

# Particle Emissions from Ship Engines: Emission Properties and Transformation in the Marine Boundary Layer

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## INTRODUCTION

Gaseous and particulate matter emissions from ship engines currently gain increasing attention regarding a possible environmental impact. They can influence the atmospheric composition and in particular the ozone chemistry in the troposphere considerably. As for any combustion source, ship engine exhaust also contains particulate matter. Exhaust particles are composed of combustion aerosol particles consisting of elemental and organic carbon, sulphate and ash (Petzold et al., 2004), and of volatile particles forming outside the combustion process in the cooling exhaust plume.

Elemental or black carbon (BC) is the most efficient particulate absorber of atmospheric solar radiation and has therefore a strong impact on the atmospheric radiation balance. Additionally, combustion particles can act as nuclei for the formation of cloud droplets and affect by that means the life cycle and radiative properties of stratus clouds at the top of the marine boundary layer.

In particular the emission of particles and their fate in the marine environment are however widely unknown. From observations so far mainly bulk aerosol properties like mass concentrations are reported, while detailed chemical analyses and aerosol microphysical data are missing.

In the framework of a combined effort ship emission studies were conducted in 2004 as part of the European Integrated Project HERCULES (High Efficiency R&D on Combustion with Ultra Low Emissions for Ships). Detailed aerosol microphysics and chemistry was measured in the exhaust gas of a single-cylinder test bed engine, which was operated at various load conditions, running on fuel with a sulphur content of 3.45 wt.-%.

The emission studies were complemented by airborne aerosol transformation studies in the marine boundary layer as part of the ICARTT-ITOP (Intercontinental Transport of Ozone and Precursors) experiment in 2004. Research flights using the DLR aircraft Falcon 20 E-5 were conducted in the English channel and in a single plume of a large container ship.

## METHODS

On board of the research aircraft, an extensive set of instruments was operated for measuring aerosol microphysical properties of both the secondary volatile aerosol, the primary combustion aerosol and trace gases H<sub>2</sub>O, NO, NO<sub>x</sub>, O<sub>3</sub>, CO, CO<sub>2</sub>, and SO<sub>2</sub>.

Figure 1 shows the flight track of the aircraft during the plume study in the exhaust of the container ship. The colour of the symbols represents the black carbon mass concentration in the plume. The plume encounters observed during the Single Plume Study are shown in Figure 2. The strength of the plume event was rated according to the CO<sub>2</sub> measured above the background signal (excess CO<sub>2</sub>: ΔCO<sub>2</sub>).

Close to the source, ΔCO<sub>2</sub> exceeded a value of 10 ppm, ranging up to > 100 ppm. Simultaneously, the BC mass concentration reached values of close to 10 μg m<sup>-3</sup>, while the Condensation Particle Counters (TSI 3760A) were above their upper detection limit of 20,000 cm<sup>-3</sup>.

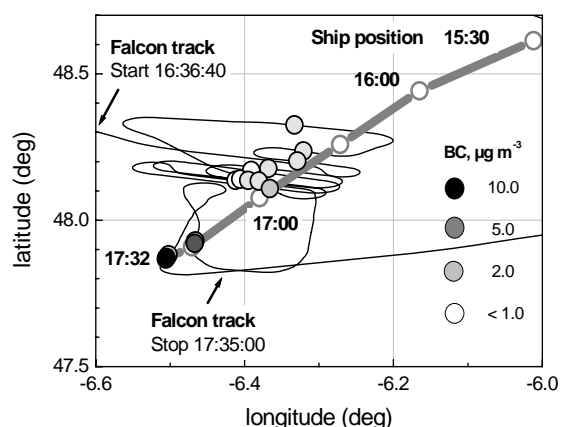


Figure 1. Tracks of the source ship and the research aircraft Falcon during the Single Plume Study; symbol colours represent Black Carbon mass concentrations in the plume.

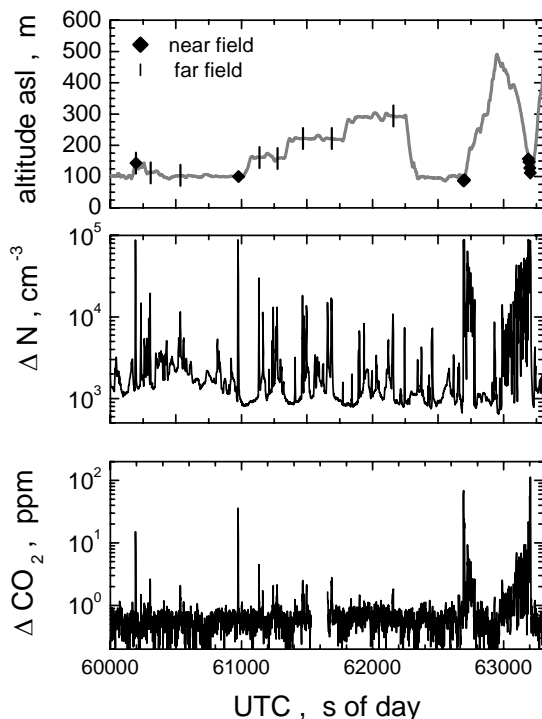


Figure 2. Time series of flight altitude in m above sea level (asl), excess  $\text{CO}_2$  ( $\Delta \text{CO}_2$ ) and excess number concentration  $\Delta N$  during the Single Plume Study.

The analysis of the measured DMA size distributions in the fresh plume yielded number concentrations of the combustion particle mode of  $5 - 7 \times 10^4 \text{ cm}^{-3}$ . The count median diameter was found at 70 nm. Comparable data from emission studies yield a total number concentration of combustion particles in the raw exhaust of  $2.5 \times 10^8 \text{ cm}^{-3}$  and a count median diameter of 52 nm.

As is shown in Figure 3, the exhaust particle mode inside the ship plume exceeds the background aerosol in the size range from 20 to 200 nm by max. two orders of magnitude. In the size ranges below and above this interval, no deviation from the background aerosol was found. The ship exhaust particle mode was still detectable in polluted air masses outside the single plume. This observation is in agreement with data reported by Osborne et al. (2001).

The plume age during the Single Plume Study was calculated from trajectory analyses of the ship plume with respect to the aircraft flight track and from the geometrical distance from the probing aircraft to the source ship at the time of emission.

The  $\text{CO}_2$  data measured during the Single Plume Study were then used for the determination of the

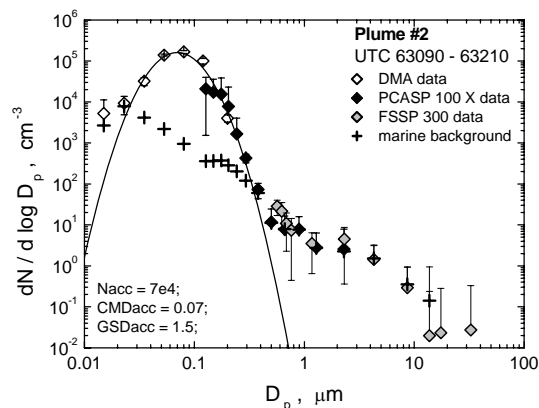


Figure 3. Composite size distributions from data from DMA, PCASP 100X and FSSP 300 for a strong plume encounter and for a marine background case; the log-normal size distribution represents the exhaust particle mode.

plume diffusion coefficients according to the plume dispersion model of Glasow et al. (2003). When using  $\Delta \text{CO}_2$  as an indicator for the plume age, plume observations extended from very young plumes in the Single Plume Study ( $t \cong 60 \text{ s}$ ) to well aged plumes in the English Channel Study ( $t \cong 10,000 \text{ s}$ ).

## CONCLUSIONS

The adapted Glasow plume dispersion model in combination with the observations from emission studies and plume studies yields a consistent picture of particle transformation processes from emission from a ship engine to atmospheric processing in the marine boundary layer during plume expansion. The results are used for the determination of emission indices of particulate matter from ships and for the estimation of life times of ship exhaust particles in the marine boundary layer.

**Keywords:** Ship emissions, combustion, marine aerosol

## REFERENCES

- Osborne, S.O., et al. (2001) Modification of the aerosol size distribution within exhaust plumes produced by diesel-powered ships, *J. Geophys. Res.*, 106, 9827-9842.
- Petzold, A., et al. (2004) Particle emissions from ship engines, *J. Aerosol Sci., Abstracts of the European Aerosol Conference*, S1095-S1096.
- Von Glasow, R., et al. (2003) Modelling the chemical effects of ship exhaust in the cloud-free marine boundary layer, *Atmos. Chem. Phys.*, 3, 233-250.

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