Dispersion and Deposition of Ragweed Pollen from Experimental Sources[1]

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ABSTRACT

Dispersion and deposition of ragweed pollen released naturally from circular area sources of four sizes (5–27 m in diameter) and artificially from point sources were studied at Brookhaven National Laboratory. Concentrations were measured by wind-impaction samplers mounted on 20° radii at four heights (0.5–4.6 m) and four or five distances from the sources to a maximum of 69 m. Deposition was measured by greased microscope slides on the ground. Differences in dispersion patterns between point and area sources are analyzed. Normalized centerline concentrations, cross-wind integrated concentrations, plume widths, plume heights and mass flux are presented as functions of distance and related to source size and meteorological variables. Deposition data are also related to distance and source size. Most deposition velocities ranged from 2–6 cm sec^{-1} but values close to area sources were much greater. Loss of airborne particles between sampling circles is compared to deposition over the same distances. Results are compared to those of previous dispersion and deposition studies and to theory.

1. Introduction

Dispersion of ragweed pollen emitted naturally from 10 circular area sources of cultivated plants and artificially from point sources was studied experimentally at Brookhaven National Laboratory over a four-year period. The original purpose of this program was to obtain adequate experimental data on dispersion of airborne pollens from living plants under natural conditions and to relate the data to source size, meteorological conditions, and other pertinent variables in the expectation of providing information useful to allergists, public health officials, botanists, plant breeders and others concerned with pollen dispersion. This objective has largely been realized. In addition, it was found that the data could be analyzed in terms of current dispersion and deposition theory to supplement previously available information on dispersion of particles from low-level sources and to determine how well such theory applies under the non-ideal conditions of these experiments. Finally, the three-dimensional nature of the measurements permits inferences concerning the shape of turbulent eddies near the ground.

In a previous paper (Raynor and Odgen, 1965) an analysis was presented of concentration measurements taken around six area sources during the first two years of the program when concentrations were measured over 24-hr periods. During the first of these years sampling was conducted at only one height but during the second year samples were taken at three heights around two of the four sources. Deposition was not measured. These limited data permitted a useful analysis of horizontal dispersion but were inadequate for a study of dispersion in the vertical or for mass balance computations. The lengthy sampling periods covering complete diurnal cycles prevented detailed correlation of dispersion rates with short-term meteorological data.

During the last two years of the program, samples from four area sources were taken only over time periods from 2–8 hr in length during periods of relatively uniform weather. Concentration measurements were taken at four heights and at four or five distances from the sources. Deposition to the ground was measured and adequate meteorological records were obtained. A detailed description of this portion of the program with tabulations of much of the original and derived data were given by Raynor *et al.* (1970). These data are used in the analyses presented below.

Portions of data from all four years were used in two subsidiary studies, one on areas within isopleths of concentration from local sources (Raynor *et al.*, 1969) and the other on the relationship between pollen concentrations of local and distant origin (Raynor *et al.*, 1968). A study of diurnal patterns of pollen emission in

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TABLE 1. Variation in normalized centerline source height concentration expressed as a percentage of the 1 m concentration with distance from point and area sources.

Source diameter (m)	Distance from edge of the source (m)	Mean normalized concentration (%)	Standard deviation s of normalized concentration (%)	Coefficient of variation s/mean	Number of cases
Point	16.8	4.4	2.0	0.45	19
	24.4	2.3	1.3	0.57	21
	41.2	1.0	0.6	0.60	21
	68.6	0.3	0.2	0.67	21
5.5	17.1	16.6	5.3	0.32	13
	38.4	6.3	3.2	0.51	13
	65.8	2.7	2.1	0.78	13
9.1	15.2	26.5	5.1	0.19	15
	35.3	10.7	3.7	0.35	15
	64.0	5.0	1.8	0.36	15
18.3	15.2	30.5	3.7	0.12	9
	32.0	16.9	5.6	0.33	9
	59.4	9.2	2.4	0.26	9
27.4	18.3	37.1	10.2	0.27	10
	36.6	19.5	6.4	0.33	10
	54.9	12.5	5.2	0.42	10

ragweed and other plants was also published (Ogden *et al.*, 1969). Previous literature on pollen dispersion from known sources was discussed in the earlier paper (Raynor and Ogden, 1965). No pertinent studies have been reported since.

2. Sources

The four area sources from which data are presented below included two circular plots, 5.5 and 9.1 m in diameter planted with giant ragweed (*Ambrosia trifida*) treated to pollinate before its normal season. Around each circular plot, annular rings, 18.3 and 27.4 m in outer diameter, respectively, were planted with dwarf ragweed (*Ambrosia artemisiifolia*). All sources were centered in a level field about 180 meters square covered with mown grass. The ragweed plants were spaced ~1 m apart, grew to ~1.5 m tall and covered the planted area uniformly at maturity. Each pre-season plot released pollen for a period of two to three weeks and the in-season plots for three to four weeks beginning after the pre-season plants had completed the process. During a pollination season, emission rate varied with time from the beginning of the season, with time of day and with current and past weather conditions (Ogden *et al.*, 1969). Accurate measurements of total emission were not obtained but calculations described below showed that amounts airborne at plot boundaries varied from 10^9 to 10^{13} grains during single sampling periods. Ragweed pollen grains are spherical, about 20 μ in diameter and covered with blunt spines. Their settling rate is ~1.56 cm sec^{-1}.

Point sources consisted of compressed-air-operated atomizing nozzles (Raynor and Smith, 1964) which sprayed a known amount of pre-stained ragweed pollen in a water suspension (Raynor *et al.*, 1966). The mean diameter of the droplets produced was ~15 μ with only a small percentage of the larger drops containing pollen grains to minimize clumping. Rapid evaporation of the drops left the pollen entrained in the ambient air. Output rates varied from 1–5$\times 10^5$ grains sec^{-1} but were constant during each run. Emissions lasted 24–60 min giving total outputs of ~3.6–7.0$\times 10^8$ grains. Point sources were elevated from 0.5–3.0 m above the ground.

3. Sampling arrays

During the pollination season, area sources were surrounded by four or five rings of sampling positions spaced 20° apart. The innermost ring was ~1 m from the plants and the outermost 68.6 m from the center of the plot. Intermediate circles were spaced at approximately equal distances. The exact distances varied with source diameter (see Tables 1 and 4). Slide-edge-cylinder samplers (Raynor *et al.*, 1970) were mounted at heights of 0.5, 1.5, 3.0 and 4.6 m. Sensitive anemometers were mounted at each sampling height, since the volume sampled by the slide-edge and its collection efficiency for a given particle are functions of wind speed. Deposition was measured by two greased microscope slides placed on a small board in the grass at the base of each sampling mast. A Hirst spore trap (Hirst, 1952) was mounted above the center of each source to measure the variation of pollen emission rate with time. Point source tests were made from the center of the same sampling array before the plants reached appreciable size and after they were removed.

4. Procedure

Area source test periods were selected on the basis of expected weather and adequate pollen emission. Since most ragweed pollen is released during early to mid-morning, tests were generally conducted during that period. Slides were usually placed in the samplers before emission began and left in until midday. Some change in temperature, humidity and wind speed could not be avoided during the course of a test due to the normal diurnal cycle of these variables, but if any significant change in other meteorological conditions such as wind direction, gustiness type or cloud cover became imminent, the run was ended. If adequate pollen remained in the plants, a second test was started after the change occurred. Eighty-four runs were obtained, 55 in the morning, nine during the midday period, three in the afternoon, nine from early morning through the afternoon and eight overnight. Little pollen was released during the night so the overnight tests were treated as morning runs if slides were left on until the morning emission. No tests were made during precipitation. Point source tests were all made under daytime, unstable conditions with at least moderate wind speeds.

Inserting the slides and erecting the sampler support masts at the beginning of each run took ~20 min and removing the slides at the end a similar time. Positions started first were ended first to equalize exposure time. In point source tests, slides were all inserted before emission started and removed after the cloud had cleared the area. Thirteen point source releases were made from near the 1.5 m height and eight from other levels.

Collected pollen grains were counted using a microscope. Slide-edge-cylinder counts were converted to average concentrations (grains m^{-3}) according to the volume sampled and the sampler efficiency. The volume was calculated by multiplying the cross-sectional area of the sampling surface by total air passage. The efficiency was determined from a calibration curve of efficiency as a function of wind speed for ragweed pollen using mean hourly wind speeds normalized by mean hourly pollen output as measured by the Hirst spore trap. This procedure gave a more accurate efficiency value than use of a simple mean wind speed for the period since greatest weight was given to the speed prevailing during the period of maximum pollen emission. Deposition counts were reduced to units of grains m^{-2} by the appropriate areal correction.

5. Analysis

For the in-season cases, the contribution of pollen from other sources was determined from measurements on the upwind side of the plot and this quantity subtracted from all measurements before further analysis. Procedures used in the various analyses are described in the corresponding sections on results. To avoid excessive tabular or graphical presentations, most of the results shown are the means of all cases from a single source. However, standard deviations are shown in some cases to document the amount of scatter in the data and selected cases are used for illustrative purposes. The data on which the analyses are based were presented with means and standard deviations by Raynor *et al.* (1970).

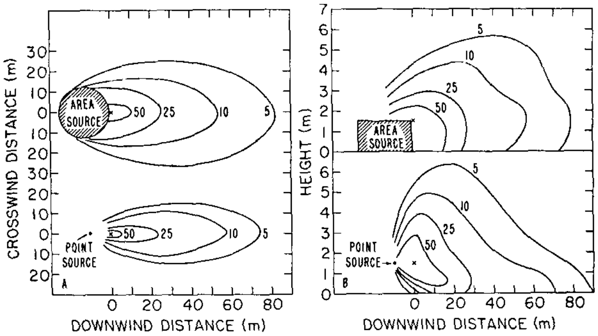

Fig. 1. Horizontal source height (A) and vertical centerline (B) dispersion patterns from a point and an area source of ragweed pollen under similar weather conditions. Concentrations are normalized to 100% at point x in the figures.

6. Results

a. Dispersion patterns

In spite of the rather crude sampling methods, concentration and deposition patterns were almost invariably orderly and internally consistent. Patterns from point and area sources, although grossly similar, differed significantly as a result of source characteristics and of the conditions under which the two types of tests were made. Area source runs were taken each day during the pollination season unless weather conditions were decidedly unfavorable, while point source tests were taken more selectively during periods of steady winds. Fifty percent of the 84 area source sampling tests had mean wind speeds of 2.0 m sec^{-1} or less at a height of 1.5 m but all point source tests had speeds above this value. Duration of the runs also contributed to differences found. Point source tests were all less than 1 hr in length while most area source runs lasted 3 hr or longer. The lower wind speeds and longer sampling periods both caused greater wind direction fluctuation resulting in wider plumes at all distances from the area sources.

These differences are illustrated in Fig. 1 for a point and a 27.4 m diameter area source run, both taken under very similar conditions, a mean 1.5 m wind speed of 2.9 m sec^{-1}, B_1 gustiness (Singer and Smith, 1953) and overcast skies. The area source test lasted for 8.25 hr and the point source test for 58 min. For an easier comparison, concentrations are normalized to 100% at the first sampling position on the downwind centerline, point x in the figure. This position was at source height, just outside the area source and 10 m downwind from

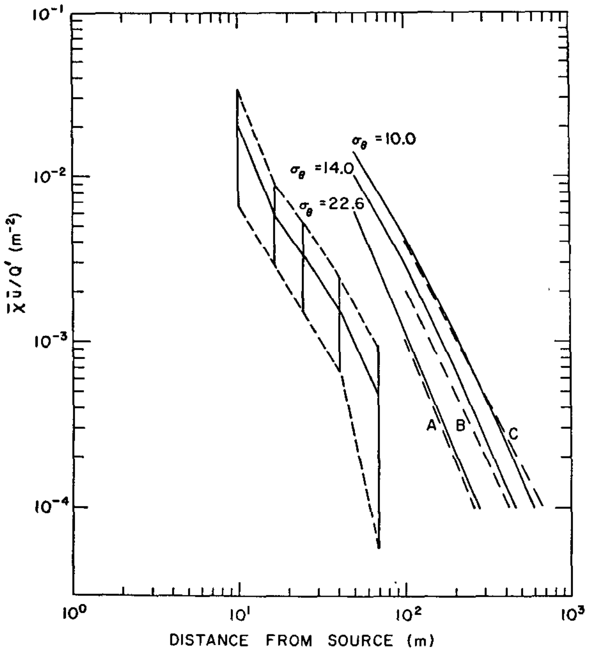

FIG. 2. Change of mean normalized source-height centerline concentration with distance. The solid line represents the mean and the dashed lines the mean plus and minus one standard deviation. Also shown are the Pasquill curves for the three most unstable categories, A, B and C (dashed lines), and experimental data from operation Prairie Grass with $\sigma_\theta = 10.0$, 14.0 and 22.6 (solid lines).

the point source. Rates of dispersion in the downwind (x) direction are nearly identical (Fig. 1a) but the isopleths from the area source are about twice as wide in the crosswind (y) direction. This results from both the crosswind extent of the source and the more variable winds during the extended sampling period. In the vertical (z) direction (Fig. 1b), the rise of the plume close to the area source is inhibited by compression of the streamlines of flow over the stand of plants and by downward components of motion in the turbulent wake. (The bimodal tendency in the vertical point source pattern is fairly common and occurs with area sources as well.)

b. Centerline concentrations

Axial concentration data ($\bar{\chi}$) from the point source experiments taken at a height of 1.5 m were multiplied by the mean source height wind speed ($\bar{u}$) and divided by the output rate (Q'). The mean and the mean plus and minus one standard deviation of the resulting normalized concentrations are plotted as functions of distance from the source in Fig. 2. For comparison, the calculated values of $\bar{\chi}\bar{u}/Q'$ for the three unstable Pasquill turbulence types, A, B and C (Hilsmeier and Gifford, 1962), and the three experimental curves with the widest σ_θ (standard deviation of lateral wind direction distribution) from the Prairie Grass data (Cramer *et al.*, 1964) are also plotted. Although the slope is similar, the ragweed data are about a factor of 5 lower. Curves almost identical to those from the ragweed tests were found in another sampling area at Brookhaven with similar surface characteristics using uranine dye on submicron-sized particles as a tracer in low-level dispersion tests. The reasons for these lower values are not completely understood but deposition and greater surface roughness are important factors and some error in the calculation of Q is possible since the exact density of the ragweed pollen as each sample was weighed could not be determined. Thirteen of the twenty-one point source tests were made with both source and sampler at a height of 1.5 m. The other eight sources varied from 0.5–3.0 m in height. No significant differences with height in either the values of $\bar{\chi}\bar{u}/Q'$ or the slopes were evident. A tendency was noted for $\bar{\chi}\bar{u}/Q'$ to increase with wind speed but the scatter was too great and the range of wind speeds too small for definitive results.

Since source output was not known for the area source tests, centerline concentrations at the 1.5 m level for all unimodal cases were normalized by the value on the inner sampling circle and averaged separately for each of the four area sources and for the point sources. Results are shown in Fig. 3 where the curves separate in order of source diameter with concentrations from the largest source decreasing most slowly with distance and those from the point source most rapidly. Also shown is a point source curve calculated from Sutton's diffusion equation (Sutton, 1947) corrected for deposition (Chamberlain, 1953), using parameters appropriate for the mean meteorological conditions during the point source runs and a V_d (deposition velocity) of 1.6 cm sec^{-1}. The slope is similar to that of the experimental point source curve beyond 10 m. The area source curves also tend toward similar slopes at distances increasing with source size.

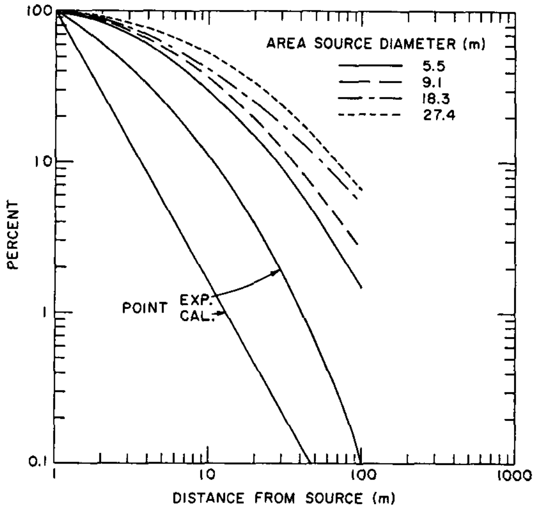

FIG. 3. Change of mean relative source-height centerline concentration with distance from the experimental point and area sources. Also shown is a calculated point source curve.

Centerline data from the five sources are summarized in Table 1 where the mean percentage of the 1 m concentration remaining at each sampling distance, the standard deviation, the coefficient of variation, and the number of cases are tabulated. The standard deviation generally decreases with distance, most rapidly for the smaller sources. The coefficient of variation increases with distance for the point and 5.5 m diameter source, but tends to level off beyond 30 m for the larger sources.

Relative centerline concentrations at three distances from the 5.5 m diameter source are related to mean wind speed in Fig. 4. To avoid clutter, data points are shown only for the central curve. Although considerable scatter is evident, the percent remaining clearly increases with wind speed. This probably results from both decreasing dispersion away from the centerline and decreasing loss by deposition as wind speeds increase. Similar results were obtained with data from the other sources except where the wind speed range was too limited to establish a slope.

c. Plume width

The plume width parameter σ_y, the standard deviation of the crosswind distribution of particles, was calculated for each case at 15, 30 and 60 m from the edge of the source at a height of 1.5 m using the method described by Raynor *et al.* (1970) in which σ_y is calculated using the length of the arc from the centerline to the point where concentrations decrease to 10% of the centerline value. Mean values of σ_y for both point and area sources are plotted as a function of distance in Fig. 5. For comparison with the point source curves, data from the three most unstable Prairie Grass categories, linear extensions of the A, B and C Pasquill curves, and curves from stack-height diffusion experiments at Brookhaven under B_1 and B_2 gustiness are shown. The slope of the point source σ_y curve is nearly parallel to the extensions of the Pasquill curves and quite similar in slope to the Prairie Grass cases. Numerical values of σ_y are higher than predicted by the Pasquill curves but between the two upper Prairie Grass curves. The Brookhaven stack-height curves have a decidedly steeper slope indicating more rapid diffusion at that level.

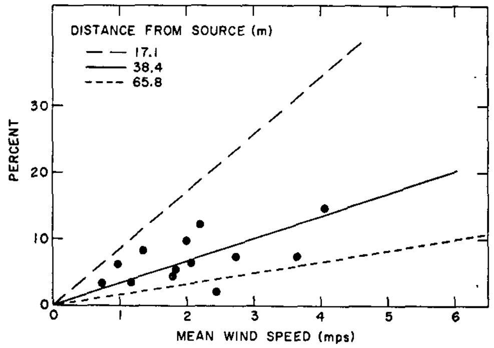

FIG. 4. Percentage of the mean relative source-height centerline concentration remaining at three distances from the 5.5 m diameter source as a function of wind speed. Data points are shown only for the solid curve.

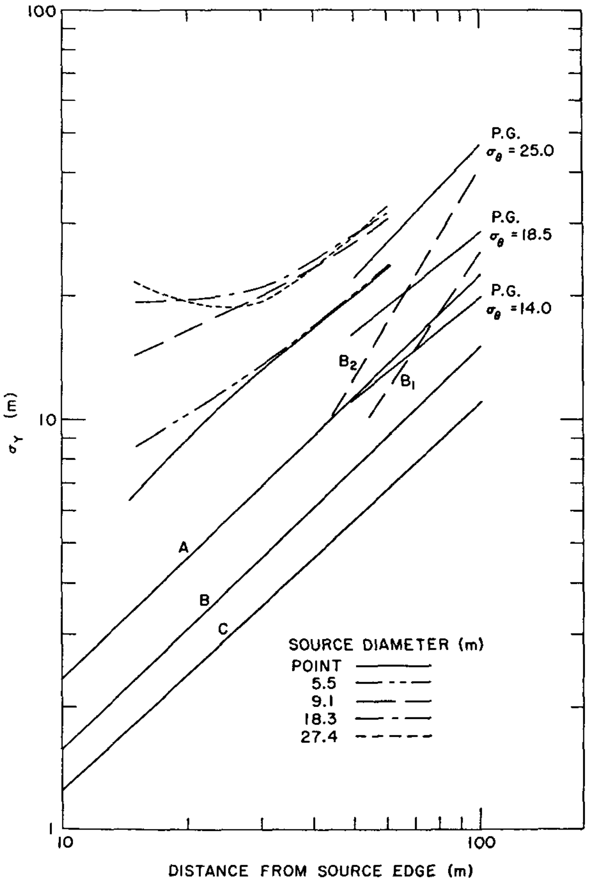

FIG. 5. Variation of standard deviation of source-height plume width (σ_y) from the five sources with distance. Also shown are linear extensions of the Pasquill curves for the three most unstable categories, A, B and C, experimental data from operation Prairie Grass (P. G.), with $\sigma_\theta = 14.0$, 18.5 and 25.0, and curves from stack-height diffusion experiments at Brookhaven National Laboratory under B_1 and B_2 gustiness.

As source size increases, σ_y also increases but more rapidly close to the source. This leads to a progressive decrease in slope with source size close to the source but little change in slope farther away. Beyond modest distances from an area source, lateral dispersion appears to proceed at the same rate as from a point source but values of σ_y are numerically larger due to the initial width of the plume.

d. Plume height

The plume height parameter σ_z, the standard deviation of the vertical particle distribution, was calculated at the same distances as σ_y for all cases using the method of Raynor *et al.* (1970). Results plotted in Fig. 6 show that σ_z is small compared to σ_y but increases slowly with distance. The area sources have somewhat larger values

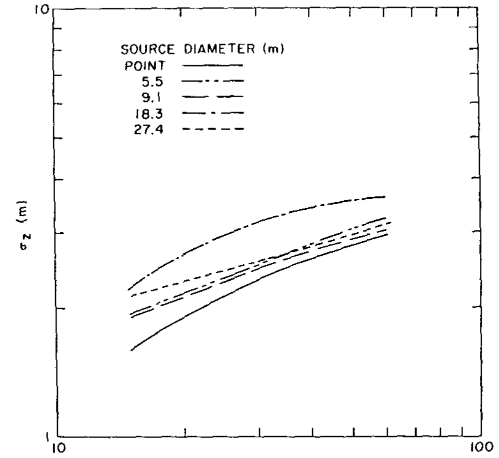

FIG. 6. Variation of standard deviation of plume height (σ_z) from the five sources with distance.

of σ_z at all distances than the point sources but do not show a clear trend in either slope or numerical value with source size. No comparable studies of σ_z for low-level sources were found for comparison but these results are similar to those obtained in other unpublished low-level tracer experiments at Brookhaven.

Since σ_y increases more rapidly than σ_z with distance from the source, the ratio, σ_z/σ_y, generally decreases with distance (Fig. 7). Curves from the point and the two smaller area sources show a constant decrease with distance. Ratios from the two larger sources are relatively low at 15 m because of the large σ_y close to these sources but agree better with the smaller sources at greater distances. Numerically, the ratios vary from 0.10–0.25, indicating that lateral predominates over vertical dispersion close to the ground even under the unstable conditions prevailing during these tests. The atmospheric motions responsible for this result are documented by unpublished data from ten sensitive bivane tests taken at a height of 2 m over similar terrain at Brookhaven with similar lapse rates. These 20–30 min tests gave ratios of σ_w/σ_v, the standard deviation of the vertical to the standard deviation of the lateral wind velocity component, from 0.12–0.37.

Both sets of data indicate a marked flattening of the eddy structure at low altitudes over level, grass-covered terrain under unstable conditions. This eddy structure must be considered in modeling dispersion from low-level sources with current diffusion theories. Diffusion parameters appropriate for stack-height release, for instance, lead to completely unrealistic results if used in a model applied to a low-level source over short travel distances under the same meteorological conditions.

The data also contribute to an understanding of ragweed pollen behavior in the atmosphere under natural conditions. Much more pollen is distributed laterally than vertically, thus enhancing the probability of early deposition and successful pollination, and decreasing the probability of long distance travel of large portions of the pollen released.

e. Crosswind integrated concentrations

Concentration data for all runs were integrated numerically along each sampling arc at the 1.5 m height (the approximate source height) to obtain arc-wise integrated concentrations which were shown by Raynor *et al.* (1970) to be essentially the same as true crosswind integrated concentrations at the same distances. Although the two larger area sources have higher values than the two smaller ones, the integrated concentrations are not proportional to source size due to other variables such as pollen output, mean length of runs and wind speed. However, the slopes are all quite similar. The data were normalized to 100% at the 1 m distance and plotted as a function of distance from the source in Fig. 8. Since the four area source curves nearly coincide, mean deposition and vertical dispersion must have been similar for pollen from all source sizes. The point source curve changes slope more rapidly with distance which may result from better vertical dispersion during point source test periods.

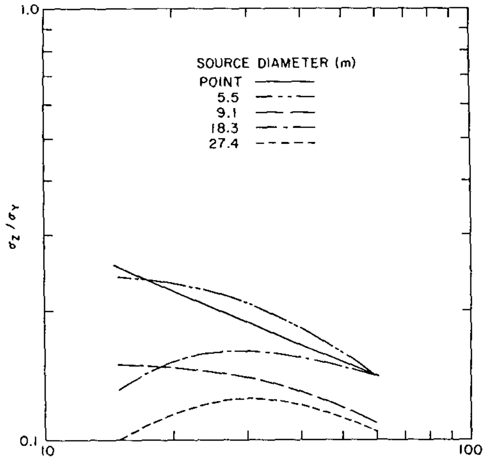

FIG. 7. Variation with distance of the ratios of standard deviation of plume height to standard deviation of plume width (σ_z/σ_y) from the five sources.

For a comparison of rate of loss in arc-wise integrated concentration with rate of loss in centerline concentration, Fig. 8 may be compared with Fig. 3. At 60 m from the source, from less than 1% to 13% of the centerline concentration remains at this level. At the same distance, from 13–30% of the crosswind integrated concentration remains.

f. Mass flux

Four cases were selected from each of the four area sources and seven from the point sources for computa-

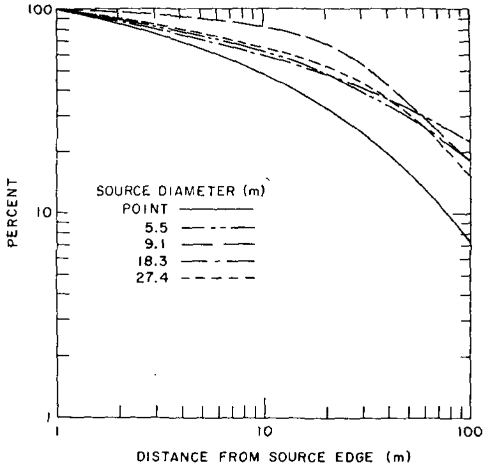

Fig. 8. Variation of mean normalized source-height arc-wise integrated concentration from the four area sources with distance.

tion of mass flux. Selection criteria were unimodal distributions and wind speeds great enough so that most of the pollen remained below the level of the upper samplers to the most distant ring. Concentrations were integrated graphically along each sampling arc at each height. These arc-wise integrated concentrations were multiplied by the total air passage at the same heights and the resulting values integrated vertically at each sampling distance to give the number of pollen grains passing each sampling arc. Results normalized to 100% at 1 m are plotted in Fig. 9 and show that from 25–65% of the material remains airborne at 60 m from the source. The area source curves are fairly tightly clustered and, as expected, do not segregate in order of source size. These curves may be compared with those in Figs. 3 and 8, which show the variation in centerline concentration and arc-wise integrated concentration at the 1.5 m height with distance. Comparison between loss in airborne particles and deposition is presented below.

Although the output of the area sources is not known, the amount of pollen released in each point source test was carefully weighed and the number of pollen grains calculated using the best estimate available of the mass of a single grain. Releases ranged from $3.6–7.0\times10^8$ grains but, as pointed out earlier, some error is possible since pollen density was not known precisely. The suitability of the integration procedure can be assessed by comparison of the integrated flux through the first sampling arc which was 10.1 m from the source to the output (Table 2). Flux values in the six tests integrated ranged from 28–74% of the calculated output with a mean of 52%. Deposition accounts for much of the difference between output and flux values. The rest may be attributed to uncertainties in the total emission and to errors in the sampling and analysis procedures.

Table 2. Comparison of grains released and grains passing the inner sampling circle.

Run	Grains emitted ($\times10^8$)	Grains through A circle ($\times10^8$)	Ratio of grains through A to grains emitted
4001	4.20	1.17	0.28
4002	5.34	2.51	0.47
4003	5.41	2.00	0.37
6021R	3.72	2.75	0.74
6024G	4.26	2.70	0.64
6025G	4.75	2.93	0.62
			Average 0.52

g. *Deposition*

The greased microscope slide method of measuring deposition (Raynor *et al.*, 1970) almost certainly underestimates deposition on the surrounding grass surfaces. Other unpublished studies using a radioactive tracer showed that deposition on a smooth sticky paper sampler averaged from 50–80% of that on adjacent grass. Furthermore, the surface area of two slides is but a small fraction of the ground surface it is intended to sample, leading to some doubt about the precision of measurements at the greater distances where counts are often very low. However, no feasible method has been devised for obtaining measurements in quantity of non-radioactive particle deposition on a grass surface and it was impractical to examine a greater area under a microscope. In spite of these deficiencies, the slide data are considered adequate for comparing deposition from one location or one period to another and are probably not greatly in error quantitatively. Another factor affecting the deposition data is the profuse settling of pollen particles, some of them clumped, close to the area source plots. During periods of very light winds, heavy deposition can occur on the innermost sampling circle without corresponding concentrations of airborne pollen being measured above. These two factors should be kept in mind when considering the data.

Mean centerline deposition for the five sources normalized to 100% at 1 m is plotted in Fig. 10. The smallest area source shows a maximum ~6 m from the

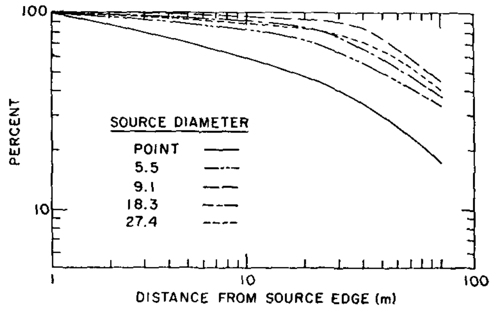

Fig. 9. Variation of mean normalized mass flux from the five sources with distance.

Table 3. Grains deposited between sampling circles within sampling grid from deposition measurements.

Source diameter (m)	Total grains deposited ($\times 10^8$)				Average grains m^{-2} deposited ($\times 10^5$)			
	A–B	B–C	C–D	A–D	A–B	B–C	C–D	A–D
5.1	3.71	2.22	1.27	7.21	3.18	0.54	0.13	0.49
9.1	11.49	3.79	2.53	18.02	9.81	1.01	0.26	1.23
18.3	41.40	11.90	8.70	62.00	26.72	3.44	1.00	4.29
27.4	72.00	18.30	12.70	103.00	27.45	3.88	1.86	7.27

plot while the others decrease consistently with distance. As shown by a comparison with Fig. 3, centerline deposition decreases at a somewhat faster rate with distance than source height centerline concentration. No more than 2% of the amount deposited per unit area at 1 m is deposited at 100 m from the plot. No relationship with source size is evident.

Mean arc-wise integrated deposition from the five sources is illustrated in Fig. 11 as a function of distance. The curves can be compared with those in Fig. 8 for arc-wise integrated concentrations at the 1.5 m level. The deposition curves show much more variability and a greater change with distance decreasing to between 2 and 15%, while the concentration curves cluster between 7 and 23% at 100 m. As expected, neither are ordered by source size.

Some idea of total deposition and average deposition per unit area within the sampling grid is given by Table 3. Both total grains deposited between sampling circles and grains deposited per square meter decrease with distance from the source and both increase with source size. Although these results are not unexpected the magnitudes involved, up to an average of 2.7×10^6 grains m^{-2} in a 14 m wide annulus around the source, are impressive. Values for the downwind direction only would, of course, be much higher.

h. Velocity of deposition

Velocity of deposition (V_d) was calculated by dividing the deposition rate by the 1.5 m air concentration for all locations where non-zero concentrations were measured at that level for four runs from each of the four area sources and six of the point source runs. Much scatter was found in the V_d values often caused by cases where either deposition or concentration was atypical in comparison with surrounding values. However, no reasonable criteria could be found for deletion of such cases since every degree of gradation existed between them and cases typical of the majority. The only cases eliminated from consideration were a few on the inner circle on the upwind side of the area source plots where deposition was abnormally high but air concentration very low.

Table 4 summarizes the mean values for each of the sampling rings for the five sources. Although the values are generally high on the inner circle around the area sources, no other consistent variation with distance or with source size is evident. Omitting the inner circle, the mean of all cases is 5.05 cm sec^{-1}, considerably larger than the computed gravitational settling rate of 1.56 cm sec^{-1}, but comparable to values found in other deposition studies over similar surface cover at Brookhaven. It will be noted that the 1962 values are larger than those found at the corresponding seasons in 1963. This

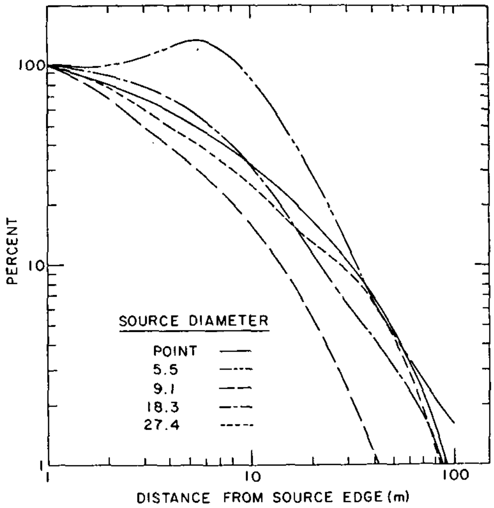

Fig. 10. Variation of mean normalized centerline deposition from the five sources with distance.

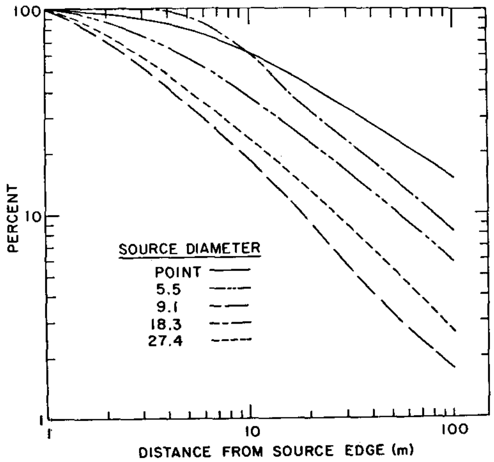

Fig. 11. Variation of mean normalized arc-wise integrated deposition from the five sources with distance.

TABLE 4. Mean values of velocity of deposition (cm sec^{-1}).

Source	Diameter (m)	Number of runs		Sampling circle A	A′	B	C	D
Point	—	6	Distance (m)	10.1	16.8	24.4	41.2	68.6
			V_d	1.90	4.40	6.12	3.25	3.96
1963 pre-season	5.5	4	Distance (m)	1.8		17.1	38.4	65.8
			V_d	5.44	—	4.83	1.85	1.82
1962 pre-season	9.1	4	Distance (m)	0.0		15.2	35.4	64.0
			V_d	140.37	—	14.75	8.46	4.63
1963 in-season	18.3	4	Distance (m)	1.0		15.2	32.0	59.4
			V_d	34.01	—	5.50	2.67	3.98
1962 in-season	27.4	4	Distance (m)	0.0		18.3	36.6	54.9
			V_d	39.90	—	5.58	5.43	4.99

may be related to the larger sources used in 1962 but is more likely caused by greater surface roughness. Although it is impossible to specify a grass height for each run, it probably averaged 15–20 cm in 1962 and 7–10 cm in 1963. Computation of V_d from concentrations measured at other levels and by other techniques gave similar results (Raynor *et al.*, 1970).

i. Loss in air concentration compared to deposition

The total deposition between sampling circles was determined by graphical integration and compared to the loss in airborne particles over the same intervals. Mean results for the five sources, including the ratios of the deposition to the air loss, are given in Table 5 for the three intervals between circles and for the total A–D circle distance. The point source ratios are uniformly low for reasons which are not apparent. Except for the 1962 pre-season source which is anomalously high, the A–B ratios are near one while the B–C and C–D ratios are mostly less than unity. The excess deposition close to the source, explained earlier, probably counteracts the low catch on the slides relative to the surrounding grass in the A–B distance.

Six of the fifteen mean ratios between adjacent sampling circles are within a factor of 2 and nine within a factor of 3. All four of the A–D area source ratios are within the latter range. Although this agreement is not as good as might be desired, it is felt that nothing better could reasonably be expected considering the crude nature of the sampling methods that had to be employed, the wide spacing between samplers, and the possible errors in the assumptions inherent in the integration process.

A number of previous deposition experiments are summarized by Gifford and Pack (1962). Simpson (1961) and Islitzer and Dumbauld (1963) estimated deposition from loss in airborne material but used tracers much smaller than ragweed pollen, worked mainly under stable conditions, and found values of V_d generally smaller. However, some tests by Islitzer and Dumbauld, using small fluorescent particles under unstable conditions, yielded values of V_d as high as 8.9 and 9.2 cm sec^{-1} over sagebrush-covered desert. They

TABLE 5. Comparison of particles deposited to loss in airborne particles.

Source	Diameter (m)			Increment of distance A–B	B–C	C–D	A–D
Point	—	Deposited	$\times 10^7$	0.95	0.57	0.58	2.10
		Air loss	$\times 10^7$	4.50	3.03	5.50	13.04
		Ratio		0.46	0.25	0.12	0.20
1963 pre-season	5.5	Deposited	$\times 10^8$	3.71	2.22	1.27	7.21
		Air loss	$\times 10^8$	3.13	2.88	2.94	8.95
		Ratio		1.06	0.70	0.32	0.69
1962 pre-season	9.1	Deposited	$\times 10^8$	11.45	3.79	2.53	18.02
		Air loss	$\times 10^8$	1.24	1.68	6.89	9.80
		Ratio		12.26	2.84	0.46	2.08
1963 in-season	18.3	Deposited	$\times 10^9$	4.14	1.19	0.87	6.20
		Air loss	$\times 10^9$	3.88	4.03	6.89	14.80
		Ratio		1.04	0.30	0.15	0.40
1962 in-season	27.4	Deposited	$\times 10^9$	7.20	1.83	1.27	10.30
		Air loss	$\times 10^9$	9.76	6.31	8.38	24.44
		Ratio		1.14	0.79	1.32	0.71

Note: Ratios are averages of individual ratios of deposition to air loss, not ratios of the averages tabulated.

TABLE 6. Comparison of pollen grains airborne at A and D circles.

Source	Diameter (m)	Grains airborne at A circle ($\times 10^8$)	Grains airborne at D circle ($\times 10^8$)	Ratio D/A
Point	—	2.32	1.02	0.44
1963 pre-season	5.5	20.43	11.49	0.45
1962 pre-season	9.1	23.05	13.25	0.60
1963 in-season	18.3	311.8	163.8	0.50
1962 in-season	27.4	554.6	310.2	0.59

also measured actual deposition on flat plates and, as in this study, found values considerably smaller, apparently reflecting the difference in catch between vegetation and a smooth surface.

j. Long-distance pollen travel

Although the occurrence of pollen and spores at high altitudes and at long distances from their sources has been well documented (Gregory, 1961), little is known about the percentage of particles released which travel appreciable distances. Such information would be valuable to all concerned with pollinosis, plant breeding, and the interpretation of pollen sampling data as well as to meteorologists concerned with problems of dispersion and air pollution. Table 6 lists the mean numbers of pollen grains airborne through the A and D circles from the five sources and the ratios of the latter to the former. Although the number of grains varies over more than two orders of magnitude, the ratios are quite similar and show that about half of the material reaching the edge of the source is still airborne some 55–65 m farther away.

The grains remaining airborne at each sampling distance were plotted and the resulting curves extrapolated to greater distances. This procedure (although subject to considerable error) indicates that about 1% of the pollen grains remain airborne at 1 km. Many of these grains must have been transported above the surface layer by this distance and were in position for potential long-distance travel. Since much of the eastern two-thirds of the United States constitutes a ragweed pollen source region and a single ragweed plant can release in excess of 10^6 grains per day during the height of the pollination season, the ubiquity of airborne ragweed pollen during late summer is not surprising.

7. Discussion

When this study was planned, it was hoped that the variation in pollen dispersion and deposition rates could be clearly related to variation in meteorological conditions but this hope has not been realized. Although pollen, once airborne, is subject to the same principles that govern the dispersion of other small particles, its emission, in contrast to that of more commonly studied air pollutants, is regulated by both biological and meteorological factors which limit release not only to a specific portion of the year but also to a limited range of weather conditions during a specific portion of the day. Therefore, dispersion of pollen from natural sources can be studied only during those time periods and under those weather conditions favorable for its emission and data under other conditions cannot be obtained.

The data gathered, however, do describe pollen dispersion from real sources in a natural environment under conditions normally prevailing during the ragweed pollination season. Although wild pollen sources are seldom as uniform and compact as the cultivated plots, dispersion from them can more readily be estimated with this background of experimental data. Since pollen clearly disperses in a manner similar to that of other small particles when due allowance is made for source geometry and particle properties, calculation of pollen dispersion by use of existing diffusion models with realistic parameters should be practical and may give the only possible solutions to problems where experimentation or extended observation is not feasible.

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REFERENCES

Chamberlain, A. C., 1953: Aspects of travel and deposition of aerosol and vapour clouds. AERE HP/R 1261, Harwell, Berkshire, England, 35 pp.

Cramer, H. E., G. M. De Santo, R. K. Dumbauld, P. Morgenstern and R. N. Swanson, 1964: Meteorological prediction techniques and data system. Rept. GCA-64-3-G, Geophysical Corporation of America, Bedford, Mass., 252 pp.

Gifford, F. A. Jr., and D. H. Pack, 1962: Surface deposition of airborne material. *Nuclear Safety*, **3**, 76–80.

Gregory, P. H., 1961: *The Microbiology of the Atmosphere.* New York, Interscience, 251 pp.

Hilsmeier, W. F., and F. A. Gifford, Jr., 1962: Graphs for estimating atmospheric dispersion. AEC Rept. ORO-545, Weather Bureau, Oak Ridge, Tenn., 10 pp.

Hirst, J. M., 1952: An automatic volumetric spore trap. *Ann. Appl. Biol.*, **39**. 257–265.

Islitzer, N. F., and R. K. Dumbauld, 1963: Atmospheric diffusion-deposition studies over flat terrain. *Intern. J. Air Water Pollution*, **7**, 999–1022.

Ogden, E. C., J. V. Hayes and G. S. Raynor, 1969: Diurnal patterns of pollen emission in *Ambrosia*, *Phleum*, *Zea* and *Ricinus*. *Amer. J. Botany*, **56**, 16–21.

Raynor, G. S., L. A. Cohen, J. V. Hayes and E. C. Ogden, 1966: Dyed pollen grains and spores as tracers in dispersion and deposition studies. *J. Appl. Meteor.*, **5**, 728–729.

——, J. V. Hayes and E. C. Ogden, 1969: Areas within isopleths of ragweed pollen concentrations from local sources. *Arch. Environ. Health*, **19**, 92–98.

——, —— and ——, 1970: Experimental data on ragweed pollen dispersion from point and area sources. BNL Rept. 50224 (T-564), Brookhaven National Laboratory, Upton, N. Y., 33 pp.

——, and E. C. Ogden, 1965: Twenty-four-hour dispersion of ragweed pollen from known sources. BNL Rept. 957 (T-398), Brookhaven National Laboratory, Upton, N. Y., 17 pp.

——, —— and J. V. Hayes, 1968: Effect of a local source on ragweed pollen concentrations from background sources. *J. Allergy*, **41**, 217–225.

——, and M. E. Smith, 1964: A diffusion-deposition tracer system. BNL Rept. 859 (T-343), Brookhaven National Laboratory, Upton, N. Y., 17 pp.

Simpson, C. L., 1961: Some measurements of the deposition of matter and its relation to diffusion from a continuous point source in a stable atmosphere. AEC Rept. HW-69292, Revised, Hanford Atomic Products Operation, Hanford, Wash.

Singer, I. A., and M. E. Smith, 1953: Relation of gustiness to other meteorological parameters. *J. Meteor.*, **10**, 121–126.

Sutton, O. G., 1947: The theoretical distribution of airborne pollution from chimneys. *Quart. J. Royal Meteor. Soc.*, **73**, 426–436.