

QUANTIFYING THE CARBON FOOTPRINT OF PARIS WITH REMOTE SENSING OBSERVATIONS

Briana Lynch^{1,2} and Sean Crowell³

¹National Weather Center Research Experience for Undergraduates Program

Norman, Oklahoma

²University of Massachusetts Lowell

Lowell, Massachusetts

³School of Meteorology, University of Oklahoma

Norman, Oklahoma

ABSTRACT

Understanding the complex temporally and spatially varying carbon dioxide (CO₂) emissions in urbanized areas is crucial to identifying causes of climate change and how they can be addressed. While many studies have been conducted to better quantify urban CO₂ (and other pollutant) fluxes, there are still many open questions about the interpretation of these measurements and how emissions scale with population, as well as how to attribute concentrations measured in urban environments to anthropogenic and natural sources and sinks. After deployment for six months (November 2015-April 2016) in Paris, France, data from the Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE™), an observing system that combines laser-based differential absorption spectroscopy measurements with tomographic techniques to create a two dimensional map of CO₂ concentrations, was interpreted and analyzed. An evolution equation for CO₂ mixing ratio within the Planetary Boundary Layer (PBL) was applied to identify and separate sources and sinks of CO₂. Results from this analysis directly verify the impacts that wind speed and direction have on CO₂, namely dilution and enhancement. Preliminary analysis characterized the relationships between CO₂ and nitrogen dioxide (NO₂) and ozone (O₃). GreenLITE™ proves to be an accurate measuring tool for CO₂, but further interpretation and analysis of data is necessary to estimate the emissions of Paris.

1. INTRODUCTION

Urban environments throughout the world contribute over 70% of fossil fuel carbon dioxide (CO₂) emissions (megacities.jpl.nasa.gov). This will only increase as the population grows and migrates towards the urban areas (Population Reference Bureau). With climate change and CO₂ levels on the rise, it is becoming an increasingly important task to partition CO₂ emissions in the urban environment into natural and anthropogenic components, and then further distinguish the different sectors of anthropogenic emissions, so that their impacts can be quantified and mitigation strategies employed.

Attempts have been made to better understand local CO₂ fluxes on varying time scales in different environments. Wang et al (2007) demonstrated the ability to estimate natural CO₂ emissions for a forest using mixing ratio measurements for fair weather days over a two year period, but more restrictions were necessary to attempt to estimate regional fluxes for an extended time with high confidence. The necessity of multiple locations was stressed to consider the effects of horizontal heterogeneity on net ecosystem exchange estimates.

A similar study of the CO₂ mixing ratios across a rural to urban gradient proved that while local fluxes were detectable, a lack of understanding of

¹ Corresponding Author Address: Briana Lynch, Department of Environmental, Earth and Atmospheric Sciences, University of Massachusetts Lowell, One University Ave., Lowell, MA, 01854
Email: Briana_Lynch@student.uml.edu

spatial and temporal resolution of emissions, along with the inability to distinguish natural from anthropogenic sources of urban carbon fluxes prevented studies from progressing (Briber et al. 2013). Even though the urban location had a longer growing season by one month, the total estimated anthropogenic emissions proved to be twenty-five times greater than the rural location.

A case study was conducted to evaluate the evolution of CO₂ in a daily cycle and its relationship with the planetary boundary layer (PBL), along with potential natural and anthropogenic sources and sinks. Two separate types of light detection and ranging (“lidar”) instruments were installed on a high plateau in a suburban environment to measure CO₂ and carbon monoxide (CO). While this study was able to confirm a horizontal gradient of CO₂ between the two points, this location is not completely representative of the urban environment so it cannot be correlated to a regional flux. (Gibert et al. 2008)

This research addresses the atmospheric and non-atmospheric processes that affect urban CO₂ emission levels in a megacity through the analysis of a CO₂ measuring system. The second section discusses the instruments used to measure CO₂ concentrations and equations used to separate changes in concentrations into causal mechanisms. The third section discusses the results and trends discovered. The fourth section presents conclusions of this work.

2. METHODS

2.1 *The GreenLITE System*

To measure CO₂ concentrations in Paris, a megacity, we used data from the Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE™) system (Dobler et al. 2015), which combines a differential laser absorption spectroscopy instrument with retrievals of CO₂ dry air mixing ratios that are used in a tomographic reconstruction technique to produce a 2D maps of CO₂ concentration. The lidar instrument is based on the intensity-modulated continuous wave (IM-CW) approach (Dobbs et al. 2001), which was used in the Multifunctional Fiber Laser Lidar (MFLL) (Dobbs et al. 2008) to

identify sources and sinks of CO₂ from space as part of the Active Sensing of CO₂ Emissions over Nights, Days and Seasons (ASCENDS) mission, which was recommended in the 2007 Decadal Survey (NRC, 2007). The MFLL has been tested in numerous airborne campaigns (Dobler et al. 2013).

The IM-CW approach transmits and receives multiple wavelengths of light, one with high absorption of CO₂ and one nearby with minimal CO₂ absorption. The difference in absorption between the wavelengths allows for the retrieval of the number density of CO₂, since atmospheric effects are similar between the two wavelengths.

The hardware for GreenLITE™ was designed by Harris Corporation. The CO₂ concentration retrieval and 2D reconstruction was developed and deployed by Atmospheric and Environmental Research, Inc. (AER). GreenLITE™ measures differential absorption along the lines of sight (“chords”) between two lidar transceivers and a series of retroreflectors, which are then used to visualize CO₂ with a two dimensional spatial map using tomographic reconstruction techniques (Dobler et al 2015). This information is displayed in a user-friendly web-based interface that shows the paths between transmitters and reflectors used to create measurement lines, or chords, as well as local weather information and the domain average CO₂ time series for the previous 24 hours (Dobler et. al 2016).

GreenLITE™ was tested in several locations before finally being deployed in Paris, France in November 2015. The initial testing of a one kilometer prototype took place in Bozeman, Montana at the Zero Emissions Research and Technology site. This prototype was then deployed in Illinois at an active ground carbon storage site for six months. A five kilometer system was initially tested in Boulder, Colorado in September 2015 at the National Oceanic and Atmospheric Administration (NOAA)’s Boulder Atmospheric Observatory (BAO).

Two transceivers for the deployment in Paris were installed on the Centre International du Textile (CIT) building at Montparnasse (denoted as T03) and on top of the Jussieu tower at the University of Pierre et Marie Curie (denoted as T04). Fifteen retro-reflectors were installed at

various locations throughout the city, denoted by R01-R16, neglecting R04 (Figure 1). The installation began during the first week of November 2015 and began running twenty-four hours a day, seven days a week on November 9th, 2015. This experiment will continue to run until November 2016. The dataset analyzed in this work included the time period from November 9th, 2015 to April 15th, 2016.



Figure 1. The transceivers are the red dots, while the retroreflectors are the green dots. T03 is closer to the bottom while T04 is above towards the top right corner. R01 starts at the bottom of dots, with R02 to the left.

2.2 Interpreting the Measurements for the Urban Domain

The mass balance equation from Gibert et al. 2008 identifies the processes that impact CO₂ within the PBL:

$$(1) \quad \rho h \frac{dX}{dt} = \rho \frac{dh}{dt} (X_+ - X) - S - A$$

where ρ is the mean molar air density; h is the PBL height; X and X_+ are CO₂ concentrations in the PBL and free troposphere, respectively; S and A are fluxes of CO₂ into the domain via surface emissions and advection.

The PBL mixing ratio X is impacted by several processes, as denoted in equation (1). CO₂ emissions (S) are mixed into the PBL. This mixing length scale is the PBL height h , which determines the volume of air into which the CO₂ is mixed, and hence its concentration (Liu and Liang, 2010). Additionally, mixing across the entrainment zone is treated as proportional to the difference between the PBL mixing ratio X and

the free troposphere mixing ratio X_+ . Properly accounting for urban boundary layer dynamics is crucial to estimating sources of CO₂ emissions.

The strength of potential sources of local emissions is another important determinant of observed concentrations. Unlike remote environments, urban concentrations can be strongly impacted by both anthropogenic and natural emissions on diurnal, weekly and seasonal time scales. Traffic patterns and heating in the winter months are big contributors to anthropogenic emissions; human respiration should be accounted for, albeit insignificant in effect in comparison (Briber et al. 2013).

Advection of CO₂ by the mesoscale weather, which is denoted by A in equation (1), is a key driver of local concentrations as well. The wind direction influences local concentrations by transporting air into the domain from outside, which might have been affected by emissions elsewhere. Additionally, even when the mixing ratio of the parcels advected into the domain is constant, changes in wind speed can either dilute or enhance mixing ratios. In this way, strong variations in winds make estimating emissions and interpreting concentration changes difficult.

3. RESULTS

Through our analysis, we discovered that CO₂ concentrations have significant variability in Paris' urban dome. We were able to confirm many of the trends previously discovered in urban environments as well as continue to expand on the idea that the PBL dynamics affects CO₂ emissions.

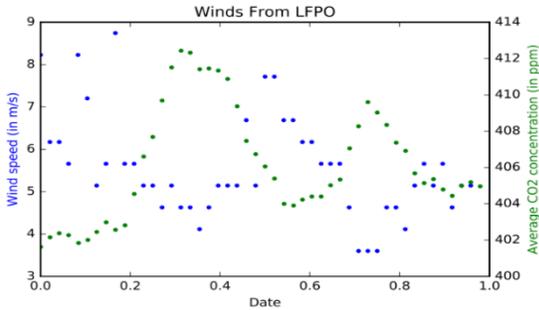


Figure 2. Daily time scale for February 1st. The blue dots represent the wind speeds observed in meters per second (m/s) at the Paris Orly (LFPO) airport at thirty minute intervals. The green dots represent the chord-averaged CO₂ concentrations in parts per million (ppm), which are plotted every thirty minutes.

While weather observations were collocated with GreenLITE™ transceivers and retro-reflectors, the measurements were taken at instantaneous times and within the turbulent section of the target area, which did not accurately represent the average wind described by advection (term A in equation 1). Instead, we used local airport data near the GreenLITE™ domain. Automated Surface Observing System (ASOS) wind data from the Charles de Gaulle airport (LFPG) and the Paris Orly airport (LFPO) were used for the same time frame. This data was obtained from the Iowa Environmental Mesonet (<https://mesonet.agron.iastate.edu/>). LFPG is located approximately 30 kilometers to the northwest of our target site. LFPO is located approximately 20 kilometers to the south. The airports both had similar trends for wind speed and wind direction over the six-month period so we chose to use LFPO to conduct our analysis. The wind data was collected at thirty minute intervals, while the GreenLITE™ data was

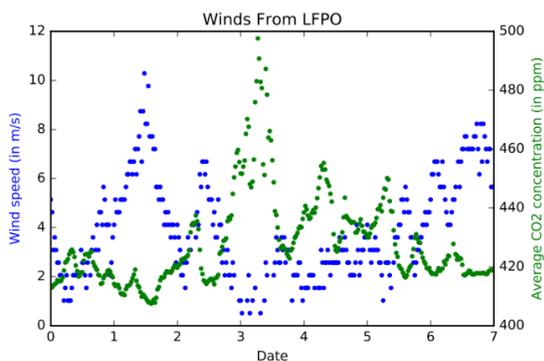


Figure 3. As in Figure 2, but for the week of February 14th – 20th, 2016. The pattern shows the dilution effects that high wind speeds have on mixing ratios.

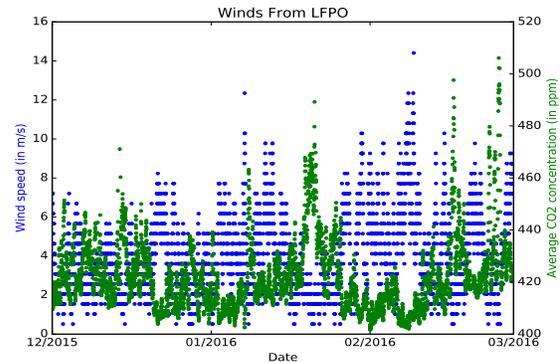


Figure 4. As in Figure 2, but for the December 1, 2015 through March 1, 2016. This figure demonstrates the intra-seasonal variability in GreenLITE observations.

collected for each chord approximately every four minutes.

Figures 2, 3 and 4 demonstrate an inverse relationship between wind speed and CO₂ concentrations in diurnal, weekly, and seasonal cycles, in line with the dilution effect of strong winds on CO₂ (and all trace gas) mixing ratios. February was chosen for Figure 2 and 3 as it exemplified typical trends. As the wind speeds decreased, the CO₂ concentrations increased. This tendency has been studied (Xueref-Remy et al. 2016), and demonstrates that GreenLITE™ is producing reasonable results from its measurements.

Figures 5 and 6 depict monthly statistics of wind speed, wind direction and domain average CO₂ concentrations using wind rose plots, which can

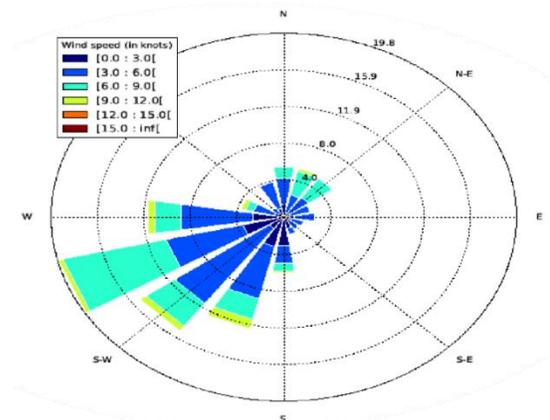


Figure 5. Wind rose plots for the month of February for wind direction and wind speed. The wind direction is indicated by the direction of the sector, and the statistics of the wind speed are indicated by the sector area and color. As expected, winds in February are largely from the southwest.

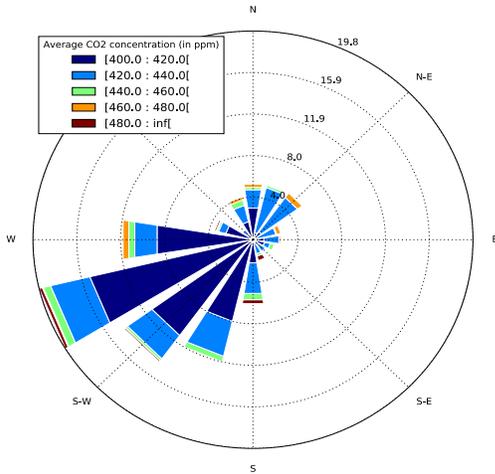


Figure 6. As in Figure 5, except that the colors represent the concentration of the chord-averaged CO₂ concentration values. In February, winds from the southwest mostly brought low CO₂ air into the urban domain.

be thought of as histograms with spatial information. The percentages inside the circles show how often that wind direction was observed while the colors denote the frequency of a certain wind speed (Figure 5) and CO₂ concentration (Figure 6).

To separate the variables in equation (1), we need a time frame that has consistent wind speed and wind direction. If we have consistency in the wind, we can treat the advection term A , which is a nuisance term, as stationary, and analyze the variations in CO₂ resulting from the other processes. March 14, 2016 through March 20, 2016 had stationary winds, largely from the north east and with low variability in magnitude as shown in Figure 7.

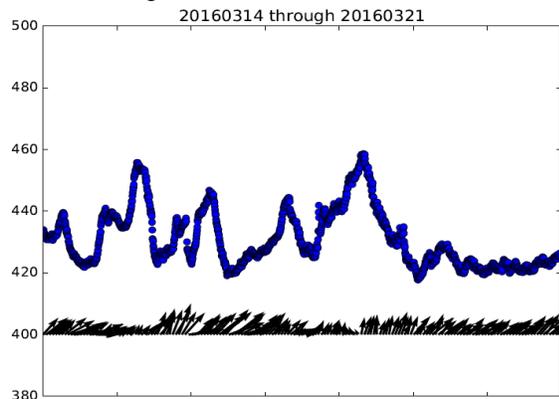


Figure 7. Weekly time series from March 14th to March 20th. The blue dots represent the CO₂ concentration. Black vectors point to where the wind is coming from with the length representing the wind speed.

Figure 8 shows the relationship between the PBL and the CO₂ concentrations for the selected week in March. The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) Reanalysis data (Global Modeling and Assimilation Office) was used to compare PBL height and GreenLITE™ CO₂ data. As the PBL height increases, the CO₂ concentrations decrease. Each diurnal cycle for CO₂ concentrations has two peaks instead of one, which would be expected if the only contributor was typical PBL evolution involving a growing mixed layer through the day and subsidence at night. On the weekend (3-19 and 3-20), the PBL height maintains its daily trend, while the CO₂ concentration range does not vary as much as it did on the weekdays. This further demonstrates that the PBL height variations are not the only contributor to CO₂ concentration variations. These two observations together suggest local emissions, perhaps from morning and evening drivers commuting to and from work.

To determine other processes that might contribute to variations in CO₂ concentrations, other pollutants were analyzed. Data from AIRPARIF (www.airparif.asso.fr), an air quality monitoring network for Paris and the Ile de France region, was used to compare nitrogen dioxide (NO₂) and ozone (O₃) to GreenLITE™ CO₂ data.

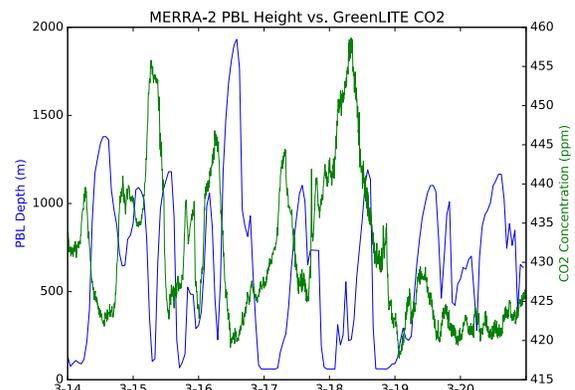


Figure 8 Time series of PBL heights from MERRA-2 (blue) overlaid on GreenLITE chord-averaged CO₂ concentrations (green). The negative correlation between the two variables is evident, as is the presence of other factors, due to two daily peaks in CO₂ that hint at traffic emissions, as well as the reduced diurnal cycle on 3/19 and 3/20.

Figure 9 illustrates a directly proportional relationship between NO_2 and CO_2 concentration. One explanation for this relationship is that both CO_2 and NO_2 are emitted by automobiles and buses (EPA 2016). The fact that NO_2 is highly reactive indicates that any correlations may be short term, and this is represented by difference outside the high traffic times. A strong anti-correlation between O_3 and CO_2 is observed in Figure 10. Further analysis is required to explore this relationship. O_3 is a product of reactions between volatile organic compounds (VOC) and NO_2 from motor vehicles (Bickford 2012), which could explain some of the negative correlation, but a full accounting requires further analysis.

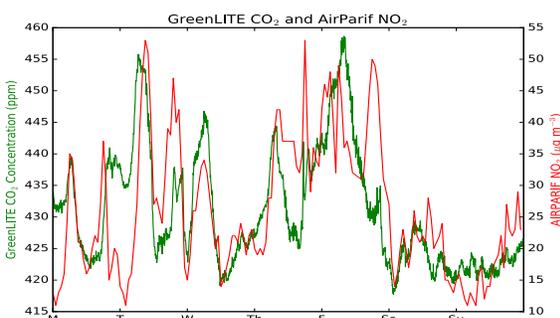


Figure 9. GreenLITE CO_2 (green) and AirParif NO_2 (red). The strong correlation between the two time series indicates a strong traffic signal in the CO_2 observations, particularly comparing weekdays and weekends.

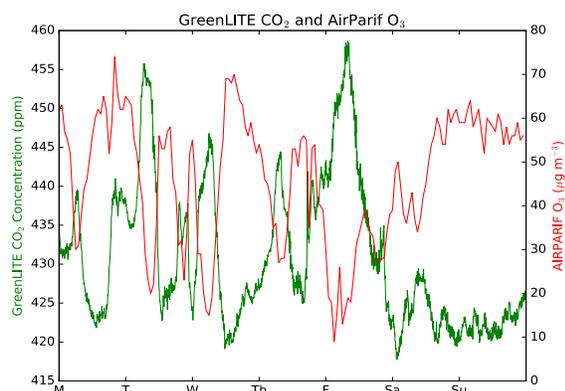


Figure 10 GreenLITE CO_2 (green) and AirParif NO_2 (red). The strong negative correlation between the two time series is as yet unexplained, but could potentially be driven by photolysis of O_3 and interaction with other pollutants, such as NO_2 in Figure 9.

4. CONCLUSIONS

Analysis shows that GreenLITE™ is a scientifically sound measuring tool for quantifying CO_2 concentrations in an urban environment. The use of lidar to measure CO_2 in the horizontal direction is a new application of a mature technology. Confirmation of the relationship between wind speed and CO_2 concentrations and with the general wind direction trend over the seasons verify past research and proper functionality of GreenLITE™. Since we were able to distinguish trends within the data sets provided, GreenLITE™ proves to be working properly as of April 2016.

The use of the PBL mass balance equation helps identify the variables within the boundary layer environment, including sources and sinks of CO_2 advection terms.

Determining a relationship between the PBL height and CO_2 concentrations directed our analysis towards other possibly present pollutants within the urban area. The identification of CO_2 sources, natural or anthropogenic, can guide the instigation of addressing climate change on a global scale.

Future work involves analysis of solar radiation and cloud cover, along with further analysis of the trends observed with NO_2 and O_3 .

5. ACKNOWLEDGEMENTS

The corresponding author would like to thank Dr. Daphne LaDue for providing the opportunity with the National Weather Center Research Experience for Undergraduates. The authors would also like to thank Harris Corporation and AER for providing the datasets used for this work, along with their assistance. This research is based on work supported by the National Science Foundation under Grant No. AGS-1560419.

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