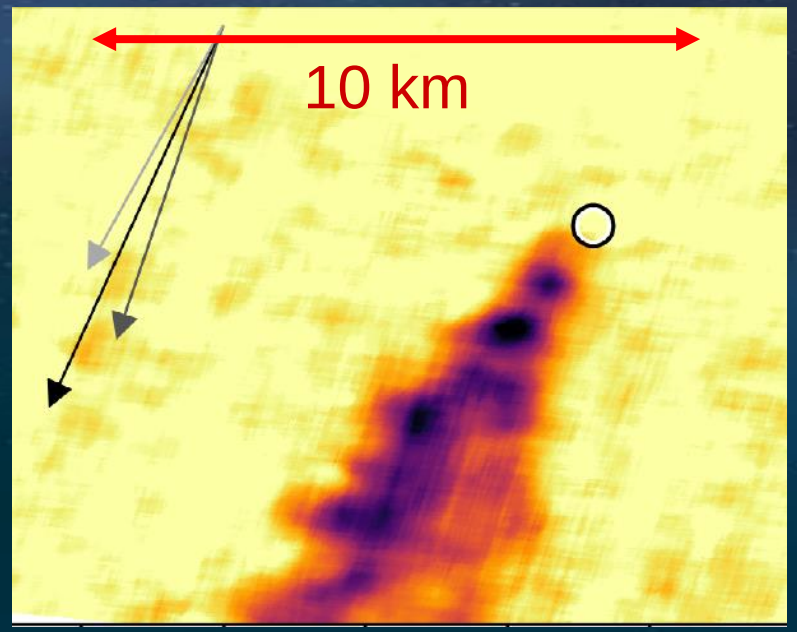
MAX PLANCK INSTITUTE
FOR CHEMISTRY

INSTITUT FÜR
UMWELTPHYSIK

High-resolution ENMAP satellite measurements of NO_2 and CO_2 in power plant plumes

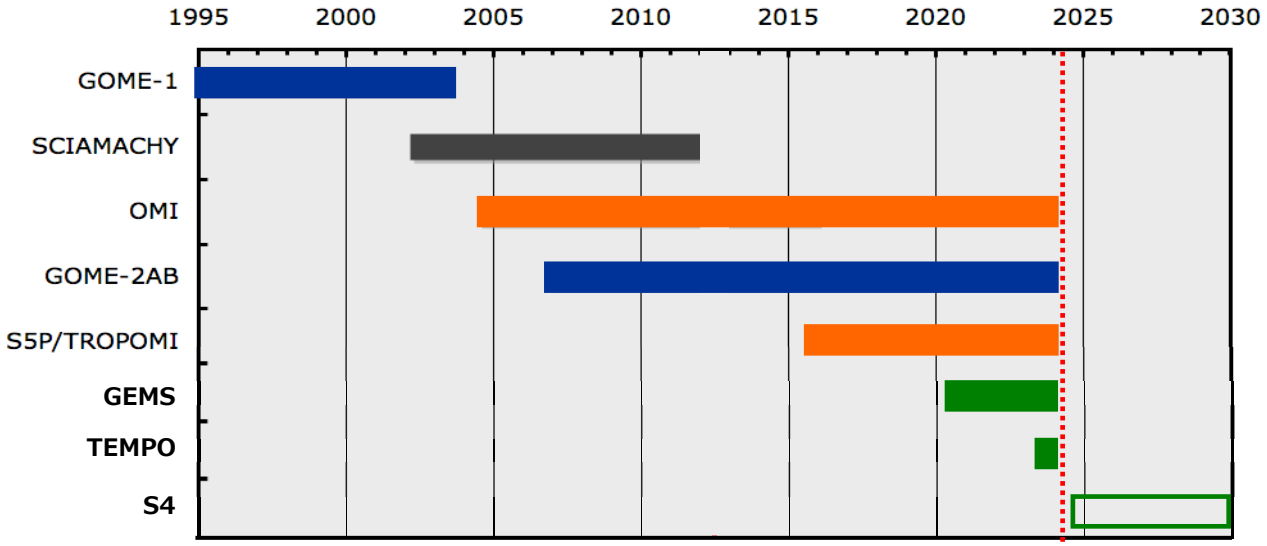
Thomas Wagner[1], Steffen Beirle[1], André Butz[2], Leonie Scheidweiler[2], Christian Borger[1,3]

[1]Max Planck Institute for Chemistry, Mainz, Germany
[2]Institute of Environmental Physics, University of Heidelberg, Heidelberg, Germany
[3]European Centre for Medium-Range Weather Forecasts, Bonn, Germany



esa

Timeline of UV/vis satellite instruments



→ the ground pixel sizes reach sub-city scale

GOME
320 x 40 km²

GOME-2
80 x 40 km²

SCIAMACHY
30 x 60 km²

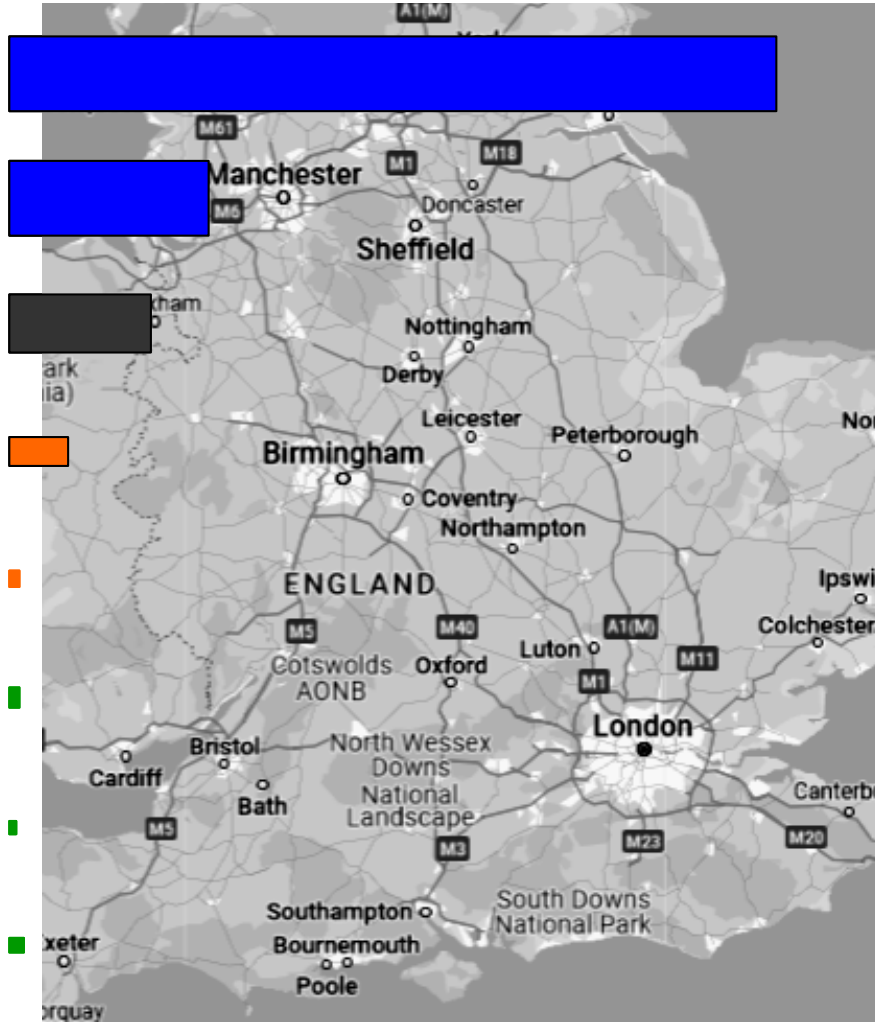
OMI
13 x 26 km²

TROPOMI
3.5 x 5.5 km²

GEMS
3.5 x 8 km²

TEMPO
2 x 4.7 km²

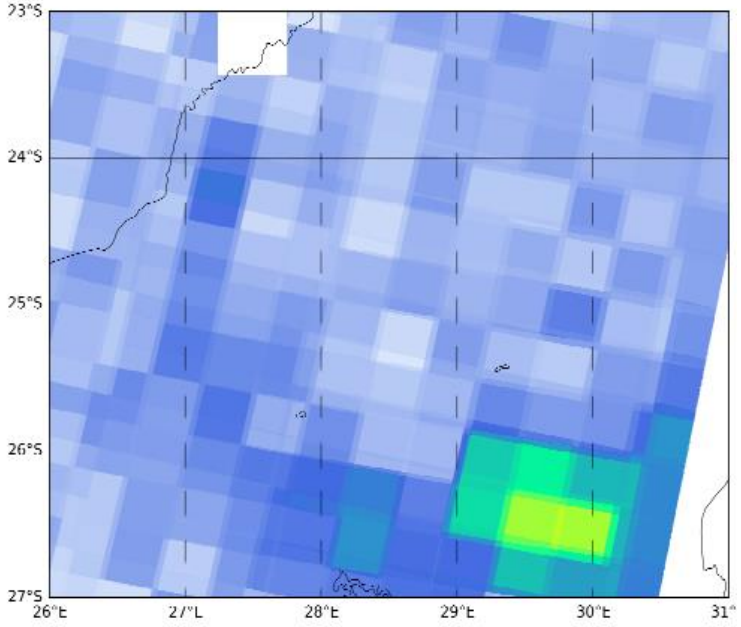
Sentinel 4
8 x 8 km²



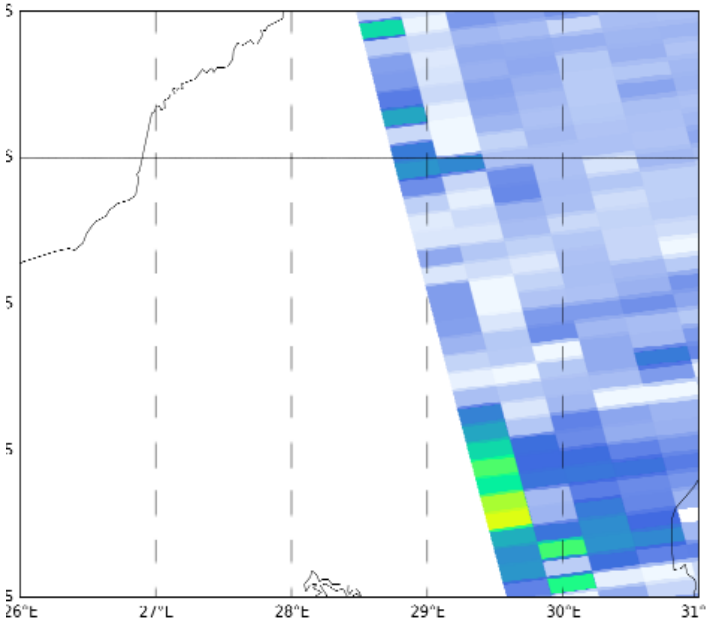
With TROPOMI we can track emission plumes

Tropospheric NO_2 over the Highveld, 29.11.2017

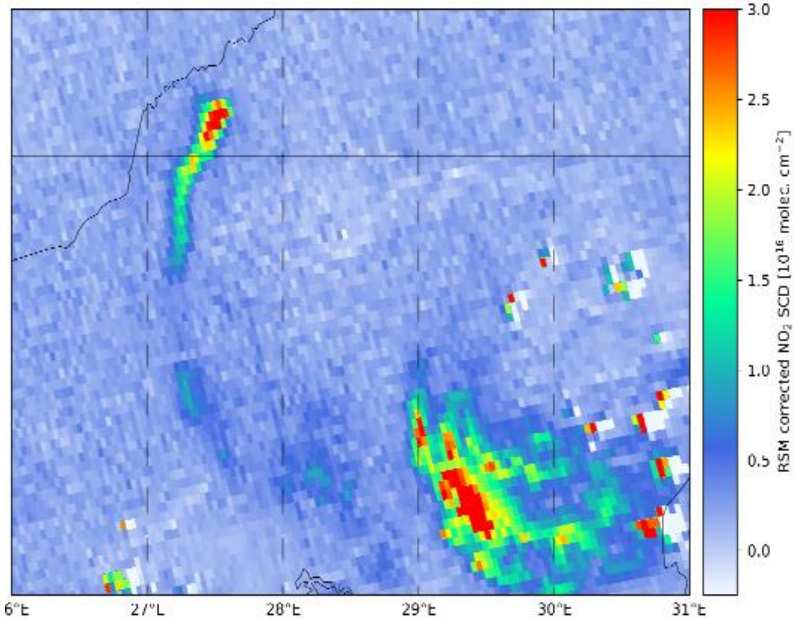
GOME-2
40 x 40 km²



OMI
26 x 13 km²



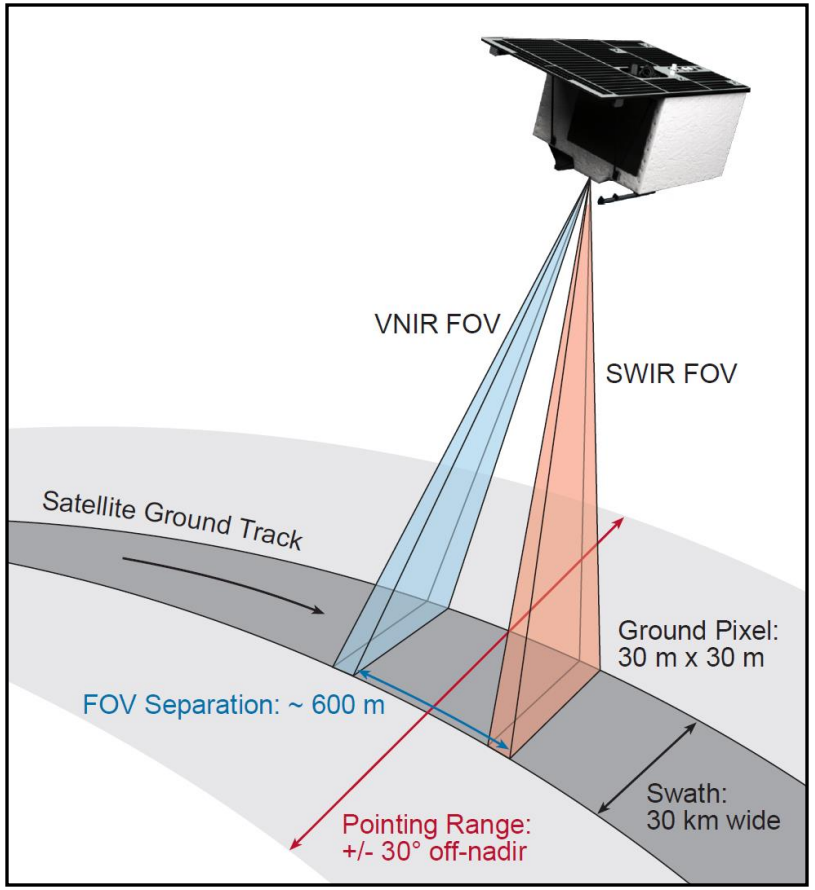
TROPOMI
3.5 x 7 km²



Novel ENMAP observations

German Spaceborne Imaging Spectrometer Mission

Launch:	1 April 2022
Spectral range:	420 nm – 2450 nm
Spectral resolution:	6.5 to 10 nm
Spatial resolution:	**30 m**
Swath width:	30 km

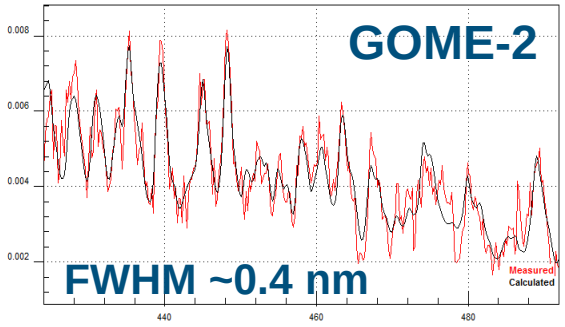


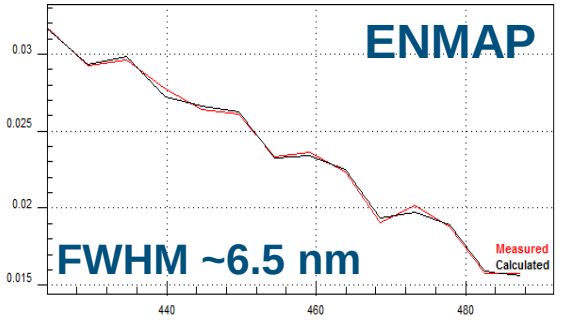
ENMAP mission:

Hyperspectral remote sensing of the Earth‘s surface

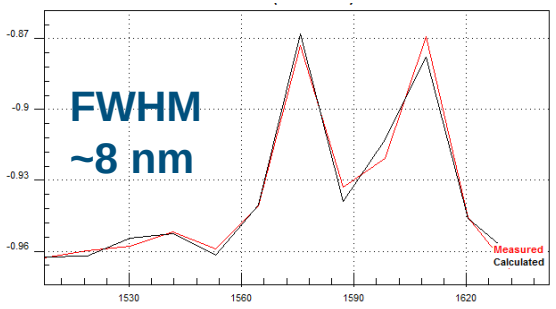
Can we also observe atmospheric trace gases?

NO_2 analysis (424 – 492 nm)





ENMAP CO_2 analysis (1500 – 1650 nm)



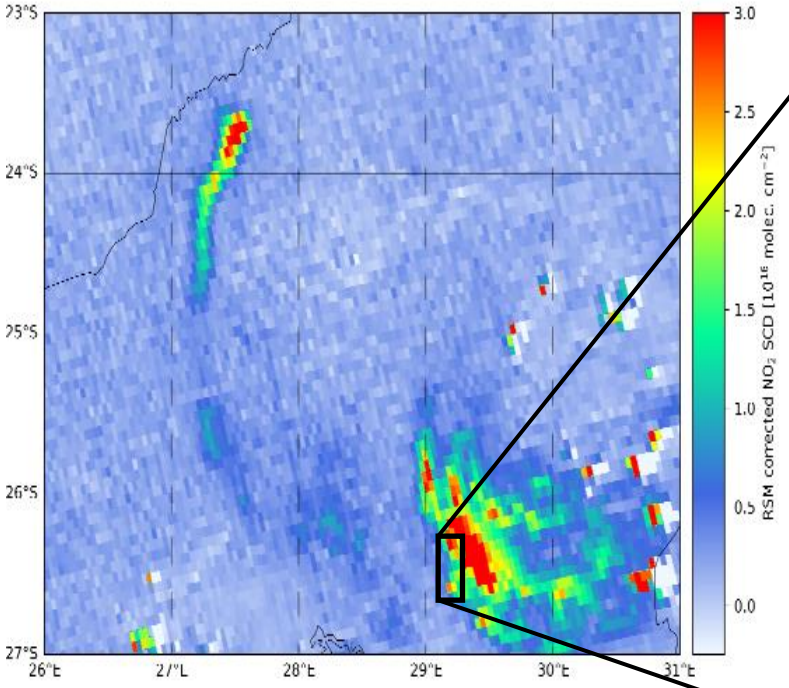
https://www.enmap.org/

DLR Deutsches Zentrum für Luft- und Raumfahrt

Novel ENMAP observations

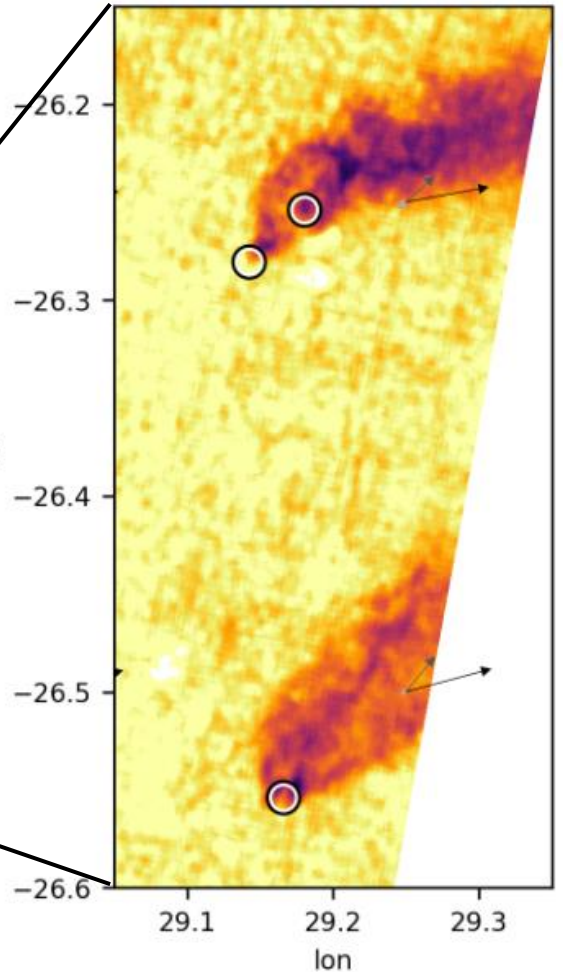
Tropospheric NO_2 over the Highveld, 29 Nov. 2017

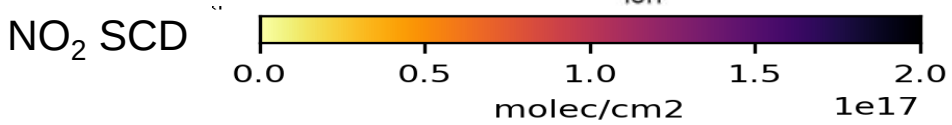
TROPOMI 3.5 x 7 km²



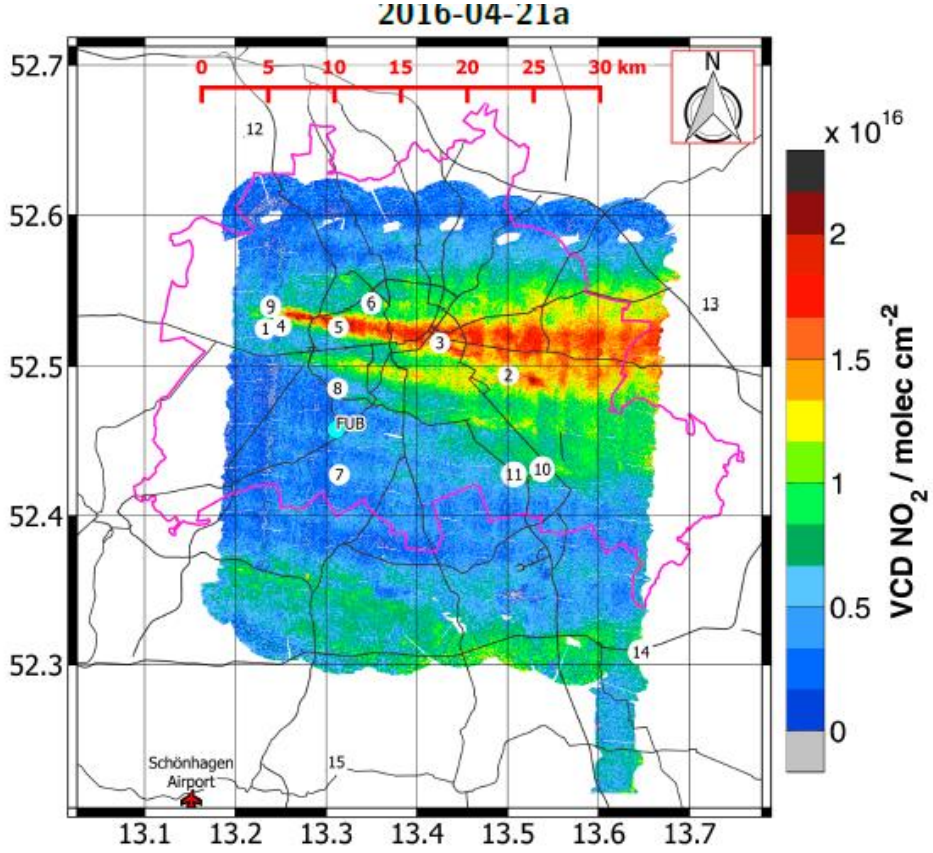
Observations over the Highveld 5 Oct. 2023

ENMAP 150 x 150 m²





Plumes can also be observed from aircraft



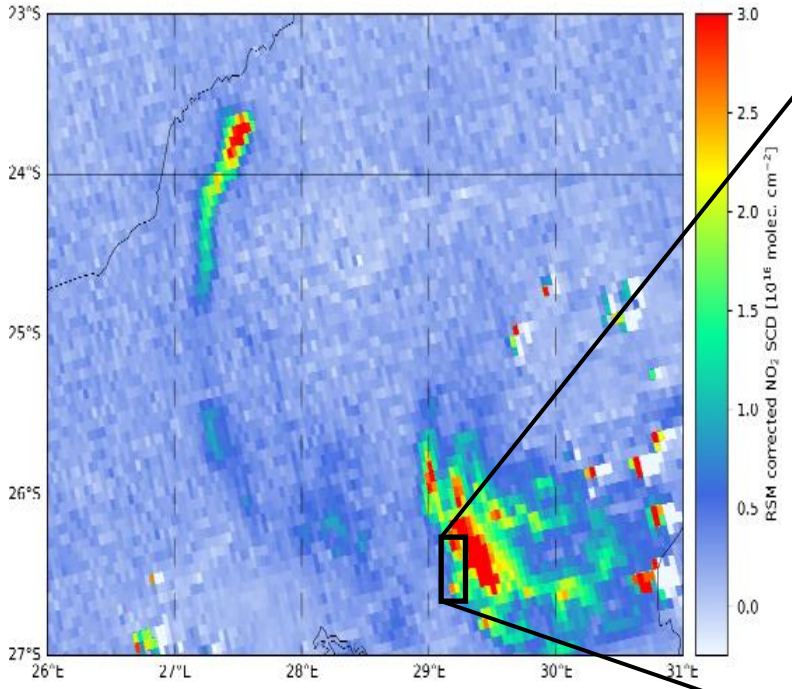
- measurement time ~2h
- average AMF: 1.7

PhD thesis Andreas Meier, IUP, Uni-Bremen, 2017
Tack et al., ACP 2019

Novel ENMAP observations

Tropospheric NO_2 over the Highveld, 29 Nov. 2017

TROPOMI 3.5 x 7 km²

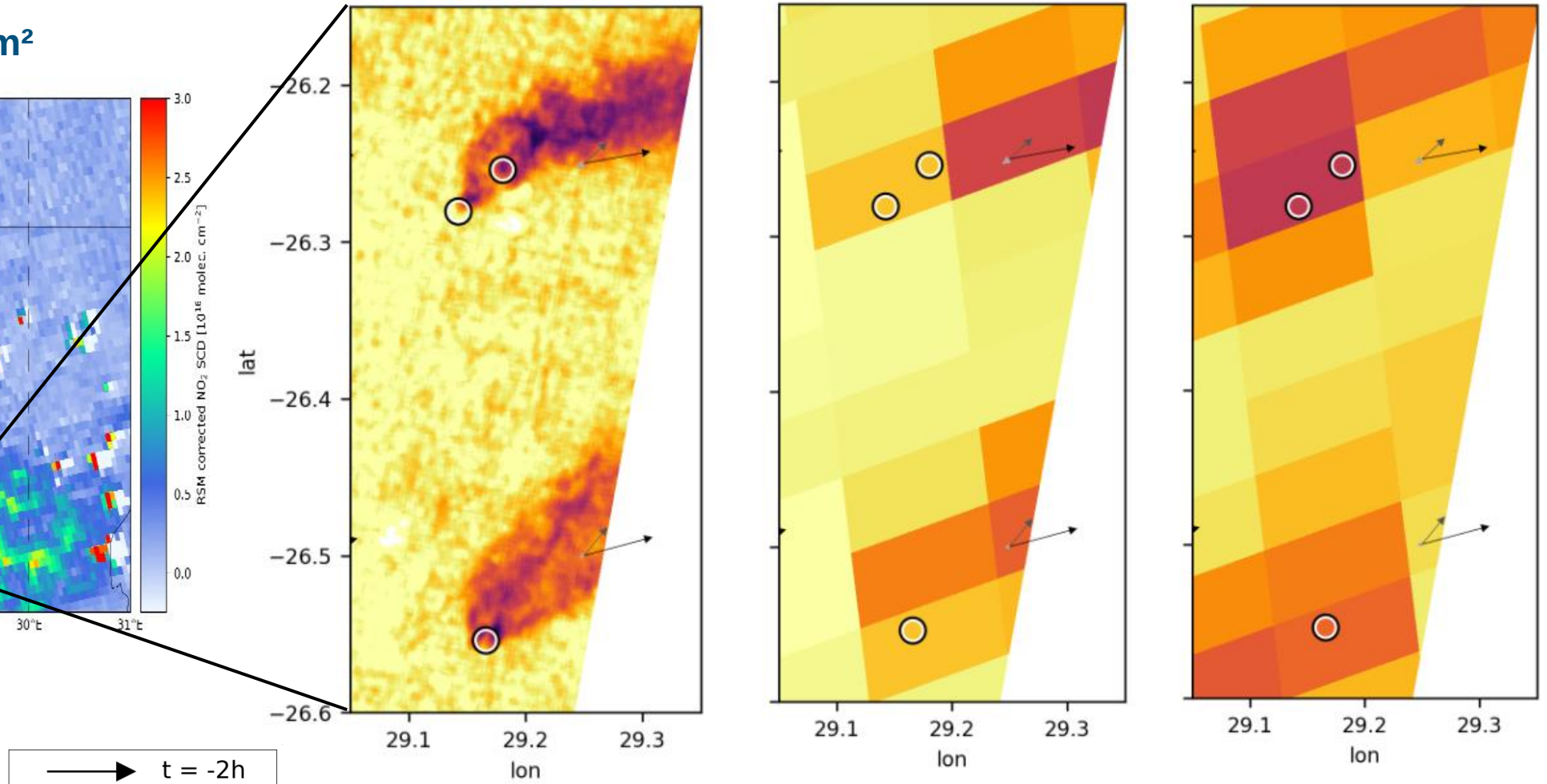


Observations over the Highveld 5 Oct. 2023

ENMAP 150 x 150 m²

ENMAP degraded

TROPOMI 3.5 x 5.5 km²



Novel ENMAP observations

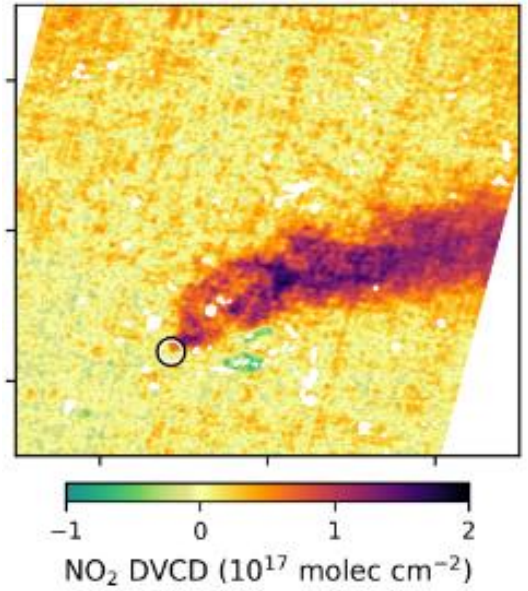
Observations over the Highveld 5 Oct. 2023

→ details of the plumes become visible:

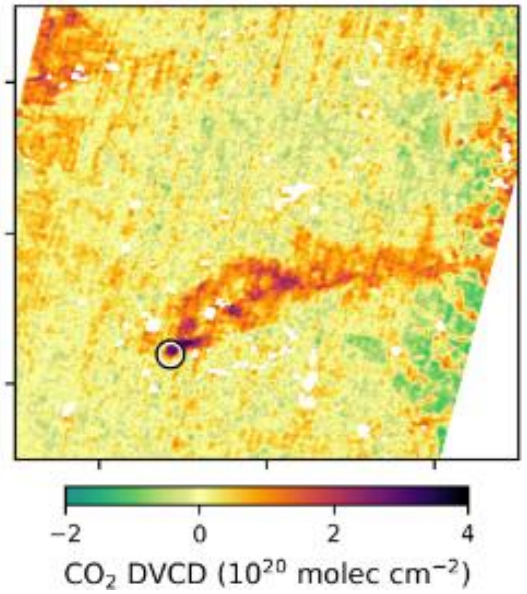
- turbulence
- NO to NO_2 conversion
- NO_x lifetime
- changing wind fields

→ NO_2 / CO_2 ratio

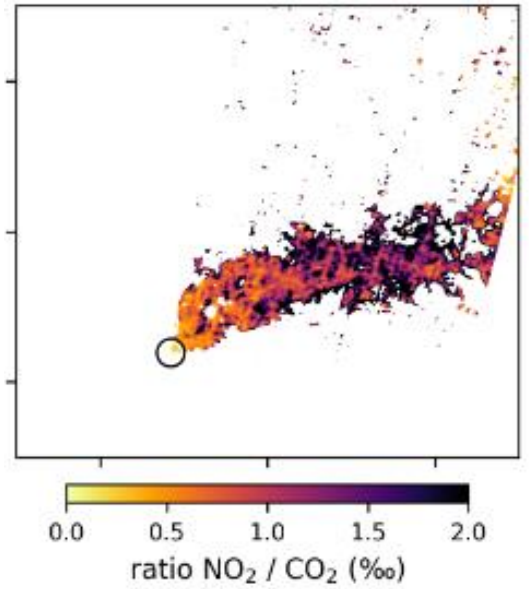
NO_2 ENMAP

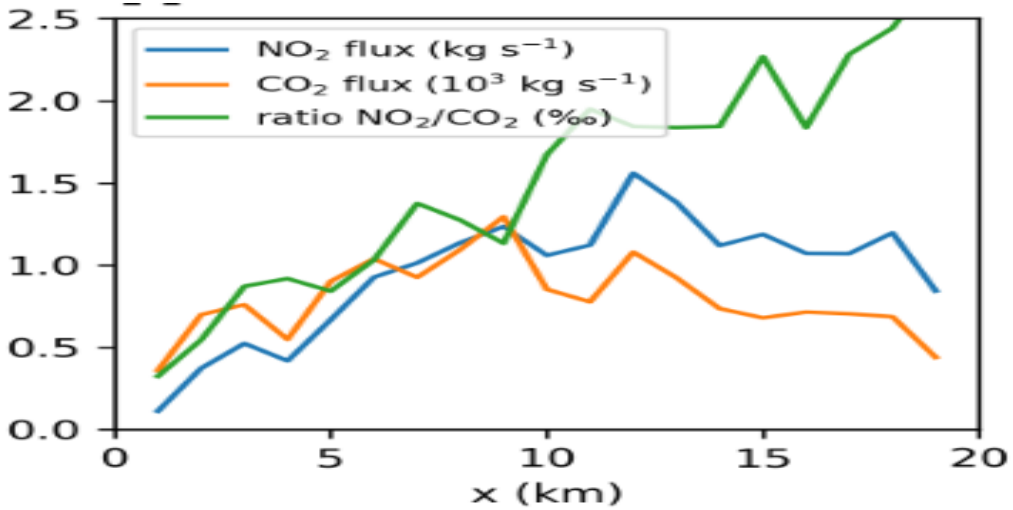


CO_2 ENMAP



ratio NO_2 / CO_2

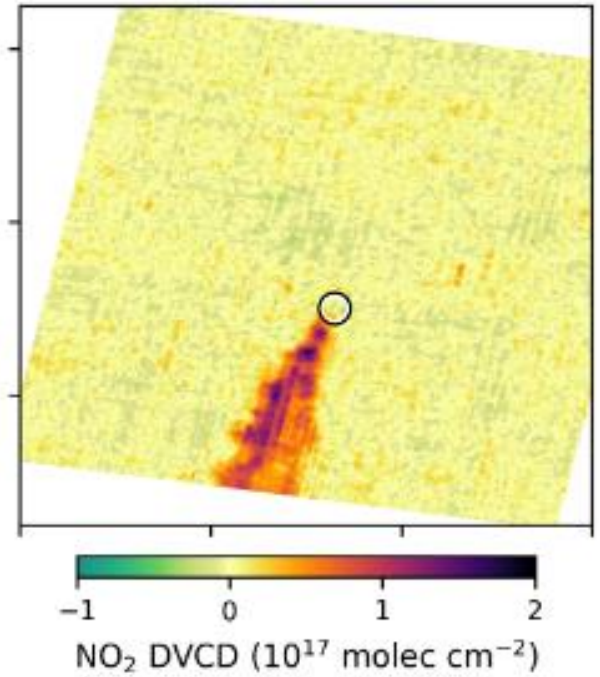




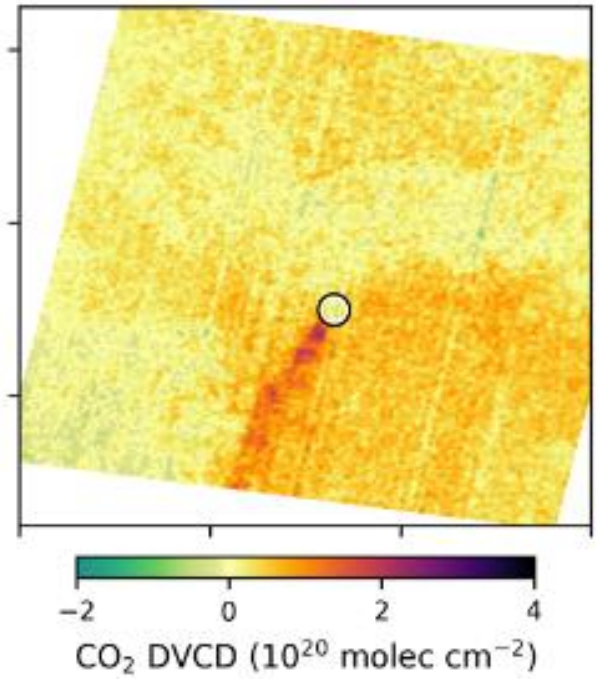
Novel ENMAP observations

ENMAP Observations over Riyadh 15 July 2023

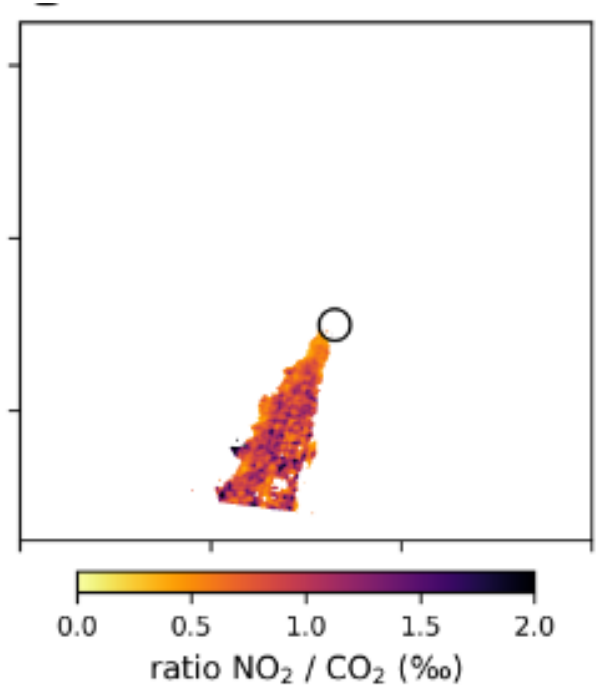
NO_2 ENMAP

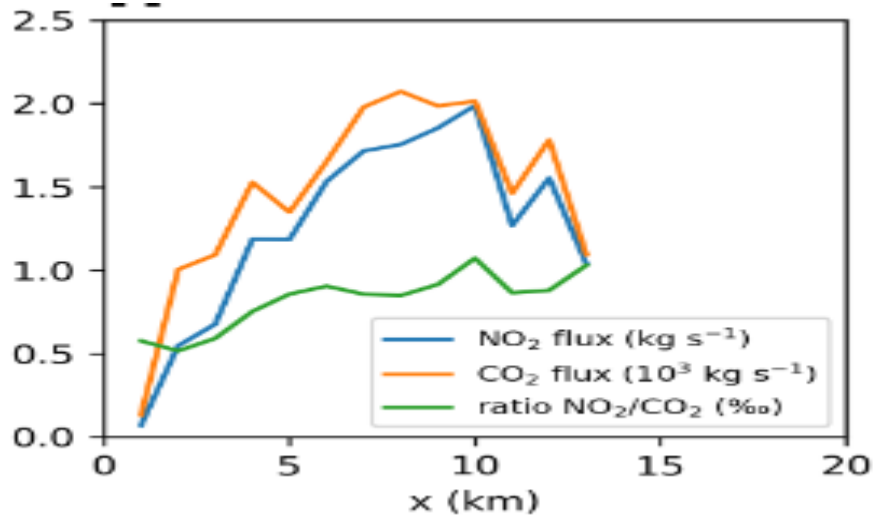


CO_2 ENMAP



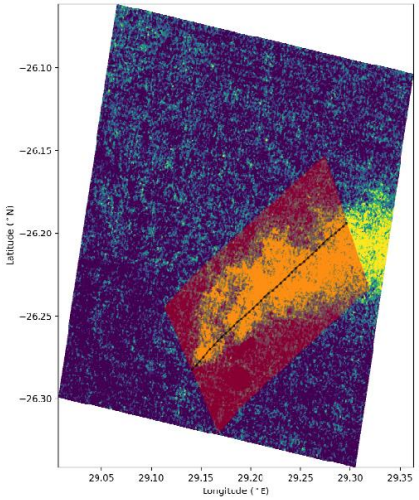
ratio NO_2 / CO_2

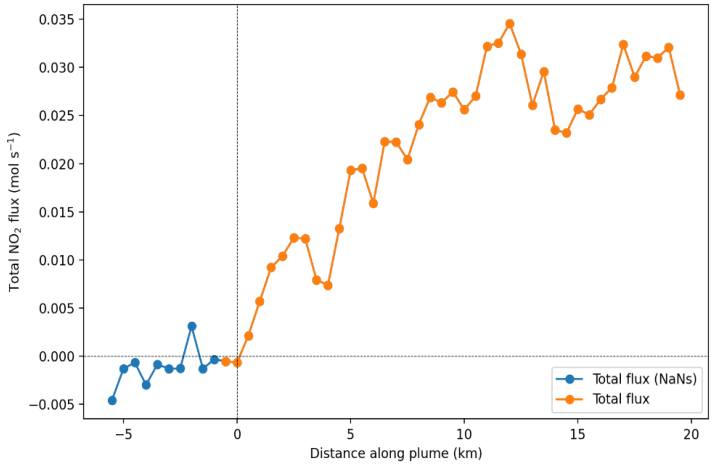




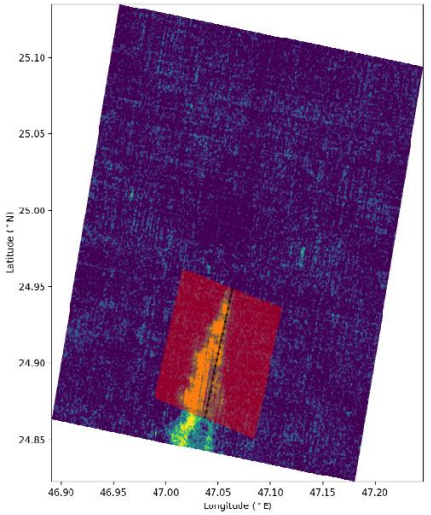
NO to NO_2 conversion (fluxes integrated across plume direction)

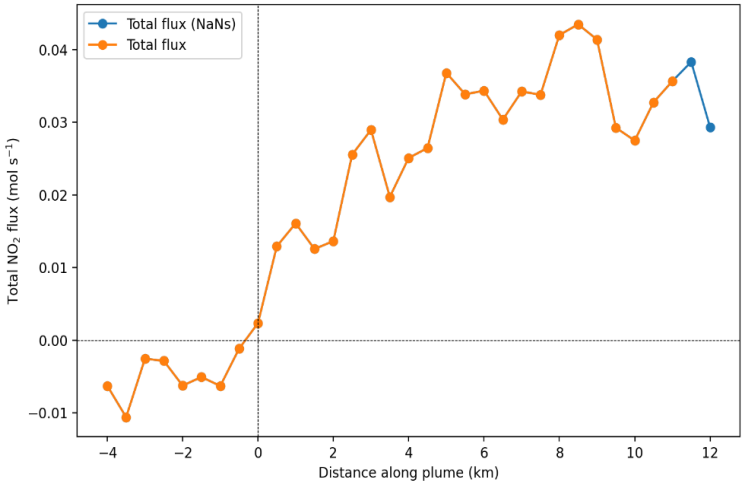
Matla, 05.10.2023



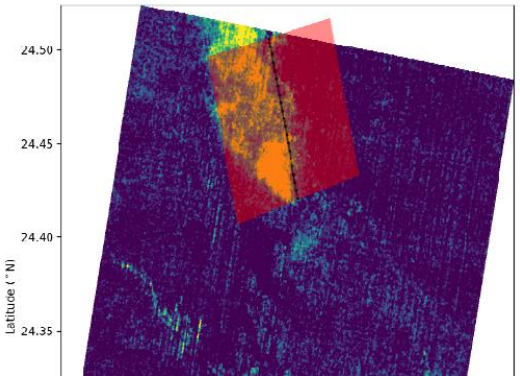


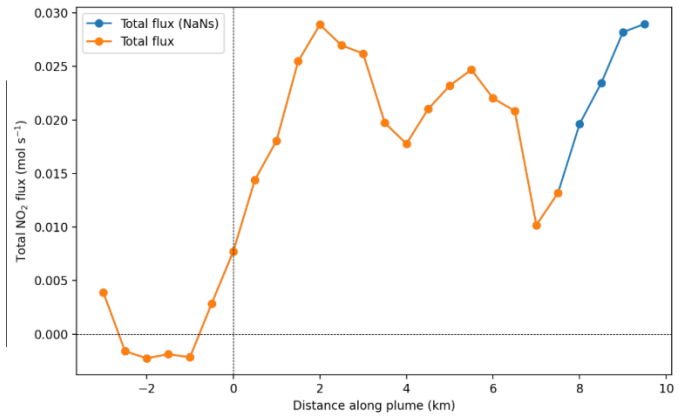
Riyadh 15.07.2023



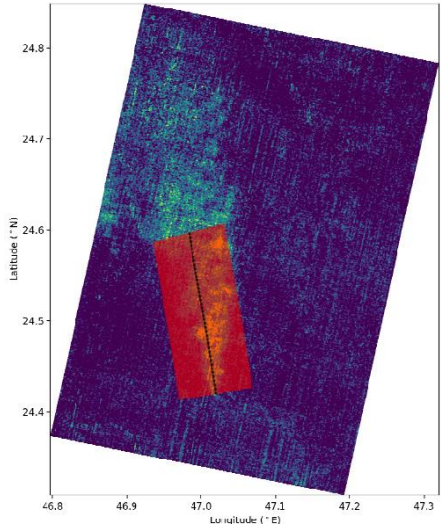


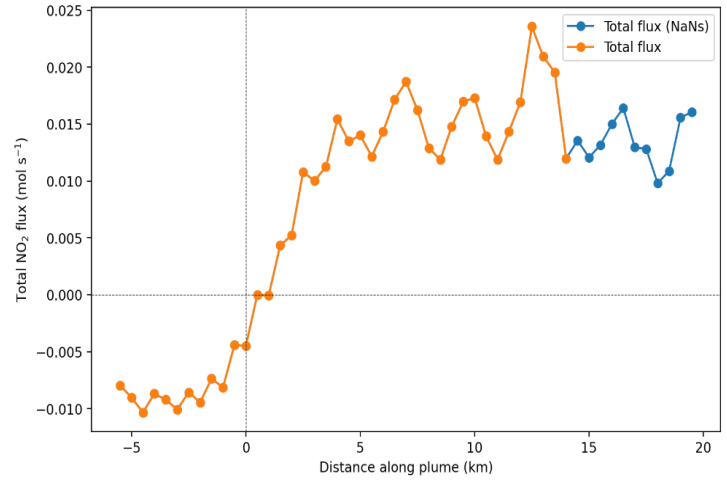
Riyadh 11.07.2023





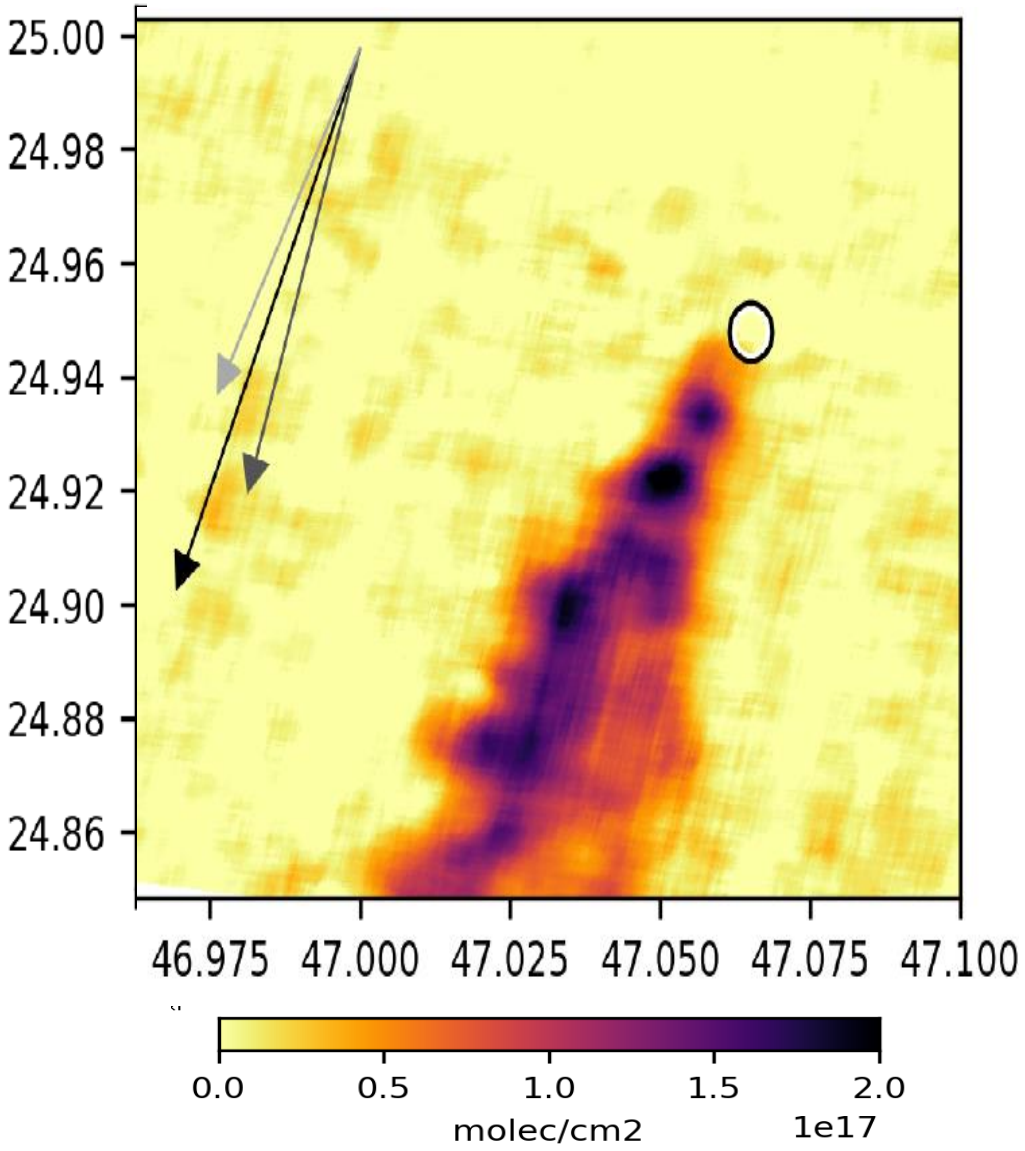
Riyadh 31.07.2023





Riyadh, power plant #9, 15 July 2023

14 km



Turbulence becomes visible

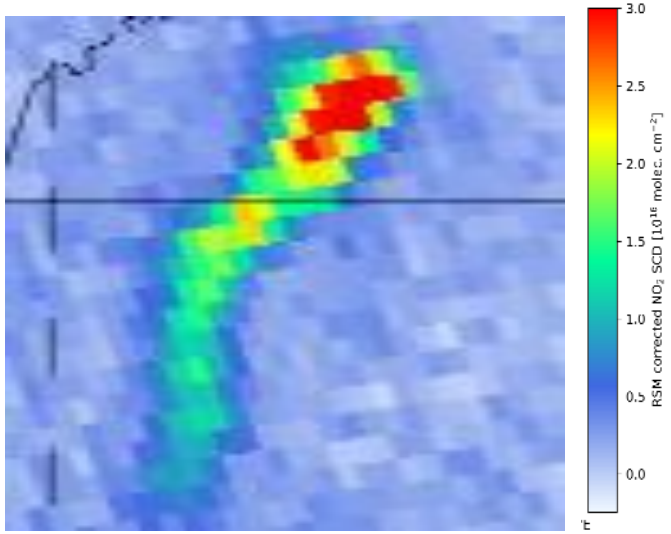
ENMAP covers an interesting size range

Advantage compared to aircraft observations: The whole plume is observed within a very short time

~1 km

dpa/picture-alliance/ Ding Dong

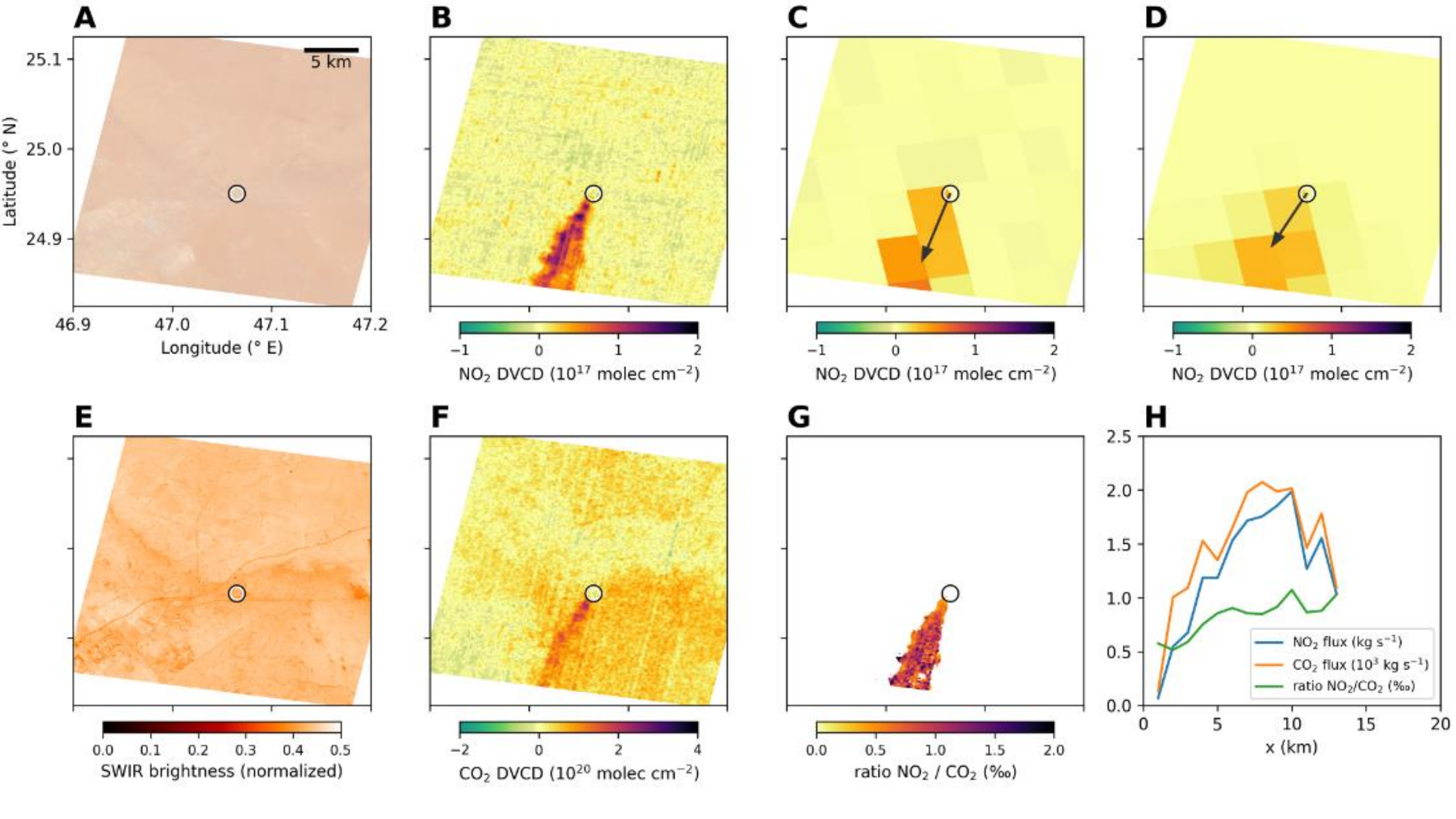
~100 km

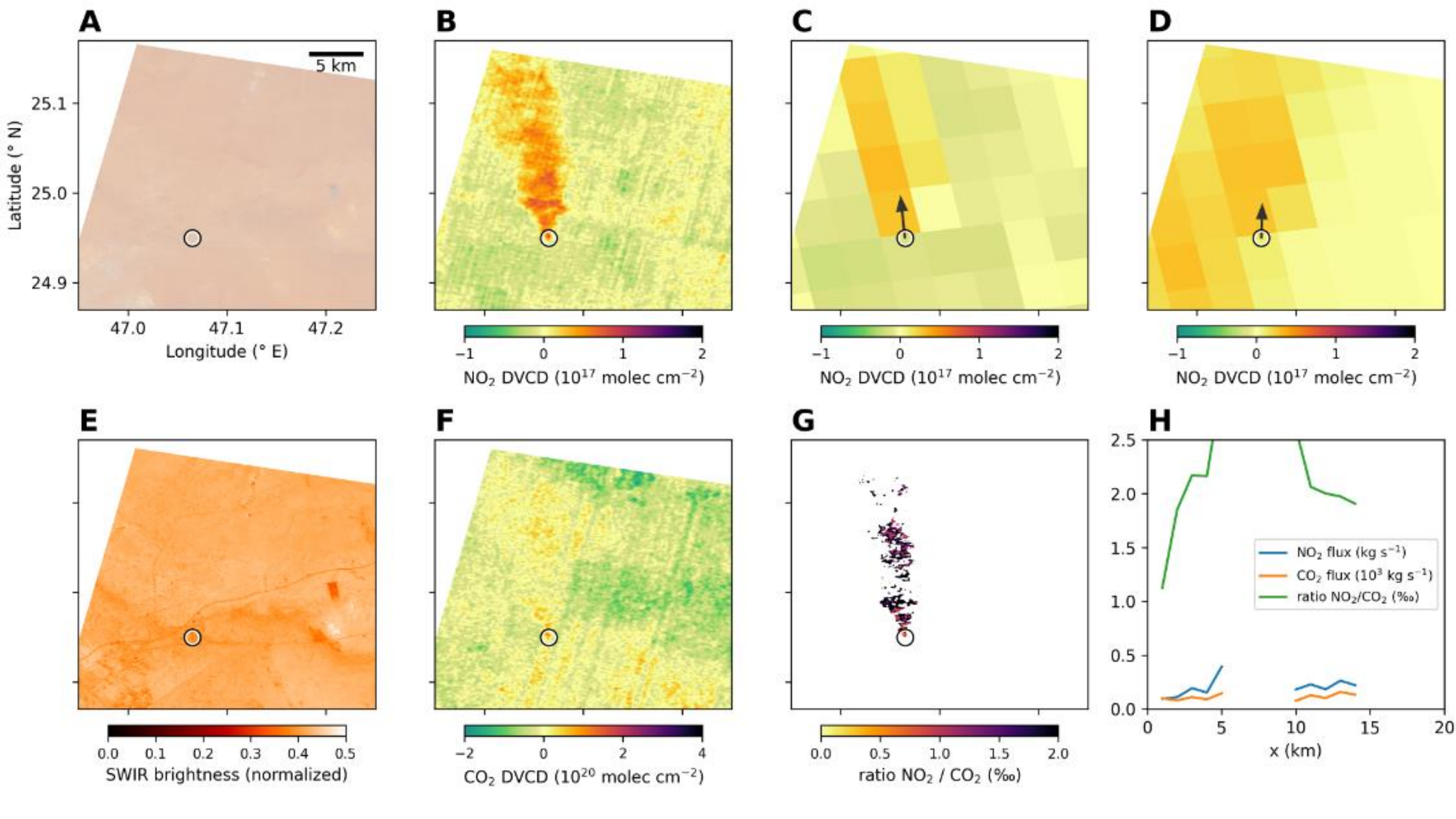


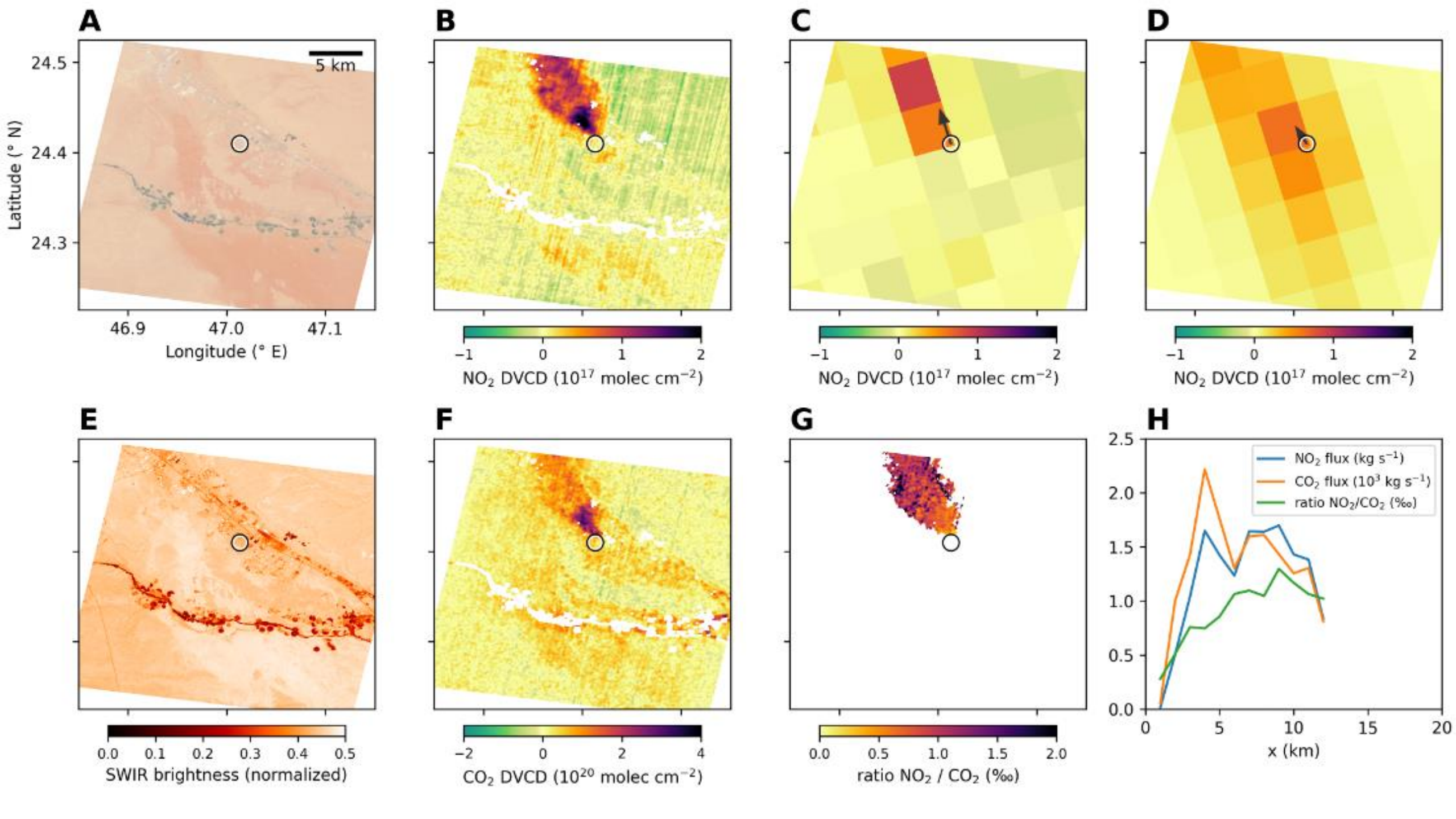
TROPOMI NO_2

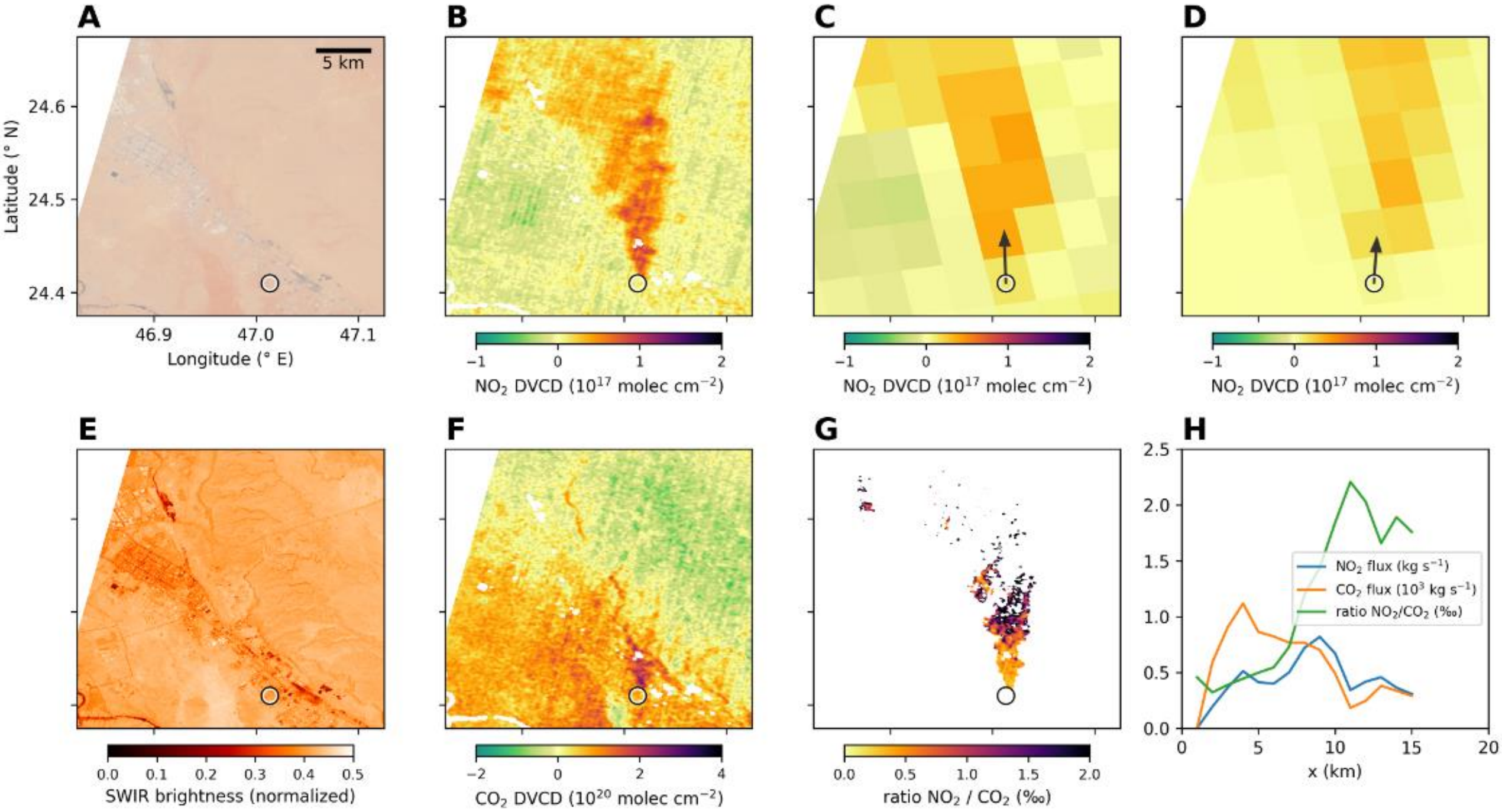
Conclusions

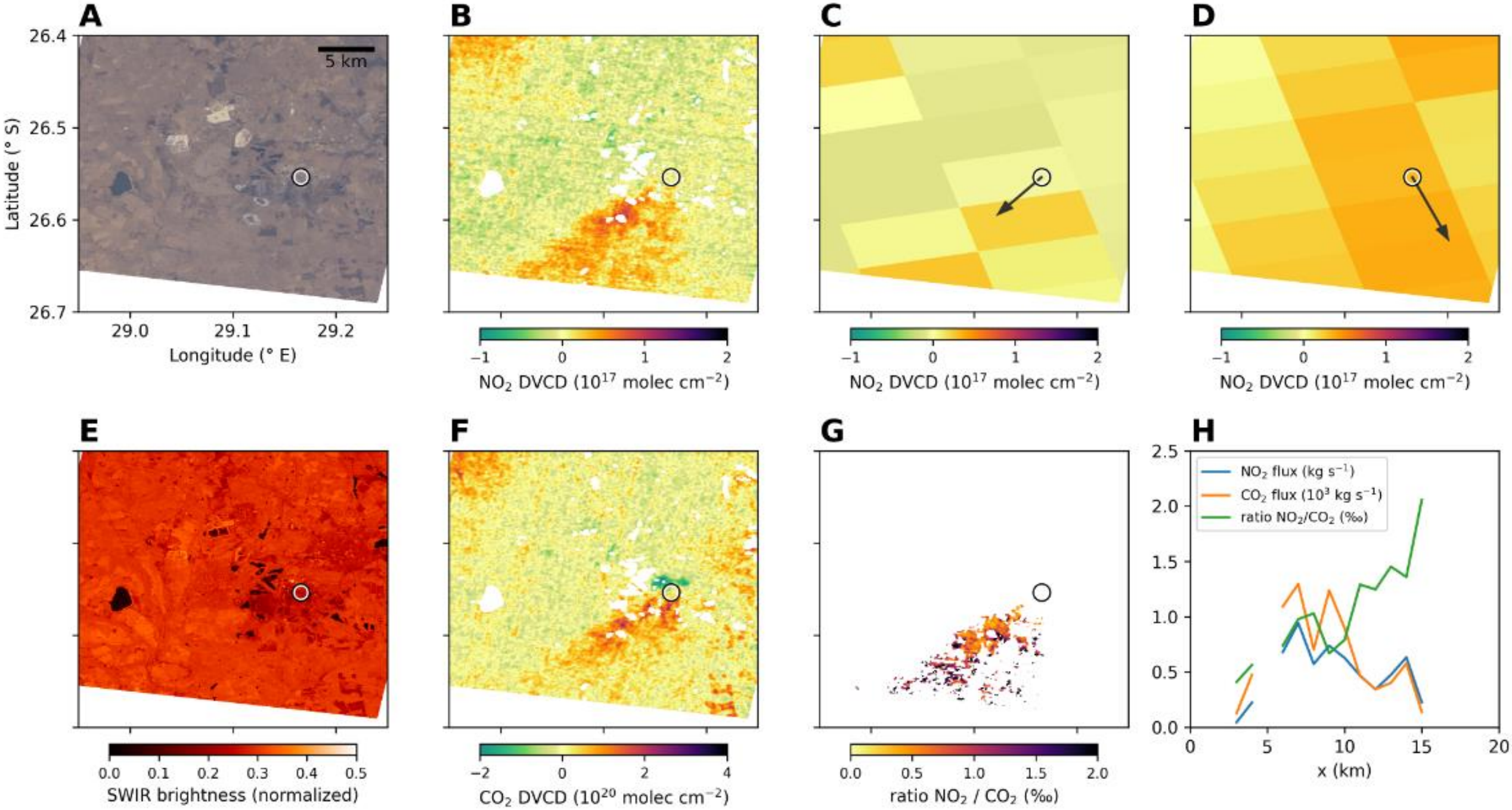
- from ENMAP spectra, NO_2 and CO_2 can be analysed at unprecedented spatial resolution (~100 m)
- power plant plumes can be observed for several tens of km downwind
- turbulence becomes visible at an intersting scale
- power plants could be classified according to their NO_2 to CO_2 ratio
- the conversion of NO to NO_2 can be quantified
- NO_x lifetime can be studied (dependence as function of distance?)

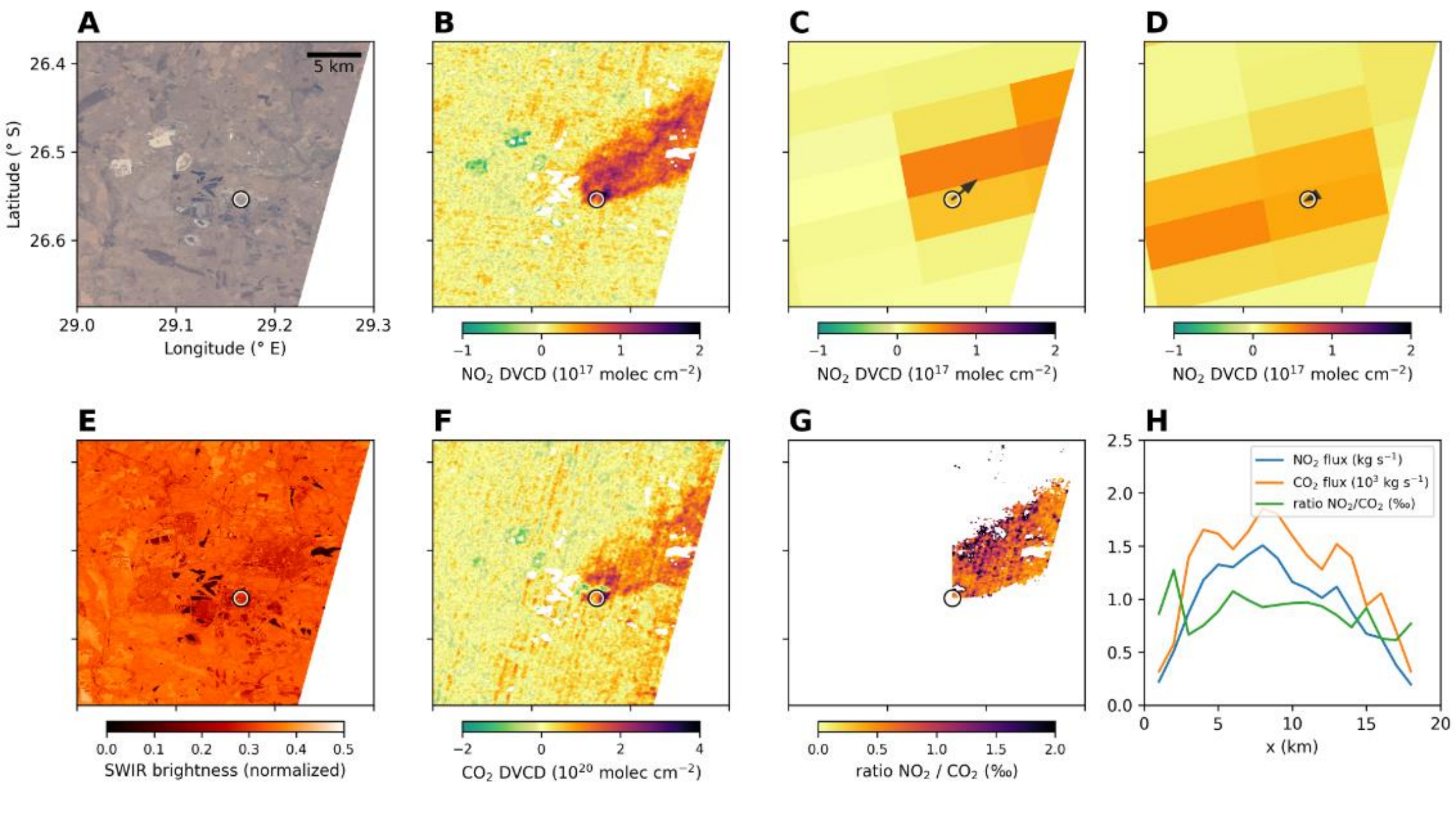

A
B
C
D
E
F
G
H
5 km
25.1
25.0
24.9
Latitude (° N)
46.9
47.0
47.1
47.2
Longitude (° E)
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
0.0
0.1
0.2
0.3
0.4
0.5
SWIR brightness (normalized)
−2
0
2
4
CO2 DVCD (10^20 molec cm^−2)
0.0
0.5
1.0
1.5
2.0
ratio NO2 / CO2 (‰)
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
x (km)
NO2 flux (kg s^−1)
CO2 flux (10^3 kg s^−1)
ratio NO2/CO2 (‰)

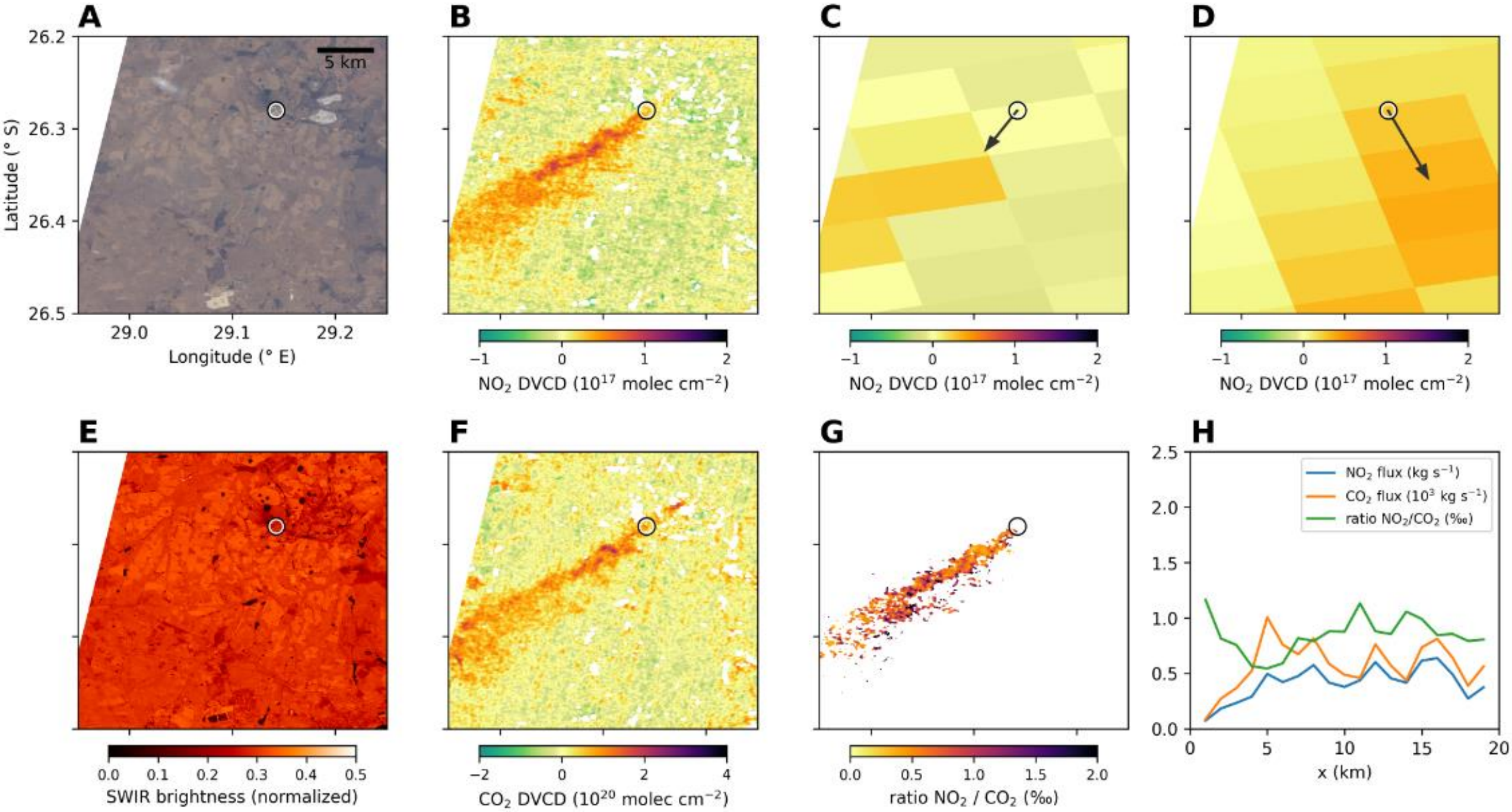

A
5 km
25.1
25.0
24.9
Latitude (° N)
47.0
47.1
47.2
Longitude (° E)
B
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
C
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
D
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
E
0.0
0.1
0.2
0.3
0.4
0.5
SWIR brightness (normalized)
F
−2
0
2
4
CO2 DVCD (10^20 molec cm^−2)
G
0.0
0.5
1.0
1.5
2.0
ratio NO2 / CO2 (‰)
H
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
x (km)
NO2 flux (kg s^−1)
CO2 flux (10^3 kg s^−1)
ratio NO2/CO2 (‰)

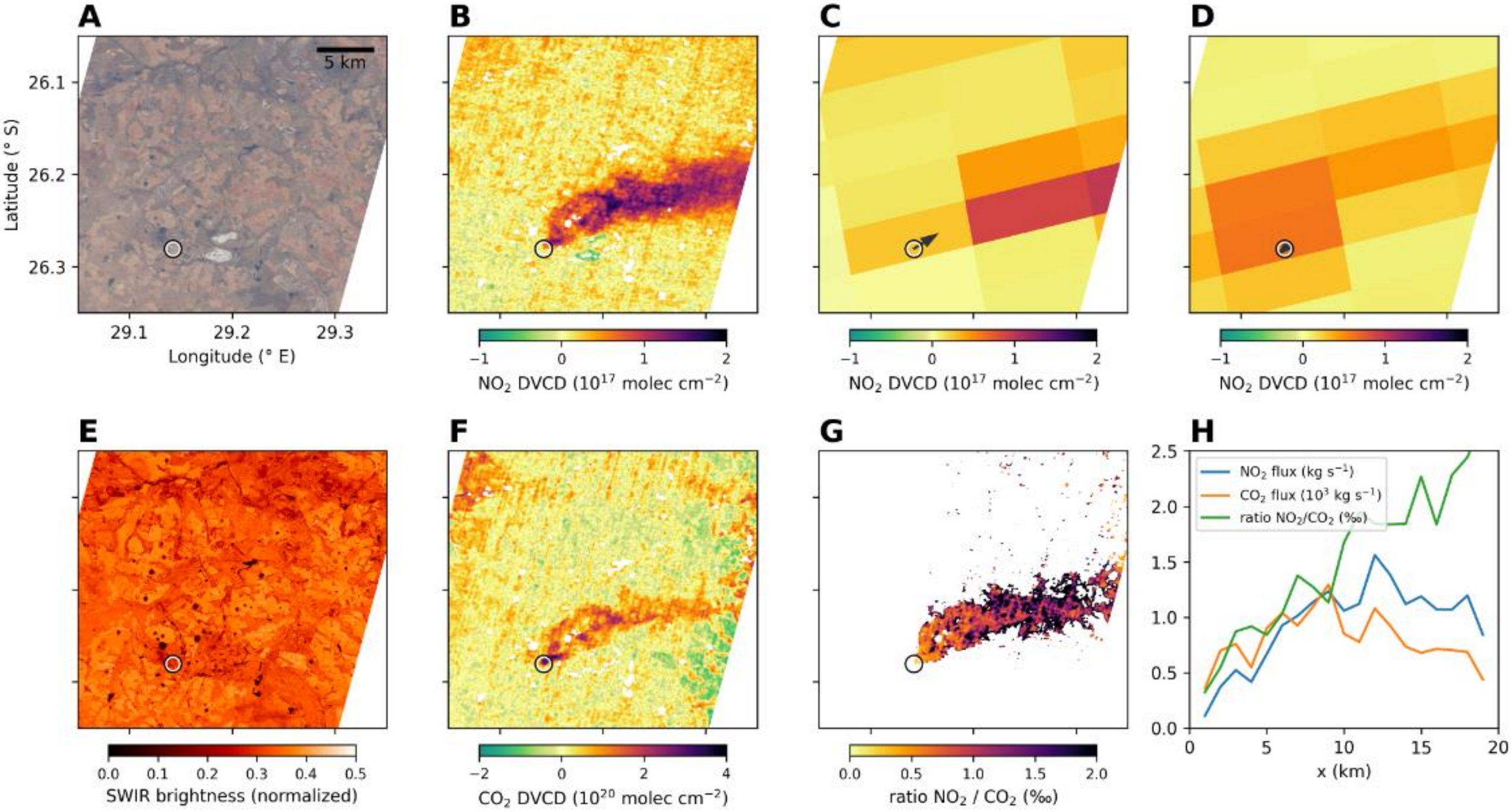

A
B
C
D
E
F
G
H
5 km
24.5
24.4
24.3
Latitude (° N)
46.9
47.0
47.1
Longitude (° E)
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
0.0
0.1
0.2
0.3
0.4
0.5
SWIR brightness (normalized)
−2
0
2
4
CO2 DVCD (10^20 molec cm^−2)
0.0
0.5
1.0
1.5
2.0
ratio NO2 / CO2 (‰)
NO2 flux (kg s^−1)
CO2 flux (10^3 kg s^−1)
ratio NO2/CO2 (‰)
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
x (km)


A
5 km
24.6
24.5
24.4
Latitude (° N)
46.9
47.0
47.1
Longitude (° E)
B
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
C
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
D
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
E
0.0
0.1
0.2
0.3
0.4
0.5
SWIR brightness (normalized)
F
−2
0
2
4
CO2 DVCD (10^20 molec cm^−2)
G
0.0
0.5
1.0
1.5
2.0
ratio NO2 / CO2 (‰)
H
2.5
2.0
1.5
1.0
0.5
0.0
0
5
10
15
20
x (km)
NO2 flux (kg s^−1)
CO2 flux (10^3 kg s^−1)
ratio NO2/CO2 (‰)


A
B
C
D
E
F
G
H
5 km
Latitude (° S)
Longitude (° E)
26.4
26.5
26.6
26.7
29.0
29.1
29.2
NO2 DVCD (10^17 molec cm^-2)
SWIR brightness (normalized)
CO2 DVCD (10^20 molec cm^-2)
ratio NO2 / CO2 (‰)
NO2 flux (kg s^-1)
CO2 flux (10^3 kg s^-1)
ratio NO2/CO2 (‰)
x (km)


A
B
C
D
E
F
G
H
5 km
26.4
26.5
26.6
Latitude (° S)
29.0
29.1
29.2
29.3
Longitude (° E)
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
0.0
0.1
0.2
0.3
0.4
0.5
SWIR brightness (normalized)
−2
0
2
4
CO2 DVCD (10^20 molec cm^−2)
0.0
0.5
1.0
1.5
2.0
ratio NO2 / CO2 (‰)
NO2 flux (kg s^−1)
CO2 flux (10^3 kg s^−1)
ratio NO2/CO2 (‰)
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
x (km)


A
B
C
D
E
F
G
H
5 km
26.2
26.3
26.4
26.5
Latitude (° S)
29.0
29.1
29.2
Longitude (° E)
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
0.0
0.1
0.2
0.3
0.4
0.5
SWIR brightness (normalized)
−2
0
2
4
CO2 DVCD (10^20 molec cm^−2)
0.0
0.5
1.0
1.5
2.0
ratio NO2 / CO2 (‰)
NO2 flux (kg s^−1)
CO2 flux (10^3 kg s^−1)
ratio NO2/CO2 (‰)
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
x (km)


A
5 km
26.1
26.2
26.3
Latitude (° S)
29.1
29.2
29.3
Longitude (° E)
B
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
C
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
D
−1
0
1
2
NO2 DVCD (10^17 molec cm^−2)
E
0.0
0.1
0.2
0.3
0.4
0.5
SWIR brightness (normalized)
F
−2
0
2
4
CO2 DVCD (10^20 molec cm^−2)
G
0.0
0.5
1.0
1.5
2.0
ratio NO2 / CO2 (‰)
H
NO2 flux (kg s^−1)
CO2 flux (10^3 kg s^−1)
ratio NO2/CO2 (‰)
0.0
0.5
1.0
1.5
2.0
2.5
0
5
10
15
20
x (km)

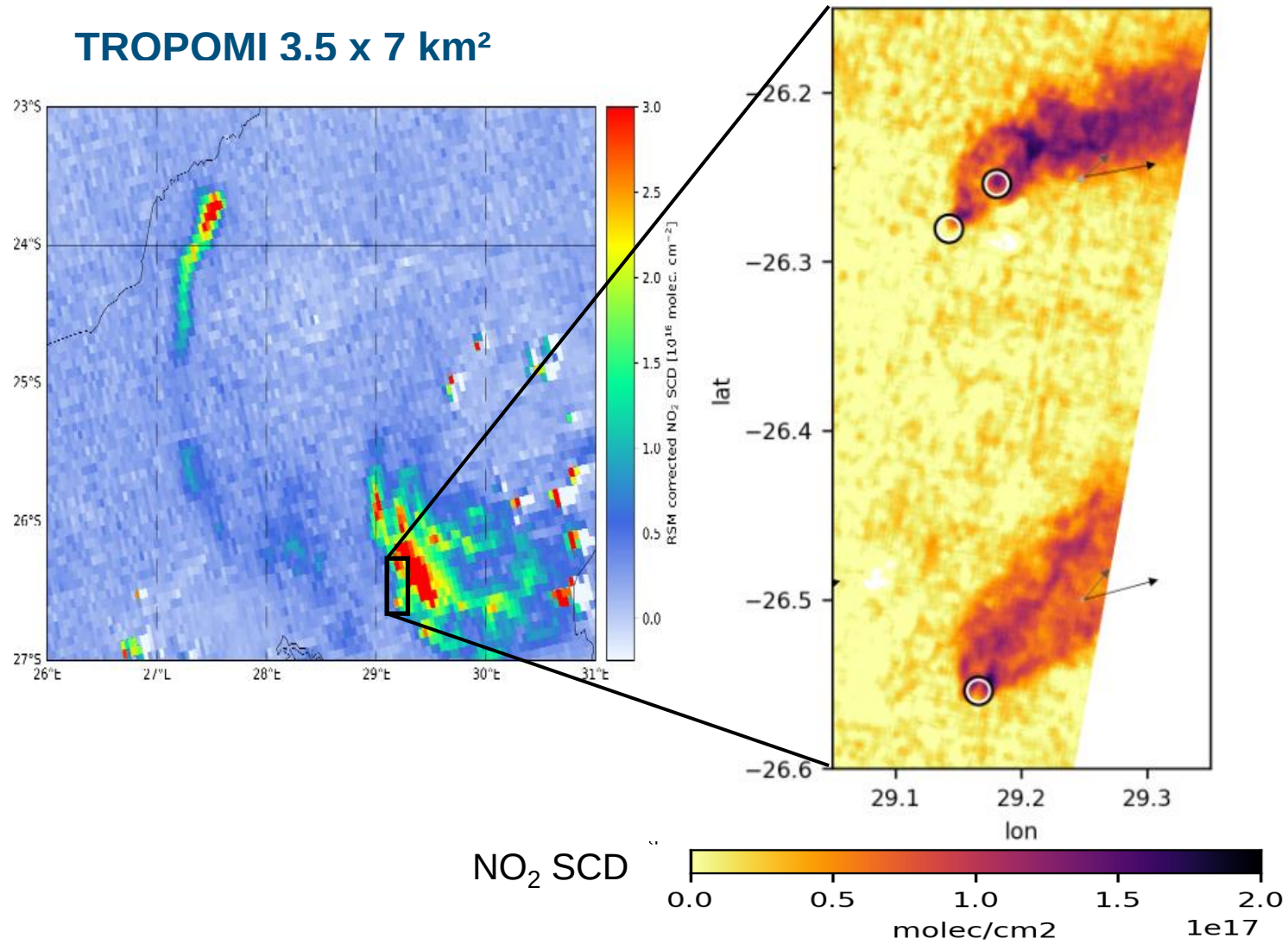
Novel ENMAP observations

Tropospheric NO_2 over the Highveld, 29 Nov. 2017

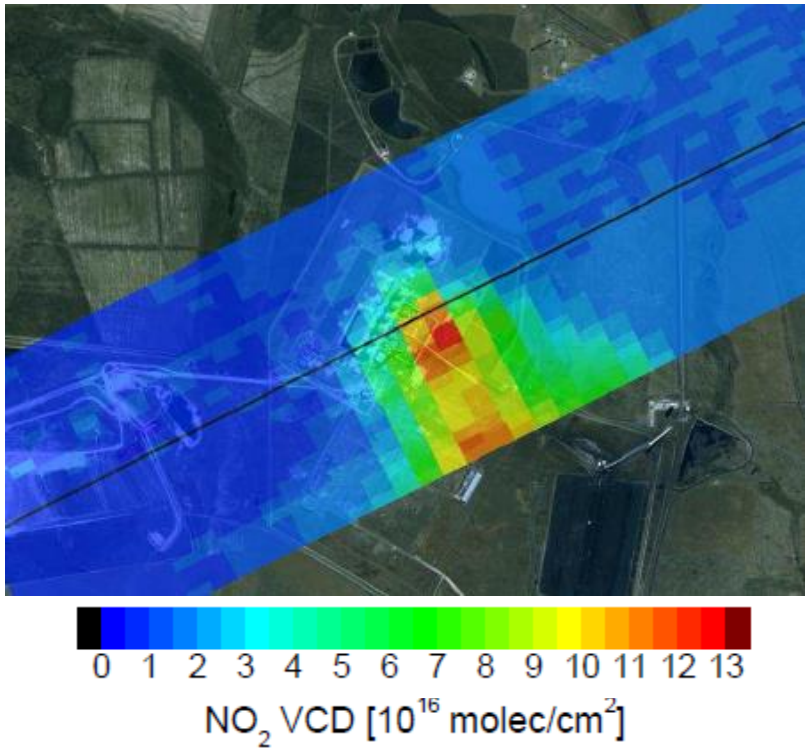
Observations over the Highveld 5 Oct. 2023

ENMAP 150 x 150 m²

TROPOMI 3.5 x 7 km²



The absolute values are similar to aircraft measurements (Majuba power plant)



- average AMF: 1.8

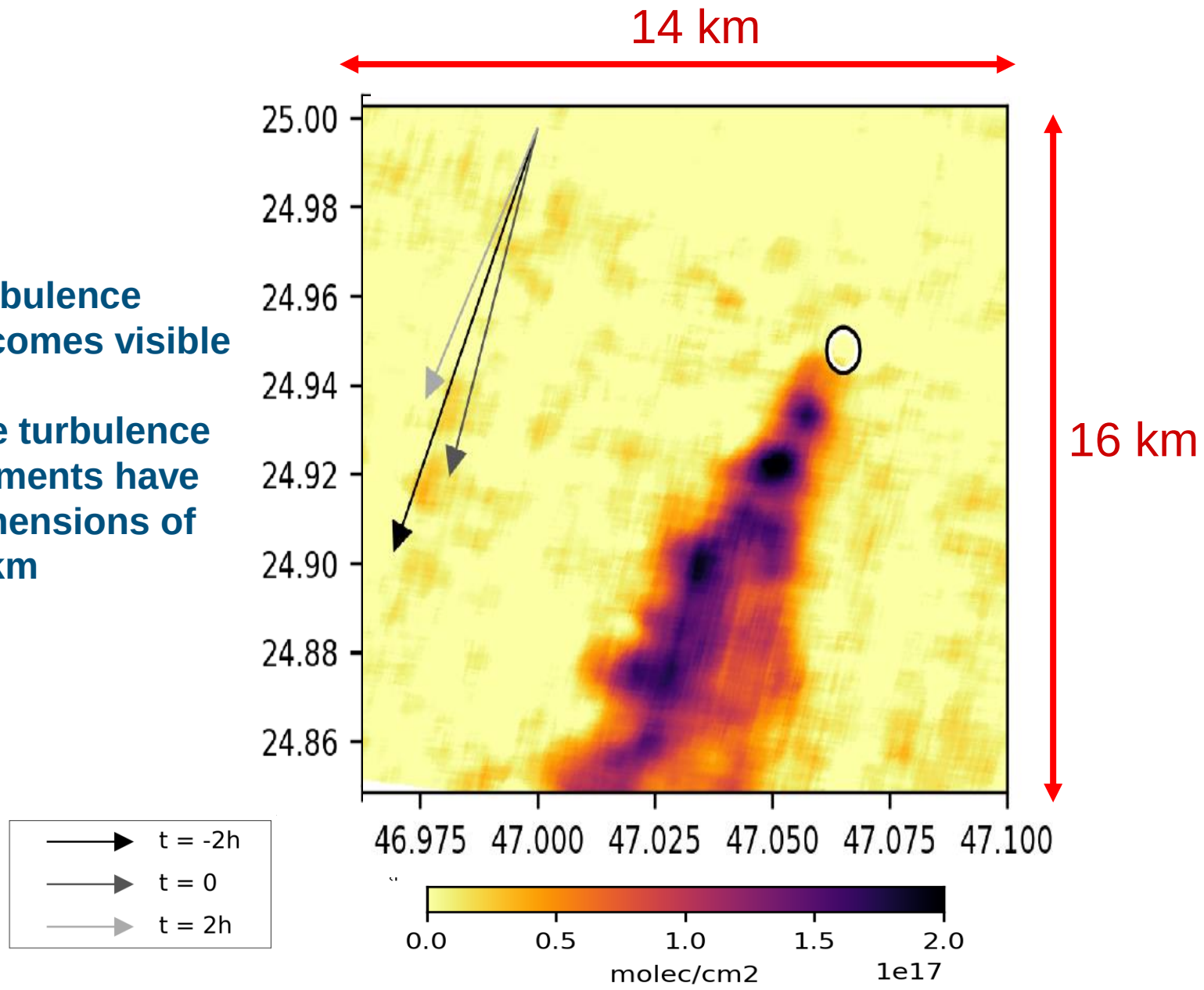
Heue et al., ACP, 2008

Evolution of the plume

Riyadh, power plant #9, 15 July 2023

Turbulence becomes visible

The turbulence elements have dimensions of ~1km



1 km

Advantage compared to aircraft observations:
The whole plume is observed within very short time