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First quantification of atmospheric carbon dioxide from the Geostationary Operational Environmental Satellite (GOES East)

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A Complementary Tool for Carbon Monitoring: Fusing Geostationary Data with ML

The Opportunity: Leveraging Existing Assets for Deeper Carbon Cycle Insights

- **Dedicated Missions Provide Precision:**
  - Missions like OCO-2, OCO-3, GOSAT, GOSAT-2 and upcoming platforms (e.g., GOSAT-GW, CO2M, MicroCarb) provide high-precision gold standard CO2 measurements.
  - Low earth orbit leads to infrequent revisits
- **GOES High Temporal and Spatial Coverage:**
  - GOES provides continuous, full-disk coverage of the Americas every 10-15 minutes at a 2 km resolution.
  - This represents a vast, underutilized dataset spanning multiple years, containing information about the atmosphere and surface at scales.

Why is This Valuable?

- **Clouds:**
  - Cloud cover is a major obstacle for all passive remote sensing missions.
  - GOES's **frequent revisits increase opportunities for getting clear-sky observations**, allowing us to fill in critical data gaps.
- **Capturing the Diurnal Cycle:**
  - Biospheric fluxes and anthropogenic emissions have strong diurnal cycles.
  - GOES can provide **observations throughout the day**, offering a new window into these crucial patterns.
- **Monitoring Transport and Local Enhancements:**
  - Improve our **understanding of source-sink dynamics** by **complementing high-precision measurements** from OCO-2/3, GOSAT, GOSAT-2 with **continuous spatial/temporal context**.

XCO_2 measurements are sparse in space and time

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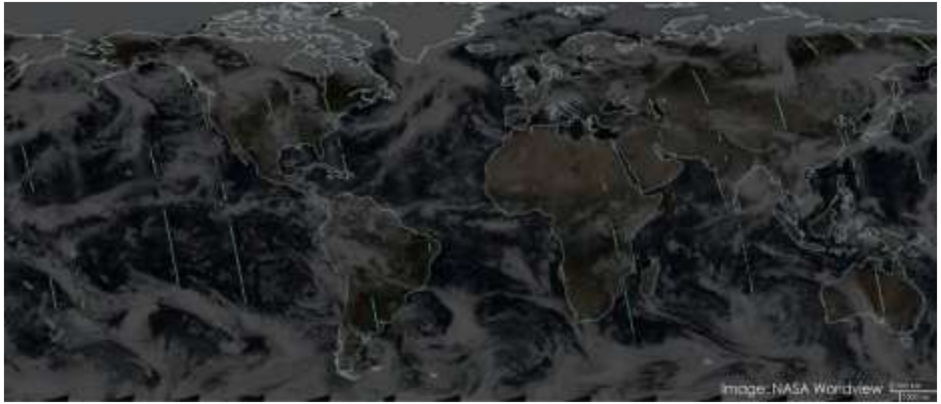

OCO-2 measurements May, 24 2021, NASA

GOES East

- OCO-2, OCO-3, GOSAT, GOSAT-2 are the gold standard in XCO2 measurement
- Sparse observations yield high uncertainty
- Complementary measurements might help bring uncertainty down

- Geostationary
- Used for weather forecasting
- 16 bands (**low spectral res.**)
- High coverage
- High frequency (10 mins)

GOES + surface reflectance + weather + machine learning can help extract knowledge from existing observations that traditional retrieval algorithms might find challenging

Images: OCO-2: NASA's Applied Remote Sensing Training Program, GOES East: NOAA

GOES East Bands Inform XCO_2 concentration

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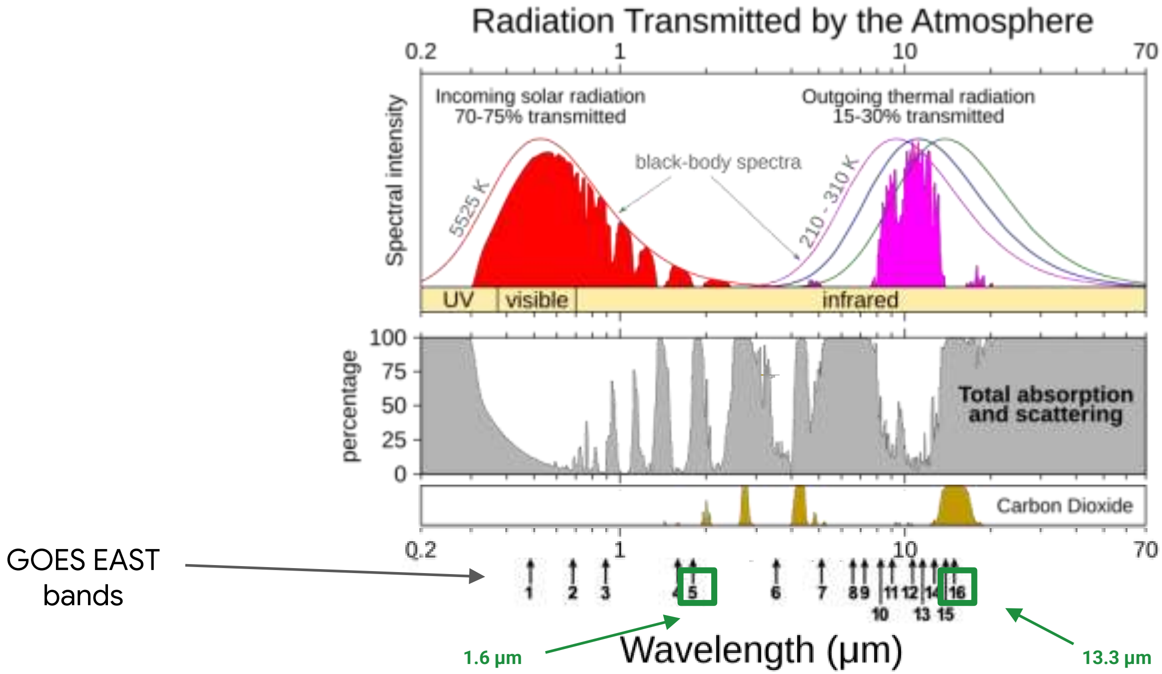


Wikimedia: Atmospheric Transmission-en.svg
NOAA: The Atmospheric Window,

Some GOES bands are in the spectrum where there's sensitivity to CO_2 in the mid and lower troposphere

Why is CO_2 Hard to See with GOES?

Low Spectral Resolution

1. Seeing CO_2: Sharp vs. Blurry View

OCO-2/3 were designed for XCO_2 estimation: *High-definition camera*

- **Sharp Vision:** Uses *1024 narrow* spectral channels (high resolution).
- **Result:** Clearly sees CO_2's unique fingerprint.

GOES ABI (meant for Weather): *90s disposable camera*

- **Broad Vision:** Uses *few wide* spectral bands (low resolution).
- **Result:** CO_2's subtle signal is blurred with other signals.

Why is CO_2 Hard to See with GOES?

Biased observations

2. What Else GOES Sees: The biases obscuring CO_2 signature

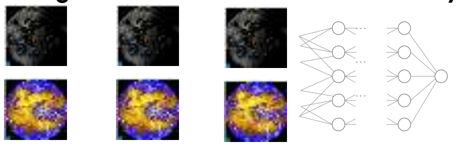
a) Surface reflectance
b) Aerosols
c) Subpixel clouds
d) Temperature, humidity
e) CO_2

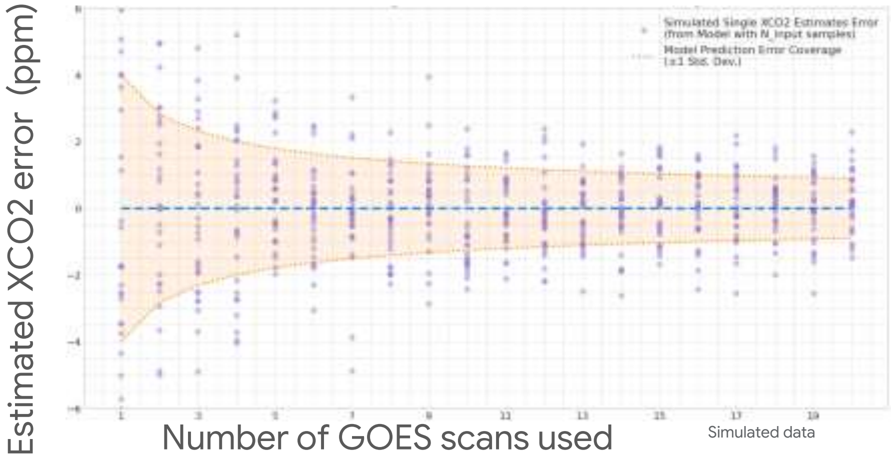
GOES wasn't built for CO_2 tracking. Its broad view mixes the faint CO_2 signal with much *louder* environmental noise.

Why is CO2 Hard to See with GOES?

Low Spectral Resolution

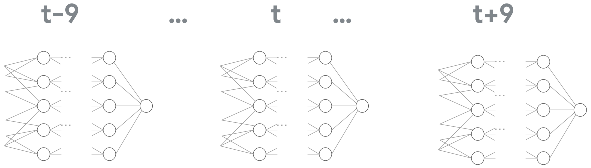
More GOES input data yields better single XCO2 estimates: Model Leverages Context to Reduce Uncertainty

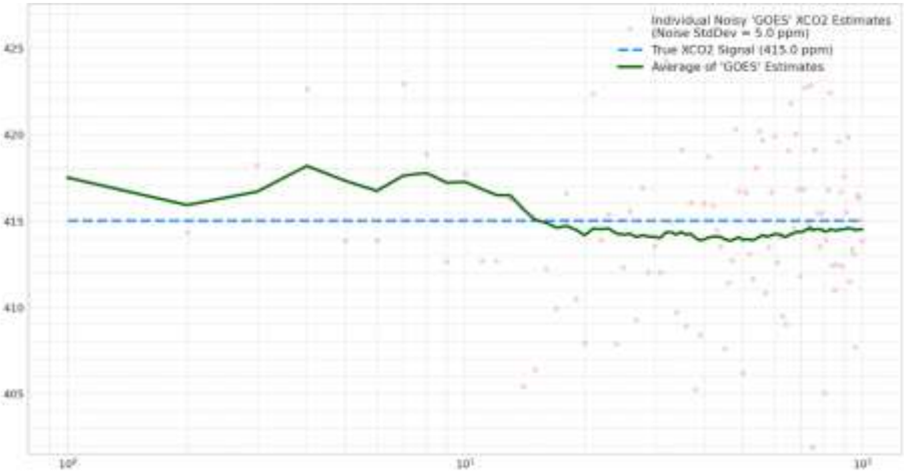




Simulated data

Averaging GOES Predictions over space and/or time helps beat down the noise





Number of XCO2 Estimates

Simulated data

The Law of Large Numbers drives down the noise for both the model and the XCO2 predictions

GOES East images from NOAA

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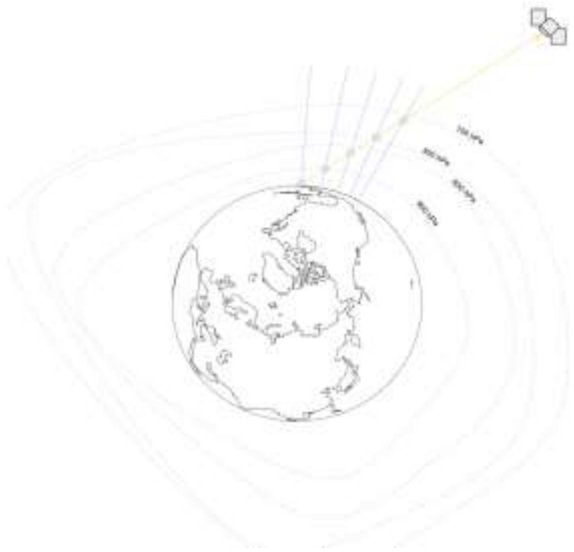
Why is CO2 Hard to See with GOES?

Biased observations

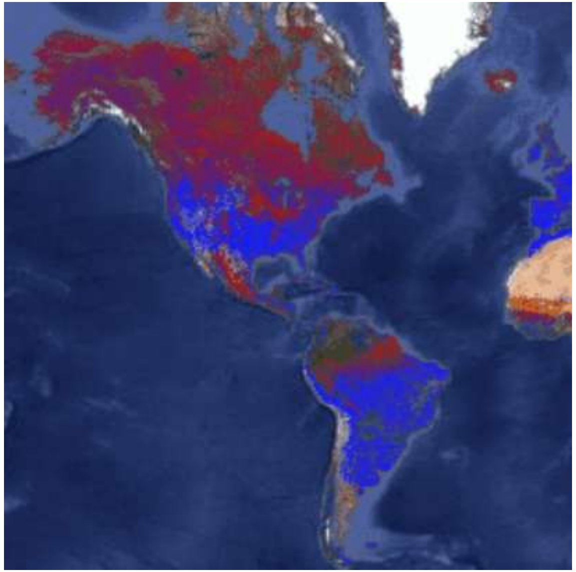
2. What Else GOES Sees: The biases obscuring CO2 signature

GOES wasn't built for CO2 tracking. Its broad view mixes the faint CO2 signal with much louder environmental noise.

ECMWF's ERA5 Weather State along radiative path



MODIS Surface Reflectance



Google Earth Engine Modis Image

Surface reflectance and weather features help the model disentangle the CO2 signal

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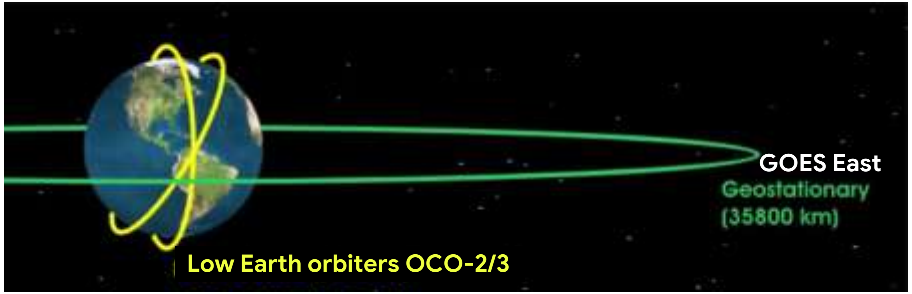
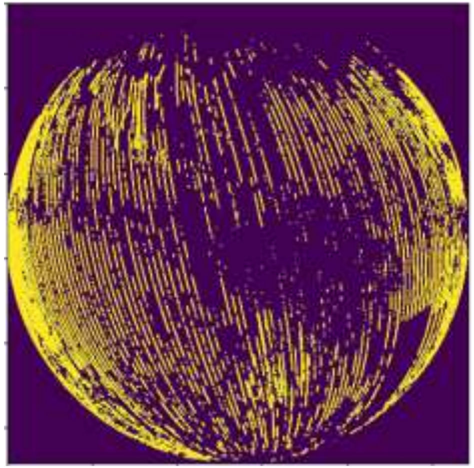
GOES East <-> OCO-2 & OCO-3 collocation



Adapted from Penn State, Meteorology and Atmospheric Science

- OCO-2,3 and GOES East have similar (~2km) footprint
- Collocated pixels within a 10 minute, ~2km window, nadir-mode
- Viewing angle cosine similarity < 70°
- GOES East sub-satellite point distance thresholding



Monthly GOES East <-> OCO-2 collocated 2023 footprints

Collocation yields ~10M OCO-2,3 soundings "*pixels*" from 2017-2021

Training & Testing the Model

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Training Set (~5M)

2017	2018	2019	2020	2021

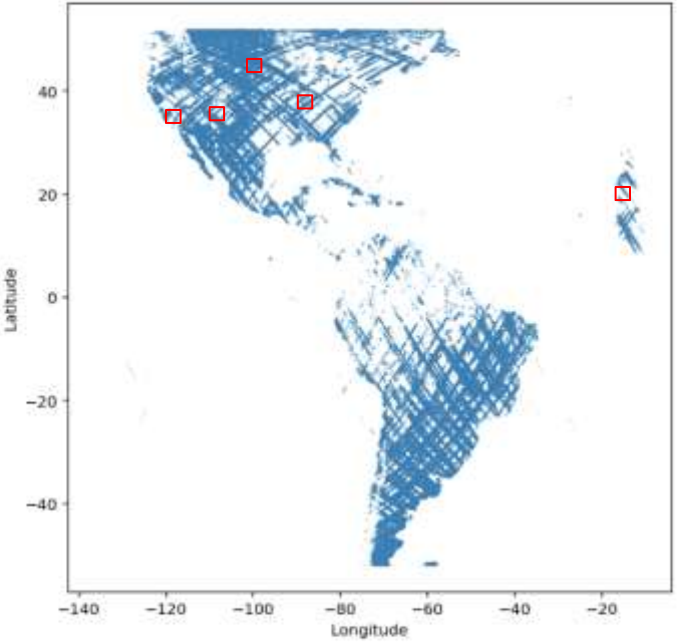
Test set (1M)

TCCON Data Archive

TCCON within GOES East perspective on 2021

Test Set:
OCO-2,3 2021 soundings
&
TCCON Stations in N. America

Latitude



Longitude

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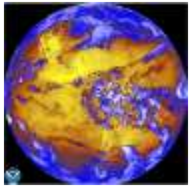
Neural Network Model

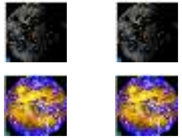
t

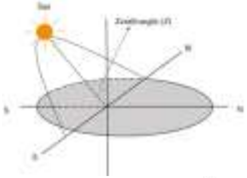
Ch. 5 (Snow/Ice band): 1.6 μm

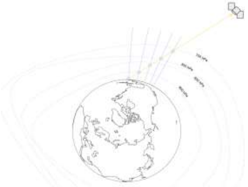


Ch. 16 (CO_2 band): 13.3 μm

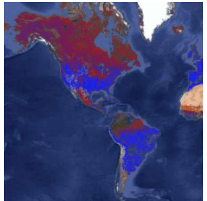
t-9, … , t-1

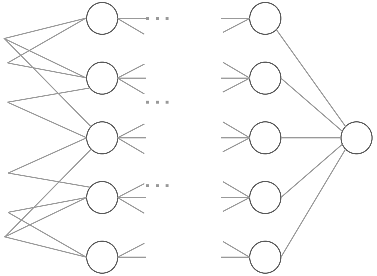




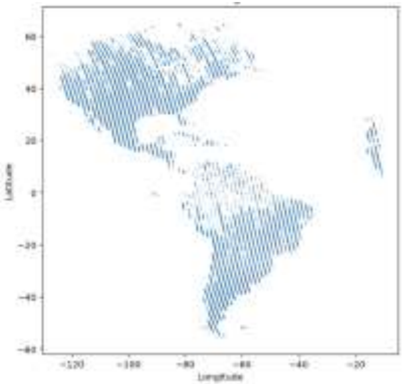


Atmospheric state along viewing angle

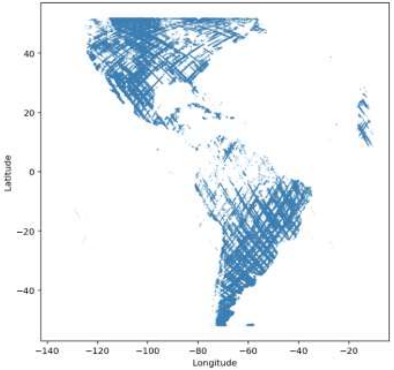




Labels: XCO_2 nadir-mode soundings



OCO-2



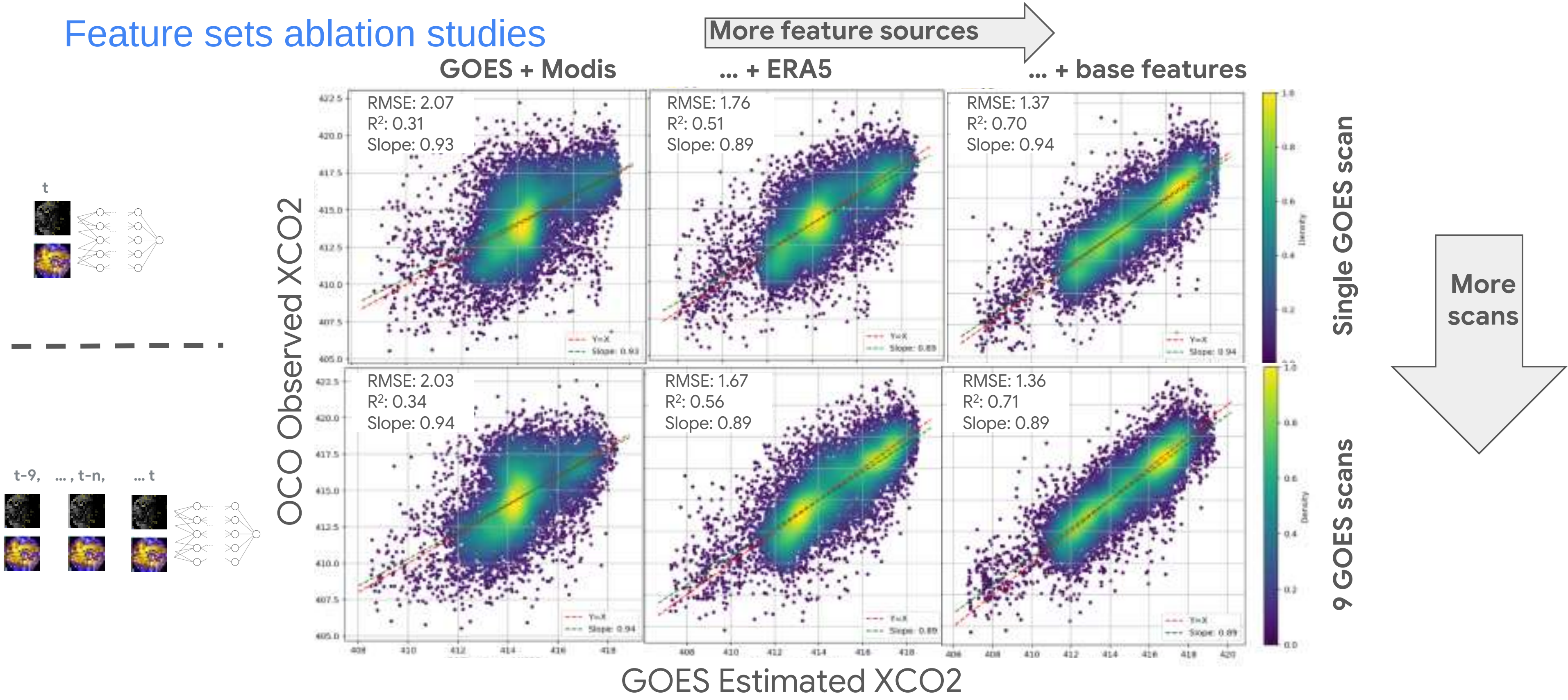
OCO-3

Train set: 10M soundings OCO-2,3 from 2019, 2020, 2022, 2023
Test set: OCO-2,3 + TCCON observations from 2021

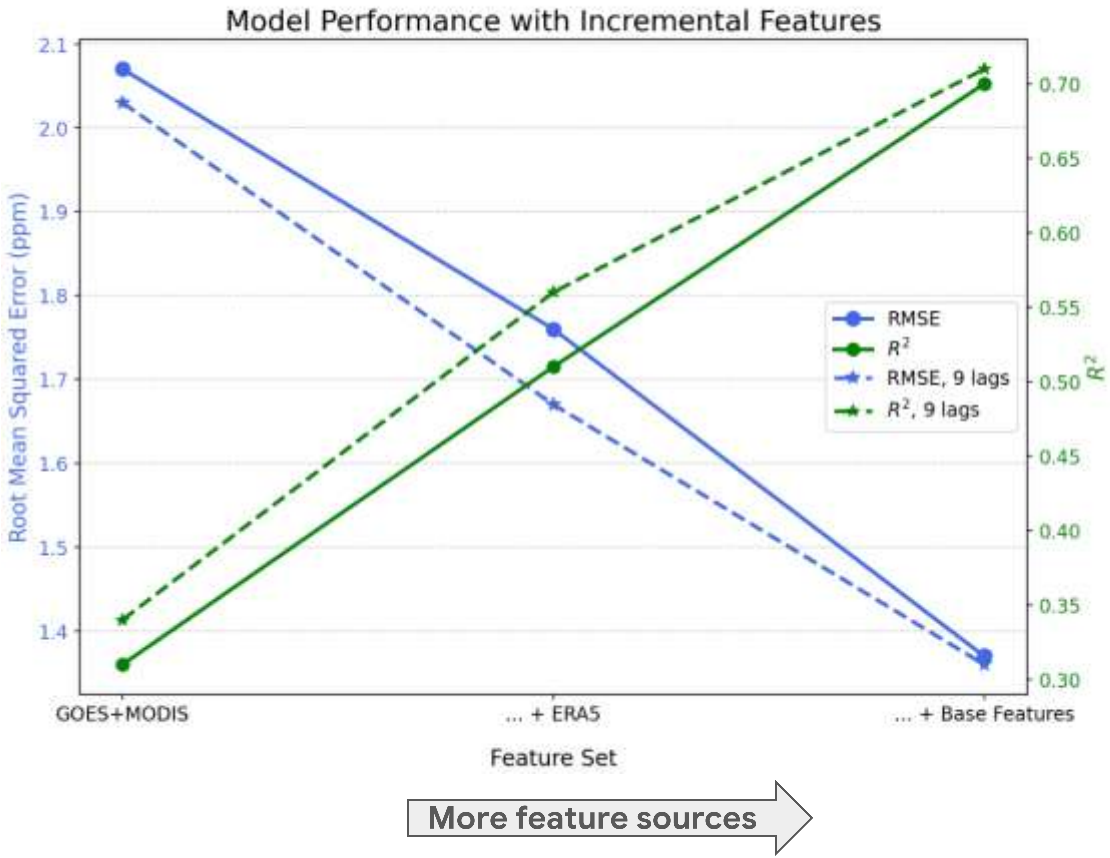
NASA's Applied Remote Sensing Training Program, GOES East, Chai et. al. 2022

Decreasing Bias & Noise with GOES Scans & Features

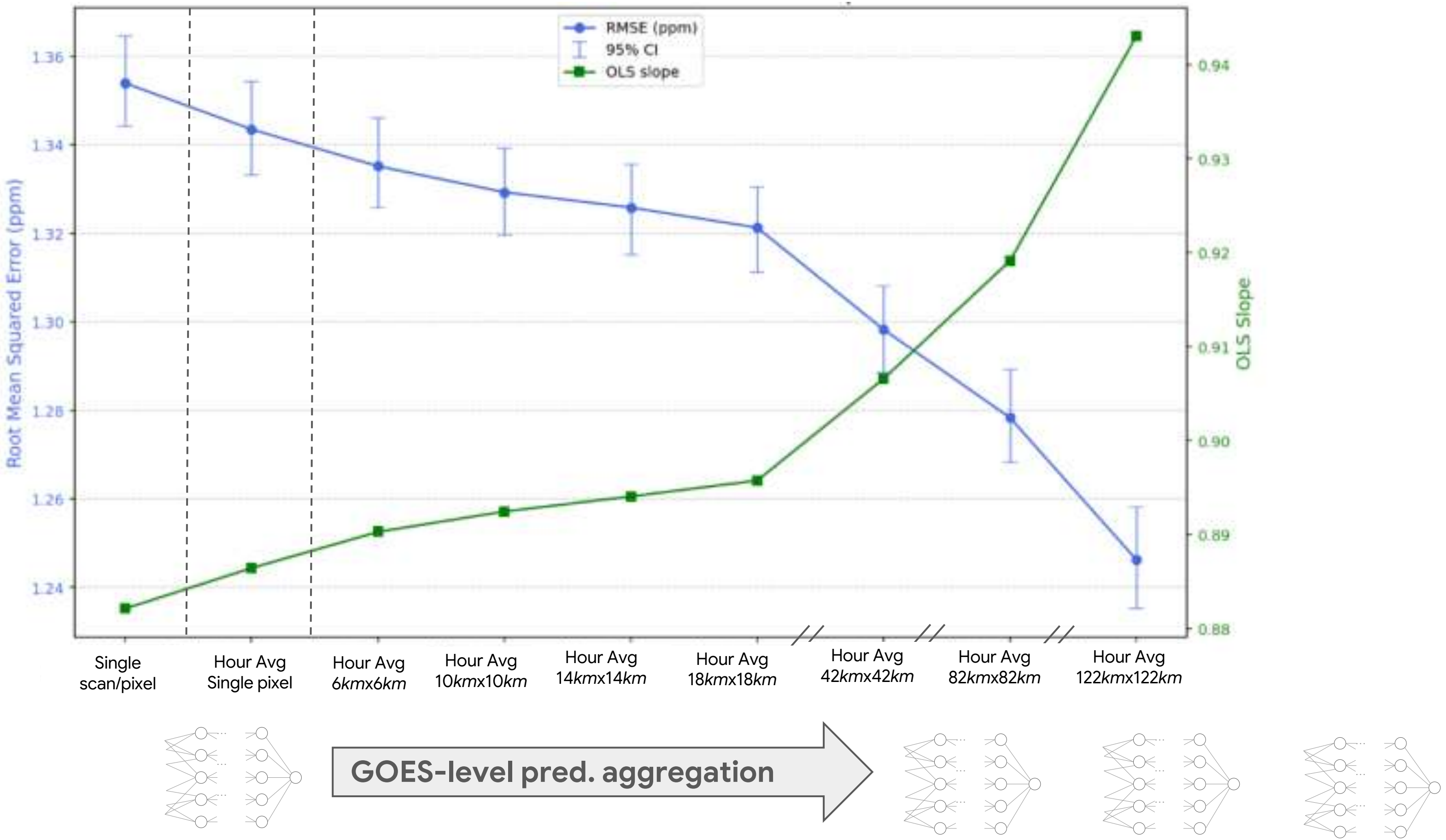
Feature sets ablation studies



Decreasing Bias & Noise with GOES Scans & Features



Decreasing Noise by Aggregating Predictions in Space/Time



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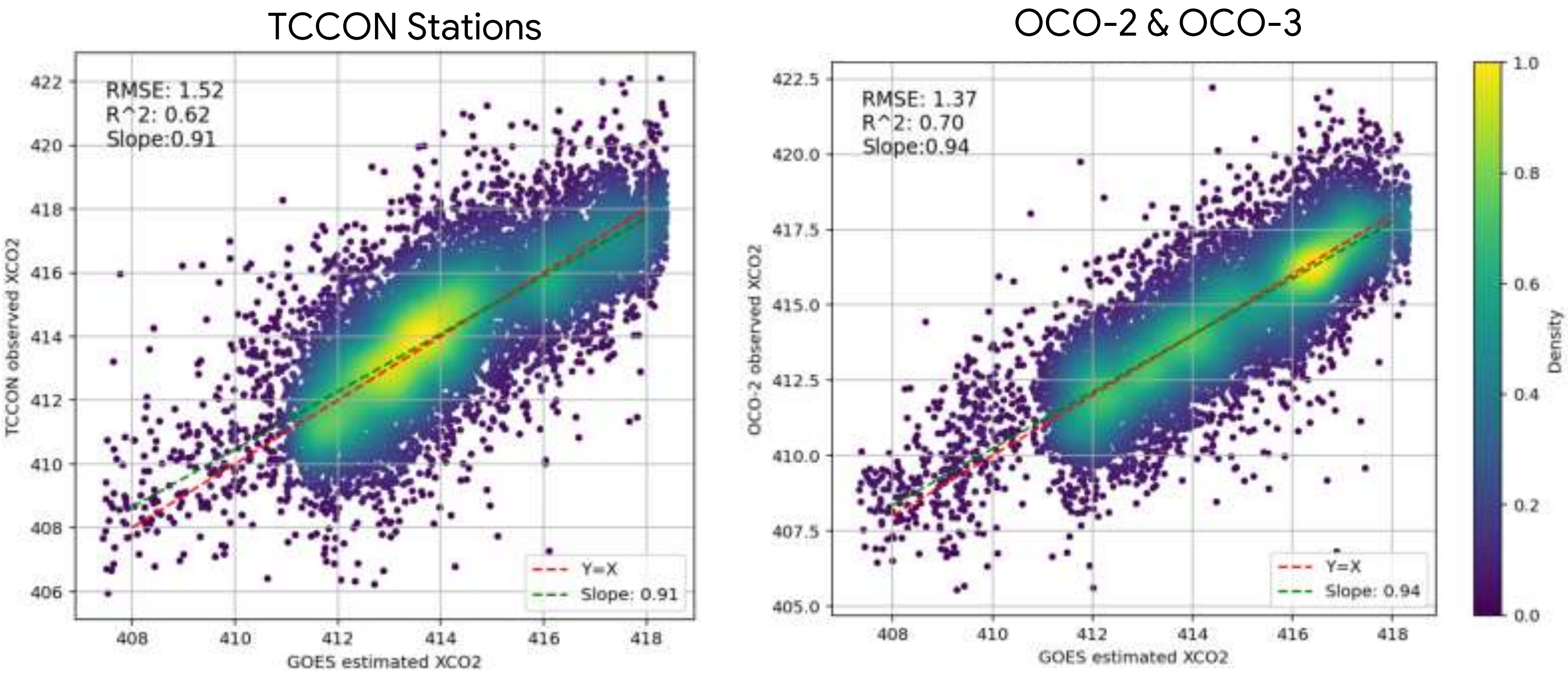
Model performance on TCCON & held-out OCO-2/3 observations



There is XCO_2 signal in the GOES Bands:
GOES predictions are within ~1.5 ppm from TCCON and OCO-2&3

Seasonal patterns in TCCON on 2021

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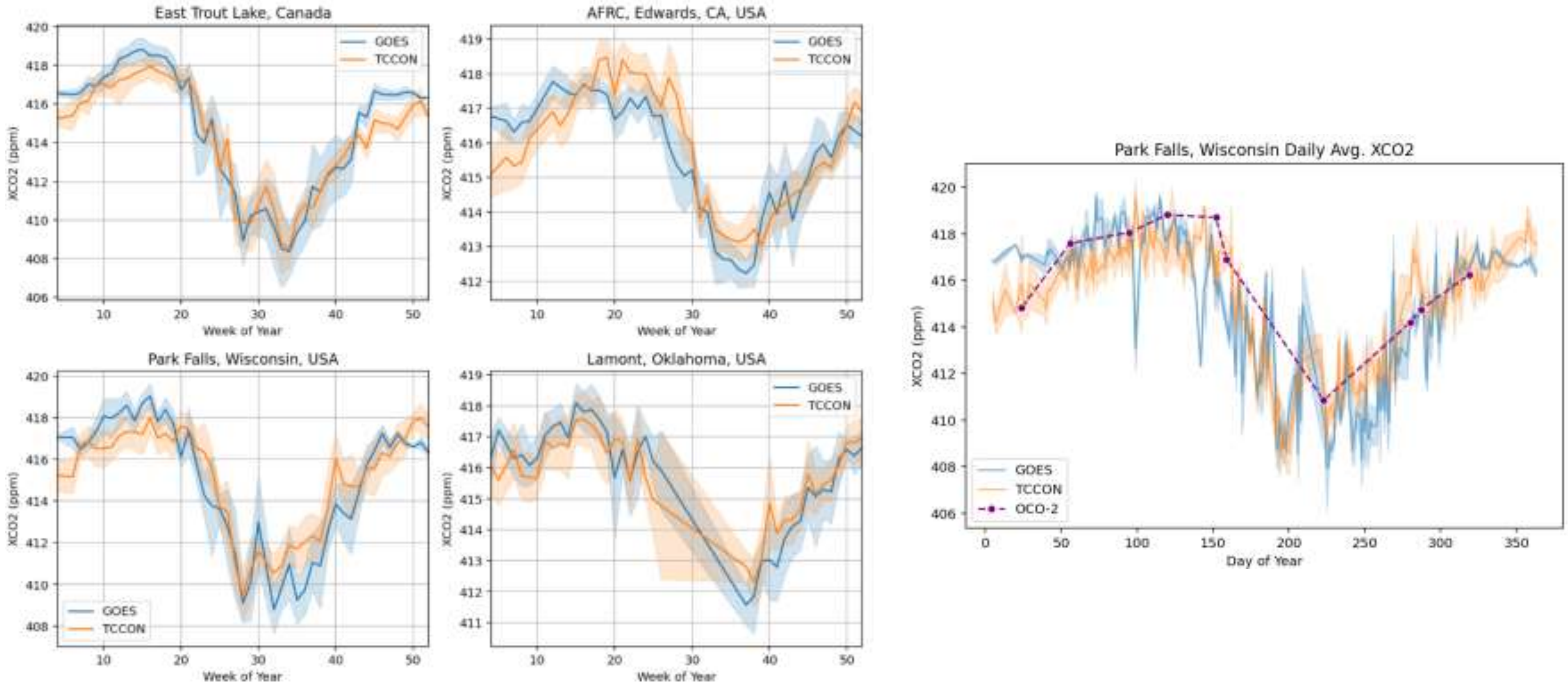
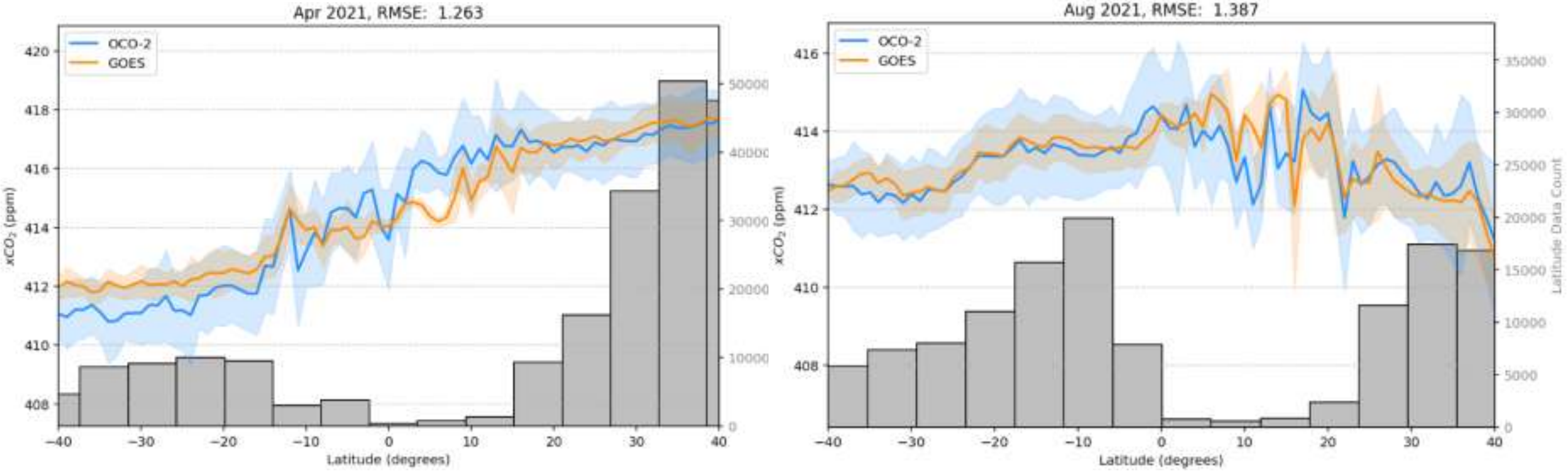


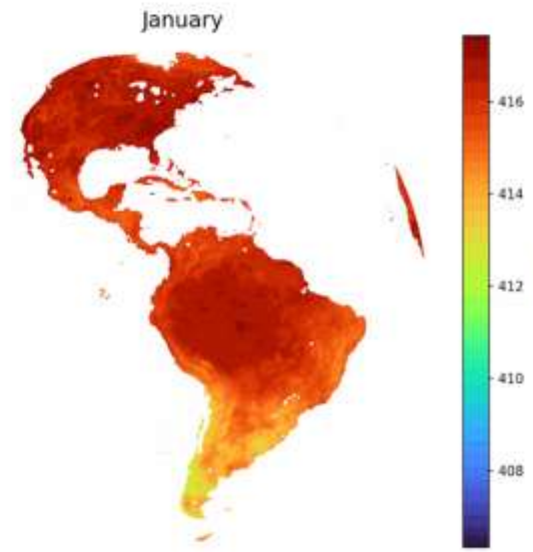
Seasonal patterns are captured by GOES model

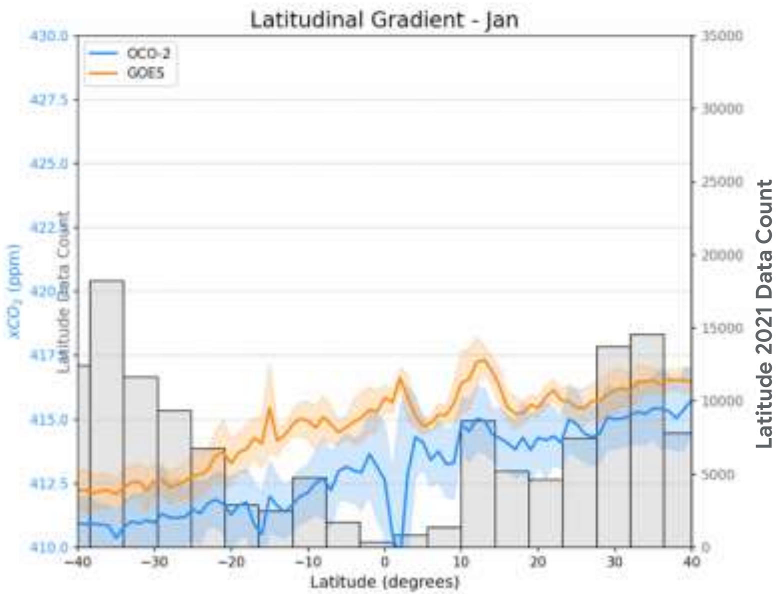
Latitudinal Gradient: OCO-2 vs GOES East model



The model can capture latitudinal gradients

Preliminary results: XCO2 throughout 2021



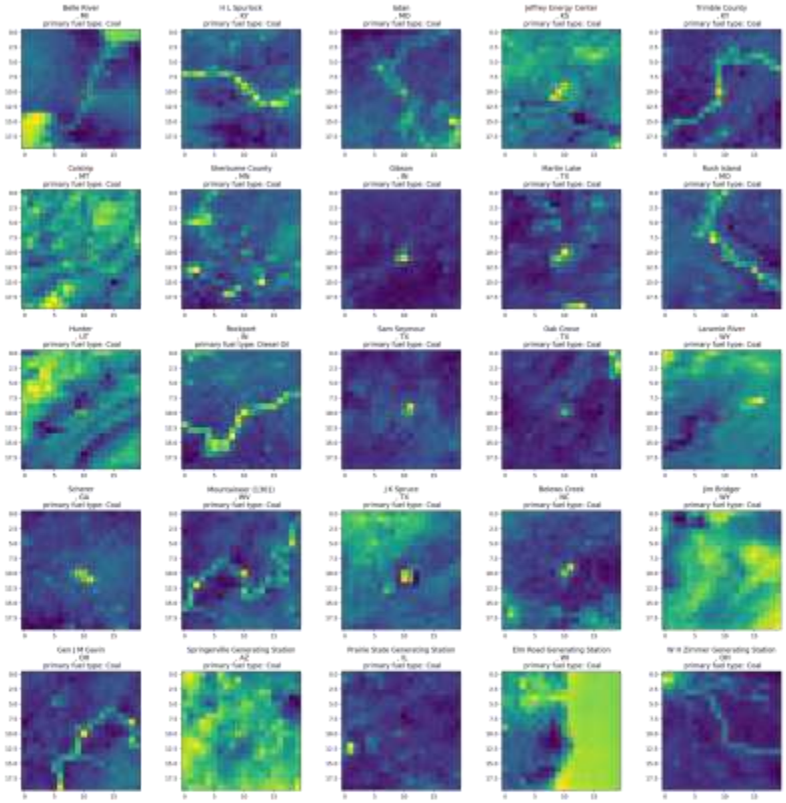


Weekly daytime 0.5 degree XCO2 average from GOES East perspective

Geographic Fine Scale Features

Can GOES see emissions from large power plants?

Preliminar results: High CO_2 emitting U.S. power plants



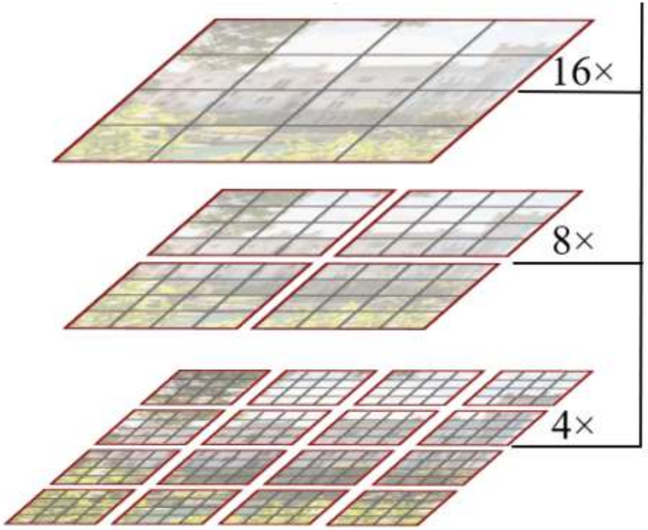
Figures show mean afternoon summer 2021 concentrations.

GOES sees some power plants better than others

Surface reflectance is still confounding

Next steps & acknowledgements

- Radiative transfer simulations for validation
- Comparison of GOES scans vs OCO-3 SAMs
- Extend to CNN and Swin transformer architectures
  - Capture spatial correlation
  - Provide additional GOES observations to the model



Liu et. al. 2021

Data Sources

- OCO-2: V11.1
- OCO-3: V11r
- TCCON: GGG2020 retrieval
- MODIS: MOD09A1.061 Terra Surface Reflectance 8-Day Global 500m
- Weather: ECMWF ARCO ERA5