Imaging DOAS NO_2 measurements during the AQABA ship campaign

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1 Project & Ship Cruise

AQABA: Air Quality and Climate Change in the Arabian Basin

- an imaging DOAS instrument was installed on board of the research vessel "Kommandor Iona" (Figure 1) for ship-based air quality measurements
- instrument is called IMPACT: Imaging MaPper for Atmospheric observaTions (Figure 2)
- took place from Toulon (France) to Kuwait City (Kuwait) and back, passing the Mediterranean Sea, the Red Sea, the Arabian Sea, and the Arabian Gulf (Figure 3)
  - the cruise was conducted from June to September 2017
  - expected are:
    - Arabian Gulf: pollution due to the presence of oil/gas rigs and ships
    - Red Sea: pollution due to ships and dust events
    - Arabian and Mediterranean Sea: clean marine air
    - sometimes pollution due to cities which are passed with Kommandor Iona

Figure 1: Research vessel Kommandor Iona
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Figure 2: DOAS telescope installed on Kommandor Iona

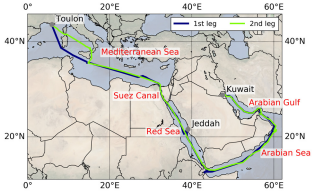

Figure 3: Track of ship cruise
In blue 1st cruise leg and in light green 2nd cruise leg is illustrated.

2 Method & Data Analysis

Method

DOAS: Differential Optical Absorption Spectroscopy

- based on Lambert Beer's law: $I(\lambda,s) = I_0 \exp(-\sigma(\lambda)\rho s)$ (Figure 4)
- a method to calculate the absorption of light travelling through the atmosphere
- can be used for visible light
- amount of trace gases can be derived from the absorption ⇒ slant column densities (SCs) can be calculated
- SCs can be converted to vertical column densities (VCs) by using air mass factors (AMF), calculated with the radiative transfer model SCIATRAN
- Imaging DOAS: measures several elevation angles simultaneously high temporal resolution possible

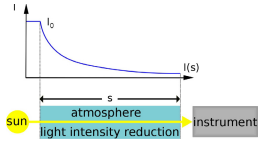

Figure 4: Illustration of the DOAS method
I: intensity at the detector
I_0: intensity of the light directly from the sun
s: light path
λ: wavelength
σ: absorption cross-section
ρ: concentration of absorbers

Spectral information

- telescope has a 45° field of view
- sorted light fibre: 50 single fibres see different elevations
  - same order at both sides
- imaging spectrometer (2D CCD) preserves spatial information
  - 2048 (spectral) x 1024 (imaging) pixels
- the different elevation angles are measured simultaneously (Figure 5)

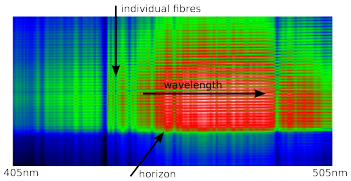

Figure 5: Spectral information
The information of an individual image. On the x-axis the wavelength are shown and on the y-axis the individual fibres are shown.

Setup for AQABA

- every 0.1 s one measurement
  → to correct for roll and pitch
- spectral direction: 2 pixels binned and cut left and right ranges which are not needed
  ⇒ 724 pixels for the wavelength range (Figure 5)
- imaging direction: 4 rows binned; 40 rows ignored
- zenith sky measurements for SZA smaller 30°
- the instrument was continuously scanning a vertical plane for three azimuth angles: starboard, port side, and bow direction

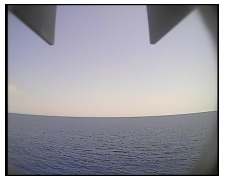

Figure 6: Picture of the video camera
Necessary for scene documentation.

3 Imaging NO_2 observations during AQABA

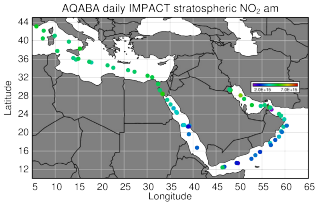

Figure 9: Stratospheric NO_2
The stratospheric NO_2 measured during AQABA in the mornging.

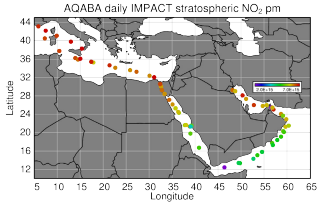

Figure 10: Stratospheric NO_2
The stratospheric NO_2 measured during AQABA in the evening.

Measurement validation with stratospheric NO_2

- calculation of VCs for the zenith-sky central viewing direction
- pm values are larger than am values → diurnal cycle of stratos. NO_2
- latitudinal dependency visible ⇒ analysis of stratospheric NO_2 perfomed well

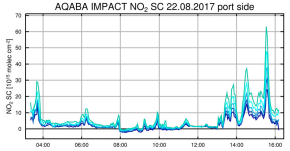

Figure 11: Arrival at Suez Canal

Arrival at Suez Canal during the 2nd leg

- NO_2 SCs increase with arrival at the Suez Canal
- highest values are observed in lowest elevation angles for all viewing directions
  → NO_2 is close to the surface
- similar results are observed also during the 1st leg

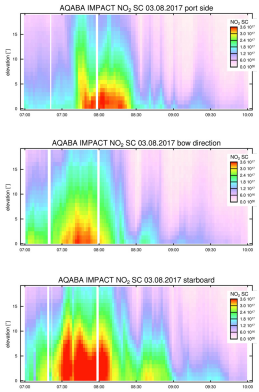

Figure 12: Departure in Kuwait

Departure in Kuwait

- large NO_2 SCs are observed when leaving Kuwait
- SCs are larger on starboard than on port side, smallest values in bow direction
- the largest NO_2 SCs are found close to the ground

Obervations in the Arabian Gulf during the 2nd leg

- many individual plumes are observed in the Arabian Gulf (Figure 13)
- most plumes are elevated and seem to be rising in the atmosphere
- most of the plumes are on the port side from morning until early afternoon when passing Katar
- possible sources are oil/gas rigs and ships
  → possible contamination by own vessel plume
- NO_2 SCs are smaller than in Kuwait
- satellite observations show no enhanced NO_2 VCs in the Arabian Gulf whereas in Kuwait satellite and MAX-DOAS observations show enhanced values (Figure 14)

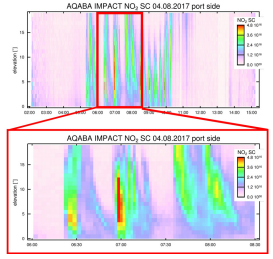

Figure 13: MAX-DOAS NO_2 SCs
Plumes in elevated layers are observed in the Arabian Gulf.

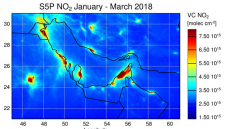

Figure 14: S5P NO_2 VCs
Enhanced NO_2 VCs in the Arabian Gulf are observed in surounding cities.
Disclaimer: The presented work has been performed in the frame of the Sentinel-5 Precursor Validation Team (S5PVT) activities. Results are based on preliminary (not fully calibrated/ validated) Sentinel-5 Precursor data that will still change.

4 Summary & Outlook

Summary

- AQABA was a measurement campaign in late summer 2017; IMPACT was successfully operated on the research vessel Kommandor Iona
- stratospheric NO_2 was successfully observed
  - latitudinal dependency and diurnal cycle are clearly visible
- polluted areas are successfully detected
  - e.g., Kuwait, Suez Canal, possibly oil/gas rigs, and ship plumes; elevated plumes are observed in Arabian Gulf

Outlook

- links to ships, oil/gas rigs, and other NO_x sources
- comparison of stratospheric and tropospheric NO_2 with satellite data

References & Acknowledgements

- Peters, E., Wittrock, F., Großmann, K., Frieß, U., Richter, A., and Burrows, J. P.: Formaldehyde and nitrogen dioxid over the remote western Pacfic Ocean: SCIAMACHY and GOME-2 validation using ship-based MAX-DOAS observations, Atmospheric Chemistry and Physics, 12, 2012.
- Ostendorf, M.: IMPACT A new ground-based imaging DOAS instrument:Development, participation at the CINDI-2 campaign and first data analysis, Master thesis, University of Bremen, May 2017.
- Altube, P.: Aircraft measurements of tropospheric NO2 with an imaging DOAS instrument, Master thesis, University of Bremen, 2012.
- Lohberger, F., Hönninger, G., and Platt, U.: Ground-based imaging differential optical absorption spectroscopy of atmospheric gases, Applied Optics, 43, 4711-4717, 2004.
- Schönhardt, A., Altube, P., Gerilowski, K., Krautwurst, S., Hartmann, J., Meier, A. C., Richter, A., and Burrows, J. P.: A wide field-of-view imaging DOAS instrument for two-dimensional trace gas mapping from aircraft, Atmos. Meas. Tech., 8, 5113-5131, doi:10.5194/amt-8-5113-2015, 2015.
- Rozanov, V., et al.: Radiative Transfer through Terrestrial Atmosphere and Ocean: Software Package SCIATRAN, J. Quant. Spectrosc. Rad. Transfer, 133, 13–71, doi:10.1016/j.jqsrt.2013.07.004, 2014.

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