STATISTICAL CHARACTERISTICS OF CONCENTRATION FLUCTUATIONS IN DISPERSING PLUMES IN THE ATMOSPHERIC SURFACE LAYER

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Abstract. Measurements have been made of concentration fluctuations in a dispersing plume from an elevated point source in the atmospheric surface layer using a recently developed fast-response photoionization detector. This detector, which has a frequency response (-6 dB point) of about 100 Hz, is shown to be capable of resolving the fluctuation variance contributed by the energetic subrange and most of the inertial-convective subrange, with a reduction in the fluctuation variance due to instrument smoothing of the finest scales present in the plume of at most 4%.

Concentration time series have been analyzed to obtain the statistical characteristics of both the amplitude and temporal structure of the dispersing plume. We present alongwind and crosswind concentration fluctuation profiles of statistics of amplitude structure such as total and conditional fluctuation intensity, skewness and kurtosis, and of temporal structure such as intermittency factor, burst frequency, and mean burst persistence time. Comparisons of empirical concentration probability distributions with a number of model distributions show that our near-neutral data are best represented by the lognormal distribution at shorter ranges, where both plume meandering and fine-scale in-plume mixing are equally important (turbulent-convective regime), and by the gamma distribution at longer ranges, where internal structure or spottiness is becoming dominant (turbulent-diffusive regime). The gamma distribution provides the best model of the concentration pdf over all downwind fetches for data measured under stable stratification. A physical model is developed to explain the mechanism-induced probabilistic schemes in the alongwind development of a dispersing plume, that lead to the observed probability distributions of concentration. Probability distributions of concentration burst length and burst return period have been extracted and are shown to be modelled well with a power-law distribution. Power spectra of concentration fluctuations are presented. These spectra exhibit a significant inertial-convective subrange, with the frequency at the spectral peak decreasing with increasing downwind fetch. The Kolmogorov constant for the inertial-convective subrange has been determined from the measured spectra to be $0.17 \pm 0.03$.

1. Introduction

A ubiquitous feature of scalars dispersing in the atmospheric boundary layer is that the concentration (of tracer or pollutant material) at a fixed point in a turbulent plume is highly variable. Indeed, it is typically observed in time series of contaminant concentrations that the standard deviation is at least as large as the mean. In consequence, measurement and modeling of the statistical characteristics of concentration fluctuations of dispersing scalars have considerable relevance to a variety of military and environmental impact assessment problems. For example, the statistical properties of concentration fluctuations in a plume are important
to the assessment of risk from the release of certain hazardous materials (e.g., toxic gases and aerosols) in which there is a nonlinear relationship between concentration and duration of exposure for a given level of harmful effect. Similarly, short-term concentration fluctuations are very relevant to estimating the ignition hazard from the leakage of flammable gases in which it is necessary to determine the probability that the instantaneous concentration lies between the lower and upper flammability limits. Other applications include the prediction of probability of visibility through obscurants, the characterization of perception of odors required to evaluate nuisance due to malodorous substances, and the determination of the rate of mixing and reaction of chemical species in turbulent flows.

The growing interest in concentration fluctuations in recent years has resulted in a number of extensive laboratory investigations of the phenomenon. Fackrell and Robins (1982a) made measurements of concentration fluctuations in neutrally buoyant plumes from both ground-level and elevated point sources in a rough-walled boundary layer modeled physically in a wind tunnel. Deardorff and Willis (1984) conducted experiments to measure scalar fluctuations in both positively and neutrally buoyant passive plumes in a convectively mixed layer simulated within a water tank. Stapountzis et al. (1986) made wind tunnel measurements of temperature fluctuations downwind of a line source in grid turbulence. Wilson et al. (1991) and Bara et al. (1992) observed concentration fluctuations in saline plumes in a rough-surface boundary layer and in grid turbulence simulated in a water channel.

The advantage of physical modeling of concentration fluctuations in wind tunnels and water channels is that stationary turbulence can be maintained over sufficiently long periods to enable the accurate measurement of the statistical properties of the instantaneous concentration of the dispersing scalar. However, laboratory investigations into the turbulent dispersion of gases incur the disadvantage that the large-scale eddy motions, which contribute to plume meander, and the full range of atmospheric stability conditions cannot be properly represented. In consequence, a number of measurements of concentration fluctuations in full-scale atmospheric field experiments have been undertaken. Jones (1983) measured concentration fluctuations in ionized air plumes using an ion collector with a resolution of 100 Hz, but these experiments were limited to downwind fetches of less than 20 m. Furthermore, the ion plume is non-passive due to electrostatic repulsion between the ions. Hanna (1984) described tracer experiments using a fog oil source in which the concentration was measured using aerosol photometers with a resolution of 1 Hz. Lewellen and Sykes (1986) measured concentration fluctuations in large elevated plumes using a lidar system, but these measurements were limited by poor spatial resolution. Sawford et al. (1985) and Sawford (1987) carried out field trials to measure the statistical characteristics of scalar fluctuations from single and multiple sources, using detectors for sulfur hexafluoride and phosphorus which were limited to a temporal resolution of 6 s. Dinar et al. (1988) observed concentration fluctuations in fog oil plumes using a high-resolution optical detector. Finally, Mylne and Mason (1991) used a photoionization detector with a 2 Hz frequency.