Identifying and accounting for the Coriolis effect in NO_2 observations and emission estimates

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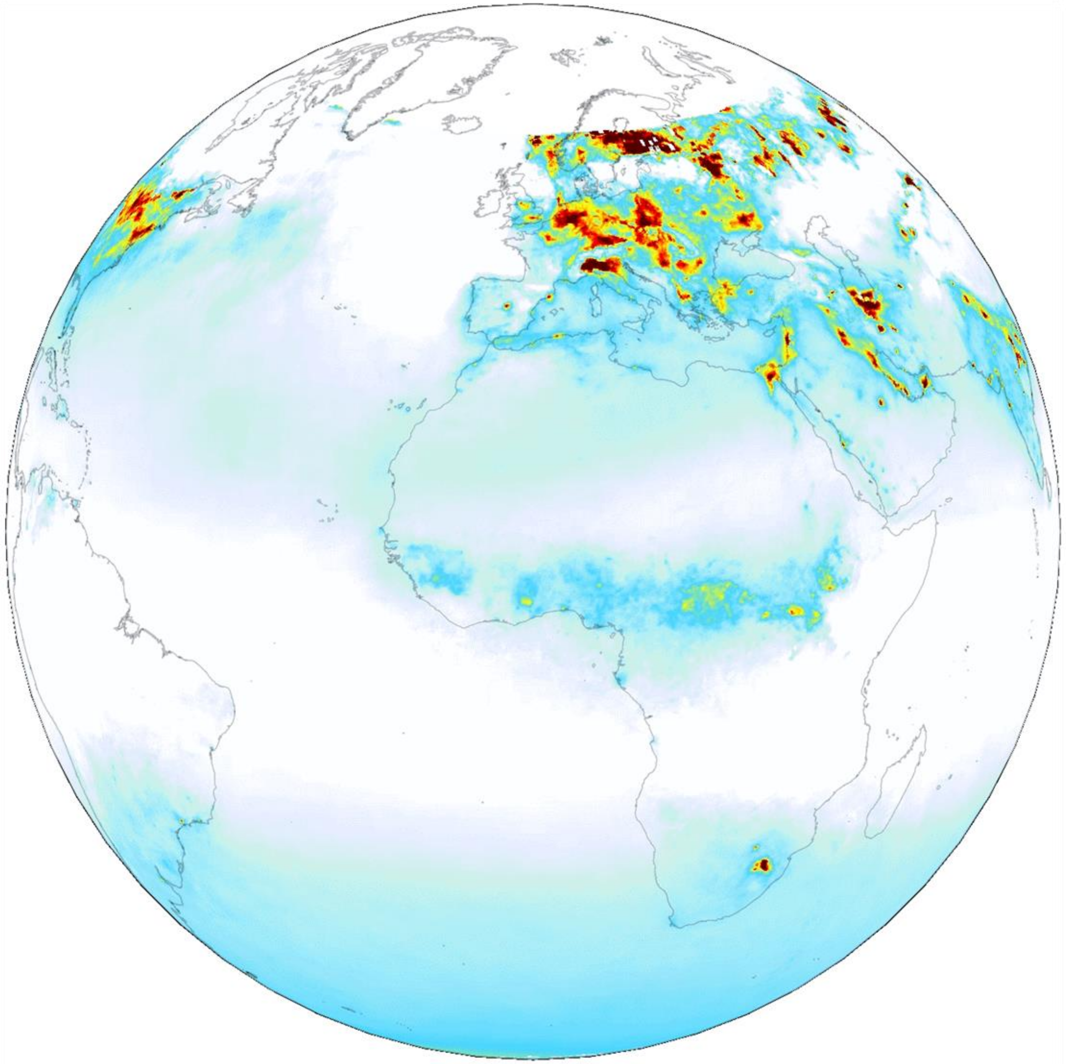

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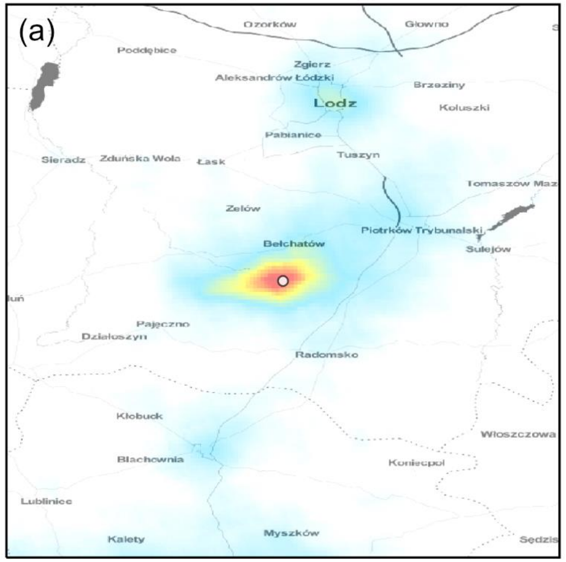
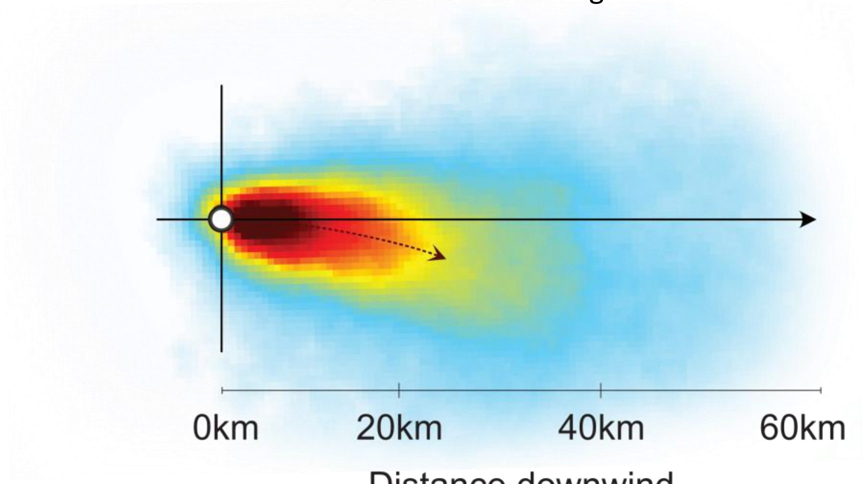
How this study came about

- PhD titled "smarter analysis of satellite data for air quality regulators"
- Testing out methods to quantify emissions from satellite observations
- Noticed a slight curvature in the wind rotated average from Belchatow power station in Poland
- Could this be due in part to the influence of the Coriolis Effect?

Temporal Average



Wind rotated average

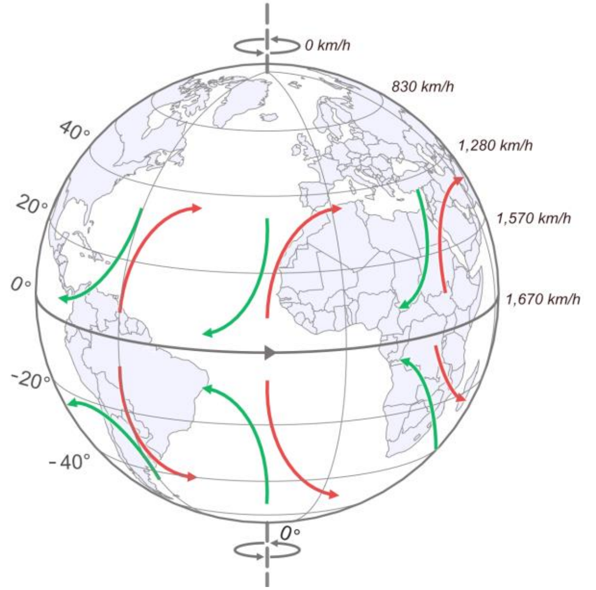


Coriolis effect

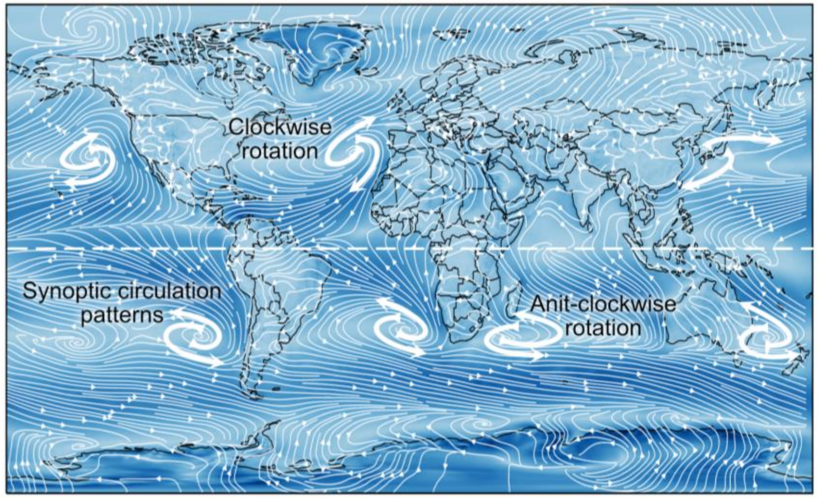
What is it?

- Inertial force that acts on an object that moves within a rotating coordinate system
- Deflects clockwise in Northern Hemisphere
- Deflects anti-clockwise in Southern Hemisphere
- Effect greatest at the poles
- Negligible at the equator
- $F_c = -2m(\boldsymbol{\Omega} \times \boldsymbol{v})$
- Influences the movement of the atmosphere
    - Greater deflection for higher wind speeds

Atmospheric Coriolis Effect



Average 100m winds (2019)



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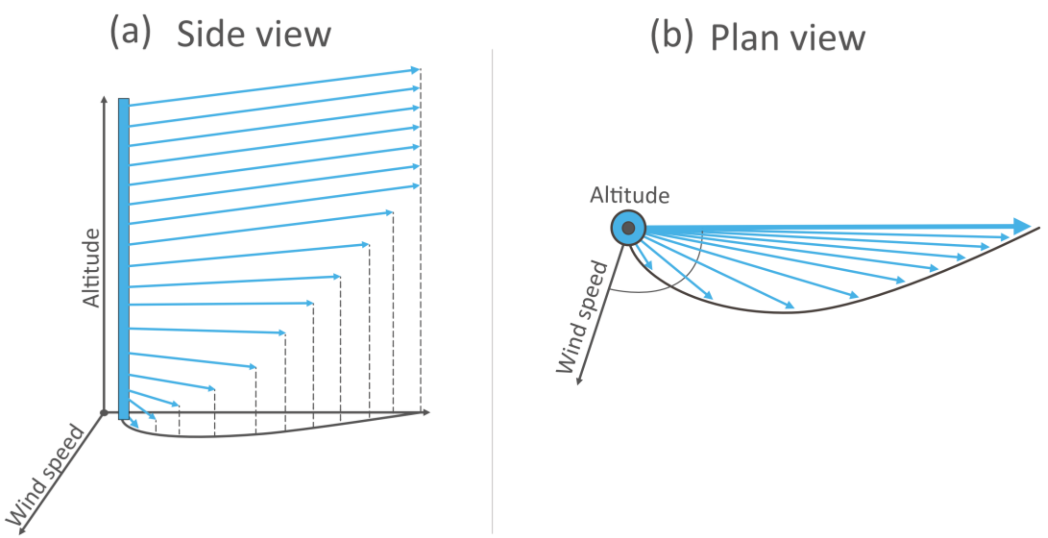
Coriolis effect

- Secondary impact of the Coriolis effect on emission plumes
- Plumes from power stations are
  - Thermally buoyant
  - Ejected at heights of +250 m
- Wind speeds increase with increasing altitude
- Coriolis force is a function of velocity $F_c = -2m(\boldsymbol{\Omega} \times \boldsymbol{v})$
- When conditions allow for the plume to ascend,
  - Plume rises into faster moving wind field
  - Wind field above is orientated at an angle to the field below
- Known as the Ekman spiral

Atmospheric Ekman Spiral



Belchatow power station, Poland

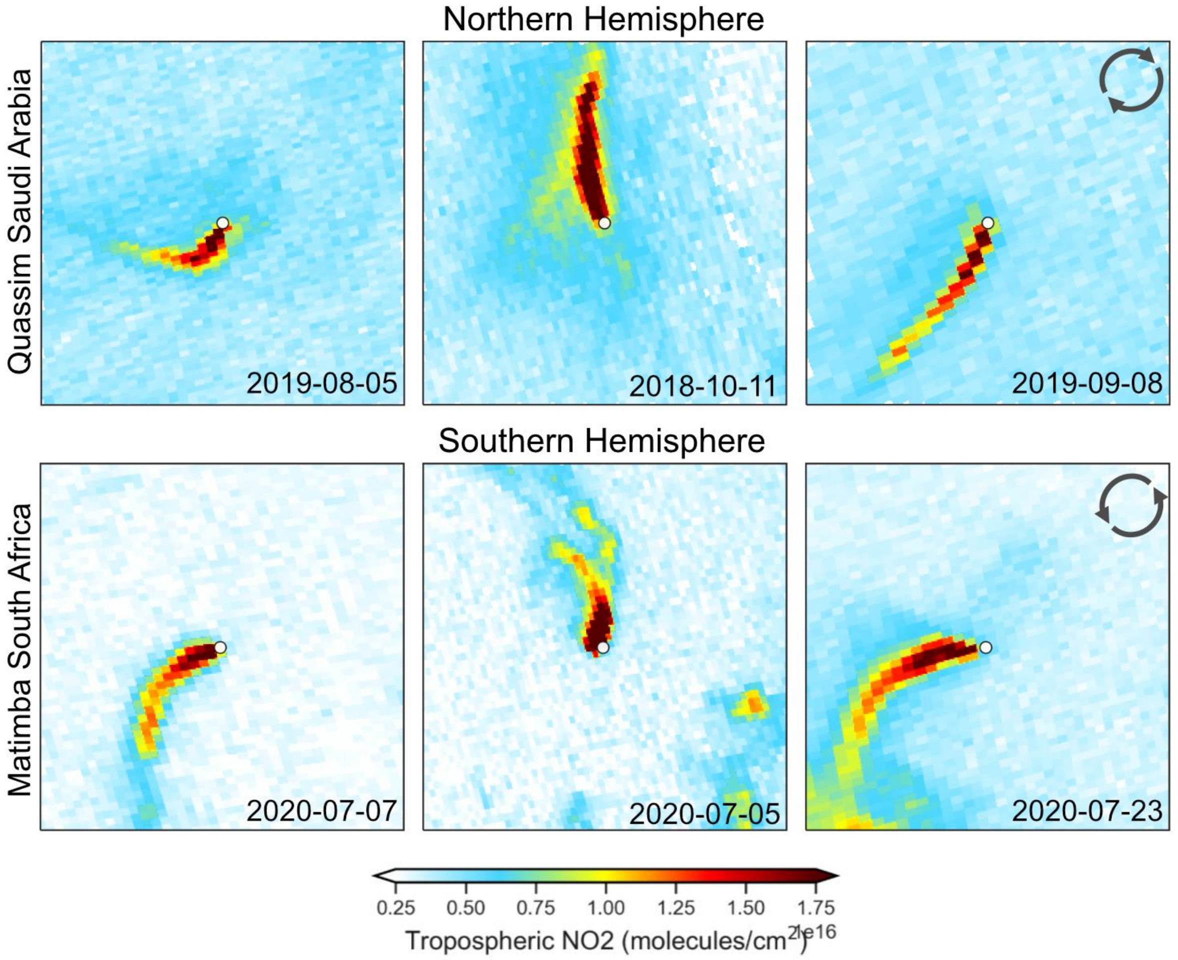
Impact on emission plumes

Emission plumes observed by TROPOMI can exhibit strong curvature

- Often (but not always) following the direction of the Coriolis force
- Local, smaller scale effect can dominate on daily timescales

Study question:

- For temporal averages, could Coriolis-induced curvature introduce a spatial bias?
- Does this effect emission quantification



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Study design

16 large industrial point sources

- Mostly coal power stations
- Northern and southern hemisphere
- Range of continents

n	Site name	Country	Type of site	Long	Lat	Stack height (m)	Capacity (MW)	Average surface pressure (hPa)
Northern Hemisphere								
1	Colstrip	USA	Coal power station	−106.61	45.8835	215	1480	900
2	Janschwalde	Germany	Coal power station	14.458	51.8344	300	3000	1006
3	Belchatow	Poland	Coal power station	19.327	51.267	300	5102	992
4	Quassim	Saudi Arabia	Oil power station	44.013	26.205	NA	915	939
5	Mae Moh	Thailand	Coal power station	99.751	18.296	200	2455	968
6	Vĩnh Tân	Vietnam	Coal power station	108.803	11.317	210	6225	992
7	Neyveli	India	Coal power station	79.441	11.558	275	3390	1002
8	Raichur	India	Coal power station	77.343	16.355	220	1720	965
Southern Hemisphere								
9	Chuquicamata	Chile	Copper smelter	−68.890	−22.314	NA	NA	736
10	Matimba	South Africa	Coal power station	27.613	−23.669	250	3690	914
11	Muja	Australia	Coal power station	116.305	−33.445	151	1094	985
12	Tarong	Australia	Coal power station	151.915	−26.784	210	1400	962
13	Tanjung	Indonesia	Coal power station	110.745	−6.445	240	2640	996
14	Hwange	Zimbabwe	Coal power station	26.470	−18.383	180	920	921
15	Jorge Lacerda	Brazil	Coal power station	−48.969	−28.452	200	857	1008
16	Millmerran	Australia	Coal power station	151.279	−27.962	141	850	967

- Produce wind rotated aggregates for each site
- Identify presence/lack of curvature

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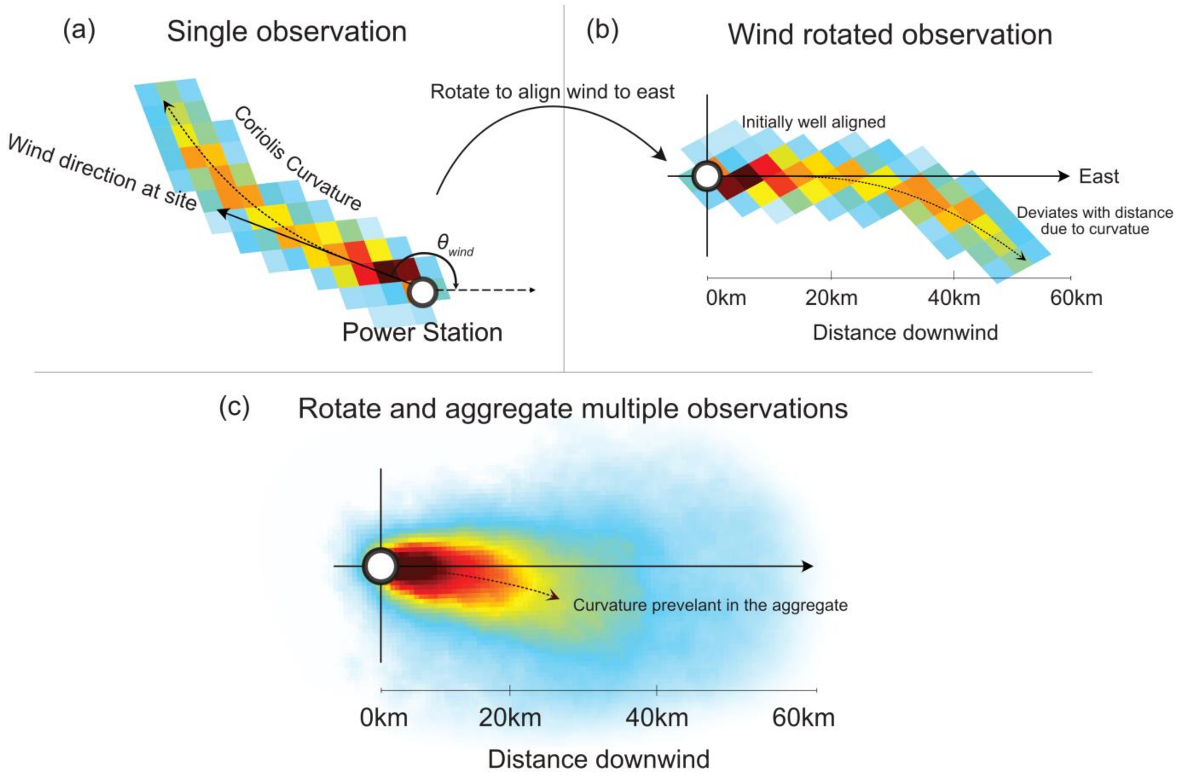
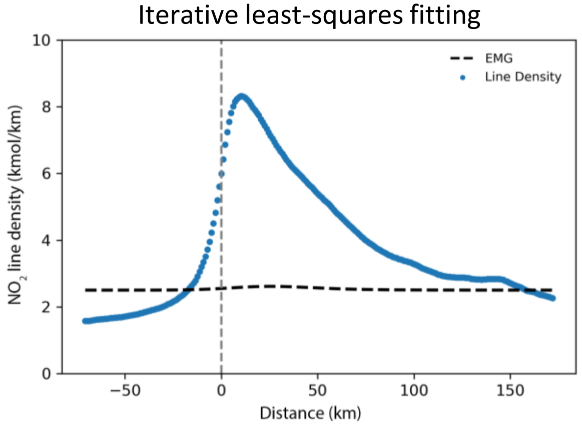
Wind rotation & EMG

- Common approach to derive emissions from satellite observations
  - Pommier et al, 2013
- Used for emissions from:
  - Cities (Goldberg et al, 2019)
  - Power stations (Fioletov et al, 2015 & Hakkarainen et al, 2021),
  - Fertiliser plants (Clarisse et al, 2019 & Dammers et al, 2019)
- Rotate all quality observations to a common axis in respect to that observations wind direction
- Fit an Exponentially Modified Gaussian (EMG)
- Extract emissions from fit parameters





$$\text{NO}_2 \text{ line density} = \alpha \left[\frac{1}{x_o} \exp\left(\frac{\mu}{x_o} + \frac{\sigma^2}{2x_o^2} - \frac{x}{x_o} \right) \Phi\left(\frac{x-\mu}{\sigma} - \frac{\sigma}{x_o} \right) \right] + \beta$$

$$\text{NO}_x \text{ emissions} = 1.33 \left(\frac{\alpha}{\tau_{\text{eff}}} \right), \quad \text{where } \tau_{\text{eff}} = \frac{x_o}{\omega}.$$

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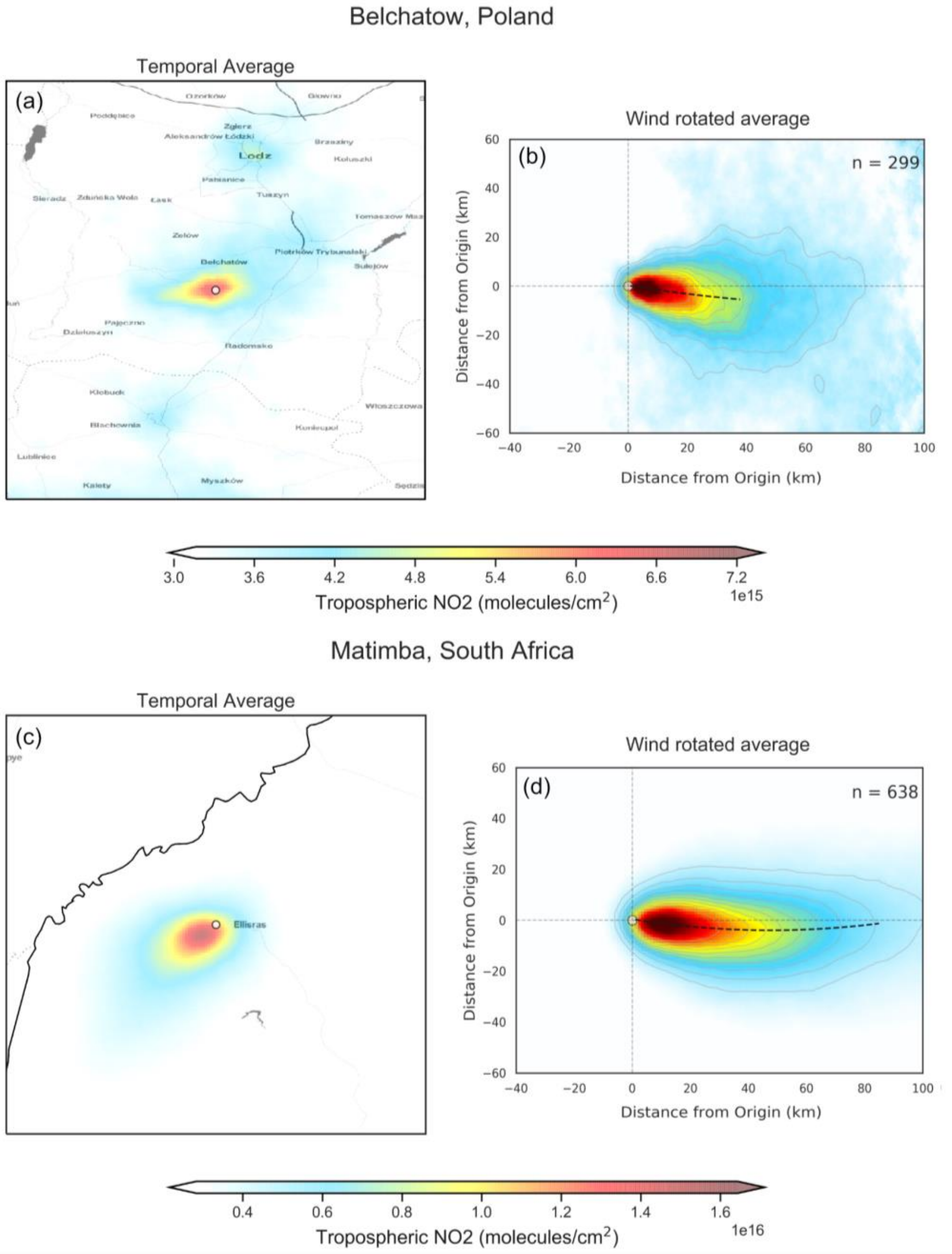
Examples of curvature

- Of the 16 sites:
  - 9 showed identifiable curvature
    - In expected direction
  - 5 showed no/negligible curvature
  - 2 showed opposing curvature
    - Discussed next slide

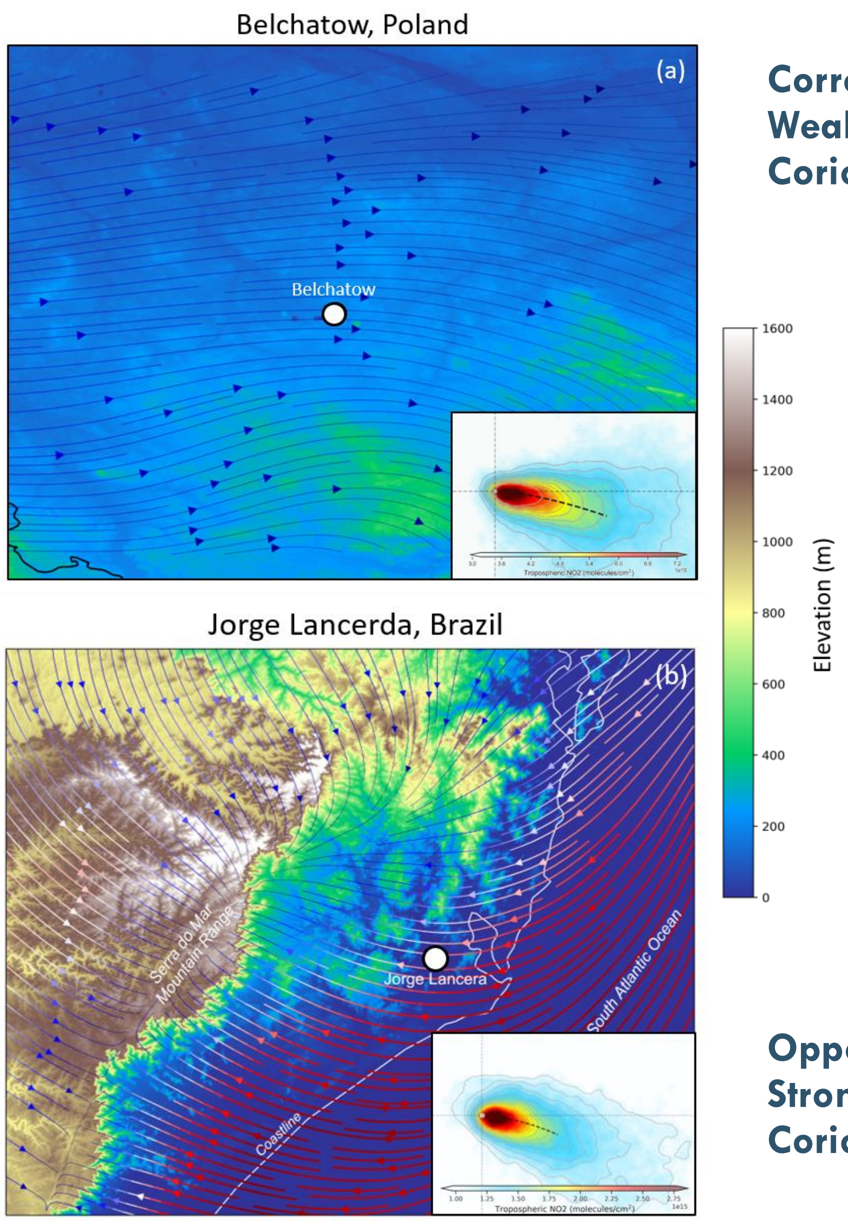
- Clear deflection of aggregate plume from the “common” axis



Opposing curvature cases

- Jorge Lacerda, Brazil
- Chuquicamata, Chile

- Both in highly variable topographic regions
- Small scale local affects dominate over larger scale Coriolis influence
- In contrast to Belchatow with low speed, uniform wind fields



Correct curvature
Weak local affects
Coriolis prevalent

Opposing curvature
Strong local affects
Coriolis not visible

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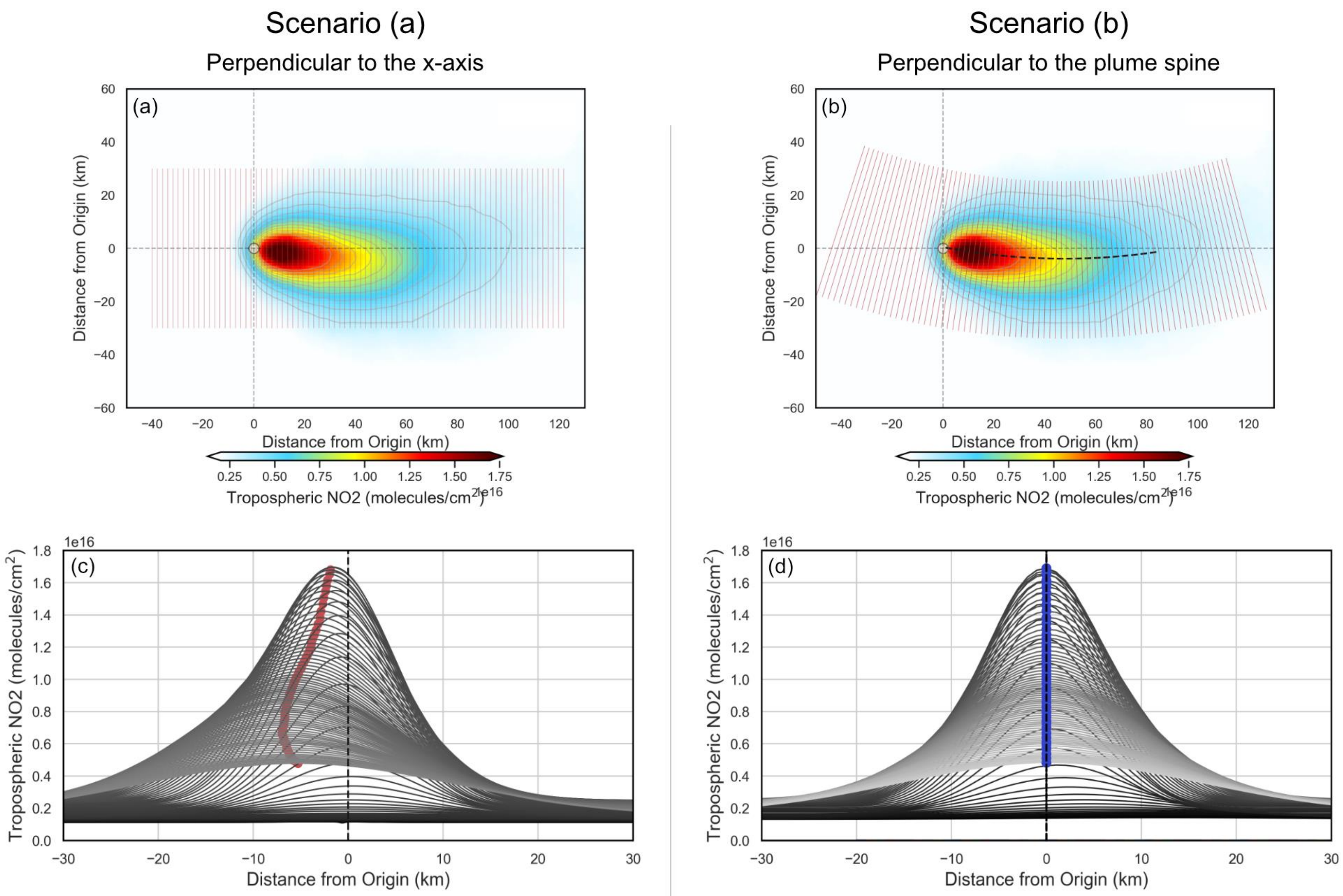
Impact on emission estimates

- Two approaches
  - a) Perpendicular to axis
  - b) Perpendicular to plume spine

- By taking transects perpendicular to the plume spine, transect peaks are realigned to the origin
- More representative path of dispersion



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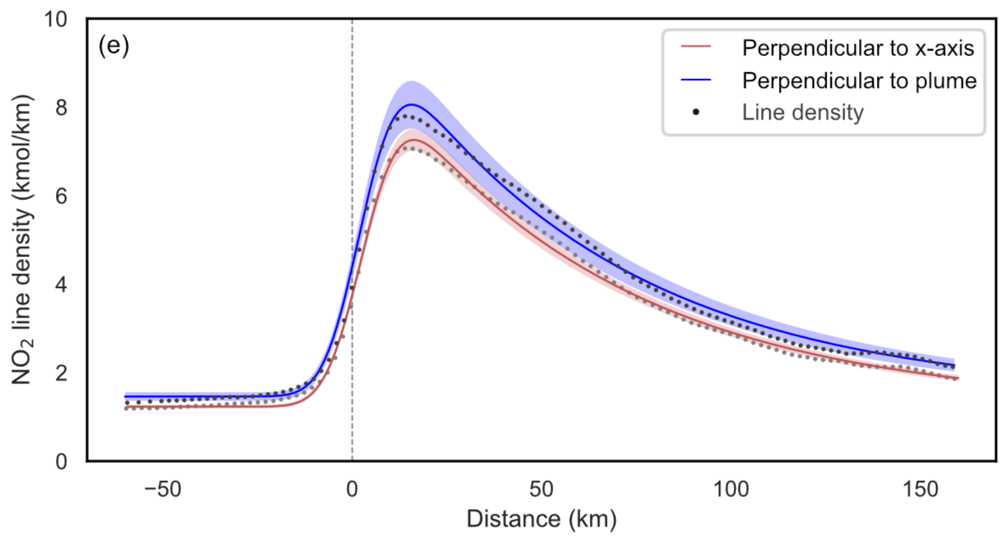
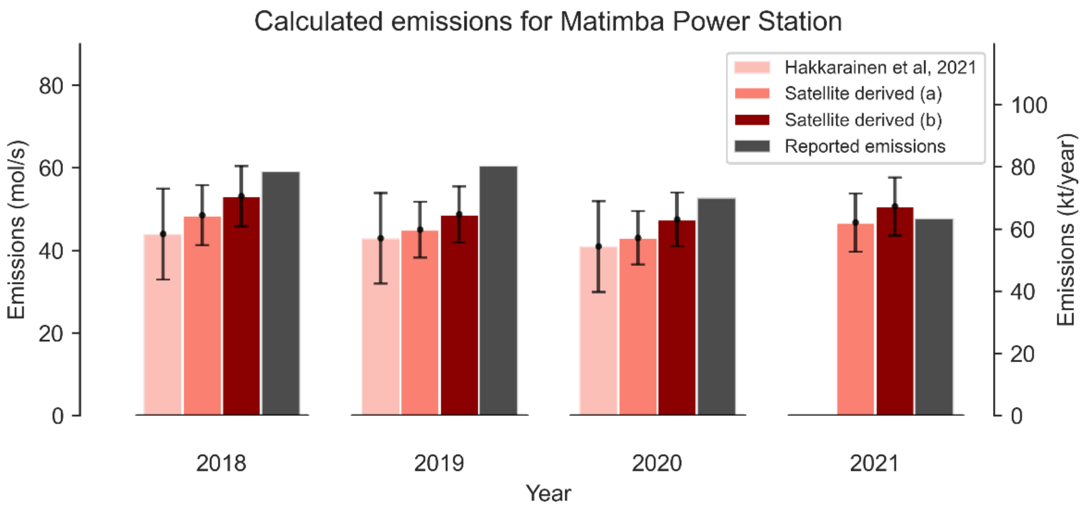
Impact on emission estimates

- Approach (b) yields a higher maximum in line density curve
- Approach (b) yielded an emission rate more comparable to reported emissions
- **9%** difference in emission estimates between (a) and (b)





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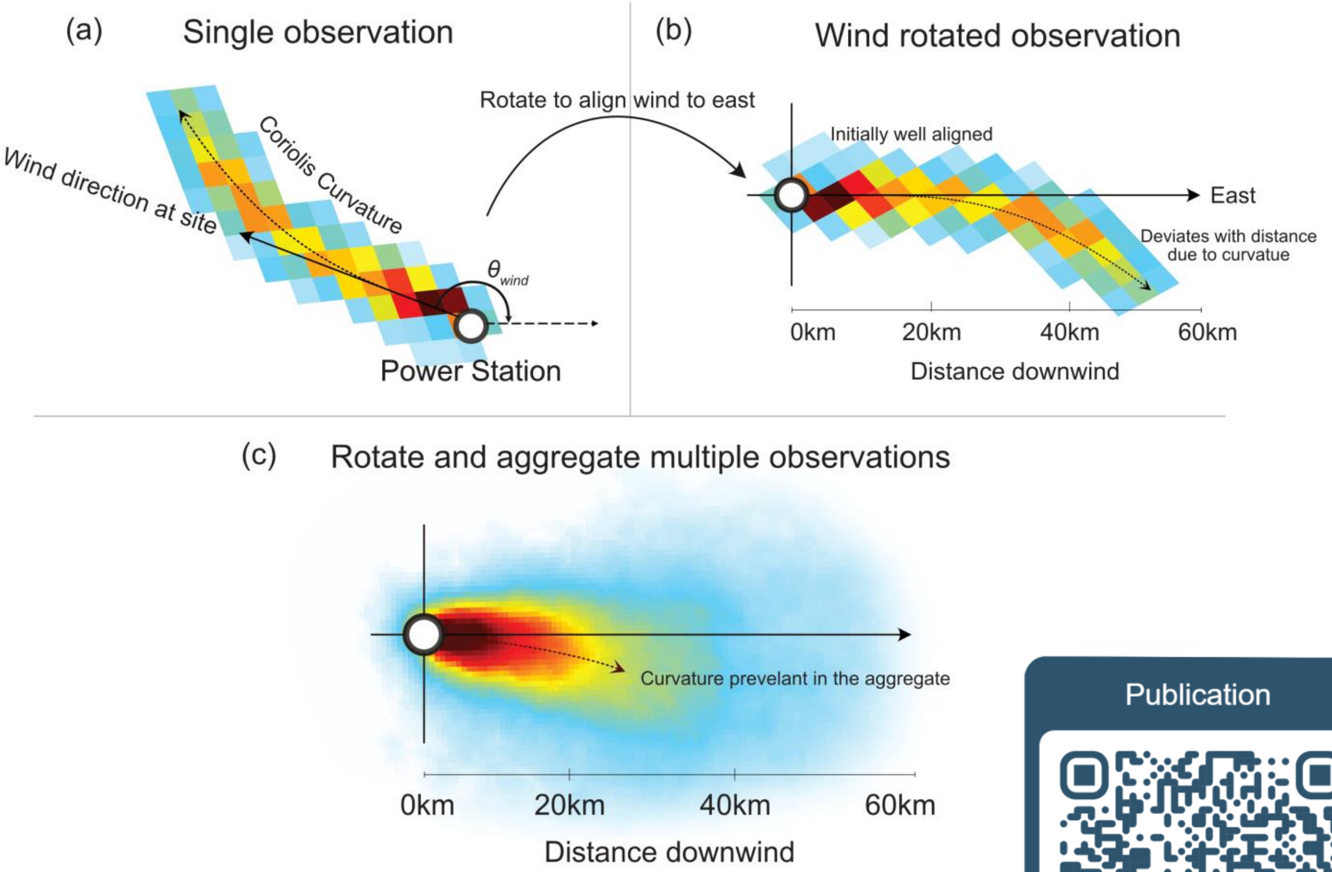
Take away points

- Coriolis induced curvature can be observed in observed emission plumes
- In certain locations with simple meteorology
  - Curvature can be high
  - Can impact emission estimates (~9%)
- Care should be taken when performing wind rotation to ensure correct alignment to common axis
- If not aligned, the curvature should be accounted for



Publication

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