Satellite Imaging for Climate Policy and Accountability

Table of Contents

Background

The world is changing. The "IPCC Special Report: Global Warming of 1.5C" states that *estimated anthropogenic global warming is currently increasing at 0.2°C (likely between 0.1°C and 0.3°C) per decade due to past and ongoing emissions (high confidence)*[1].

The Stern Review on the Economics of Climate Change, commissioned by the UK Treasury[2], the *price of no action on climate change would be equivalent to 5% of GDP per year in perpetuity, with a real risk of 5-6 degrees temperature increase*[3].

Whether or not one agrees with the adage, "*you cannot change what you cannot measure*", the importance of measuring climate impact is self-evident. Further, the "*climate has no wall*[4]", providing unique empirical challenges, and political complexity.

Related Policy

The world is responding, employing both policy and technology.

Globally, climate policy has offset about a third of the emissions growth we would have seen without any intervention.[5] The Paris Climate Agreement[6] saw "*186 countries—responsible for more than 90 percent of global emissions—submit… carbon reduction targets, known as "intended nationally determined contributions" (INDCs). INDCs turn into NDCs—nationally determined contributions—once a country formally joins the agreement.*", to limit warming to 2, or preferably 1.5 degree Celsius, compared to pre-industrial levels.

The US commitments to the agreement, for instance, included cutting overall GHG emissions by 26-28% by 2030. Initiatives to achieve this include the Clean Power Plan (CPC)[7], aimed at reducing carbon emissions from electricity generation by 32% by 2030 – particularly focusing on coal-

[1] 'Summary for Policymakers — Global Warming of 1.5 ºC', accessed 31 May 2021, https://www.ipcc.ch/sr15/chapter/spm/.

[2] 'The Economics of Climate Change: The Stern Review', Grantham Research Institute on climate change and the environment, accessed 31 May 2021, https://www.lse.ac.uk/granthaminstitute/publication/the-economics-of-climate-change-the-stern-review/.

[3] Nicholas Stern, 'The Price of Change', *International Atomic Energy Agency*, accessed 31 May 2021, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull48-2/48205692528.pdf.

[4] 'An Integrated Global Greenhouse Gas Information System (IG3IS)', *World Meterological Organization - Bulletin* 66 (1), 2017, accessed 1 June 2021, https://library.wmo.int/doc_num.php?explnum_id=3415.

[5] 'The Impact of Current Climate Policies on Greenhouse Gas Emissions', Grantham Research Institute on climate change and the environment, accessed 28 May 2021, https://www.lse.ac.uk/granthaminstitute/news/the-impact-of-current-climate-policies-on-greenhouse-gas-emissions/.

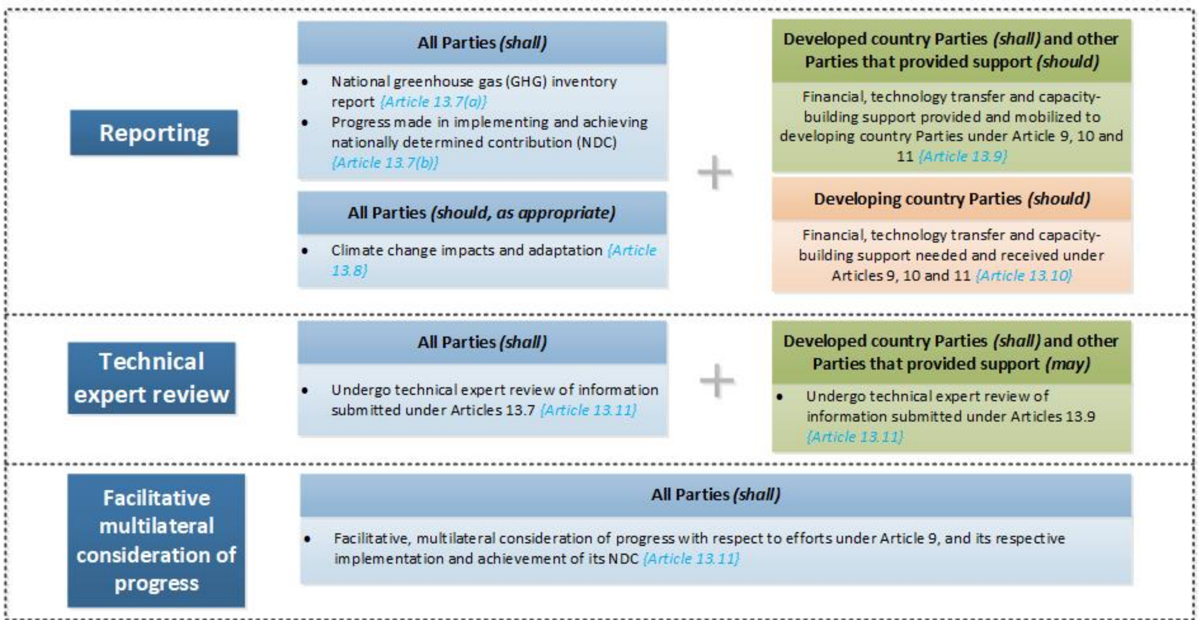
[6] February 19 and 2021 Melissa Denchak, 'Paris Climate Agreement: Everything You Need to Know', NRDC, accessed 31 May 2021, https://www.nrdc.org/stories/paris-climate-agreement-everything-you-need-know.

[7] OAR US EPA, 'FACT SHEET: Overview of the Clean Power Plan', Overviews and Factsheets, accessed 1 June 2021, fact-sheet-overview-clean-power-plan.html.

burning power plants. Across the pond in the UK, 3 plants remain operational, with a planned phaseout by 2025[8].

The Paris Agreement and its compliance is not without criticism[9], as, "*there is… no sure way of independently verifying whether national governments are telling the truth about… emissions or… knowing by how much global anthropogenic emissions are actually increasing.*"[10]. *Each nation's basic estimate of its emissions comes from "self-reported national statistics"*[11].

Article 13 of the Paris Agreement: transparency of action and support



* The transparency framework shall provide flexibility in the implementation of the provisions of this Article to those developing country Parties that need it in the light of their capacities *{Article 13.2}*;
* The transparency framework shall recognize the special circumstances of the least developed countries and small island developing States *{Article 13.3}*.

There is also evidence of under-reporting of greenhouse gases in US cities[12] to the order of 18%, and this problem is often worse at a national level[13] in political and unevenly developed landscapes. Beyond gaps in data, there are inconsistent methodologies and assumptions in

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[8] 'Coal Countdown', *Power Stations of the UK* (blog), accessed 1 June 2021, https://www.powerstations.uk/coal-countdown/,.
[9] Kilian Raiser et al., 'Is the Paris Agreement Effective? A Systematic Map of the Evidence', *Environmental Research Letters* 15, no. 8 (August 2020): 083006, https://doi.org/10.1088/1748-9326/ab865c.
[10] 'Paris Conundrum: How to Know How Much Carbon Is Being Emitted?', Yale E360, accessed 29 May 2021, https://e360.yale.edu/features/paris-conundrum-how-to-know-how-much-carbon-is-being-emitted.
[11] John Fialka,ClimateWire, 'Inside the Quest to Monitor Countries' CO 2 Emissions', Scientific American, accessed 31 May 2021, https://www.scientificamerican.com/article/inside-the-quest-to-monitor-countries-co2-emissions/.
[12] Kevin Robert Gurney et al., 'Under-Reporting of Greenhouse Gas Emissions in U.S. Cities', *Nature Communications* 12, no. 1 (December 2021): 553, https://doi.org/10.1038/s41467-020-20871-0.
[13] 'China Underreporting Coal Consumption by up to 17%, Data Suggests', the Guardian, 4 November 2015, http://www.theguardian.com/world/2015/nov/04/china-underreporting-coal-consumption-by-up-to-17-data-suggests.

aggregation at such scale (guidance and analysis[14] across the UK, India, US, China, Germany, etc), despite standardized reporting templates within the UNFCCC guidelines[15]. Within self-reported data, there is no dearth of processes[16] and tools and review national emissions. The UK Department of Energy and Climate Change, for instance, publishes elaborate guidelines[17] for organizations to conduct measurement. These are aggregated and feed into national statistics.

Continuous Reporting

Table 2-6 Horizontal summary of telemonitoring specification in each country/region

Country	Number of installations	Media: Water/Air	Pollutants	Reporting frequency	Publicly available online
China	10,492 for air; 19,591 for water	Both	Air: SO_2, NO_x, PM, O_2, temperature, volume, humidity Water: COD, P, NH_3-N, volume, BOD_5, N, TSP, pH	Not specified **(but real-time)**	Yes
India	40,000+	Both	Air: PM_{10}, $PM_{2.5}$, SO_2, NOx, O_3 Water: pH, TSS, TDS,	15 seconds	Yes

This is still premature. As of June 2020, EU contracted reports[18] still explore options ranging from

- Periodic Manual
- Periodic Automated
- Near-Realtime Automatic (human operator/regulator to monitor)
- Fully automated real-time

continuous emission monitoring (CEM) systems. All automated solutions look towards technology. We thus turn our attention to alternate data sources to verify reported data and the role of technology in the same.

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[14] 'Technical Assistance on Industrial Emissions – Assignment #3 Online Realtime Monitoring of Industrial Emissions', Circabc - European Commission, accessed 29 May 2021, https://circabc.europa.eu/ui/group/06f33a94-9829-4eee-b187-21bb783a0fbf/library/44dd9a9e-27fd-430d-8b36-ac29dfebde07/details.

[15] 'Reporting Requirements | UNFCCC', accessed 1 June 2021, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-convention/greenhouse-gas-inventories-annex-i-parties/reporting-requirements.

[16] 'Reporting and Review under the Paris Agreement | UNFCCC', accessed 17 May 2021, https://unfccc.int/process-and-meetings/transparency-and-reporting/reporting-and-review-under-the-paris-agreement.

[17] 'Guidance on How to Measure and Report Your Greenhouse Gas Emissions', n.d., 75.

[18] 'Technical Assistance on Industrial Emissions – Assignment #3 Online Realtime Monitoring of Industrial Emissions'.

Technology

CO_2 from burning forests or dying vegetation contains carbon-14, burning fossil fuels like coal, oil, and natural gas releases virtually none. By measuring C-14 presence in parcels of air, researchers can attribute CO2 to natural biogenic sources and anthropogenic activity – perhaps even at the source. "*Such forensic examination of atmospheric CO2 is not done routinely".*[19]

Commercial Aircraft Sampling

"NOAA(National Oceanic and Atmospheric Administration) and the University of Colorado have spent a decade perfecting ways to… measure the tiny presence of C-14… it would need 5,000 air samples from aircraft and the ground to develop an accurate picture of man-made carbon emissions in the United States. NOAA already collects 20,000 air samples around the world every year. During the last three years, the Obama administration approved a NOAA budget proposal starting at around $5 million per year to analyse 5,000 C-14 measurements each year. So far, Congress has rejected it each year"[20].

Efforts here include CONTRAIL[21] and MOZAIC (now, IAGOS[22]), both involving sensors aboard aircraft, the latter being funded by the European Commission with plans to operate 600 flights annually.

One drawback here is poor coverage, both due to low adoption by airlines (and US Government), and the resulting data is very limited in terms of point-to-point time-bound coverage (rather than systematic traversal). Having said this, it has low infrastructure cost.

(Ground-Based) Observation Stations

The UK has 4 physical towers to measure, with high precision and frequency (3 seconds), the Kyoto Basket gases[23] at different sampling heights. Spectroscopy is utilized exploiting differential absorption wavelengths of CO2 among other gases to estimate values.[24]

A key drawback is the physical infrastructure needed and the geo-limitation of the readings. xCO2 column values are also not available for the entire atmosphere – readings estimate values in-situ. The distribution of such stations and their methodologies varies.

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[19] 'Paris Conundrum'.

[20] Fialka,ClimateWire, 'Inside the Quest to Monitor Countries' CO 2 Emissions'.

[21] 'Atmospheric CO2 Mole Fraction Data of CONTRAIL-CME | Data / Resources | National Institute for Environmental Studies', National Institute for Environmental Studies, Japan, accessed 30 May 2021, http://www.nies.go.jp/doi/10.17595/20180208.001-e.html.

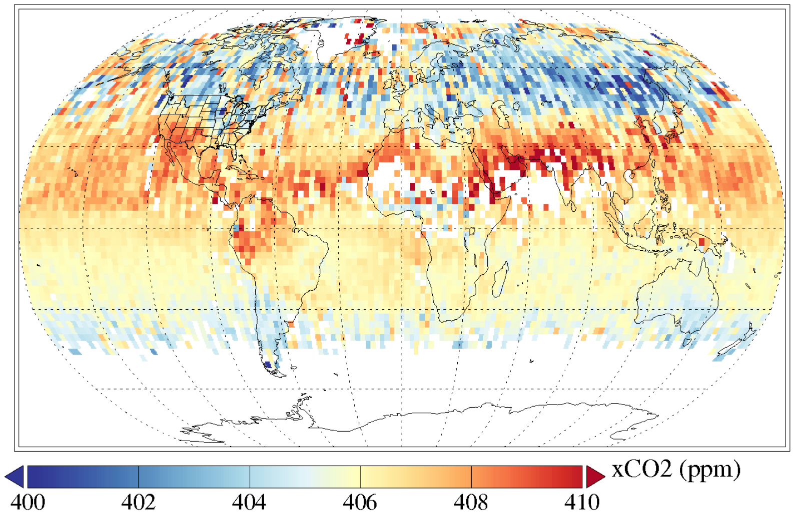
[22] 'Data – IAGOS', accessed 1 June 2021, https://www.iagos.org/iagos-data/.

[23] 'Monitoring and Verification of Long Term UK Atmospheric Measurement of Greenhouse Gas Emissions', GOV.UK, accessed 30 May 2021, https://www.gov.uk/government/publications/uk-greenhouse-gas-emissions-monitoring-and-verification.

[24] Alistair J Manning et al., 'Methodology Report Verification of Emissions Using Atmospheric Observations', n.d., 39.

Another example of an observation network includes TCCON[25]. Challenges include varying methodologies on-ground, low and ad-hoc coverage, and distributed datasets. This network is used to verify, as ground truth, data received from…

Global amounts of xCO2 in June-July 2018; OCO-2 Lite V9r



Satellite Coverage

Satellites are a promising new avenue for measuring climate impact. While lots of prior art exists for satellite monitoring of toxins and CFCs, CO2 monitoring is relatively new. These sources are used to cross-validate[26] – and, following missions have taken off in recent years:

- GOSAT (JAXA, 2009) – the first satellite mission dedicated to GHG observations. ODIAC dataset is modelled on it, by fusing national CO2 emissions inventories downscaled by satellite-observed nighttime lights. *ODIAC makes it possible to implement GHG budget analyses… such analyses allow stakeholders to assess progress on GHG management towards global accords, such as the Paris Agreement, using atmospheric observations from Japan's GOSAT, NASA's OCO-2, OCO-3 missions, and future satellite missions.*[27]

- OCO-2 (2014), OCO-3 (2019)[28]: NASA's Orbiting Carbon Observatory's (OCO-2, OCO-3), like GOSAT, make high spectral resolution measurements to derive CO2 column-averaged dry air mole fractions (XCO2)[29]. OCO-2 makes 8 parallelogram-shaped footprints (1 x 2km2) across a 10km patch, over 14 revolutions of the planet per day. The OCO-2 mission cost 467m USD.[30]

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[25] Ailin Liang et al., 'Comparison of Satellite-Observed XCO2 from GOSAT, OCO-2, and Ground-Based TCCON', *Remote Sensing* 9, no. 10 (October 2017): 1033, https://doi.org/10.3390/rs9101033.
[26] Liang et al.
[27] 'EfSI Offers a Solution to Existing Gaps in Global Emission Inventories.', n.d., https://www.usra.edu/efsi-case-study-odiac.
[28] Annmarie Eldering et al., 'The OCO-3 Mission: Measurement Objectives and Expected Performance Based on 1 Year of Simulated Data', *Atmospheric Measurement Techniques* 12, no. 4 (15 April 2019): 3, https://doi.org/10.5194/amt-12-2341-2019.
[29] 'GES DISC Dataset: OCO-3 Level 2 Bias-Corrected XCO2 and Other Select Fields from the Full-Physics Retrieval Aggregated as Daily Files, Retrospective Processing VEarlyR (OCO3_L2_Lite_FP EarlyR)', accessed 31 May 2021, https://disc.gsfc.nasa.gov/datasets/OCO3_L2_Lite_FP_EarlyR/summary.
[30] 'Orbiting Carbon Observatory-2 Launch Press Kit' (NASA), accessed 31 May 2021, https://www.jpl.nasa.gov/news/press_kits/oco2-launch-press-kit.pdf.

- CarbonSAT, 2016[31] - the Chinese satellite[32], serving as another example

[31] 'China Launches Satellite to Monitor Global Carbon Emissions', accessed 1 June 2021, http://english.www.gov.cn/news/top_news/2016/12/22/content_281475522238423.htm.
[32] *Report for Mission Selection: Carbonsat Flex*, ESA SP, 1330/1-2 (Noordwijk, the Netherlands: ESA Communications, 2015).

Focus on Energy (Coal)

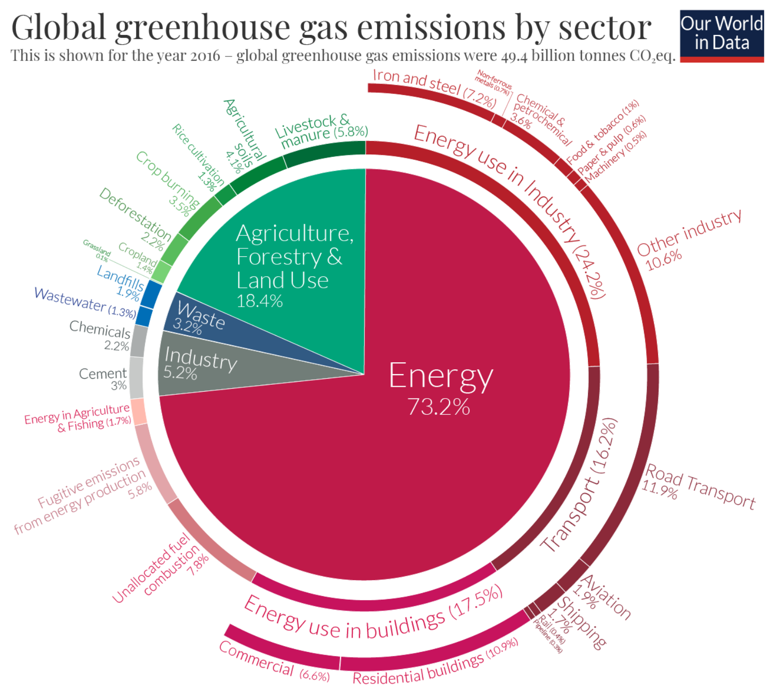
The Energy Sector is the largest contributor to GHG emission.

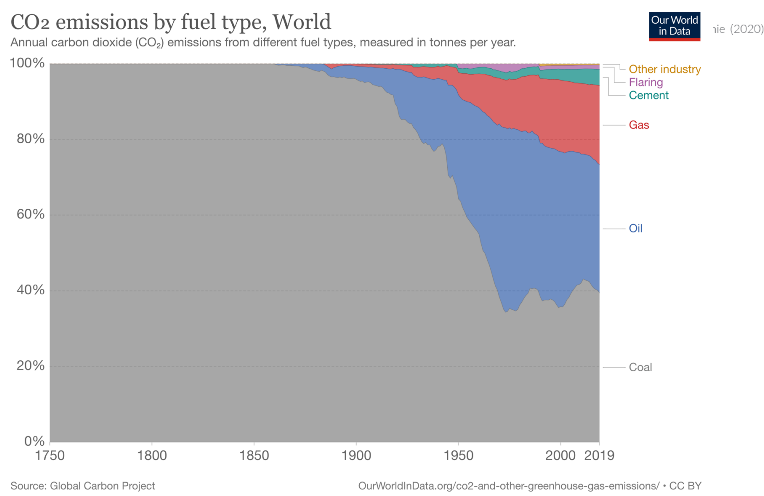
A significant subcomponent of Energy is electricity generation and consumption[33]. Of production modes, coal is both prevalent[34,35] and a significant contributor to GHG.

As policies to shut down coal come about[36], visibility and air quality improvements are reported[37].

Coal Plants are interesting in that they may not be fully closed, but transformed into gas/oil plants. While aggressive measures exist to shut them down[38], they are still growing in prevalence in the developing economies of Asia.[39]

Their emissions contribution (up to 30% by country) is of relevance, as variations in the same might be strong enough to overcome variability in atmospheric through other sources.





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[33] OAR US EPA, 'Sources of Greenhouse Gas Emissions', Overviews and Factsheets, US EPA, 29 December 2015, https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions.
[34] 'CO2 Emissions by Fuel', Our World in Data, accessed 1 June 2021, https://ourworldindata.org/emissions-by-fuel.
[35] 'Frequently Asked Questions (FAQs) - U.S. Energy Information Administration (EIA)', accessed 31 May 2021, https://www.eia.gov/tools/faqs/faq.php.
[36] 'More U.S. Coal-Fired Power Plants Are Decommissioning as Retirements Continue - Today in Energy - U.S. Energy Information Administration (EIA)', accessed 30 May 2021, https://www.eia.gov/todayinenergy/detail.php?id=40212.
[37] Mark Pearson, 'As Coal-Fire Power Plants Close, Our Skies Are Clearing', Durango Herald, accessed 30 May 2021, https://www.durangoherald.com/articles/as-coal-fire-power-plants-close-our-skies-are-clearing/.
[38] 'Global Coal Plant Tracker | End Coal', accessed 29 May 2021, https://endcoal.org/tracker/.
[39] Huileng Tan, '"Coal Is Still King" in Southeast Asia Even as Countries Work toward Cleaner Energy', CNBC, 1 October 2019, https://www.cnbc.com/2019/10/01/coal-is-still-king-in-southeast-asia-despite-clean-energy-efforts.html.

Objective

Our objective is to use NASA's public OCO-2/OCO-3 satellite data[40] to track if coal plant shutdowns are associated with a notable change in satellite-determinable data as a cross-reference for self-reported mechanisms.

This study focuses on the Sammis Power Plant in the US[41], a bituminous coal plant at lat-long (40.531322, -80.631731) in Ohio. Notably, 4 units (1-4) contributing to 30% of its capacity were shut down in June 2020, and its reported emissions have declined year on year[42].

The purpose is not to evaluate the Paris Treaty, EndCoal.org[43] or the CPC specifically, but to reason about the feasibility of satellite data to validate self-reported emissions data, focused on specific regions and time-events (such as plant closures or fires) – "natural events" possibly leading to differences in differences.

Ahead of satellite visits[44], closures could be planned for controlled settings for tracking. Finally, we assess the gap between this tool and "true-realtime" monitoring. Prior work to study such data for (larger) cities[45] and (running emissions of) coal plants exists[46].

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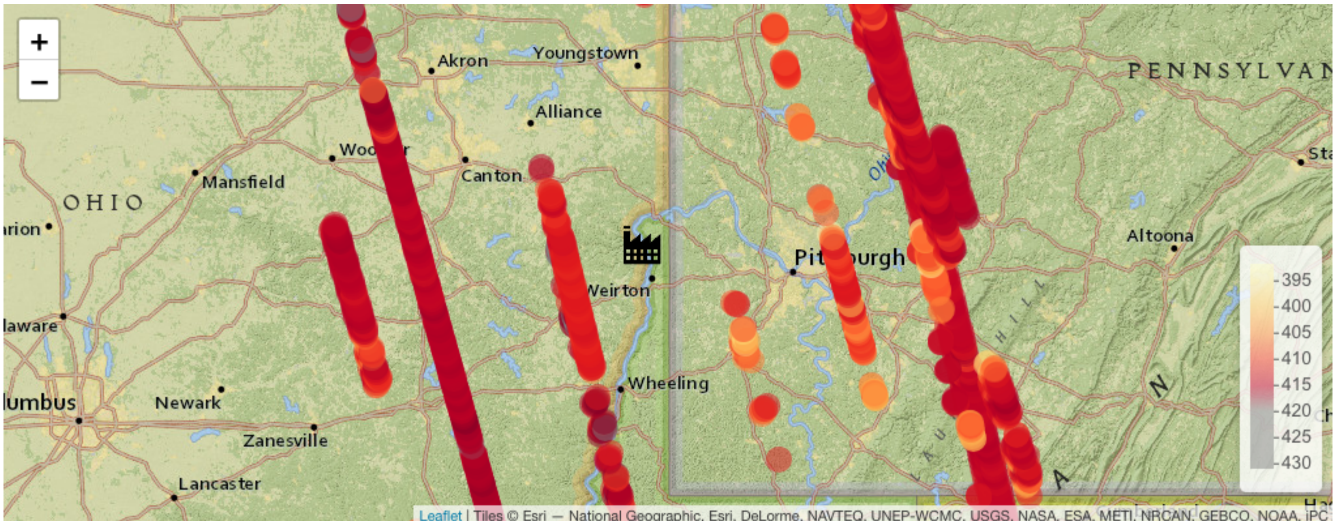
[40] 'GES DISC Dataset: OCO-3 Level 2 Bias-Corrected XCO2 and Other Select Fields from the Full-Physics Retrieval Aggregated as Daily Files, Retrospective Processing VEarlyR (OCO3_L2_Lite_FP EarlyR)', 3.
[41] 'Sammis Plant', Global Energy Monitor, 30 April 2021, https://www.gem.wiki/Sammis_Plant.
[42] 'GHG Facility Details', accessed 1 June 2021, https://ghgdata.epa.gov/ghgp/service/facilityDetail/2019?id=1006794&ds=E&et=FC_CL&popup=true.
[43] 'Global Coal Plant Tracker | End Coal'.
[44] Dominic Ford, 'Live World Map of Satellite Positions', In-The-Sky.org, accessed 1 June 2021, https://in-the-sky.org//satmap_worldmap.php.
[45] Yan Wang and Guangdong Li, 'Mapping Urban CO2 Emissions Using DMSP/OLS "City Lights" Satellite Data in China', *Environment and Planning A: Economy and Space* 49, no. 2 (1 February 2017): 248–51, https://doi.org/10.1177/0308518X16656374.
[46] Ray Nassar et al., 'Quantifying CO2 Emissions From Individual Power Plants From Space', *Geophysical Research Letters* 44, no. 19 (2017): 10,045-10,053, https://doi.org/10.1002/2017GL074702.

Methodology



The above figure showcases flyby events in 2020.

We crop and download the 10r OCO-2 dataset from GES-DISC[47], on a small patch between (-77, -83) long and (37, 43) lat and a generous (approx. 200km) buffer around Sammis plant (centre). This yields over 2000 files over 2-3 hours. About 85% are empty nc4 files, the rest are subsequently processed in R (code)[48].

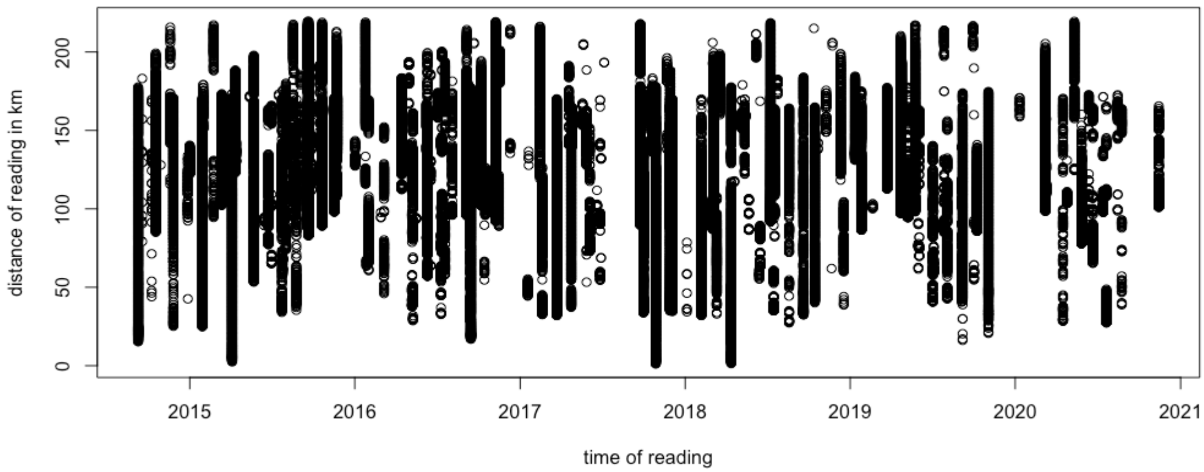
As the satellites are already dispatched, this is low-cost. This is favoured over early OCO-3 data, as it is unprocessed/un-debiased and only available from 2019. Having said this, OCO-3 promises to eventually support "*snapshot mode*", producing 80 by 80 km measurements, overcoming OCO-2's challenge with air currents.

[47] 'GES DISC Dataset: OCO-3 Level 2 Bias-Corrected XCO2 and Other Select Fields from the Full-Physics Retrieval Aggregated as Daily Files, Retrospective Processing VEarlyR (OCO3_L2_Lite_FP EarlyR)'.
[48] Aditya Gupta, *Ca9/Oco2-Climate*, 2021, https://github.com/ca9/oco2-climate.

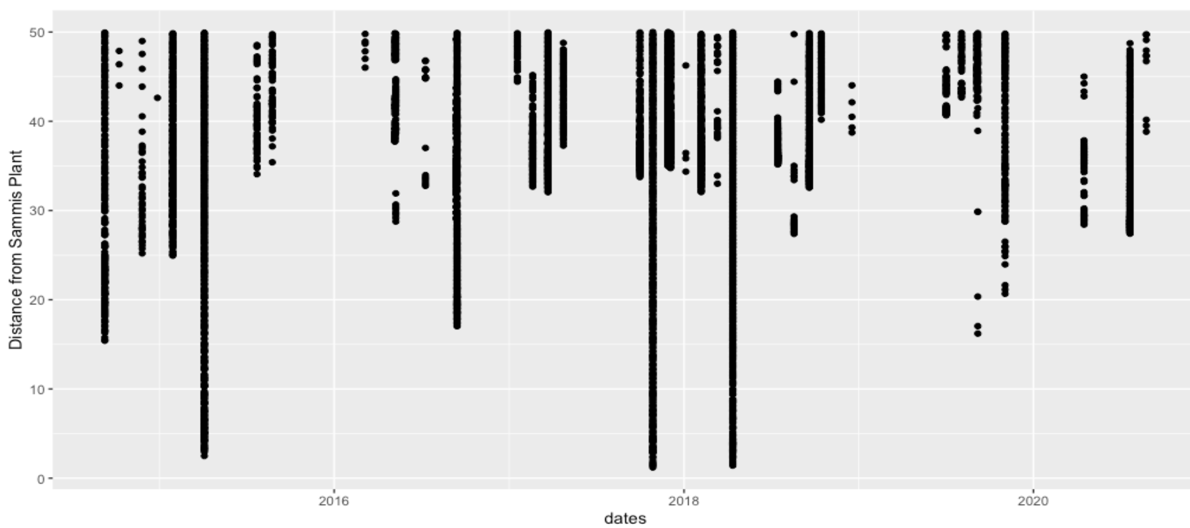
Results

Frequency

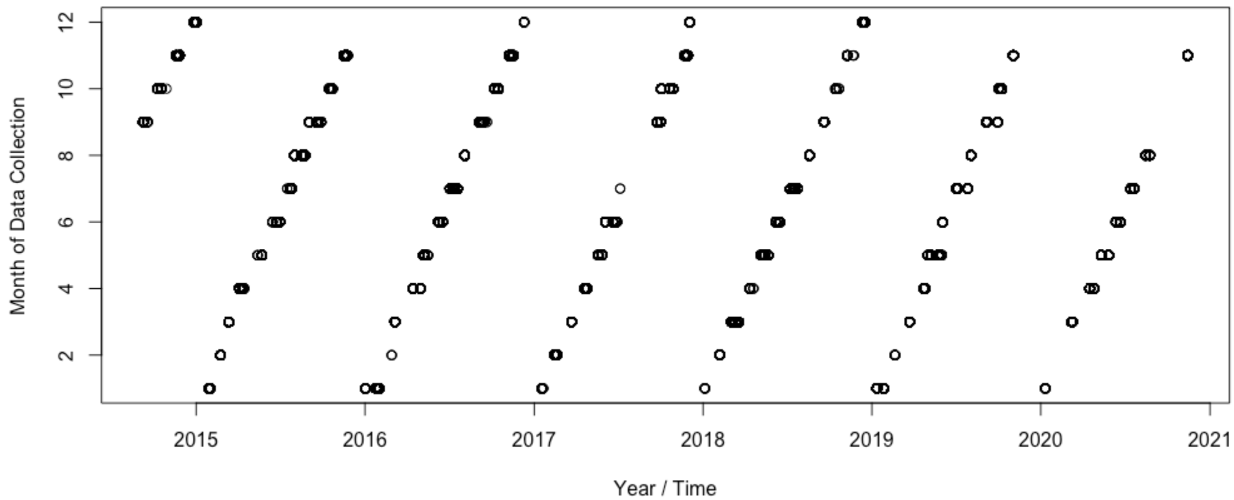
Over the years, the satellite makes several visits to the site:



On a few occasions it approaches under 50km, but rarely more than a few times a year and seeming irregularity:

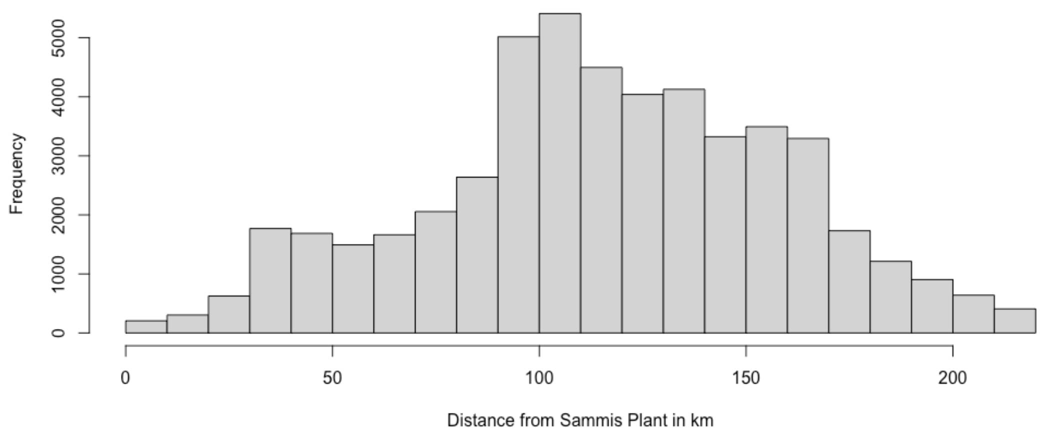


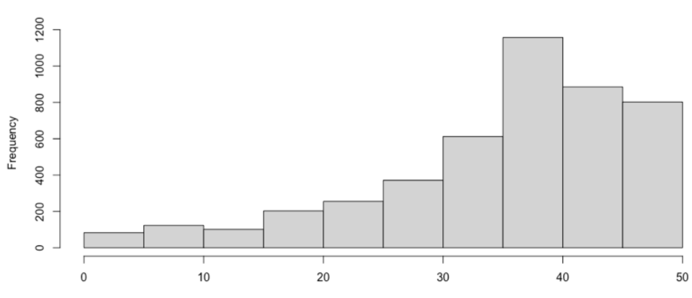
It is also apparent that a stable monthly frequency is not seen even within 200km:

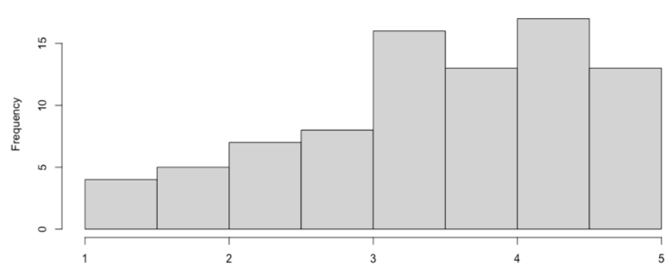


Flybys

Unlike other papers[49] we're not blessed with a direct flyover, with graphs below showing the count of observations (of approx. 50000) within range:

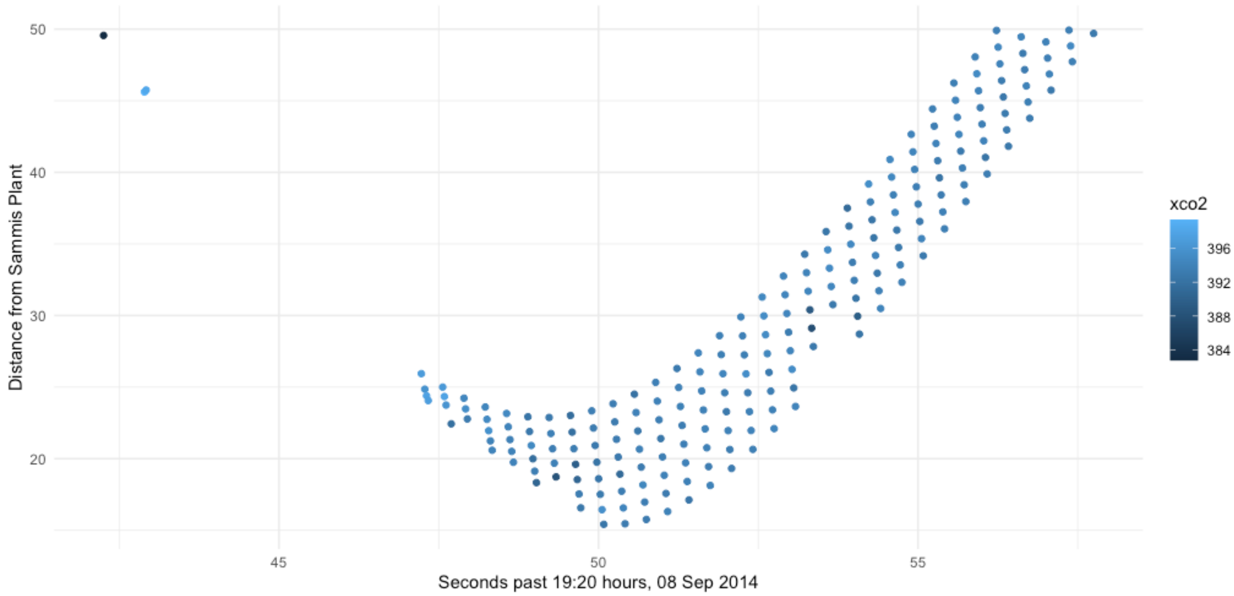






[49] Nassar et al., 'Quantifying CO2 Emissions From Individual Power Plants From Space'.

A closer look at a fly-by in 2014 shows us that it is really comprised of a series of quick 8-region snaps over a few seconds.

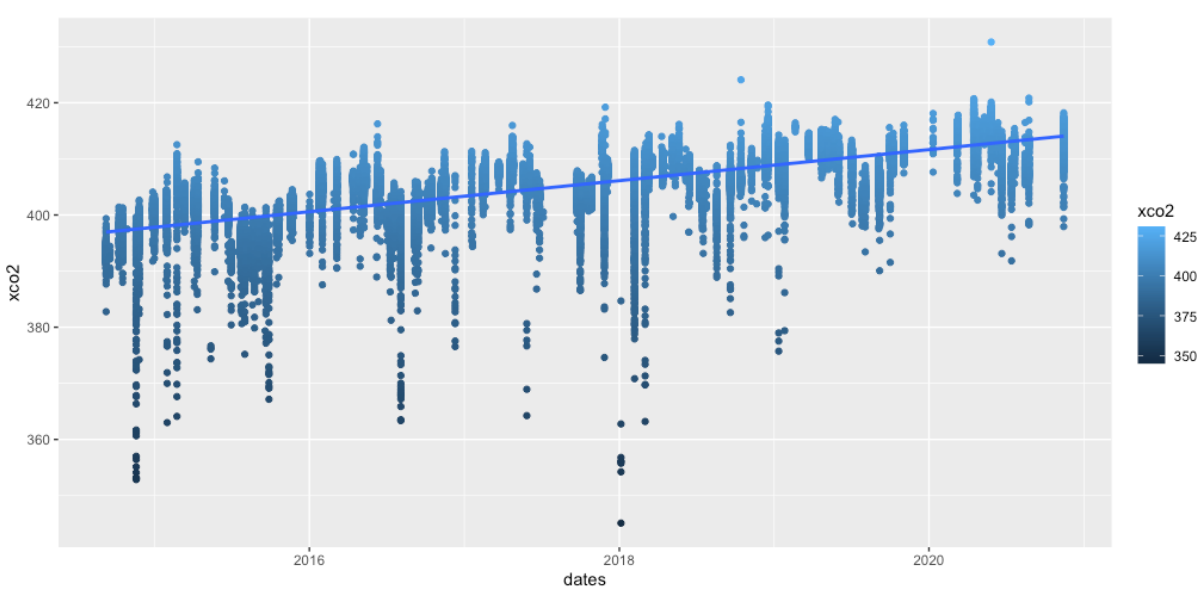


External Factors (Omitted Variables)

Several challenges remain with point readings of xCO2 values. For one, the distance from Sammis Plant explains virtually none of the variability in xCO2.

	xco2	
Predictors	*Estimates*	*p*
(Intercept)	405.00 (404.84 – 405.15)	**<0.001**
dist	-0.00 (-0.00 – -0.00)	**<0.001**
Observations	50538	
R^2 / R^2 adjusted	0.000 / 0.000	

This is because there are overarching seasonal and annual(baseline) trends to the xCO2 data. The planet



"breathes" over the year, but is also seeing a regular xCO2 increase year on year (2-3 ppm/py) in background CO2.

Accounting for the year, and month of the readings into the model, we can isolate expected change in xCO2 to other factors (ceteris paribus).

As anticipated, most months (except June) have statistically significant and strong seasonality effects on XCO2 readings, much more so than distances:

- within this patch *("dist" from Sammis)*
- or nearby cities
  (Pittsburgh – dist_pitts, or Cleveland, dist_cleve)

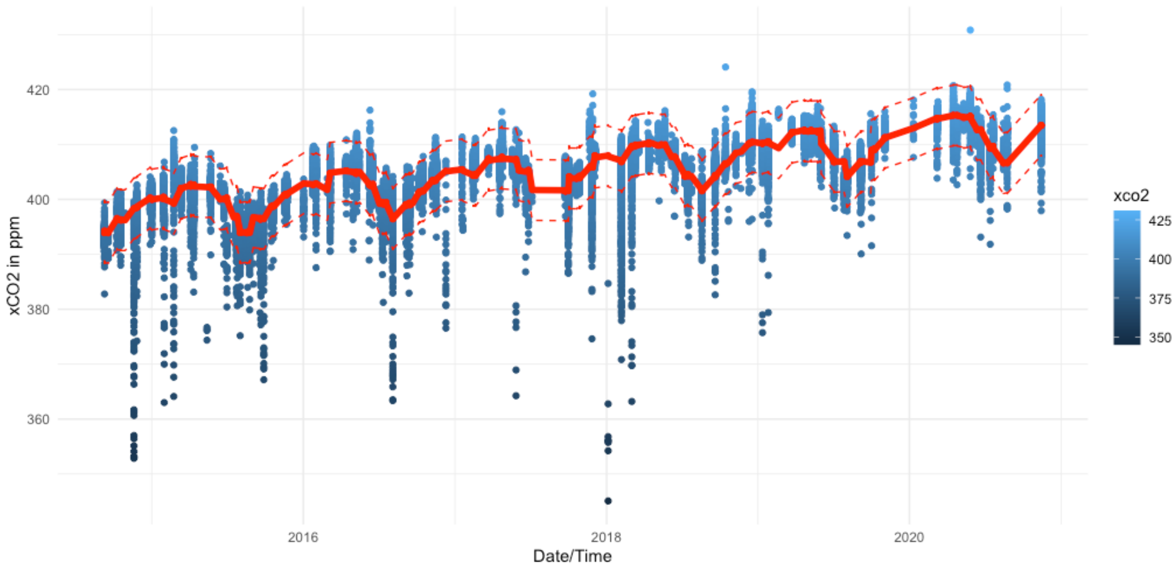
When accounted for, these temporal parameters explain a great deal of variability in the data (78%). Our new predicted XCO2 model with a 95% confidence band (in red) is shown below.

At this point, we make two observations – the distance from the plant or cities, while statistically significant (non-random), does not actually cause much variability in the readings. A 100km distance here is linked with a 1ppm XCO2 change, the instrument error is 2-3x larger[50]. This is a distance at which local effects of CO2 would likely diffuse – making estimates unreliable.

	XCO2 in PPM	
Predictors	*Estimates*	*p*
(Intercept)	-4707.39 (-4738.86 – -4675.93)	**<0.001**
year	2.53 (2.52 – 2.55)	**<0.001**
Feb	-0.87 (-1.03 – -0.70)	**<0.001**
Mar	1.95 (1.82 – 2.08)	**<0.001**
April	2.29 (2.17 – 2.42)	**<0.001**
May	2.09 (1.95 – 2.22)	**<0.001**
Jun	-0.06 (-0.22 – 0.09)	0.427
Jul	-3.42 (-3.56 – -3.28)	**<0.001**
Aug	-6.15 (-6.32 – -5.99)	**<0.001**
Sep	-3.63 (-3.74 – -3.51)	**<0.001**
Oct	-1.29 (-1.41 – -1.17)	**<0.001**
Nov	0.75 (0.62 – 0.87)	**<0.001**
Dec	2.48 (2.32 – 2.64)	**<0.001**
dist	-0.01 (-0.01 – -0.00)	**<0.001**
dist_pitts	0.00 (0.00 – 0.01)	**<0.001**
dist_cleve	0.00 (0.00 – 0.00)	**<0.001**
Observations	50538	
R^2 / R^2 adjusted	0.780 / 0.780	

[50] Brian Connor et al., 'Quantification of Uncertainties in OCO-2 Measurements of XCO_2: Simulations and Linear Error Analysis', *Atmospheric Measurement Techniques* 9, no. 10 (27 October 2016): 5227–38, https://doi.org/10.5194/amt-9-5227-2016.

Second, a lot of observed values sit well outside the 95% confidence range – lending support to the argument around omitted variables.



Wind – the ultimate "spillover" effect

One of the major challenges in creating valid counterfactuals for climate measurement is determining areas where readings would (otherwise) be as close to the ones in the concerned area (neighbourhood), without actually being affected by the treatment (nearby emissions). This just doesn't happen with climate – *"there are no walls"*.

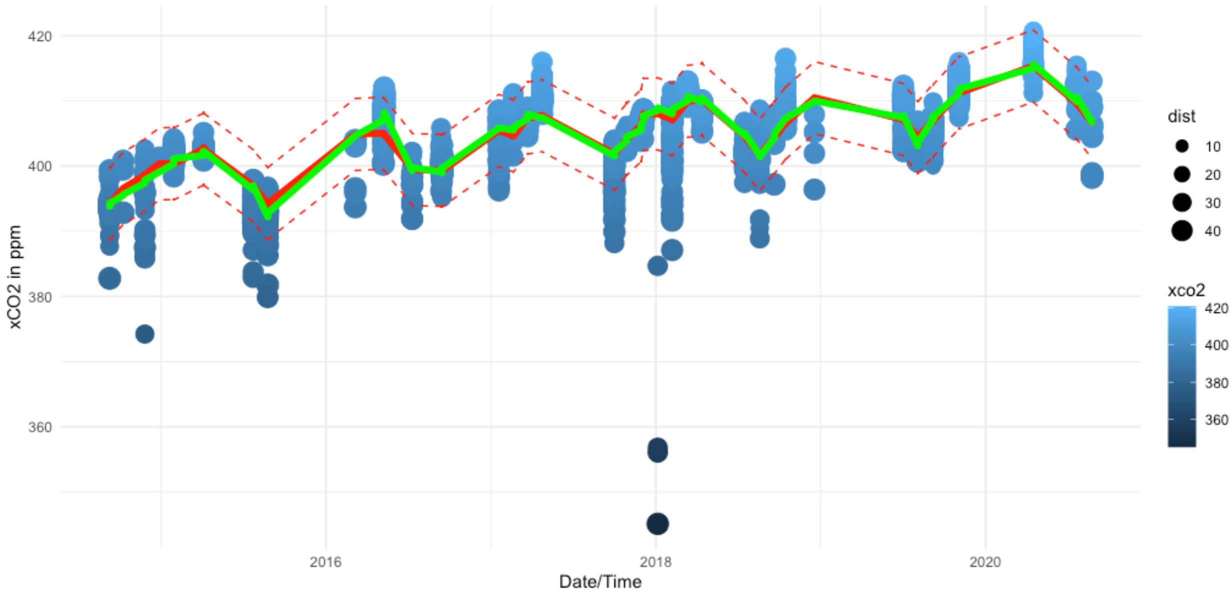
As such, we've no choice but to compare xCO2 point readings (as opposed to flux) with the wider neighbourhood (200 km radius), and a wider time window.

Other advanced work[51] estimates CO2 "plumes" from known chimney heights and wind from a trailing satellite over direct-flybys, against reported-emissions database develop a ground truth mapping between XCO2 readings (particularly, *their differences*, or flux values) and on-ground emissions (albeit with high uncertainty).

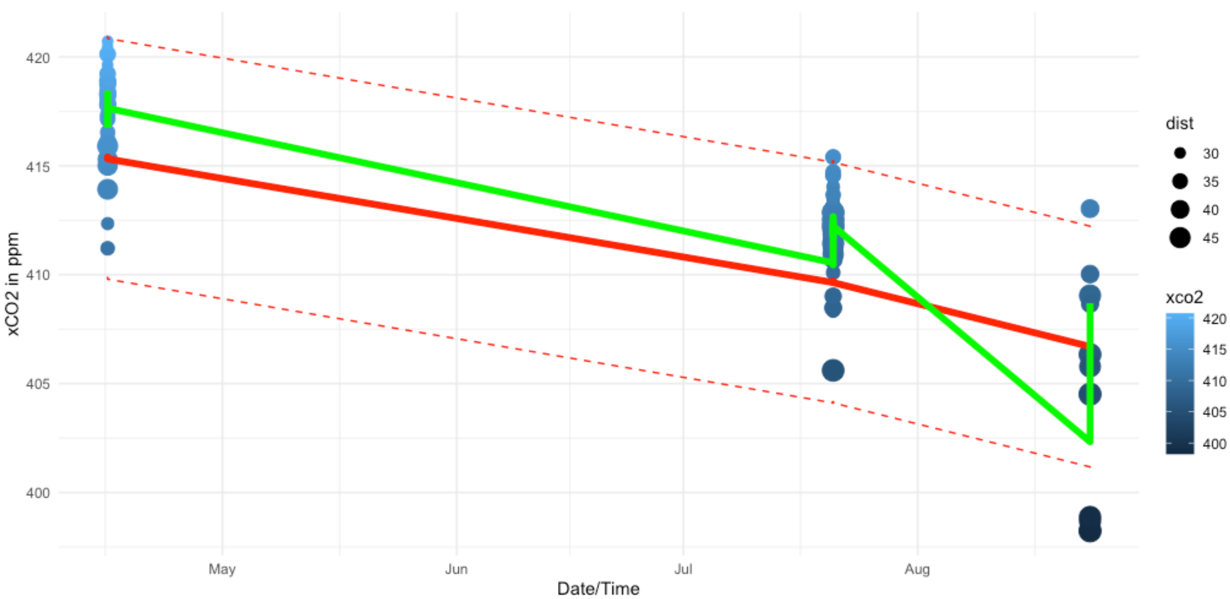
The state of Penn aggregates 200M tonnes of CO2, Pittsburgh accounting for 14.5 $\pm$ 6 Mt CO2[52], and in the same ballpark as our 15M metric tonne emissions plant. As such, comparable xCO2 variability vis-à-vis distance from these spots is thus unsurprising.

[51] Nassar et al., 'Quantifying CO2 Emissions From Individual Power Plants From Space'.
[52] Daniel Moran et al., 'Carbon Footprints of 13 000 Cities', *Environmental Research Letters* 13, no. 6 (1 June 2018): 064041, https://doi.org/10.1088/1748-9326/aac72a.

Readings



Here, we see the red showing xCO2 for the bounding lat/long radius (distances up to 200km), and the green line showing the pattern observed for the (distances up to 50km). Zooming into the event of interest:



We find that:

- We lack readings for June 2020 (the period of unit closure):
- Most treatment readings (fitted line in green) are within the expected range (red lines), however, there are some outliers from the post-August suggesting lower-than-usual carbon readings

Conclusion

Despite the temptation from above outliers, there isn't sufficient evidence to claim that July/August 2020 readings of OCO-2 in the lat-long range reflect the changes in its operating capacity/units.

Ultimately, seasonal and unexplained variability in XCO2 far outweigh the signal available at the current density of available data, particularly given the frequency and proximity of flybys – we have to be lucky to get a good match. Wind, plume size/direction, el-Nino, and nearby cities/other emitters and sinks are **critical omissions**, but possible to model. Further, too much time has elapsed between readings (and effects would have dissolved) for pointed flux measurements, and any source limited to a few seconds of data per year will have this issue.

This is not to say there is no promise here. Once the necessary infrastructure is established, the cost of additional analysis and review is minimal – and these techniques evidence possibilities.

We currently have 0.002% (3420 seconds of 6 years, over 160 days) seconds temporal coverage within a 200 km radius. This figure is 0.0002% within a 50km radius (352 seconds over 39 days). By adding 1-2 satellites in operation we can almost double 200km radius coverage, making weekly readings and tracing major events possible. The added cost of this should be to the tune of 1B USD – however, that figure falls comfortably shy of 1% of US GDP, and even 1% of the anticipated cost of climate change.

While conventional ground-up reporting processes and tooling advance and converge to increasingly automated and reliable machinery, the above techniques are less corruptible to perverse incentives of self-reporting, close to being fully viable, and show great potential to drive climate accountability (*via spot checks*, as a starter). With ongoing momentum and investment[53,54] including geostationary satellites[55], they are set to be the future of global real-time carbon sensing.

[53] Planet, 'Carbon Mapper Launches Satellite Program to Pinpoint Methane and Carbon Dioxide Super Emitters', accessed 1 June 2021, https://www.prnewswire.co.uk/news-releases/carbon-mapper-launches-satellite-program-to-pinpoint-methane-and-carbon-dioxide-super-emitters-827980651.html.
[54] 'Carbon Mapper Satellite Network to Find Super-Emitters', *BBC News*, 15 April 2021, sec. Science & Environment, https://www.bbc.com/news/science-environment-56762972.
[55] Berrien Moore III et al., 'The Potential of the Geostationary Carbon Cycle Observatory (GeoCarb) to Provide Multi-Scale Constraints on the Carbon Cycle in the Americas', *Frontiers in Environmental Science* 6 (2018), https://doi.org/10.3389/fenvs.2018.00109.

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