Physical and Environmental Factors Limiting the Measurement of Anthropogenic Carbon Dioxide Emissions from Space

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1. Introduction

Roughly 70% of the anthropogenic activities responsible for the release of fossil-fuel-based carbon dioxide ($FFCO_2$) are concentrated in cities. This abundant greenhouse gas (GHG) is a key driver of climate change, and several policies exist to address such emissions. Within the past decade, NASA's space-based Orbiting Carbon Observatory instruments (OCO-2 and -3) have made high-resolution observations of column-averaged CO_2 concentrations on a near-global scale. These observations are routinely used to constrain regional and local/urban emissions from cities around the world. Additionally, the United States has released a national strategy to advance an integrated Greenhouse Gas Measuring, Monitoring, and Information System (GHGMMIS) with a focus to "improve atmospheric-based GHG quantification approaches". While several studies have demonstrated OCO-2 and -3's ability to constrain emissions at a variety of scales, a notable result is the that of Byrne et al. (2022). Using aggregated soundings from OCO-2 spanning 2015-2020, Byrne et al. derived national net CO_2 emission contributions from 100+ countries around the world (**Fig. 1**); however, close inspection of the aggregated observations over the United States reveals a gradient in observation density: the western U.S. is more densely sampled than the eastern U.S. Not only could such a gradient bias national emission estimates to be more reflective of the western U.S. but the quality of high-resolution city-level constraints within the U.S. could vary as well. The work presented here investigates and quantifies the causes of such a gradient with a particular focus on urban/local implications.

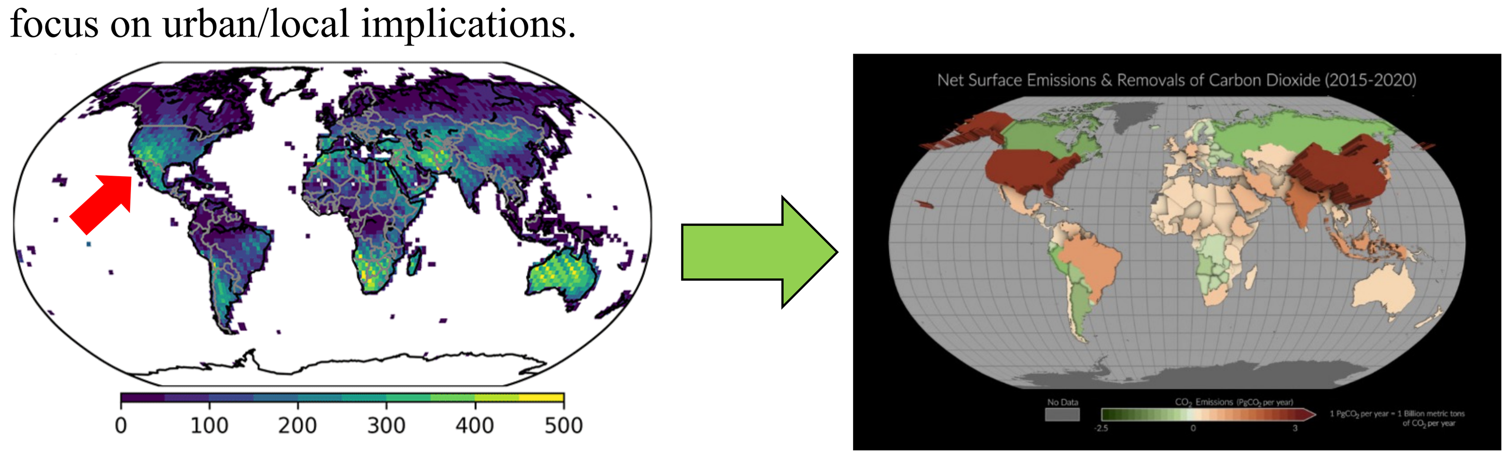

Figure 1: (Left) The number of aggregated OCO-2 soundings from 2015-2020 used by Byrne et al., 2022. [fig. modified from paper]. The spatial distribution over CONUS is indicated by the red arrow. **(Right)** Resulting national emission totals for countries around the world [fig. from NASA's Scientific Visualization Studio].

3. Instrument-Specific Features

The sun-synchronous orbit of OCO-2 provides "uneven" coverage over the United States. At the high resolution shown in **Fig. 4**, consistent bands appear over the region. When considering the cities identified as OCO-3 SAM targets, it becomes clear that not all cities fall under a high-density observation band. This on-/off-track feature could also explain the saw-tooth pattern in **Fig. 3**. Furthermore, the orbit of the ISS not only affects the spatial coverage of OCO-3 but its ERT also. ERT in odd-numbered months is double the ERT of even-numbered months.

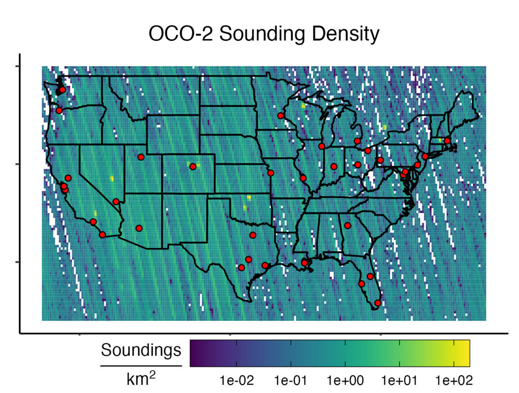

Figure 4: Averaged OCO-2 sounding density over CONUS. Target OCO-3 cities are indicated in red.

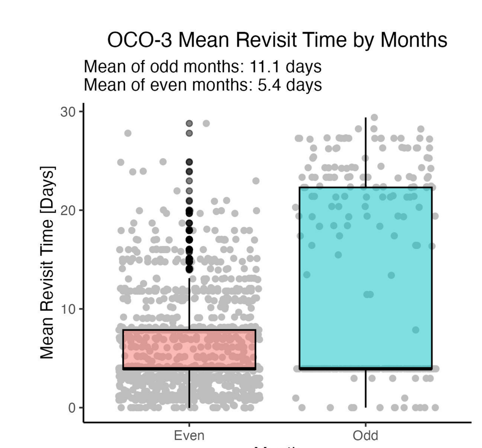

Figure 5: OCO-3 ERTs grouped by odd-/even-numbered months.

4. Physical/Environmental Features

This work also considers four physical/environmental factors influencing OCO-2 and -3's ability to collect observations over urban areas: urban cloud cover, annual precipitation, aerosol optical depth (AOD), and isoprene concentration. The distributions of these influences are presented in **Fig. 6**. Vo et al. (2023) developed a method to estimate a city's effect on cloud cover, reporting local enhancements for many cities throughout the United States. Additionally, estimates of total regional annual precipitation were aggregated for their work. Using their dataset with ERTs revealed no statistically significant correlation between local urban cloud cover (**Fig. 7, col. 1**); however, the relationship between regional background precipitation and revisit time was significant when considering the OCO-2 instrument (**Fig. 7, col. 2**). Using data from MERRA-2, the relationship between ERT and aerosol optical depth (AOD) was explored. Regressions demonstrate that AOD is a statistically significant factor for both instruments (**Fig. 7, col. 3**). Although isoprene concentrations are, on average, higher in the southeastern United States, there was only a statistically significant relationship when considering OCO-2 (**Fig. 7, col. 4**).

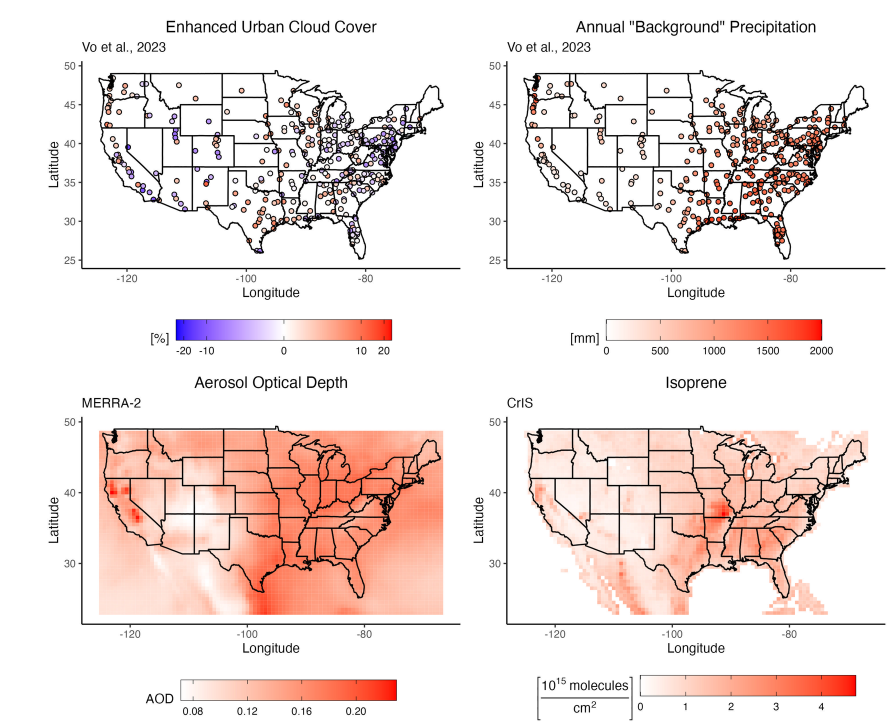

Figure 6: The spatial distributions of environmental factors potentially influencing OCO-2 and -3's ERTs are presented here.

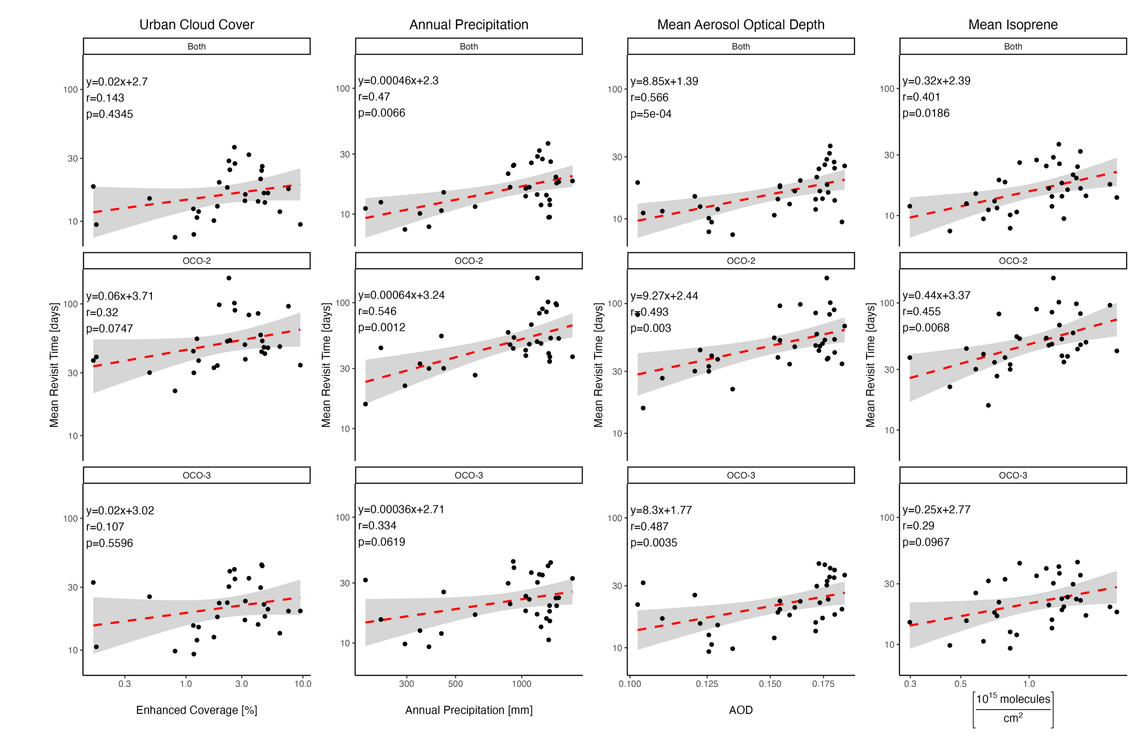

Figure 7: Relationships between each instrument's ERT and environmental factors are presented here.

2. OCO-2,3 Revisit Times

Considering U.S. cities identified as OCO-3 targets and investigating their coincident "good quality" transects from the OCO-2,3 instruments, spatial distributions similar to Byrne et al. (2023) were revealed. Both OCO-2 and OCO-3 appear to "favor" the West Coast of the U.S. although the trend is not as striking in the OCO-2 distributions (**Fig. 2, red**). Regarding OCO-3, not only are West Coast cities better sampled, the orbit of the ISS "favors" even-numbered months (**Fig. 2, blue**); however, such an orbital pattern is expected (Eldering et al., 2019). Ideally, the time between such transects ("revisit time") must be *minimized* so that the number of observations over each target city can be *maximized*. **Fig. 3 (top)** presents the average *effective* revisit time (ERT; time between successful observations) for each city and demonstrates a longitudinal dependence. While all instrument-specific (and combined) ERTs increase significantly (**Fig. 3, bottom**), OCO-2 is more susceptible to east-west features.

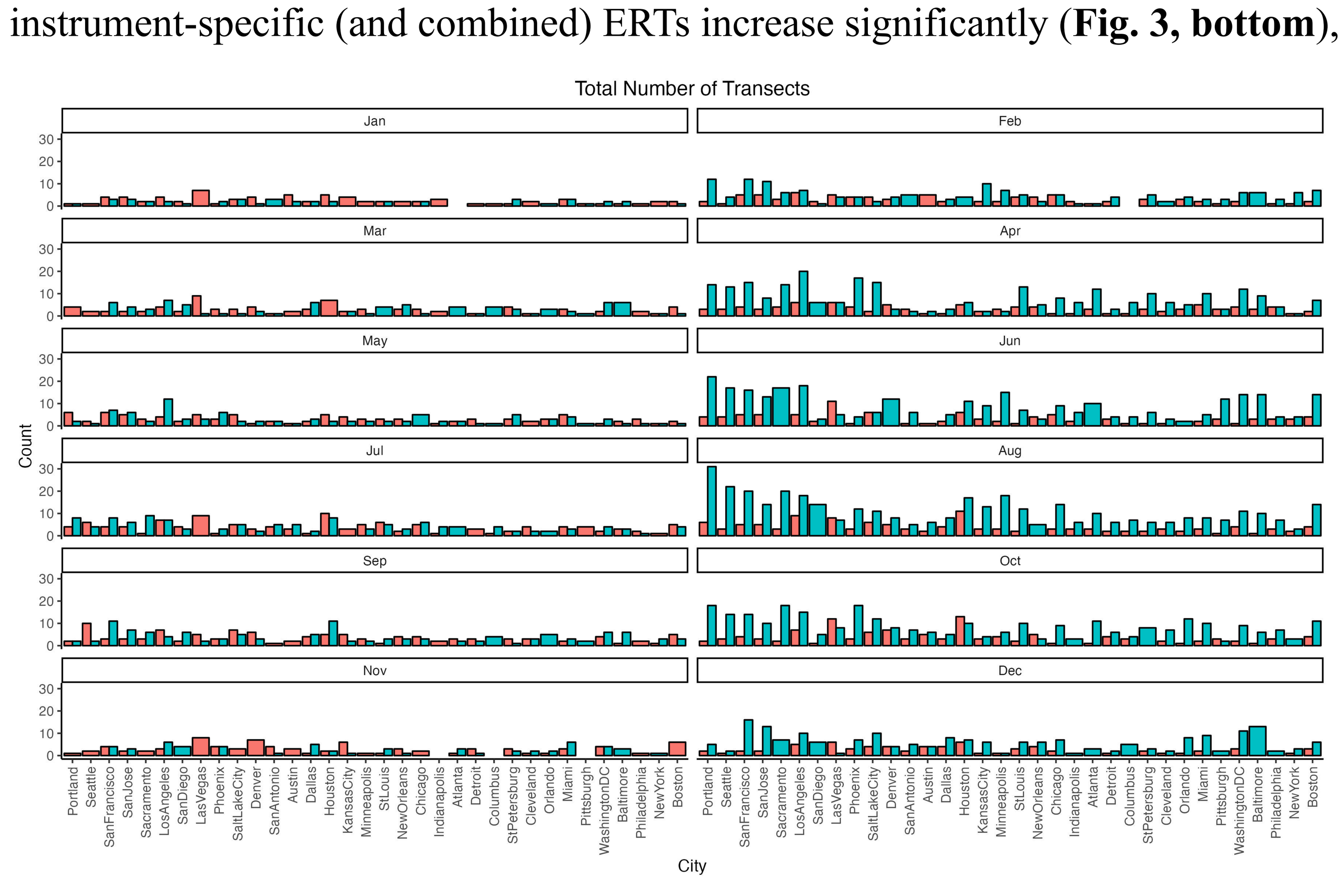

Figure 2: The total number of transects from the OCO-2 and -3 instruments are recorded here, disaggregated by month. Cities are arranged by their west-to-east longitudes.

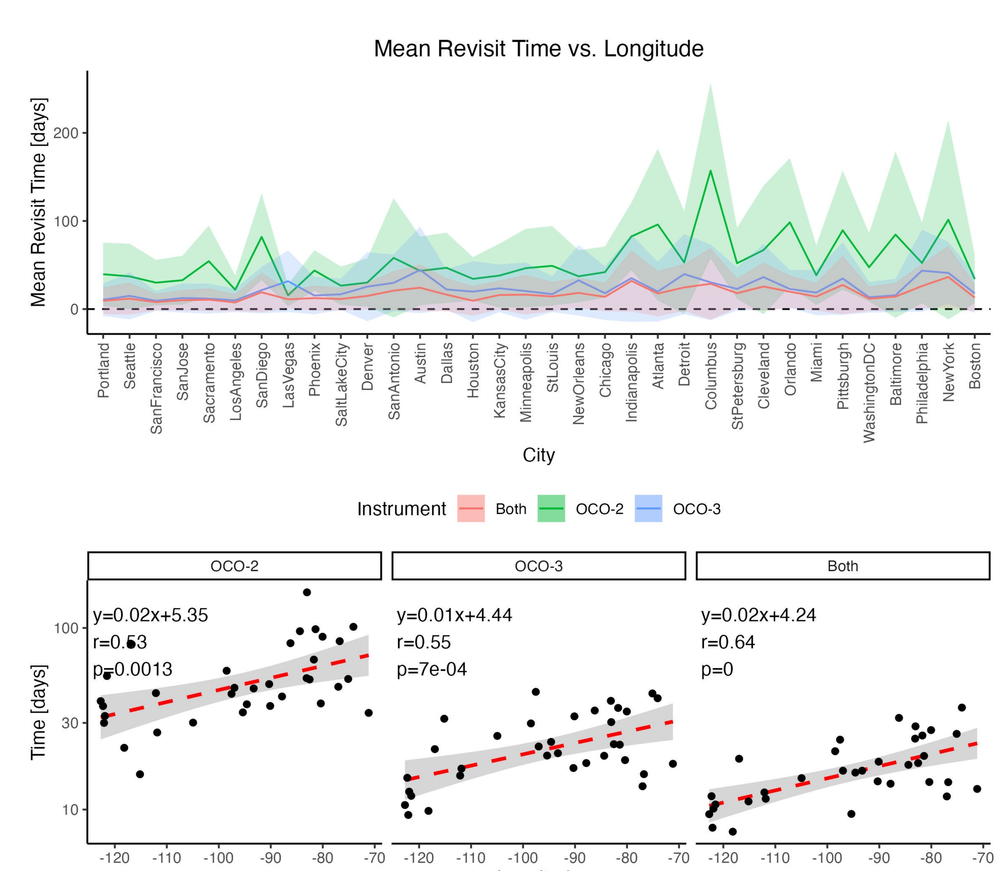

Figure 3: (Top) The mean effective revisit times for a collection of U.S. cities is shown, determined for OCO-2 and -3. **(Bottom)** Linear regressions for these revisit times are presented for each instrument.

5. Interpolating Coverage across CONUS

Presented in **Fig. 8** is a high-resolution estimate of "un-observed" CO_2 emissions across CONUS. A model was built using a multilinear regression to predict the mean ERT (from using *both* instruments) at each *(x,y)* location (**Tab. 1**). Flux estimates from the Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC) were multiplied by estimated revisit times to calculate the amount of CO_2 emitted between instrument revisits. Results in the figure are relative to annual emissions, revealing that the eastern half of the U.S. is more difficult to constrain at a sub-annual scale. The model was then applied to emissions at a seasonal scale (**Fig. 9**), using corresponding seasonal data from the environmental factors under consideration. Results demonstrated that certain times of the year are more conducive to local/urban observations than others. Autumn and winter months are less influenced by annual precipitation and AOD.

Table 1: The linear model used to predict the revisit time of the OCO-2,3 system. This model was driven by annual precipitation amounts (precip) and AOD.

Multilinear Regression

$$\ln(y_{\mathrm{ERT}}) = \alpha x_{\mathrm{precip}} + \beta x_{\mathrm{AOD}}$$

$\alpha \approx 9.22 \times 10^{-5}\ \mathrm{mm}^{-1}$

$\beta \approx 9.73$

$R^2 \approx 0.4$

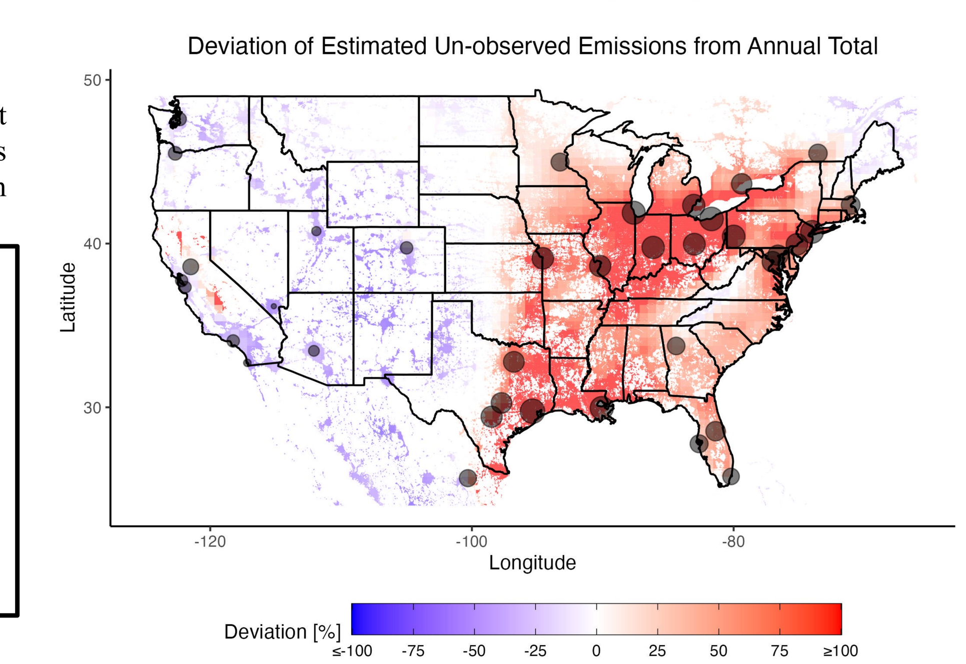

Figure 8: A spatial estimate of "un-observed" CO_2 emissions across CONUS relative to annual estimates.

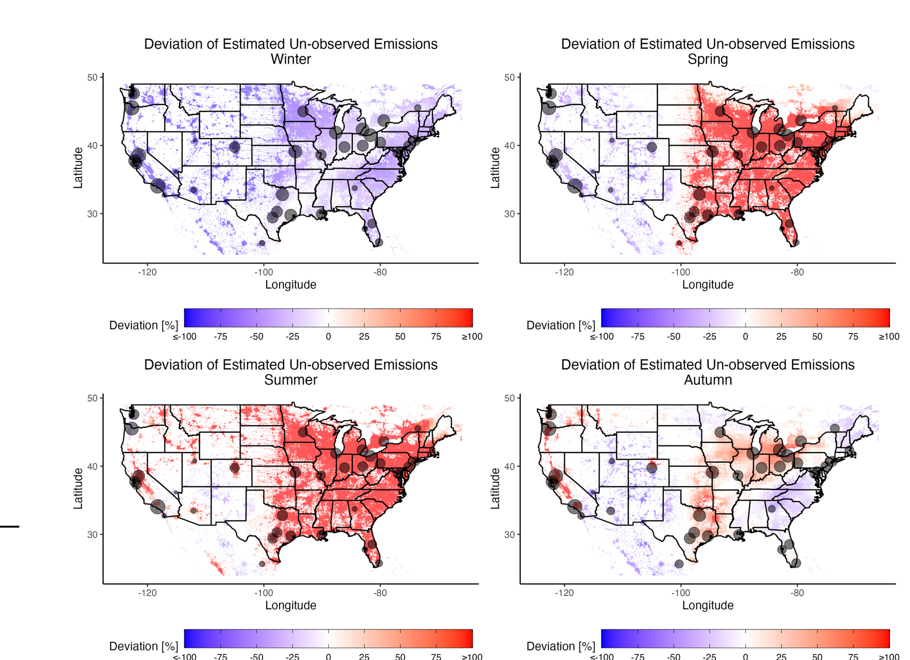

Figure 9: A spatial estimate of "un-observed" CO_2 emissions across CONUS relative to seasonal estimates.

6. Conclusions

Results from this work demonstrate that, while the OCO-2 and -3 instruments are flagship CO_2–observing platforms, they are limited by their characteristics. The sun-synchronous orbit of OCO-2 is most effective at constraining emissions from "on-track" cities while OCO-3 is most effective in even-numbered months. Such characteristics have implications for local/urban studies and seasonally resolved regional studies. Additionally, regional environmental factors such as cloud cover and AOD influence revisit times considerably. During the autumn and winter months, effective revisit times are considerably decreased, potentially allowing emissions to be constrained at a sub-annual scale; however, summer months prove to be difficult. Such biases have the potential to influence observation-driven estimates of total CO_2 emissions and should be considered in discussions regarding uncertainty; however, many biases could be addressed by future space-based missions that implement a geo-synchronous platform, drastically increasing revisit times and increasing the likelihood of sub-annual observations.

References:
https://www.zotero.org/groups/5538323/iwggms20_ert