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ADECEES: Anomaly DEtection of CO_2 Emissions via Ensemble Segmentation

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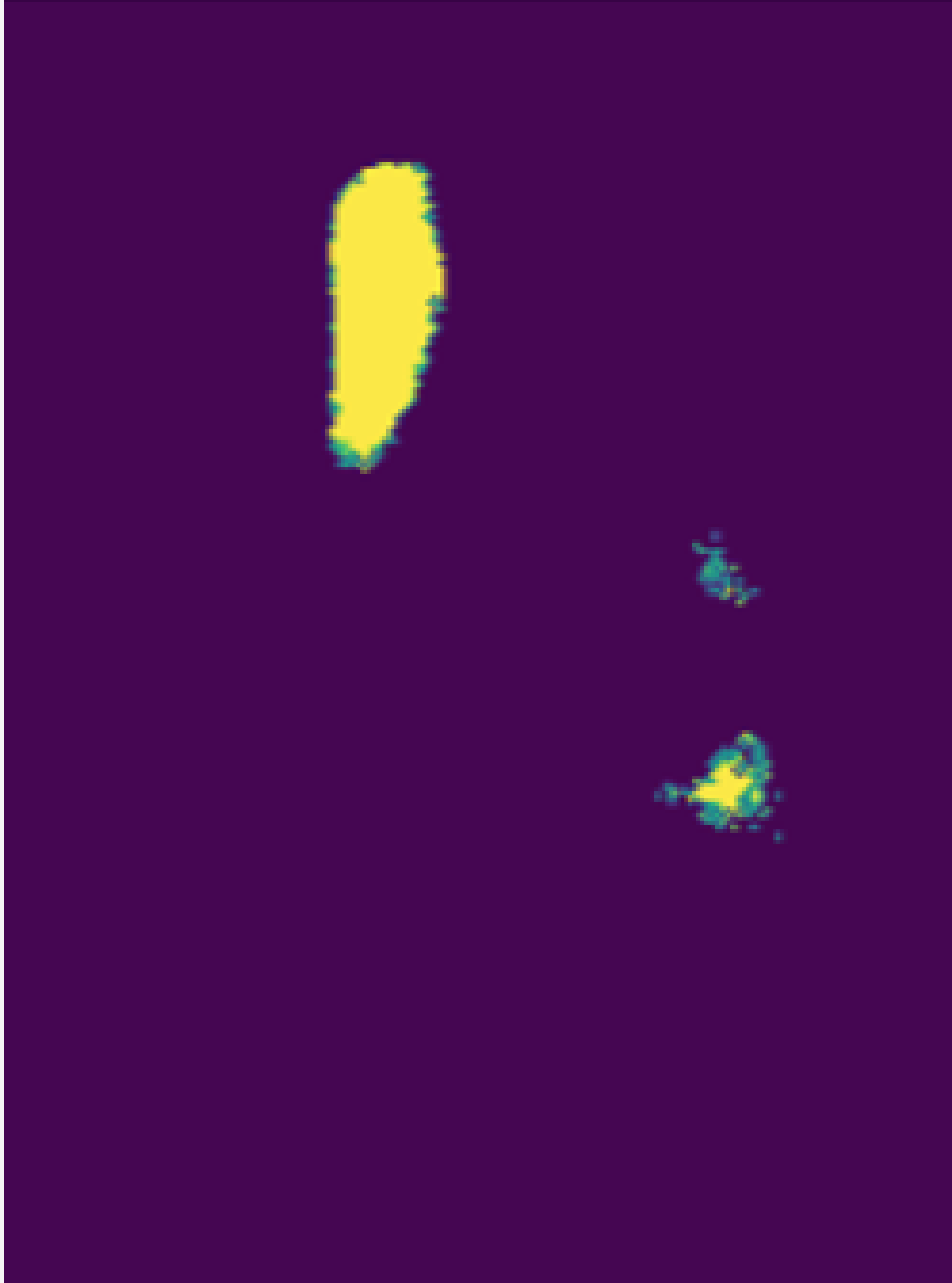
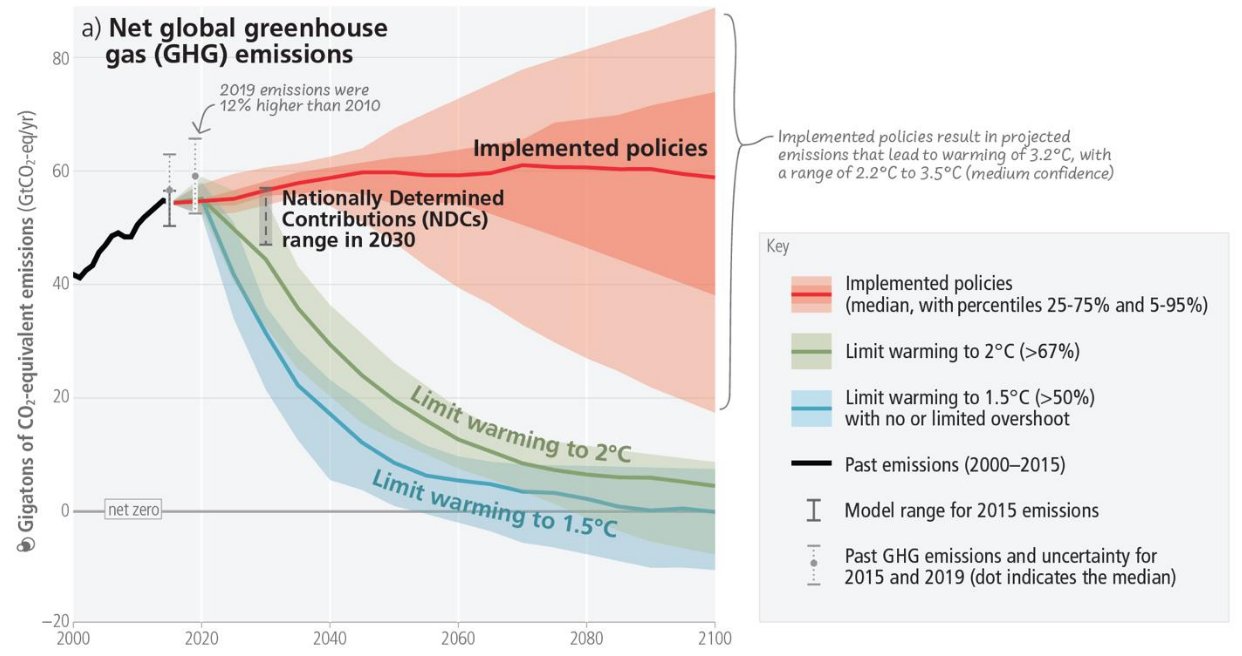


Context

We need to reduce our CO_2 emissions

CO_2 contributed ~0.8°C to historical warming



IPCC, 2022: *Climate Change 2022: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844.

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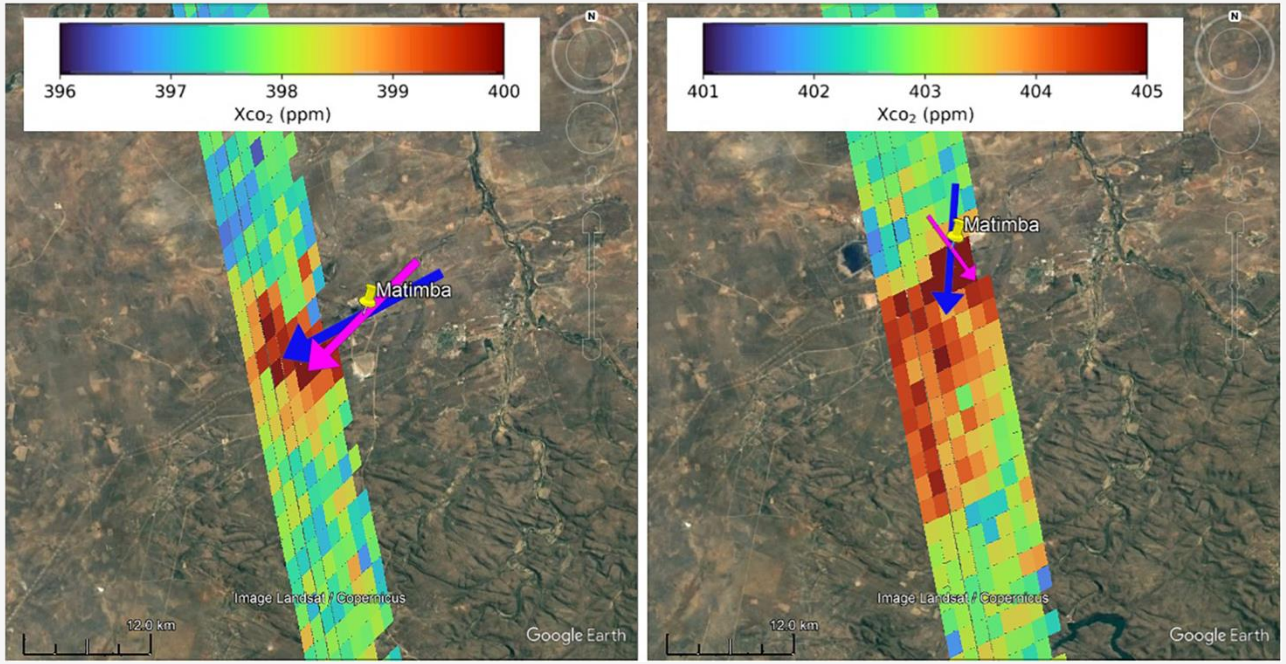
Point source monitoring
Where are we ?

Monitoring of CO_2 emissions is difficult
Plumes are not optically visible
Multiple overpasses are needed to constrain emissions

Most studies focus on known sources



Nassar R, Mastrogiacomo JP, Bateman-Hemphill W, McCracken C, MacDonald CG, Hill T, O'Dell CW, Kiel M, Crisp D. Advances in quantifying power plant CO2 emissions with OCO-2. Remote Sensing of Environment. 2021 Oct 1;264:112579.

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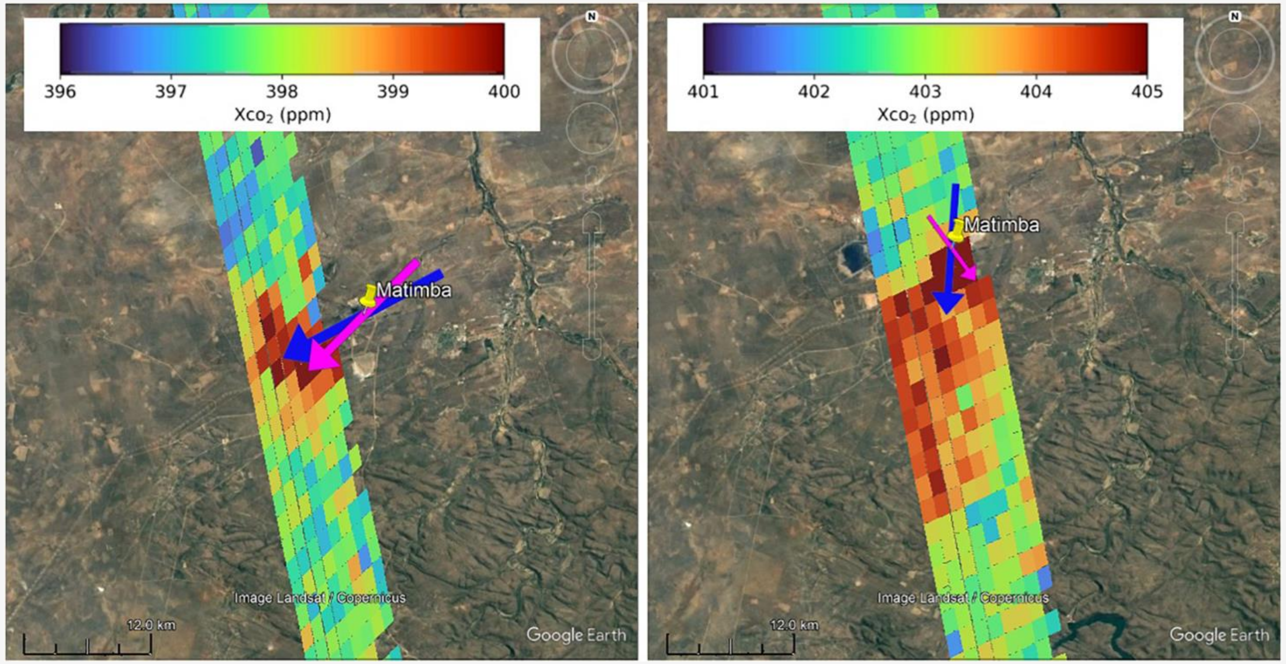
Our solution

An end-to-end framework to monitor CO_2 emissions

Diffusion-based anomaly detection system

Multi-purpose

- Detect new sources
- Detect variations in emissions



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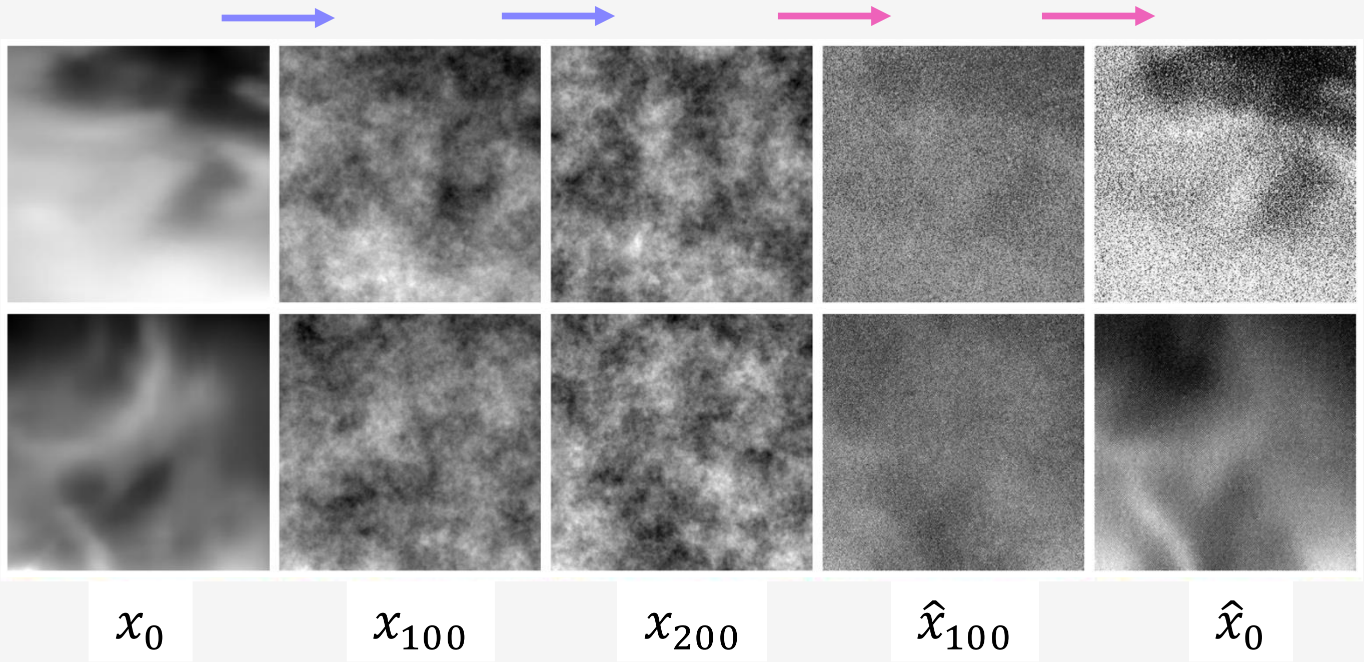
Methods

We use partial diffusion to detect anomalies
How?



$q(x_t|x_{t-1})$ Forward diffusion

$p_\theta(x_{t-1}|x_t)$ Backward diffusion

The context is kept, the anomaly gets removed

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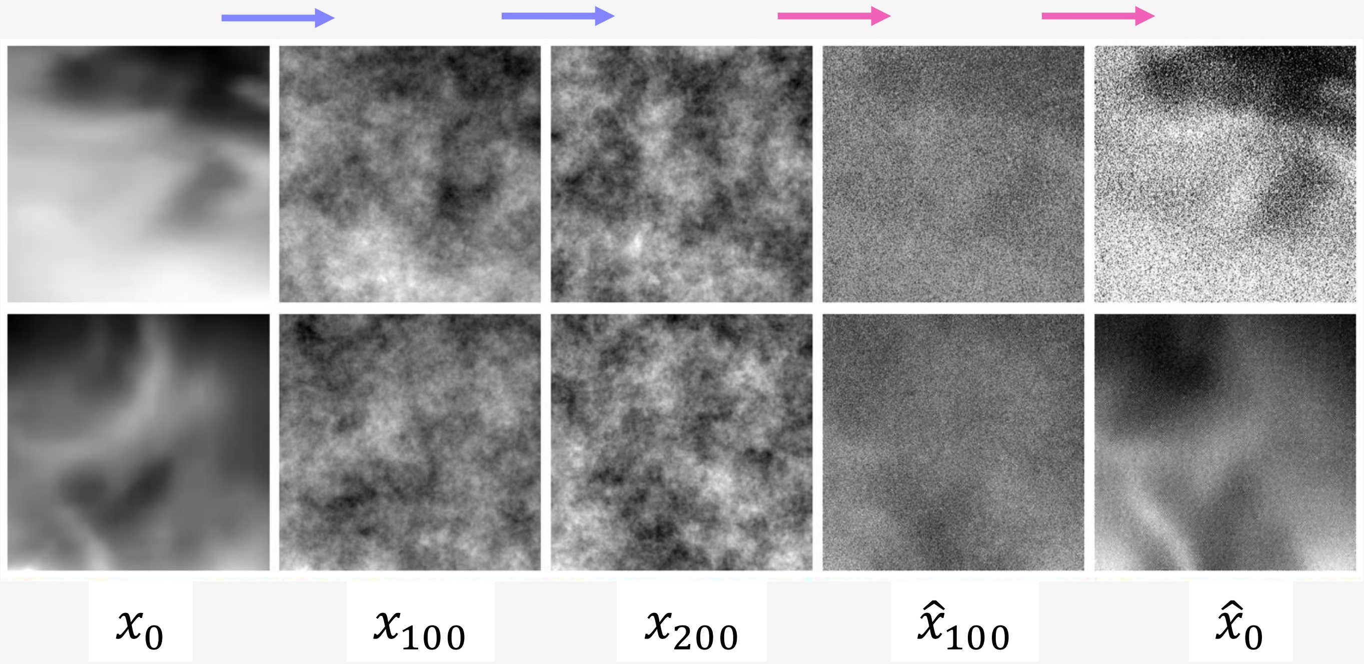
How?



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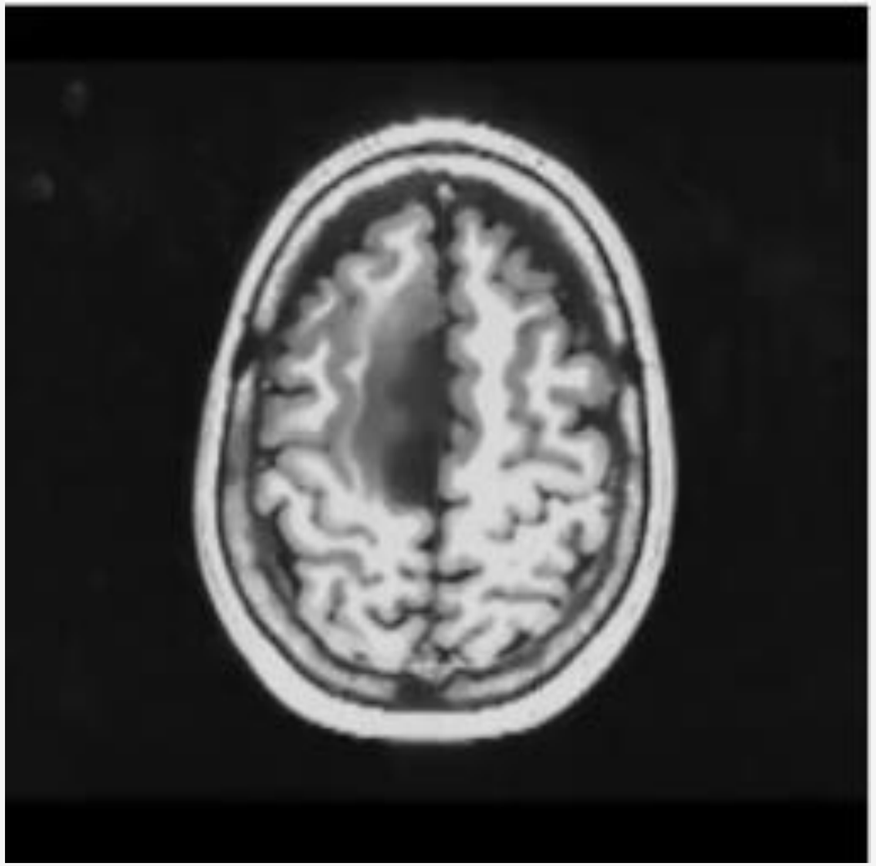


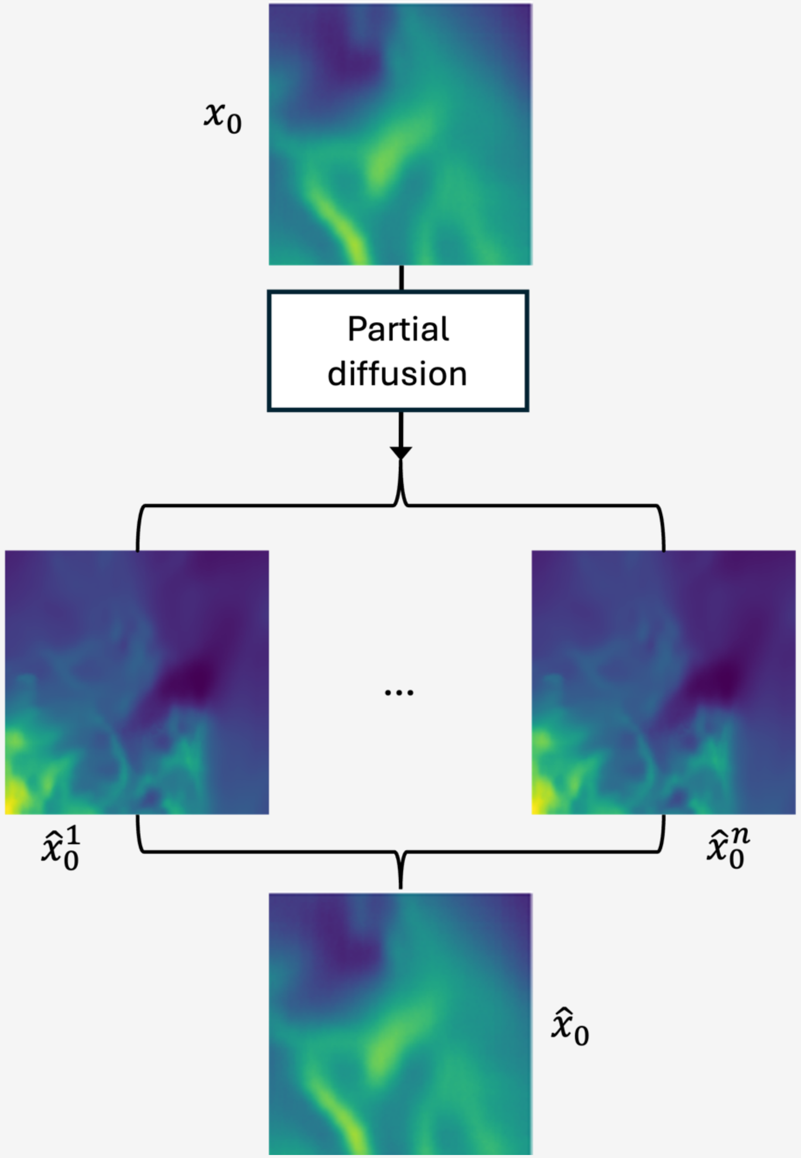
Wyatt, J., Leach, A., Schmon, S.M. and Willcocks, C.G., 2022. Anoddpm: Anomaly detection with denoising diffusion probabilistic models using simplex noise. In *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition* (pp. 650-656).

Inference

We use ensemble prediction

We generate $n = 50$ outputs $\hat{x}_0^{1,\dots,n}$ from x_0

$\hat{x}_0$ is the average of each output



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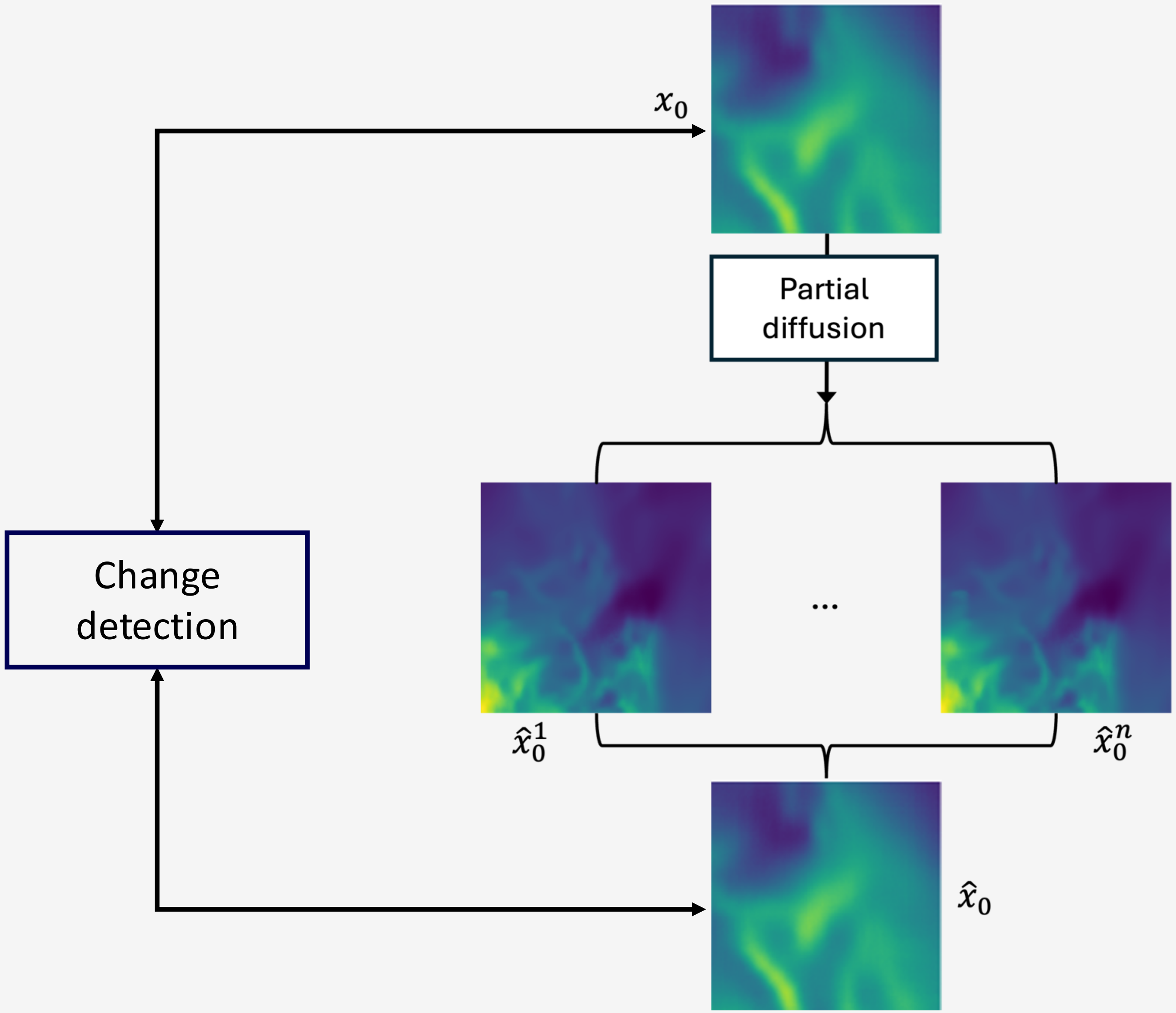
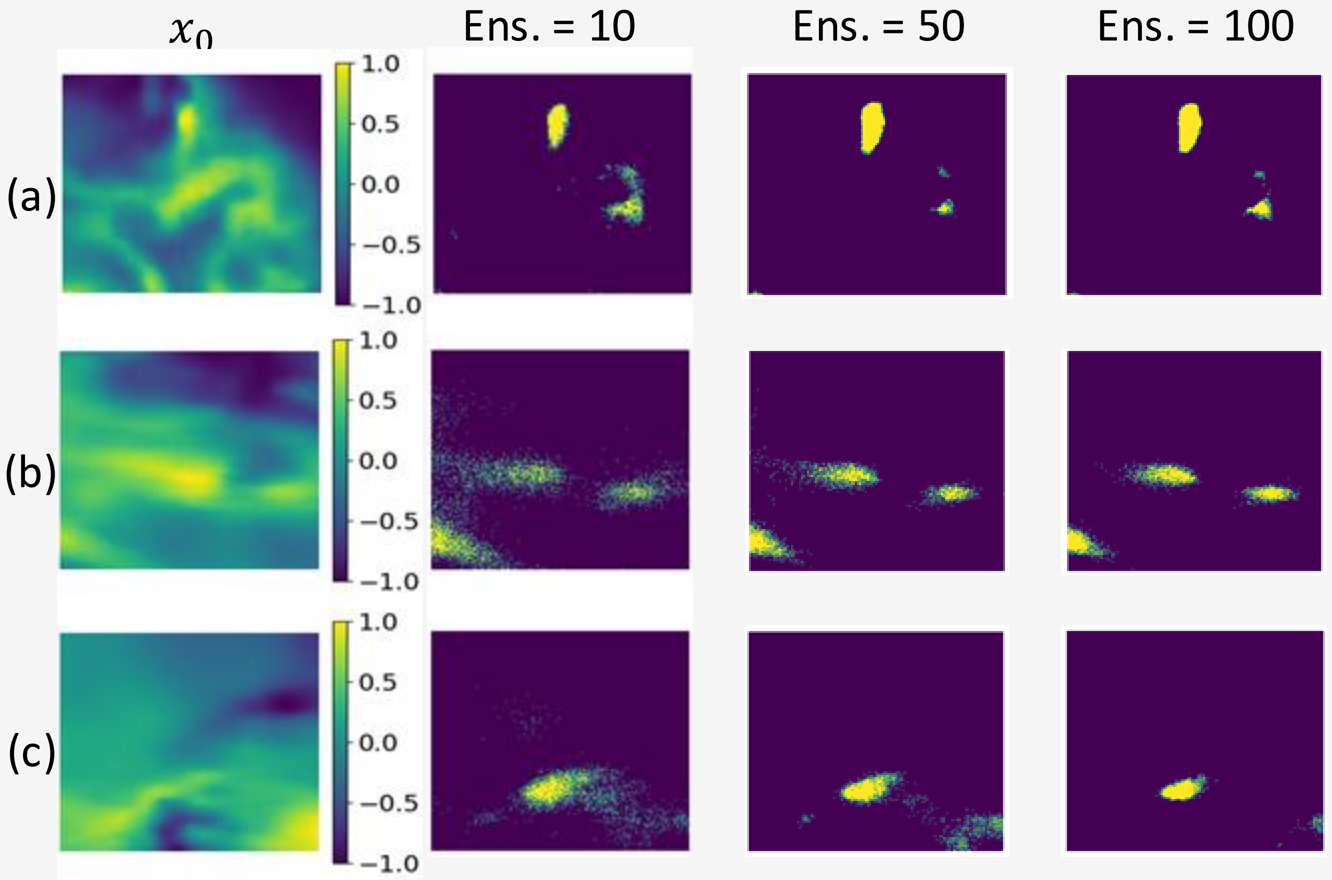


Inference
We use ensemble prediction

We generate $n = 50$ outputs $\hat{x}_0^{1,\ldots,n}$ from x_0

$\hat{x}_0$ is the average of each output
We can highlight areas with (un)certainties



Training

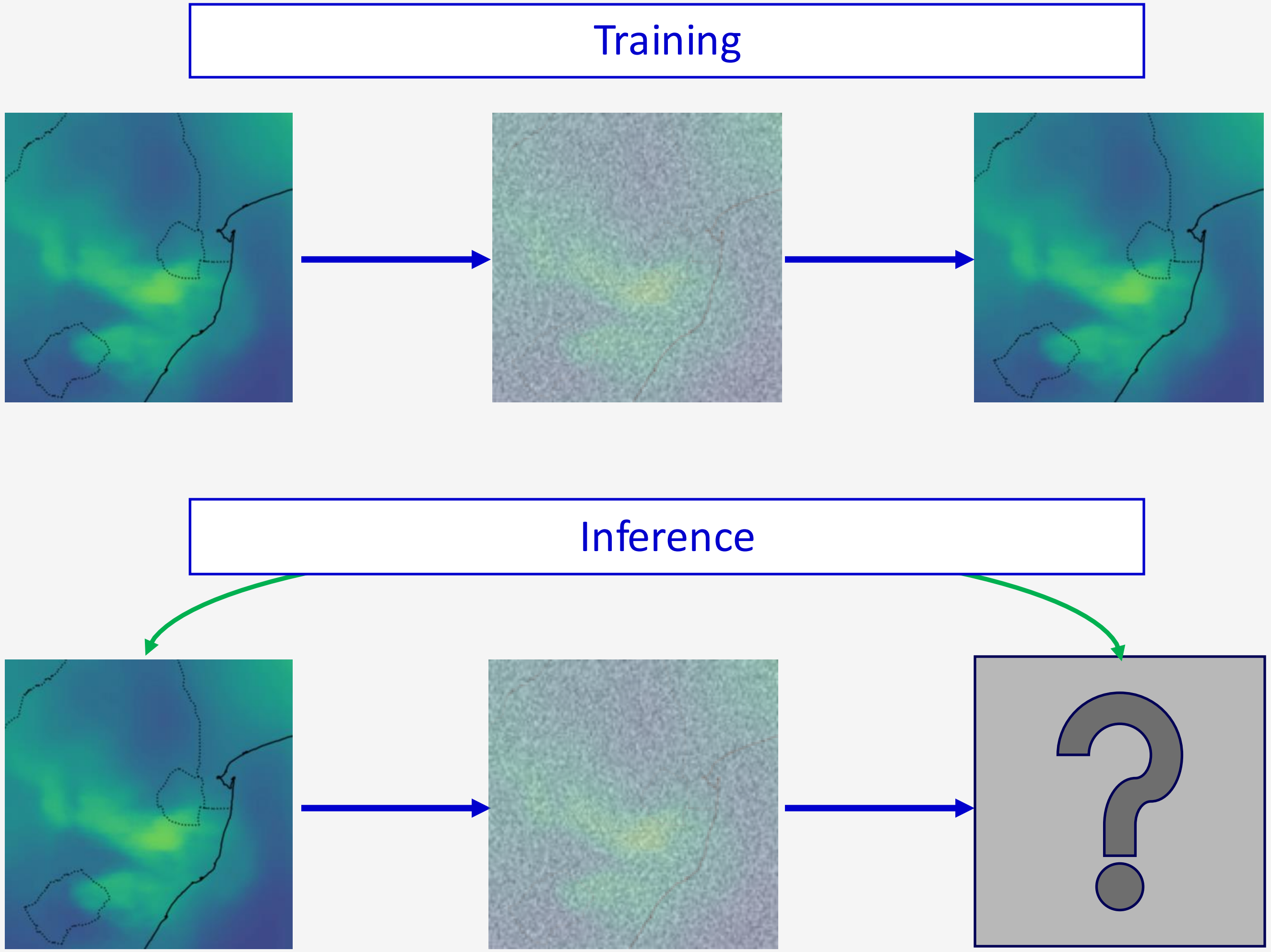
We train the model on “healthy” CO_2 maps

Training

- Before the opening of a powerplant
- During a period of constant emissions

Inference

- When a powerplant is active
- After changes are made to a point source (e.g. new infrastructures, unit closures)



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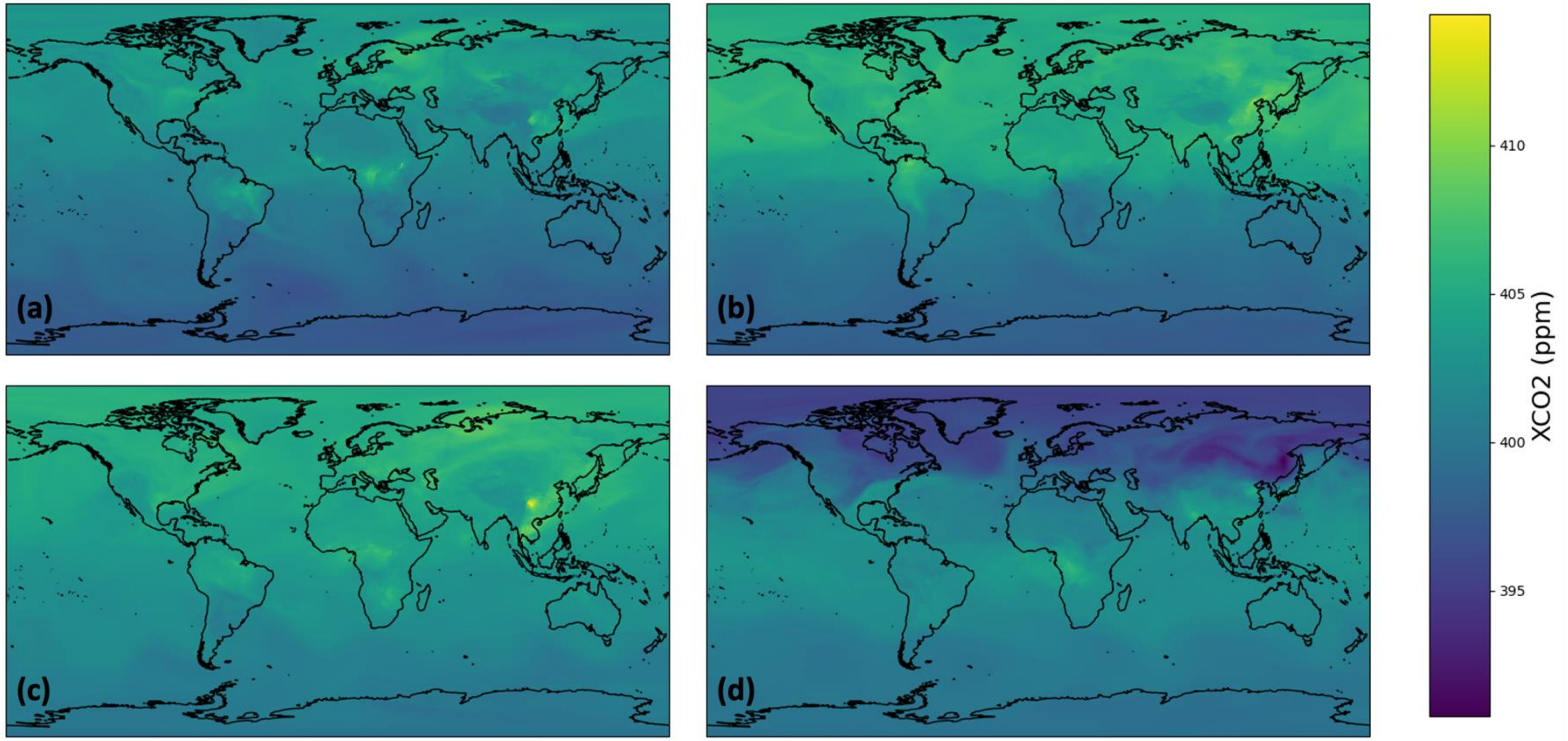
Dataset

We use a global daily high spatial resolution XCO_2[1] dataset with a 0.03°×0.04 ° resolution



Rakotoharisoa, A., Cenci, S. and Arcucci, R., 2025. A High Resolution Spatially Consistent Global Dataset for CO2 Monitoring. *Remote Sensing*, *17*(9), p.1617.

[1]: column-averaged dry air mole fraction of CO_2

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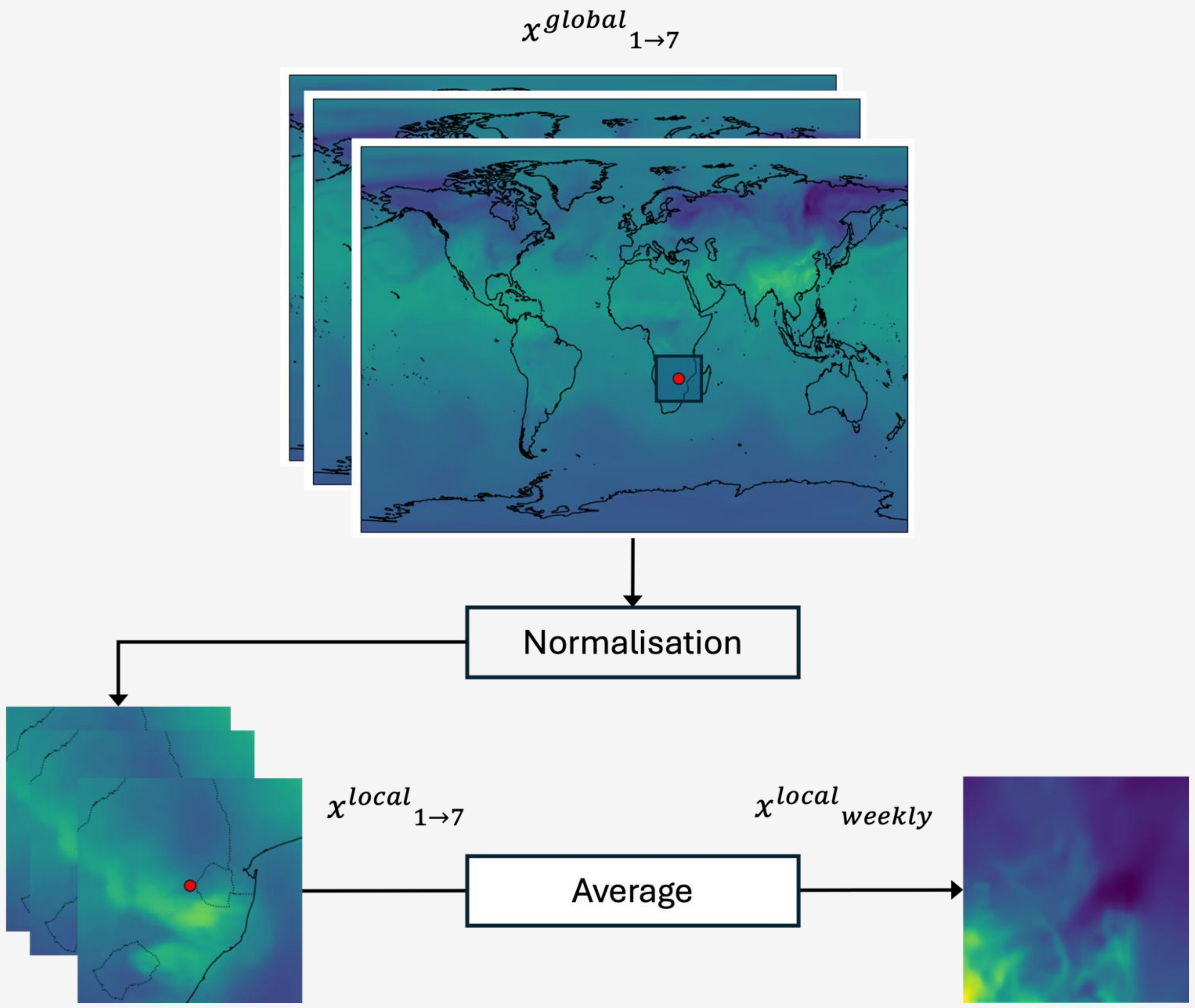
Data preprocessing
We remove exceptional events

The maps are normalized around the area of interest

We produce a weekly average to remove the influence of exceptional events



Results

Results
Sites investigated

Coal mines selection
Not continuously active between 2015 and 2022
Remote locations that might need additional monitoring

Table 2: Coal mines and their characteristics for emissions detection

Mine (Abbrv.)	Loc. (Lat,Lon)	Prod. (Mtpa)	Active	Closed	Reason
Benga (Bg.)	-16.17°, 33.66°	1.24	07/19–01/21	07/16–01/18	Extension
Otvalny (Ot.)	54.15°, 87.13°	2.50	01/17–12/17	01/21–12/21	Rehabilitation
Invierno (Iv.)	-53.00°, -72.42°	2.30	06/18–12/19	06/20–12/21	Closed
Hazelwood (Hw.)	-38.25°, 146.38°	15.30	06/18–12/19	06/20–12/21	Rehabilitation

Powerplant selection
Emissions reported to have varied

Table 3: Powerplants and the possible reason for emission change

Power plant (Abbrv.)	Loc. (Lat,Lon)	Reason for emission variation
Niederaussem (Nd.)	50.99°, 6.67°	Units got retired in 2020 and 2021
Parish (Pa.)	29.48°, -95.63°	Unit upgraded with carbon capture in 2017 [28]

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Results
Detection of point sources

The performance of the system depends on the threshold t

Accuracy of the method is influenced by the location of the point source

A higher threshold results in better overall performance

Table 1: Detection rate of various point sources using ADECEES depending on the threshold t. Best for each site in **bold**.

	t=0.3				t=0.5				t=0.7			
	Bg.	Ot.	Iv.	Hw.	Bg.	Ot.	Iv.	Hw.	Bg.	Ot.	Iv.	Hw.
Acc.	0.50	0.60	**0.50**	0.50	**0.60**	0.80	**0.50**	0.50	**0.60**	**0.90**	0.40	**0.70**
Prec.	0.50	0.56	**0.50**	0.50	0.57	0.71	**0.50**	0.50	**0.60**	**1.00**	0.43	**0.67**
Recall	**1.00**	**1.00**	**1.00**	**1.00**	0.80	**1.00**	**1.00**	**1.00**	0.60	0.80	0.60	0.80
F1-Sc.	**0.67**	0.71	**0.67**	0.67	**0.67**	0.83	**0.67**	0.67	0.60	**0.89**	0.50	**0.73**

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Results

Variations of emissions

We notice a decrease in anomalies over time for both powerplants

This highlights the impact of reduced emissions on CO_2 concentration

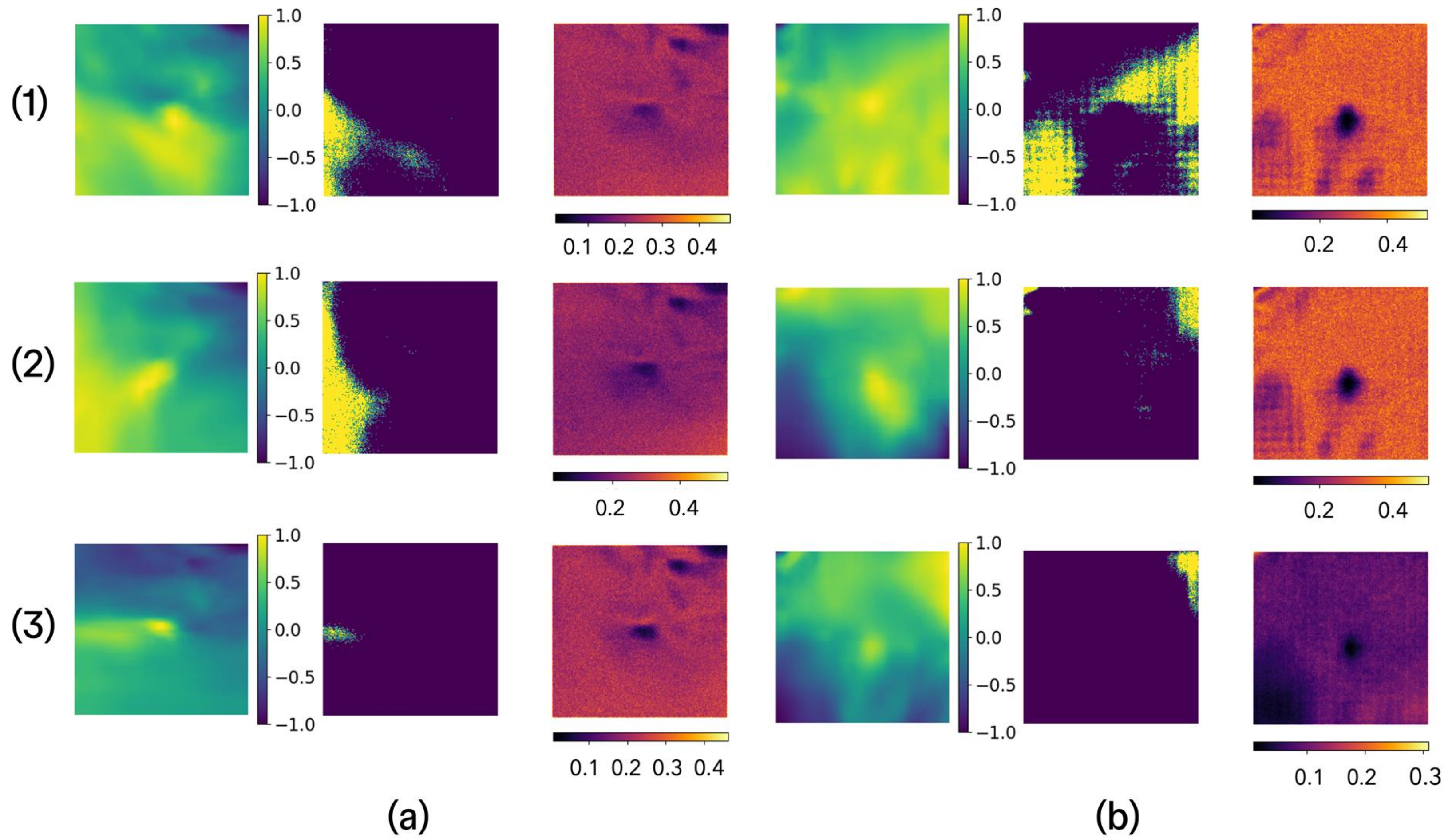

Figure 2: Visualization of CO_2 profiles, predicted anomalies and their variance as detected by ADECEES for the Niederaussem plant (a-1, a-2 and a-3 being from first week of May 2017, May 2018 and May 2021 resp.) and Parish plant (b-1, b-2 and b-3 being from last week of April 2016, April 2018 and April 2019 resp.).

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Future works

Improve the framework by considering auxiliary variables

Link detection rate to emission rate

Conclusion

We introduce an end-to-end CO_2 emission detection system

The system can be applied to multiple problems, including point source detection confirming changes in emissions levels

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