Coherent Lidar Characterization of the Boundary Layer in Estimation of Urban-Scale Greenhouse Gas Emissions

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Abstract: The Indianapolis Flux Experiment (INFLUX) aims to incorporate aircraft measurements, surface-based in situ and remote observations, and chemical transport models to improve greenhouse gas emissions estimates on urban scales. During INFLUX we deployed a compact, continuously-operating coherent Doppler lidar to provide information on boundary layer winds, turbulence, and aerosol structure as input for the model and aircraft-based emissions calculations and for validation of model performance. The lidar performs a repeating sequence of scans and stares to estimate the wind, horizontal and vertical velocity variance, and backscatter gradient profiles. Using these observations, a robust algorithm has been developed to estimate boundary layer depth, a key parameter in the emissions calculations, under both daytime and nighttime conditions. The presentation will discuss lidar performance, scan strategies, development and performance of the boundary layer depth algorithm, meteorological conditions observed, and use of the data for both model-based and top-down aircraft-based emissions estimates.

Keywords: Coherent Lidar, Wind Measurements, Turbulence, Boundary Layer, Greenhouse Gas Emissions Estimates

1. Introduction

Improving quantification of greenhouse gas emissions at urban scales is becoming increasingly important for establishing baselines and evaluating mitigation strategies to slow down the increase of atmospheric CO$_2$ and methane. Currently estimates rely primarily on “bottoms-up” techniques, in which emissions from all identified discrete sources within an area of are summed to produce an overall estimate for the area[1]. The Indianapolis flux (INFLUX) experiment incorporates aircraft and surface-based observations, as well as chemical transport models, to investigate potential improvements in regional scale emissions estimates gained by applying top-down and modeling approaches. INFLUX observational components include several-times-per-month aircraft measurements of gas concentrations and meteorological parameters, as well as a number of towers observing CO$_2$, CH$_4$, and CO augmented by a single unattended Doppler lidar to estimate wind, turbulence and aerosol structure in the boundary layer. The Doppler lidar serves a critical role for both the observational and modeling components of INFLUX by providing continuous information on mixing and transport within the urban boundary layer.
2. Doppler Lidar Deployment during INFLUX

Utility of Doppler lidar for mass balance studies was initially demonstrated during the Uintah ozone study [1] where observations from the NOAA High Resolution Doppler Lidar (HRDL, [2]) were combined with aircraft measurements to assess leakage from gas wells in the Uintah basin oil and gas field. The investigation applied a mass balance technique, where the aircraft equipped with chemical sensors sampled methane gas concentrations upwind and downwind of the city, as shown in Fig. 1. By calculating the differences in the aircraft-measured upwind and downwind concentrations and incorporating lidar measured wind speed and direction profiles and boundary layer depth, the upwind and downwind methane fluxes and emission rates could be computed.

Rather than deploy our research lidar for the multi-year INFLUX study we chose to purchase and deploy a commercial, low-pulse-energy, high pulse rate Doppler lidar for the study [3]. The lidar, sold by Halo Photonics, was installed on the roof of a classroom building at Ivy Tech Community College northeast of Indianapolis in April, 2013, and operated, with the exception of a maintenance interval in summer 2013, continuously until spring, 2015, when it was sent back to the manufacturer for maintenance and performance upgrades. An upgraded version of the lidar was redeployed in January, 2016.

For INFLUX, we employ a fixed scan pattern, repeated every 20-30 minutes, to measure the needed boundary layer parameters. The pattern includes several conical scans at different elevation angles for measurement of horizontal wind profiles, vertical scans at orthogonal azimuths for observations of low level winds under stable conditions, and fixed vertical stares to observe vertical turbulence and mixing. Estimates of vertical velocity variance and aerosol backscatter profiles are computed from the vertical stares to characterize atmospheric mixing. Figure 3 shows a plot of wind speed and direction measured during daytime hours on June 17, 2016, while Figure 4 shows a 1-hour
time height cross-section of vertical velocity variance and aerosol backscattered signal observed on the same day. The growth of the mixing layer to about 2000 m is clearly seen in both figures. However, the presence of a residual aerosol layer extending from the surface to ~1.5 km above the surface between 12Z and 16Z is also observed, complicating the ability to measure mixing layer depth based on backscatter gradient during that period. For this reason, we use both aerosol and vertical velocity variance for estimation of mixing layer depth, as described in section 3.

To meet the observational requirements for the long-term INFLUX study, the lidar needed to operate continuously and reliably, and to provide profiles of wind speed and direction, vertical velocity variance, and backscatter structure from near the surface to the top of the boundary layer under all conditions. The initial instrument was quite reliable, but we identified many cases, typically under low-aerosol conditions, where the instrument did not appear to make measurements to the top of the boundary layer. To better quantify the occurrences of low sensitivity, we developed a technique where we compared the maximum range of vertical and horizontal measurements of signal-to-noise ratio (SNR) and velocity variance. We assumed that when the instrument was characterizing the full boundary the horizontal range would be significantly greater than the vertical range. Using this somewhat subjective criteria we could see that the ranges were approximately equivalent a significant portion of the time, giving some indication that the sensitivity of the original instrument was not sufficient to measure through the boundary layer under all conditions. Based on this conclusion, the instrument was returned to the manufacturer for several modifications designed to improve sensitivity.

The upgraded instrument, which featured higher pulse energy, improved processing, and slightly longer pulses, was reinstalled in Indianapolis in early 2016, and has continued to operate as part of the study. A scatter plot of horizontal versus vertical range for vertical velocity variance, measured over 3 months in early 2016, is shown in Figure 4. The figure shows that horizontal range exceeds vertical range for a large portion of the cases examined, and provides us with some confidence that the instrument is operating with sufficient sensitivity to see to the top of the boundary layer under almost all conditions. We attribute the cluster of points near the 1:1 line at 4 km range to mid-level clouds, which provide an artificial extension of the vertical range.
3. Automated Boundary Layer Height Estimation

Knowledge of boundary layer depth is essential for both mass-balance and model-based emissions estimate. Using lidar data, we have been investigating development of robust automated algorithms to detect the top of the boundary layer under a variety of daytime and nocturnal conditions. The algorithms use the lidar-based estimates of profiles of horizontal and vertical velocity variance, backscatter structure (as evidenced by signal to noise ratio, SNR), and horizontal wind velocity, which are selectively applied depending on time of day and observed atmospheric properties. Under daytime conditions vertical velocity variance and backscatter structure are generally of greatest utility, while wind velocity and horizontal velocity variance are most effective at night. In Figure 4 the red line shows an estimate of boundary layer depth for a daytime convective boundary layer overlaid on the vertical velocity and lidar SNR profiles. In this case the boundary layer is fairly obvious in both the vertical velocity variance and SNR profiles. However, our analyses have shown that no single variable can be used without caution. For example, although the reduction in vertical velocity variance is frequently a good indicator of increased stability associated with boundary layer top, in the presence of free troposphere gravity waves the unfiltered vertical velocity variance can lead to an overestimate of boundary layer thickness. We are continuing to analyze the INFLUX data set, with its variety of conditions extending over multiple seasons, to further refine and improve boundary layer height estimates.

Figure 6: Lidar-measured SNR and vertical velocity variance compared with WRF model-estimated TKE for 10-day period. The right figure is a blow-up of the time period marked by the red box on the left.
4. Model validation

One component of the INFLUX study involves application and validation of numerical models that use emissions estimates from surface sites or emissions inventories in combination with meteorological data to estimate large scale emissions. The lidar wind and turbulence measurements are employed in the model studies both as input data, which are assimilated into the models, and for evaluation of model performance [5]. Figure 6 (left) shows a comparison of lidar-measured vertical velocity variance and backscatter structure (evidenced by SNR) over a 10-day period with estimates of turbulence kinetic energy (TKE) generated by a version of the Weather Research and Forecasting (WRF) model with real-time data assimilation applied at high resolution. A blowup of two days during the sequence is shown in the right figure. The similarity between the model and observational results is quite evident in this comparison, although for this model run the observational data shows a somewhat deeper boundary layer than predicted by the model.

5. Future Plans

We are continuing deployment of the Halo lidar at INFLUX. During summer 2016 plans are to deploy a micro-pulse aerosol lidar alongside the INFLUX Doppler instrument to compare aerosol and velocity variance based techniques for estimating boundary layer height. Studies are also planned to assess the need for a second Doppler lidar to the southwest of Indianapolis; the combination of the two instruments would provide upwind and downwind observations under most wind conditions, enabling investigation of issues such as urban heat island effect on emission estimation.

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7. References


