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SOME OBSERVATIONS OF THE ALONG-WIND DISPERSION PARAMETER

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1. INTRODUCTION

Many of the atmospheric dispersion experiments conducted in recent years were designed to measure crosswind or vertical dispersion. Relatively few data exist describing the along-wind dispersion parameter, σ_x, the standard deviation of the air concentration of the tracer in the along-wind direction. This may partly be due to the greater interest in continuous sources in which along-wind dispersion may be neglected. The instantaneous line-source experiments used in this analysis were not designed to determine σ_x, but had, in addition to extensive surface exposure measurements, a few sequential samplers located throughout the sampling region. The sequential sampling data at least provided estimates of tracer arrival and departure times thereby permitting estimates of σ_x.

The experimental σ_x values are compared with values of σ_x derived from calculations based on turbulence and wind shear. Unfortunately, comparison of observed and calculated σ_x for each trial is not possible due to inadequate meteorological data. The initial phase of the along-wind dispersion is attributed to the effect of turbulence and in later stages the effect of wind shear is presumed to become the dominant mechanism (see Tyldesley and Wallington, 1965). The meteorological data were insufficient to distinguish these processes in the dispersion data, although some qualitative evidence exists to indicate a greater contribution of wind shear further downwind.

Frequently in dispersion modelling, for simplicity, it is assumed that the crosswind and along-wind dispersion parameters are about equal. A comparison of mean along-wind dispersion with estimates of mean crosswind dispersion is presented.

2. ALONG-WIND DISPERSION DATA

The experiments used in this analysis involved instantaneous line sources of fluorescent particles (FP) generated by an aircraft passing upwind and parallel to the sampling line. The three experiments considered were conducted at Ft. Wayne, Indiana (Hilst and Bowne, 1966), Victoria, Texas (Smith and Miller, 1966) and Oceanside, California (Smith and Niemann, 1969). The first two provided most of the data and represented very different terrain features, a Texas coastal location and an urban area in the midwest. All experiments used "rotorods" at most sampling locations to give a measure of total particle count. A few sampling sites were equipped with sequential drum samplers thereby permitting σ_x to be extracted directly by taking the second moment of the particle count as a function of time. This procedure results in σ_x in units of time rather than the more conventional length units used in crosswind and vertical dispersion.

Ft. Wayne is a moderately industrialized city about 10 km wide surrounded by flat farmland. Each trial consisted of two releases of FP (yellow and green) by separate aircraft several kilometers upwind of the city at altitudes of 91 to 214 m. A total of 36 trials were conducted, all after 1800 LST. The sampling array consisted of 5 arcs (16 km length). One arc was upwind of Ft. Wayne, three were within the city and the last one was downwind in the rural area about 15 km from the release line. Ten sequential (15 min intervals) samplers were also located on these arcs.

Arrival and departure times of the particulate cloud at each sequential sampler were tabulated by Hilst and Bowne. The duration of the plume over the sampler was divided by 4.3 to give σ_x. This procedure assumes that the tracer duration over the sampler represented passage of 95% of the particles (with a Gaussian distribution). The travel time was computed as the interval between time of release and the mid-point of the time between arrival and departure at a sampler. The σ_x data for Ft. Wayne are shown in Figure 1 as a function of travel time. The solid line is the average of the regression lines for the individual trials. Due to a very large scatter in the σ_x data, a linear regression was done for each trial and those trials with correlation coefficients of less than 0.4 were rejected (6 out of 13). The remaining data and the average regression line for those trials are shown in Figure 1.

The Victoria tracer test consisted of 17 offshore releases of FP near Corpus Christi, Texas. The terrain is flat, rising only 120 m in the first 120 km, then gently rolling hills to 160 km inland. The tracer was released from a jet aircraft early in the evening. The flight path (160 km) was a few kilometers offshore and parallel to the coast. Most of the releases were at a height of 90 m. Six main sampling lines were set up. Four of them were parallel to the coastline about 160 km in length spaced evenly from

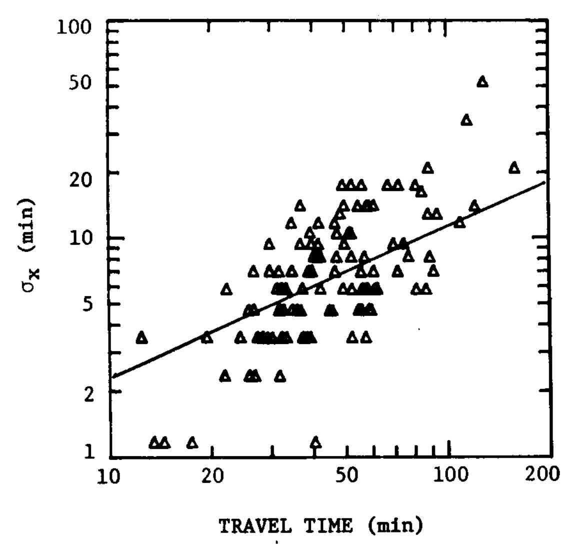

Figure 1. Summary of along-wind dispersion data collected at Ft. Wayne. The solid line is the average of the regression lines for the individual trials.

40 to 180 km downwind of the release line. Another 16 km sampling line was set up along the beach. The last sampling line was normal to the others, through the midpoint of the release line. The sequential samplers were preset for hourly increments.

The program was conducted during the summer when the predominant flow is onshore with the seabreeze manifesting itself only as variations in the wind speed. The water is sufficiently warm to produce a deep (200 to 600 m) adiabatic layer above the surface.

The along-wind dispersion was determined by Smith and Miller at each sequential sampler for each trial by examining the sequential particle count. The time between 16% and 84% of the total particle count was considered to be $2\sigma_x$ in units of time (with the assumption that the particle distribution was Gaussian). The time at which 50% of the particles had passed was used to determine the travel time. The σ_x data as a function of travel time are shown in Figure 2. The solid line is the average of the regression lines for the individual trials, obtained in the same was as for Ft. Wayne (2 out of 15 trials were rejected).

An FP tracer diffusion study was conducted along the California coast between Oceanside and Del Mar. The project consisted of a number of different types of releases and sampling methods designed to characterize diffusion in the shoreline region, similar to the Victoria experiment. The area is characterized by a marine inversion usually based from 300 to 600 m above the sea with onshore flow below the inversion and a deep seaward flow aloft. The aircraft releases were made several kilometers offshore and most were at a height of about 60 m. Smith and Niemann tabulated σ_x at 23 km downwind for each trial by taking the second moment of the sequential samples (15 min intervals) at that location. The travel time was determined from the mid-point between the arrival and departure time. The regression line for σ_x as a function of travel time is shown in summary Figure 3. The Oceanside data points, because so few in number and only one point (at 23 km) per trial, could not be analyzed in a manner similar to the other two experiments. They are included in Figure 3 for reference.

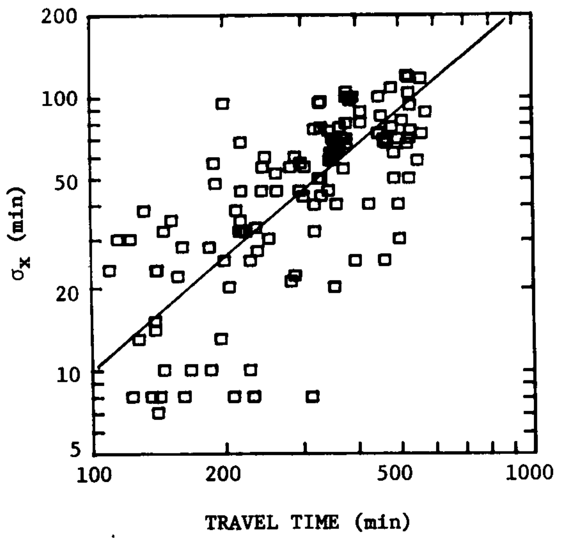

Figure 2. Summary of along-wind dispersion data collected at Victoria. The solid line is the average of the regression lines for the individual trials.

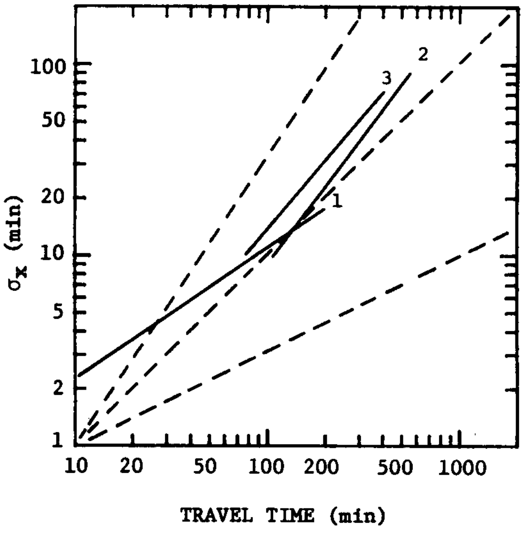

Figure 3. Summary of dispersion data at: 1 - Ft. Wayne, 2 - Victoria, and 3 - Oceanside. The dashed lines show lines with slopes of 0.5, 1.0 and 1.5.

3. ALONG-WIND DISPERSION MODELS

The problem of along-wind dispersion is simplified by considering only instantaneous sources. Smith and Hay (1961) suggested that the maximum rate of growth of the standard deviation of an instantaneous cluster of particles is proportional to the square of the turbulent intensity along the axis of measurement. Then the equation for the turbulence generated along-wind standard deviation is

$$\sigma_{x_t} = 3\, i^2\, T, \qquad (1)$$

where the intensity of turbulence, i, is given by

$$i^2 = \overline{u'^2}\, \overline{u}^{-2} \qquad (2)$$

and u' is the turbulent velocity component in the along-wind direction, $\bar{u}$ is the mean wind speed, and T is the travel time. Both $\overline{u'^2}$ and $\bar{u}$ are averaged through the depth of the plume for the duration of travel to the sampling distance X, which is assumed to equal $\bar{u}T$.

As the cluster grows, the wind shear can be expected to have a more dominant role in the observed dispersion. Saffman (1962) estimated the contribution of wind shear to dispersion by solving the diffusion equation with an effective diffusivity that depended upon the interaction of wind shear and vertical transport. He assumed a linear wind profile and a vertical diffusivity constant with height. Saffman's equation for the shear induced variance is

$$\sigma_{x_s} = \frac{1}{\bar{u}}\sqrt{\frac{1}{25}\,\psi^2 K_z T^3}, \qquad (3)$$

where ψ is the slope of the wind speed profile, and K_z is the vertical turbulent diffusivity. The rapid growth ($\sigma \propto T^{3/2}$) is attributed to the growing cluster entering layers of additional wind shear. Saffman found that at very long travel times when the effect of an upper boundary to mixing becomes more pronounced, the growth becomes proportional to $T^{1/2}$.

Csanady (1969) solved the diffusion equation with an effective diffusivity based on the wind shear of an Ekman profile. His results on crosswind spread divided the contribution to the total spread between the turbulent and shear induced components. When we express this as the along-wind variance,

$$\sigma_x^2 = \sigma_{x_t}^2 + \sigma_{x_s}^2 \qquad (4)$$

where the turbulent (σ_{x_t}) and shear (σ_{x_s}) contributions are given by Eqs. 1 and 3, respectively.

4. VALIDATION OF ALONG-WIND DISPERSION MODELS

Eq. 4 suggests that the growth of σ_x should be proportional to t^α where α would be between 1 and 1.5. The exponent, α, would be closer to 1.0 initially when the growth is dominated by turbulence and at later stages closer to 1.5 when the growth is dominated by wind shear. For any particular experiment, the rate of growth predicted by Eq. 4 depends upon the magnitude of the constants in Eqs. 1 and 3. The larger growth rate due to wind shear would decrease after an upper boundary to vertical mixing becomes effective. However, this restriction is not expected to apply to Ft. Wayne or Victoria data.

The slopes of the dispersion data for the three experiments may be compared to the reference slopes of 0.5, 1.0, and 1.5 in Figure 3. The slopes of the individual trials varied from 0.46 to 1.28 at Ft. Wayne and from 0.76 to 2.01 at Victoria. The average slopes of the Ft. Wayne (0.67) and Victoria (1.3) data shown in Figure 3 suggest the increased importance of wind shear for the longer travel times represented by the Victoria data. Although there is large scatter between individual trials and a Student -t test indicates that neither the Ft. Wayne nor the Victoria data differ significantly from a slope of 1.0 (at the 10% level) the average slopes do differ significantly from each other (less than the 1% level). There is some uncertainty in the σ_x data at shorter travel times due to σ_x approaching the sequential sampling interval. This might produce an upward bias in the σ_x data at short travel times and a possible bias in lowering the slope of σ_x with travel time.

A quantitative test of Eqs. 1, 3, and 4 is not possible due to the inadequate (for this analysis) meteorological measurements made during these experiments. But the average dispersion data shown in Figure 3 may be compared with calculated values of σ_x using reasonable values of the appropriate meteorological parameters: $\bar{u} = 5$ m sec^{-1}, $\psi = 0.015$ sec^{-1}, $i = 0.2$, $H = 500$ m, and $K_z = 5$ m^2 sec^{-1}. The results of these calculations, shown in Figure 4, suggest that Eq. 4 can provide approximate estimates of σ_x, with turbulence being the dominant dispersion mechanism close to the source (Ft. Wayne) and wind shear the dominant one further downwind (Victoria). The values of the meteorological parameters used will determine the relative placement of the curves in Figure 4 but it is felt that the values that were used are representative of the two sites. However, considerable uncertainty still exists as to whether Eq. 4 can provide accurate estimates of σ_x during a particular trial if appropriate meteorological data were available.

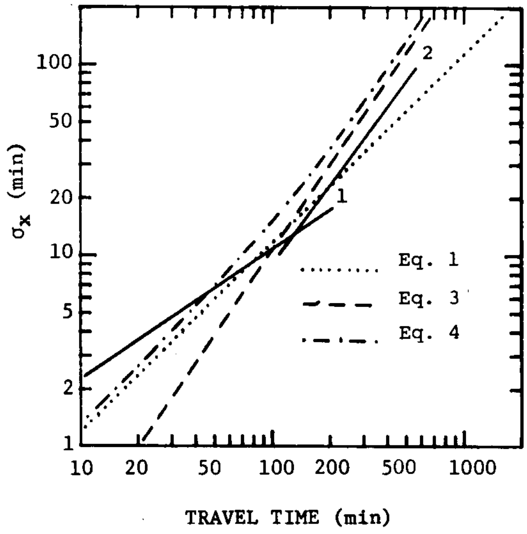

Figure 4. The dispersion data at Ft. Wayne (1) and Victoria (2) compared to predictions of along-wind dispersion by turbulence (Eq. 1), wind shear (Eq.3), and the combined effects of both (Eq. 4).

5. COMPARISON WITH CROSSWIND DISPERSION

Frequently in dispersion modelling, σ_y and σ_x are assumed to be equal. When Victoria σ_x data are reanalyzed in terms of length rather than time, the average regression line for the individual trials becomes

$$\sigma_{x(m)} = 7.3\ t^{1.3}_{(min)} . \qquad (5)$$

This curve is shown in Figure 5 with a curve by Heffter (1965) for

$$\sigma_{y(m)} = 30\ t^{1.0}_{(min)} \qquad (6)$$

for average values of crosswind dispersion at longer travel times. Figure 5 suggests that σ_x may be about a factor of two larger than σ_y at the longer travel times (10 hr).

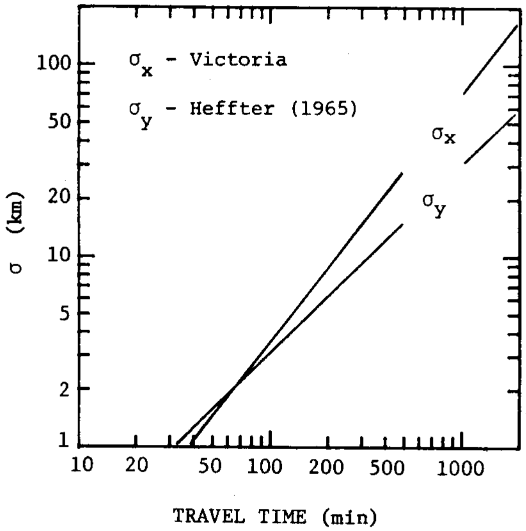

Figure 5. The along-wind dispersion at Victoria is compared with average crosswind dispersion at large travel times as given by Heffter (1965).

6. CONCLUDING REMARKS

The results of an analysis of observed along-wind dispersion, σ_x, at two different sites suggests that the along-wind dispersion is the result of both turbulence and wind shear. Although considerable scatter is evident in these data, the results are felt to be representative. It is suggested that in future experiments, more attention be paid to the quality of sequential sampling data and sufficient meteorological measurements be obtained to accurately test along-wind dispersion theories.

7. ACKNOWLEDGMENTS

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