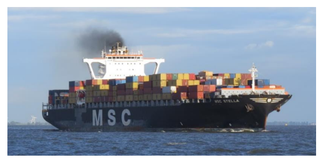
MAX-DOAS Measurements of Shipping Emissions on Neuwerk

André Seyler[1], Folkard Wittrock[1], Lisa Kattner[1,2], Barbara Mathieu-Üffing[1,2], Enno Peters[1], Andreas Richter[1], Stefan Schmolke[2], Norbert Theobald[2], and John P. Burrows[1]

[1]Institute of Environmental Physics (IUP), University of Bremen

[2]Federal Maritime and Hydrographic Agency (BSH), Hamburg

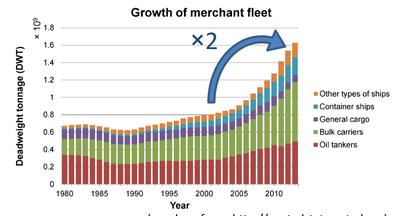


www.mesmart.de

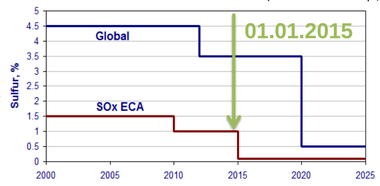
1. Motivation

Shipping emissions:

- Pollution components: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOCs), black carbon (BC), polycyclic aromatic hydrocarbons (PAH), particulate matter (PM)
- Impact on marine tropospheric chemistry, ecological and climatic effects (formation of ozone and aerosols, acidification, albedo)
- Health risk (pulmonary/cardiovascular) in harbor cities and coastal regions
- Especially dangerous due to combustion products from heavy oil fuels with high sulfur content and strong soot emission
- **Capacity of global merchant fleet has doubled since 2000 -> fraction of shipping emissions on global emissions is increasing**



(numbers from: http://unctadstat.unctad.org)

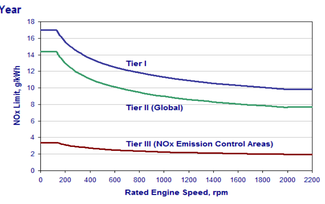


Reduction of sulfur content in heavy oil fuel within SECA zones and globally as determined by MARPOL Annex VI

Political measures:

- Convention of the International Marine Organization (IMO) for Prevention of Marine Pollution from Ships (MARPOL 73/78 Annex VI)
- **Limitation of sulfur content in heavy oil fuels in Sulfur Emission Controlled Areas (SECA), starting Jan 2015 only 0.1% sulfur is allowed**
- Establishment of general Emission Controlled Areas (ECA)
- Regulation of NO_x emissions for newly built engines

ECA zones around the world



Limitation of NO_x emission by engines, built after 2000 (Tier I), 2011 (Tier II), and 2016 (Tier III)

2. Objectives

MeSMarT – **Me**asurements of **S**hipping Emissions in the **Mar**ine **T**roposphere – a project coordinated by the University of Bremen with support of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) and the Helmholtz Zentrum Geesthacht

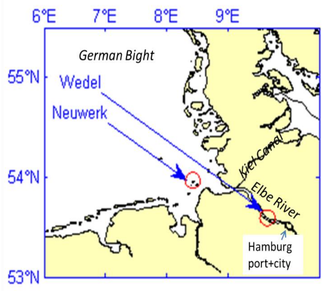
- Assessment of different measurement systems such as remote sensing, in-situ, and passive sampling measurements as methods for long-term monitoring of shipping emissions in the North and Baltic Sea
- **Establishment of remote sensing instruments like MAX-DOAS to support the surveillance of international emission regulations**
- Improvement of ship emission data bases by measurements of the actual distribution of trace gases and aerosols related to ship emission, validation of satellite measurements and model data
- Description of the influence of ship emissions and its secondary products on the marine environment
- **Development of a concept for controlling ship emissions**

3. Operational area and platforms

Stationary platforms:

Neuwerk: ~6 km to navigation channel in the mouth of Elbe

Wedel: ~0.5 km to navigation channel of Elbe river close to Hamburg, the biggest German harbor



Operational area: German Bight and Baltic Sea

Ship (routinely used by BSH):

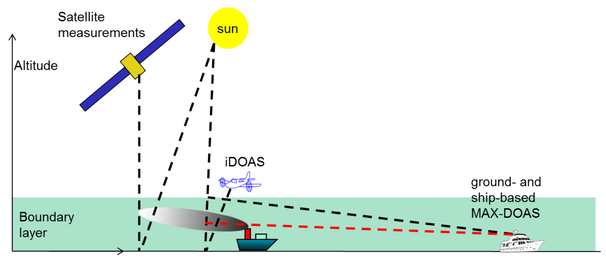
RV Celtic Explorer
(Marine Institute, Galway, Ireland)
Up to now four campaigns in the German Exclusive Zone

Monitoring car:

Mobile measurement station equiped with MAX-DOAS and in-situ devices

4. Methods

A. Passive remote sensing with Differential Optical Absorption Spectroscopy (DOAS) using different platforms (here only MAX-DOAS results from the ground are presented)



MAX-DOAS: Multi-axis observations from land and ship – different lines of sight provide a 3-dimensional picture of the trace gas of interest

Detection:

UV/vis (300 to 570 nm) measurement of scattered sunlight, Differential Optical Absorption Spectroscopy – DOAS to get the averaged absorption along all contributing light paths -> Slant Column

Further retrieval:

Using O_4 and H_2O as proxys for the effective light path to calculate **profile information (VMR) for NO_2 and SO_2**

Detection limits: NO_2 ~0.1 ppb, SO_2 ~0.2 ppb for typical viewing conditions, time resolution 1 to 5 min

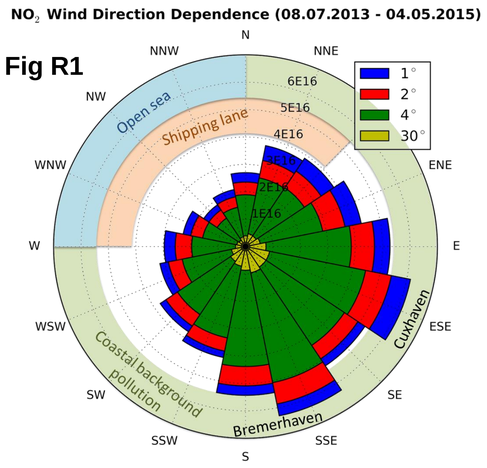
B. Continuous in situ measurements of SO_2, NO_x, O_3, and CO_2: with trace gas monitor in ambient air

C. Complementary data: Meteorolocical data and AIS (Automatic Identification System) ship data

5. Selected Results and Discussion

MAX-DOAS measurements:

- Figures R1 and R2 show the impact of the shipping lane close to Neuwerk on coastal air quality
  - ➢ Enhanced background pollution from the shoreline and the cities of Cuxhaven and Bremerhaven
  - ➢ In sector from W to N: wind from the open North Sea → all emissions coming from ships
  - ➢ The fraction of shipping emissions on the overall emissions is much higher for SO_2 than for NO_2
- Figures R3 and R4 show single day measurements: emissions of passing ships are visible as peaks
  - ➢ Scanning horizontally: movement of ships and ship plumes can be studied (see Fig. R3)
  - ➢ Using AIS and wind data → peaks can mostly be allocated to individualships (see Fig. R4)
  - ➢ Not every NO_2 peak has a corresponding SO_2 peak → different sulfur content in fuel



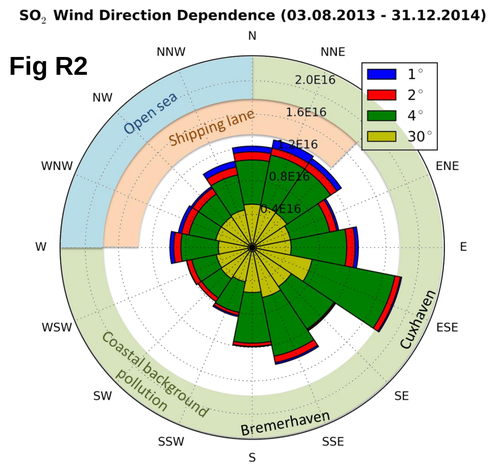
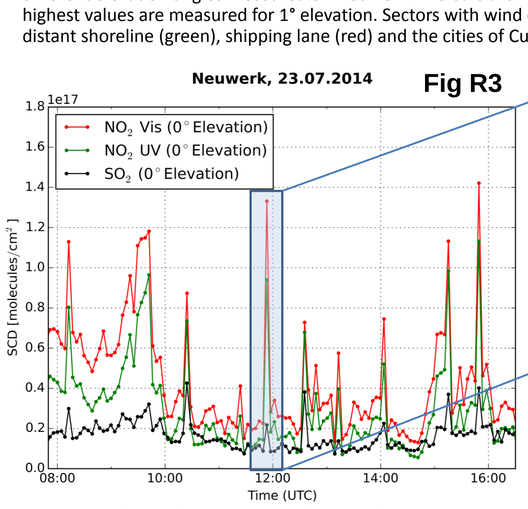
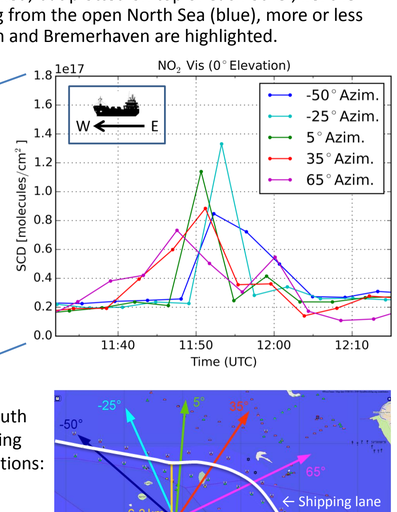


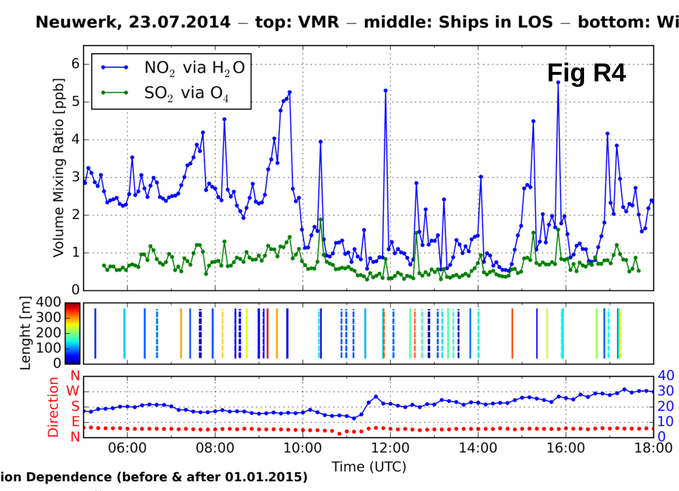
Figure R1 and R2: Dependence of NO_2 and SO_2 slant column densities (in molecules per cm^2) on wind direction for different elevation angles measured on Neuwerk. The bars are not stacked, but plotted on top of each other, i.e. the highest values are measured for 1° elevation. Sectors with wind coming from the open North Sea (blue), more or less distant shoreline (green), shipping lane (red) and the cities of Cuxhaven and Bremerhaven are highlighted.





Azimuth viewing directions:

Figure R3: Slant column densities of NO_2 and SO_2 measured on Neuwerk on Wednesday, 23 July 2014 (left) and detailed view of the NO_2 measurements in the different azimuthal viewing directions for one of the ship emission peaks (right)



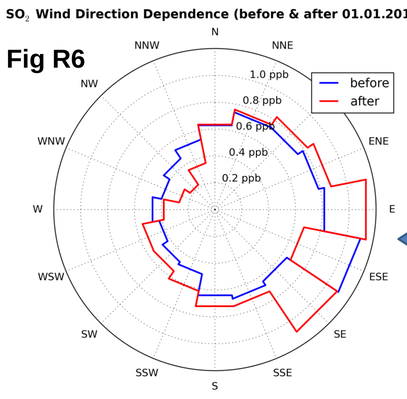
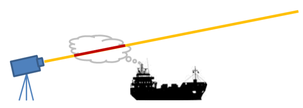


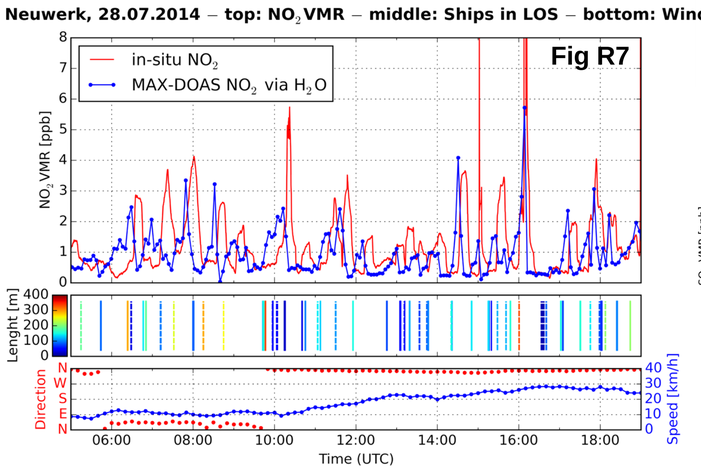
Figure R4, R5, R7: VMR, AIS and wind data
Top: MAX-DOAS NO_2 and SO_2 VMR
Middle: bars indicating that a ship is in the line-of-sight, solid bars: moves from left to right (west to east), dashed vice versa, colors representing ship length
Bottom: wind speed and direction

Figure R6: Dependence of SO_2 volume mixing ratios on wind direction before and after the change in regulations

Comparison to in-situ data:

- Figures R7 to R9 show comparisons of MAX-DOAS with in situ volume mixing ratios
- In particular for the Neuwerk site the best agreement for NO_2 was found when using water vapour as a proxy for the effective light path length
- A certain time is needed for the emission plumes to travel to the in-situ instrument, depending on wind speed → time delay between MAX-DOAS and in situ measurements (see Fig. R7)
- Since ship plumes usually never cover the whole light path very high peaks are usually underestimated



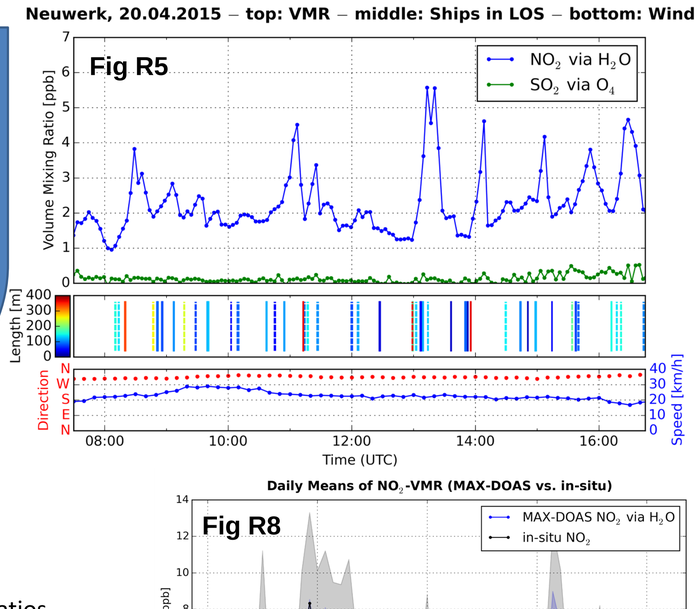


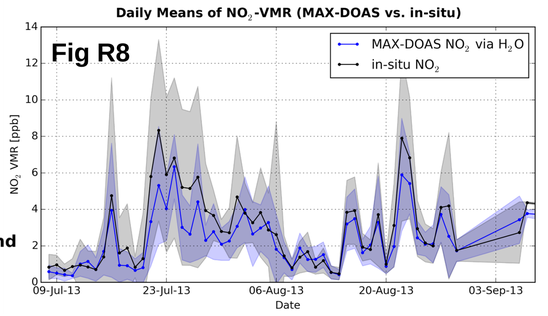
Influence of fuel sulfur content regulations:

- On the 1st of January 2015, the allowed sulfur content inside ECA decreased from 1.0% to 0.1%
- SO_2 measurements since then: no ship emission peaks visible anymore (see Fig. R5)
- SO_2 values below the MAX-DOAS detection limit (~0.2 ppb)
- Wind direction dependence: much less SO_2 from shipping lane (see Fig. R6)

before

after





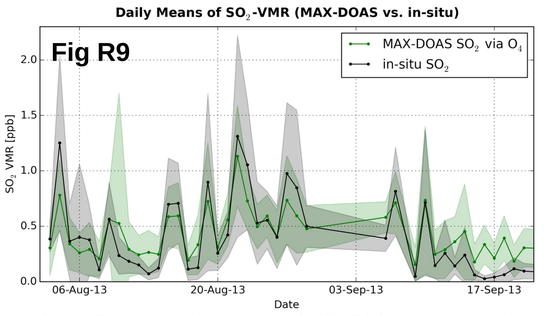


Figure R8 and R9: Daily means of MAX-DOAS and in-situ NO_2 (top) and SO_2 (bottom) volume mixing ratios, the shaded areas show the standard deviation

Acknowledgements

- This project is funded by the "Federal Ministry of Transport and Digital Infrastructure"
- The authors thank the staff of the BSH Laboratory in Hamburg-Sülldorf for their assistance and their great support.
- Part of the instruments have been funded by the University of Bremen.
- The staff of the "Institut für Hygiene und Umwelt", Hamburg supports our work with instruments and the possibility to use their calibration units.
- The „Wasser- und Schiffahrtsamt Cuxhaven and Hamburg" provides support to establish the long-term monitoring stations on Neuwerk island and in Wedel

Selected references

- International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI Prevention of Air Pollution from Ships (entered into force 19 May 2005) *http//:www.imo.org/…regulation-13* http://www.imo.org/blast/mainframe.asp?topic_id=1709&doc_id=10262
- Eyring, V., et al., SeaKLIM (Impact of Ship Emissions on Atmosphere and Climate), Final Report (2010)
- Moldanovà, J. et al., 2009. Characterisation of particulate matter and gaseous emissions from a large ship diesel engine. Atmospheric Environment 43, 2632–2641.
- Berg, N. et al., Ship Emission Measurements by the Chalmers IGPS System during the Rotterdam campaign 2009, Report
- Gomez, L. et al, Long-path averaged mixing ratios of O_3 and NO_2 in the free troposphere from mountain MAX-DOAS, Atmos. Meas. Tech., 7, 3373-3386, 2014.
- Alföldy et al., Measurements of air pollution emission factors for marine transportation in SECA, Atmos. Meas. Tech., 6, 1777-1791, 2013.
- **Kattner, L. et al., Monitoring compliance with sulphur content regulations of shipping fuel by in-situ measurements of ship emissions, ACPD, 15, 11031-11047**