Assessment of global particle number emissions from shipping and effect of scrubbers

N. Kuittinen[1], J. Jalkanen[2], J. Alanen[1], L. Ntziachristos[1], P. Karjalainen[1],
P. Aakko-Saksa[3], E. Asmi, H[2]. Lihavainen, H[2]. Timonen[2], T. Rönkkö[1]

[1]Aerosol Physics Laboratory, Physics Unit, Tampere University

[2]Atmospheric Composition Research, Finnish Meteorological Institute

[3]VTT Technical Research Centre of Finland

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Structure of this study

Particle number emission factors were measured in laboratory with 1.6 MW Wärtsilä engine for variety of marine fuels

On-board campaign was carried out on a cruise ship to study the effect of sulfur scrubbing

Results were compared to ship plume chase study on the Finnish coastline

Emission factors applied in Ship Traffic Emission Assessment Model (STEAM) to produce estimate of global PN emissions from shipping

Industry reports were studied to produce estimates of the effect of new fuel sulfur regulation in 2020

Determining PN emission factors for different marine fuels

Wärtsilä Vasa 4R32 LN E	Liquid fuel operation mode	Natural gas operation mode*
Nominal power (kW)	1640	1400
Number of cylinders	4	4
Speed (rpm)	750	750
Bore (mm)	320	320
Stroke (mm)	350	350
Compression ratio	13.8	12

- Six fuels were tested on the same 1.6 MW medium-speed Wärtsilä Vasa 4R32 LN E ship engine
    - Heavy fuel oil (HFO), 2.2% sulfur
    - Intermediate fuel oil (IFO), 0.375% sulfur
    - Blend of biofuel and light fuel oil (BIO30), < 5 ppm sulfur
    - Marine diesel oil (MDO), 0.08% sulfur
    - Marine gas oil (MGO), < 10 ppm sulfur
    - Natural gas with pilot injection (NG)
- Measurements were conduted at 75% and 25% loads, corresponding to cruising and maneuvering conditions

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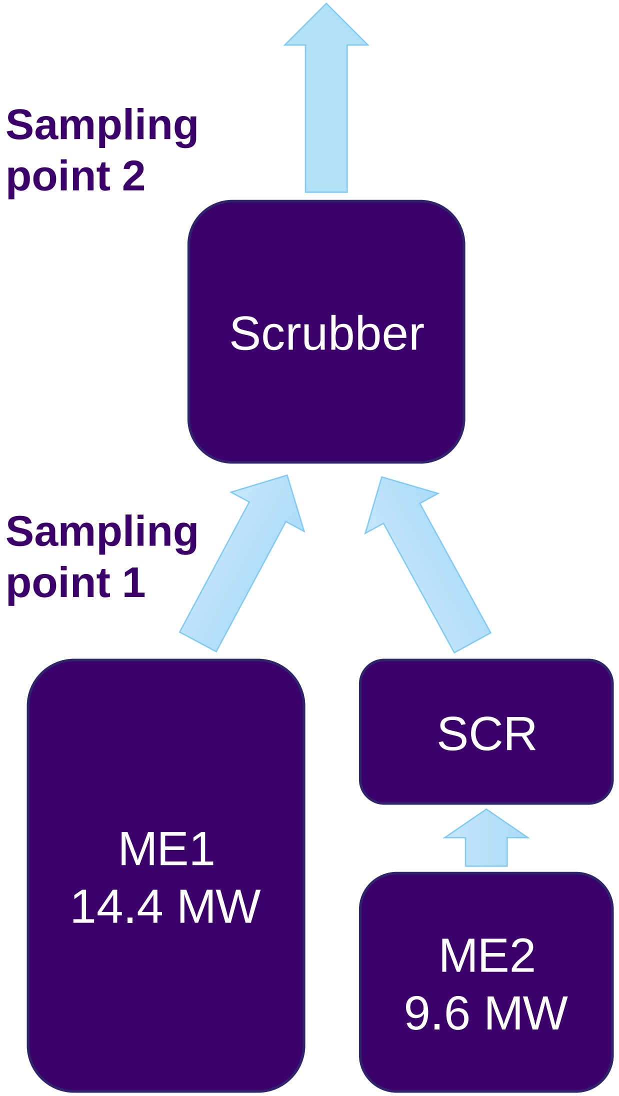
Studying the effect of scrubber

- Field campaign was conducted on-board a modern cruise ship
  - Campaign took place inside the Baltic and North Sea SECA
- Exhaust was sampled from two 4-stroke, medium-speed engines, one engine at a time
  - ME1: Main engine with a nominal power of 14.4 MW
  - ME2: Main engine with a nominal power on 9.6 MW, applying SCR catalyst for NOx reduction
- Both engines were run on steady load points of 75% and 40%
- The engines combusted heavy fuel oil (HFO) with 0.7% sulfur



Sample conditioning

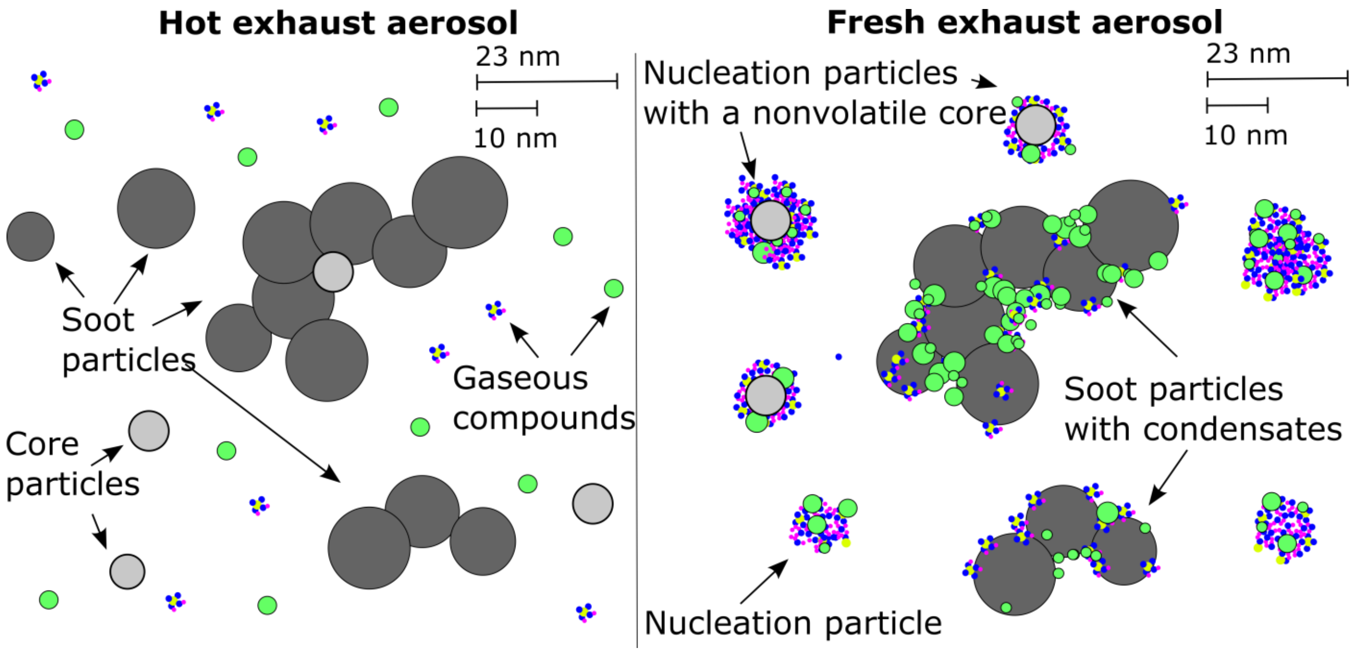
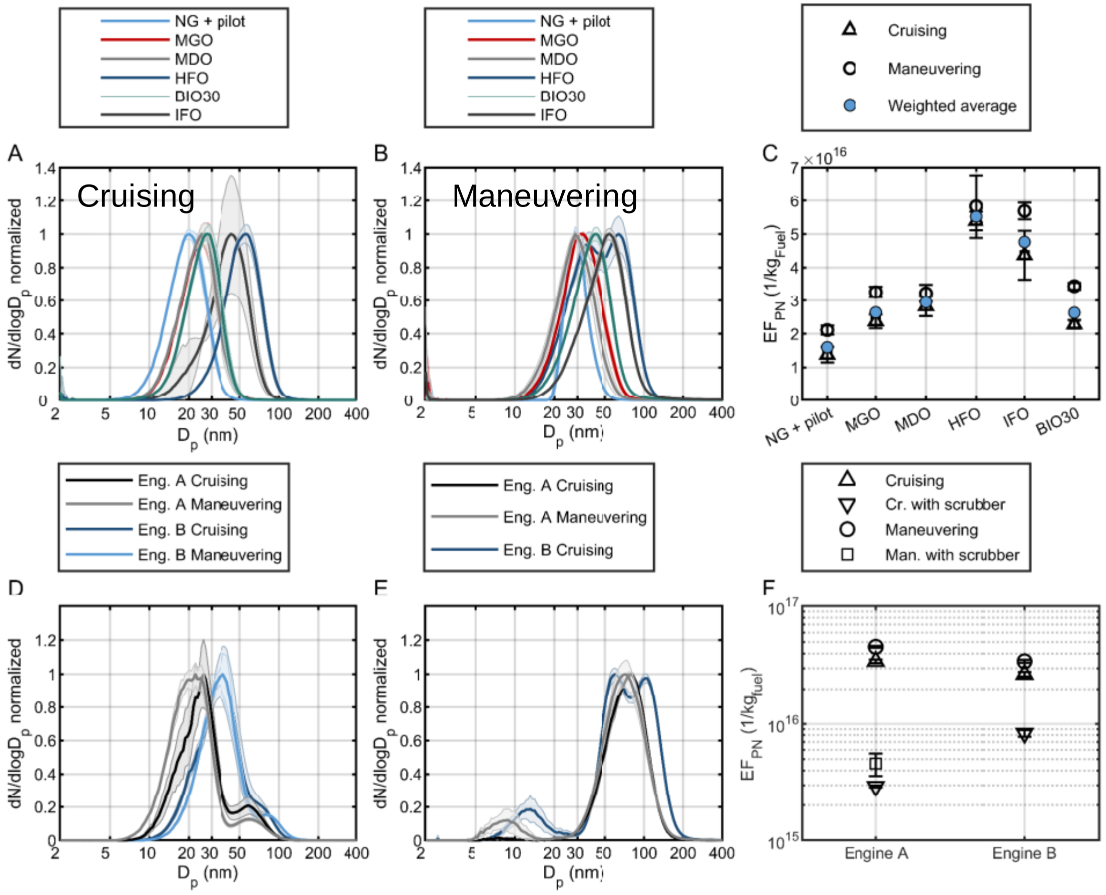


Figure: Karjalainen et al. 2016

- Porous tube diluter together with residence time tube was used to mimic the atmospheric dilution processes producing 'fresh' exhaust aerosol (Keskinen & Rönkkö, 2010)
- Catalytic stripper at 350°C (eg. Amanatidis et al., 2018) was applied to study non-volatile particles in the scrubber campaign
- CPCs (TSI or Airmodus with cut-points at 2.5 nm or 7 nm) were used for particle counting

PN size distributions and emission factors

- The majority of the particles were in the UFP size range (<100 nm), and in most of the cases, nucleation mode particles dominated the distributions
  - GMDs lowest for LNG and highest for HFO
  - Lower load produced larger particles
- Compared to HFO, lighter liquid and gaseous fuels decrease PN emissions of marine engines
  - However, this is not as significant as one would expect from the corresponding impacts on emitted PM (e.g. Sofiev et al.)



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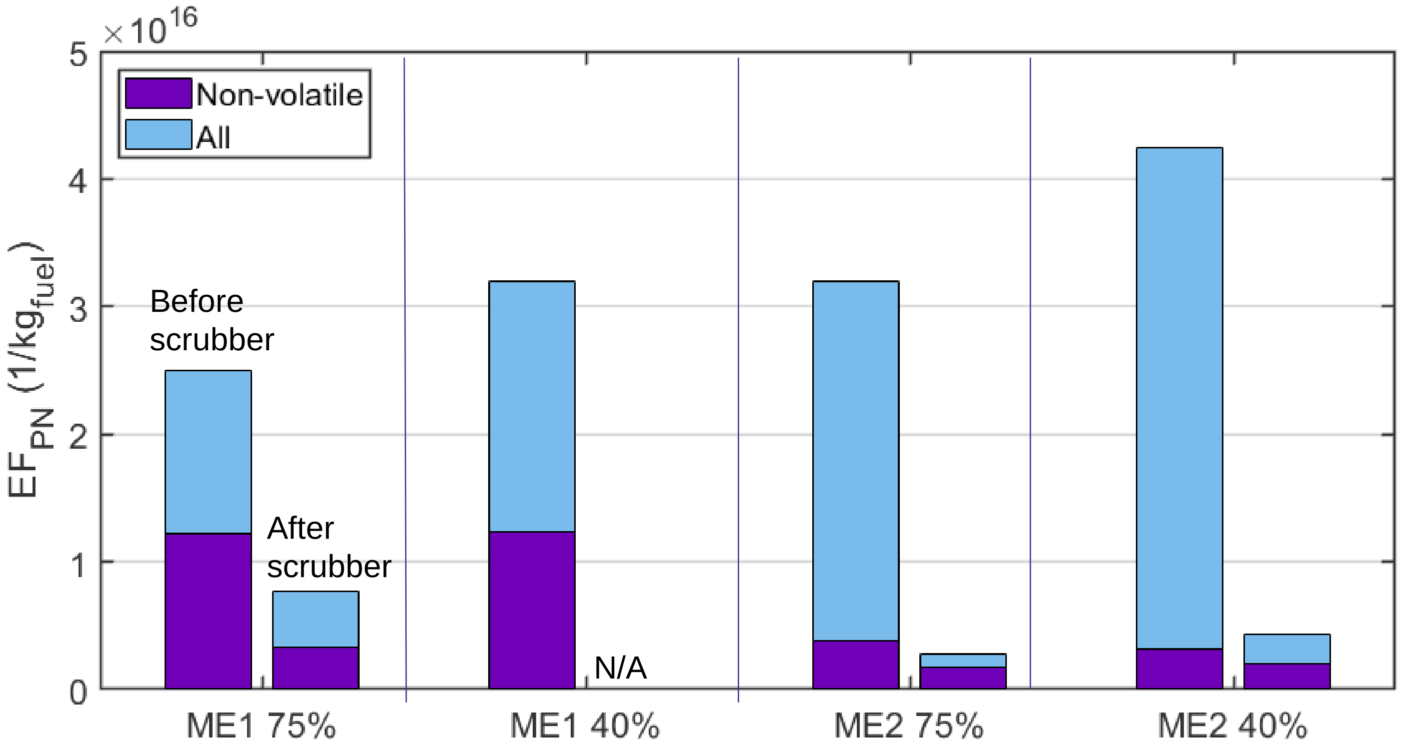
PN reduction over scrubber

- By comparing PN emission factors over the scrubber, total PN was reduced by 69-91%
- ME2 applying SCR produced higher PN emissions, but hey were also more efficiently reduced in the scrubber
- Largest reduction was seen in volatile PN
- Also non-volatile (primary) particles were reduced by 36-73%



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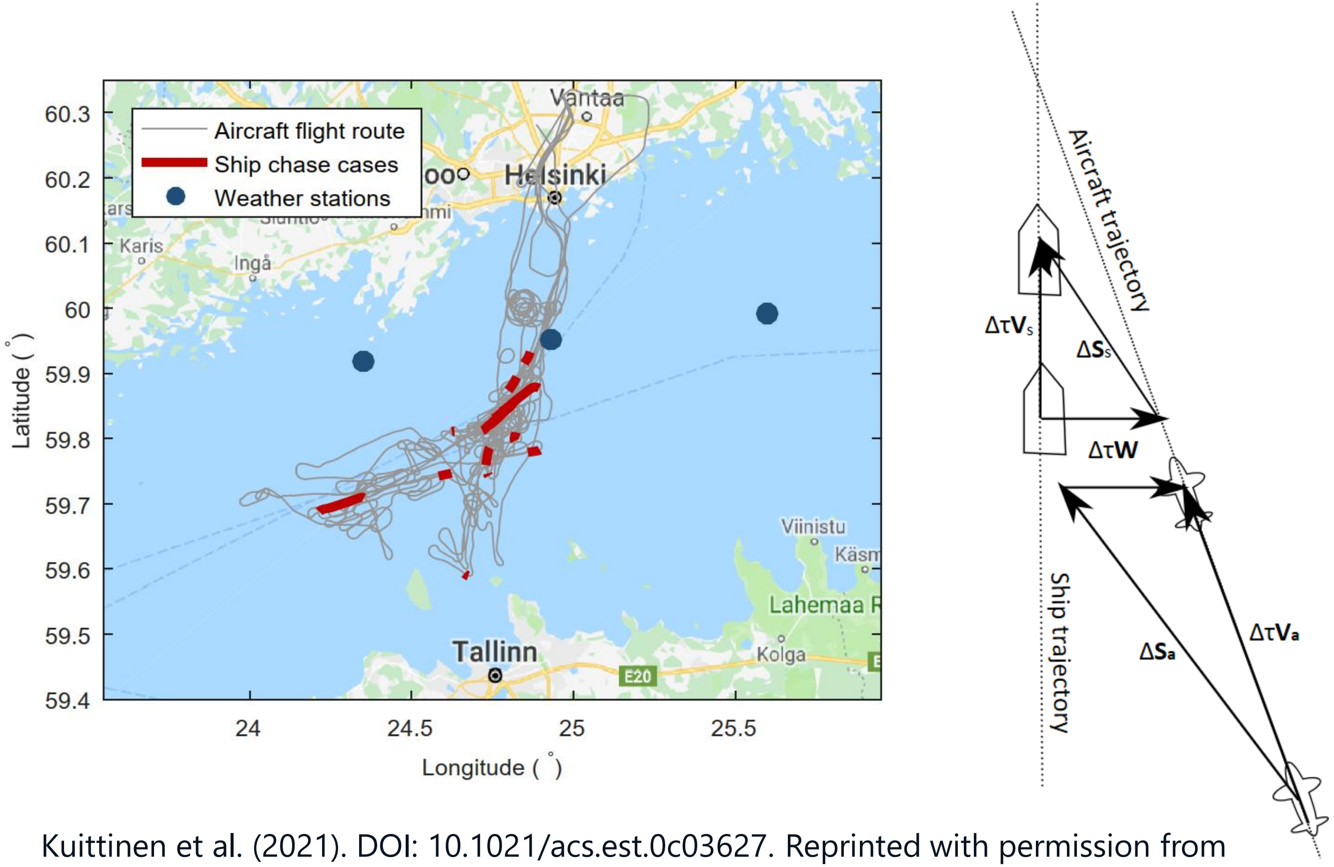
Plume measurements on the Baltic Sea

- Real-world ship plume chase experiments performed with research aircrafts in the Gulf of Finland in the Baltic Sea (SECA, 1% sulfur limit)
- The research aircraft located target ships and flew along their plumes as close as possible to their funnel exhaust
- PN emission factors obtained from CPC and CO2 data for 23 ships
- Size distributions were measured by EEPS on part of the flights



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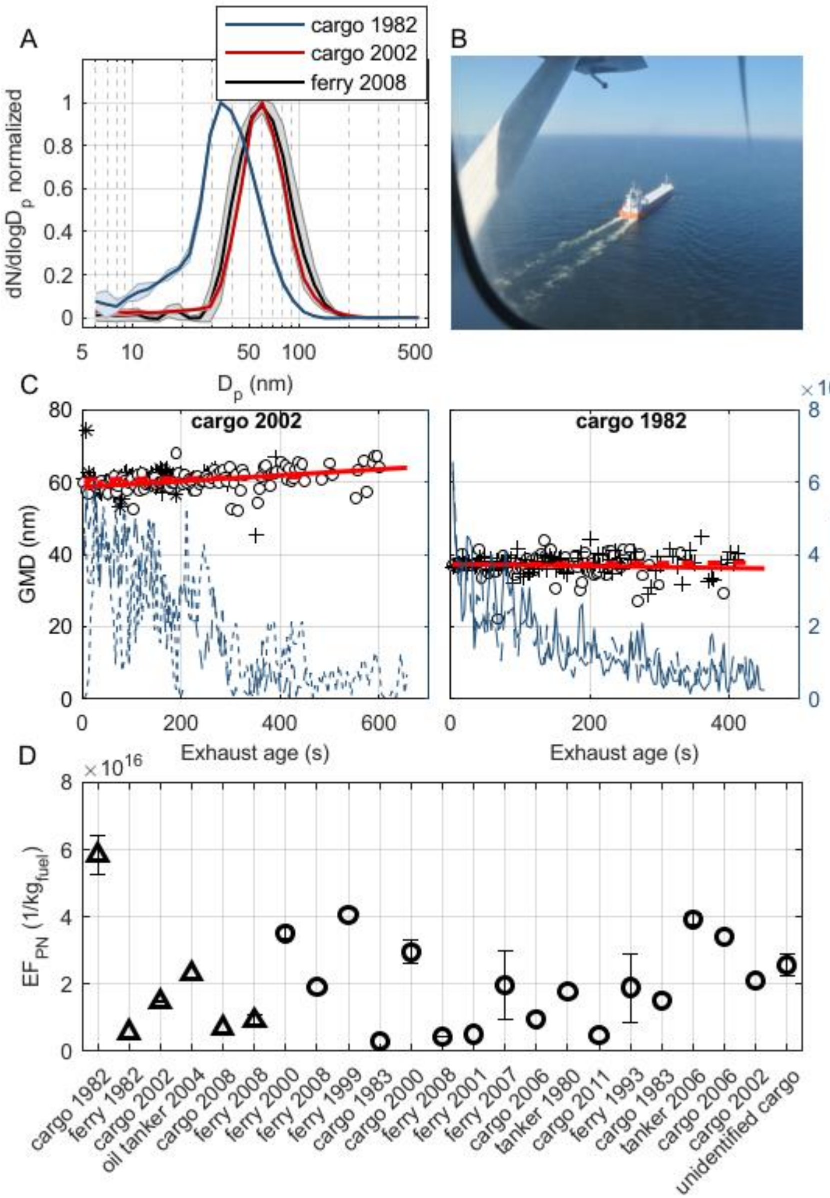
Particle characteristics in the real-world plumes

- The particle number size distributions and PN emission factors resembled those measured in the laboratory, confirming the applicability of the laboratory emission factors
- The mean diameter of the particles only marginally changed over several minutes after emission, suggesting that particles in the plume of marine vessel exhaust have relatively high atmospheric residence times
- Fuel and technology information obtained from the ship operators were incomplete, but fuels mainly included HFO and IFO with sulfur contents below 1%



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Ship Traffic Emission Assessment Model (STEAM)

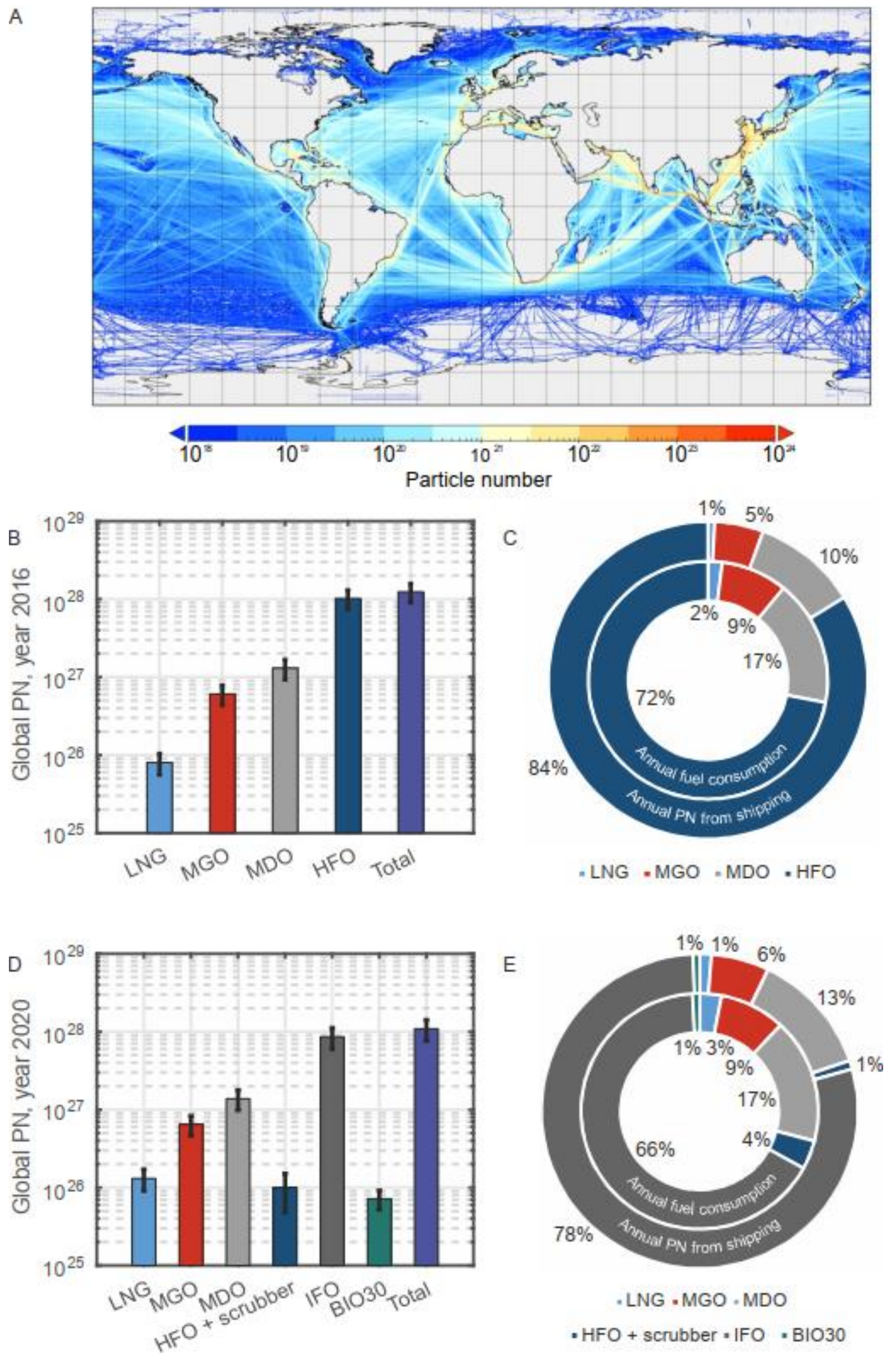
- STEAM was used to calculate the global marine fuel consumptions in 2016 and 2020
    - The model indicated 8.6% increase in total energy consumption
- For each cruising vessel, the technical description was obtained from IHS Fairplay and the fuel use and emissions were modeled by applying water resistance calculations on the speeds indicated by the AIS data
- The fuel type per vessel was designated according to engine characteristics and sulfur limitations in specific locations (i.e., ECAs)
    - Because data on the adoption of different marine fuel qualities in 2020 was not available, contributions of different fuels to total fuel consumption in 2020 were assumed based on industry reports
- The fuel-based EF_{PN} in this study showed 8–50% higher values at low load conditions. To consider this, a weighted average of low (30% weight) and high load (70% weight) values was applied in STEAM,

Global PN emissions from shipping

- The global PN emissions from ship traffic in 2016 displays elevated PN emission levels on the main oceanic shipping lanes but, importantly, also near densely populated port cities (27% emitted in the Southeast Asia)

- The total number of fresh exhaust particles produced from ship traffic was estimated to be 1.22 × 10^{28} annually, same order of magnitude with an estimate for total continental anthropogenic PN emissions of 1.3–1.5 × 10^{28} (Paasonen et al.)

- When considering the marine fuel usage and introduction of new fuels in 2020 and applying the emission factors presented in this study, total annual PN seems to decrease by only 11% to 1.09 × 10^{28} (±0.33 × 10^{28}) compared to year 2016



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Conclusions

- Fresh PN emission factors were determined for variety of available marine fuels
- Scrubber efficiently reduced the number of all particles by 69-91%, and the number of non-volatile particles by 36-73%
- The global freshly emitted PN from ship traffic was estimated to be 1.22×10^{28} in 2016 and reduce marginally by 11% in 2020 if heavy fuel oil is mainly replaced by intermediate fuel oils
- Our study implies that shipping remains as a significant source of anthropogenic PN emissions that should be accounted for in future climate modeling and consideration of health impacts

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