Quantification of CO_2 emissions over the Greater Toronto Area: Comparison of model simulations with OCO and EM27/SUN measurements

Environment and Climate Change Canada
Environnement et Changement climatique Canada

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July 13
13:00-15:00 PDT

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ABSTRACT

- Atmospheric CO_2 is the most important greenhouse gas. Urban areas are estimated to be responsible for more than 70% of global fossil fuel CO_2 emissions. While many cities now have emission reduction policies, the observation methods to verify their outcomes are limited. Satellite measurements and high resolution modelling are effective ways to monitor and quantify CO_2 in the atmosphere. In this study, we present and analyze the XCO_2 (column averaged dry-air CO_2 mole fraction) distributions over the Greater Toronto Area (GTA) using the results of the GEM-MACH model (Global Environmental Multiscale model - Modelling Air quality and Chemistry) with 2.5 km resolution for the period of April to August 2020. The simulated values are compared with multiple OCO-3 SAM (Snapshot Area Map) and OCO-2 Target mode observations collected over the GTA. The comparison between the XCO_2 measurements by two EM27/SUN instruments located in the GTA with the simulated values and the OCO observations are discussed as a step toward combining these datasets to improve our understanding of GTA emissions.

BACKGROUND & OBJECTIVES

- One of the main objectives of the United Nations Framework Convention on Climate Change (UNFCCC) Paris agreement is to reduce anthropogenic CO_2 emissions
- While covering about 3% of the Earth's land, urban areas are the residence of ~54% of the global population and the source of about 70% of anthropogenic CO_2 emissions
- The number and size of urban areas are increasing rapidly around the world
- Better understanding of urban-scale CO_2 emissions can improve our understanding of the carbon cycle and provide critical insights for local climate mitigation policies
- Ground-based observations are not always available for all cities
- Planned carbon monitoring satellites are potentially new opportunities to expand the spatial and temporal resolution and coverage of the ground-based network
- Several studies have shown the capabilities of current space-based measurements in estimation of local scale CO_2 emissions (Kiel et. al. 2021, Wu et. al. 2020, Yang et. al. 2020, Nassar et. al. 2017)
- Meteorological and transport models are also capable to be used to simulate GHG (Pugliese et. al. 2018, Ye et.al. 2020)
- In Canada urban areas cover ~0.25% of the land area while urban population accounts for ~80% of total population
- Greater Toronto Area (GTA) is among the largest fossil fuel CO_2 emitters in Canada
- Here we use atmospheric models coupled with satellite/ ground-based CO_2 data to simulate urban CO_2 concentrations in the GTA and present the utility of satellite data to improve urban scale CO_2 emission estimations over GTA

GEM-MACH MODEL

- For this study, we chose the GEM-MACH (Global Environmental Multi-scale – Modelling Air quality and CHemistry) (Moran et al., 2013) to simulate atmospheric CO_2 mixing ratios over GTA
- GEM-MACH is an online chemistry–transport model embedded in Canadian weather forecast model GEM (Côté et al., 1998a, b)
- The model domain used here is "Pan Am" domain with 2.5 km horizontal grid spacing nested in a North American domain with 10 km grid spacing (Figure 1)
- The model has a hybrid vertical coordinate with 80 vertical levels from surface to 0.1 hPa
- CO_2 is not a chemical species predicted by GEM-MACH model. For this study, we modified the version used by Pugliese et. al. 2018 with a set of special inert tracer fields to account for CO_2 concentration from different sources and lateral boundary conditions
- GEM-MACH-GHG (Kim et. al. 2020) with North American domain (10 km horizontal grid spacing) were run with a 3-day spin-up for the dates we had good OCO-2/3 SAM/target data over GTA to provide the CO_2 boundary conditions and meteorological data
- CarbonTracker Near Real Time for North America (CT-NRT.v2021-3) (Jacobson et. al. 2021) dataset with 1x1 degree resolution was used for 10 km and for 2.5 km resolution simulation for surface fluxes except for fossil fuels that ODIAC (Tomohiro et. al. 2015) dataset with 1x1 km resolution was used

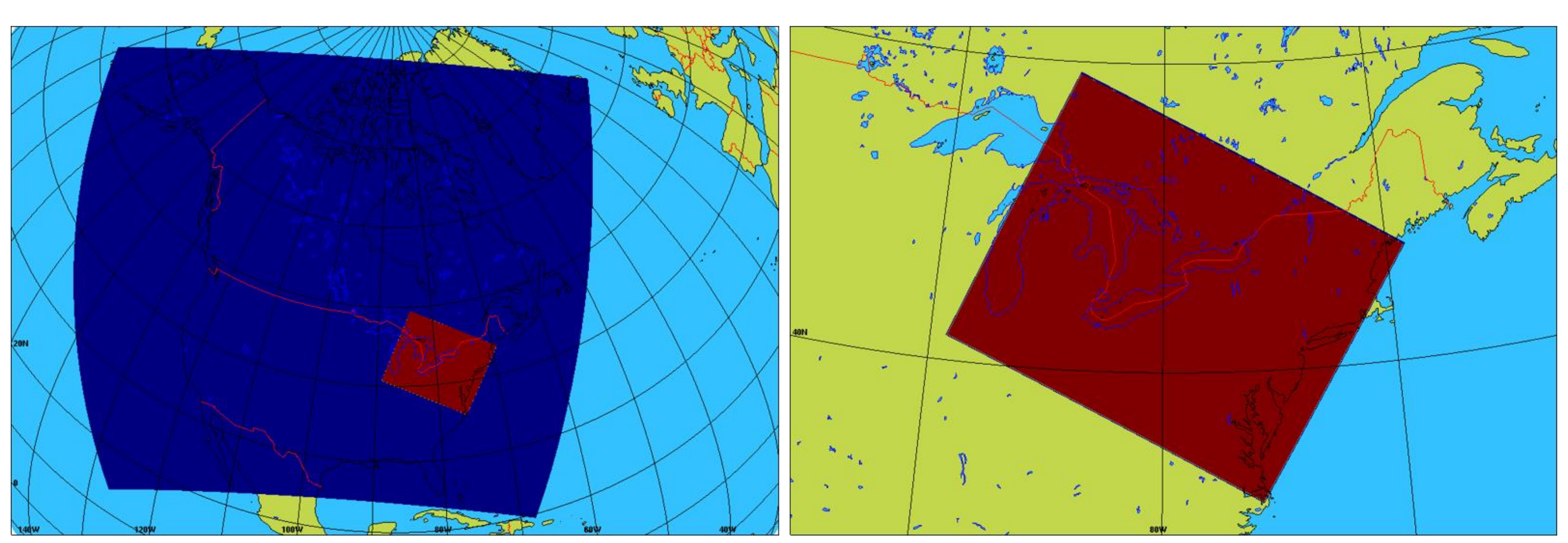


Figure 1: North American model domain with 10 km horizontal grid spacing (Blue), and the nested "Pan Am" model domain with 2.5 km horizontal grid spacing (red).

OCO-2/3 MEASUREMENTS

- NASA's Orbiting Carbon Observatiory-3 (OCO-3) has been on board International Space Station (ISS) since May 2019
- OCO-3 collects solar spectra in four modes: nadir, glint, target and SAM (Snapshot Area Map)
- In SAM mode, OCO-3 can measure XCO_2 (the column-averaged carbon dioxide dry-air mole fraction) from large contiguous areas (approximately 80x80 km) over a time span of two minutes (Eldering et. al. 2019)
- OCO-2 target mode has been designed to provide the primary dataset for validation of XCO_2 data
- In target mode, OCO-2 overlapping swaths covers an area of approximately 20x20 km (Crisp et. al. 2017)
- In this study we use v10 product of OCO-3 SAM and OCO-2 target mode observations of XCO_2 collected over Greater Toronto Area between April and November 2020 (some examples at Figures 2 and 3)
- The data are publicly available through the NASA Goddard Earth Science Data and Information Services Center(GES DISC) for distribution and archiving (http://disc.sci.gsfc.nasa.gov/)

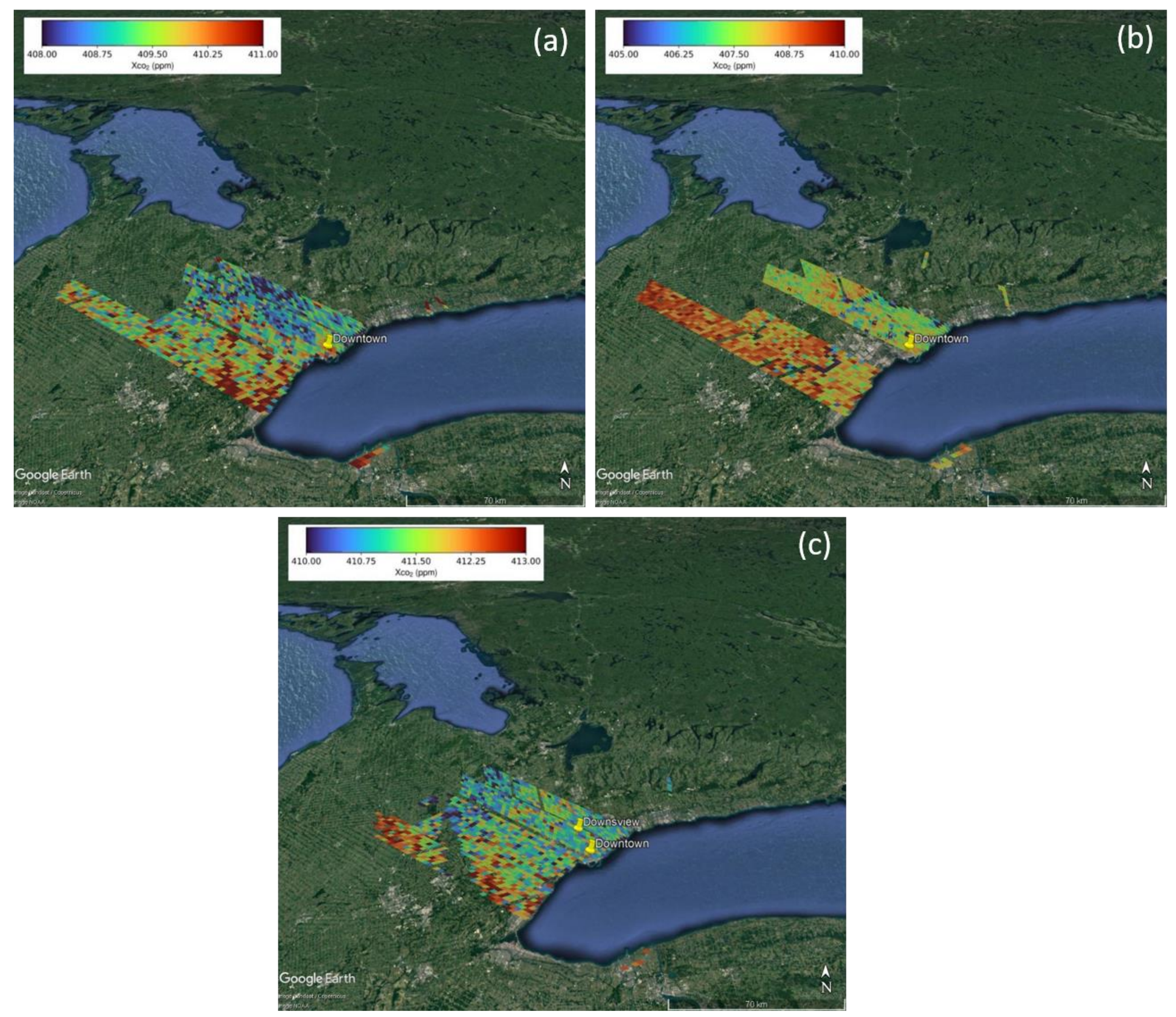


Figure 2: OCO-3 XCO_2 SAM measurements over Greater Toronto Area a) Jun. 26, 2020; b) Jun. 30, 2020; c) Jul. 4, 2020.

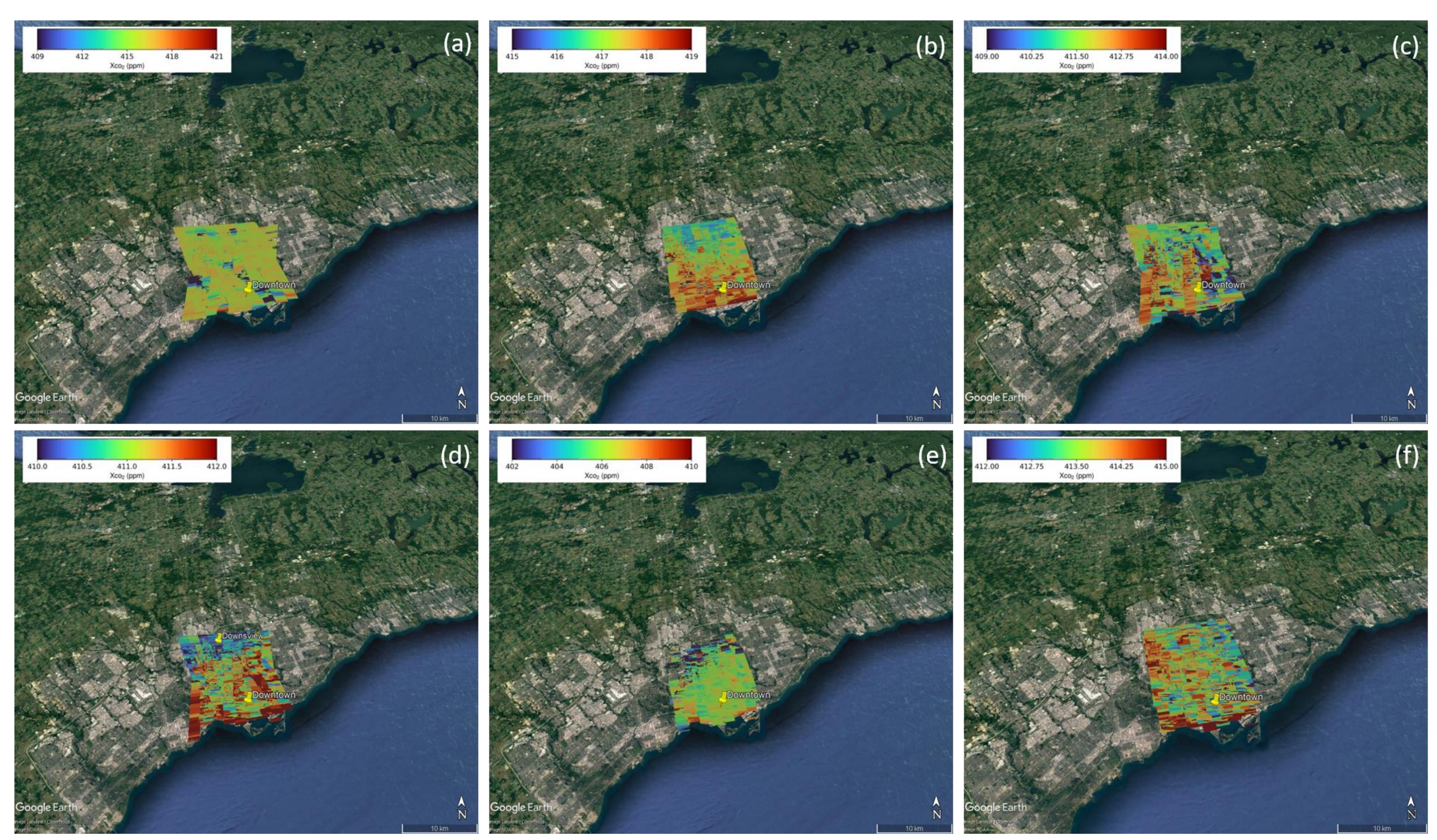


Figure 3: OCO-2 XCO_2 Target measurements over Greater Toronto Area. a) Apr. 22, 2020; b) May. 3, 2020; c) Jun. 18, 2020; d) Jul. 4, 2020; e) Aug. 7, 2020; f) Nov. 11, 2020.

RESULTS

- EM27/SUN is a portable FTIR spectrometer (Gisi et. al. 2012) widely used by COCCON (COllaborative Carbon Column Observing) Network to measure XCO_2 and XCH_4 (Frey et. al. 2019)
- Two EM27/SUN are located in two sites in GTA area; Downtown site at latitude 43.660 and longitude -79.399 and Downsview site at latitude 43.780 and longitude -79.468 (Figures 2c and 3d)
- EM27/SUN data within +/-30 minutes of the OCO-2/3 overpass time were taken into account
- We used OCO-2/3 XCO_2 soundings (v10) collected over GTA within +/-0.1 in latitude and longitude around the sites
- The median XCO_2 value for each OCO-2/3 overpass and co-located EM27/SUN was calculated (Figure 4)

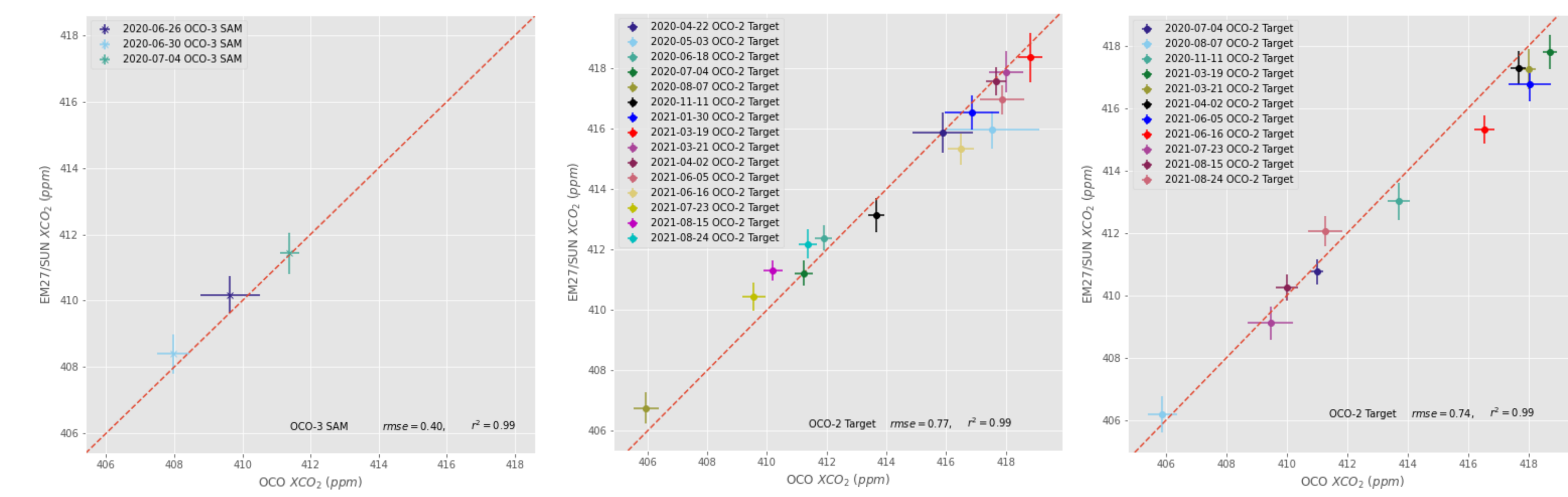
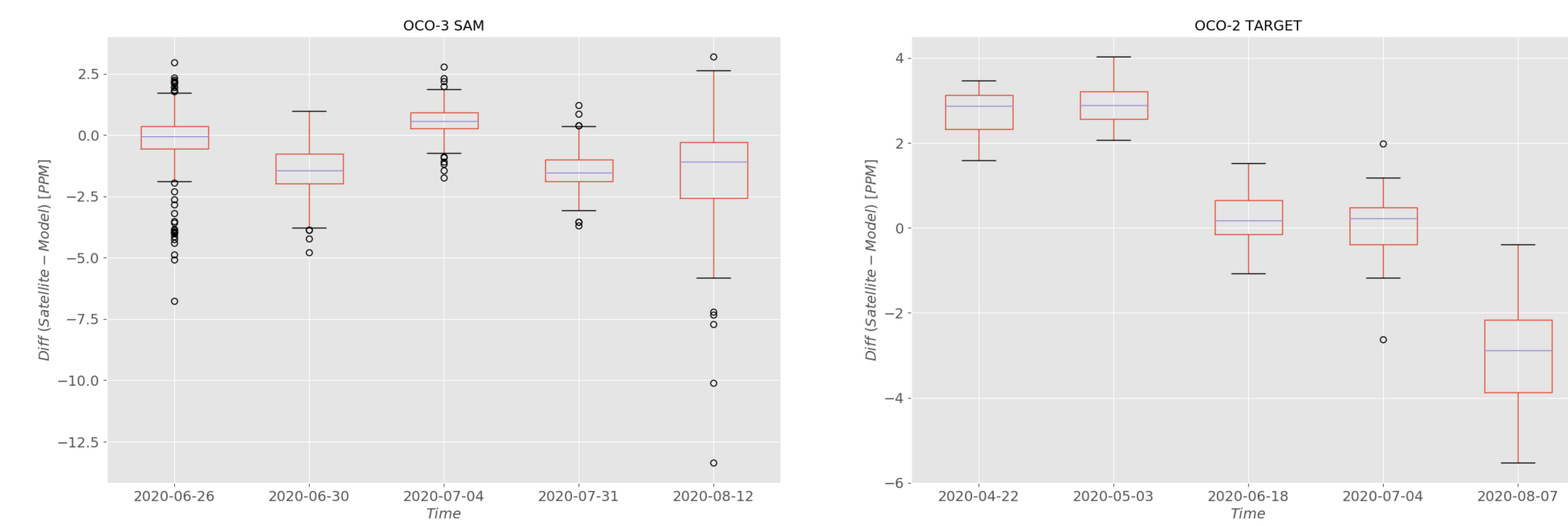


Figure 4: Relationship between the median XCO_2 values for OCO-2/3 and co-located EM27/SUN measurements (left: OCO-3 SAM vs Downtown site; middle: OCO-2 target vs Downtown site; right: OCO-2 target vs Downsview site. The dashed line represents the one-by-one line.



- GEM-MACH simulated XCO_2 mixing ratios were converted to dry air mixing ratios using model-simulated specific humidity
- OCO-2/3's pressure weighting functions (PWF) and averaging kernels (AK) were applied to the model data following Rodgers and Connor (2003) (Figure 5 top panels)
- GEM-MACH model values for afternoon hours (1 - 5 PM Toronto local time) were compared with EM27SUN measurements collected at Downtown site (Figure 5 bottom panel)

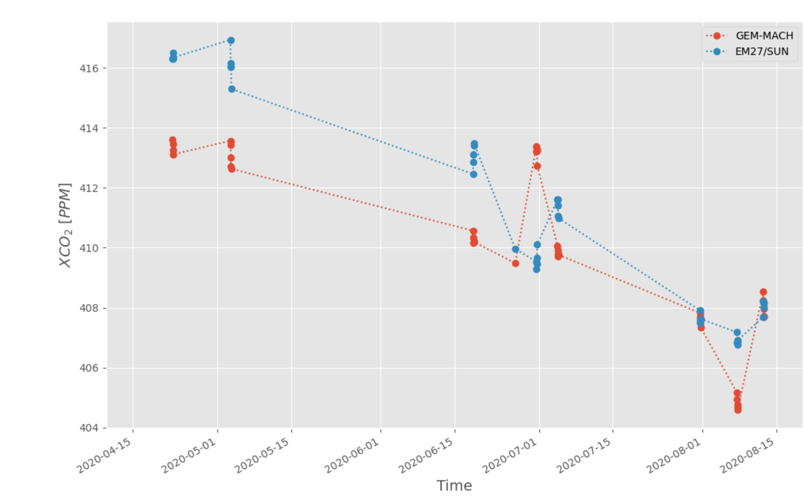


Fig. 5.: Top left: OCO-3 SAM vs. GEM-MACH model; Top right: OCO-2 Target vs. GEM-MACH model; Bottom right: EM27SUN vs. GEM-MACH model. In top panels the red box show first and third quartiles plus blue line as median. The whiskers show 2 standard deviation and the points are outliers.

SUMMARY & FUTURE WORK

- The OCO-2/3 XCO_2 values collected over GTA were compared with the EM27/SUN data and GEM-MACH model simulations
- The GEM-MACH-GHG model with 10 km horizontal resolution were run for selected dates with a 3-day spin-up to provide CO_2 boundary conditions and meteorological variables for nested domain with 2.5 km horizontal resolution
- CarbonTracker and ODIAC datasets were aggregated to the 2.5 km resolution model domain to be used as surface fluxes
- Biospheic CO_2 surface flux estimated from the Vegetation Photosynthesis & Respiration Model (VPRM) with 0.02x0.02 degree resolution generated by Gourdji (2021) are being processed to be used as area emissions instead of CarbonTracker fluxes with 1x1 degree resolution

REFERENCES

- Crisp, D., Pollock, H. R., Rosenberg, R., Chapsky, L., Lee, R. A., Oyafuso, F. A., ... & Wunch, D. (2017). The on-orbit performance of the Orbiting Carbon Observatory-2 (OCO-2) instrument and its radiometrically calibrated products. Atmospheric Measurement Techniques, 10(1), 59-81.
- Sharon Gourdji (2021), Biospheric CO2 surface flux estimates from the Vegetation Photosynthesis & Respiration Model (VPRM) in the eastern USA and Canada: November 2016 to December 2020, National Institute of Standards and Technology, https://doi.org/10.18434/mds2-2382 (Accessed 2022-07-07)