Towards spaceborne monitoring of localized CO_2 emissions:
an instrument concept and first performance assessment

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EGU 2020 – Session AS3.15 – Display D3213

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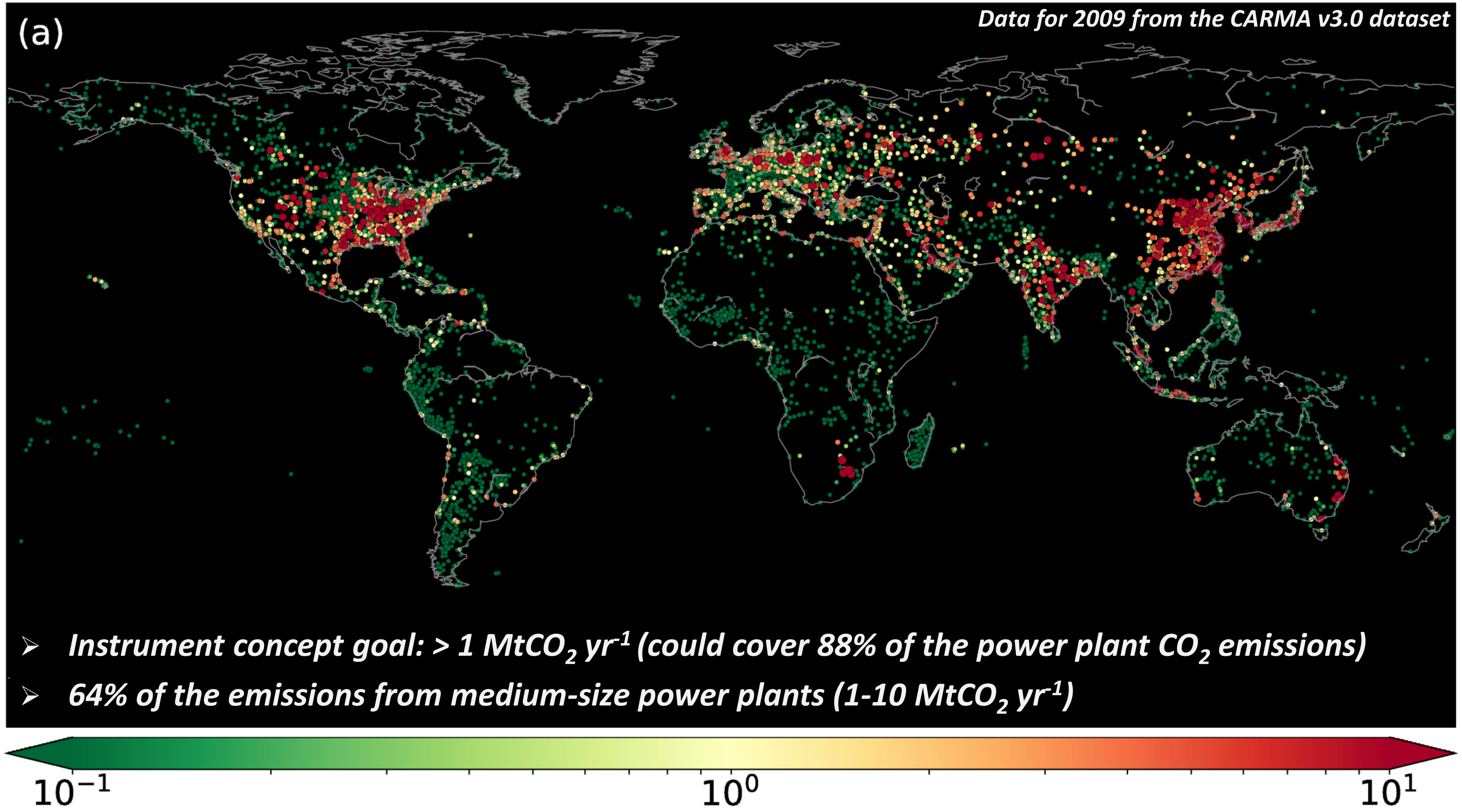
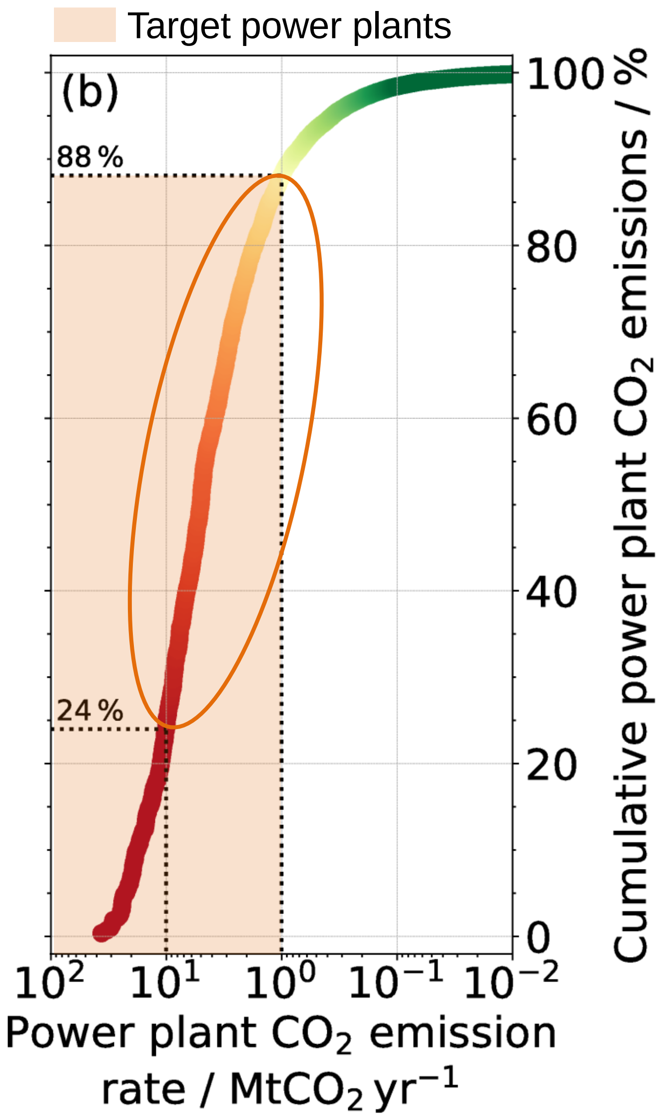
Why monitor localized CO2 emissions? How would the proposed instrument concept contribute?

- *UN Framework Convention on Climate Change requires every country to report their CO_2 emissions*
- *The Paris climate agreement requires independent verification of the reported emissions*
- *Power plants are the main source and represent approx. one third of all anthropogenic CO_2 emissions*
- *We propose the concept of an imaging spectrometer optimized for sub-plume resolution (50×50 m^2) to also resolve emissions from medium-size power plants (1-10 $MtCO_2\ yr^{-1}$), currently not targeted by other satellite missions*
- *Such an instrument would be a valuable companion and complement to the fleet of current and planned satellite missions measuring atmospheric CO_2 column concentrations*

Global distribution of power plant CO_2 emissions

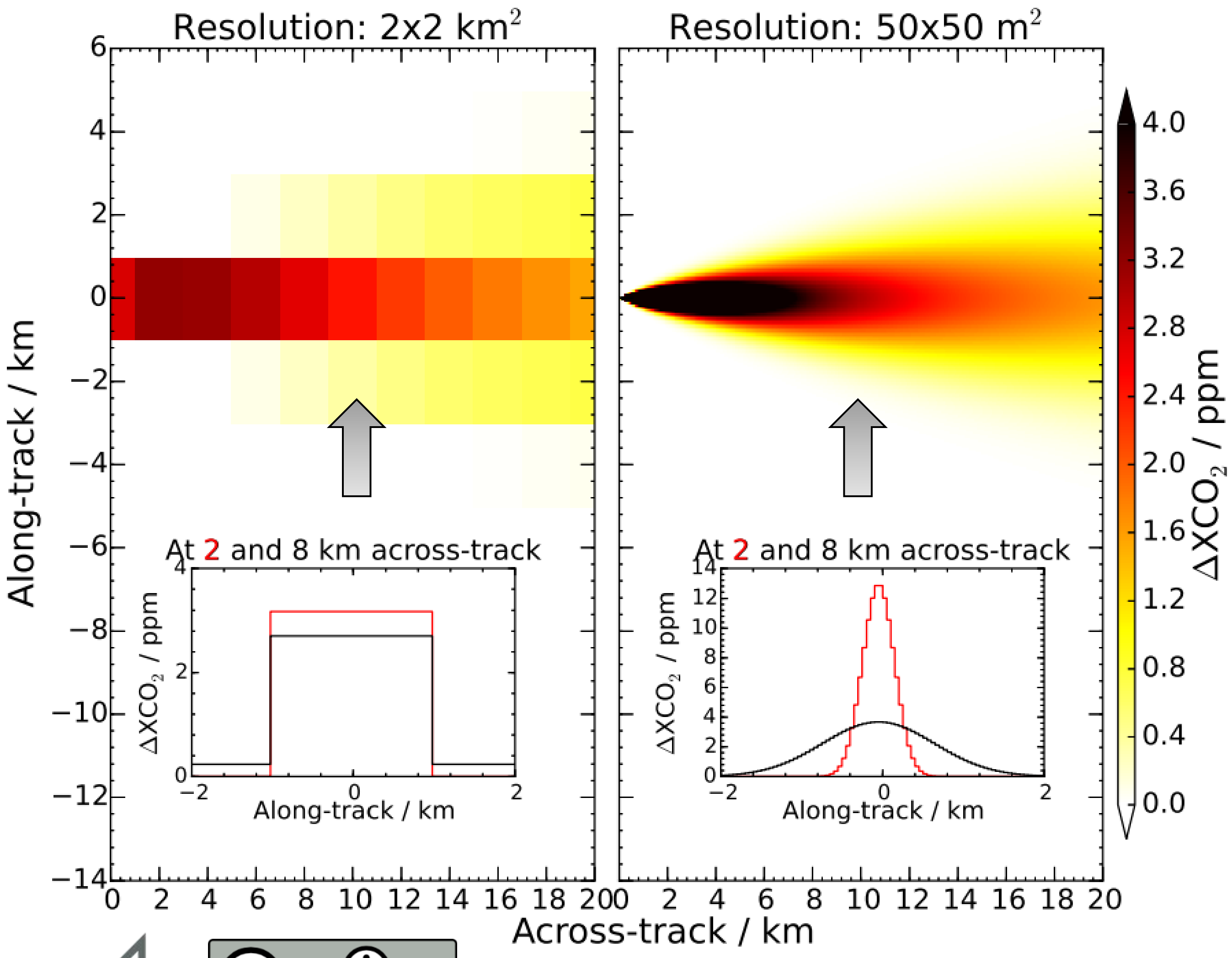


- *Instrument concept goal: > 1 $MtCO_2\,yr^{-1}$ (could cover 88% of the power plant CO_2 emissions)*
- *64% of the emissions from medium-size power plants (1-10 $MtCO_2\,yr^{-1}$)*



Ummel, 2012; Strandgren et al., 2020, in press

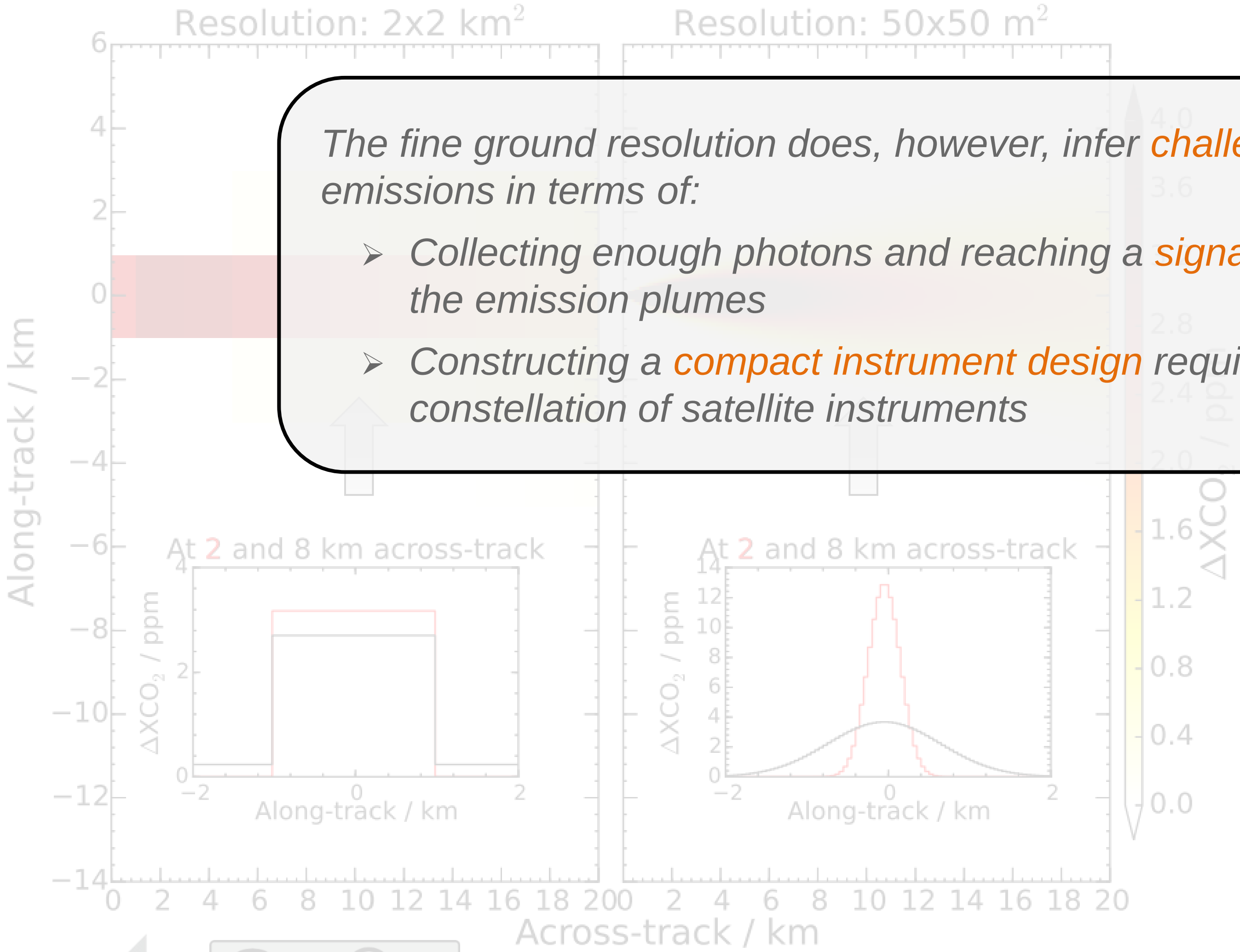
Fine ground resolution key to measure localized CO_2 emissions



- Power plant emissions cause large column concentration enhancements in the vicinity of the source
- But, these enhancements become small when averaging with the background in km-scale ground pixels
- Point source detection and quantification of medium-size power plant emissions need fine ground resolution

Wilzewski et al., 2020

Fine ground resolution key to measure localized CO_2 emissions



The fine ground resolution does, however, infer challenges for the monitoring of localized CO_2 emissions in terms of:

- *Collecting enough photons and reaching a signal-to-noise ratio (SNR) sufficient to resolve the emission plumes*
- *Constructing a compact instrument design required for global monitoring through a constellation of satellite instruments*

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Proof of concept and spectral sizing using spectrally degraded GOSAT measurements

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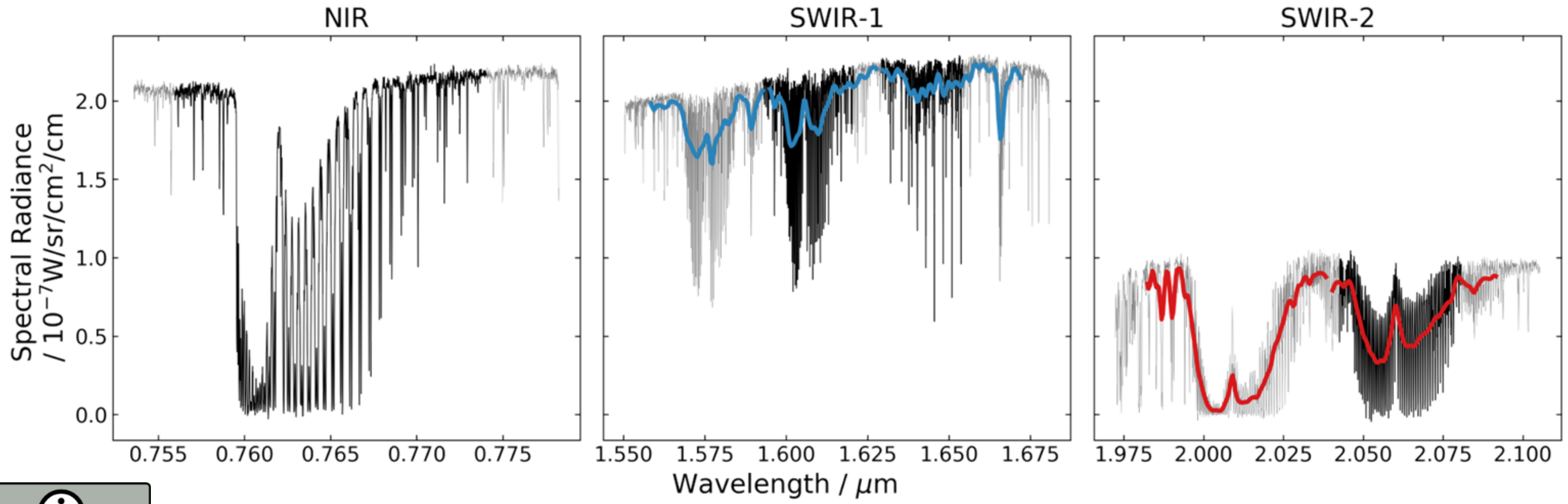
Spectral sizing of proposed instrument concept

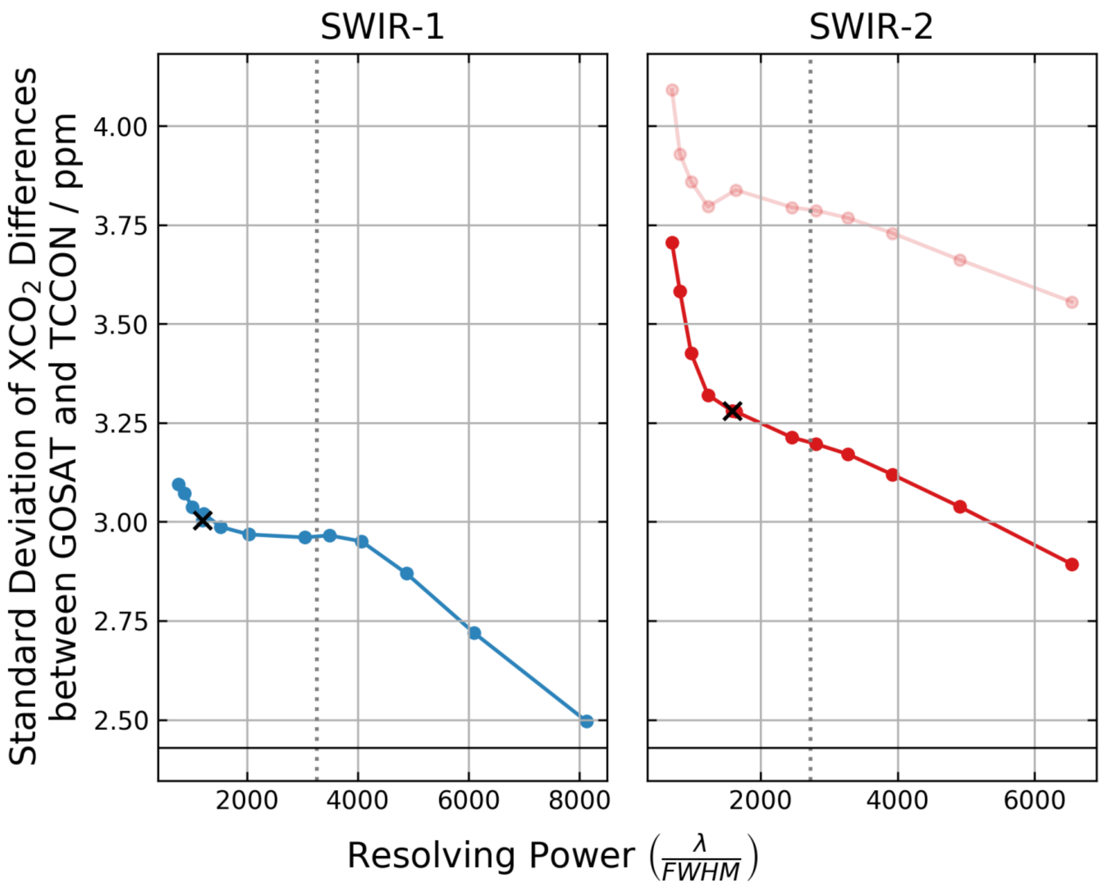
- *For a compact instrument design a single spectral window shall be used.*
  - *Two alternative spectral windows, SWIR-1 and SWIR-2, are investigated*
- *Measured GOSAT spectra (grey thin lines) are convolved to mimic spectra of proposed instrument concept (**blue** and **red** bold lines)*
- *XCO_2 is retrieved using the RemoTeC algorithm and the convolved spectra*
- *Black thin lines show the spectra used for native GOSAT XCO_2 retrievals with RemoTeC*



Wilzewski et al., 2020

Spectral sizing of proposed instrument concept

- Increasing level of spectral degradation is performed in order to determine the appropriate spectral resolution for the proposed instrument
- XCO_2 retrieved from spectrally degraded GOSAT spectra is compared to reference data from TCCON[1]
- Modifications of the light path due to scattering aerosol are accounted for in retrievals from SWIR-2 spectra. (Light red line shows results for SWIR-2 retrievals when scattering is neglected)
- Due to low sensitivity to aerosol, retrievals from SWIR-1 spectra neglect scattering
- Black crosses mark the spectral resolution chosen for further analysis

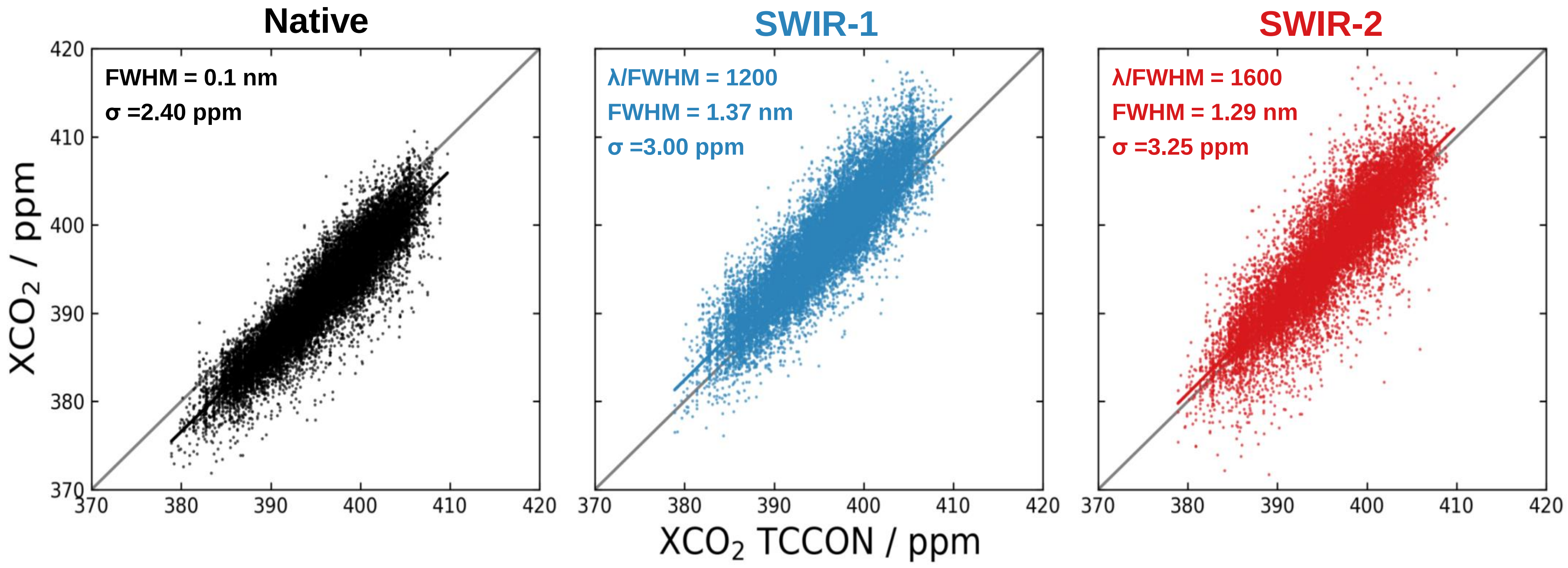


[1]Total Carbon Column Observing Network

Wilzewski et al., 2020

Validation with TCCON measurements

- *Precision of XCO_2 retrieved from spectrally degraded GOSAT spectra below 1% for both SWIR-1 (3.00 ppm) and SWIR-2 (3.25 ppm) with respect to reference TCCON measurements*
- *Precision decreases only moderately compared to native GOSAT retrievals (2.40 ppm)*

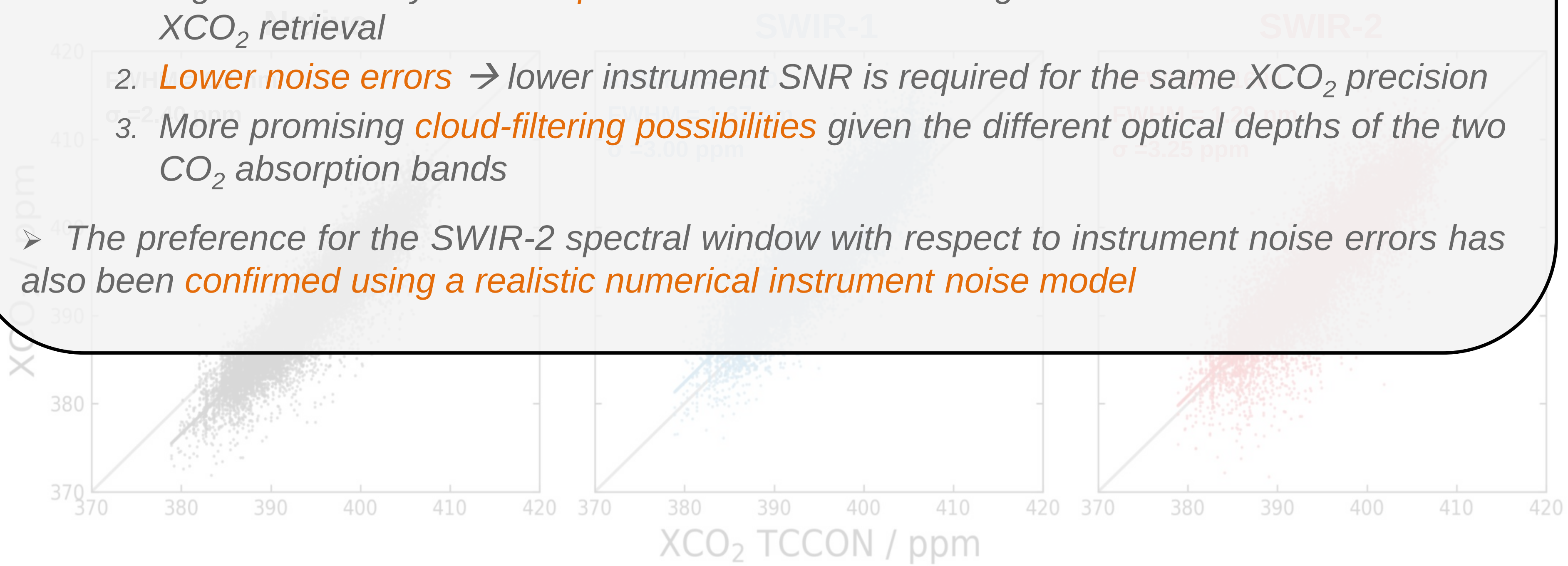


Wilzewski et al., 2020

Validation with TCCON measurements

Conclusion

- Analysis using spectrally degraded GOSAT measurements shows similar precision for the two alternative spectral windows SWIR-1 and SWIR-2
- However, the SWIR-2 spectral window is preferred for the proposed instrument concept, mainly due to three reasons:
  1. Higher sensitivity to atmospheric aerosol → scattering can be better accounted for in XCO_2 retrieval
  2. Lower noise errors → lower instrument SNR is required for the same XCO_2 precision
  3. More promising cloud-filtering possibilities given the different optical depths of the two CO_2 absorption bands
- The preference for the SWIR-2 spectral window with respect to instrument noise errors has also been confirmed using a realistic numerical instrument noise model



Wilzewski et al., 2020

Assessing the proposed instrument's CO_2 monitoring performance through simulations

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Step 1: Simulating synthetic measurements

Preliminary instrument design
Orbit, spectral sizing, optical design and detector properties → SNR

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

Strandgren et al., 2020, in press

Step 1: Simulating synthetic measurements

Preliminary instrument design
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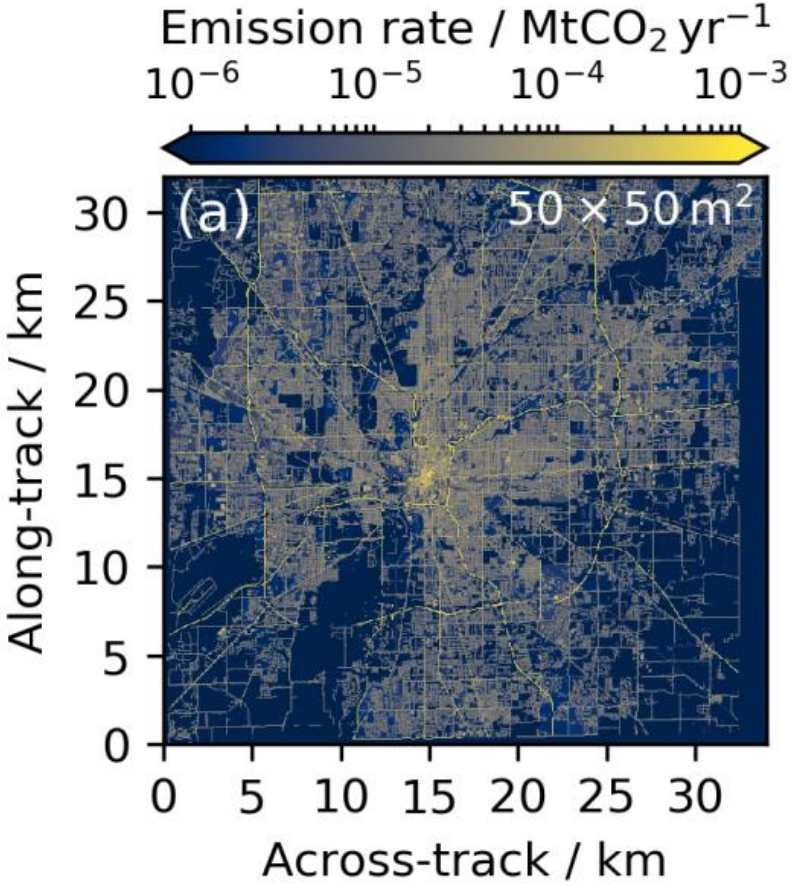
Realistic urban emission scenario
Hestia data for Indianapolis



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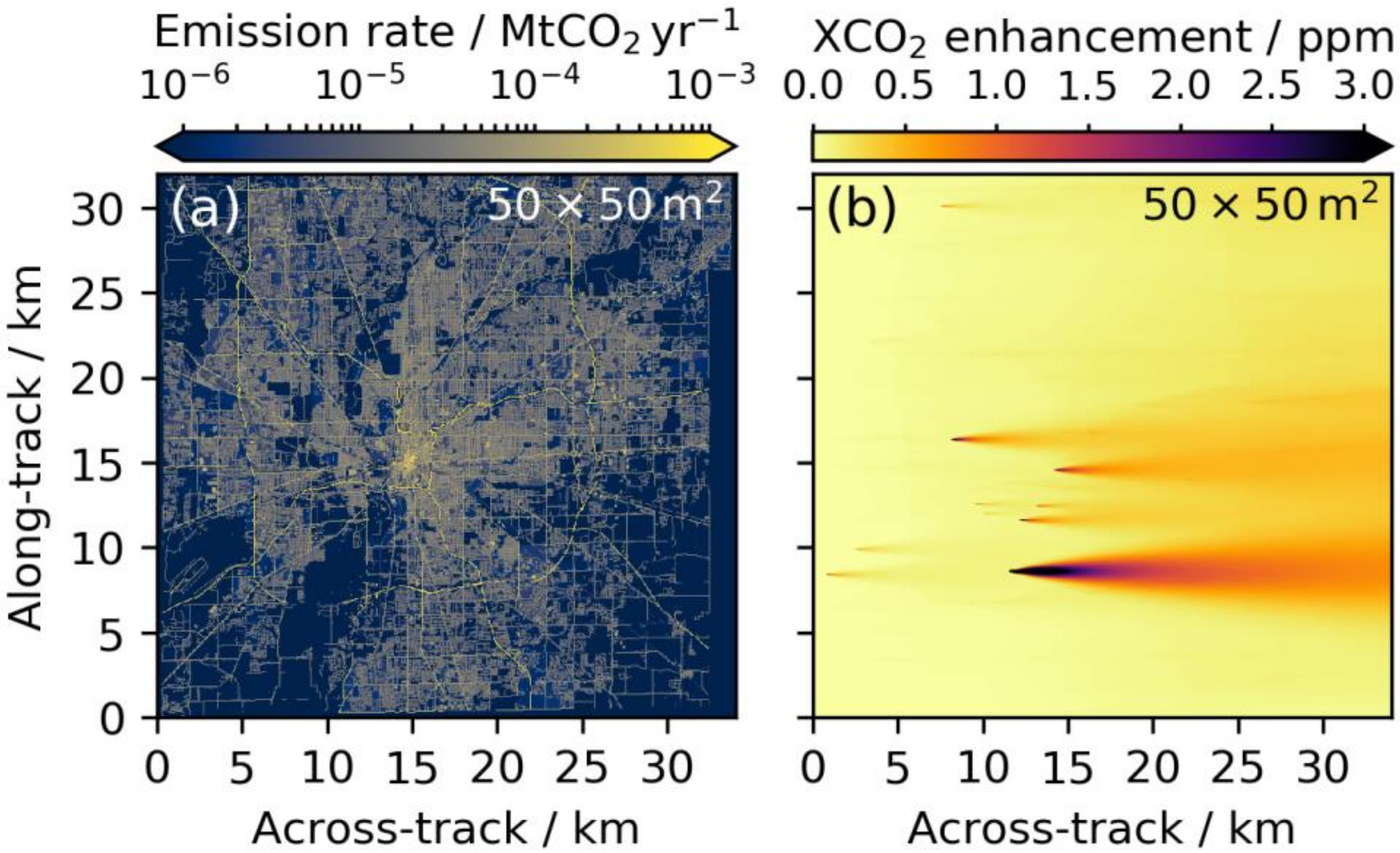
3D CO_2 concentration field
Gaussian plume model



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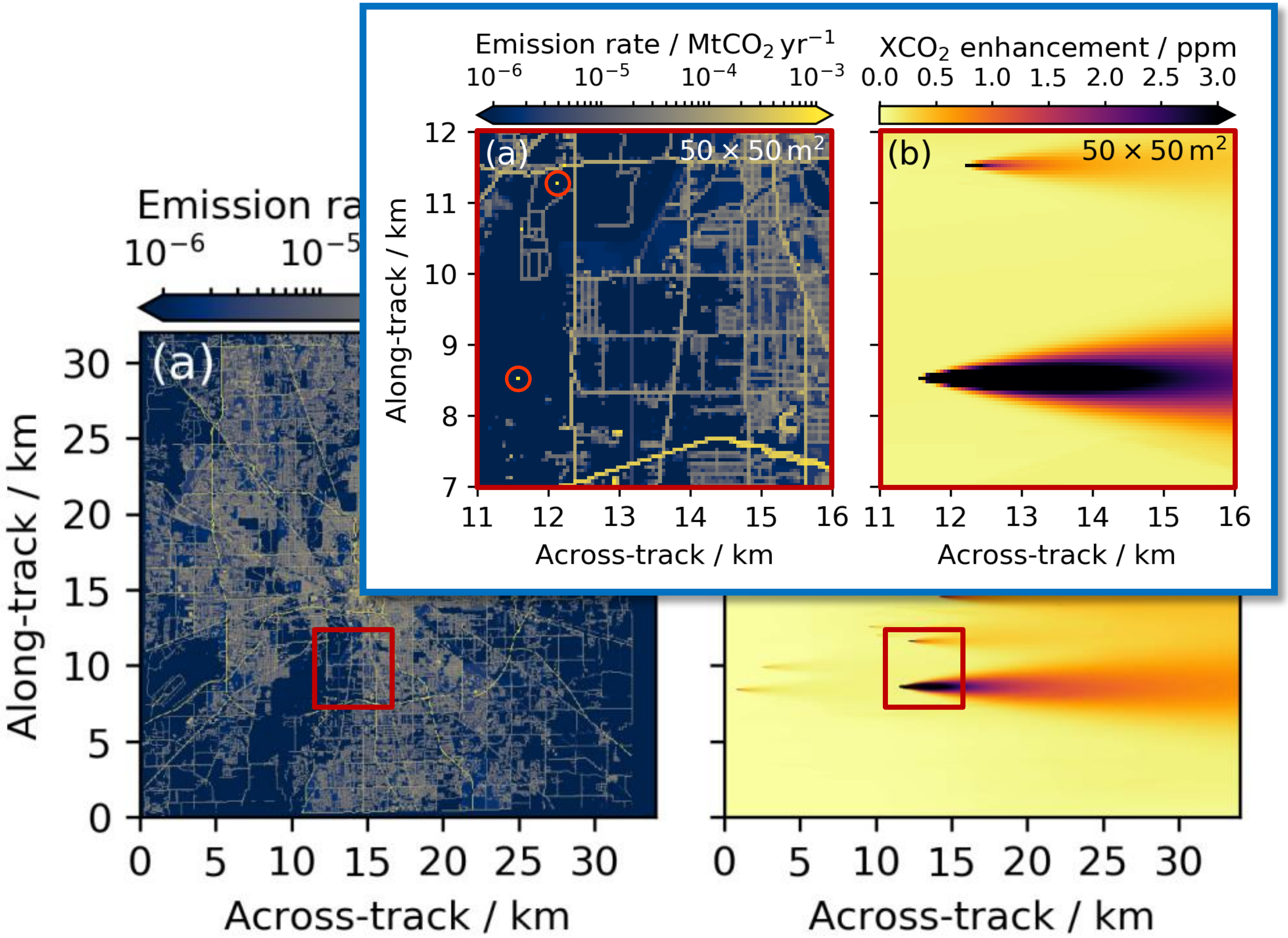

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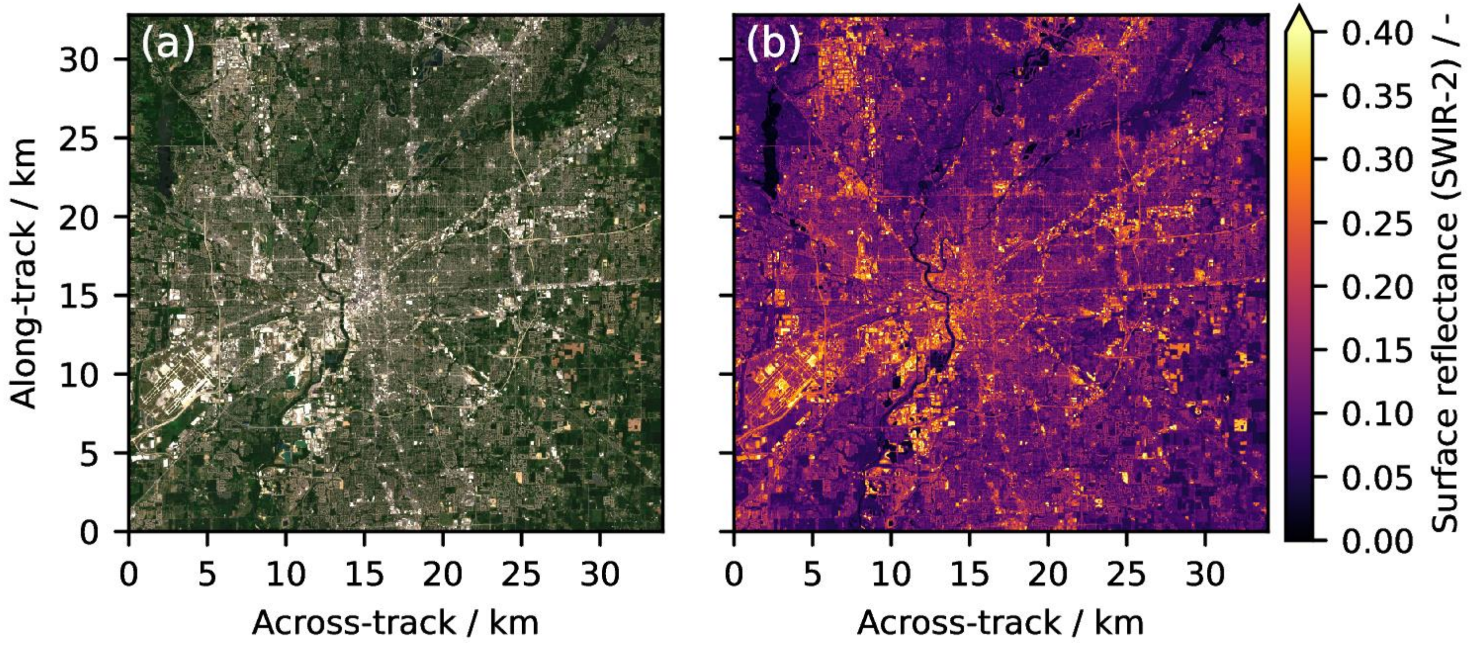
Surface albedo
Sentinel-2 data



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→

Radiative transfer model
- Sun-satellite geometry
- Numerical instrument noise model

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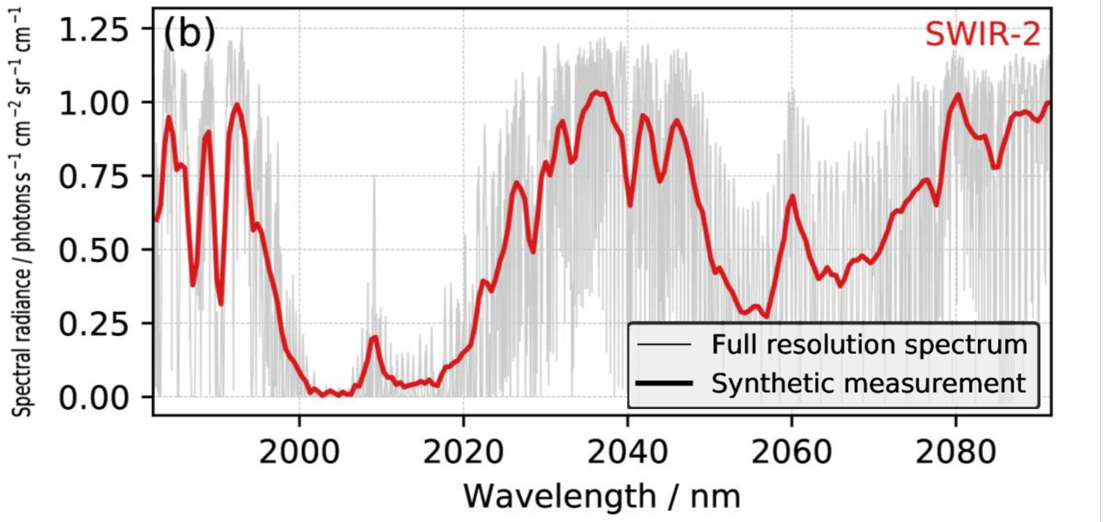
Simulated synthetic spectrum

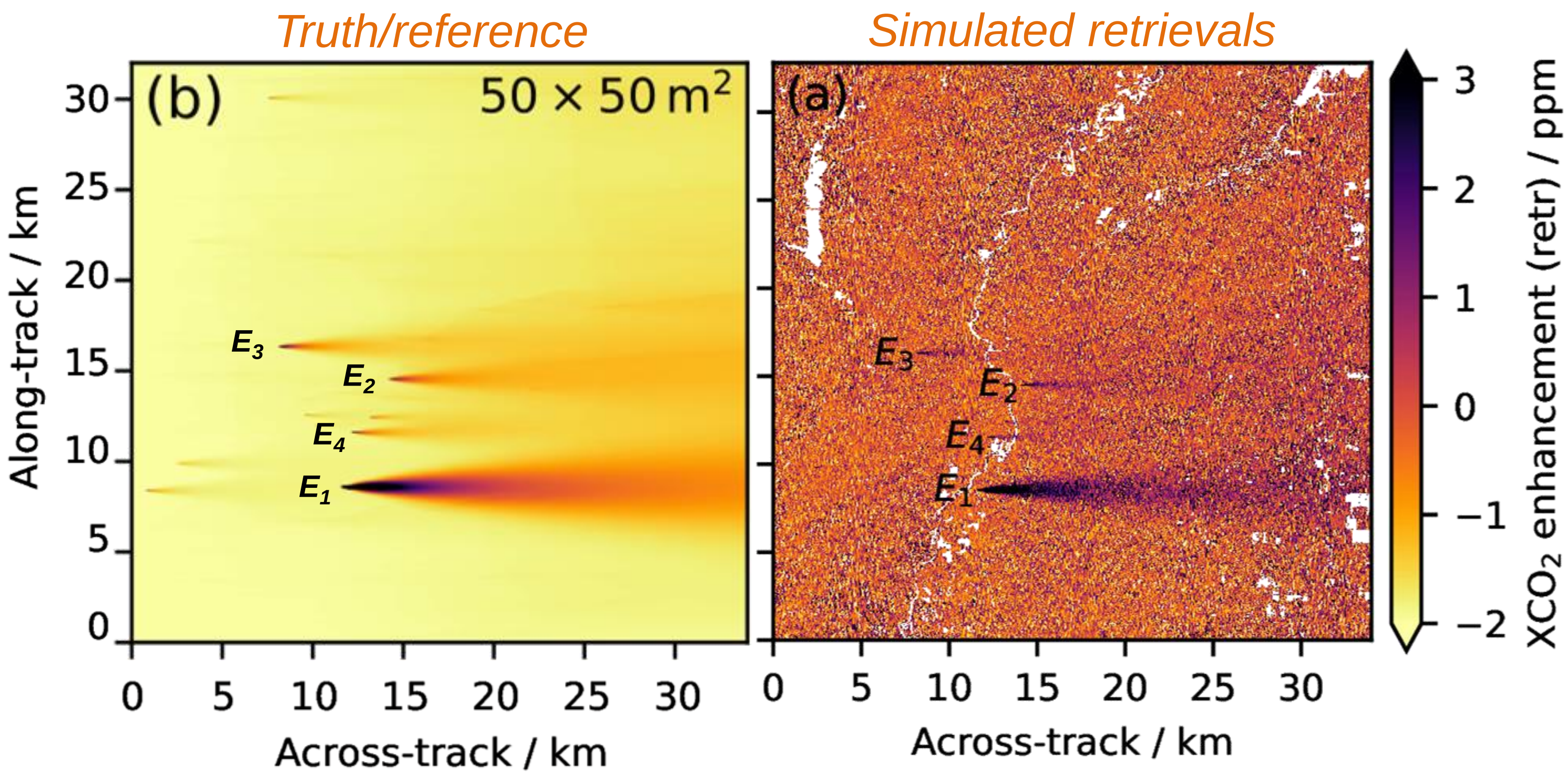


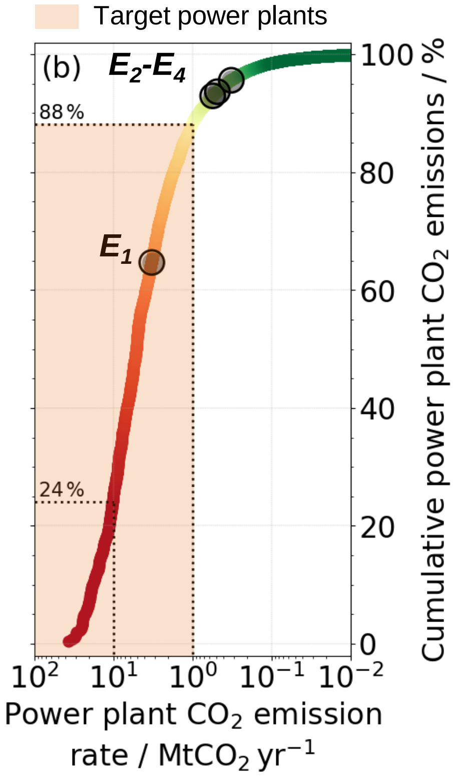
= what the proposed instrument would measure for the given scenario and instrument design

Strandgren et al., 2020, in press

Step 2: Retrieve corresponding XCO_2 from the synthetic measurements

- *During the retrieval, a set of variables in the state vector (XCO_2, H_2O, albedo, solar/spectral shift) are fitted*
- *The ability to find the true parameters is limited by the instrument's noise level (SNR)*
- *Hence, we can evaluate the instrument's CO_2 monitoring capabilities by looking at the retrieved (noisy) XCO_2 field*





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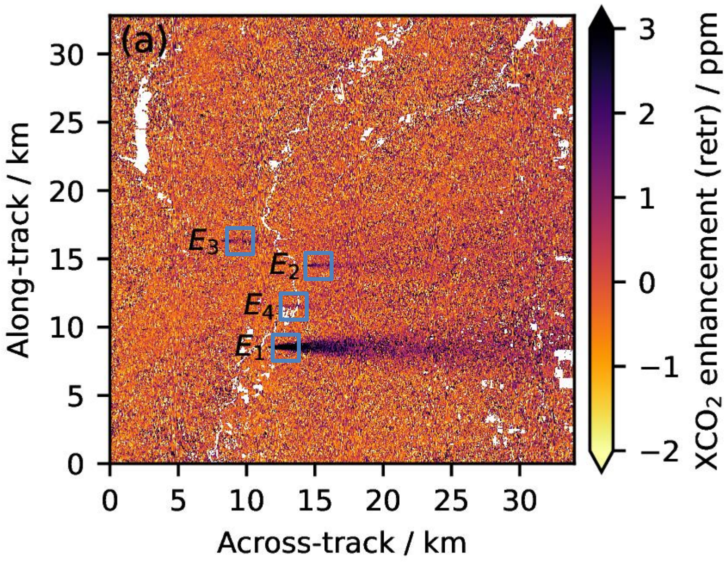

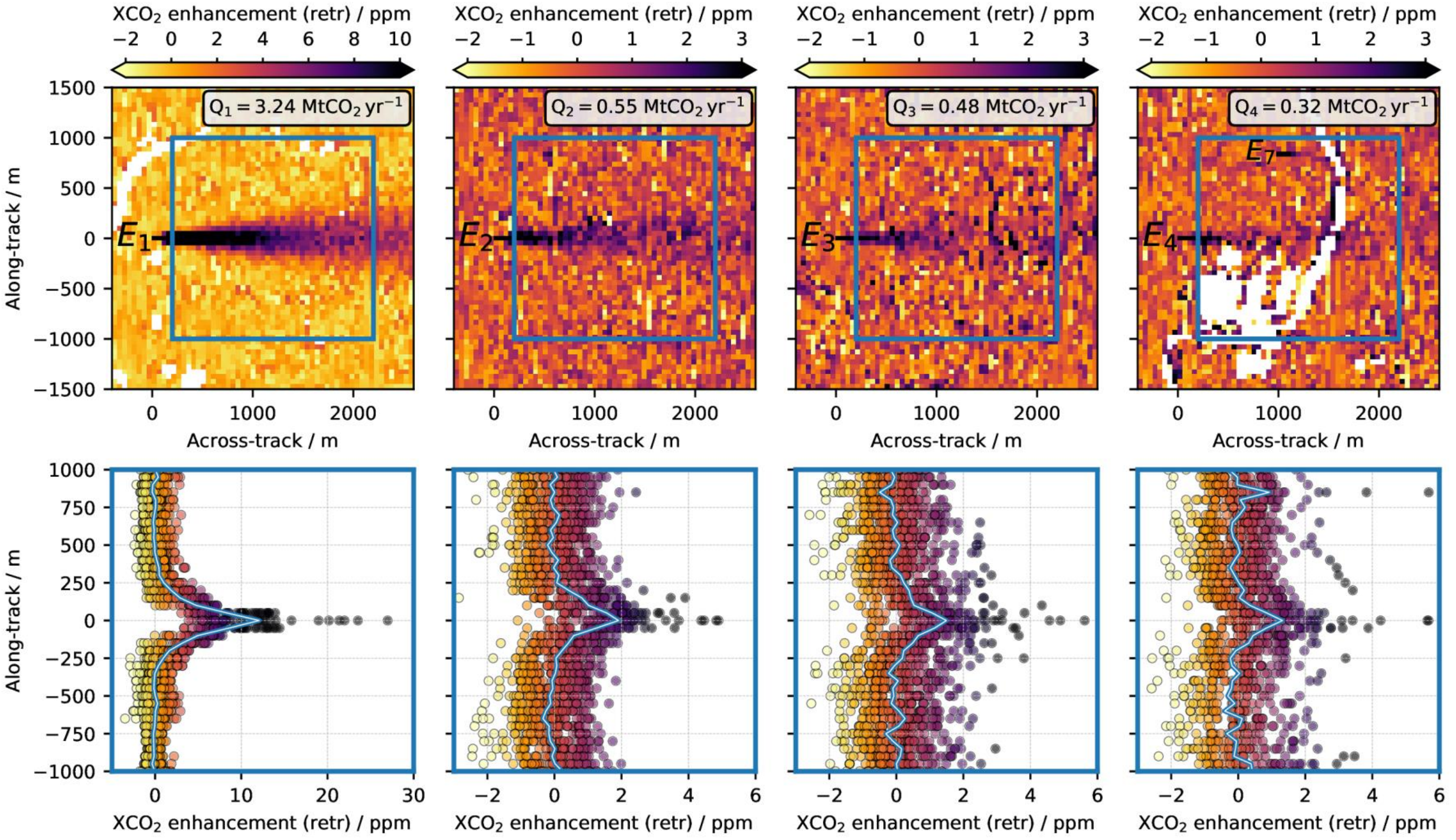

Upper panels Retrieved two-dimensional fields of XCO_2 enhancements in the vicinity of the four strongest CO_2 emitters E_1, E_2, E_3 and E_4 within the Hestia Indianapolis dataset. **Lower panels** Corresponding per-pixel (circles) and average (solid lines) along-track XCO_2 enhancements within the area 200 to 2200 m downwind and -1000 to 1000 across-wind of the respective emitters. The blue rectangles in the upper panels show the areas from which the corresponding per-pixel and average along-track XCO_2 enhancements, depicted in the respective lower panels, are extracted and calculated. The color of the circles follow the color bars in the respective upper panels.

Strandgren et al., 2020, in press

Summary and conclusions

- *Systems for the independent verification of reported CO_2 emissions are needed*
- *Emissions from medium-size power plants (1-10 $MtCO_2$ yr^{-1}) are responsible for a significant part of anthropogenic CO_2 emissions in general and from the power plant sector in particular*
- *In order to independently monitor such emissions from space we propose an imaging spectrometer with a fine ground resolution of 50 x 50 m^2*
- *Measurements near 2.0 µm (SWIR-2 window) are most promising for this task*
- *Simulations using a realistic instrument design, emission scenario and surface albedo show that when the instrument is only limited by its own noise, plumes from emitters with a source strength down to 0.3 $MtCO_2$ yr^{-1} can be resolved*

  → *Significant margin for additional error sources (e.g. aerosols, meteorology)*
- *The compact instrument design, with a single spectral window, would allow for a constellation of satellites, hence increasing the spatial coverage and temporal resolution*

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Outlook

The next steps that we are currently working on include:

- *Simulate CO_2 plume dispersion with LES, rather than Gaussian, modeling*
- *Include scattering effects by atmospheric aerosol in the radiative transfer simulations also at local/urban scale*
- *Quantify the ability to inversely determine the corresponding CO_2 emission rates under various conditions representing for example different emission source strengths, seasons, surface albedo, meteorological conditions etc.*

Thank you for you interest!

Please feel free to contact me for any questions
Email: anytime
EGU live chat: 2020/05/06, 08:30-10:15 CEST

Johan.Strandgren@dlr.de

Further details and references can also be found in the following publications:

Wilzewski et al., AMT, 2020

Strandgren et al., AMTD, 2020