Monitoring shipping emissions in the German Bight using MAX-DOAS measurements

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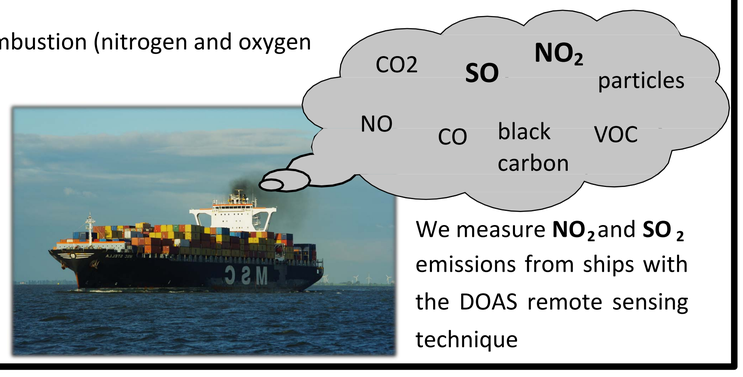
Why measure shipping emissions?

- Shipping is generally the most energy efficient transportation mode (per t per km)
- But shipping accounts for around 80% of total merchandise worldwide trade volume
- Seaborne trade grows fast, despite the economic crisis (annual growth rate 3-4 % in the years 2010 to 2014)
- 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



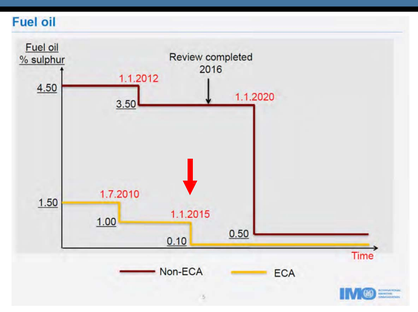
We measure **NO_2** and **SO_2** emissions from ships with the DOAS remote sensing technique

Important change in existing 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)
- NOx 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

- Starting 2020 global sulphur cap 0,5% for regions outside ECAs
- **Global need for compliance monitoring e.g. using DOAS approaches**



MeSMarT project

- "**M**easurements 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 measurement sites and platforms:**

MAX-DOAS on radar tower Neuwerk (see corresp. Setion)

MAX-DOAS Wedel

Measurement truck: mobile air quality monitoring station, here in Bremerhaven

RV Celtic Explorer: Several ship cruises on North and Baltic Sea

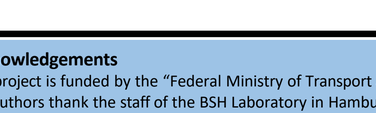
White numbers: Annual ship movements

Map: http://www.bing.com/maps/ (01.04.2014), Data: http://www.wsv.de/ (09.05.2014)

MAX-DOAS measurement geometry and analysis

- **DOAS** = **D**ifferential **O**ptical **A**bsorption **S**pectroscopy
- 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 = Concentration of absorber integrated along the light path
- Retrieval of path-averaged near-surface VMRs from MAX-DOAS SCDs applying the approach of the effective light path which can be estimated using O_4 SCDs

MAX-DOAS instrument setup:



Grating spectrometer:

Measurement geometry:

Light source: the sun

❶ Off-axis measurement through ship plume

❷ Zenith-sky reference to cancel out stratospheric absorption

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
- Time series from July 2013 until July 2016
- Two channel MAX-DOAS (UV, vis)
- Multiple azimuthal viewing directions to cover the region and main shipping lane

MAX-DOAS

Airpointer in-situ

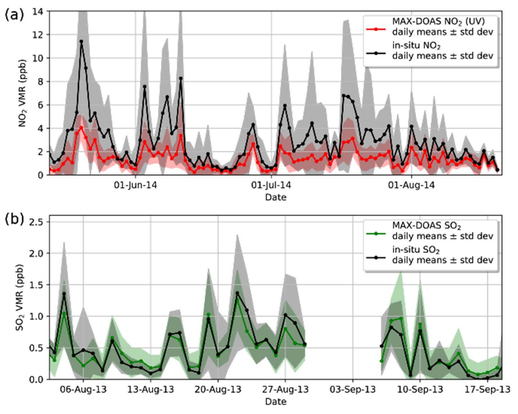
White numbers: Annual ship movements

Map: http://www.bing.com/maps/ (01.04.2014), Data: http://www.wsv.de/ (09.05.2014)

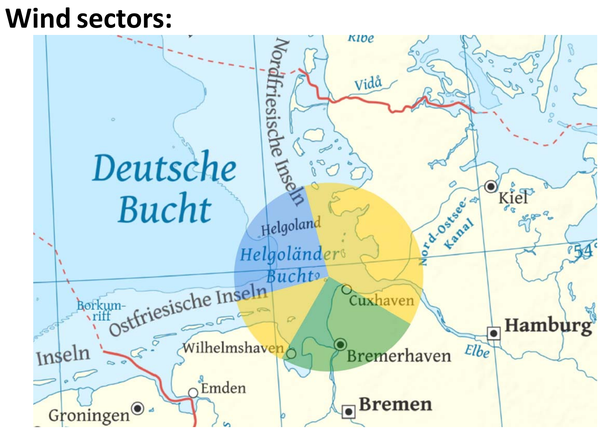
Results

Comparison of MAX-DOAS to in situ measurements

- Comparison of MAX-DOAS (UV) and in situ daily mean VMRs of NO_2 and SO_2 show a very good agreement in day-to-day-variability of the different methods
- Since no correction factors are used for the MAX-DOAS results accounting for the difference in profile shapes of the trace gas and the proxy O_4 and other parameters affecting the radiative transfer the absolute values are different
- Larger absolute differences in NO_2 can be at least partly attributed to plume chemistry: MAX-DOAS sees the ship plumes in an earlier state than the in situ, with more of the emitted NO_x being NO



Wind sectors:

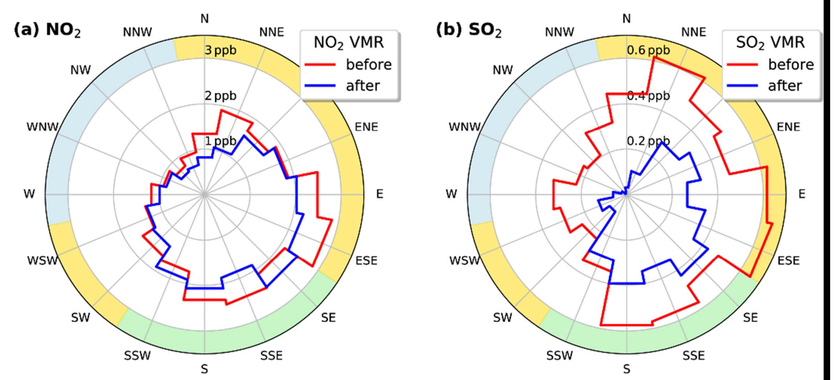


Classification:

- 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)

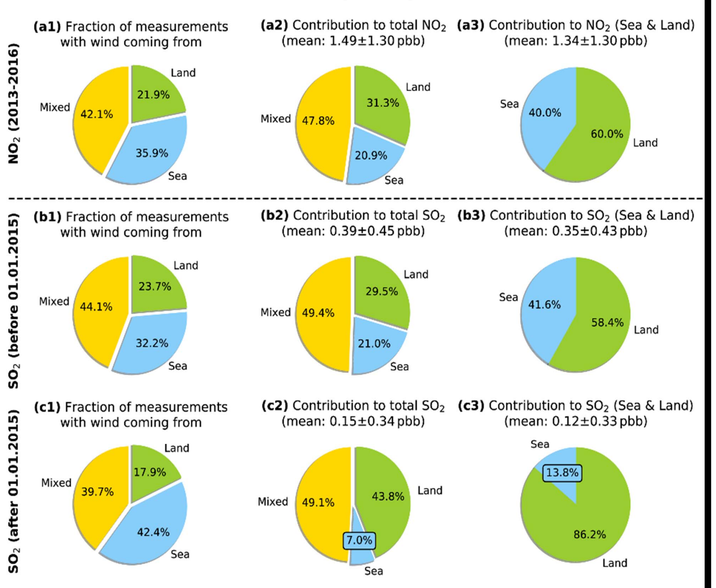
Dependence of NO_2 and SO_2 pollution levels on wind direction:

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



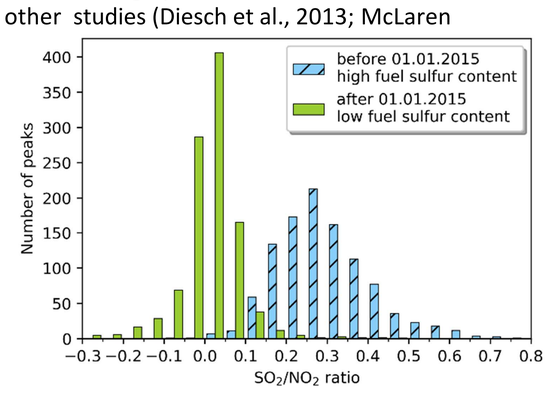
Contributions of ships vs. land-based pollution sources on coastal air quality on Neuwerk:

- To trade ship emissions off against land-based emissions (e.g. industry, road transport), two representative sectors of wind directions have been chosen (blue and green sectors in map above)
- 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 January 2015, the relative contribution of shipping sources was reduced to 14%, the absolute amount decreased by a factor of 8
- Since 2015, the vast majority of SO_2 emissions can be attributed to land sources, ships play only a negligible role



SO_2 to NO_2 ratios in ship plumes

- Emission factors cannot be measured by MAX-DOAS directly
- However, 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 analysed 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 SO_2 to NO_2 ratios to about 0.05 in average
  → good agreement with Kattner et al. (2015), who found that 95% of the ships are sticking to the new limits
- Measurements from sites closer to the shipping lanes (Wedel, see poster by Schmitt et al.) and more recent results from Bremerhaven show higher ratios (around 0.15), which can be explained different NO to NO_2 titration in the plumes



Conclusions

- Long-term measurements of NO_2 and SO_2 using a MAX-DOAS instrument demonstrated the feasibility of monitoring pollution originating from ships remotely
- The overall contribution of ship emissions to pollution levels at the measurement sites 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 SO_2 emissions since January 2015
  Results are accepted for publication in: Seyler, A. et al. (2017). Monitoring shipping emissions in the German Bight using MAX-DOAS measurements. Atmospheric Chemistry and Physics

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