



Mobile mapping of PM and PNC in a Baltic Sea harbour city: spatio-temporal variability and local ship-related emission events

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ABSTRACT

Ship emissions are important sources of atmospheric pollutants in coastal regions, yet their spatio-temporal variability in harbour residential areas remains poorly characterized. This study assessed ambient PM and particle number concentration (PNC) in the Baltic Sea harbour city of Warnemünde–Rostock (Germany), where maritime and touristic activity occur in close proximity to residential areas. A stroller-based mobile platform measured PM, PNC, lung-deposited surface area, black carbon (eBC) and ozone during 56 repeated surveys covering 238 km over 14 days, complemented by rooftop stationary PM monitoring. For campaign-wide analysis, the common 3.76 km route was divided into 20 m segments. Walk-segment medians and 90th percentiles were used to distinguish recurrent spatial patterns from isolated plume encounters, and predefined micro-environments were compared using walk-specific zone statistics. Whole-survey median PNC ranged from 2.4×10^3 to $1.2 \times 10^4 \text{ cm}^{-3}$, while short-duration peaks exceeded $2.4 \times 10^5 \text{ cm}^{-3}$. The strongest campaign-wide upper-tail hot-spot occurred along the Seepromenade during a temporary festival. Among maritime locations, the Warnow ferry terminal represented the clearest recurrent hot-spot, whereas the cruise-terminal vicinity showed episodic enhancements dependent on vessel activity, wind direction, and other factors. During unfavorable downwind conditions, the high PNC plume peaks reached the urban and residential route sections. In contrast, PM_{2.5} varied only narrowly among the predefined microenvironments, while stationary daily PM_{2.5} remained generally low. Repeated high-resolution mobile monitoring therefore provides essential complementary information to fixed-site measurements by resolving short-lived plume encounters and fine-scale spatial concentration gradients and supports targeted mitigation measures such as ferry electrification and greater use of shore power.

1. Introduction

Air pollution is responsible for almost 250,000 premature deaths per year in the EU (EEA, 2025) and is the fifth leading risk factor for mortality worldwide (Health Effects Institute, 2019). A significant number of severe health problems, such as asthma, chronic obstructive pulmonary disease (COPD), cardiovascular problems (e.g. stroke) and respiratory diseases (e.g. lung cancer) are attributed to elevated levels of air

pollutants. Latest research has also shown a linkage between prenatal exposure to high levels of air pollution and developmental delay at age three as well as psychological and behavioural problems later on including symptoms of attention deficit hyperactivity disorder (ADHD), anxiety and depression (European Commission, 2024b; WHO, 2021). In this context, it is estimated that air pollution costs the EU economy up to €850 billion per year (European Commission, 2024b).

European ambient air legislation and WHO guidelines primarily

Abbreviations: eBC, Equivalent Black Carbon; ECA, Emission control area; GPS, Global positioning system; HFO, Heavy fuel oil; IMO, International Maritime Organization; LDSA, lung deposited surface area; MGO, Marine gas oil; OPS, Optical particle sizer; P90, 90th percentile; PM, Particulate Matter; PM10, particulate matter smaller than 10 µm in the aerodynamic diameter; PM2.5, particulate matter smaller than 2.5 µm in the aerodynamic diameter; PM1, particulate matter smaller than 1 µm in the aerodynamic diameter; PMx, PM10, PM2.5 and PM1; PNC, particle number concentration; UFP, ultrafine particles; UVP, ultraviolet absorbing particulate matter; WHO, World Health Organization.

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regulate particulate pollution using PM_{2.5} and PM₁₀ mass concentration (European Commission, 2024a). Although the revised EU Ambient Air Quality Directive introduces more stringent limits from 2030, particle number concentration (PNC) and ultrafine particles (UFP) are not subject to binding ambient-air limit values.

The air pollutant with the strongest evidence for adverse health issues is PM_{2.5} (EEA, 2025). In this context, small particles like PM₁ or even ultrafine particles (UFP; particles <100 nm) are particularly concerning because epidemiological and toxicological studies have suggested that the smaller the particles, the more toxic they might be. Because of their small sizes they might penetrate deeply into the human lungs and even the bloodstream through lung translocation, thus causing systemic toxicity (Cassee et al., 2019; Oberdörster et al., 2005). However, neither PM₁ nor UFP are explicitly regulated.

Current and future (from 2030) allowed EU ambient daily mean and annual mean values for PM_{2.5} and PM₁₀ including the maximum number of exceedances (exc.) as well as WHO recommendations are summarized in Table 1 (European Commission, 2008; European Commission, 2024a; WHO, 2021).

Approximately 90% of global trade goods are transported by ocean-going vessels (German Federal Government, 2017). Consequently, exhaust emissions from ships significantly contribute to global air pollution including PM, NO_x, CO, SO₂, and volatile organic compounds (VOCs). Regarding this, PM is of particular concern since it has been shown that particles from marine engines mainly consist of black carbon (BC) and can occur in very high particle number concentrations (PNC) in the UFP size range (Jeong et al., 2023). In addition, PM may contain significant levels of carcinogenic polycyclic aromatic hydrocarbons (PAHs) and toxic heavy metals depending on the fuel type (Aakko-Saksa et al., 2023; Jeong et al., 2025; Chu-Van et al., 2018; Saraji-Bozorgzad et al., 2025). PAHs and other harmful compounds are present also in the gas phase (Bendl et al., 2024). Besides these primary pollutants, ship emissions also undergo atmospheric processes and significantly contribute to formation of secondary organic aerosols (SOA) (Perez et al., 2016).

Previous measurements in Baltic and other European harbour environments have shown that individual ship plumes can produce strong, short-lived increases in PNC, often dominated by nanometre-sized particles, while their magnitude and spatial extent depend strongly on vessel operation and meteorological conditions (Pirjola et al., 2014). A land-based campaign in the port of Rostock identified exhaust plumes from 73 ships within one week using rapid changes in particle number and size distribution, while single-particle mass spectrometry enabled differentiation of particle signatures associated with different marine fuels (Rosewig et al., 2024). Regional modelling has also demonstrated that shipping contributes to coastal air pollution in the North Sea and western Baltic Sea, with effects extending beyond the immediate port area (Aulinger et al., 2016). However, repeated high-resolution measurements along pedestrian routes in residential Baltic harbour districts remain scarce, particularly studies that distinguish recurrent spatial patterns from isolated plume encounters.

Table 1
Comparison of current, future (from 2030) EU ambient-air limit values and WHO-recommended air quality guideline levels for daily mean and annual mean PM_{2.5} and PM₁₀ concentrations, including maximum number of exceedances (exc.).

	Currently in EU daily/annual mean	from 2030 in EU daily/ annual mean	WHO recommendation daily/annual mean
PM _{2.5} [$\mu\text{g m}^{-3}$]	/25	25 (18 exc.)/10	15 (3-4 exc.)/5
PM ₁₀ [$\mu\text{g m}^{-3}$]	50 (35 exc.)/40	45 (18 exc.)/20	45 (3-4 exc.)/15

Over years, there have been efforts to reduce the environmental impact of international shipping. The International Maritime Organization (IMO) has adopted stringent regulations under Annex VI of the International Convention for the Prevention of Marine Pollution from Ships (MARPOL) by implementing so-called Emission Control Areas (ECAs) (IMO, 2008a). Among others, these ECAs include North Sea, Baltic Sea, English Channel, and the U.S. coastline, applying to all vessels over 300 gross tons. Inside these designated ECAs (sometimes referred to Sulphur ECA: SECA), SO_x emissions are indirectly regulated by limiting the marine fuel sulphur content (FSC) to a maximum of 0.1% (w/w), while outside ECAs the FSC is limited to 0.5% since 2020 (IMO, 2008a).

Furthermore, NO_x emissions from ships are governed by the IMO treaty (IMO, 2008b). Nonetheless, aside from FSC and NO_x, there are currently no direct or indirect regulations addressing ship emissions, including PM.

Common marine low-speed engines are typically designed to burn heavy fuel oil (HFO) or marine gas oil (MGO). HFO is produced from residuals of crude oil refining and contains higher concentrations of e.g. sulphur, ash, metals, and organic compounds such as PAHs compared to MGO (Streibel et al., 2017). MGO is similar to diesel fuel and is typically compliant with FSC regulations (Jeong et al., 2023). Consequently, conventional HFOs with high sulphur content have increasingly been replaced by MGO or low-sulphur HFOs to comply with the IMO regulation. Another legal option to continuously operate on high sulphur HFOs is the on-board implementation of an emission abatement systems i.e. a wet scrubber for SO_x reduction (Oikawa et al., 2003; Andreassen and Mayer, 2007). However, other pollutants than SO_x are either ineffectively or not at all affected by this approach, as the scrubbers are engineered to capture water-soluble SO_x, and not less water soluble, potentially harmful, compounds (Bendl et al., 2024). In the Baltic Sea, the number of vessels equipped with scrubbers rose rapidly following IMO regulations, from 2019 to 2023 by about 300% (Jalkanen et al., 2023). Especially in the open-loop operation, where scrubber washwater is discharged directly to the sea, the effluent poses environmental pollution risks (Lunde Hermansson et al., 2026). In this regard, since 01.07.2025 Denmark has banned the discharge of open loop scrubber washwater in its territorial waters (12 nautical miles). For ships with scrubbers in closed operation, the ban on washwater discharge will come into force on 01.07.2029. (Danish Shipping, 2024). Other countries might follow this approach.

All these circumstances are of great concern, in particular for residents of coastal areas and close to harbours. Even when legislative levels of ambient PM_{2.5} and PM₁₀ are met, personal exposure to PM might pose severe health risks (Cepeda et al., 2017; Schraufnagel, 2020). This can be e.g. due to short-time but high peak concentrations of PM_x (here PM₁₀, PM_{2.5} and PM₁), PNC and/or chemical components on PM, the proximity of micro-environments (e.g. residential areas) to the pollutant source, and prevailing meteorological conditions (Cepeda et al., 2017). Additionally, micro-scale spatio-temporal variability is often unknown and can be substantial, meaning that stationary measurements may not fully represent exposure to all individuals within the study area (Bendl et al., 2023).

Ship emissions are highly dynamic in both magnitude and composition. Emission rates depend on vessel type, fuel properties, engine configuration and load, operational mode and exhaust-abatement technology, while the measured particle characteristics are further modified by plume dilution, atmospheric transformation and meteorological conditions (Petzold et al., 2008; Jalkanen et al., 2012). Consequently, harbour air pollution is often characterized by intermittent, spatially confined plume events rather than stable concentration fields, and their detection depends strongly on measurement location and temporal resolution (Pirjola et al., 2014). This dynamic emission behaviour limits the ability of daily PM mass averages or individual fixed monitoring sites to characterize short-term near-source particle-number variability and provides a rationale for repeated

high-time-resolution mobile measurements.

Aim of this study was to investigate the spatio-temporal variability of several PM parameters by a mobile measurement system in order to estimate the personal exposure of residents, commuters, and visitors of a typical sea-side town with various shipping traffic by these pollutants. PM parameters measured were PM₁, PM_{2.5}, PM₁₀, PNC, the corresponding lung deposited surface area (LDSA) (Lepistö et al., 2025), BC as well as the gaseous pollutant O₃. In doing so, hotspots and pollution sources were identified, and recommendations were given to improve ambient air quality. In addition, the spatio-temporally resolved data was compared to average PM_x values of a stationary measurement station located within the study area to see if regulative PM₁₀ and PM_{2.5} measurements are meaningful to assess the personal exposure of citizens.

2. Materials and methods

2.1. Study area & measurement strategy

Mobile measurements were conducted in Warnemünde and Hohe Düne, two coastal districts of Rostock with combined population of approx. 9000 inhabitants (Rathaus Rostock, 2025). Both districts are separated by the Warnow estuary, which is also the entry gate for ships and vessels from the Baltic Sea to Rostock Port. Warnemünde and Hohe Düne are connected by a small car diesel-powered ferry service “Warnow-Fähre”, which runs every 10 to 20 min throughout the day depending on season (Weiße Flotte, 2025). The city centre of Rostock (population ca. 210,000 (Rathaus Rostock, 2025)) is located ca. 10 km inland from Warnemünde/Hohe Düne; shipyards, ferry terminals, fishing harbour etc. are located in between along the Warnow. Rostock Port is the fourth largest German harbour and thereof the largest in the Baltic Sea with ca. 30 million tons of handled goods and ca. 2.6 million passengers per year (www.rostock-port.de). Regarding latter, there are regular ferry connections to Trelleborg (Sweden), Gedser (Denmark), and Klaipeda (Lithuania), some of which depart and return several times a day. Moreover, cruise-ship terminals are located in Warnemünde, and Hohe Düne features a naval base and a yacht harbour.

The measurement routes were designed to characterize the spatio-temporal variability of PM₁, PM_{2.5}, PM₁₀, PNC, LDSA, equivalent BC

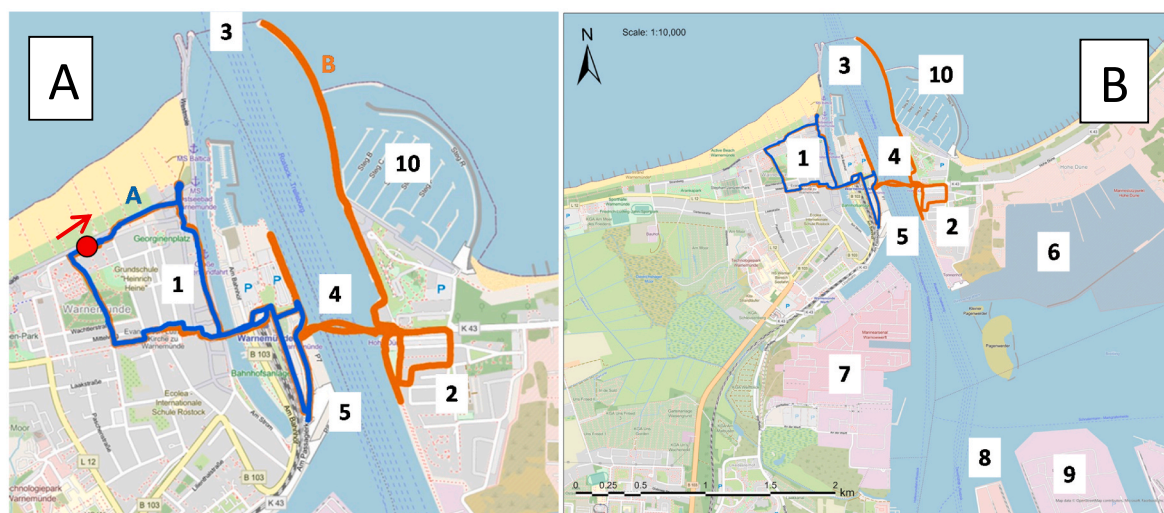
(eBC), ultra-violet PM (UVP), and O₃ using a custom-built mobile measurement platform mounted in a modified stroller (Section 2.2.1 and SI).

Route selection was guided by several criteria: (i) comprehensive coverage of the study area; (ii) the ability to identify emission sources and local hotspots; (iii) to characterize typical micro-environments, including residential zones, public places and frequented touristic areas; (iv) characterize near-ground pollutant concentrations along pedestrian routes used by residents and visitors.

All surveys started and ended at the same location (GPS: 54.180024, 12.081502) and followed the route in the same direction to improve comparability among repeated measurements. The start/end location was situated close to the DWD meteorological station no. 4271 (“Rostock-Warnemünde”, station ID: 10170) of the German Meteorological Service (Deutscher Wetterdienst, DWD). Freely available meteorological data from this station were used in this study (DWD, 2026). Meteorological data from this station were used to provide the corresponding wind speed, wind direction, temperature, relative humidity and atmospheric pressure conditions (Section 2.2.5).

The fixed common Route A (Fig. 1, blue line) was 3.76 km long and typically required approximately 50 min to complete. On 13 selected surveys, Route A was extended to form Route B (Fig. 1, orange line). The Route B extension included a crossing of the Warnow by the local ferry and measurements in Hohe Düne, including residential areas, the pier, the navigation channel and the yacht-harbour vicinity. Its exact length and duration varied according to the selected extension and prevailing field conditions. Route B surveys were purposive exploratory measurements conducted in response to meteorological conditions, vessel activity and other observed events; therefore, the additional Route B sections were not used to estimate campaign-wide spatial frequencies. The common Route A portion of these surveys was retained in the repeated-route analysis.

In total, 56 mobile surveys were conducted between 5 and 18 July 2023, covering 238 km. Forty-three surveys comprised Route A only, while 13 included the Route B extension. Route A was normally scheduled at approximately 08:00, 12:00 and 16:00 to characterize inter-day and intra-day variability; additional or delayed surveys were conducted when required by field conditions. Exact measurement times,



● Start/End of mobile & location of stationary measurements, A: Route A, B: Route B
1 & 2: Residential Areas, 3: Port Entry, 4: Warnow Ferry, 5: Cruise-ship Terminal, 6: Naval Base, 7: Shipyards,
8: Ferry Terminal, 9: Industrial Harbour, 10: Yacht Harbour

Fig. 1. Map of the Warnemünde city centre, Port Rostock channel and the Hohe Düne residential area with marked mobile measurement Route A (blue) and Route B (orange). All routes started from the Start/End point (red, A) always in easterly direction.

route classifications and durations are provided in Table S1.

During all surveys, the operators recorded field observations, including passing vessels, ferry operation, road and service vehicles, smokers, food stalls, cleaning activities and other potential local sources. Vessel presence and movements were subsequently checked using field notes, cruise schedules and online vessel-tracking information (Myshiptracking, 2026).

For reference and to provide context for the mobile measurement campaign, online stationary monitoring of PM compliant with current EU legislation (European Commission, 2008) was conducted nearby the DWD station (Section 2.2.2).

2.2. Instruments and measurement techniques

2.2.1. Mobile measurements

A mobile measurement system was developed, which is described in detail in (Bendl et al., 2023). In summary, it consists of an actively ventilated, water-proof aluminum box with adjustable internal shelves, which serves as housing for all online instruments and samplers. These are connected to omni-directional inlets (801565, TSI) in a breathing zone by short conductive tubes. All inlets were positioned 1.0 m above ground. This standardized height represents near-ground conditions relevant to children, seated adults and wheelchair users but is below the typical breathing height of a standing adult. The box was placed and secured in a modified stroller (Cab 2, Thule) including features to absorb vibrations. The temperature inside the box was kept within the operating range of the instruments. A photograph of the setup is shown in Fig. S1 in the Supplementary Information (SI).

PM_x size-distributions (OPS 3330, TSI), PNC, LDSA and size modes (DISCmini, Testo) were measured at 1 Hz resolution; O₃ using Personal Ozone Monitor (POM, 2BTechnologies) in 0.3 Hz resolution. eBC and ultraviolet PM (UVP) (MA200, Aethlabs; 150 mL min⁻¹, dual-spot) were measured at 0.1 Hz resolution. eBC (880 nm) represents mainly soot particles, while UVP (375 nm) typically indicate woodsmoke, tobacco and biomass burning. GPS coordinates were acquired at 1 Hz (64s, Garmin). The OPS was manufacturer calibrated with Polystyrene Latex (PSL) according to ISO 12501-1/4. OPS-derived PM₁, PM_{2.5} and PM₁₀ concentrations were obtained directly from the cumulative mass-concentration output using a uniform particle density of 1 g cm⁻³ for all optical size bins. No refractive-index correction was applied, while the instrument dead-time correction was enabled. To avoid particle losses and minimize the time delay, the OPS was placed directly under the inlet. Prior to each measurement, the instruments' flowrates were checked/calibrated using a mass flow meter (4043 H, TSI) as well as zero-filter checks (OPS) and automatic zero adjustments (DISCmini) were performed. The time was synchronized based on the GPS satellites. All pollutant records were time-synchronized with the GPS coordinates. Spatial harmonization and aggregation of the repeated PNC measurements are described in Section 2.2.3. eBC and UVP data were post-processed using centered moving average (CMA).

2.2.2. Stationary measurements

For stationary measurements an ambient PM monitor APDA-372 (Horiba) was installed in the dedicated environmental enclosure on the roof of the IOW building in Warnemünde (18 m above ground, GPS: 54.179364, 12.080714) next to the DWD meteorological station and the start/end point of the route. The device fulfills all requirements for regulative ambient PM₁₀ and PM_{2.5} measurements according to (European Commission, 2008), in addition, it records PM₁ values and aerosol size distributions in the range of 0.18–18 µm. The time-resolution for recording of PM₁, PM_{2.5} and PM₁₀ data was 1 min, enabling robust averaged data of specific measurement periods like averages of 0–24 h and over walk durations (route A and B). According to legislation (European Commission, 2008), sampling points higher than 8 m above ground may be appropriate if the station is representative of a large area, which was chosen for this study. The main reason and

advantage of higher placement was that there was no restriction from any site, which could cause discrimination due to wind speed and direction. The measurements took place from 5 July to 18 October 2023.

2.2.3. Spatial harmonization and aggregated mapping of repeated mobile measurements

PNC measurement values were time-synchronized with the 1 s GPS records and spatially processed in ArcGIS Pro (Esri, ver. 2.3). All spatial calculations were performed in the projected coordinate reference system ETRS89/DREF91/2016 UTM Zone 33N to enable distance-based analysis in meters. A complete GPS trajectory from Walk 28 was used as the geometric reference for the common Route A (total length of 3762.98 m). The reference route was divided according to cumulative distance into 188 complete 20 m segments and one residual terminal segment of 2.98 m.

All GPS-linked PNC measurements from the 56 mobile surveys were assigned to the nearest reference-route segment using planar distance, with maximum matching distance of 10 m. Measurement points located >10 m from the reference route, including points belonging to the Route B extensions, were excluded from the common-route (Route A) analysis. In several locations where the route geometry was spatially close or overlapping, nearest-segment assignment could be ambiguous.

For each combination of walk and route segment, the median PNC was calculated from the corresponding valid 1 s measurements. Walk-segment combinations containing fewer than three valid PNC measurements were excluded. This first aggregation step produced one representative PNC value for each valid walk-segment combination and prevented sections with slower walking speeds, stopping periods, or a greater number of GPS observations from receiving disproportionate statistical weight.

To characterize the spatial distribution across repeated surveys, the 90th percentile (P90) was subsequently calculated for every route segment across the contributing 20 m walk-specific segment medians. The number of contributing walks was retained as a separate segment-coverage variable. Segment-level median, mean, maximum, exceedance frequency, and coverage statistics were calculated in the same manner for supplementary spatial analyses.

The segment-level P90 statistics were then visualized in ArcGIS Pro (Fig. 4).

A walk-by-distance heat map was generated in Origin (2026) (OriginLab Corporation, ver. 10.3.0.180) from the walk-specific median PNC values for the 188 complete 20 m segments. Each heat-map cell therefore represents the median PNC for one walk and one 20 m route segment. Missing or excluded walk-segment combinations were displayed as white cells and resulted primarily from route deviations (e.g. due to route closure), GPS variability, ambiguous assignment in spatially close or overlapping route sections, or fewer than three valid measurements. No interpolation, smoothing, or replacement of missing values was applied.

2.2.4. Microenvironment-level aggregation and assessment

To compare pollutant concentrations among distinct urban and maritime microenvironments, selected contiguous 20 m route segments were grouped a priori according to surrounding land use and proximity to potential emission sources. The predefined zones comprised the Seepromenade (0–400 m), Alter Strom commercial promenade (600–1060 m), Mittelmole outside the ferry terminal (1400–1600 m), Warnow ferry terminal (1600–1800 m), cruise-terminal vicinity (1800–2400 m), Warnemünde city centre (2800–3200 m), and Kurpark green-space reference (3360–3560 m). Transition sections between these zones were excluded from the zone-level comparison.

For each walk and zone, the median was calculated across the available 20 m segment-level medians. A walk-zone combination was retained only when at least 50% of the segments assigned to the zone contained valid data. Zone-level summary statistics were subsequently calculated across the retained walk-specific zone medians, thereby

assigning equal weight to each walk. For the Seepromenade, walks conducted during Warnemünde Week (1–9 July 2023) were compared descriptively with walks conducted outside this period.

2.2.5. Meteorological and vessel-activity information

Meteorological observations were obtained from the DWD Rostock-Warnemünde station no. 4271 (station ID: 10170) located close to the mobile-route start/end point. Wind speed, wind direction, temperature, relative humidity and atmospheric pressure were matched to the exact start and end times of each mobile survey. Walk-specific meteorological summaries are reported in Table S1, and wind-direction distributions during selected source events are presented as wind roses (in SI Fig. S4-S59 produced in Origin).

Cruise-ship presence and berth assignments were reconstructed from the published Warnemünde cruise schedule (<https://der-warnemuender.de/>) and field observations and are summarized in Table S3. Scheduled arrival and departure times were compared with the exact survey intervals. Online vessel-tracking information and field notes were additionally used to identify passing vessels and operational events. The published schedule documents planned vessel presence but does not establish engine load, auxiliary-engine operation or exact plume strength.

3. Results and discussion

3.1. Mobile and stationary PM measurements –general overview

Table S1 in SI provides a summary of the median concentrations of PM_{10} , $PM_{2.5}$, PM_1 , PNC, LDSA, eBC, UVP, and O_3 as well as exact execution times of all 56 experimental mobile measurements of route A and B. In addition, Table S1 includes median values of PM_{10} , $PM_{2.5}$, PM_1 derived from stationary measurements, as well as corresponding meteorological data-relative humidity (RH), temperature (T), air pressure (p), wind speed (WS), wind direction (WD) measured on site. Stationary data are expressed as 0-24 h daily medians as well as medians calculated over the exact time intervals corresponding to the concurrent mobile measurements, allowing for a direct comparison between mobile and stationary measurements. Median values were used instead of means, as they better characterize the non-normal distribution of PNC and are less affected by short-term extreme peaks occurring in proximity to emission sources.

In summary, the 0-24 h PM_x median values of the stationary measurement station ranged from $6.4 \mu g m^{-3}$ PM_{10} (13.07.2023), $3.4 \mu g m^{-3}$ $PM_{2.5}$ (13.07.2023) and $2.2 \mu g m^{-3}$ PM_1 (13.07.2023) to $15.9 \mu g m^{-3}$ PM_{10} (08.07.2023), $7.3 \mu g m^{-3}$ $PM_{2.5}$ (08.07.2023) and $5.7 \mu g m^{-3}$ PM_1 (07.07.2023). All 24 h mean values were well below current and forthcoming EU daily PM_{10} and $PM_{2.5}$ limit values as well as the WHO recommendations and indicated that the background ambient air quality at the stationary rooftop location regarding PM was very good. To provide broader temporal context, the continuous rooftop APDA-372 record was evaluated from 5 July to 18 October 2023. Across 106 complete days, the median daily $PM_{2.5}$ concentration was $5.3 \mu g m^{-3}$ (IQR: $3.82\text{--}7.19 \mu g m^{-3}$). During the 14-day mobile campaign, the corresponding value was $5.0 \mu g m^{-3}$ (IQR: $4.42\text{--}5.85 \mu g m^{-3}$), compared with $5.4 \mu g m^{-3}$ (IQR: $3.75\text{--}7.44 \mu g m^{-3}$) during the subsequent period. The campaign therefore did not coincide with an unusually elevated sustained rooftop $PM_{2.5}$ episode. Higher concentrations occurred later, including 10–12 September, when daily medians reached $20.2\text{--}27.7 \mu g m^{-3}$.

For the mobile measurements, median PM_x ranged from $3.4 \mu g m^{-3}$ PM_{10} (16.07.2023 morning), $1.1 \mu g m^{-3}$ $PM_{2.5}$ (05.07.2023 afternoon) and $0.4 \mu g m^{-3}$ PM_1 (05.07.2023 afternoon, 06.07.2023 evening, 13.07.2023 afternoon) to $29.2 \mu g m^{-3}$ PM_{10} (17.07.2023 afternoon), $5.2 \mu g m^{-3}$ $PM_{2.5}$ (05.07.2023 morning) and $2.3 \mu g m^{-3}$ PM_1

(10.07.2023 afternoon). The stationary measurements taken during the exact same intervals ranged from $5.1 \mu g m^{-3}$ PM_{10} (16.07.2023 morning), $3.0 \mu g m^{-3}$ $PM_{2.5}$ (16.07.2023 morning) and $1.9 \mu g m^{-3}$ PM_1 (05.07.2023 afternoon, 13.07.2023 afternoon) to $97.9 \mu g m^{-3}$ PM_{10} (17.07.2023 afternoon), $23.9 \mu g m^{-3}$ $PM_{2.5}$ (17.07.2023 afternoon) and $11.3 \mu g m^{-3}$ PM_1 (10.07.2023 afternoon). These simultaneous measurements provide complementary temporal and spatial information, but their absolute concentrations are not directly interchangeable because the stationary monitor sampled at 18 m above ground, whereas the mobile measurements were conducted at 1 m using a different instrument and sampled changing near-ground air masses.

An exceptionally high PM_{10} and $PM_{2.5}$ episode on 17.07.2023 afternoon was detected by both mobile and stationary measurements (Fig. S3, Table S1), although absolute average mass concentrations differed by a factor of 3-5. During this period, mobile measurements recorded the lowest PNC of the entire campaign ($2400 cm^{-3}$) and only moderate eBC ($0.8 \mu g m^{-3}$). Given that winds were exclusively westerly at that time, it can be assumed that this was attributed to the presence of relatively large particles, most likely sea salt and/or resuspended mineral dust from the beach.

Apart from this event, all PM_x median mass concentrations measured (mobile and stationary) remained low, showing no indication of elevated ambient air pollution or air quality concerns for local residents and visitors.

Regarding PNC, the mobile measurements ranged from $2400 cm^{-3}$ (17.07.2023 afternoon) up to $12044 cm^{-3}$ (10.07.2023 morning). The latter walk also exhibited the highest detected eBC ($2.3 \mu g m^{-3}$) although PM_x levels were comparatively low ($9.4 \mu g m^{-3}$ PM_{10} , $2.2 \mu g m^{-3}$ $PM_{2.5}$, $1.0 \mu g m^{-3}$ PM_1). This suggests that an increased number of small BC particles, characteristic for fresh combustion emission, were present in the ambient air. In general, most of the measurements along route A (29 out of 43) yielded median PNC values between $4000 cm^{-3}$ and $8000 cm^{-3}$, which is unusually elevated for a clean coastal ambient air. These findings indicate that PM in the measurement area was dominated by particles of small size and mass. In addition, the inter-day and intra-day variability of PNC of the mobile measurements is expressed in Fig. 2 by showing box plots of median and mean PNC values for all 43 Routes A.

The results confirm consistently elevated PNC levels in the ambient air, with three median values exceeding $10^4 cm^{-3}$ ($10,333 cm^{-3}$ on 05.07.2023 morning, $12,044 cm^{-3}$ on 10.07.2023 morning; $11,975 cm^{-3}$ on 13.07.2023 afternoon). In addition, the box-plots representation (Fig. 2) points out substantial intra-day variability, particularly during the first half of the measurement campaign (up to 10.07.2023 morning). This pattern suggests that ambient PNC was strongly influenced by multiple short-term emission events and/or local hotspots with high PNC peaks followed by moderate or even low values. The variability was even more pronounced during the first half of the campaign until 10.07 morning than in the second half from 10.07.2023 midday until end of the campaign.

Although substantial intra-day variability occurred on individual dates, no consistent morning, midday, afternoon or evening pattern was apparent across the campaign. Similarly, no repeatable week-day-weekend pattern was evident, indicating that typical urban rush-hour effects played a minor role due to low emissions and/or high emission dispersion by wind. The direction and magnitude of intra-day changes differed among dates, indicating that temporal variability was driven mainly by changing source activity and meteorological conditions rather than by a stable diurnal cycle. Overall, PNC proved to be a more sensitive indicator of short-term air pollution events than PM_x . Identification of the corresponding emission sources requires detailed, spatio-temporally resolved analysis of the repeated surveys presented in Section 3.2.

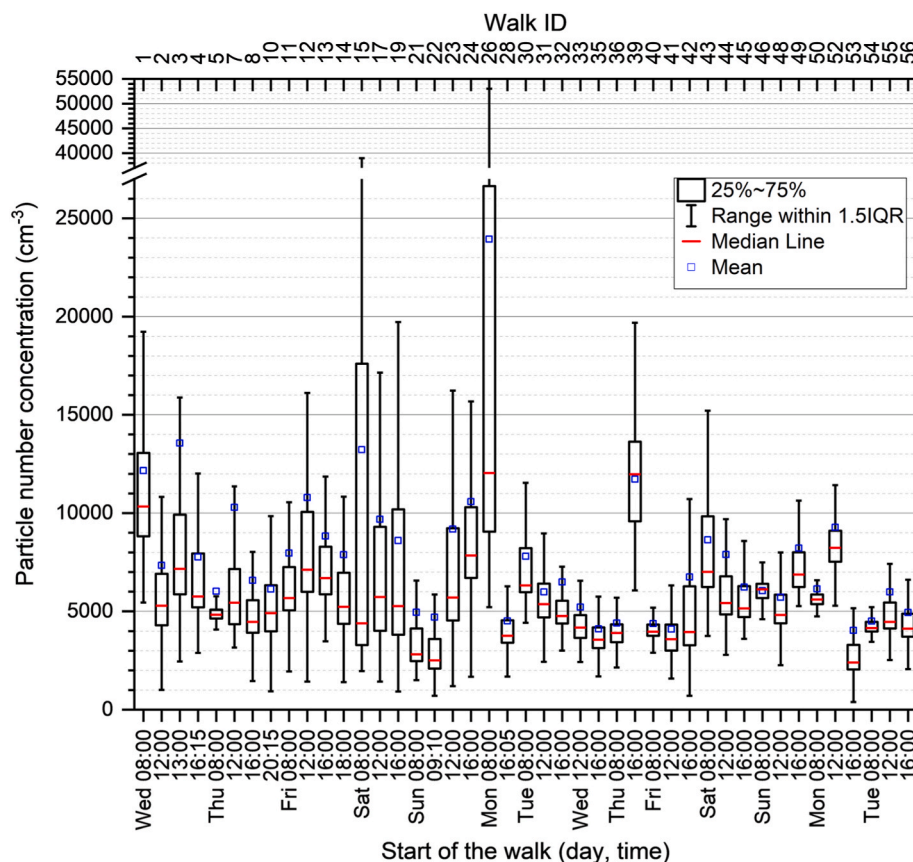


Fig. 2. Box-plots of median and mean PNC from all measurements along route A ($n = 43$), demonstrating the inter-day and intra-day variability during the measurement campaign (Wednesday 05.07.2023 to Tuesday 18.07.2023).

3.2. Campaign-wide spatiotemporal variability and specific PNC events

3.2.1. Spatio-temporal variability and patterns along Route A

To distinguish campaign-wide spatiotemporal patterns from variability among individual surveys, PNC measurements from all 56 walks were harmonized along the common Route A (Fig. 1). The 13 surveys that included Route B were retained because they also covered Route A. Measurements from the additional Route B sections were excluded from this analysis. Fig. 3 presents the median PNC for every valid walk-segment combination, with each row representing one survey and each column representing one 20 m route segment (see section 2.2.3).

The heat map provides complementary information on temporal and spatial variability. Broad horizontal bands indicate walks during which PNC was generally elevated or reduced over large parts of the route, whereas vertically aligned elevated cells indicate route sections where increased PNC recurred during multiple surveys (potential hotspots). Because each cell represents a 20 m segment median, the visualization emphasizes spatially recurrent patterns while reducing the influence of individual 1-s peaks caused, for example, by a passing smoker, a single vehicle or a brief direct plume interception.

The heat map shows substantial variability both among walks and along the route. Several surveys exhibited generally increased PNC over extended route sections, whereas other surveys remained predominantly within the lower concentration classes. This demonstrates that the concentration measured at a given location depended not only on the surrounding microenvironment but also on time-dependent conditions, including source activity, wind direction and whether the walking route intersected an individual plume. Generally, there was no statistically identifiable difference in the Route A medians among the walks conducted during morning, midday, afternoon and evening. However, during specific days, intra-day variability is visible with various

patterns. There was also no statistically identifiable overall day-of-week difference from the 56 surveys restricted to their common Route A section.

Nevertheless, several vertically aligned features indicate recurrent spatial patterns. Elevated concentrations were repeatedly observed near the beginning of the route along the Seepromenade, along parts of the Alter Strom commercial promenade, and near the Mittelmole and Warnow ferry approach. In contrast, the Kurpark section generally remained within the lower concentration classes. Elevated concentrations around the cruise terminal were less spatially and temporally consistent, with individual strong events occurring during only part of the campaign, when the cruise ships were present.

To characterize the upper part of the concentration distribution without allowing a single extreme survey to determine the spatial pattern, the P90 of the walk-specific segment medians was calculated for each 20 m route segment (Fig. 4). Thus, the P90 map identifies locations that experienced elevated concentrations during a meaningful proportion of the repeated surveys, while isolated maximum events are considered separately in Section 3.2.3.

The highest P90 values occurred within approximately the first 200 m of the Seepromenade, identifying this section as the strongest campaign-wide upper-tail hotspot. Field observations documented several temporary food stalls using charcoal/wood grills at this location during Warnemünde Week, together with a high density of visitors and associated service activity. From Walk 26 onward (see Fig. 3), the median PNC for the broader Seepromenade zone decreased from $6.90 \times 10^3 \text{ cm}^{-3}$ during Warnemünde Week to $4.95 \times 10^3 \text{ cm}^{-3}$ outside the event period (Table 2), which supports the observation that these temporary sources were major contributors to the hotspot. The hotspot therefore cannot primarily be attributed to maritime emissions.

Elevated P90 values also occurred along Alter Strom (Route Zone 2),

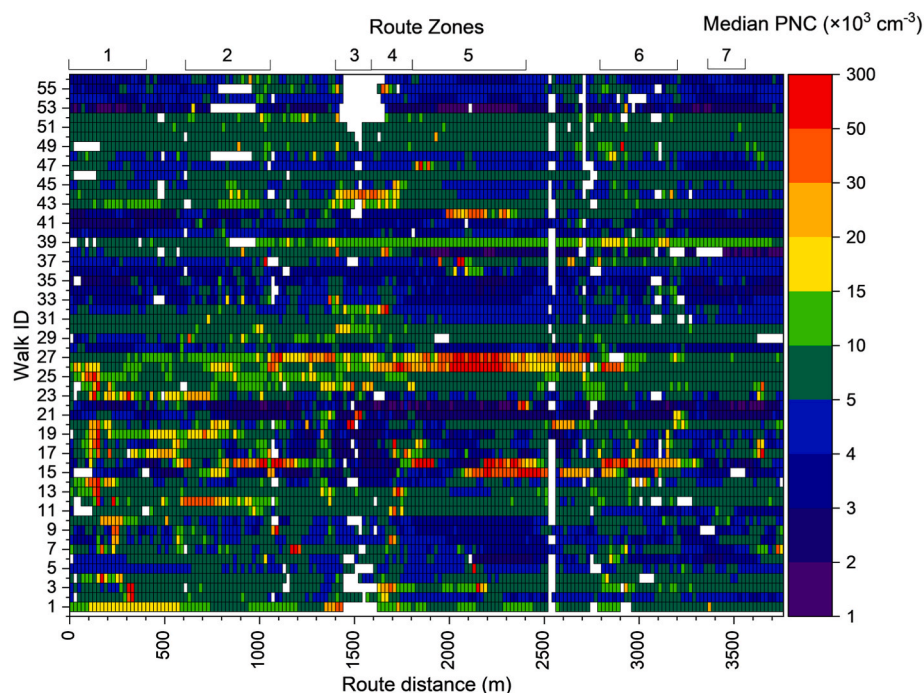


Fig. 3. Walk-by-distance heat map of median particle number concentration (PNC) for 56 repeated mobile surveys along the common Route A. The route was divided into consecutive 20 m segments, and each cell represents the median of valid 1 s PNC for one walk–segment combination. Only combinations containing at least three valid measurements are displayed. White cells indicate missing or insufficiently populated combinations, resulting mainly from route deviations. PNC is expressed as $\times 10^3 \text{ cm}^{-3}$. Numbers above the heatmap indicate predefined route zones: 1, Seepromenade; 2, Alter Strom commercial promenade; 3, Mittelmole outside the ferry terminal; 4, Warnow ferry terminal; 5, cruise-terminal vicinity; 6, Warnemünde city centre; and 7, Kurpark green-space reference (Table 2). The horizontal line between Walks 25 and 26 separates surveys conducted during and outside Warnemünde Week, respectively. Walk-specific measurement details are provided in Table S1.



Fig. 4. Spatial distribution of the 90th percentile (P90) of walk-specific median particle number concentration (PNC) along the common Route A. For each route segment, P90 was calculated across all contributing walks after excluding walk-segment combinations containing fewer than three valid 1 s measurements. The number of contributing walks varied locally because of route deviations and spatial-assignment limitations. PNC is expressed as $\times 10^3 \text{ cm}^{-3}$. Numbers indicate predefined route zones: 1, Seepromenade; 2, Alter Strom commercial promenade; 3, Mittelmole outside the ferry terminal; 4, Warnow ferry terminal; 5, cruise-terminal vicinity; 6, Warnemünde city centre; and 7, Kurpark green-space reference (Table 2).

where several potential sources coincided, including permanent food-selling boats, restaurants, smokers and small-vessel activity. Influence from vessels navigating the channel cannot be excluded. Median zone

PNC was descriptively higher during Warnemünde Week than afterward, at 6.66 versus $5.66 \times 10^3 \text{ cm}^{-3}$, while the corresponding P90 values were 12.27 and $9.17 \times 10^3 \text{ cm}^{-3}$. This difference is consistent

with increased local activity during the festival but cannot be separated fully from temporal and meteorological differences between the two periods.

Among the maritime zones, the Warnow ferry terminal (Route Zone 4) represented the clearest recurrent ship-related hotspot. Its elevated P90 was consistent with repeated but intermittent plume encounters, because the ferry was not necessarily present at the terminal when each survey passed this section, and plume interception also depended on wind direction.

The cruise-terminal vicinity (Route Zone 5) showed a more heterogeneous pattern. Some segments and walks exhibited pronounced upper-tail concentrations, whereas much of the zone remained within moderate P90 classes. This pattern indicates episodic influence from cruise ships, terminal buses, taxis, service vehicles, passing vessels and other harbour activities rather than a uniformly persistent hotspot.

Overall, the aggregated maps show that maritime traffic contributed to repeated short-term PNC enhancements, particularly around the Warnow ferry and during selected cruise-terminal situations. However, the strongest campaign-wide hotspot was associated with proximity to the cooking combustion emissions during the specific outdoor event. The results also illustrate relatively high spatio-temporal variability of PNC within a relatively small area.

3.2.2. Comparison of predefined microenvironments

Warnemünde Week summer festival (01.-09.07.2023; [Warnemünde Week, 2023](#)), coincided with the first 25 surveys. The event included sailing regattas and other cultural events and attracted large numbers of visitors. Field observations documented increased local activity, including temporary food stalls, including charcoal- and wood-fired grills, sales booths and increased service activity along the Seepromenade ([Fig. 4](#), Zone 1).

[Table 2](#) shows statistics of selected parameters for Route Zones. More parameters are provided in the SI ([Table S2](#)). The predefined microenvironment analysis showed substantial differences in both typical PNC levels and upper-tail concentrations (P90) among route sections ([Table 2](#)). This comparison was based on walk-specific zone medians, thereby assigning equal statistical weight to each survey regardless of walking speed, stopping duration or the number of valid 1-s observations within a zone. The Seepromenade exhibited higher PNC during Warnemünde Week than outside the event period (median PNC: +39%; P90 PNC: +50%; walks exceeding $10 \times 10^3 \text{ cm}^{-3}$: 24.0% vs. 6.5%), whereas the maritime zones were characterized primarily by elevated upper-tail concentrations and occasional high-concentration events. In contrast, $\text{PM}_{2.5}$ medians varied only narrowly among the selected zones.

Alter Strom had the second-highest typical PNC among the zones, with a median of $5.87 \times 10^3 \text{ cm}^{-3}$ and a P90 of $10.80 \times 10^3 \text{ cm}^{-3}$. This is consistent with its function as a mixed commercial and transport microenvironment rather than a purely maritime source zone. The Mittelmole section outside the ferry terminal and the Warnow ferry terminal had moderate medians of 5.02 and $5.17 \times 10^3 \text{ cm}^{-3}$, respectively, but comparatively high P90 values of 12.30 and

$11.94 \times 10^3 \text{ cm}^{-3}$. Moreover, 16.3% and 14.3% of walks in these two zones exceeded $10 \times 10^3 \text{ cm}^{-3}$. The contrast between moderate median and elevated upper-tail statistics indicates intermittent plume influence rather than continuously elevated concentrations.

The cruise-terminal vicinity had the lowest median PNC among the non-reference urban and maritime zones, at $4.92 \times 10^3 \text{ cm}^{-3}$, but a substantially higher P90 of $11.52 \times 10^3 \text{ cm}^{-3}$. This pattern is consistent with occasional high-concentration events occurring under particular combinations of vessel activity, terminal traffic and meteorological conditions. It therefore supports interpretation of the cruise-terminal area as an episodic rather than persistent hotspot. The selected event analyses in [Section 3.2.3](#) provide examples of such conditions.

The Warnemünde city-centre zone had a median PNC of $5.84 \times 10^3 \text{ cm}^{-3}$ but a lower P90 of $8.82 \times 10^3 \text{ cm}^{-3}$, indicating moderately increased but less extreme conditions. The Kurpark green-space reference had the lowest P90, $7.84 \times 10^3 \text{ cm}^{-3}$, and only 1.8% of walks exceeded $10 \times 10^3 \text{ cm}^{-3}$. This supports its use as the comparatively low-exposure reference zone.

In contrast to PNC, median $\text{PM}_{2.5}$ concentrations varied only narrowly among the selected zones, from 2.14 to $2.59 \mu\text{g m}^{-3}$. The $\text{PM}_{2.5}$ difference between the Seepromenade during and outside Warnemünde Week was also small, at 2.59 compared with $2.55 \mu\text{g m}^{-3}$. Thus, the pronounced spatial and event-related differences apparent in PNC were not reflected to the same extent by particle mass.

Median LDSA showed greater spatial variation than $\text{PM}_{2.5}$ and was highest at the Seepromenade during Warnemünde Week, at $17.60 \mu\text{m}^2 \text{ cm}^{-3}$, compared with $12.62 \mu\text{m}^2 \text{ cm}^{-3}$ outside the event period. Alter Strom and the city-centre zone also showed comparatively elevated median LDSA values of 15.55 and $15.19 \mu\text{m}^2 \text{ cm}^{-3}$, respectively. These findings indicate that particle-number- and surface-area-based metrics were more responsive to local combustion-related and event-related variability than $\text{PM}_{2.5}$ mass during this campaign.

The dependence of concentrations in the cruise-terminal and surrounding urban zones on cruise-ship presence and meteorological conditions is evaluated separately in [Section 3.2.3](#).

3.2.3. Cruise-ship presence, meteorological context and spatial influence

Cruise ships were scheduled at berths P7 and/or P8 during at least part of 32 of the 56 surveys, including 17 walks with one ship and 15 walks with two ships ([Table S3](#)). Cruise-ship presence alone was not associated with a systematic increase in the Zone 5 ([Fig. 4](#)) median: the corresponding medians were $5.07 \times 10^3 \text{ cm}^{-3}$ without a docked cruise ship, $4.36 \times 10^3 \text{ cm}^{-3}$ with one ship, and $5.67 \times 10^3 \text{ cm}^{-3}$ with two ships. Nevertheless, the four highest Zone 5 walk medians, ranging from 24.67 to $45.58 \times 10^3 \text{ cm}^{-3}$, occurred during Walks 15, 16, 26 and 27, when two cruise ships occupied berths P7 and P8. In contrast, other walks with one or two docked ships showed moderate or low concentrations, and elevated Zone 5 concentrations also occurred during some surveys without a docked cruise ship. These findings demonstrate that the presence or number of docked ships alone was insufficient to explain terminal-area PNC.

Table 2

Particle number concentration (PNC; $\times 10^3 \text{ cm}^{-3}$), $\text{PM}_{2.5}$ ($\mu\text{g m}^{-3}$), and lung-deposited surface area (LDSA; $\mu\text{m}^2 \text{ cm}^{-3}$) concentrations in predefined Route A microenvironments. Statistics were calculated across walk-specific zone medians. Only walk-zone combinations with valid measurements for at least 50% of the corresponding 20 m route segments were retained. Warnemünde Week was defined as 1–9 July 2023, inclusive. N refers to the number of valid PNC walk-zone combinations.

Zone	Distance (m)	n	Median PNC (P25–P75)	P90 PNC	Walks $\geq 10\text{k}$ PNC (%)	Median $\text{PM}_{2.5}$	Median LDSA
1A) Seepromenade —during Warnemünde Week	0–400	25	6.90 (4.83–9.97)	12.11	24.0	2.59	17.60
1B) Seepromenade —outside Warnemünde Week	0–400	31	4.95 (3.67–5.77)	8.09	6.5	2.55	12.62
2) Alter Strom commercial promenade	600–1060	55	5.87 (4.67–7.95)	10.80	14.5	2.54	15.55
3) Mittelmole outside ferry terminal	1400–1600	49	5.02 (3.78–7.80)	12.30	16.3	2.14	13.46
4) Warnow ferry terminal	1600–1800	56	5.17 (4.18–7.22)	11.94	14.3	2.27	13.93
5) Cruise-terminal vicinity	1800–2400	56	4.92 (3.96–6.35)	11.52	10.7	2.14	13.39
6) Warnemünde city centre	2800–3200	56	5.84 (4.56–6.73)	8.82	7.1	2.27	15.19
7) Kurpark/green-space reference	3360–3560	56	4.93 (3.81–5.99)	7.84	1.8	2.25	14.05

Because cruise-ship exhaust is emitted from elevated stacks, the location of maximum near-ground influence depends on plume rise, advection, atmospheric stability and turbulent mixing, and may occur some distance downwind rather than immediately adjacent to the berth (Seinfeld and Pandis, 2016). Hovorka et al. (2026) measured approximately 100-fold increases in the number concentration of 5–340 nm particles at distances of 20–600 m behind cruising ships, with plume expansion and turbulent dilution governing their early evolution. Therefore, the cruise-ship influence was evaluated not only in the immediate cruise-terminal vicinity (Zone 5) but also in Alter Strom (Zone 2) and the Warnemünde city centre (Zone 6).

A descriptive comparison indicated that ship-present surveys with easterly-to-southeasterly winds were more likely to show increased PNC in the terminal and surrounding urban zones. The clearest example was Walk 16 (Fig. S19), when two cruise ships were docked and winds were predominantly easterly. Median PNC reached $31.49 \times 10^3 \text{ cm}^{-3}$ in the cruise-terminal zone, $30.92 \times 10^3 \text{ cm}^{-3}$ in the city-centre zone and $26.61 \times 10^3 \text{ cm}^{-3}$ along Alter Strom, while the Kurpark reference remained at $2.99 \times 10^3 \text{ cm}^{-3}$. Field observations also recorded a visible plume and exhaust odour toward the urban area. For this reason, the Walk 16 (Fig. S19) was extended along the whole Alter Strom channel, and high PNC was observed. As unusually elevated PNC were observed up to the beginning of the Kurpark (Zone 7), it is expected that larger residential area downwind the cruise ships were affected during this particular event. Nevertheless, similarly oriented winds did not produce increased concentrations during every ship-present survey, indicating that vessel operating conditions, atmospheric dispersion/mixing and other factors were also important. Based on the observation, the cruise ships were moored and idling during the whole day. Therefore, this particular event could have been avoided if the cruise ships used available electricity connections instead of generating electricity by the engines. Note that contribution of other sources cannot be fully distinguished without chemical or other specific analysis.

A descriptive comparison using walk-specific meteorological medians (Table S1) indicated that elevated cruise-terminal PNC depended strongly on wind direction. The four highest Zone 5 walk medians occurred at wind directions of approximately $70\text{--}160^\circ$ and relatively low wind speeds of $2.1\text{--}2.6 \text{ m s}^{-1}$. Across the six ship-present walks with median wind directions between ca. 60° and 170° , the median PNC was $28.08 \times 10^3 \text{ cm}^{-3}$ in Zone 5 and $8.27 \times 10^3 \text{ cm}^{-3}$ in Zone 6, compared with $4.42 \times 10^3 \text{ cm}^{-3}$ and $5.45 \times 10^3 \text{ cm}^{-3}$, respectively, during ship-present surveys with other wind directions. These results indicate that higher near-ground PNC was more likely when the Route A sections in Warnemünde were located downwind of the cruise terminal. However, similarly oriented winds did not produce elevated concentrations during every ship-present survey, confirming that vessel operating conditions, plume rise, atmospheric mixing and the timing of plume interception were also important.

Continuous 10 min DWD observations during the campaign further showed that winds capable of transporting emissions from the cruise-terminal area toward Warnemünde, defined here as approximately $60\text{--}170^\circ$, occurred during 30.8% of the campaign period. Winds capable of transporting emissions across the navigation channel toward Hohe Düne, approximately $210\text{--}285^\circ$, were more frequent and accounted for 41.9% of the period. The remaining 27.3% comprised mainly along-channel or other directions that did not clearly place either residential area directly downwind of the terminal. These campaign-specific frequencies demonstrate that measurements restricted to Route A on the Warnemünde side would not characterize potential downwind concentrations on the opposite side of the channel under a substantial proportion of the observed meteorological conditions. Route B was therefore used during selected surveys to investigate the Hohe Düne pier and nearby residential area. Representative Route B plume encounters are presented in Section 3.2.4.

3.2.4. Selected source-related concentration events

The aggregated spatial analysis identified recurrent and intermittent spatial patterns but cannot by itself distinguish the sources responsible for individual concentration events. Also, the real pollutant peaks in 1–10 s resolution are shown, some of which would not be visible in the previous approach due to averaging. Moreover, aggregation into 20 m segment medians reduces the influence of brief concentration peaks and therefore does not fully describe the rapid pollutant dynamics occurring during direct plume encounters. Such short-duration enhancements can contribute substantially to the inhaled particle-number dose, particularly when PNC increases by one or more orders of magnitude above background. Although the adverse health relevance of ultrafine-particle exposure is well established, the specific toxicological importance of individual second-scale ambient peaks remains insufficiently characterized (Cassee et al., 2019). The following surveys are therefore presented as real-world examples illustrating how vessel activity, road traffic, smokers and meteorological conditions affected the measured pollutant dynamics. These cases are not assumed to be representative of every survey; their interpretation is supported by the campaign-wide results in Sections 3.2.1 and 3.2.2. Fig. 5 presents Walk 26 on 10 July 2023, and Fig. 6 presents Walk 47 on 16 July 2023. Maps of all 56 walks are provided in Figs. S4–S59.

During route A 26 on Monday 10.07.2023 (Fig. 5A), a generally elevated level of PNC can be observed. The background PNC was approximately in the range of $10,000 \text{ cm}^{-3}$, the highest of all 56 walks, see also Fig. S4 and following. The median PNC reached $12,044 \text{ cm}^{-3}$ (Table S1, Fig. 2). Moderate winds (mainly 2.6 to 3.4 m s^{-1}) were blowing from south-southeast. After the start of the route, short and moderate increases of PNC (ca. $20,000 \text{ cm}^{-3}$) were detected along the road “Seepromenade” and near the small channel “Alter Strom”. In general, only little road traffic was observed, but cleaning and waste collection activities on the streets were observed, probably linked to the finished Warnemünde Week the day before. PNC increased when crossing the bridge over the channel “Alter Strom” (08:10–08:11). On 08:15, a passenger tourist boat Baltica (47 m length, 8 m width, 378 gross tonnage, powered by two six-cylinder four-stroke diesel engines (IMO number 5302063, www.vesselfinder.com) departed from a nearby pier close at the harbour entrance (see Fig. 5A). Due to the prevailing wind direction, this maneuver had no influence on the results. At 08:19, the Warnow ferry departed the Warnemünde jetty, causing a short but distinct peak of PNC up to ca. $60,000 \text{ cm}^{-3}$. The vessels, two diesel-powered small car ferries, operate continuously from 4 a.m. till 11 p.m. with 20 min intervals that increase to 10 min during peak season, which was also during the time of our measuring campaign. Overnight service runs every 30 min (Weiße Flotte, 2025). The exhaust outlet is located only a few meters above water level, considerably lower than that of larger ships, which facilitates direct dispersion of emissions into the pedestrian breathing zone. During the campaign, a predominantly local increase in PNC was observed due to Warnow ferry service, with its magnitude depending mainly on wind direction.

The route continued towards the Warnemünde Cruise Centre, where two large cruise ships were moored at docks P7 and P8 (vessel #1: 228 m length, 29 m width, 47,800 gross tonnage; vessel #2: 300 m length, 35 m width, 100,000 gross tonnage). Such large vessels typically feature tall exhaust stacks, allowing plumes to disperse over longer distances before reaching ground level. Additionally, increased road traffic (buses and taxis) was observed in this area. PNC reached two short maximum peaks above $260,000 \text{ cm}^{-3}$, followed by decrease to ca. $60,000 \text{ cm}^{-3}$ for a few minutes and then further to ca. $20,000 \text{ cm}^{-3}$ until it increased again for a few minutes up to ca. $50,000 \text{ cm}^{-3}$. After this, PNC stabilized at ca. $10,000 \text{ cm}^{-3}$ until the end of the route. The prevailing wind direction let us assume that all these ship and road traffic activities strongly influenced the PNC results, and therefore, the ambient air quality in large parts of the measurement area.

During Route B-47 (Fig. 6) on Sunday 16.07.2023, the situation was different. Background PNC levels were below 3000 cm^{-3} , whereas the

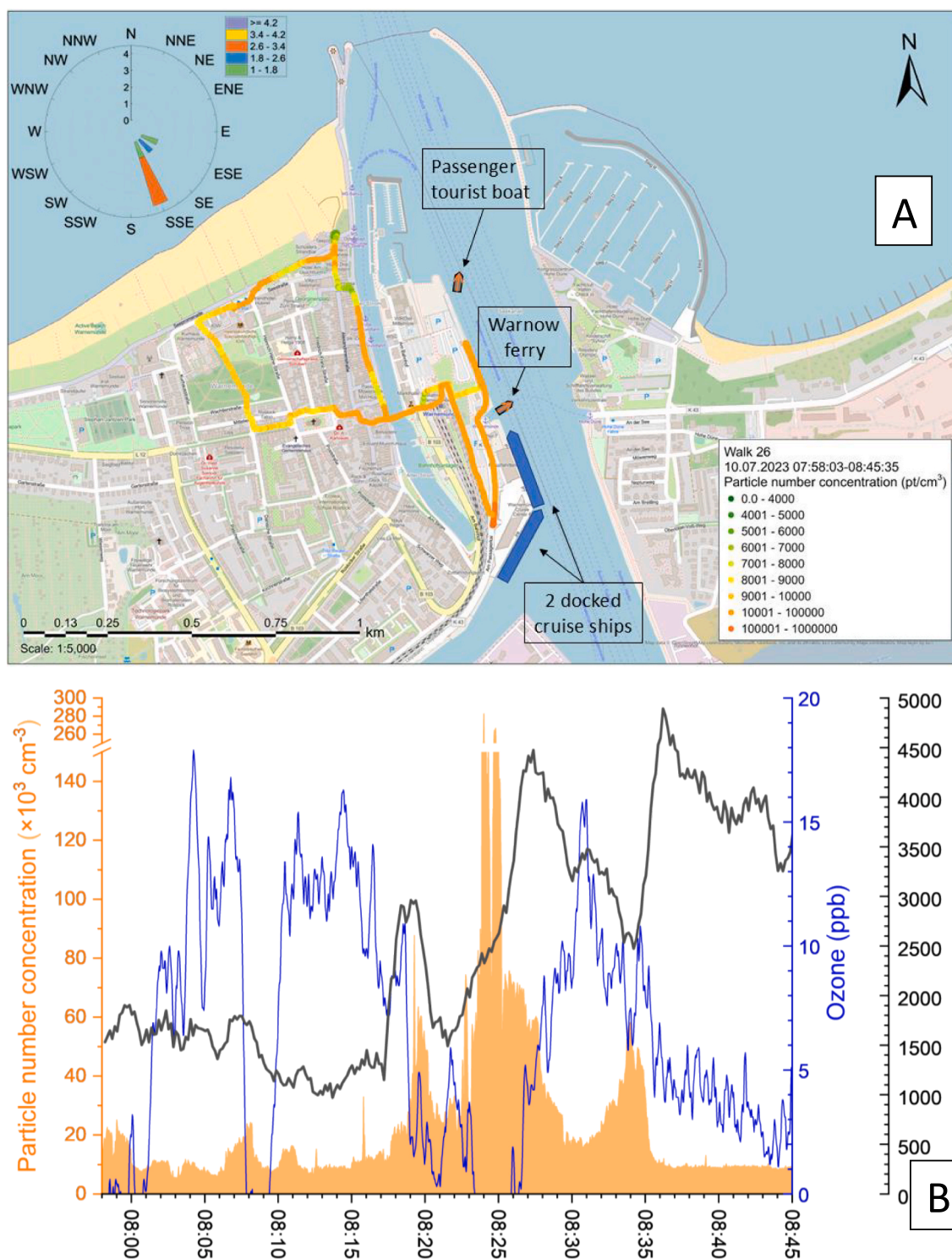


Fig. 5. A: Spatio-temporally resolved PNC data of route A (walk 26, 10.07.2023 morning), including the corresponding wind rose and ship-traffic situation with two docked cruise ships, operating Warnow ferry. During the period, several other boats were passing the channel. B: Dynamics of PNC, ozone and eBC concentration during the walk. 60 s moving averages are plotted.

whole-walk median was 5257 cm^{-3} (see Table S1). Two docked cruise-ships (vessel #1: 223 m length, 31 m width, 56,200 gross tonnage; vessel #2: 253 m length, 38 m width, 71,300 gross tonnage) were docked at the Warnemünde Cruise Centre (berths P7 and P8). Prevailing winds averaged 5 to 6 m s^{-1} from the south-southwest. Consequently, no distinct emission-related events were detected in Warnemünde city prior to 9:36, when the cigarette smoker walked past the operator.

Crossing the estuary by the Warnow ferry, PNC featured many

intensive peaks up to ca. $180,000 \text{ cm}^{-3}$. Moreover, at 9:58, a cargo vessel (153 m length, 21 m width, 10,500 gross tonnage) passed downstream towards the Baltic Sea, causing similar PNC values detected along the pier of Hohe Düne until close to the yacht harbour, where results decreased again to background levels. Shortly after reversing at the yacht harbour PNC re-increased and remained at high levels with several signal peaks up to $160,000 \text{ cm}^{-3}$ along the pier of Hohe Düne and at a residential area close by except at the southernmost part of the

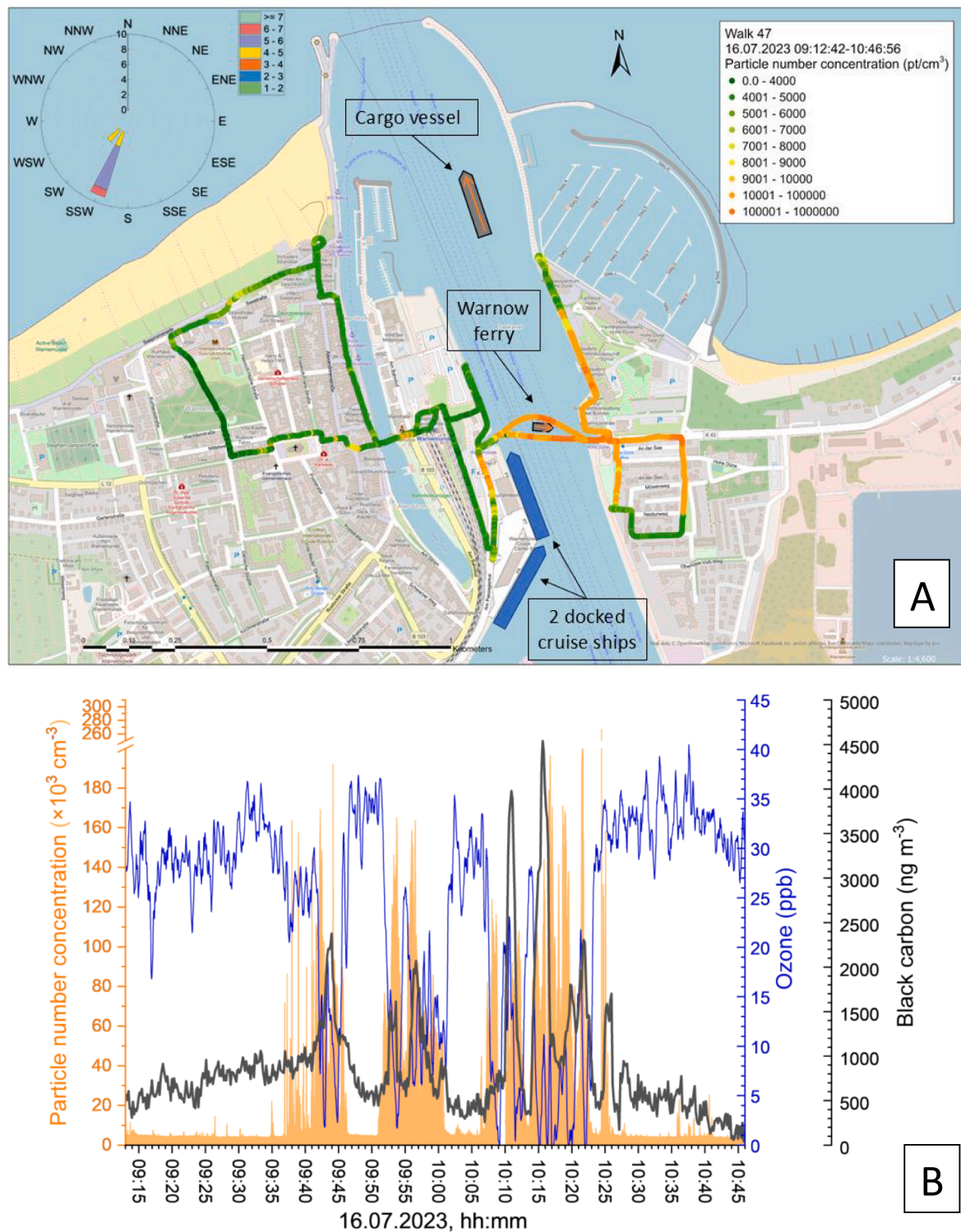


Fig. 6. A: Spatio-temporally resolved PNC data from route B (walk 47, 16.07.2023 late morning), including the corresponding wind rose and ship-traffic situation with two docked cruise ships, the operating Warnow ferry, one passing large cargo vessel and small boats passing the channel. B: Dynamics (60 s moving average) of PNC, ozone and eBC concentration during the walk.

residential area, where PNC dropped to below 4000 cm^{-3} . PNC showed again significant peak concentrations when getting closer to the ferry jetty of Hohe Düne with maxima of up to $250,000 \text{ cm}^{-3}$ when entering the Warnow ferry and during the crossing back. Short-term elevated PNC levels were also detected between the ferry jetty of Warnemünde and the Warnemünde Cruise Centre. After having passed this, measured parameters decreased to background levels and remained at this until

the end of the route.

The results during the prevailing winds (south-southwest) suggest that people on the Warnow ferry and along the pier towards the yacht harbour were significantly exposed to exhaust emissions from the ferry itself and the two docked cruise-ships. People in the residential area south-east from the Hohe Düne ferry jetty were also exposed to emissions but during our measurements the docked cruise-ships had a larger

impact than the Warnow ferry. The passed cargo vessel could also have played a role, however, passing vessels have only a short time effect, while moored cruise ship can pose a stable source of emissions over the docked period, when producing electricity by continuously running the on-board engines.

The stroller-based portable measurement platform can also be deployed for short-term stationary monitoring and ship plume characterization at selected locations, in addition to its capability for mobile, spatio-temporally resolved pollutant measurements. Since the location is fixed, it is possible to focus on passing ships and compare the peaks of their emission plumes. Stationary ship plume measurements in Warnemünde have been conducted previously (Rosewig et al., 2024), however, the biggest advantage of using the stroller platform is its portability and effectivity in terms of the time and manpower. The stroller can be also easily transferred to various locations for short-term stationary monitoring. Therefore, it can also act as a suitable tool for determining the appropriate and representative location for a long-term measuring station. With proper documentation of passing vessels or the use of Automatic Identification System (AIS) data, individual plumes can be reliably attributed to specific ships, if no other emission sources are present in the immediate vicinity. In the following section, stationary measurements at the pier of Hohe Düne on 06.07.2023 from 18:00 till 18:50 (as part of a Route B-9) are exemplarily shown and discussed (Fig. 7). Apart from PNC, O₃ and eBC concentrations are illustrated.

Background concentrations at the beginning of the stationary measurements (Fig. 7) were approximately 3000 cm⁻³ PNC, <500 ng m⁻³ eBC, and around 35 ppb for O₃. At 18:05, a diesel-electric cruise-ship (253 m length, 32 m beam, 71,304 gross tonnage, installed power 36 MW) departed the dock (1.2 km distance) and slowly passed the observation site, resulting in an immediate short-term PNC increase of up to 200,000 cm⁻³ directly after it passed the measurement point in ca. 100 m distance. It was followed by several small tourist boats (up to ~20 m in length), whose contributions were considered minor based on their previously observed emission signatures.

Shortly after the cruise ship passed by, a helicopter circled above and around the vessel at low altitude, possibly contributing to a transient PNC peak of almost 40,000 cm⁻³. Along with the increase of PNC, eBC concentration also rose, however, the eBC maximum of ca. 3500 ng m⁻³ occurred with a delay of about 2–3 min. This delay likely reflects

differences in particle size and composition between freshly emitted ultrafine particles (dominating PNC) and larger soot aggregates. It is unlikely that the lag was caused by the Aethalometer response-time, as PNC and eBC peaks coincided during other ship plume events (e.g. at 18:45).

As the cruise ship was maneuvering away from the nearby dock, the offset likely resulted from transient plume dynamics associated with variable engine load. During low load operation, nucleation-mode particles might dominate (high PNC), followed by enhanced soot formation as engine load and exhaust temperature increase or additional engines are engaged. Furthermore, soot particles may have arrived later than ultrafine particles due to their distinct physical behavior and dispersion characteristics.

In parallel with the PNC increase, O₃ concentrations dropped rapidly to zero and near-zero levels. This ozone depletion can be attributed to titration of NO present in the diesel exhaust plume (not directly measured in this study), which, in turn, reacts immediately with atmospheric O₃ to form NO₂ and O₂ (Seinfeld and Pandis, 2016).

Within minutes, the concentration of O₃ recovered to the initial levels in the atmosphere, indicating the end of the fresh plume. The same trend, but to a lower extent, was observed when other vessels passed by e.g. at 18:25 (small tanker; 73 m length, 11.5 m beam, 1,236 gross tonnage, 1,492 kW engine with direct propeller), 18:40 (hybrid ferry; 169.5 m length, 24.8 m beam, 24,000 gross tonnage), and 18:45 (large crude oil tanker; 245 m length, 42 m beam, 59,611 gross tonnage). Latter passage was additionally accompanied by parallel short-term increases of PNC (ca. 80,000 cm⁻³) and eBC (>2000 ng m⁻³), whereas the passage of the hybrid ferry entailed a depletion of O₃ but only a moderate increase of PNC (ca. 20,000 cm⁻³) and no detectable rise of eBC. Hybrid ferries have a battery pack retrofitted at one of the diesel-powered generators. The battery pack is charged at open sea operation when generators work most efficiently. In port, the battery pack, in turn, powers the electric powertrain and less power from the diesel engines is required (Scandlines, 2025). As a consequence, PNC and eBC emission were significantly reduced, however, NO emissions from the remaining diesel-powered engines seemed to be still sufficient to notably deplete O₃.

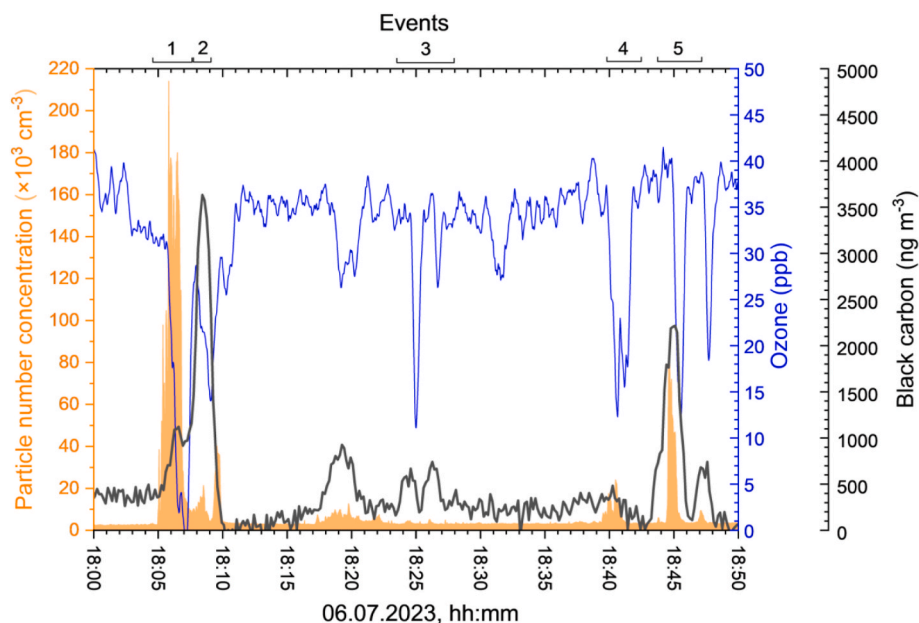


Fig. 7. Dynamics (60 s moving average) of PNC, O₃ and eBC during stationary measurements using a mobile monitoring platform at the end of the Hohe Düne pier (GPS: 54.186981, 12.091515) for emission characterization of passing ships, 06.07.2023. Event 1 represents “cruise ship and small boat”, 2: “helicopter passing”, 3: “small cargo ship”, 4: hybrid ferry, 5: large cargo ship.

3.2.5. Source signatures, co-pollutants and limitations

The selected events showed that fresh combustion plumes were most clearly identified by rapid increases in PNC, frequently accompanied by increased eBC and, in several ship-plume encounters, a simultaneous decrease in O₃. The O₃ depletion is consistent with rapid titration by NO in fresh exhaust, although NO_x was not measured directly in this study (Seinfeld and Pandis, 2016). Short, highly localized peaks associated with smokers or individual vehicles were generally distinguishable from maritime plumes by their limited spatial extent and field observations. The repeated near-source peaks observed at the Warnow ferry were consistent with its low exhaust outlet and frequent operation, whereas emissions from cruise ships and larger passing vessels could influence broader downwind areas following plume rise, advection and turbulent atmospheric mixing.

PNC was more responsive to these combustion-related events than PM mass. Median PM_{2.5} varied only narrowly among the predefined zones, whereas PNC and LDSA showed pronounced spatial and event-related differences. This is consistent with Hovorka et al. (2026), who observed strongly enhanced sub-micrometer PNC in ship plumes at distances of up to several hundred meters behind cruising vessels, while the corresponding increase in supermicrometer particle mass was comparatively small. Ship-related particle-number enhancements may therefore remain poorly represented by PM_{2.5} or PM₁₀ mass alone. Direct comparison between the mobile OPS-derived PM concentrations and rooftop APDA-372 measurements is additionally limited by the different sampling heights, measurement principles, averaging intervals and sampled air masses, so these data are treated as complementary rather than directly comparable.

Increases in eBC provided supporting evidence of soot-containing combustion aerosol, although their magnitude differed among events, probably because of differences in vessel type, fuel, engine load, plume age and atmospheric dilution. More robust characterization of source-specific emission signatures would require repeated measurements under comparable operating and meteorological conditions, ideally including longer stationary sampling periods at fixed locations. In our study, eBC is an optically derived equivalent mass and was measured without a size-selective inlet; it should therefore not be expected to exhibit direct mass closure with OPS-derived PM_{2.5}. UVPM showed increased values during several surveys with elevated combustion-related activity, including a maximum whole-walk median of 2.3 µg m⁻³ during Walk 26. However, eBC and UVPM were used only as supporting indicators rather than for quantitative source attribution. At the 10 s acquisition interval, filter-based optical measurements can exhibit increased noise under the relatively low particle-loading conditions encountered during the campaign because the change in optical attenuation over each measurement interval is small (Liu et al., 2021). This limitation is particularly relevant while measuring low background concentrations.

Whole-walk LDSA was positively associated with PNC but not with PM_{2.5}. Because LDSA and PNC were obtained from the same DISCmini and LDSA depends partly on particle number and size, this relationship does not constitute independent confirmation.

Source attribution remains indicative rather than quantitative. Several potential sources often operated simultaneously, including cruise ships, the local ferry, passing vessels, road and terminal traffic, smokers and food-related activities. Cruise schedules documented vessel presence but not auxiliary-engine operation or engine load. Furthermore, NO_x, SO₂ and source-specific chemical tracers were not measured, and walk-level meteorological summaries may not capture short-term changes in wind direction during individual plume encounters. The campaign was limited to 14 summer days, and the Route B extensions were selected purposively rather than repeated in a standardized manner. The interpretations therefore rely on the combined consistency of spatial patterns, vessel timing, meteorological conditions, field observations and co-pollutant behaviour, rather than on any single source indicator.

The mobile inlet height of 1.0 m was below the typical breathing zone of a standing adult and was closer to the breathing height of children and seated adults, including wheelchair users. Because measurements immediately adjacent to low-level exhaust outlets represented only a limited subset of the dataset, the inlet-height difference is unlikely to have affected the campaign-wide spatial patterns.

4. Summary and conclusions

This study combined 56 repeated mobile surveys with rooftop stationary monitoring to characterize near-ground particle concentrations in Warnemünde and Hohe Düne during a 14-day summer campaign. Daily stationary PM_x concentration medians indicated generally low background PM mass levels during the campaign, whereas the walking measurements repeatedly detected short-duration, spatially localized enhancements in particle number concentration across several micro-environments. Campaign-wide aggregation using repeated 20 m route segments, spatial P90 values and predefined zones distinguished recurrent spatial patterns from isolated plume encounters and individual local events. Depending on wind direction, plume rise and atmospheric dispersion, emissions from ships—particularly larger vessels with elevated exhaust stacks—may influence near-ground concentrations at locations some distance downwind, including residential areas. Mobile monitoring should therefore complement fixed-site measurements in harbour environments, because a small number of stationary stations may not resolve short-lived plume encounters and fine-scale spatial variability across all potentially affected areas.

The following main contributors to elevated PNC were identified in Warnemünde and Hohe Düne:

- Temporary local events: Concentrations at the Seepromenade were higher during Warnemünde Week than outside the festival period, consistent with increased visitor numbers, road traffic, food preparation and other temporary activities. The specific festival during the sampling campaign takes place once per year and is localized, therefore, long-term health impact of affected people is supposed to be minimal. However, multiple similar events occur over the course of the year and increase the overall pressure on air quality.
- Cruise-terminal activity: with continuous use of engines for power generation, cruise vessels maintaining engine operation for on-board power generation were a source of elevated PNC when present. The elevated PNC was observed in both Warnemünde and Hohe-Düne residential areas. However, the elevated PNC strongly depends on meteorological situation. Due to the high-mounted exhaust stacks, engine emissions can travel longer distances and might affect direct surroundings as well as more remote areas like residential areas, confirmed by our measurements. Since the cruise terminal in Warnemünde is highly frequented in season (appr. 130 stops between mid-April and end-Dec 2023) and surrounded by residential areas as well as public places, full usage of shore power supply is strongly recommended, especially as it was available on site.
- Diesel-powered city ferry (Warnow ferry): The ferry connecting Warnemünde and Hohe Düne across the river Warnow produced short-term but frequent local PNC peaks due to its low exhaust outlet and high operating frequency. Modification to modern exhaust after-treatment or even better switching to electrical powertrain is highly recommended. The emission effect seems to be predominantly local due to the low-mounted, short exhaust stack. However, commuters and staff of the ferry might be strongly affected due to their frequent exposure. Additionally, the high frequency of ferry service exposes people in the immediate vicinity such as residents and tourists. Given that this was a near constant source of emissions, when present, its contribution must be considered for air quality assessments.
- Passing seagoing ferries and (large) vessels (cargo, tanker): The number of passing vessels is considerable but durations of each passage are in the framework of minutes. However, these ships also

feature high-mounted exhaust chimneys i.e. emissions can travel larger distances and might affect direct surroundings as well as more distant areas depending on engine type (e.g. hybrid ferry vs. conventional powertrain) and fuel used (MGO vs. scrubbed or low sulphur HFO). Therefore, IMO regulations should be tightened with respect to fuels used (no HFO even with applied scrubber systems or sulphur reduced) and exhaust abatement systems (regulation of PM, PN, HC, and CO in addition to SO₂ and NO_x).

Road traffic, terminal vehicles, smokers and food-related activities also produced highly localised concentration peaks. Overall, the study demonstrates that mobile, high-time resolution PNC and PM measurements are highly effective for identifying and characterizing dynamics, spatio-temporal variability of air pollution hotspots and sources such as road and maritime traffic. The presented approach enables plume tracking, identification of hot-spots and can be used for real-world personal exposure assessment in urban coastal environments, providing valuable information for future air quality management and mitigation strategies. Real air quality measurements should also accompany emission models for their verification and/or improvement.

CRedit authorship contribution statement

Jan Bendl: Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – original draft. **Sandra Piel:** Writing – review & editing, Visualization, Investigation. **Andreas Schüller:** Investigation. **Helena Osterholz:** Writing – review & editing, Project administration. **Thomas Adam:** Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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