

# Local Source Estimation of CO<sub>2</sub> in the Boundary Layer through DIAL Observations and Atmospheric Transport and Dispersion Calculation

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**Abstract:** To formulate appropriate emission reduction policies, it is important to accurately determine CO<sub>2</sub> emissions. Especially for CO<sub>2</sub> emissions from large emission sources and urban areas, their statistics and estimates are considered to have uncertainties, and highly accurate emissions are required. For this purpose, inversion analysis has been developed to estimate emissions by assimilating satellite data into a transport model. Since DIAL (Differential Absorption Lidar) provides spatial-temporal variations of vertical profiles, data assimilation of these profiles is expected to improve the accuracy of emission estimation. We have developed a direct-detection 1.6- $\mu\text{m}$  DIAL. Since 2015, we have observed the vertical profiles of CO<sub>2</sub> concentration during the daytime and nighttime from 0.5km up to 2.5 km in western Tokyo. In this study, as a preliminary step of quantitative emission estimation, we attempted to estimate sources satisfying the characteristic diurnal variations of vertical profiles of CO<sub>2</sub> concentration in the boundary layer observed by DIAL using simple CO<sub>2</sub> transport and dispersion model calculations.

## 1. Introduction

Carbon dioxide (CO<sub>2</sub>) accounts for 76% of total greenhouse gas emissions and is the most significant contributor to global warming. Accurate understanding of CO<sub>2</sub> emissions is important to formulate appropriate emission reduction policies. Especially for CO<sub>2</sub> emissions from large-scale emission sources and urban areas, their statistics and estimates are considered to have uncertainties, and highly accurate emissions are required. For this purpose, inversion analysis has been developed to estimate emissions by assimilating satellite data into a transport model [1]. However, the information obtained from satellites is a two-dimensional distribution of column concentrations, and the observation time is limited. In contrast, the differential absorption lidar (DIAL) can provide spatial-temporal variations of vertical profiles, which can be used in combination with DIAL to improve the accuracy of emissions estimation.

We have developed a direct-detection 1.6- $\mu\text{m}$  DIAL to measure vertical profiles of CO<sub>2</sub> concentration [2,3]. CO<sub>2</sub> concentration vertical profiles from an altitude of 0.45 km to 2.5 km

have been measured at Tokyo Metropolitan University, located in western Tokyo, during daytime and nighttime, mainly on clear days with an altitude resolution of 300 m and an integration time of 1 hour.

In this study, as a preliminary step of quantitative emission estimation, we attempted to estimate sources satisfying the characteristic diurnal variations of vertical profiles of CO<sub>2</sub> concentration in the boundary layer observed by DIAL using simple CO<sub>2</sub> transport and dispersion model calculations.

## 2. Atmospheric Transport and Dispersion Calculation

Simple atmospheric transport-dispersion equation is written as

$$\frac{\partial C_i}{\partial t} = -u \frac{\partial C_i}{\partial x} - v \frac{\partial C_i}{\partial y} + K_H \frac{\partial^2 C_i}{\partial x^2} + K_H \frac{\partial^2 C_i}{\partial y^2} + K_z \frac{\partial^2 C_i}{\partial z^2} + S_i \quad (1)$$

where  $C_i$  is CO<sub>2</sub> mixing ratio at each grid,  $u$  and  $v$  is horizontal wind speed,  $K_H$  is lateral eddy diffusivity,  $K_z$  is vertical eddy diffusivity, and  $S_i$  is source term [4]. Calculations were carried

out by interpolating each pressure altitude surface wind data from the numerical weather forecast mesoscale model to a spatial resolution of 1 km x 1 km, an altitude resolution of 105 m and a time interval of 30s.

Fig. 1 shows topographic map of the analysis area. The area is 111x132 km (138.75-140.25E, 35.2-36.2N) including the Kanto Plain and forested areas, centered approximately on the DIAL observation point (139.37E, 35.66N). The lidar station is located at the western edge of the Kanto Plain, and there is a mountainous area with an elevation of more than 1000 m to the west.

The forest source/sink was set in the forest area of the land cover classification, considering the daily changes in total photosynthesis and ecosystem respiration for each month in the terrestrial ecosystem model VISIT [5]. Fig. 2 shows the set value of net ecosystem exchange for August in the analysis area. Fig.3 shows diurnal variation of ecosystem for each month. The nighttime values are positive emissions due to respiration only, while the daytime values are negative absorptions due to the addition of photosynthesis. The forest area is widely distributed, mainly to the west of the station.

Fossil fuel data from ODIAC 2022 [6] were used as the fossil fuel source. Fig. 4 shows the set value of fossil fuel emissions for August 2019 in the analysis area. The fossil fuel sources are concentrated in the city center and the Keihin and Keiyo industrial zones located to the east of the observation point.

The CO<sub>2</sub> source/sink was set at the pressure surface corresponding to the altitude of each location, with diurnal variations of the monthly mean values in each database. The CO<sub>2</sub> concentration variations were obtained as a three-dimensional time series by numerically calculating the advection-diffusion equation based on the diurnal variation of the vertical eddy diffusivity and the wind at each pressure surface. The Meso-Scale Model (MSM) provided by Japan Meteorological Agency was used as wind data, interpolated in time. The lateral eddy diffusivity is set to constant. The program was run 12 hours before the start of lidar observations.

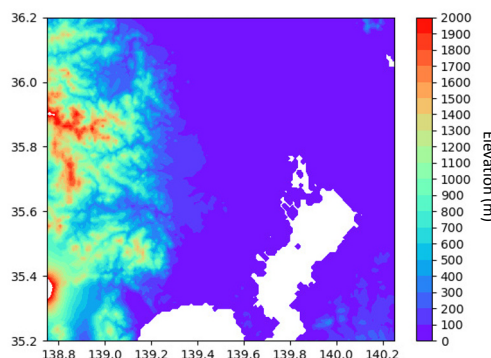


Figure 1. Topographic map of the analysis area

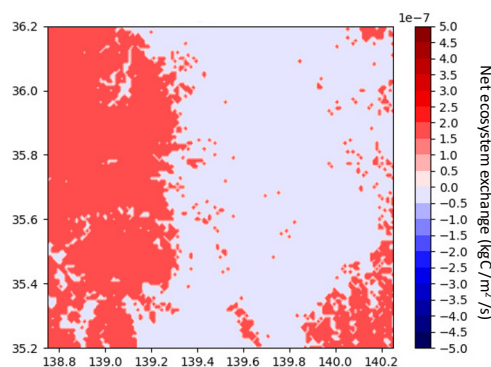


Figure 2. Net ecosystem exchange field

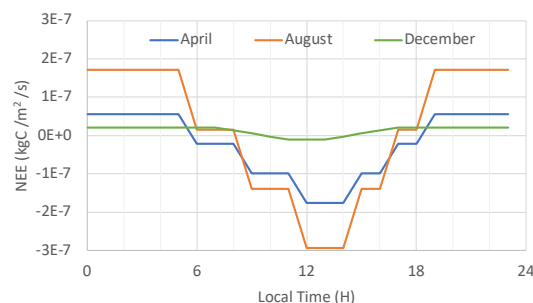


Figure 3. Diurnal variation of net ecosystem exchange

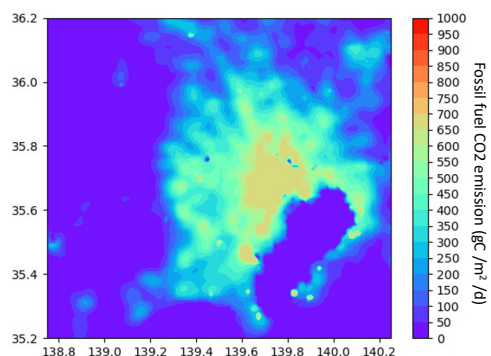


Figure 4. Fossil fuel CO<sub>2</sub> emission field

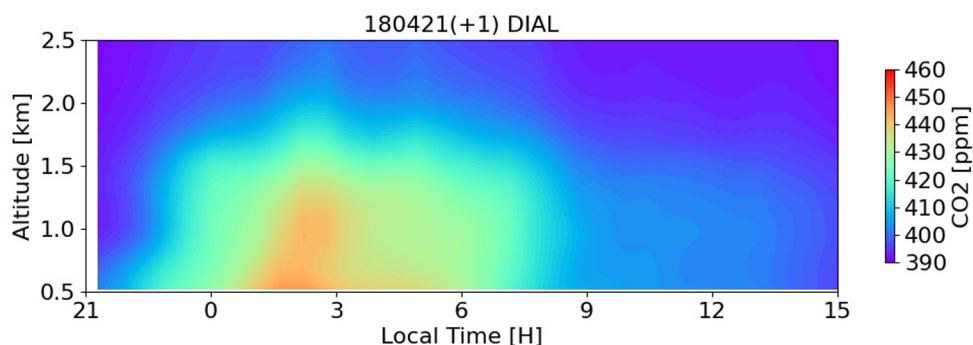


Figure 5. Observed time-height cross section of CO<sub>2</sub> mixing ratio by DIAL

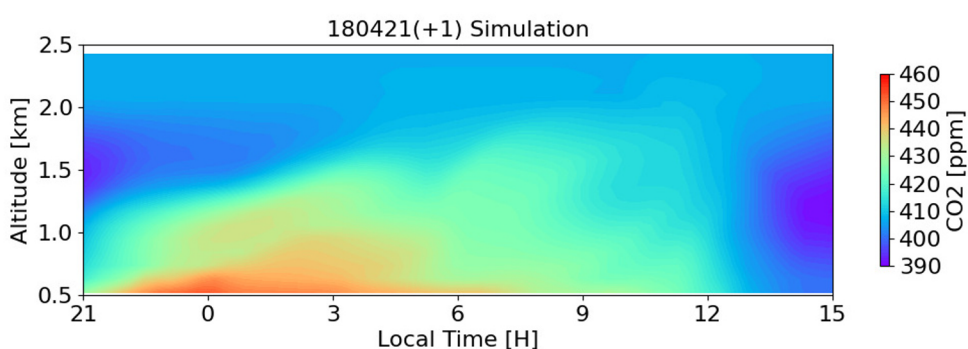


Figure 6. Time-height cross section of CO<sub>2</sub> mixing ratio by simple transport and dispersion simulations over the DIAL site

### 3. Comparison of Observations and Simulation Results

Fig. 5 shows the observed time-height cross section of CO<sub>2</sub> mixing ratio using DIAL, and Fig. 6 shows the time-height cross section of CO<sub>2</sub> mixing ratio by the simple transport and dispersion simulations over the DIAL site. The background level of the CO<sub>2</sub> mixing ratio in the simulation is set to match the observations. Although observations and simulation results are not in full agreement, the timing of the increase and the altitude distribution are generally in agreement. Forest sources are located at higher altitudes and thus contribute to the increase or decrease in CO<sub>2</sub> up to approximately 1.5 km, while fossil fuel sources are located at lower altitudes and thus generally only affect the increase in CO<sub>2</sub> below 1 km.

### 4. Conclusion

Simple atmospheric transport and dispersion simulations reproduced most of the CO<sub>2</sub> concentration variations observed by DIAL. Due to the topographically unique location of the DIAL site, winds converged at various

altitudes over the site during the night, causing CO<sub>2</sub> from different sources to concentrate and increase in concentration. Although the current simulation results do not agree quantitatively with the observed results, adjustment of the vertical diffusion coefficient would improve the quantitative accuracy.

Since DIAL provides spatial-temporal variation of vertical profiles, combining DIAL observations with model calculations may allow us to identify and monitor CO<sub>2</sub> sources / sinks even with a single point of observation. Furthermore, the addition of satellite data is expected to improve the accuracy of identifying large-scale emission sources and estimating emissions.

### 5. References

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