Quantifying Localized Carbon Dioxide Emissions from Space:
The CO2Image Demonstrator

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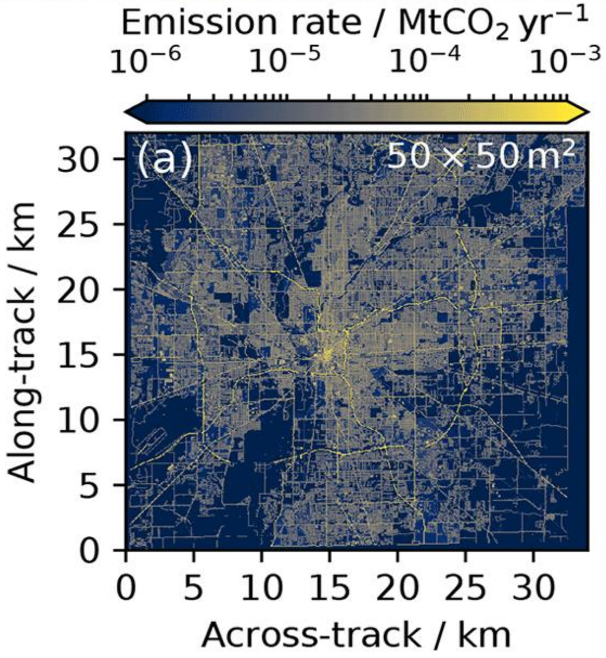
CO2Image: zooming in on localized sources

- Point source detection and estimation have been identified as key elements for a monitoring and verification support capacity targeting CO_2 emissions (CO_2 Red Report, Pinty et al., 2017)
- Global survey missions (e.g. OCO-2, CO2M) with ground pixel resolution on the scale of 2 km x 2 km can resolve point-source emissions of roughly > 10 $MtCO_2$/year
- Increasing the spatial resolution of the ground pixel (to 50 m x 50 m) increases the sensitivity substantially, to **> 1 $MtCO_2$/year**



Hestia emissions inventory from Gurney et al., 2018, disaggregated to 50 m x 50 m

from Strandgren et al., AMT, 2020

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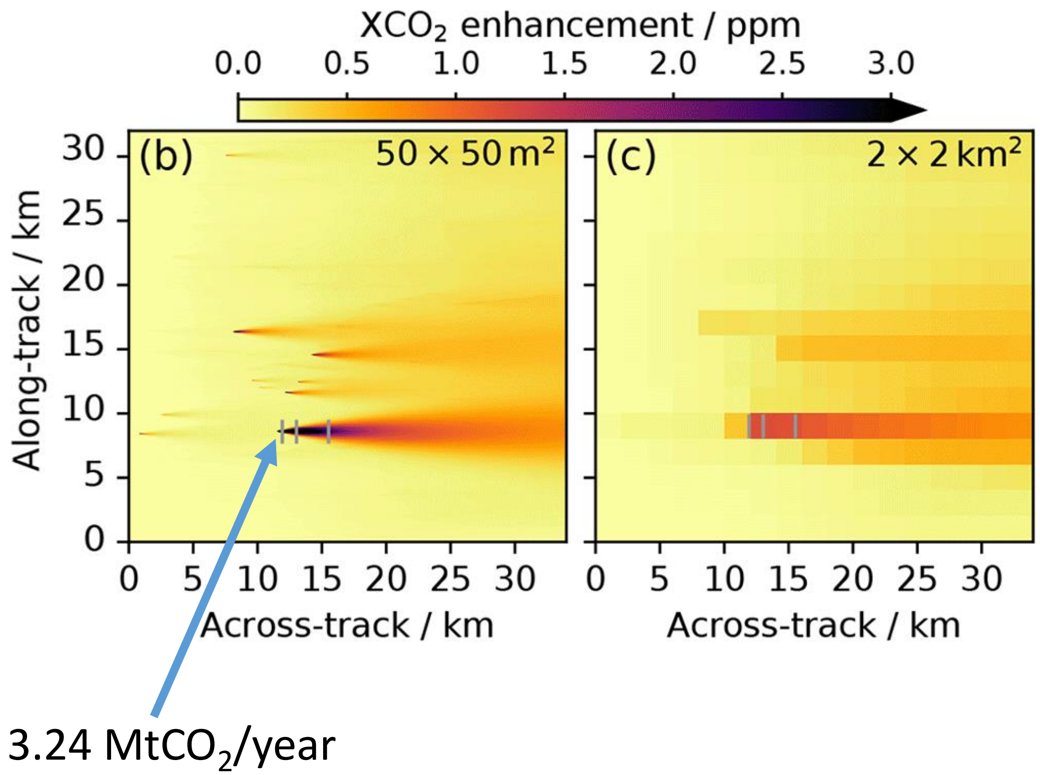

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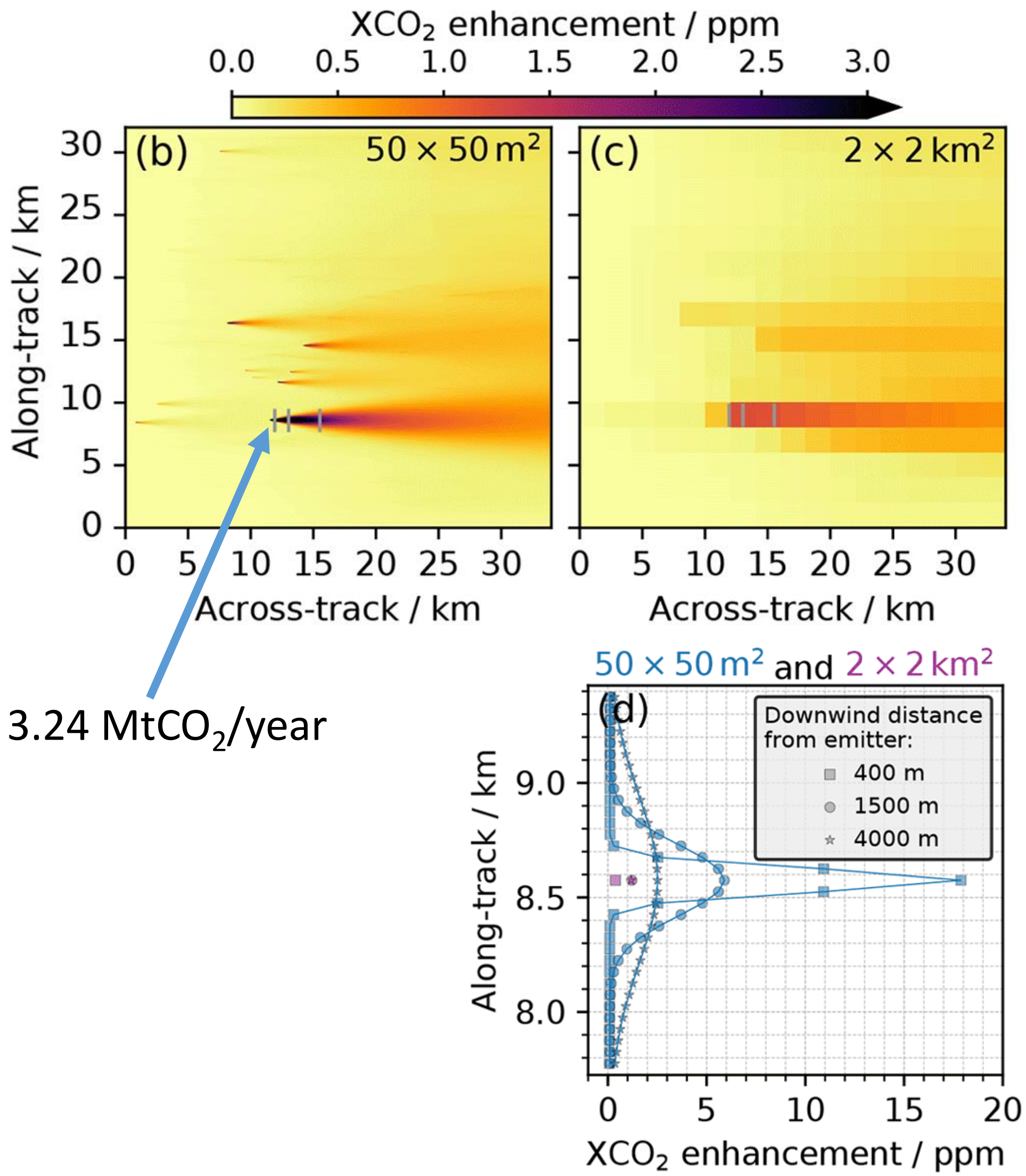
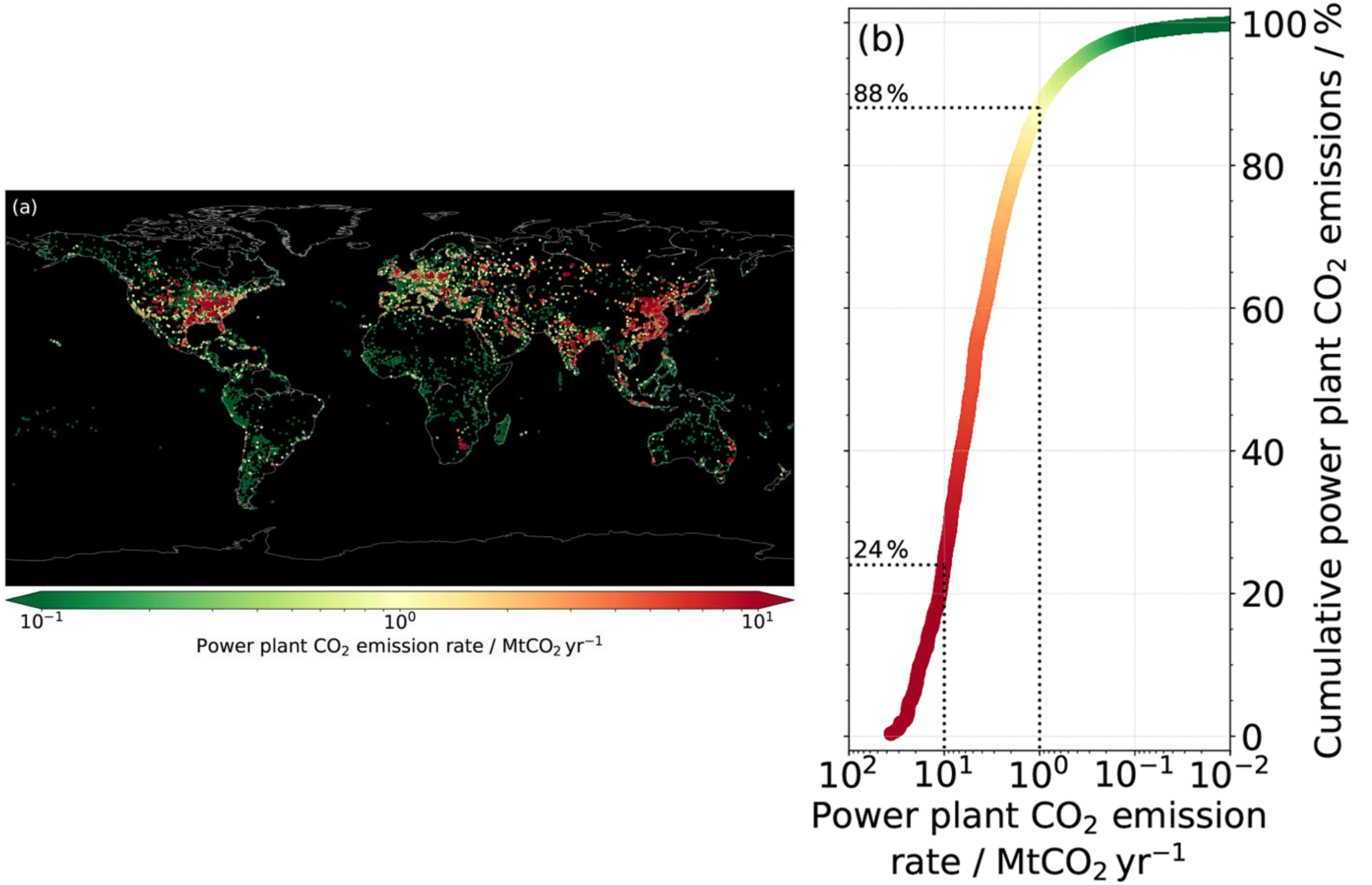


CO2Image: zooming in on localized sources

- A higher sensitivity (down to 1 $MtCO_2$/year) means that a higher proportion of point sources would be quantifiable based on remote sensing measurements:
  - A sensitivity threshold of > 10 $MtCO_2$/year could resolve 24% of emissions from coal-fired powerplants worldwide
  - A sensitivity threshold of > 1 $MtCO_2$/year could resolve 88% of emission from coal-fired powerplants worldwide



from [Strandgren et al., AMT, 2020]

CO2Image: zooming in on localized sources

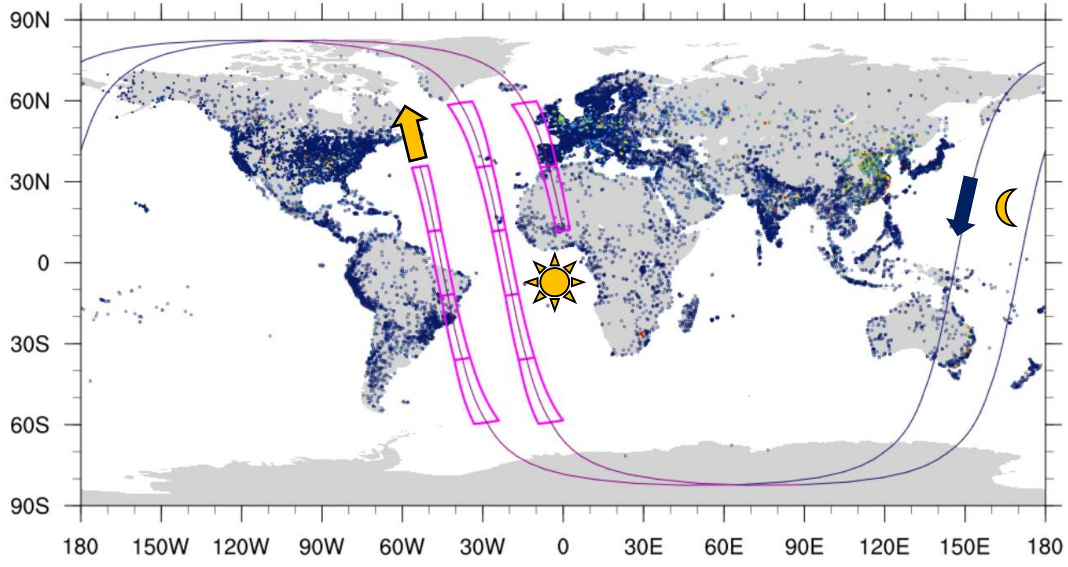
Benefits of fine (< 50 m) ground resolution:

- Enhanced concentration contrast
- Plume sampling by multiple ground pixels (plume detection via NO_2 is not required)
- Plume shape analysis for constraining turbulent dispersion

Drawbacks:

- Dense coverage on larger scales is not possible
- Operation restricted to “target mode”, focusing on a few 50 km x 50 km scenes per orbit

Thus: conceived of as a “magnifying glass” to complement measurements from CO2M, and other survey missions.



- Orbit altitude: 575 km
  → *Inclination = 97.6618°*
  → *Orbital period T = 1.60033 h*
  → *Orbits per day = 14.9969*
  → *Velocity = 7.57304 km/s*
- Agility = ± 25°
  - along track
  - across track
- Integration time = 89 ms
- ≈ 5 targets per branch between 60°S & 60°N
  → *time for repositioning*

CO2Image: instrument description

Fine ground-pixel resolution (<50 m) and target mode require…

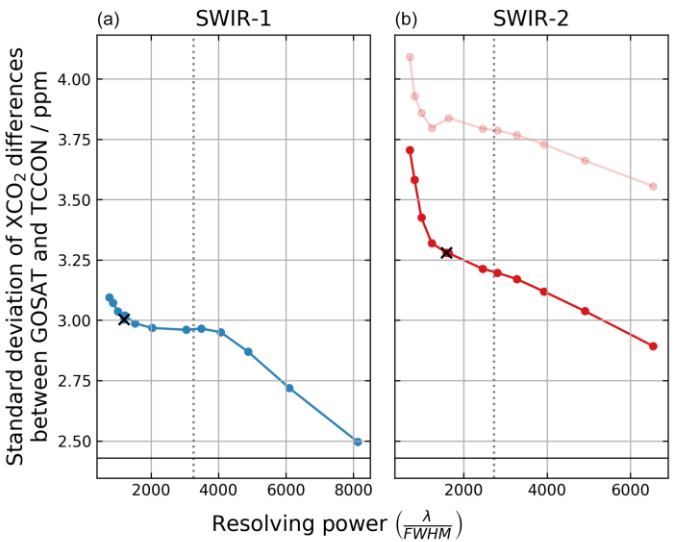
…a large telescope, fast optics, and forward motion compensation.

Orbit	600 km, sun-synchronous
Mass	90 kg
Swath	50 km
Spatial resolution	$50 \times 50\,\mathrm{m}^2$
Spectral range	1559–1672 or 1982–2092 nm
FWHM (2.5 pix)	1.37 or 1.29 nm
Resolving power	1200 or 1600 (–)
Aperture diameter	15.0 cm
f number (f_{num})	2.4 (–)
Optical efficiency (η)	0.48 (–)
Integration time (t_{int})	70 ms
Detector pixel area (A_{det})	$900\,\mu\mathrm{m}^2$
Quantum efficiency (Q_{e})	$0.8\,\mathrm{e}^-\,\mathrm{photon}^{-1}$
Dark current (I_{dc})	$1.6\,\mathrm{fA\,pix}^{-1}\,\mathrm{s}^{-1}$
Readout noise	$100\,\mathrm{e}^-$
Quantization noise	$40\,\mathrm{e}^-$

…collecting sufficient photons and CO_2 absorption signal in the spectral domain, i.e. **coarser but not too coarse spectral resolution**:

- **Preference to SWIR-2 (2 micron) over SWIR-1 (1.6 micron):** SWIR-1 too noisy due to smaller CO_2 absorption optical depth (even when accounting for typically higher albedo).
- **“Optimal” resolving power ~1500 (1-1.5 nm at 2 micron).** Smaller resolving power implies (unresolvable) **correlations with surface spectral reflectance**.

Retrieval error as a function of spectral resolution, derived from degradation of GOSAT spectra



Wilzewski et al., AMT, 2020

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CO2Image: optimizing sampling to optimize plumes

To have a “good” image of an easy-to-interpret plume, we need:

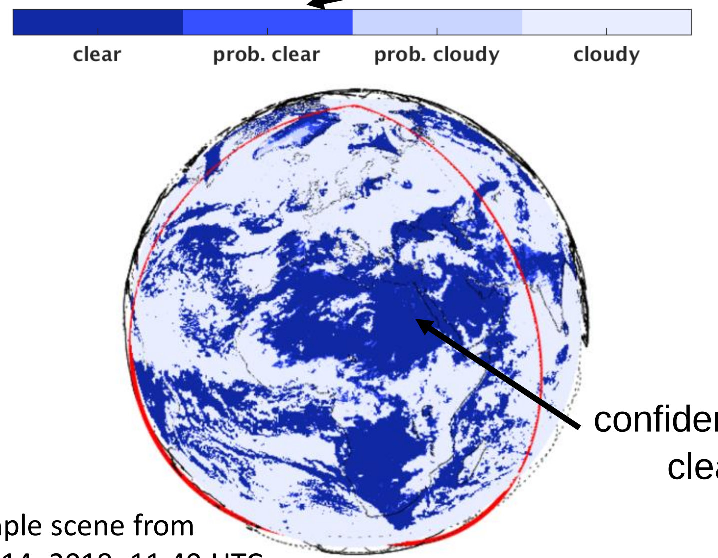
1. A cloud-free scene
2. A strong enough emission source
3. Enough wind – but not too much…
4. A detectable signal
5. A good knowledge of the wind speed (and direction)
6. A plume advected over land
7. Enough light

Can we optimize any of these factors through our choice of overpass time?

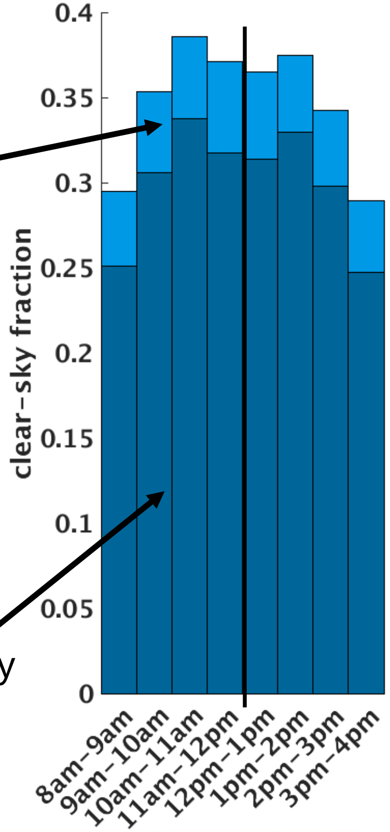
CO2Image: optimizing cloud cover

Cloud cover data from EPIC on DISCOVR:

- EPIC: Earth Polychromatic Imaging Camera at L1 point
- Provides images of the sunlit half of the earth
- Data every 1-2 hours: less frequent than geostationary, but globally consistent
- Assessment of cloud fraction for local overpass times from 8:00-16:00
- 8-km resolution at nadir
- Analysis at 0.1° resolution using data from 2018



Example scene from
June 14, 2018, 11:40 UTC



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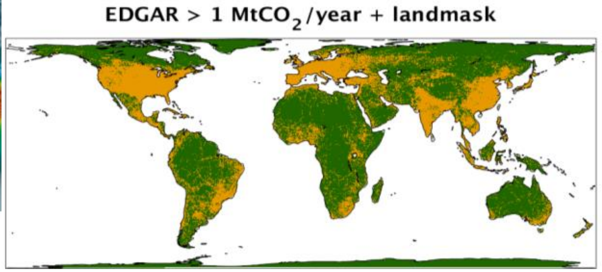

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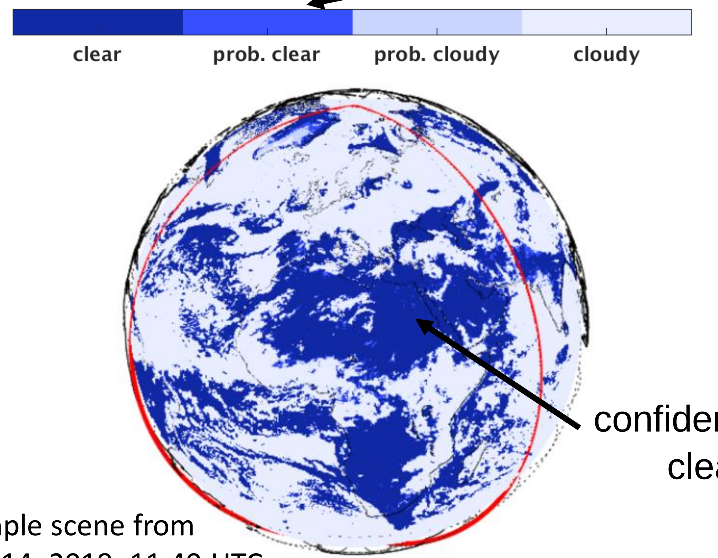

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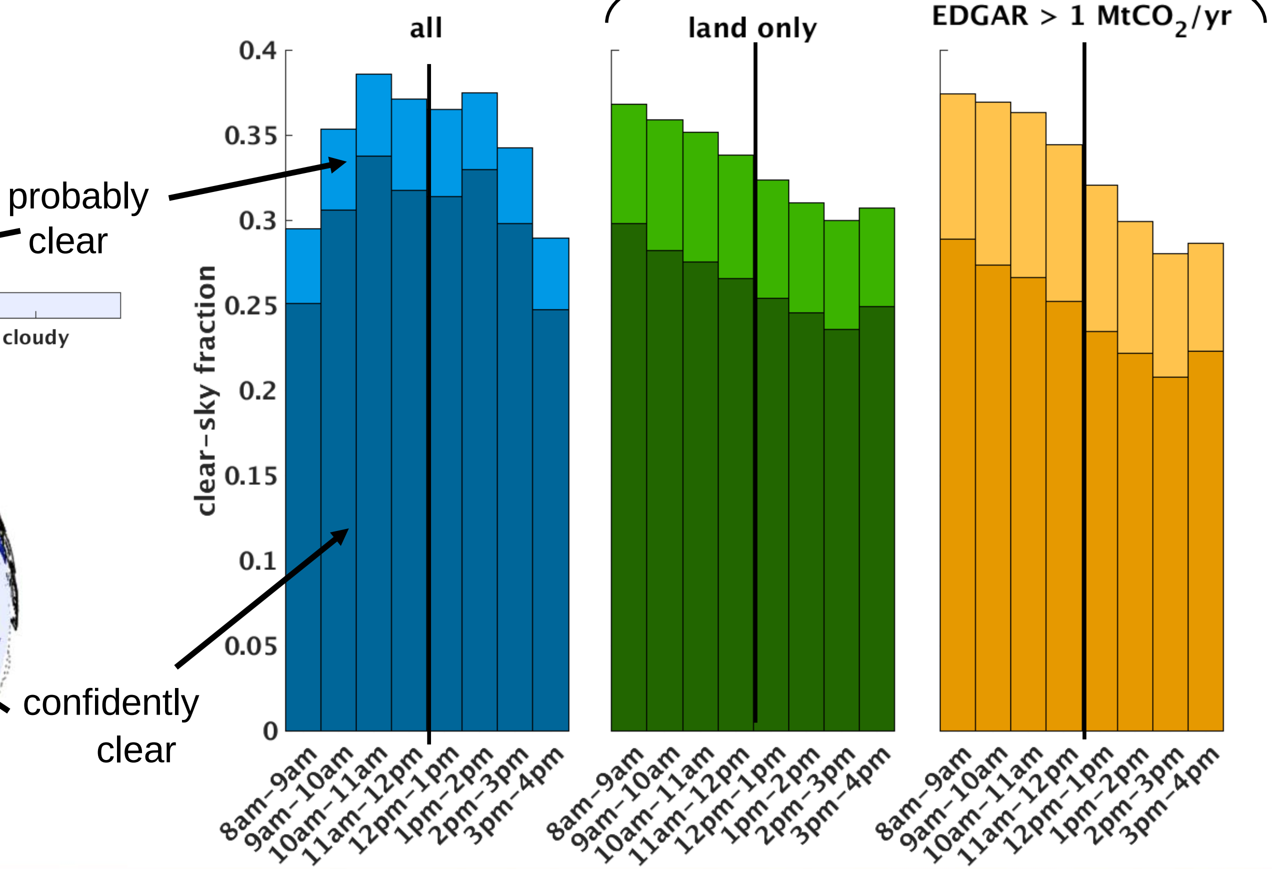
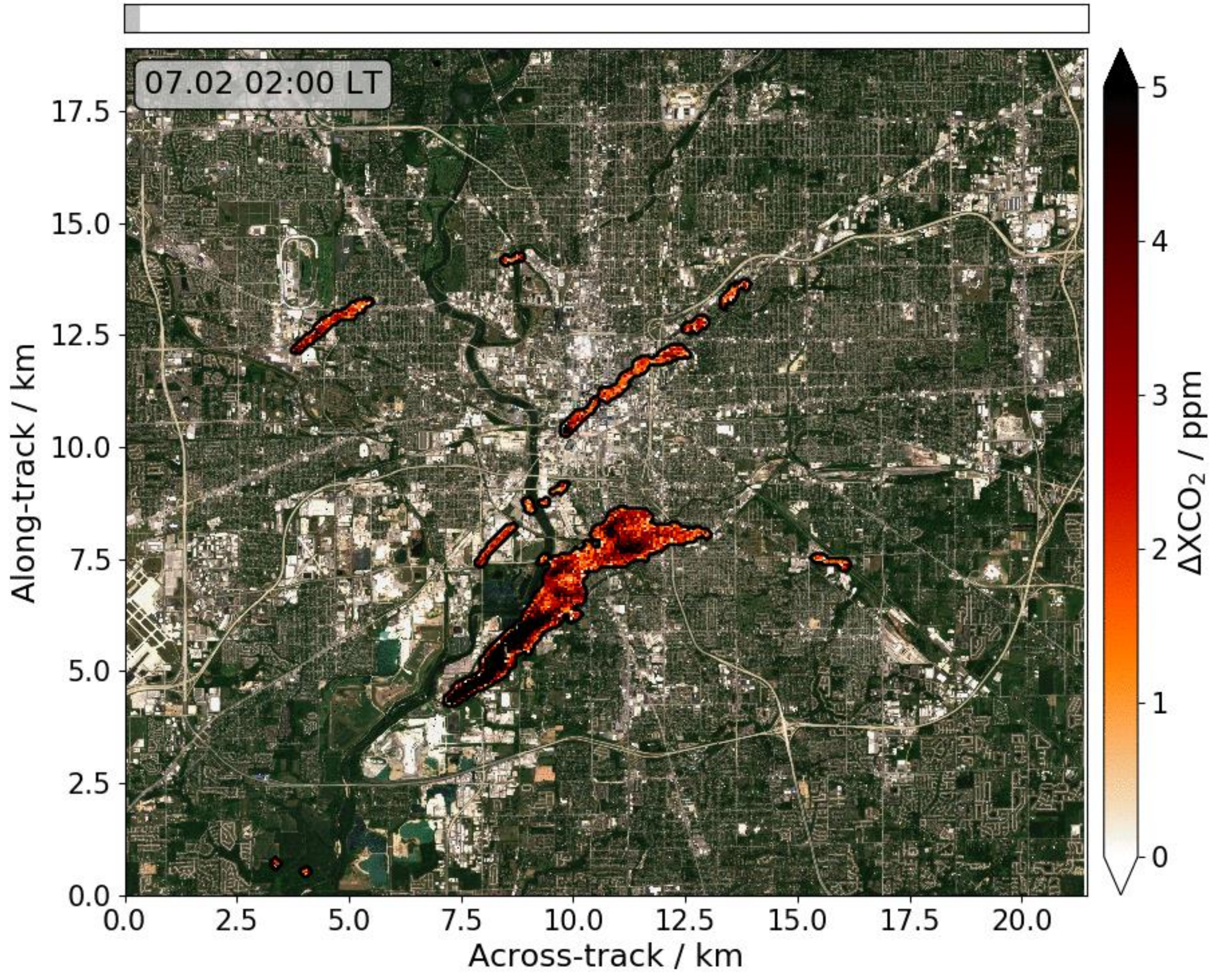


Morning overpasses have more cloud-free scenes over land targets.

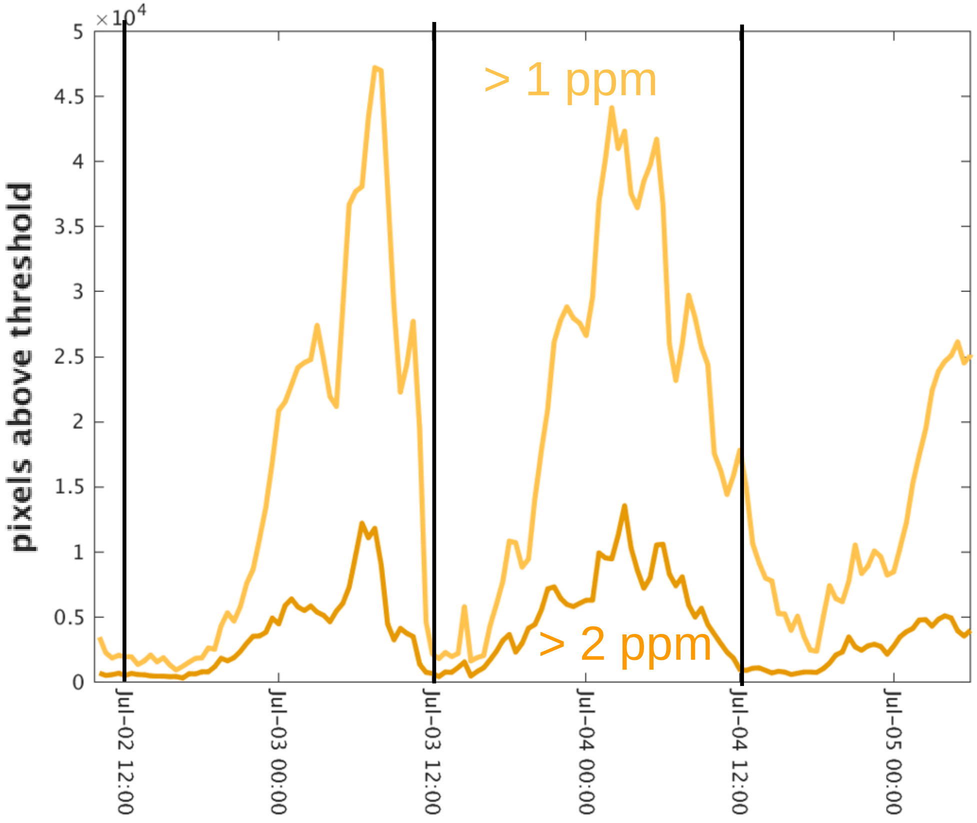
CO2Image: optimizing detectable signal

- 50-m ground resolution with ICON-LES simulations
- Emissions from Hestia (K. Gurney)
- No cloud filtering
- Plume-detecting mask shown over 24 hours, for one day in July



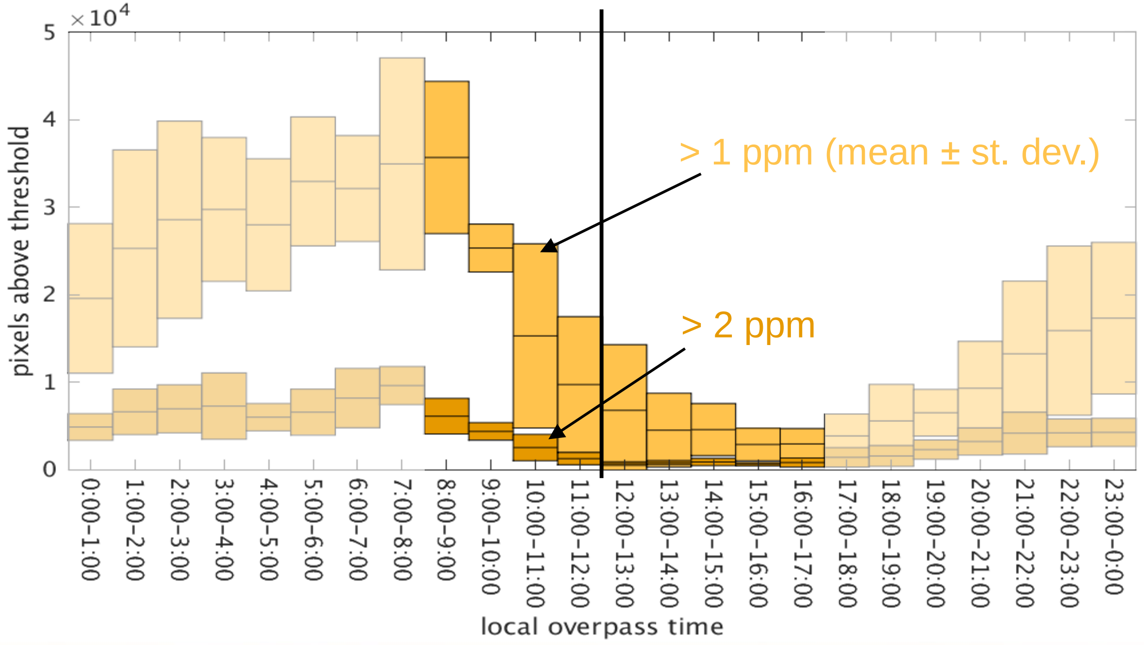
CO2Image: optimizing detectable signal

- 50-m ground resolution with ICON-LES simulations
- Emissions from Hestia (K. Gurney)
- No cloud filtering
- Summing pixels with concentrations above the 1 ppm or 2 ppm over three days of simulation

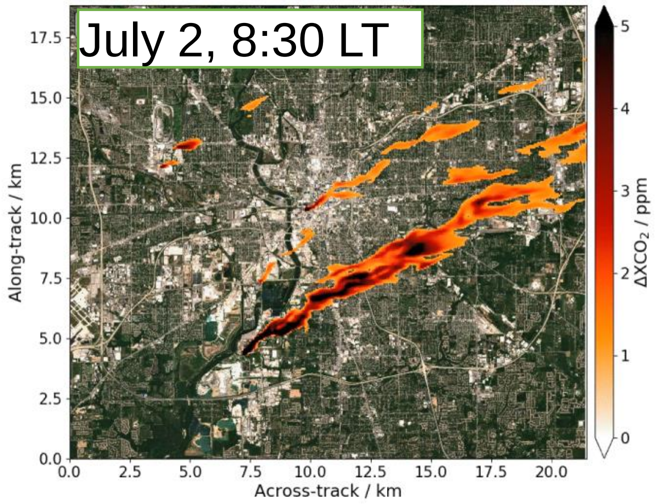


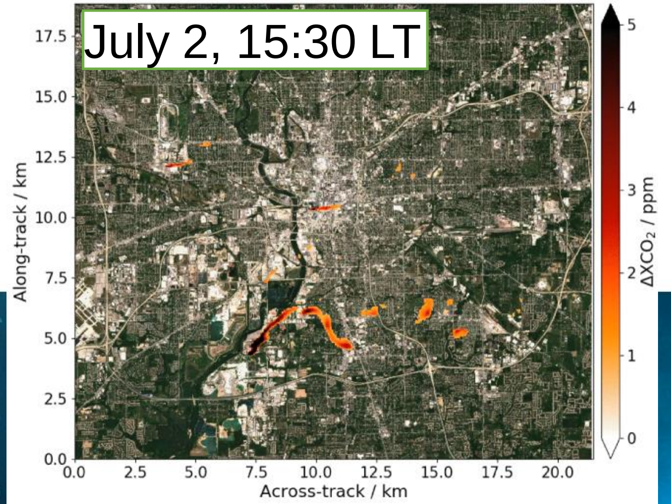
CO2Image: optimizing detectable signal

- A strong diurnal variability is found
- Plumes are more easily detected in the morning – for this three-day simulation



- Developing turbulence and deepening PBL over the day disperses the plumes

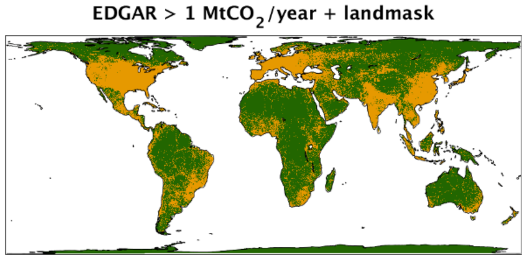


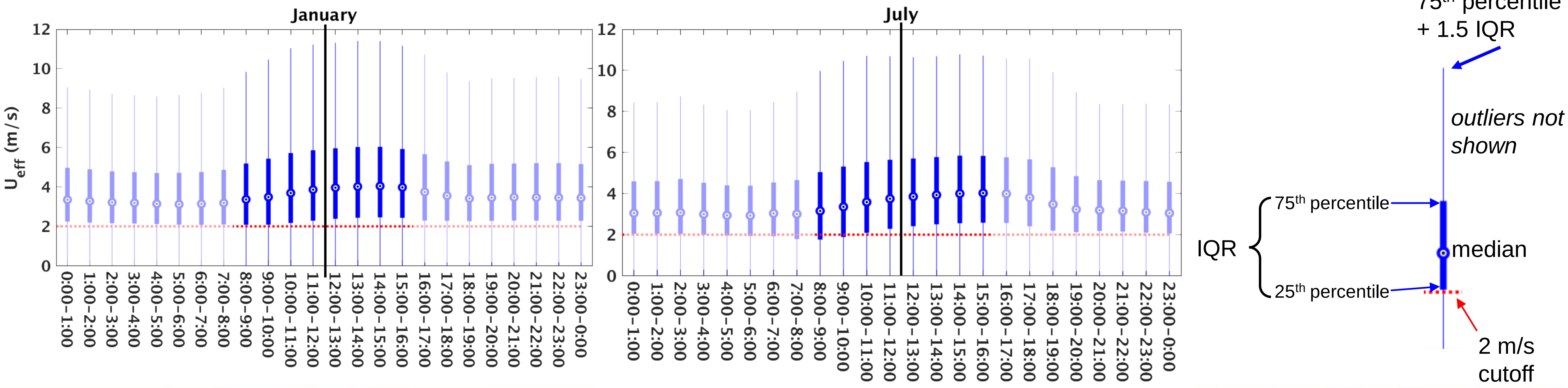


Earlier overpasses result in more detectable pixels under turbulent conditions.

CO2Image: optimizing winds

- Based on ERA5 10-m wind speed for 2019, applying empirical multiplicative factor of 1.4 for effective wind speed U_{eff} (based on Varon et al., 2018; Reuter et al., 2019)
- Analysis restricted to land regions with emissions > 1 $MtCO_2$/year in 0.1° EDGAR pixel
- Wind speed should be greater than 2 m/s:
  - Lower wind speeds good for detection but bad for source quantification
  - Too high wind speeds lead to lower in-plume enhancements





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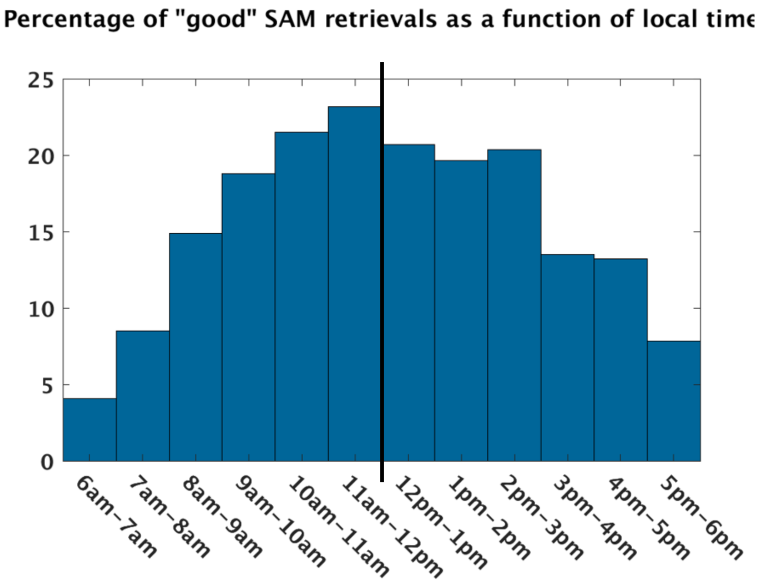
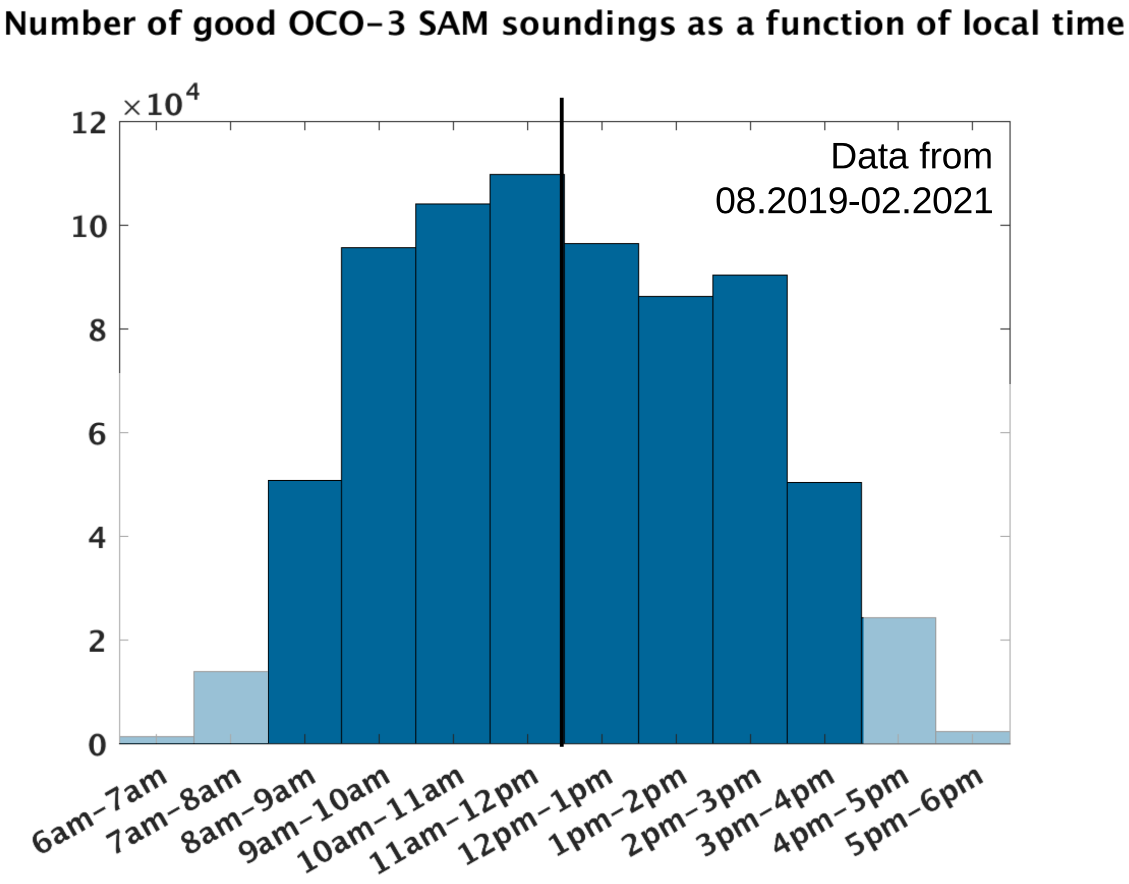
More overpasses with too-low wind speeds before noon, work ongoing to assess wind uncertainty vs. time of day…

CO2Image: optimizing retrievals

- Earlier overpasses result in larger SZAs…
- OCO-3 snapshot scenes provide some “real-world” idea of the net effect, given variable local overpass time
- Cloud cover is rolled into this
- Measurement geometry is also relevant



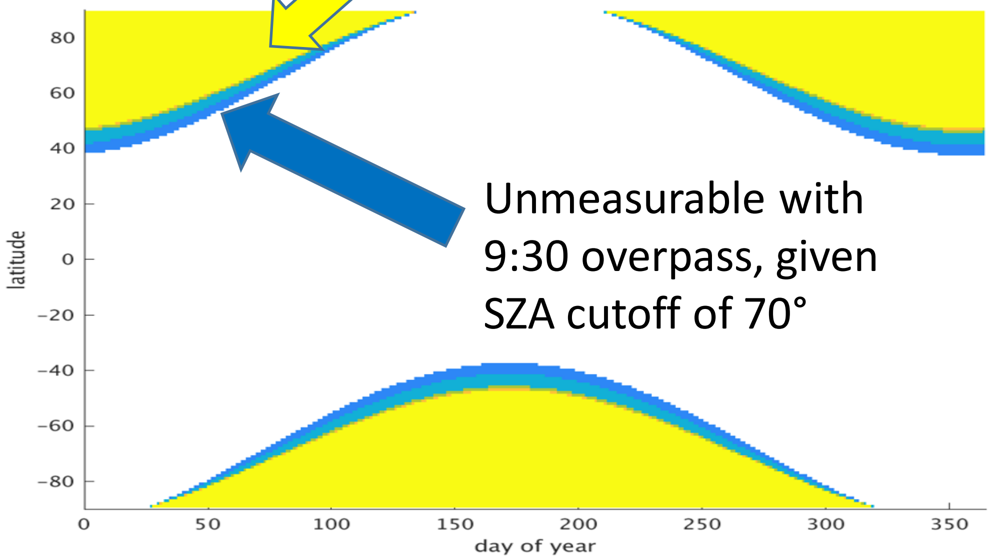
OCO-3 retrievals in snapshot area mode (SAM) show maximum yield for very low VZA (0°-5°) and moderate SZA (45°-50°).



CO2Image: optimizing overpass time

- Clear benefits of morning overpass time (like S5!)
- More (and longer) LES plume simulations needed for generalization, and impact on emission estimation
- Temporal variability of emissions found to be of little import, given the focus on CO_2 point sources
- Must consider the loss in coverage for the whole mission, combined with the optimal measurements of individual plumes

Unmeasurable with 12:00 overpass, given SZA cutoff of 70°



Unmeasurable with 9:30 overpass, given SZA cutoff of 70°

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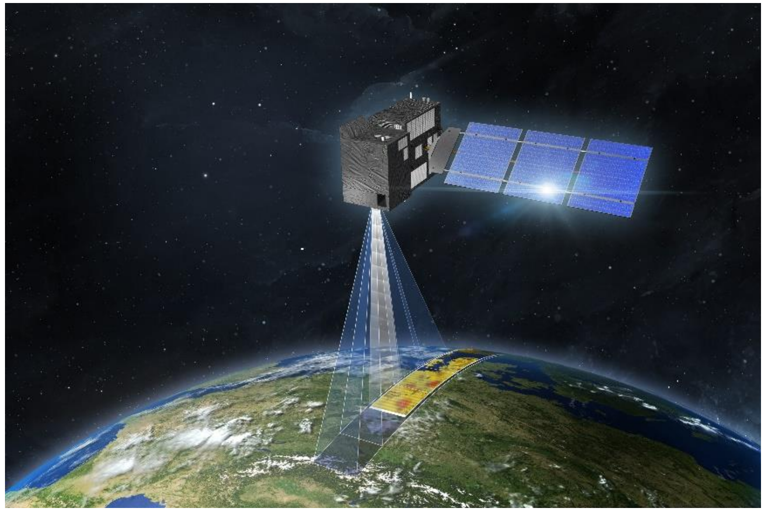
CO2Image: next steps

- Mission is funded, and has entered Phase B
- End-to-end simulator under development
- Developing and applying novel plume detection and quantification methods – currently looking for a PhD candidate for this project!
- Launch planned for 2026: complementary to the timeline of CO2M



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