Monitoring shipping emissions in the German Bight using MAX-DOAS

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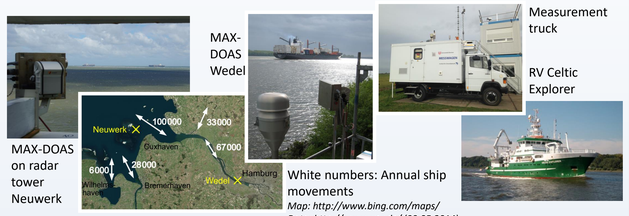
MeSMarT project

- **"Me**asurements of **S**hipping Emissions in the **Mar**ine **T**roposphere" – a project coordinated by the University of Bremen with support of the German Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie, BSH) and the Helmholtz Zentrum Geesthacht (HZG)
- **MeSMarT permanent measurement sites and platforms for campaigns:**

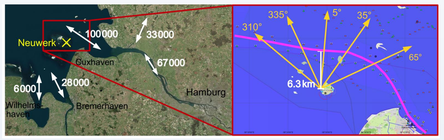


Measurement site Neuwerk

- Neuwerk is a small island in the German Bight, close to the mouth of the Elbe river
- Close to main shipping channel into the Elbe river towards the port of Hamburg
- Measurements from July 2013 until July 2016
- Two channel MAX-DOAS (UV, vis)
- Multiple azimuthal viewing directions to cover the region and main shipping lane

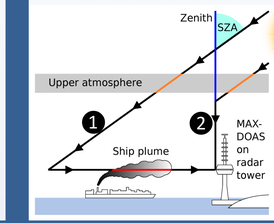
Left panel: Map of the region, Numbers denote annual ship movements
Map: http://www.bing.com/maps/
Data: http://www.wsv.de/ (09.05.2014)

Right panel: Azimuthal MAX-DOAS viewing directions covering the main shipping lane
http://www.freie-tonne.de, based on OSM



MAX-DOAS measurement geometry

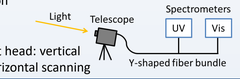
- **DOAS = D**ifferential **O**ptical **A**bsorption **S**pectroscopy
- Idea: Measure spectra of back-scattered sunlight from the atmosphere, fit absorption cross sections of multiple absorbers (e.g. NO_2, O_3, H_2O, O_4) simultaneously to measured optical depth
- Retrieved quantity: Slant column density (SCD)
  = Concentration of the absorber integrated along the light path



Light source: the sun

❶ Off-axis measurement through ship plume
❷ Zenith-sky reference to cancel out stratospheric absorption

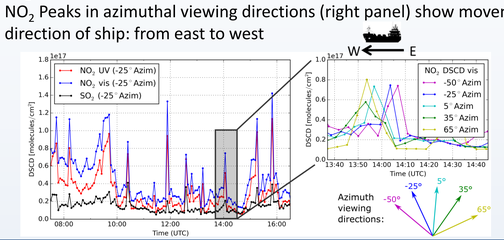
Setup of ground-based **M**ulti-**A**xis-DOAS instrument:



Pan/Tilt head: vertical and horizontal scanning

Measured slant columns of NO_2 and SO_2

- Slant column densities of NO_2 and SO_2 measured on Neuwerk on Wednesday, 23 July 2014 in 0° elevation (towards the horizon)
- Sharp peaks in NO_2 and SO_2 signal: pollution plumes emitted from ships
- Enhanced coastal background pollution in the morning
- SO_2 fraction varies due to different fuel sulfur content
- NO_2 Peaks in azimuthal viewing directions (right panel) show movement direction of ship: from east to west



Wind sector classification

- Blue sector: wind from open North Sea, shipping is the only pollution source
- Green sector: mainly land-based air pollution (traffic, industry, …)
- Yellow sector: air mass contains shipping emissions as well as land-based air pollution (mixed origin)

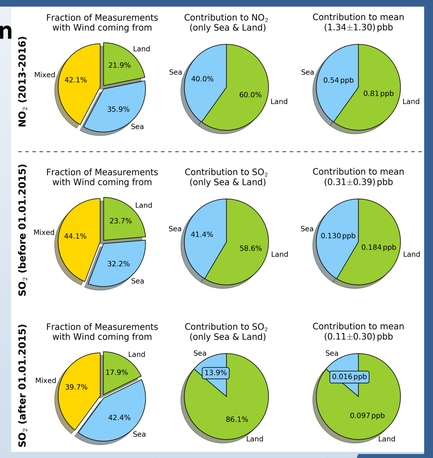
Dependence of NO_2 and SO_2 pollution levels on wind direction:

- Red curve: before 1 January 2015
- Blue curve: after 1 January 2015

- Volume mixing ratios calculated using O_4 as a tracer for the effective horizontal light path length (Gomez, 2014)
- NO_2: No regulations → no significant change in emission
- SO_2: Allowed fuel sulfur content dropped from 1.0 % to 0.1 %
  → significantly lower SO_2 emissions, especially from the open North Sea

Contributions of ships vs. land-based pollution sources on coastal air quality on Neuwerk:

- To trade ship emissions off against land-based emissions (e.g. industry, road transport), two representative sectors of wind directions have been chosen
- Excluding data with mixed air mass origin, the contribution of shipping sources to pollution on Neuwerk is around 40% for both NO_2 and SO_2 in the years 2013 and 2014, a significant, but surprisingly small fraction
- Since 2015, the relative contribution of shipping sources was reduced to 14%, the absolute amount decreased by a factor of 8, even though the wind was coincidentally blowing more often from the open sea in this time period
- Since 2015, the vast majority of SO_2 emissions can be attributed to land sources, ships play only a negligible role



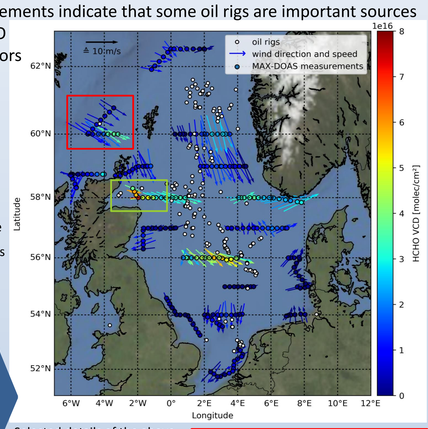
Both statistics (polar plots and pie charts) show clearly:
→ Stricter limits on fuel sulfur content are working
→ Signicantly improved air quality in the North Sea coastal regions with respect to SO_2

Enhanced HCHO downwind of oil rigs

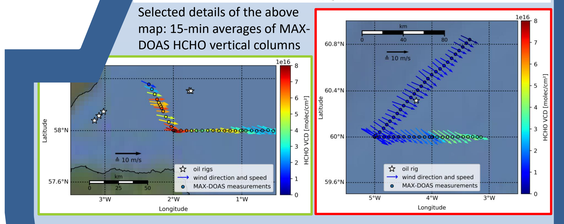
- MAX-DOAS measurements of formaldehyde (HCHO) on-board the irish research vessel Celtic Explorer during the annual BSH summer survey in North and Baltic Sea in August 2015
- Background values of 0.5-1E16 molec/cm² in good agreement with GOME 2A satellite measurements of HCHO
- Measurements indicate that some oil rigs are important sources of HCHO precursors

1-hour averages of HCHO vertical columns from SCD in 30° elevation (geom. AMF), DOAS-fit with fixed reference

Oil rig positions from OSPAR database



Selected details of the above map: 15-min averages of MAX-DOAS HCHO vertical columns



Shipping emissions

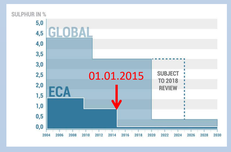
PM, SO_2, CO, NO_2, VOCs, NO, Black carbon, CO_2

- Shipping is generally the most energy efficient transportation mode (per t per km)
- Shipping accounts for ≈ 80% of total merchandise worldwide trade volume
- Seaborne trade grows fast, despite the economic crisis
- Capacity of global merchant fleet doubled in the last decade
- Shipping accounts for a significant part of the emissions from the transportation sector
- Emissions of NO_2 from high temperature combustion (nitrogen and oxygen from ambient air)
- Emissions of SO_2 directly linked to fuel sulfur content
- Local scale: affecting air quality and harmful for human health
- Global scale: changing atmospheric composition and impact on climate

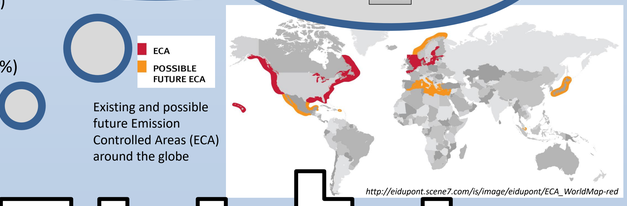
Regulations

- International Maritime Organization (IMO): Convention for Prevention of Marine Pollution from Ships (MARPOL 73/78 Annex VI)
- Establishment of general Emission Controlled Areas (ECA)
- NO_x emission limits for newly built engines
- Limitation of sulfur content in heavy oil fuels
- Since January 2015 only 0.1% sulfur is allowed (before: 1%) in ECAs like North Sea and Baltic Sea

Marine fuel sulfur limits



http://www.aecmaritime.com/eca

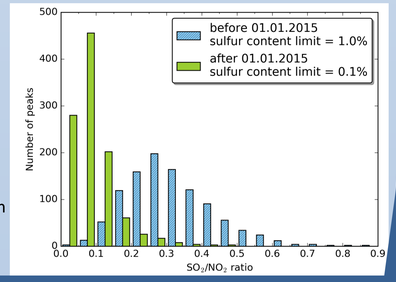


Existing and possible future Emission Controlled Areas (ECA) around the globe

http://eidupont.scene7.com/is/image/eidupont/ECA_WorldMap-red

SO_2/NO_2 ratio in ship plumes

- Emission factors cannot be measured by MAX-DOAS directly
- Ratio of SO_2 to NO_2 in ship plumes gives a good estimate of the SO_2 to NO_x emission ratio of the ships
- More than 2000 individual ship plumes were identified in the data and analyzed for the SO_2 to NO_2 ratio
- Results varied between ships (different sulfur content in fuel) but on average yielded values of about 0.3 for the years 2013/2014 → good agreement with results from other studies (Diesch et al., 2013; McLaren et al., 2012)
- Implementation of stricter sulfur limits in shipping fuel lead to a large reduction in SO2 to NO2 ratios → good agreement with Kattner et al. (2015), who found that 95% of the ships are sticking to the new limits



Conclusions

- **MAX-DOAS instrument can measure emission peaks from single ships as well as background pollution**
- **The overall contribution of ship emissions to pollution levels at the measurement site is large but land based sources still dominate, even in the immediate vicinity of shipping lanes**
- **Fuel sulfur limit regulations are working: Significant reduction of SO2 emissions since January 2015**

Acknowledgements
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