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Verification of CH_4 and N_2O emissions using UAV-based measurements

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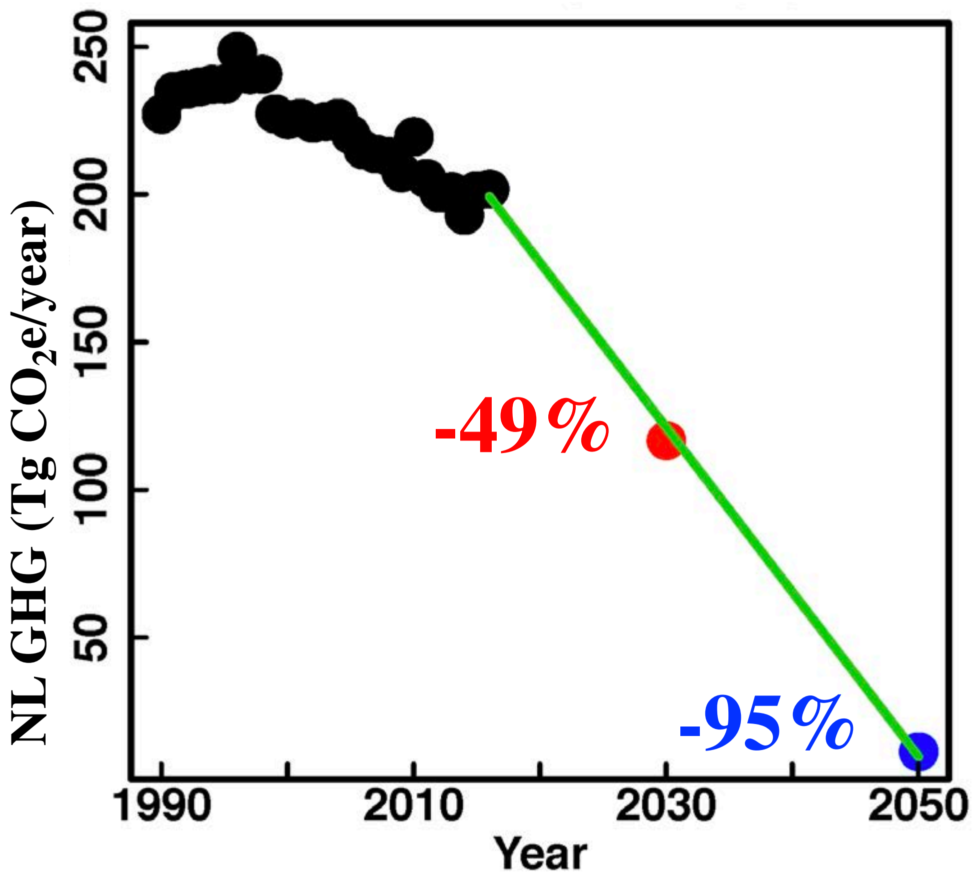
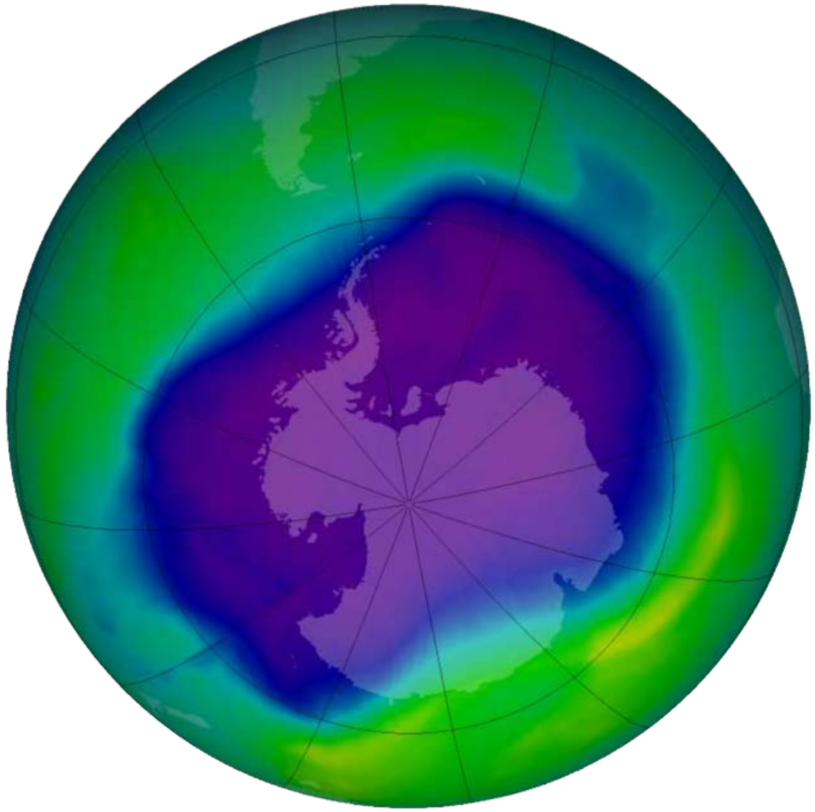
Climate Change and Ozone depletion

Dutch GHG emissions reduction target



The ozone hole



*What is the **magnitude** of GHG emissions?*
*What **mechanisms/processes** control these emissions?*

Unmanned Aerial Vehicle (UAV)

Also known as Remotely Piloted Aircraft Ssystem (RPAS) or Drones

Inspire 1 (x 2)

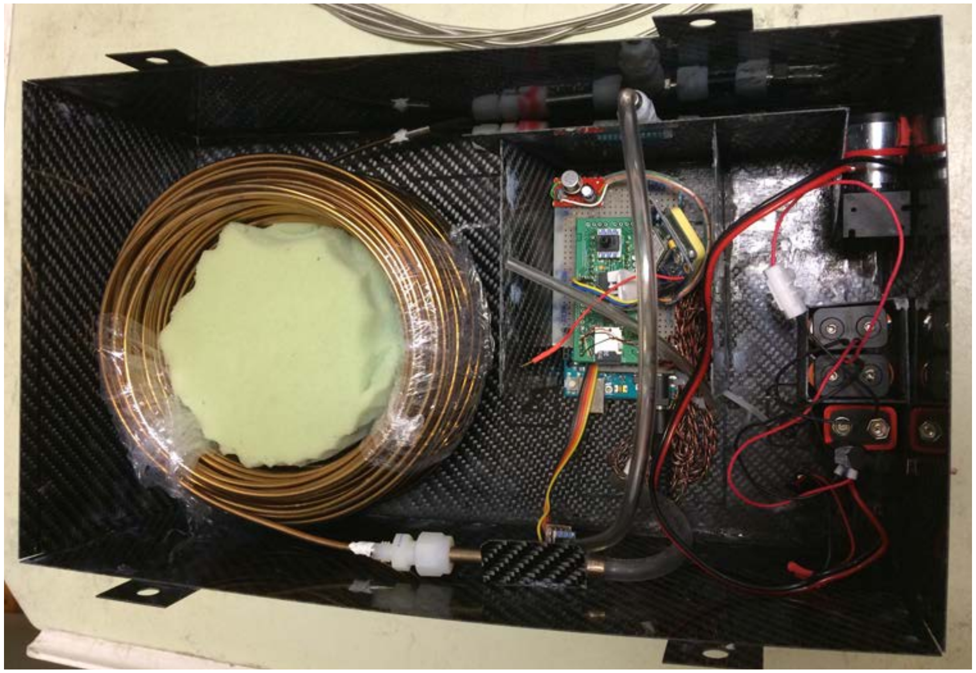
- ~15 minutes flight
- Drone weight 2.9 kg
- Maximum takeoff 3.5 kg
- In practice 4.0 kg

Inspire 2 (x 1)

- ~30 minutes flight
- Drone weight 3.5 kg
- Maximum takeoff 4.3 kg

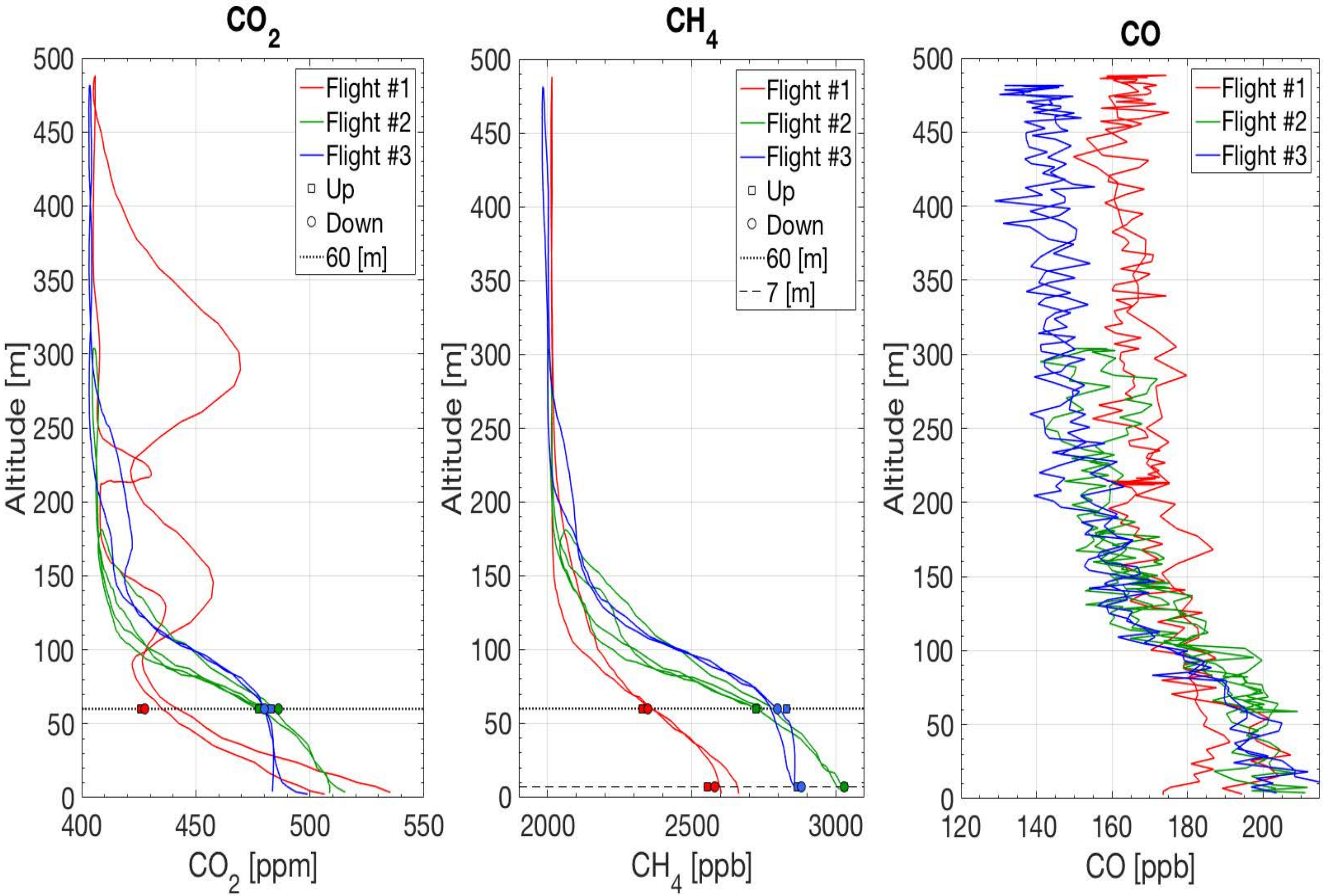
Ruisdael purchase: payload heavier than 1kg

UAV-based active AirCore Approach



- AirCore tubing:
  - 1/8” OD. 0.005” WT
  - 50 m (165 ft)
  - 450 g (1 lb)
  - 350 mL air volume
- Sampling time: 15 min at 21 mL/min
- Flow varies a bit proportional to the ambient pressure
- Total weight: ~ 1.0 kg (~ 2.2 lbs)

UAV AirCore flight Lutjewad



Andersen et al., 2018

Field measurements

1. CH_4, CO_2, and CO mole fraction profiles, recently N_2O and COS

2. $\delta^{13}C$ and δ^2H in CH_4 measurements of collected air samples from drone flights

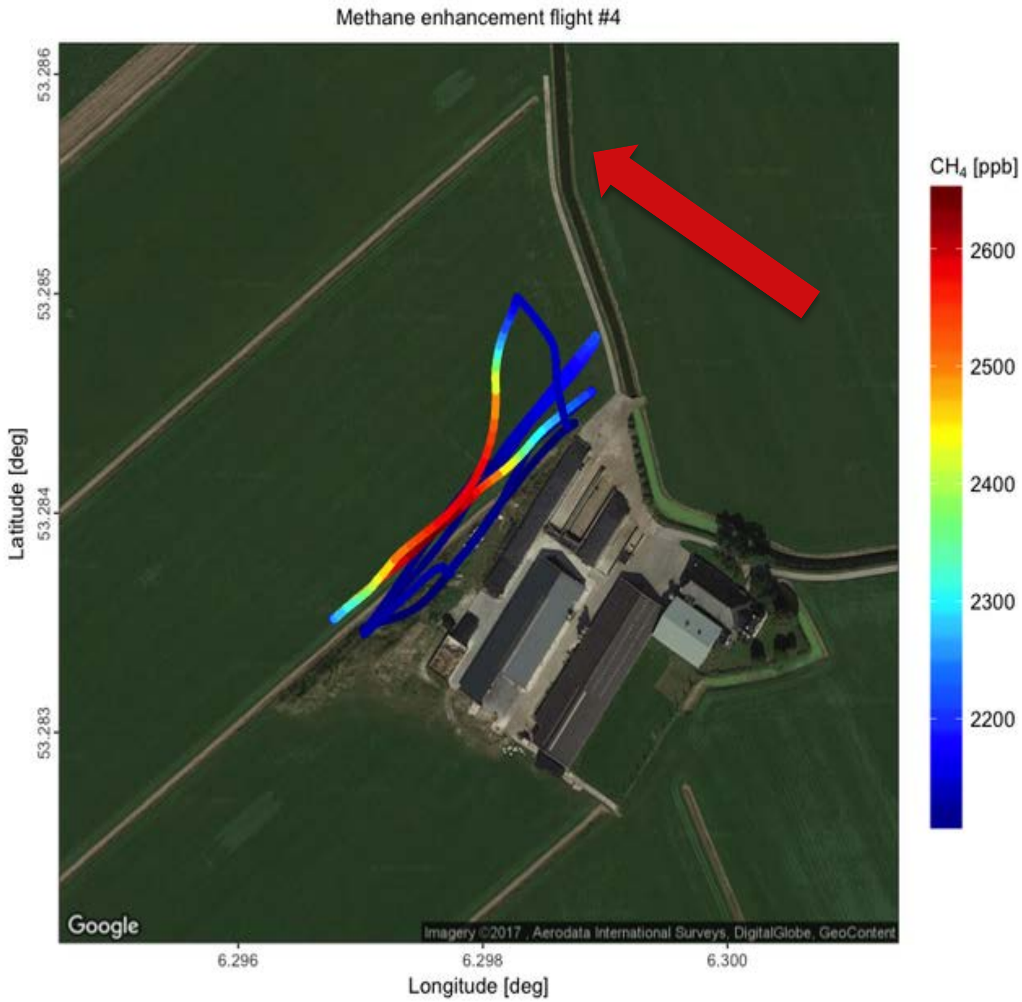
3. Ground-level u, v; profiles T, RH, u and v from a lightweight radiosonde

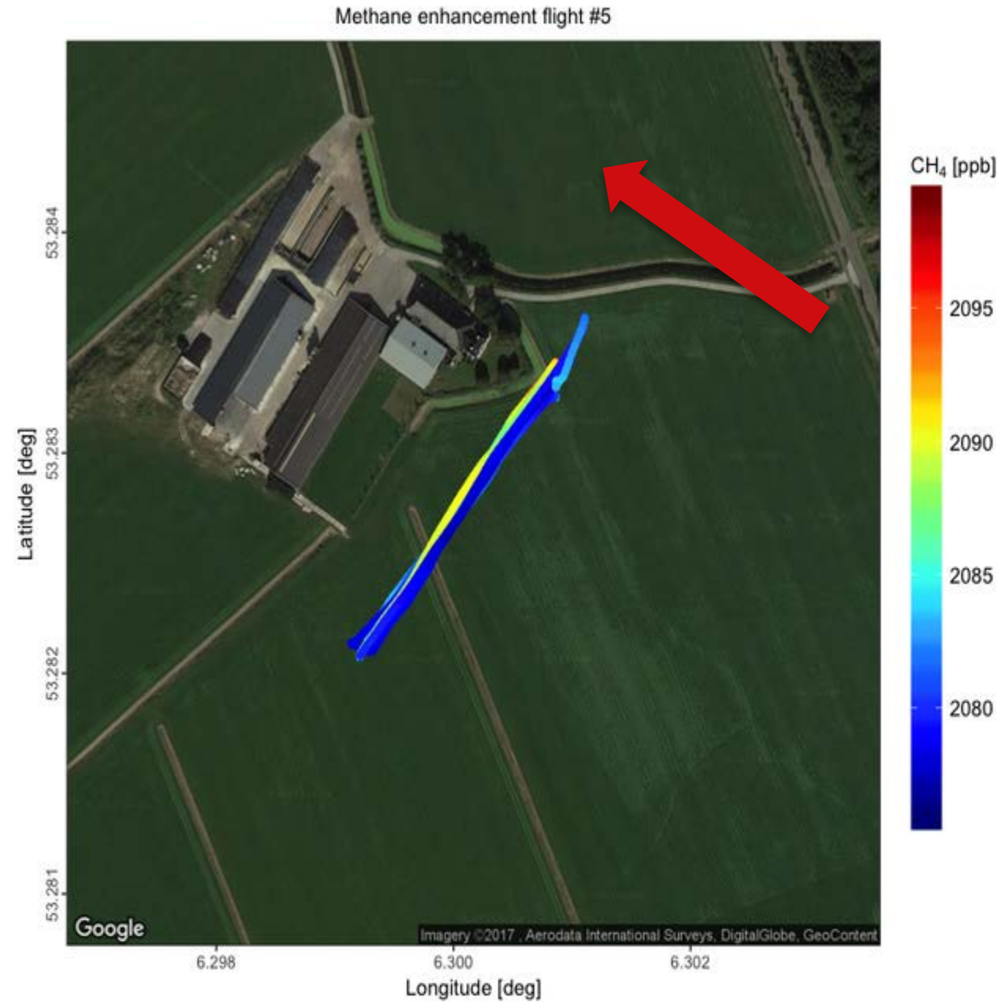
Application I: Quantifying dairy farm methane emissions

- Bottom-up inventory Netherlands 2010
  - 48% cattle & manure
  - 26% oil & gas
- Grijpskerk, Netherlands

- 280 adult cows + 140 young cows
- Manure storage underground
- Measurement dates
  - March 27, 2017
  - May 3, 2018
  - March 29, 2019

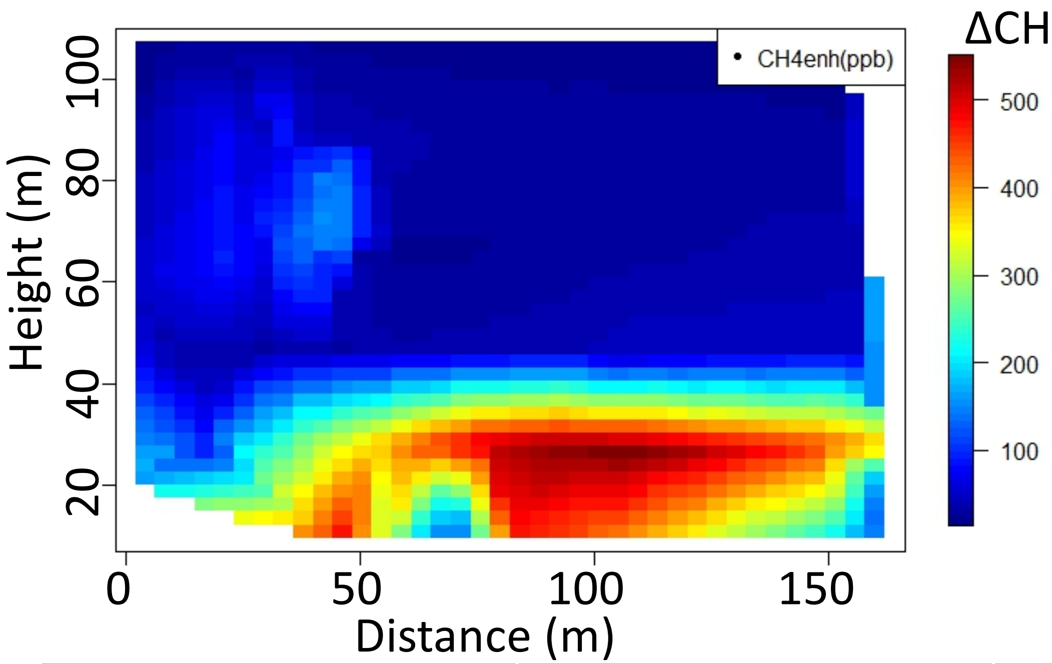
Example flight track March 2017





Wind speed: 4.5 m s^{-1}

The mass balance approach



$$Q_{flux} = v \iint CH_4 dx dz N_{air} \cos(\alpha)$$

v	Wind speed
N_{air}	The molar density of air
α	Angle between the wind direction and the direction normal to the flight track

	Grijpskerk this study	**California Dairy 1** ***Arndt et al., 2018***	**California Dairy 2** ***Arndt et al., 2018***
Total emissions (kg CH_4/day)	320 – 397	6985 – 7219	3046 – 3715
Animal Units	350	4590	3088
Emissions per unit (kg CH_4/year)	334 – 414	555 – 574	360 – 439

Application II: Quantifying coal-mining shaft emissions

- Global coal mining emissions 41 (26 – 50) Tg CH_4 yr^{-1} (bottom-up)
- Europe's emissions 28 (22 - 34) Tg CH_4 yr^{-1} (top-down)

[Saunois et al.. 2016]

According to bottom-up emissions:

Silesia coal mining-related CH_4 emissions ~0.5 Tg/yr.

- 1.2% of global coal mining emissions
- 1.7% of Europe's emissions
- ~2.5 million cows

Quantifying coal-mining shaft emissions

2017 (14 flights)

Pniowek V

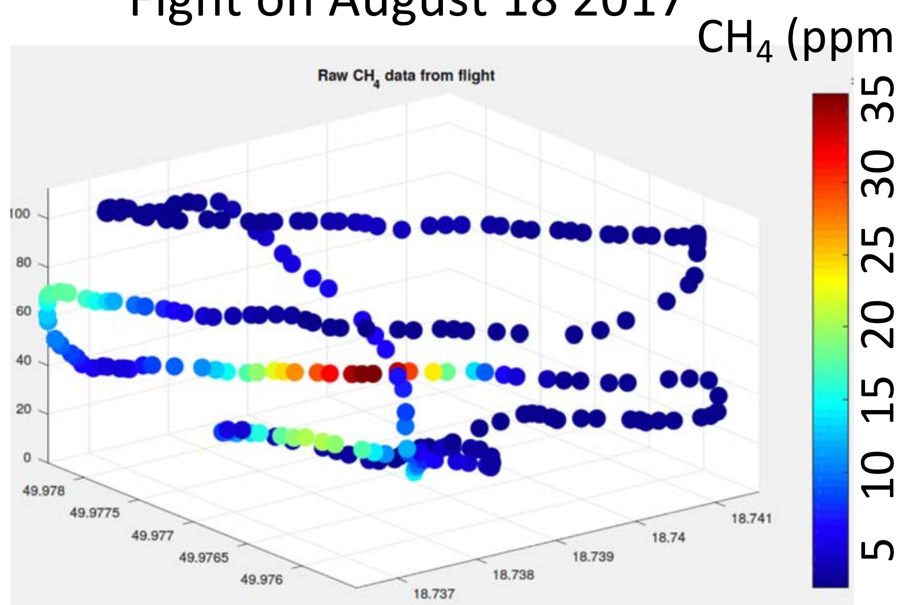
Inventory:
20.6 kton CH_4/year

2018 (59 flights)

Pniowek V
Pniowek IV
Borynia IV
Brzeszcze IX
Zofiowka V

Pniowek V

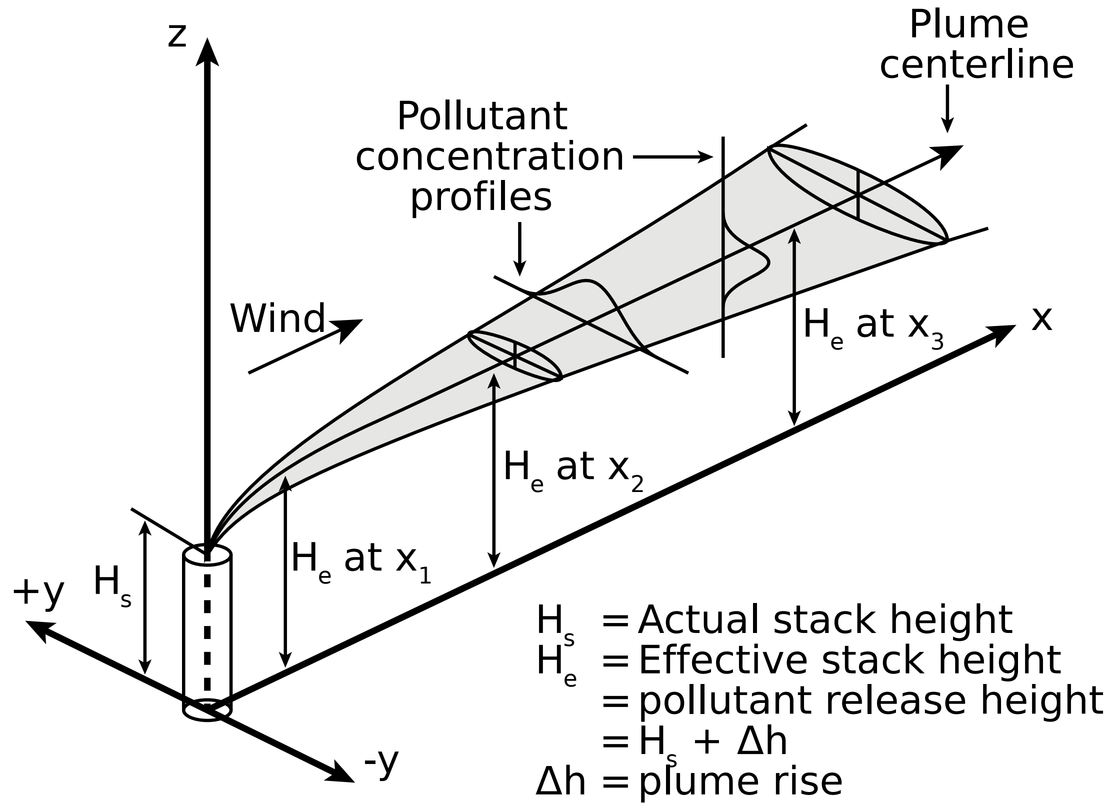
Fight on August 18 2017



Gaussian plume model

$$C(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \left[e^{-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2} + e^{-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2} \right]$$

- C: concentrations. g/m^3
- u: mean wind speed. m/sec
- Q: emission rate. g/sec
- **H**: effective stack height
- σ_y: standard deviation of plume concentration distribution in y-direction
- σ_z: standard deviation of plume concentration distribution in z-direction



Stability Class D (rural):

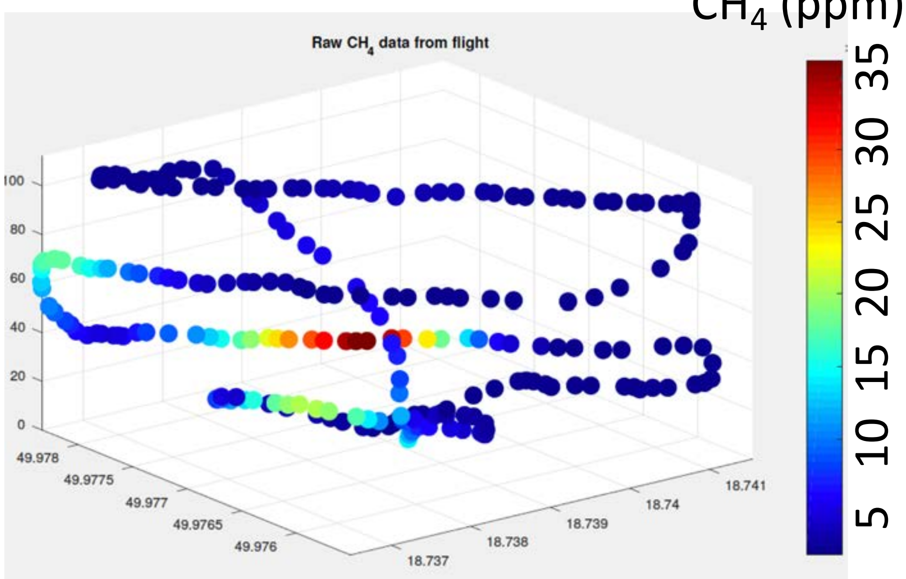
$$\sigma_y = 0.085x / \sqrt{(1 + 0.0001x)}$$

$$\sigma_z = 0.059x / \sqrt{(1 + 0.0015x)}$$

Emission estimates using the Gaussian plume inversion

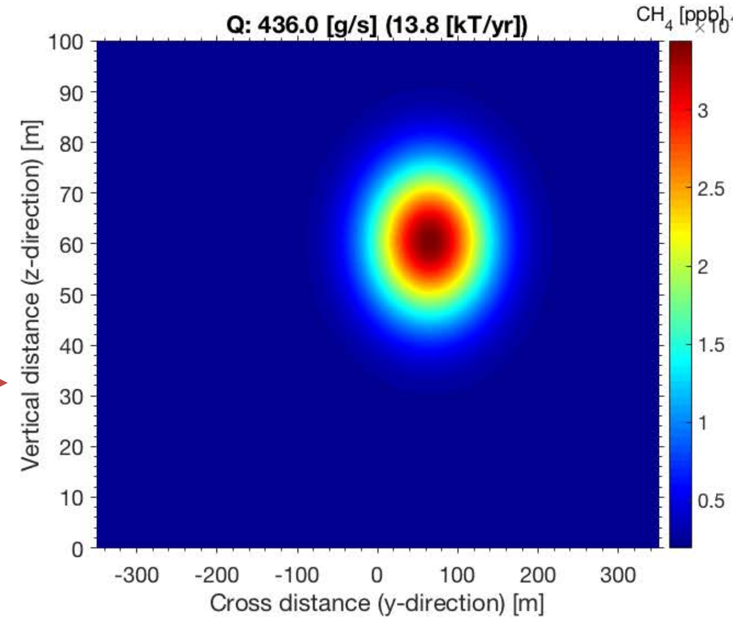
Flight on August 18 2017

CH_4 (ppm)

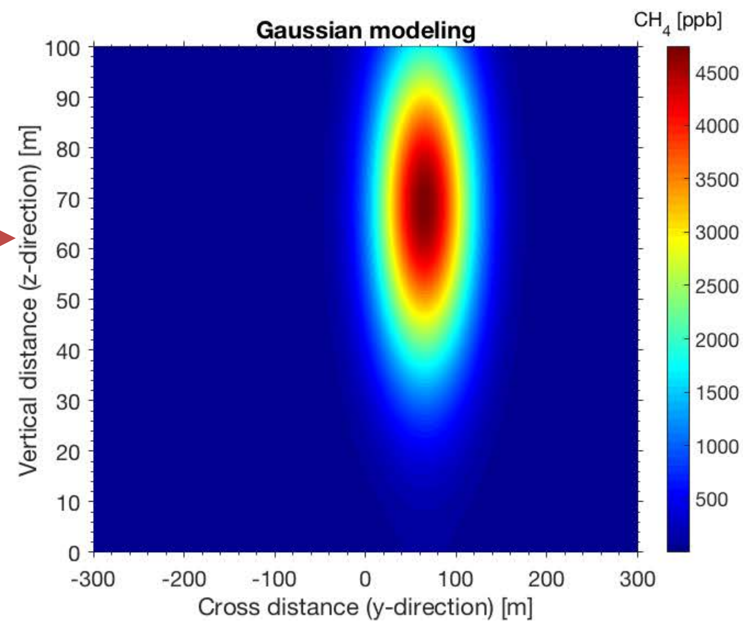


Inversion

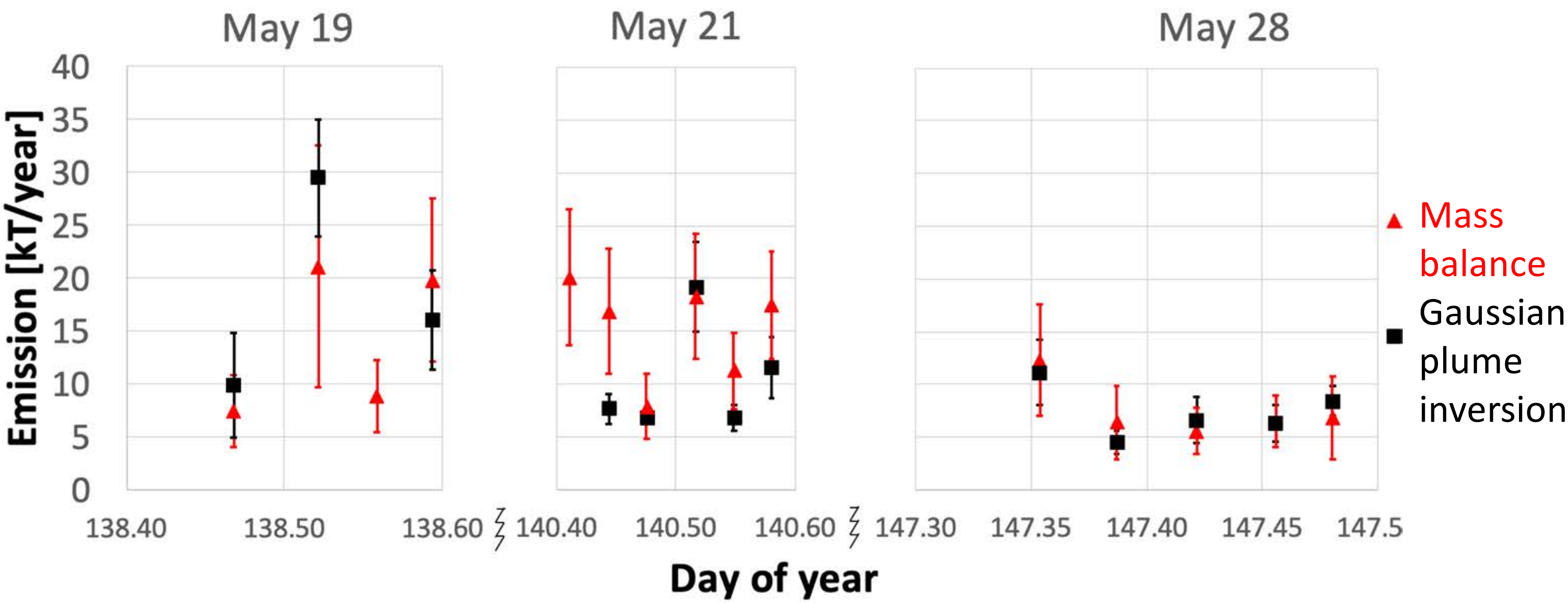
H, $\boldsymbol{\sigma}_y$, $\boldsymbol{\sigma}_z$



Stability Class C



Quantified Emission rates of Pniowek V shaft

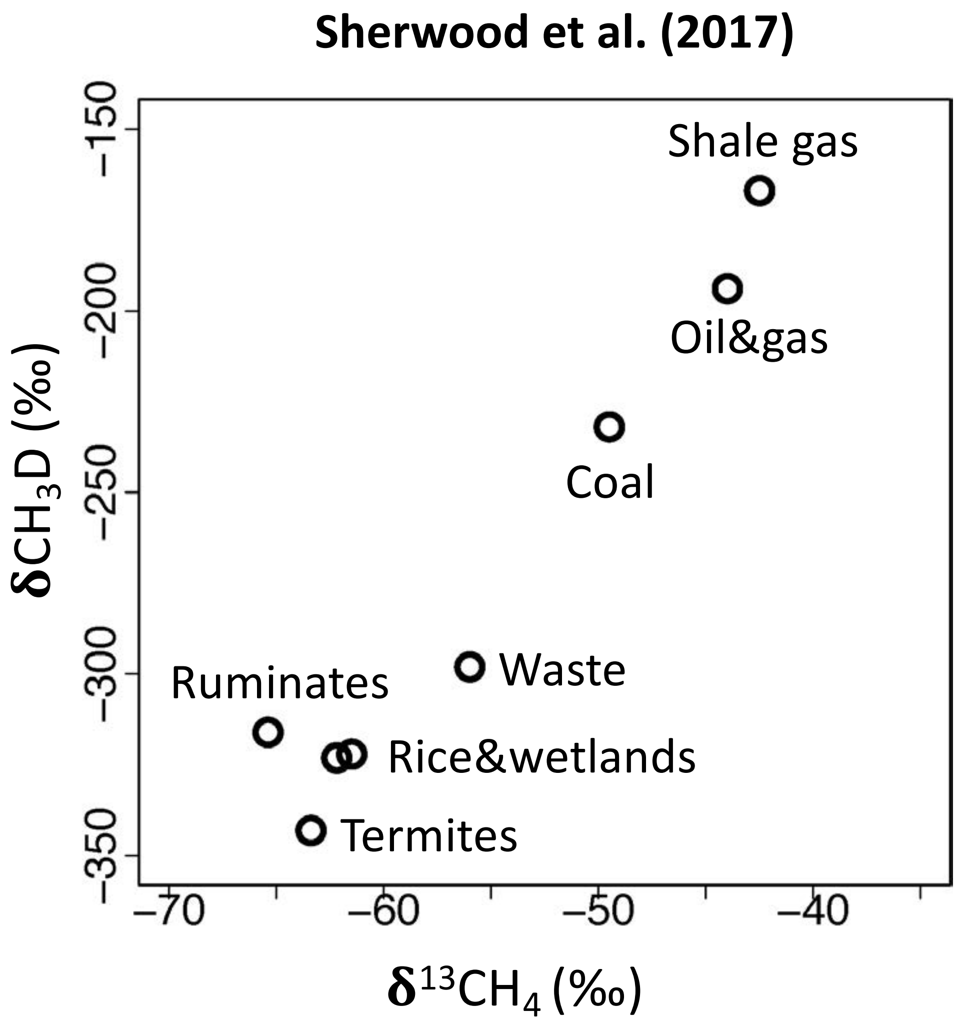


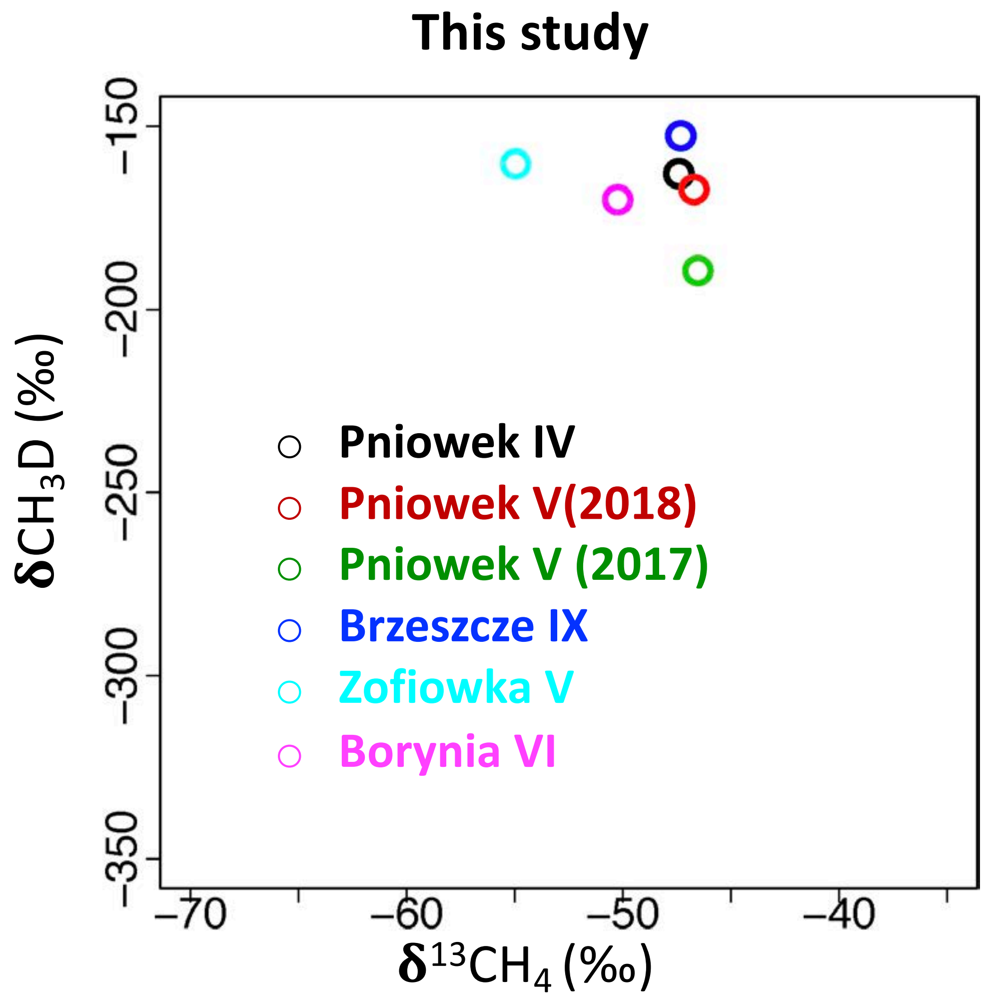
- Mass balance vs. Gaussian plume inversion
  - An average difference of 1.2 kton CH_4/year
- Variations in the estimates for different days
  - Verification of the inventory estimates at high temporal resolution

Emissions of different shafts

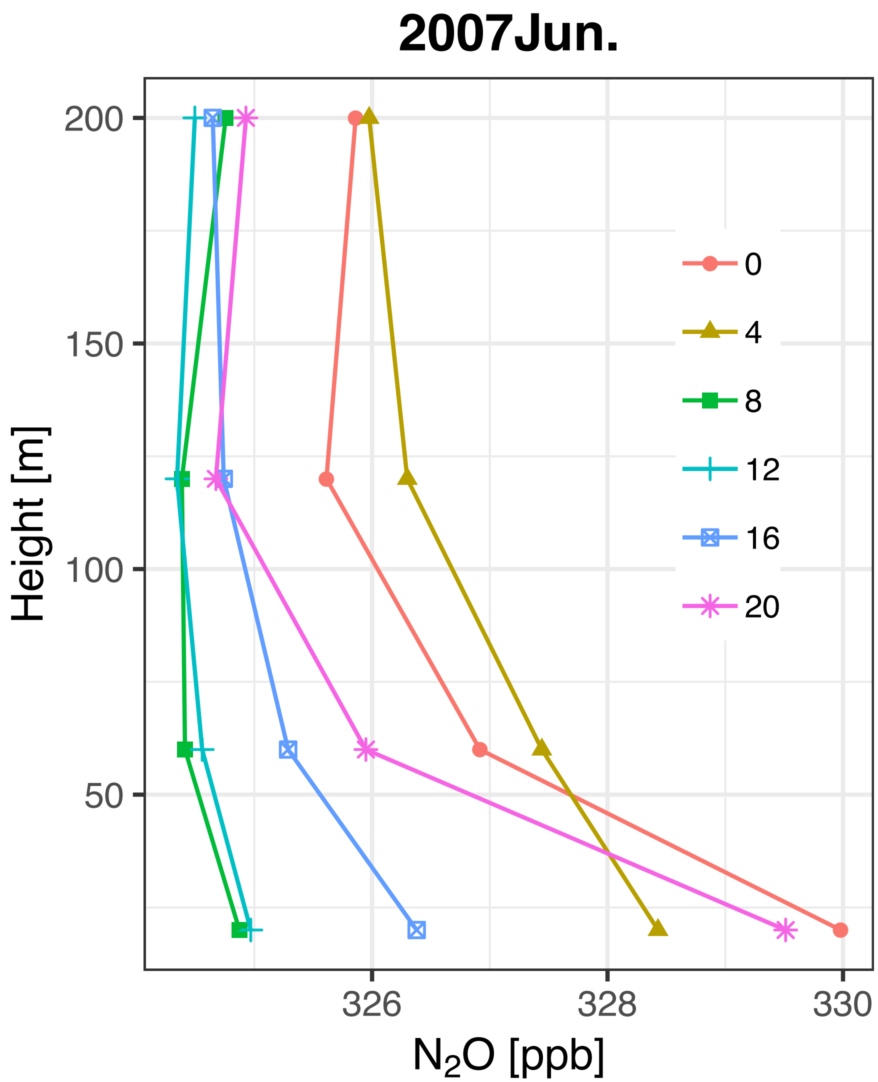
Shaft	Current inventory	Mass balance approach	Gaussian inversion
#1	20.6	10.8 ± 5.1 (N = 10)	12.1 ± 3.5 (N = 15), Min - Max: 4.5 – 29.5
#2	20.6	2.5 ± 1.2 (N = 3)	3.1 ± 0.8 (N = 8), Min - Max: 0.9 – 10.5
#3	5.6	5.6 ± 3.0 (N = 1)	5.2 ± 1.4 (N = 7), Min - Max: 2.4 – 10.2
#4	10.05	1.9 ± 0.7 (N = 1)	3.5 ± 1.2 (N = 4), Min - Max: 1.1 – 11.7
#5	9.63	9.5 ± 3.7 (N = 2)	7.8 ± 2.1 (N = 3), Min - Max: 5.2 – 9.3

$\delta^{13}C$ and $\delta^{2}H$ of various shafts





Application III: Quantification of N_2O and CH_4 Emissions using nighttime profiles at the Cabauw tower



Poster: Xin Tong

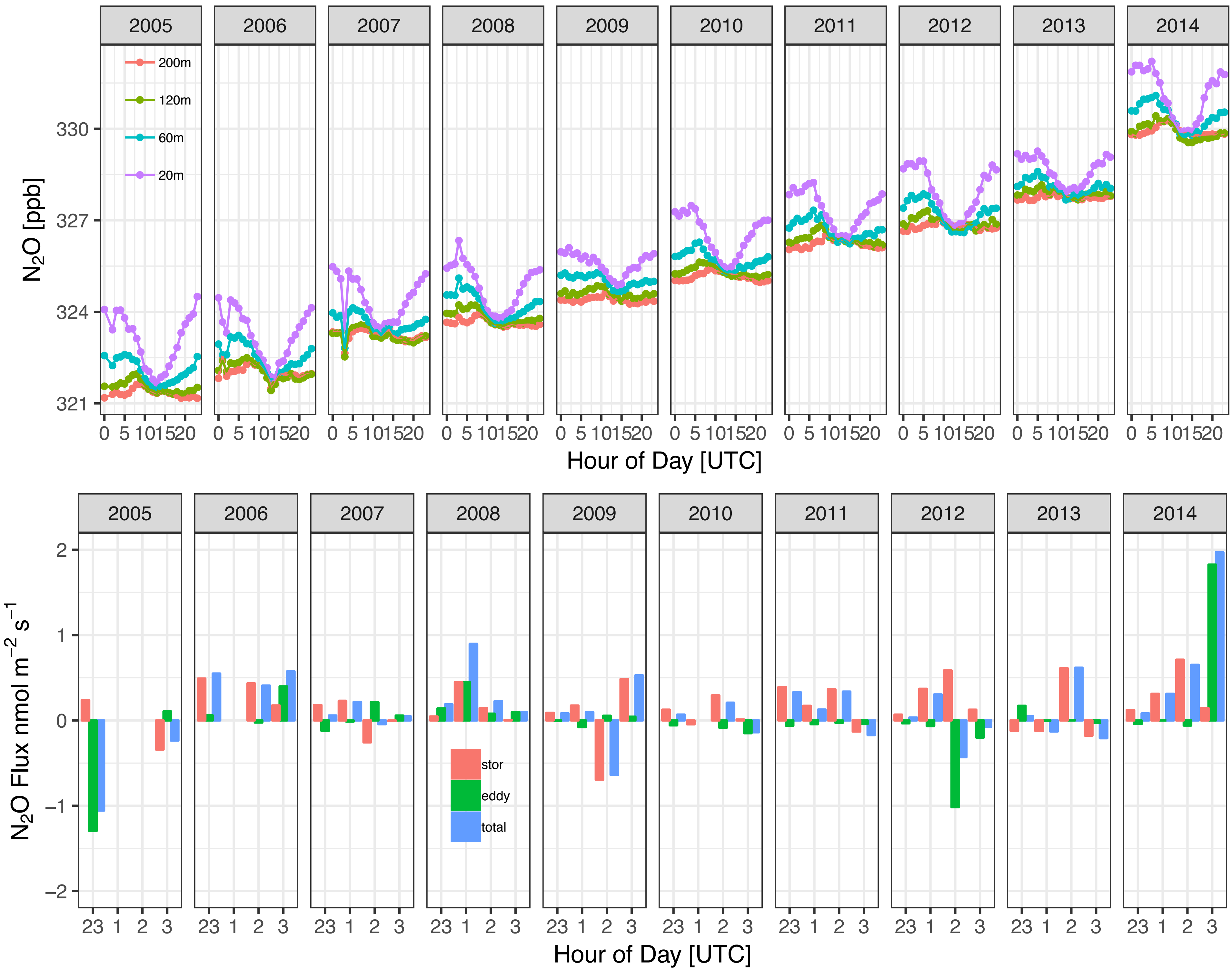
$$F_{CH4} = \int_0^{Z_r} \frac{1}{V_m}\frac{\partial \bar{c}}{\partial t} dz + \frac{1}{V_m} . \overline{\acute{w}\acute{c}}\,(Z_r) + \ldots$$

Storage Turbulence

- $F_{Eddy} * V_m = \overline{\acute{w}\acute{c}} = K_C \frac{dc}{dz}$ K_C: the eddy diffusivity
- H = $\rho_{Air} C_p K_T \frac{dT_{pot}}{dz}$ H: sensible heat flux measurements

Assuming:
The same turbulent exchange coefficients for heat, water vapor and other trace gases.

- $K_C = K_T$ $F_{Eddy} = \frac{H}{C_p M_{Air}} \frac{\frac{\partial c}{\partial z}}{\frac{\partial T_{pot}}{\partial z}}$



2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
200m
120m
60m
20m
N_2O [ppb]
330
327
324
321
0 5 101520
Hour of Day [UTC]
N_2O Flux nmol m^{-2} s^{-1}
2
1
0
−1
−2
stor
eddy
total
23 1 2 3
Hour of Day [UTC]

Conclusions and discussion

- UAV-based Active AirCore provide 3D high-precision CH_4 measurements
- Good agreement between Mass Balance Approach and Gaussian plume Inversion Approach
- Potentials
  - Multiple drones
  - Combine with tracer ratio methods
  - Multiple species measurements