on linear graph paper before the standard deviation can be obtained. Several experiments were analyzed using least squares methods and the results were found to be not significantly different from those when the line was drawn by eye. Therefore, the first technique of plotting the data on normal probability paper and employing a straight line fitted by eye was the method adopted to obtain the value of  $\sigma_z$ .

Only one value of  $C_z$  for each radial arc could be computed when the maximum count was used as the basis for the computation. If there were double peaks or no definite maximum in the sampling results of a given level, then the computation of  $C_z$  was disregarded for that arc. Mean values of  $C_z$  computed in this manner are also contained in Table 1 with the range of values obtained throughout the experiment.

#### 4. Computation of $C_y$

*Method I.* Method I for the computation of  $C_y$  used the maximum count obtained at each level. This count was assumed to be the value at the centerline of the plume. Levels where either there was no definite peak or there was a double peak were not used for the evaluation of  $C_y$ . Eq (1) was rewritten for the centerline concentration and then solved for  $C_y$  using the appropriately assumed value of  $n$  and the previously computed value of  $C_z$  obtained by Method I. The form of the resulting equation is given below as Eq (6):

$$C_y = \frac{Q^* \exp[-(z-h)^2 / (C_z^2 x^{2-n})]}{x_{\max} \pi C_z \bar{u}_z x^{2-n}}, \tag{6}$$

where

$Q^*$  = source strength corrected for efficiency of the dispensing and sampling system.

$\bar{u}_z$  = the mean wind speed at some height  $z'$  which is the mean height between the highest and lowest layers sampled.

$x_{\max}$  = maximum concentration at height  $z$ .

The value of  $Q^*$  was obtained by computing the mass transport through a section of a vertical cylinder. A system efficiency was then defined for each radial distance as follows:

$$(Q^*/Q)100 = E, \tag{7}$$

where

$Q^*$  = number of particles transported through the cylinder wall per unit time.

$Q$  = number of particles placed in the aerosol generator per unit time.

$E$  = efficiency in per cent.

The computation of efficiency of the system and the use of a corrected value for the source strength take into account any losses of fluorescent particle material at the source or in the air due to fallout, deposition, or other process.

The mean wind speed between the highest and lowest level sampled was used in the computation of  $C_y$  because it gave a more realistic representation of the wind speed carrying the FP material than the value measured at 100 ft on the meteorological tower. The wind speed at 100 ft was measured and a 1/7 power law profile was used to obtain the value of the wind speed at the desired height,  $z'$ .

The mean values of  $C_y$  as well as the range of values computed using Method I are listed in Table 1.

*Method II.* Values of  $C_y$  were obtained using the graphical technique in a manner very similar to the way in which values were obtained for  $C_z$ . The counts on the sampler collected at any one altitude on each radial arc were added, and then cumulative relative frequencies were computed for each level. The cumulative relative frequencies in per cent were plotted as the abscissa on normal probability paper while the ordinate was the bearing of the midpoint of the sample. Fig. 3 is

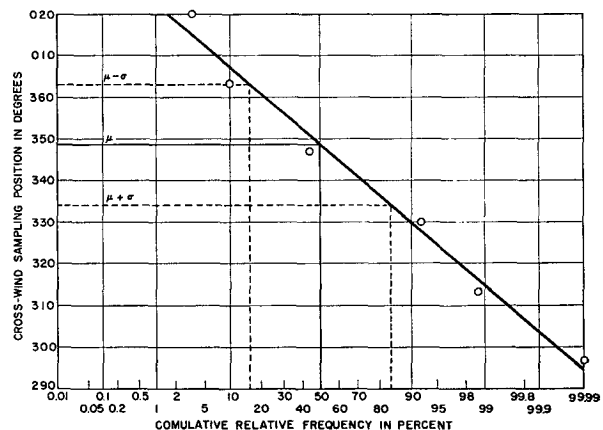


FIG. 3. Plot of the cumulative relative frequency in per cent of the fluorescent particle count at 400 ft above the surface and on the arc 8 km from the source vs. the bearing in degrees of the sample, used in calculating  $C_y$ , 6 September 1960.

an example of data plotted in this way. The standard deviation of the distribution for each level was obtained by reading the value of the ordinate at 50 per cent and at either 84.1 or 15.9 per cent. The value of  $C_y$  obtained was then converted from degrees to meters using the appropriate distance from the source.  $C_y$  can then be evaluated using the following formula (Sutton, 1953):

$$C_y = \sqrt{2} \frac{\sigma_y}{x^{(2-n)/2}} \tag{8}$$

Table 1 contains the values of  $C_y$  and the range of values of  $C_y$  computed by this method.

5. Discussion of results

The results tabulated in Table 1 are mean values of  $C_y$  and  $C_z$  computed using both Methods I and II. A noteworthy feature of the results as presented is the consistently high values of  $C_y$  in comparison with those for  $C_z$ . The values of  $C_y$  in Table 1 are similar in magnitude to the hourly values of Sutton's diffusion coefficients reported by Smith & Singer (1957). The tabular values of  $C_z$  are more similar to the 3-min values given by Sutton (Haltiner & Martin, 1957). Part of this difference, but only a part, between the magnitude of the values of  $C_z$  and  $C_y$  is believed to be due to the sampling technique used. Some distortion may come from the use of the "floating grid" system. The aircraft sampler in effect integrates across the plume, thus taking into account the whole spectrum of eddies active in diffusion. On the other hand, the sampler is operating at only one altitude at any given time and is less affected by variations in vertical diffusion. It seems reasonable to expect that the values of  $C_y$  measured in this manner would be larger than corresponding coefficients obtained by use of a 3-min fixed sampler. Even after allowance is made for differences which may be due to sampling methods, the measured values of  $C_y$  at this shoreline location are greater than those measured over more uniform sites.

A comparison of Methods I and II is provided in Table 2 for one day, 6 September 1960. There are several important facts to be pointed out. The values of  $C_z$  from both methods are estimates that might be expected

from 3-min samples. Both sets of values are similar in not only magnitude but trend. The values of  $C_z$  decreased as the sampling progressed to distances further and further from the source. An explanation of this fact will be offered in Section 6.

The values of  $C_y$  computed using Method I and the values of  $C_y$  at 2 and 4 km from Method II are similar to the values of  $C_y$  that might be expected from a sampling period of 1 hr. The values from both methods have the same trend, that is, to increase as the sampling progressed farther from the source. Such an increase seems reasonable since the fluorescent particle material is being subjected to larger and larger eddies and hence to more and more pronounced eddy diffusion as time passes and the material travels farther from the source. One might speculate at this point that at intermediate ranges, beyond 5 miles or so, Sutton's equations may suffer from a deficiency not unlike that found in the classical diffusion equations. Although there is no upper limit on  $C_y$ , most published values are below 1.00. Perhaps this is due to the fact that most of the reported values of  $C_y$  have come from experiments where the samplers are quite close to the source. From the form of the equation used to compute  $C_y$  in Method II, it is reasonable to conclude that  $C_y$  will increase as the distance from the source increases since the value of the standard deviation will usually become greater as the diffusing material is spread by larger and larger eddies. It is apparent that Method I tends to minimize the influence of the larger eddies. Part of this insensitivity again may be due to the averaging process used in computing  $C_y$ .

6. Discussion of diffusion regime observed on 6 September 1960

The mean values of  $C_z$  and  $C_y$  computed using Methods I and II for 6 September 1960 have been presented in Table 2. Data were obtained at 2, 4, 8 and 16 km during a 3-hr period of sampling which commenced at 1150 EST and was completed at 1507 EST. Notice that  $C_z$  decreases with distance out to 16 km but that  $C_y$  increases out to 16 km. Such results suggest that there was a vertical stabilizing influence occurring which reduced vertical diffusion while permitting horizontal diffusion to increase.

Fig. 4 is a reproduction of the surface map showing the synoptic situation at 0100 EST on 6 September 1960. Note the position of the warm front west of Lake Michigan. Fig. 5 is a plot of the aircraft soundings taken over both water and land prior to and after the sampling was completed. Warm advection aloft was already taking place when the first soundings were made. This advection continued throughout the sampling period as evidenced by the soundings taken after the sampling was completed. The inversion base was at 1800 ft initially, while 5 hr later it was at 700 ft. The inversion base was thus lowering at approximately 200

TABLE 2. Sutton's parameters calculated by Methods I and II for experiment No. 18, 6 September 1960.

Radial distance (km)	$n=0.23$				Time of sampling (EST)
	$\bar{C}_z$ ( $m^{n/2}$ )		$\bar{C}_y$ ( $m^{n/2}$ )		
	Method I	Method II	Method I	Method II	
2	0.20	0.11	0.49	0.48	1150-1220
4	0.14	0.08	0.50	0.55	1225-1255
8	0.08	0.06	0.56	0.97	1300-1344
16	0.07	0.06	0.68	1.11	1350-1507

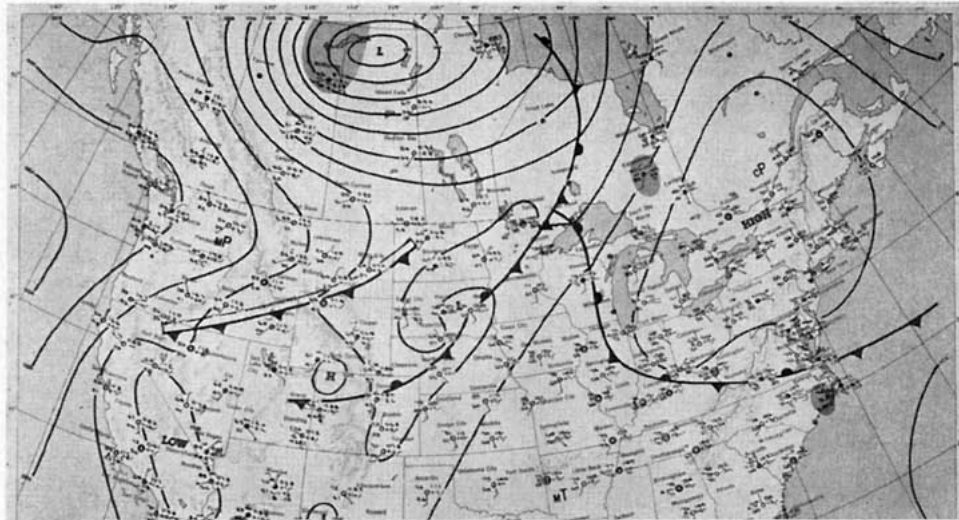


FIG. 4. Surface weather map at 0100 EST on 6 September 1960.

SYMBOL	SURFACE	BRNG	RAD (km)	MORNING	AFTERNOON
o—o	Land	320°	0.1	11:47	17:25
v—v	Water	160°	3.0	11:55	17:17
x—x	Land	340°	4.0	12:13	17:38

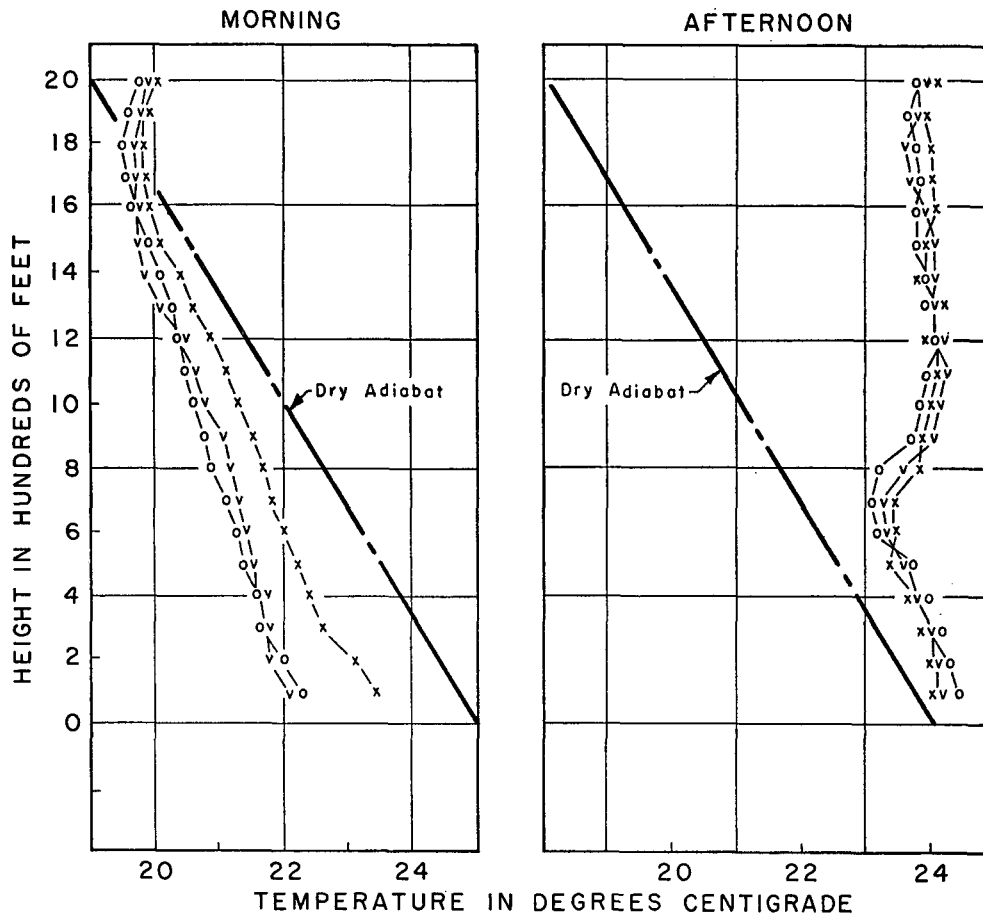


FIG. 5. Plot of the vertical temperature distribution as recorded by aircraft sounding on 6 September 1960.

ft per hr while the sampling was taking place. The damping effect of this stabilization on the vertical diffusion is evident in the computed coefficients of Table 2. Although the day had clear skies with a light wind from the SSE, so that the sampling runs were made over land, the effect of the warm advection was dominant with the result that vertical diffusion decreased as sampling progressed inland. This is a case where, for all practical purposes, there was no significant spatial variation in the turbulent diffusion regime, but only a temporal variation. In this particular situation, the change of air trajectory from water to land seemed to make little difference in the diffusion process. It is apparent that the larger advective effects outweigh the localized shoreline influences.

Although the values of  $C_z$  computed using Method II agree well with the values from Method I, the same cannot be said about the values of  $C_y$ , although the trend is the same for both methods. Nevertheless, the argument concerning the influence of warm advection is not invalidated by the differences in the values of  $C_y$  computed by the two methods. The damping effect of the warm advection in increasing vertical stability is shown in the vertical coefficients. The values of  $C_y$  computed using both methods do not show any such effect of stabilization, but rather indicate that horizontal diffusion is becoming more pronounced with distance downwind. Because Method II utilizes a plot of the actual observed sampler counts for computing  $C_y$  and because there is a sound physical basis for believing that horizontal crosswind diffusion will increase with distance downwind owing to the participation of larger and larger eddies in the horizontal diffusion process, the values of  $C_y$  obtained from Method II must be accepted although they are unusually large. Since both methods give values of  $C_y$  which increase as distance from the source increases, it is clear that diffusion in the horizontal crosswind direction became increasingly effective with time and distance from the source. Concurrent advection of warm air aloft led to stabilization and low values of vertical diffusion which decreased in magnitude with increasing distance from the source.

## 7. Conclusions

The results from thirteen experiments of atmospheric diffusion in transitional states near a lake shore have been presented. Two independent methods of analysis are described that give values of Sutton's  $C_y$  and  $C_z$  which are higher than values from other diffusion experiments that have been performed over more uniform terrain. Although part of the difference may be due to the sampling method, it is felt that some of the difference must be attributed to the shoreline regimes where the experiments have been held. In such an area the atmosphere is nearly always in an almost neutral state. There have been no observations of extremes of either

stability or instability, so it is reasonable to assume that diffusion in the horizontal crosswind direction will remain at a high value during most of the time.

Generally, the values of  $C_z$  obtained from both methods of analysis are of the same magnitude as the 3-min sampling values given by Sutton, whereas the values of  $C_y$  obtained by either method are of the same magnitude as the 1-hr sampling values obtained at Brookhaven. The values of  $C_y$  found by using Method II indicate in certain experiments, at least, that the fluorescent particle material is being subjected to larger and larger eddies as the material diffuses farther and farther from the source. Indications are that Sutton's equations are inadequate to represent diffusion regimes beyond 5 miles or so from the release point.

The experimental data from 6 September 1960 have been presented in more detail to show the effect of warm advection in producing a time transition of diffusion as far as 16 km from the source. The effect of the warm advection aloft is evidenced in the computed coefficients using either Method I or Method II.

These experiments over the shoreline area are the first of a series designed to reveal the mechanisms of diffusion in this particular transitional state. The area near a shoreline is only one of many regions where diffusion patterns are complex due to the complex turbulent regime which is caused by two very different underlying terrain types. Superimposed upon this local regime is the general synoptic pattern. The net result is a diffusion state which contains several transitions in time and space.

The original data used in this and subsequent analyses are presented in a technical report, O3632-8-T, Office of Research Administration, Univ. of Michigan. A copy of this report may be obtained by writing to the authors.

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