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Integrating Lidar and Atmospheric Boundary Layer Measurements to Determine Fluxes and Dynamics of Particulate Emissions from an Agriculture Facility

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Abstract

Lidar technology offers the ability to quantify concentrations of small particulates in the atmosphere in certain ranges of time and space. While this is a valuable tool to visualize the behavior of plumes emitted from the surface, the actual flux of particles cannot be estimated from such data alone. To determine the mass flux of particles, the concentrations must be properly integrated with wind and turbulence properties.

The goal of this study is to utilize a model that uses wind and particle density information to calculate the flux of particles from an animal facility near Ames, Iowa. The model is a simplified conservation equation for particle density in the atmosphere. This approach essentially quantifies fluxes in and out of a box centered over the facility and estimates the surface source by assuming conservation of mass.

In addition, we hypothesize that distinct turbulence structures will sometimes interact with the intermittency of the surface emission from the buildings, resulting in episodic changes in emission fluxes from the site. A second objective involves documenting how intermittent the emission plumes are and how they are connected to periodic large scale turbulence events.

Lidar data of particle size and density in the vicinity of the site were collected during an intensive field campaign lasting nearly 2 weeks. In addition to the lidar data, turbulence data were measured at several levels on each of three towers, located upwind, inside and downwind of the source area.

The model requires measurements of the vertical profiles of both concentrations of particulates and the mean horizontal wind. The concentrations were measured using the lidar, while winds were measured using a combination of cup anemometers and sonic anemometers. This allows the emission fluxes to be calculated during 15 to 30 minute periods when winds are consistent.

Flux calculations await the final calibration of the lidar returns using measured particle densities. Flux estimates will be made when distinct plumes are observed under steady-state wind conditions.

Current results are presented showing evidence of episodic plumes of CO_2 in response to intermittent vertical motions of turbulences.

Introduction

Agricultural facilities and operations result in emission of various particles and gases to the atmosphere. Among these are small particles. The emissions of small particulates from such facilities need to be quantified in order to determine the effects of such operations on air quality. Unfortunately, the size and heterogeneous nature of such facilities makes it impossible to make any simple direct measurements of emission rates.

The emergence of lidar allows measurements to be made of the spatial distribution of particles including size and density. The USU lidar was developed exactly for this purpose and allows the spatial distribution of particle density to be quantified for the atmosphere in the vicinity of an agricultural facility. However, lidar measurements of particle density will not yield the actual rate of emission from the site. This requires an integration of particle density data from the lidar with wind and turbulence information.

Determining the surface flux of particulates in this way still poses a challenge. The animal facilities especially are quite heterogeneous and variable in size. The sources have a spatially complex pattern and have distinct effects on wind and turbulence. The typical micrometeorological approaches used to estimate surface fluxes are also problematic in these cases, since they are predicated on a uniform surface or source region of adequate spatial extent.

In this case we propose using a simplified form of the conservation equation for particle density of the air to estimate the emissions for a confined animal facility near Ames, Iowa. The simplified conservation equation can be written as:

$$\frac{\partial \overline{\rho_p}}{\partial t} + \bar{u}\frac{\partial \overline{\rho_p}}{\partial x} = \frac{\partial}{\partial z}(\overline{w^{'}\rho_p^{'}}) \qquad (1)$$

where ρ_p is the density of particles, u is the horizontal velocity, w is the vertical velocity, t is time, and x is distance along the mean horizontal wind direction. The primes in the last term denote the instantaneous deviation of the value from the temporal mean. The last term describes the change with height of the vertical flux of particulates. In simple terms, the equation states that changes of the vertical particle flux with height are related to lateral transport or horizontal advection of particles by the mean horizontal wind. The plumes from an individual facility will only in fact rise up to a finite distance, depending upon the source strength and intensity of the turbulence. At some height z_r, the average particle density will not be affected by the local source region being studied.

Noting the above, and assuming steady-state conditions, equation (1) can be integrated to yield:

$$\int_0^{z_r} \bar{u}\frac{\partial \overline{\rho_p^{'}}}{\partial x} dz = (\overline{w^{'}\rho_p^{'}})_{sfc} \qquad (2)$$

We now have an expression relating the flux at the surface with the horizontal changes of particle density.

$$\textit{Surface Flux} \quad \int_0^{z_r} \bar{u}\frac{\overline{}_p}{x} dz \qquad (3)$$

Solving this equation requires knowledge of the vertical profiles of mean horizontal wind and particle density. Essentially, equation (3) expresses the surface flux as the difference between the flux into and out of the sides of a controlled volume. Equation (3) also calculates the surface source as the difference between the lateral fluxes in and out of the control volume. A similar approach was used to estimate water vapor fluxes from irrigated patches on the landscape by Hipps and Zehr (1995) and Prueger et al. (1996).

Methods

The experiment was conducted at an animal facility near Ames, Iowa. The study was conducted in late August and early September of 2005. The animals were confined in separate buildings spaced over the site. A 20-meter tower was located in the middle of the facility, and there were 7-meter towers both upwind and downwind of the site. Measurements were made at three heights on the large tower and two heights on the smaller towers. At each location, high frequency measurements of 3-dimensional wind, air temperature, water vapor density, and CO_2 density were made. All measurements were made at 10 Hz. The 3-D sonic anemometer (Model CSAT3 – CSI, Logan, UT) was used for measurements of wind and temperature, while the LiCor Model 7500 was used to measure water and CO_2 densities. In addition, a vertical array of cup anemometers was mounted on each 7-meter tower.

The lidar and other air quality measurements during this experiment are described elsewhere in these workshop proceedings. These measurements allow the actual particle density at certain size ranges to be computed for each spatial element mapped by the lidar.

The first step is to document periods when plumes were observed and the lidar was scanning in an appropriate pattern to measure the upwind and downwind faces of the control volume. The setup and a conceptual picture of this approach are depicted in Figure 1.

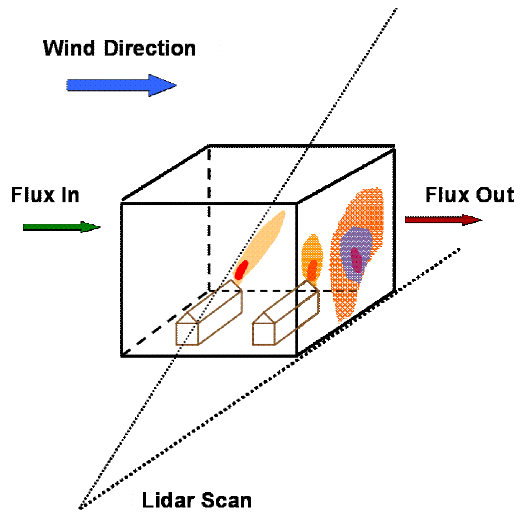

Figure 1. Representation of the approach used to calculate surface emissions.

When distinct plumes of emission were observed during fairly steady-state conditions, the wind and lidar data can be input into equation (3) to solve for the average surface emission. These calculations will be completed for all periods during the experiment that meet the above criteria.

Periods will be identified when distinct turbulence structures are present and related to fluctuations in plume activities. The intermittent nature of both the turbulence and emission will be conducted by examining the time series of turbulence data and plume behavior as measured by the lidar.

Preliminary Results

Currently the lidar data are being calibrated to measured particle concentrations to produce images with actual density units. These must be produced before the flux calculations can be made. However, the turbulence measurements of vertical wind and CO_2 density can be used to look at some of the intermittent behavior of CO_2 from the facility.

Some connections between episodic turbulence structures and emission can be observed by looking at the vertical wind and CO_2 density time series. Figure 2 illustrates a case in which there is a strong coherence between large updrafts of vertical wind and CO_2 density at the 12-meter level on the tower in the middle of the complex. There are about 15 minutes of data plotted.

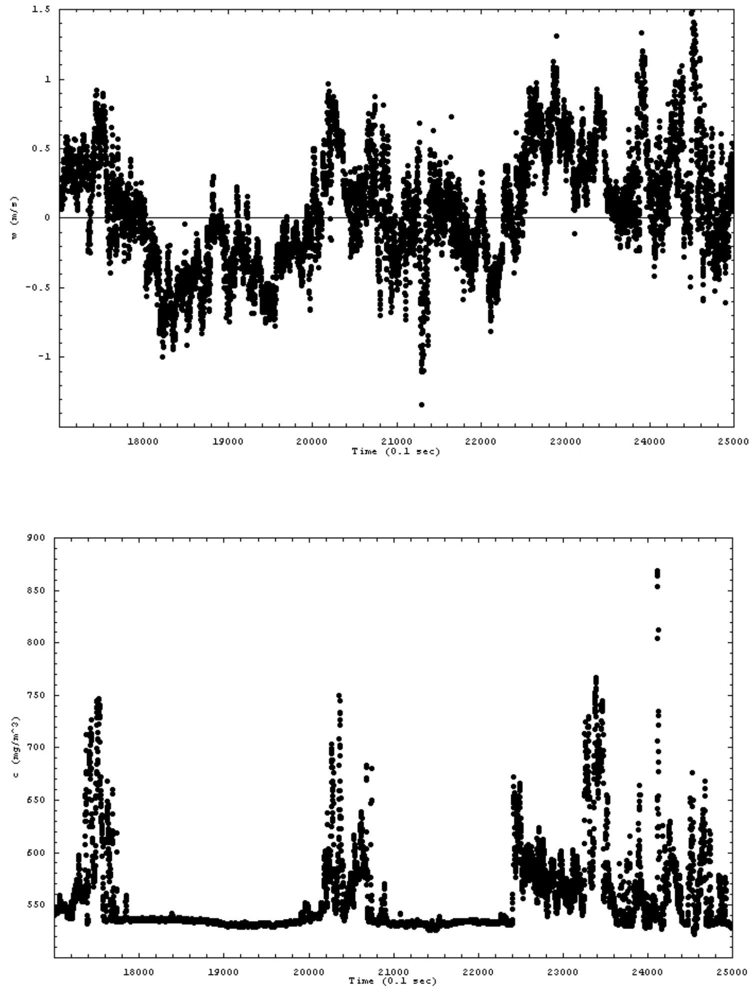

Figure 2. Time series of vertical velocity and CO_2 density at a height of 12 meters above sources.

The data are from a period in the morning when convection was just starting to couple the lowest surface layer with the air above. Note that the CO_2 remains near constant during periods of either weak vertical motion or downward vertical gusts. The source of the CO_2 is the buildings below, and under these conditions, it does not reach the sensor. However, periodically strong updrafts associated with passage of a large eddy bring up plumes of larger CO_2 density.

Future analyses will examine the coherence between plume emissions and transport with distinct turbulence events and structures. This will indicate how emissions are affected by periodic large scale eddies sweeping the source area. The implications for modeling the transport of particulates will be addressed.

References

Hipps, L.E. and D.F. Zehr. 1995. Determination of evaporation from integrated profiles of humidity and temperature over an inhomogeneous surface. *Boundary-Layer Meteorol.* 75: 287-299.

Prueger, J.H., L.E. Hipps, and D.I. Cooper. 1996. Evaporation and the development of the local boundary layer over an irrigated surface in an arid region. *Agric. for. Meteorol*. 78: 223-237.