PLUME CONCENTRATION STATISTICS IN THE ATMOSPHERIC BOUNDARY LAYER

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Introduction

The concentration at a fixed point in a turbulent plume is highly variable, with standard deviation comparable to or greater than the mean value, significantly skewed and is zero for a significant fraction of the time. A complete description of the concentration field thus requires knowledge of the variance, skewness and higher moments in addition to the mean. Indeed, Barry [1] and more recently Chatwin [2] argue that we should be concerned with the frequency distribution of concentration.

This more complete description is of practical importance because (i) it is necessary in order to describe and predict short-term high exposures to air pollution; (ii) the concentration variance is a direct measure of the statistical uncertainty in measurements or predictions of the mean; (iii) the rate of turbulent chemical reactions depends on the reactant concentration covariance; (iv) assessment of the hazard risk from leakage of flammable gases depends on the instantaneous concentration field.

In this paper we examine the relative effects of large- and small-scale (compared with the plume) turbulent motions on concentration statistics by comparing conditional or "in-plume" statistics (zero readings excluded) and unconditional statistics for a set of concentration measurements made in ground-level plumes in the atmosphere.

2. Conditional/Unconditional Relationships

Once the fraction of non-zero readings (the intermittency, I) in a (concentration) time series is known, there exist very simple relationships between conditional and unconditional statistics and for many purposes the zeros represent redundant information. We are interested in the frequency distribution, $P(\theta)$, defined as the probability that the concentration, C, equals or exceeds θ and the nth concentration moment,

$$\overline{C^n} = - \int_0^\infty \theta^n \, dP(\theta) \quad .$$

Using subscript "p" to denote conditional or "in-plume" statistics, we have

$$P(\theta) = I \, P_p(\theta) \tag{1}$$

and

$$\overline{C^n} = I \, \overline{C_p^n} \tag{2}$$

The first few normalized central moments, the intensity of concentration fluctuations, $i = \sigma/\bar{C}$; the skewness, $S = \overline{(C-\bar{C}^3)}/\sigma^3$ and kurtosis, $K = \overline{(C-\bar{C})^4}/\sigma^4$, where σ is the standard deviation, are of greatest interest.

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Data Description and Analysis

Details of the field experiments from which the data derive have been given by Sawford et al. [3]. The basic data consist of approximately 1h time series of 6s average concentration measured at a fixed point downwind of the source. The lateral distance, y, of the receptor point from the mean-plume centreline and the 1h mean-plume dispersion, σ_y, were determined from the mean-plume crosswind concentration profile measured from bag samplers. All experiments were carried out during a period of a year in day-time neutral to unstable conditions.

Spurious small but non-zero readings due to baseline drift and noise were eliminated by subtracting a threshold value from each reading and treating resultant negative values as zero. Because baseline anomalies varied from run to run (according to signal strength etc) different thresholds were chosen for each record but were typically $\sim 0.1\ \bar{C}$.

From these data, representative unconditional frequency distributions were determined by the simple regression analysis described by [3]. Other concentration statistics were calculated in the usual way.

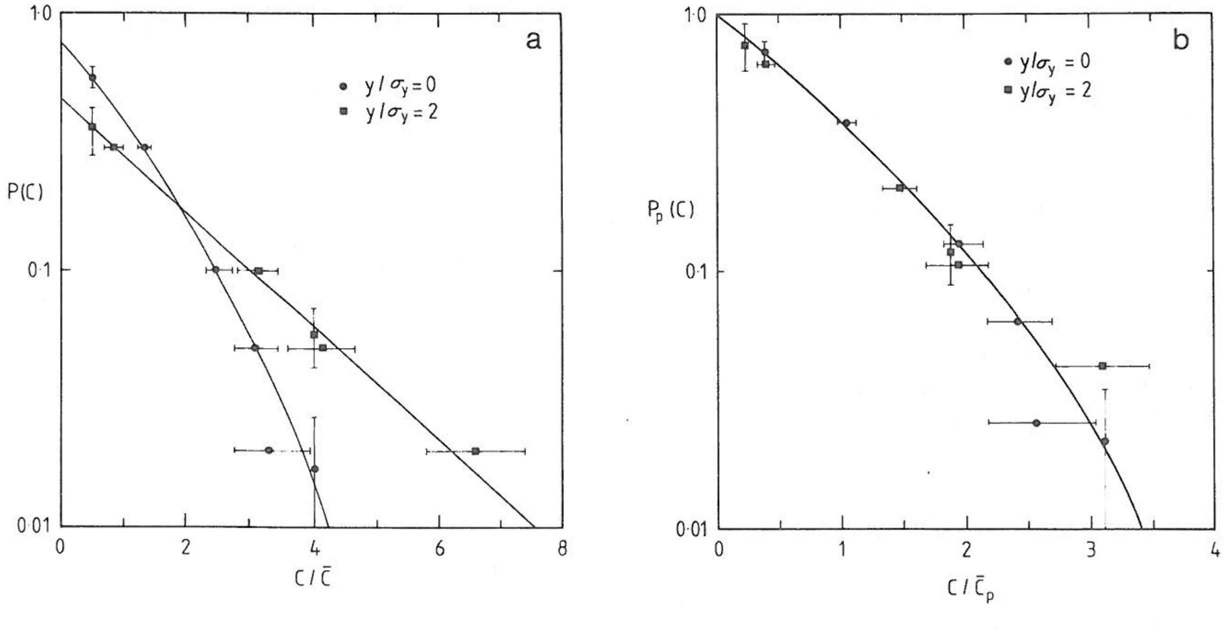

Fig.1. Unconditional (a) and conditional (b) frequency distributions for 6s average concentration at $y/\sigma_y = 0$ and 2.

Results

Figure 1(a) shows unconditional frequency distributions for 6s concentrations 25m down-wind of the source on the plume centreline, $y/\sigma_y = 0$, and near the edge of the plume, $y/\sigma_y = 2$. The error bars represent 95% confidence limits. As noted by [3], the centreline and plume edge distributions are markedly different. Figure 1(b) shows the same distributions transformed to conditional form using (1) and (2) with intermittencies estimated from Figure 1(a). In this form the plume-edge and centreline data collapse remarkably well and it is no longer entirely clear whether the difference in the shape of the distributions apparent in Figure 1(a) is significant.

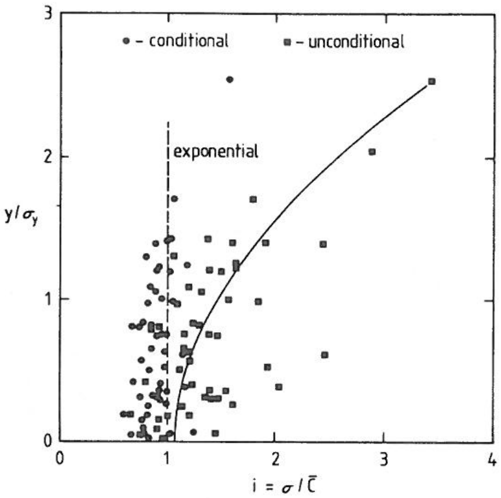

Fig.2. Unconditional and conditional intensity of fluctuations for 6s average concentration as a function of y/σ_y.

Perhaps a clearer picture of the variability in the data is conveyed by Figure 2 which shows the intensity of fluctuations for all the 6s concentration records. The trend for i to increase with y/σ_y for unconditional statistics was noted by [3] and is consistent with a wide range of laboratory [4] and field [5] measurements. As for the frequency distribution, the variation with y/σ_x is greatly diminished, if not entirely eliminated, for conditional statistics. Note that not only is this "explained" variation reduced but so is the unexplained variation or "scatter". Similar conclusions hold for the skewness.

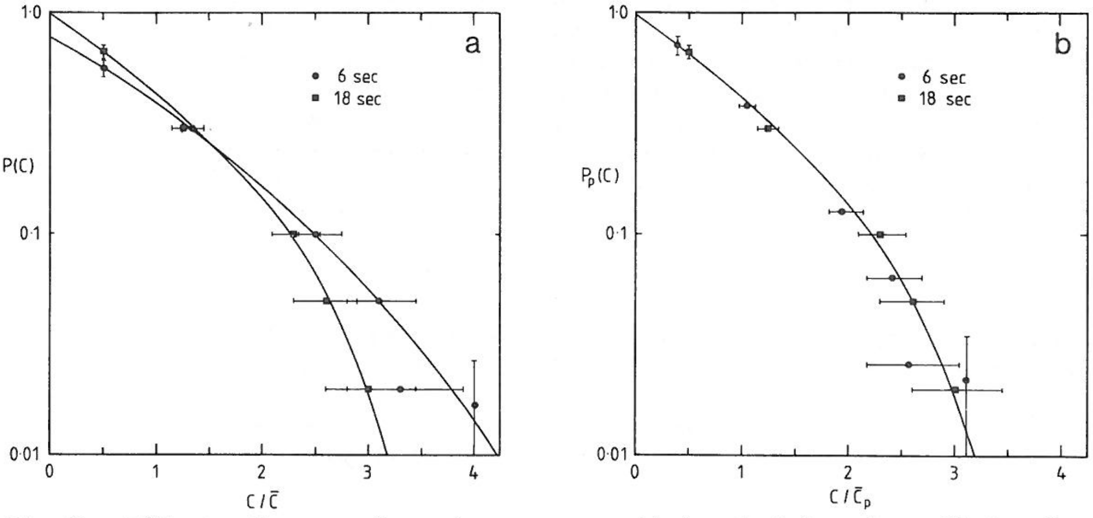

Fig.3. Effect of averaging time on unconditional (a) and conditional (b) frequency distributions for $y/\sigma_y = 0$.

The effect of averaging time on the unconditional frequency distribution is shown in Figure 3(a). As expected, increased averaging decreases the proportion of high relative concentrations and increases the intermittency. However, Figure 3(b) shows that increased averaging has a much weaker effect on the conditional frequency distribution. The reason is not that "in-plume" fluctuations are unaffected by averaging, but rather that $\bar{C}_p$ is also reduced so that the effect on i_p is reduced. It is also likely that much of the "in-plume" variation (which Jones [6] has shown to occur on very small scales) has already been smoothed by the 6s averaging.

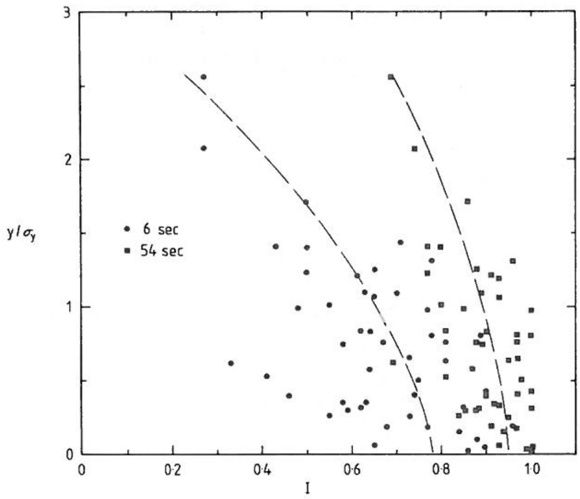

Fig.4. Intermittency as a function of y/σ_y and averaging time.

In a sense, Figure 4 complements Figures 1-3 in that it confirms that the variation which is removed by conditional sampling is reflected in the intermittency. As expected, and in agreement with wind tunnel [4] and other field [5] data, intermittency decreases with y/σ_y and increases with averaging time. It also carries most of the scatter apparent in the unconditional statistics in Figure 2.

Conclusions

Analysis of concentration statistics in ground-level plumes in the atmosphere has shown that much of the variation (both explained and unexplained) resides in the intermittency. In-plume or conditional statistics are much less variable. Broadly speaking, intermittency is determined by eddies large compared with the plume while the in-plume structure sampled by conditional statistics is due to smaller eddies. Therefore it may be profitable (or even necessary) to treat explicitly the effect of large scales of the flow and to model only in-plume concentration statistics. Since large-scale effects appear to dominate, for many purposes precise modelling of the in-plume statistics may not be critical.

References

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