Spatial distributions of NO_2 in emission plumes observed by imaging DOAS from aircraft

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Motivation

Objectives

- Measurements of tropospheric trace gases, e.g. NO_2, at good spatial resolution and coverage
- NO_2 pollution mapping, identification of source regions and source strengths
- Detailed investigation of spatial variability of NO_2 column amounts

Advantages of aircraft measurements and the IUP imaging DOAS instrument AirMAP

- High spatial resolution ~100 m (down to <30 m) at useful spatial coverage
- Many viewing directions observed at the same time within a broad stripe below the aircraft
- Full coverage with no data gaps independent of flight altitude

The AirMAP instrument in the Cessna aircraft

AirMAP: Airborne imaging DOAS Measurements of Atmospheric Pollution

Instrument developed at IUP Bremen in 2011

Flight campaigns in June 2011 (AWI Polar-5 aircraft) and August 2013 (FU Berlin Cessna aircraft)

Cessna 207 Turbo (D-EAFU)

Owner & Operator: FU Berlin since 1988
Speed: typ. 50-60 m/s
Ceiling height: 6000m
Operating height: typically 800 – 1500 m
(during the AirMAP campaign 2013)

Photograph: The Cessna aircraft at Flugplatz Schönhagen, Brandenburg, Germany. *by Mareike Ostendorf*

NO_2 observations downwind of a power plant

Power Plant

Location: Wilhelmshaven
53.565°N, 8.147°E
Emission report (http://prtr.ec.europa.eu):
Emission of NO_x/NO_2: 1.900-2.650 t/a
NO is emitted from the power plant and is subsequently converted to NO_2

Observations of the NO_2 emission plume

Flight on 24.08.2013
Flight pattern #1: along the plume and back
Flight pattern #2: crossing the plume several times at different distances from the stack

Spatial distribution of NO_2

- NO_2 enhancement downwind of the power plant stack clearly visible
- Localised NO_2 vertical column maxima reach up to $1 \cdot 10^{16}$ molec/cm²
- Distribution is strongly inhomogeneous
- The same localised NO_2 maximum is probably observed twice in Pattern #1
- The plume evolution differs strongly from uniform Gaussian plume dispersion

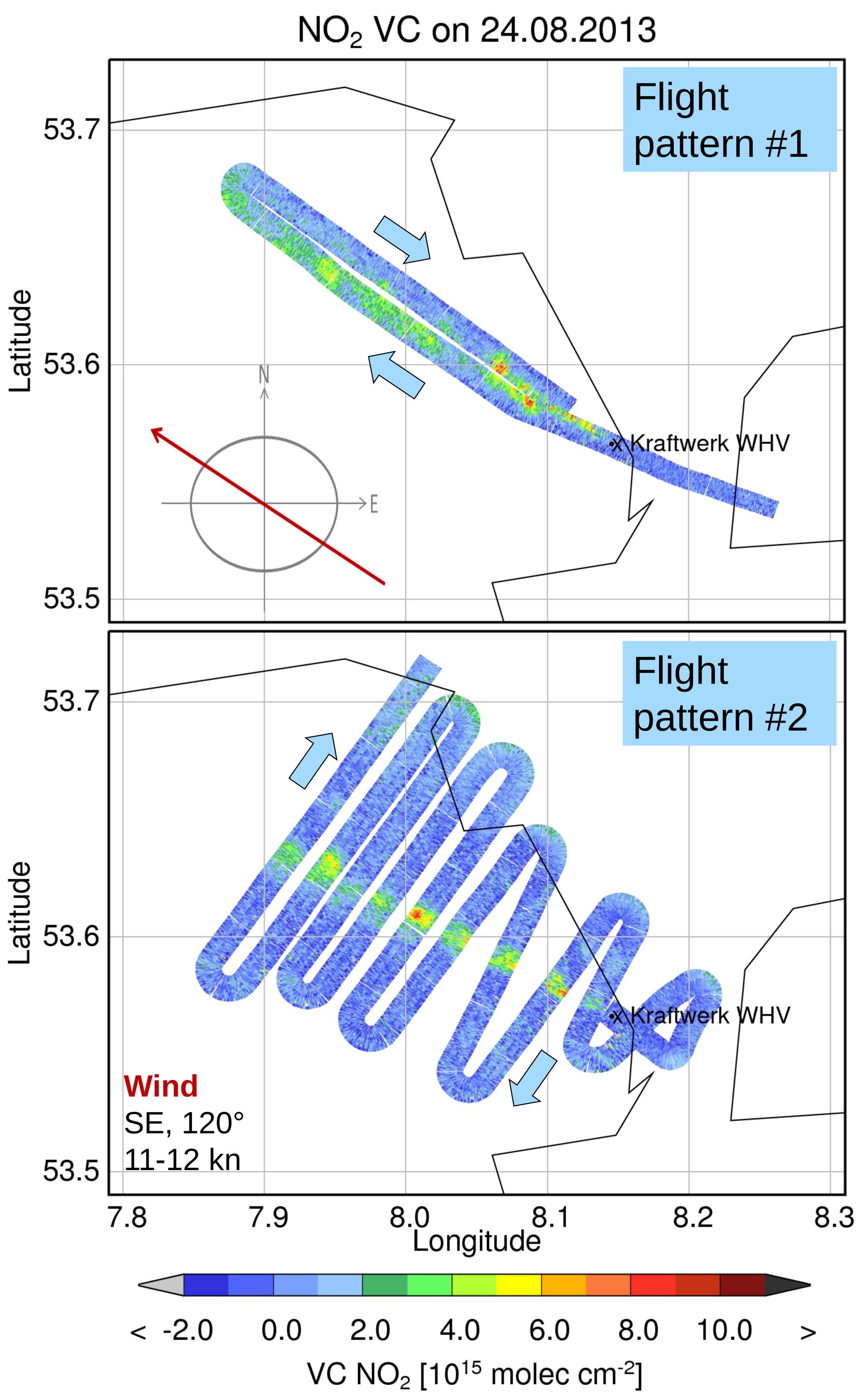


Figure (above): Spatial distribution of NO_2 vertical columns downwind of the Wilhelmshaven power plant on 24.08.2013 for two flight patterns, #1 along the plume direction (top) and #2 crossing the plume (bottom) at different distances. The arrows mark the flight direction.

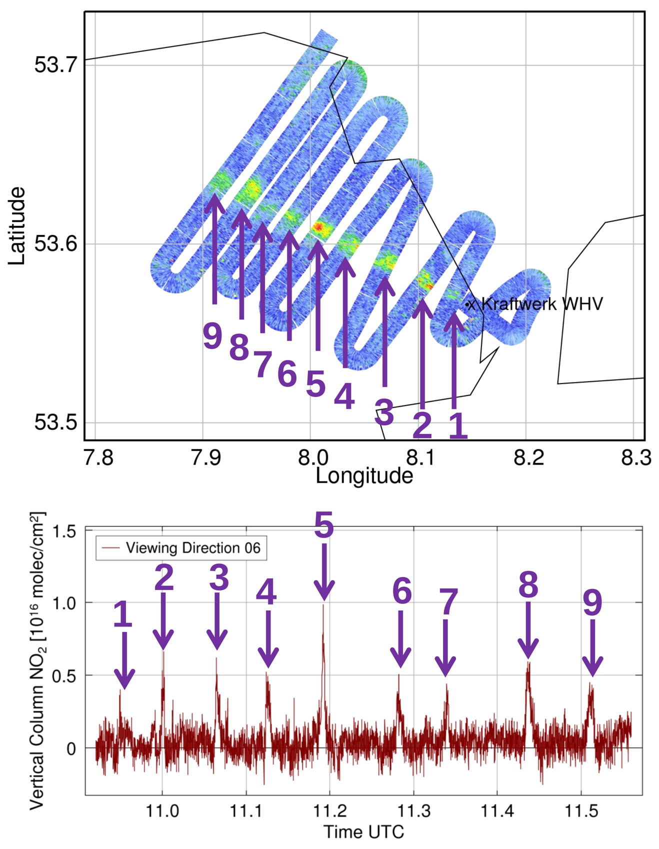
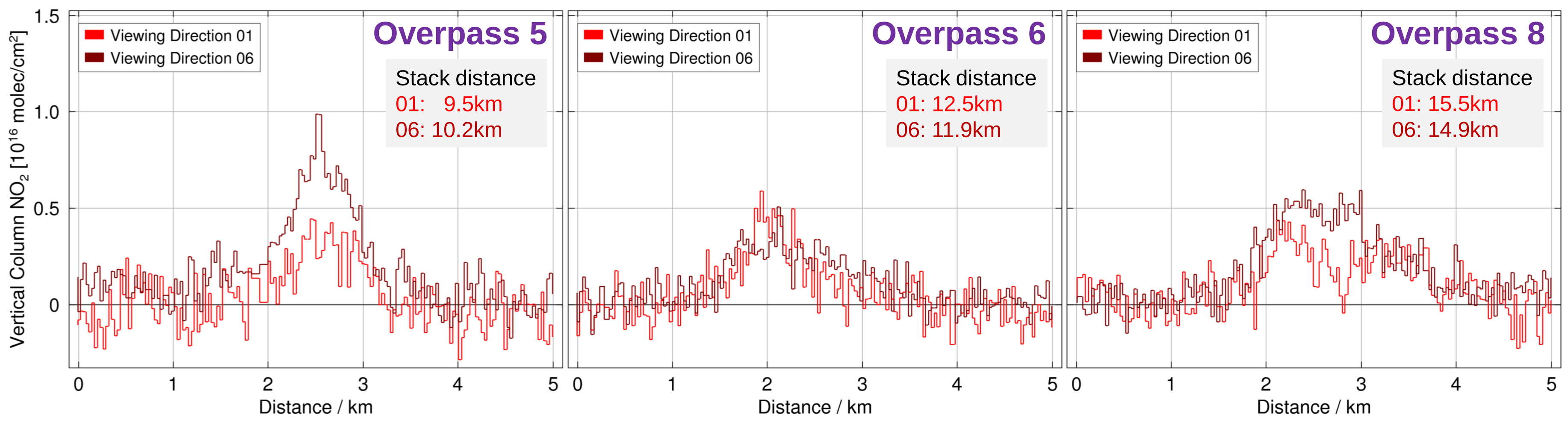


Figure (left): Numbered overpasses in flight pattern #2 (top) and time series of NO_2 vertical columns for example viewing direction 06 showing maxima in NO_2 amounts for the 9 individual overpasses.

Figure (below): Plume cross sections of the NO_2 vertical column amount observed during flight pattern #2 for two different viewing directions, 01 and 06, at three different overpass locations, overpass 5 (left), overpass 6 (middle) and overpass 8 (right). The distance given on the horizontal axis is the track length along flight direction, i.e. across the plume, with individual zero points for each overpass.



- Large differences in integral NO_2 amounts are observed between the viewing directions, i.e. for only slightly different distances from the exhaust stack (see insets in figures)
- With increasing distance from the stack (overpass 5 to 8), the plume slightly broadens
- Overpass 6 shows much less NO_2 than overpass 5, although further away from the stack, while generally, conversion from NO to NO_2 leads to an increase of NO_2 with time and distance

Instrumental setup and viewing geometry

- Optics: Wide angle objective and fibre bundle (35 fibres)
- 2 nadir ports: spectrometer objective and picture camera
- Acton 300i imaging spectrometer
- Spectral window: 412 - 453nm; 0.5-1.0nm resolution
- Detector: Frame transfer (FT), 512x512 pixel, 8.2x8.2 mm²
- Field of view: ~48° across track (θ), ~1.5° along track (γ)
- Swath width: on the order of flight altitude H
- Viewing directions: max. 35 LOS (line of sight)
- Averaging across track: combining fibres to 9 LOS (θ_i)
- Exposure time t_{exp}: 0.5 s
- Flight speed typ. 60 m/s
- Spatial resolution: <100m across track (at ~1km flight altitude, 9 viewing directions), ~ 30 m along track
- Positioning information: from GPS sensor and gyrometer to determine correct geolocation

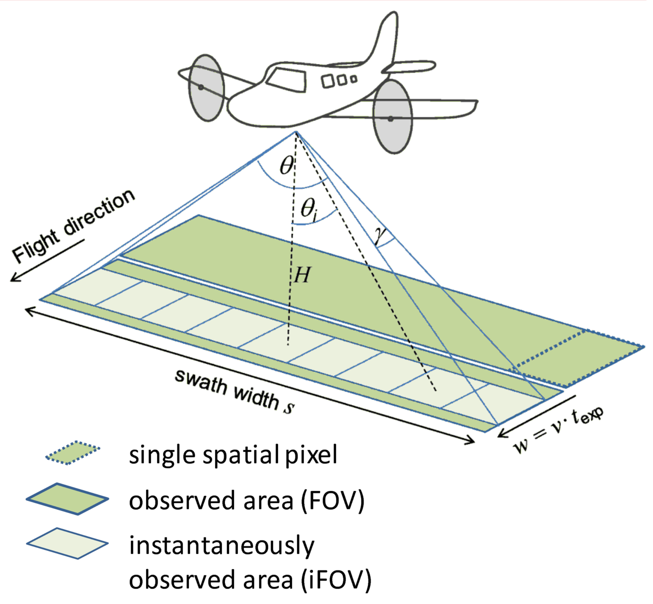


Figure: Sketch of the viewing geometry

The AirMAP instrument allows gap-free measurements along and across flight direction

NO_2 retrieval

Retrieval Settings

Fitting window: 425 – 450 nm
Trace gases: NO_2 (293K), O_3 (241K), O_4 (296K), H_2O (HITRAN)
Atmospheric effects: Ring (SCIATRAN calculated), quadratic polynomial, intensity offset
Reference I_0: rural scene from same LOS
Slit function: individual for each LOS

Detection Limit for NO_2

Slant Column detection limit ~10^{15} molec/cm²; optical density rms on the order of 10^{-3}

Air mass factors, AMF (SCIATRAN)

Rayleigh atmosphere, 1 km NO_2 box profile, 5% albedo, SZA and LOS dependence.

Emission estimates

NO_2 emission flux calculations

- Flux calculations at different distances from stack
- Approximation of source strength is achieved via discrete sum over the product of vertical columns VC, wind speed u and path length dl.

$$Q \cong \int_L VC \cdot \vec{u} \cdot d\vec{l} \approx \sum_i VC_i \cdot \vec{u} \cdot d\vec{l}_i$$

Example calculation for overpass 5

- 9 different values for Q from 9 viewing directions, i.e. different distances from stack the stack (pattern #2)
- Calculated fluxes vary between 1.8 and $5.5 \cdot 10^{23}$ molec/s.

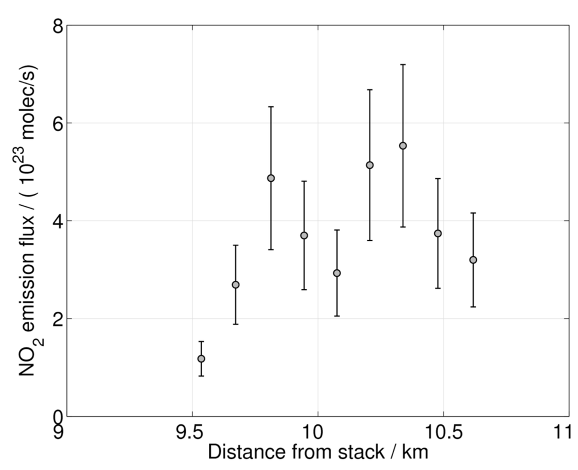


Figure: NO_2 emission flux calculated for different distances from the exhaust stack within overpass 5. The emission results are strongly variable.

Summary and Outlook

- NO_2 vertical column amounts have been observed from aircraft downwind of a power plant.
- Imaging capabilities of AirMAP allow plume observations at good spatial coverage and resolution.
- The spatial NO_2 distribution is non-uniform and varies strongly along the plume.
- With increasing distance from the stack, the plume slightly broadens.
- Instead of gradually increasing, the NO_2 is often confined in bubble-like structures.
- The results have implications for the importance of emission sources and downwind chemistry, because localised amounts of NO_2 lead to different effects than a smoothly averaged distribution.
- Possible reasons for the non-uniform distributions and plume evolution include source variability, chemical transformations and local meteorology.
- Further analysis of the plume structure will be performed including dynamics and plume chemistry.

Selected References

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