Creating a Model of Background CO2 Levels for Toronto from a Particle Simulation, Tower and Aircraft Measurements

G. Cassidy (McMaster University), E. McGee, K. Strong (University of Toronto), J. Kim (Environment Canada)

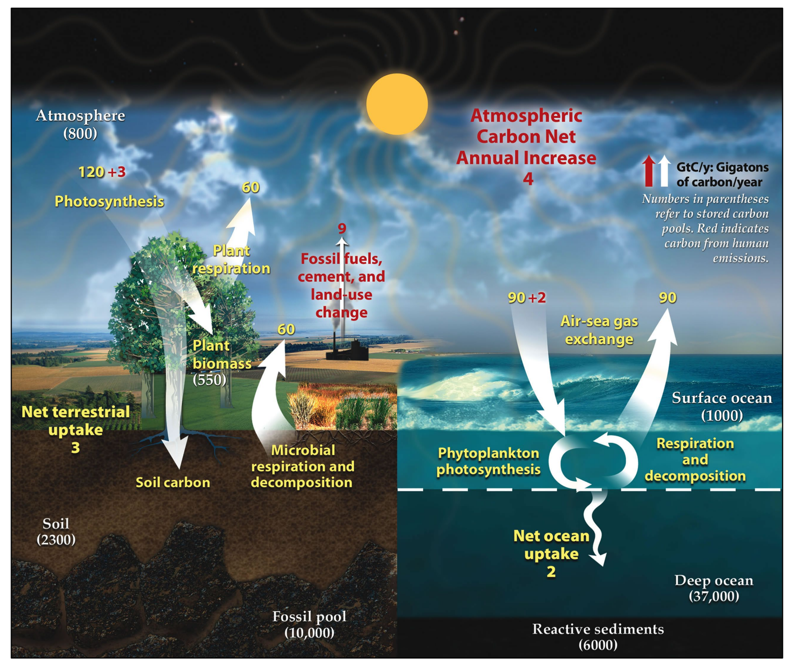

Figure 1: An illustration of the carbon cycle. These sources and sinks make up the CO2 "background", while local city emissions would be "enhancements" on this background.

Introduction

Carbon dioxide (CO2) is the largest contributor to the greenhouse gas effect, and monitoring its emission and spread is vital to studying climate change. CO2 is emitted primarily through human activities, such as the burning of fossil fuels for transportation and energy, and absorbed into plants through photosynthesis. Cities have a high density of CO2 sources, and isolating the emissions from just those sources is difficult. We aim to create a theoretical **"background" of emissions** for Toronto, Ontario using non-urban measurements of CO2.

Measurements

Two types of CO2 measurements were used to construct the theoretical background. Both of these types are "in-situ", meaning the air is directly observed and a very accurate measurement of CO2 concentration is taken. First was **tower measurements** from sites in Egbert and Turkey Point Beach, Ontario (indicated by the purple star and maroon star respectively in Figure 3). This instrument is on a tower, 800 meters above ground, and is taken automatically with a 1-hour frequency year-round. The other source was measurements taken from an **aircraft**, which flies above an airport in Wisconsin, taking measurements twice monthly. These measurements were smoothed using the curve fitting method published by the Global Monitoring Laboratory [1]. This method gives us a continuous equation from limited data, allowing us to extract a CO2 value for times that we don't have direct observations.

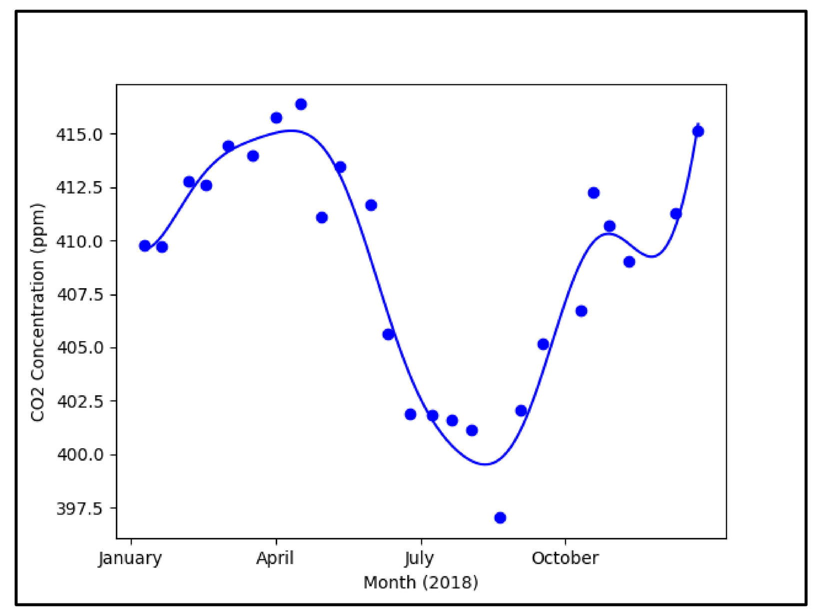

Figure 2: the CO2 measurements taken by the aircraft for the year 2018 are represented by the dots. These are the measurements taken at an altitude between 1000 and 2000 meters. The smoothed equation is shown by the solid line.

Particle Simulation

The Stochastic Time-Inverted Lagrangian Transport Model (STILT) is a model of particle dispersion. It uses meteorological wind speed measurements to simulate the path of a particle backward in time. All particles start at the **receptor** location. These particles spread out because of the chaotic and turbulent nature of the simulation. With 500 particles simulated, this STILT simulation tells us quantitatively where the gas in Toronto came from at a given time. STILT also simulates the height of the **Planetary Boundary Layer** (**PBL**) at the location of each particle.

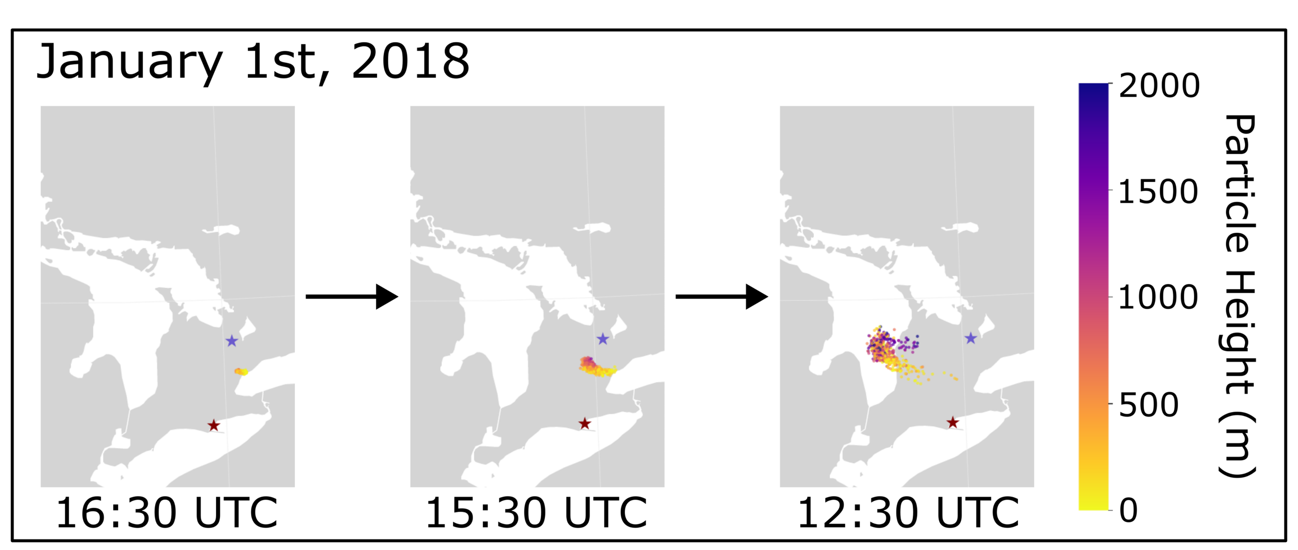

Figure 3: STILT Particle simulation for particles coming from the Toronto Atmospheric Observatory. Particles are shown as small dots, with colour representing altitude. Not shown: intermediate steps, full simulation extends back 24 hours.

References:
[1] Curve Fitting Methods. https://gml.noaa.gov/ccgg/mbl/crvfit/crvfit.html
[2] You Y. et al, Quantifying the Impact of the COVID-19 Pandemic Restrictions on CO, CO_2, and CH_4 in Downtown Toronto Using Open-Path Fourier Transform Spectroscopy. *Atmosphere*. 2021; 12(7):848. https://doi.org/10.3390/atmos12070848
[3] McGee E. et al. (2023, June 12). Using High Arctic TCCON Stations to Validate Modelled Carbon Monoxide and Methane. NDACC-IRWG/TCCON/ COCCON Annual Meeting 2023. https://tccon-wiki.caltech.edu/pub/Main/2023Spa/Erin_McGee_TCCON2023.pptx

Constructing the Model

A boundary was defined by the limits of the tower measurements (See Figure 4). Once particles pass outside that boundary, we determine a CO2 concentration for each based on the following method. The PBL height at the particle's location is sampled when it passes the boundary. If the particle is above the PBL, it is assigned a CO2 value from the binned-and-smoothed aircraft measurements for that moment. If it is below, the closest surface station to the measurement is sampled at the time of exit. This is done for all 500 particles, and these assigned CO2 values are averaged to get a theoretical background value of CO2 for that receptor site at the time of release. We use this technique only for afternoon times (12:00-4:00 PM), as the increased convection from the heat means the atmosphere is more well mixed on the surface, and thus easier to predict. The air at night is too heterogeneous with nighttime emissions not being mixed through convection. We've also limited our study to the winter months, as the CO2 sink from increased plant life in the summer is difficult to predict and model. The most significant issue in applying this method is the low density of tower sites outside Toronto. These sites must be close enough to Toronto that the simulated particles will pass close to it, but far enough from urban areas so as not to be influenced by the local emission that the background is supposed to isolate against.

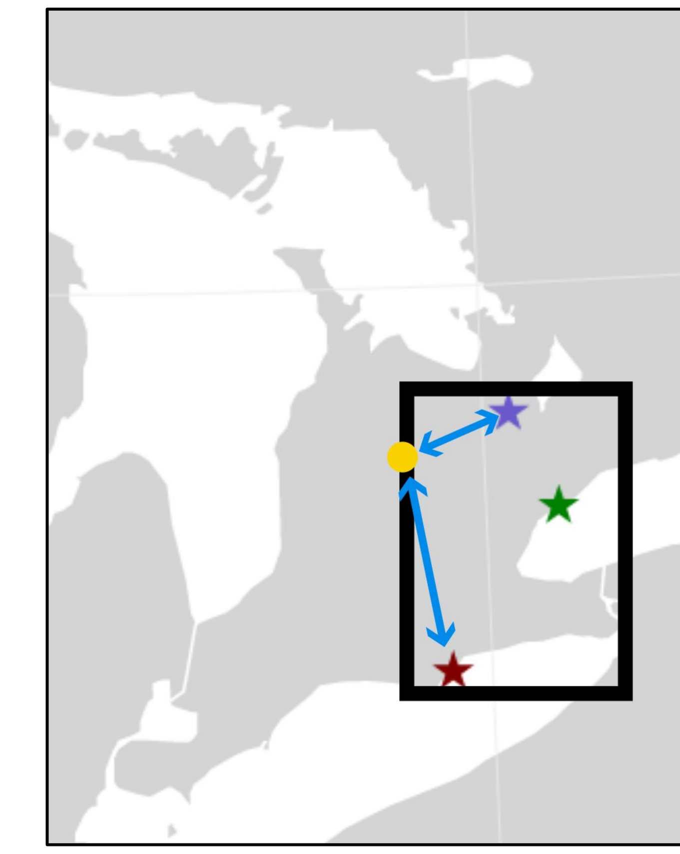

Figure 4: Once a particle (yellow) exits the defined boundary (black), if it is below the Planetary Boundary Layer it samples the nearest surface site (purple and maroon stars). The receptor in Toronto is marked with green.

Next Steps and Uses

This is a model of a *theoretical* background of CO2, meaning there is no measurement that the model can be directly compared to as verification, without the city disappearing or "turning off" for a period of time. Although, the lockdown period in March 2020 of the COVID-19 Pandemic provides an imperfect natural experiment of this sort. CO2 emissions from vehicles and industry were greatly reduced in this time [2], and an intriguing next-step would be to compare this model to measurements taken in that period.
This model can be used in combination with multiple urban CO2 measurements to determine which areas are experiencing carbon enhancements – spikes in CO2 not seen in the background. This can help when investigating unaccounted for sources of carbon in cases where emissions are being underreported or unreported.

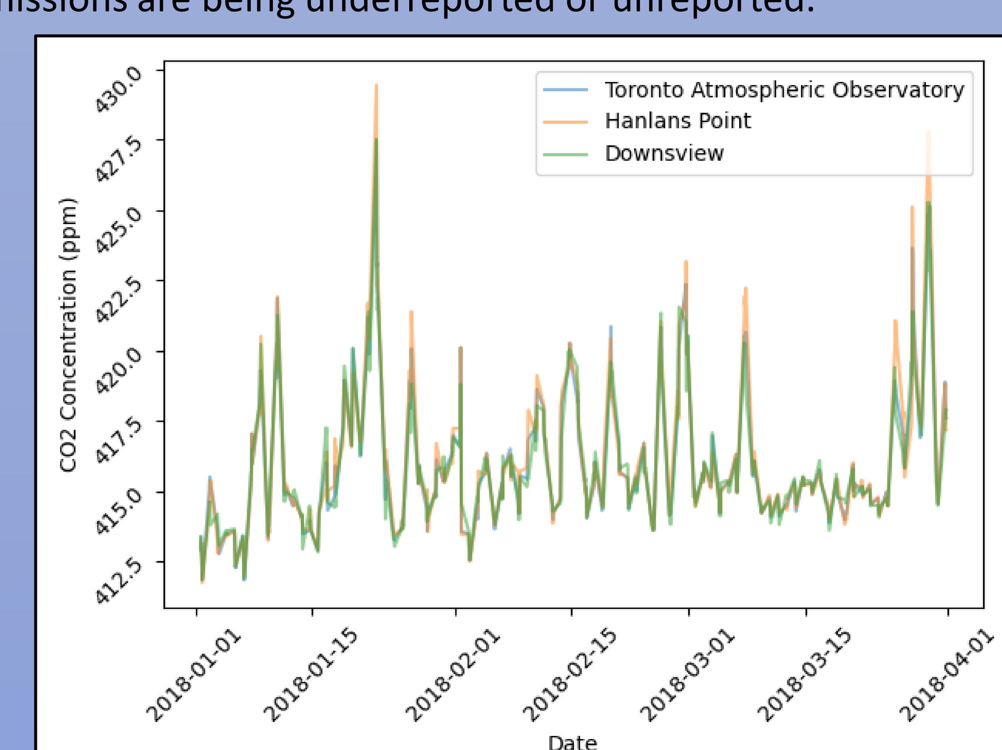

Figure 5: The result of the CO2 background model, with 3 different receptors around the Toronto area. Note the similarities between the curves, due to the receptors' proximity.

Comparing AMAP models with TCCON

An example of how the model we created might be used can be seen in another project: comparing measurements of atmospheric CO and CH4 from the Total Carbon Column Observational Network (TCCON) with various global and semi-global models of those gasses [3]. Here we see measurements taken by the TCCON Station in Lamont, Oklahoma compared with 4 different models. This type of comparison can be used to validate the models based on the more accurate measurements, or help reveal gaps in our understanding of the global system.

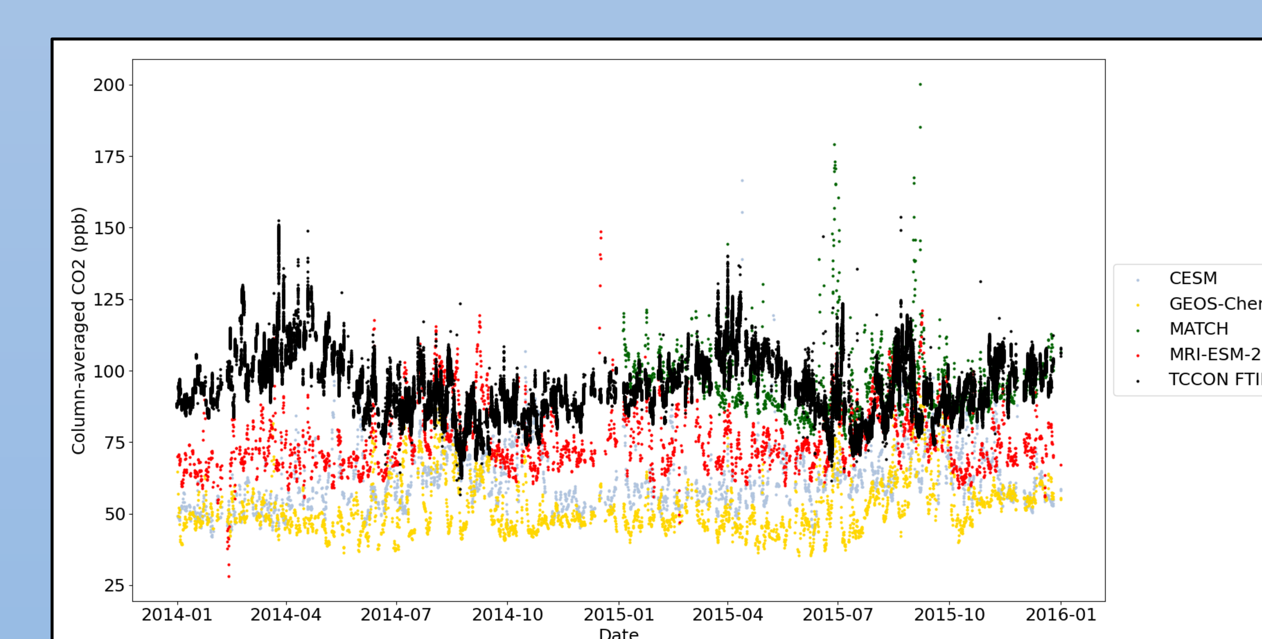

Figure 6: A comparison of modelled and measured CO concentration at Lamont, Oklahoma, USA. The black markers are the measurements taken by the TCCON station at the site, while the rest are column averaged models.