Monitoring Shipping Emissions with MAX-DOAS Measurements

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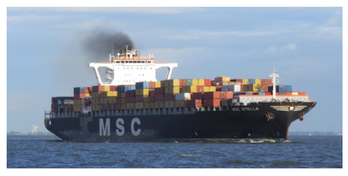
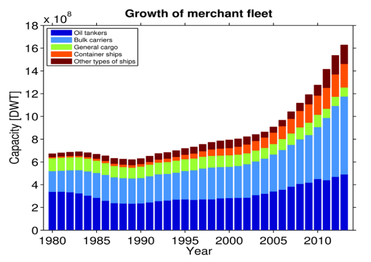
1. Motivation

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) for people living 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**



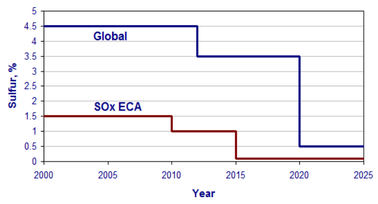


Growth of merchant fleet (from http://unctadstat.unctad.org)

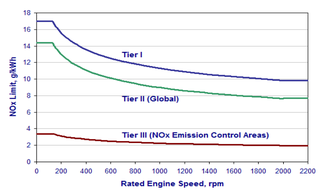
Political measures:

- 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 from newly built marine engines

ECA zones around the world



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



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

2. Objectives

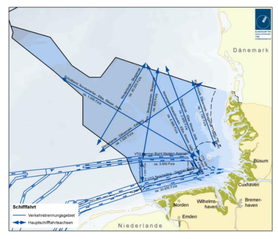
MeSMarT – **Me**asurements of **S**hipping Emissions in the **Mar**ine **T**roposphere – a project coordinated by the University Bremen with support of the Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) and the Helmholtz Zentrum Geesthacht

- 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

German Bight and Baltic Sea:

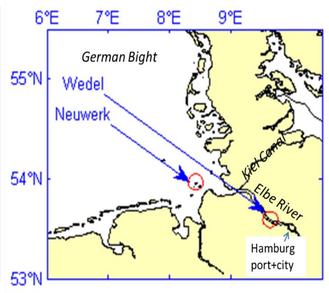
- German Exclusive Economic Zone, with 12-nm-zone und main shipping routes
- An area already covered with extensive research concerning water quality and oceanography by BSH



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



Ship (routinely used by BSH):

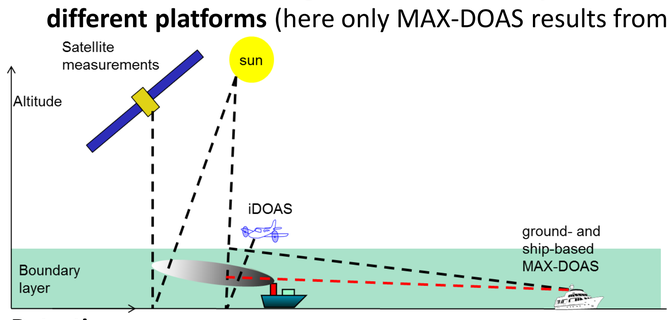
RV Celtic Explorer
(Marine Institute, Galway, Ireland)
Up to now three campaigns in the German Exclusive Zone

In the near future: monitoring car

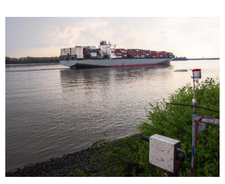
Mobile measurement station equiped with MAX-DOAS and in situ devices

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:

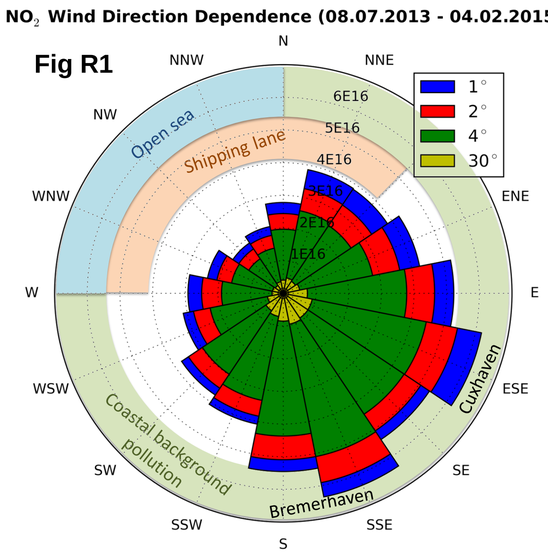
Using O_4 and H_2O as proxys for the effective light path to calculate **profile information (VMR) for NO_2 and SO_2**

Detection limits NO_2 ~100 ppt, SO_2 ~200 ppt 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



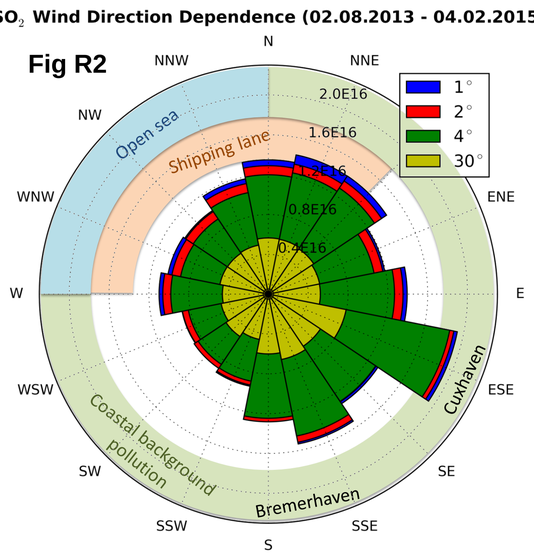


Figure R1 and R2: Dependence of NO_2 and SO_2 slant column densities (in molecules per cm^2) on wind direction for different elevation angles measured on Neuwerk. Sectors with wind coming from the open North Sea (blue), more or less distant shoreline (green) and shipping lane (red) and the cities of Cuxhaven and Bremerhaven are highlighted.

MAX-DOAS data:

- Figures R1 and R2 show the impact of the shipping lane close to Neuwerk on coastal air quality
- Figure R3 shows single day measurements: Emissions of passing ships are clearly visible as peaks in the data that can mostly be allocated to single ships using AIS and wind data
- Not every NO_2 peak has a corresponding SO_2 peak -> different sulfur contents in fuel

Neuwerk, 23.07.2014 – top: VMR – middle: Ships in LOS – bottom: Wind

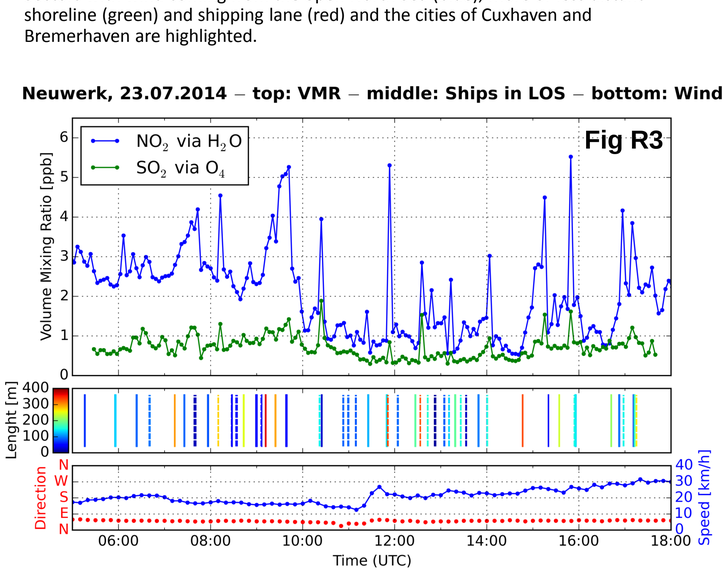
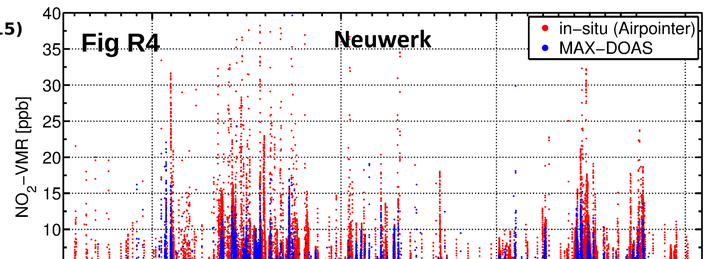
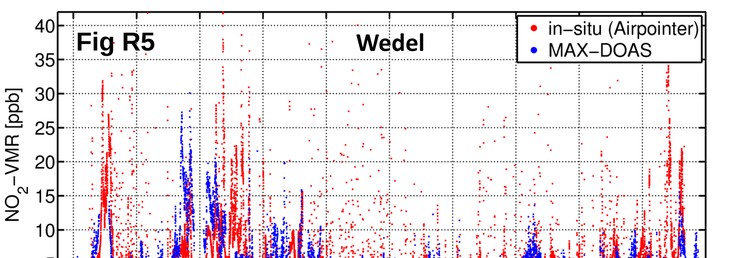
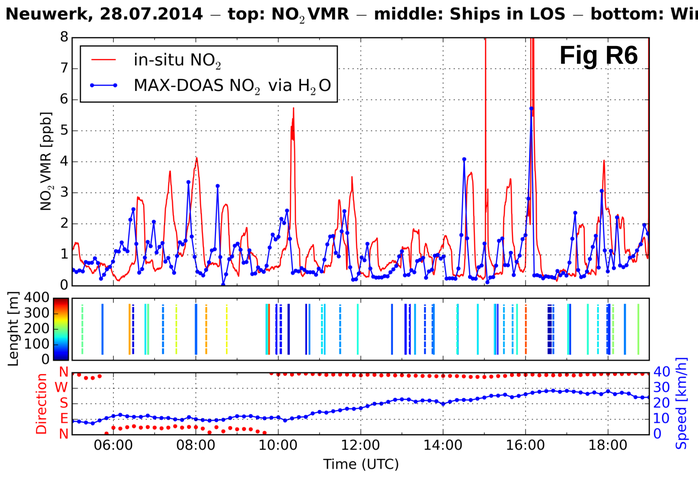


Figure R3: VMR, AIS and wind data for Neuwerk on Wednesday, 23 July 2014
On top: MAX-DOAS NO_2 and SO_2 VMRs
In the middle: bars indicating that a ship is in the line-of-sight, solid bars: moves from left to right (west to east), dashed vice versa, colors representing ship length
On the bottom: wind speed and direction





Neuwerk, 28.07.2014 – top: NO_2 VMR – middle: Ships in LOS – bottom: Wind



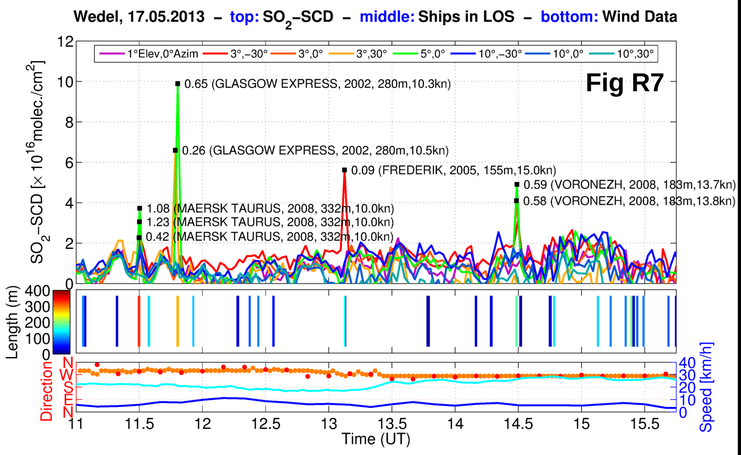
Further interpretation of data:

- Figure R7 illustrates exemplarily how the MAX-DOAS measurements can be used to estimate emissions from single ships
- NO_2 to SO_2 ratio (numbers close to the peaks) together with information on the engine load (speed) of the ships allows to estimate the fuel quality
- For the ships monitored on that day sulphur contents of 0.2 (Maersk Taurus) to 2% (Frederik) are assessed
- Changing numbers for one ship reflect the NO to NO_2 conversion within the plume

MAX-DOAS vs. in situ data:

- Figures R4 to R6 show comparisons of MAX-DOAS with in situ NO_2 volume mixing ratios
- In particular for the Neuwerk site the best agreement was found when using water vapour as a proxy for the effective light path
- A certain time is needed for the emission plumes to travel to the in-situ instument, depending on wind speed -> time delay between MAX-DOAS and in situ measurements (see Figure R6)
- Since ship plumes usually never cover the whole light path very high peaks are usually underestimated (notably for Wedel where the distance to passing ships is ~500m, Figure R5)

Wedel, 17.05.2013 – top: SO_2–SCD – middle: Ships in LOS – bottom: Wind Data



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