



Long-duration shipboard performance of a humidity-conditioned optical particulate matter monitor along inter-polar transit routes: Antarctic inter-unit agreement and Arctic redeployment

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Abstract. Optical particulate matter (PM) measurements aboard ships are vulnerable to relative-humidity (RH)-dependent particle growth, sampling disturbances, and platform exhaust. We evaluated the long-duration field performance of the Tiny Aerosol Monitor with Tiny Aerosol Conditioner (TAM/TAC) using two co-deployed instruments during an Antarctic voyage and the subsequent Arctic redeployment of the same physical instrument (unit 70). The Antarctic loggers recorded every scheduled 10 min time step from 25 October 2022 to 3 May 2023 (27,342 records per unit), and unit 70 recorded every scheduled time step during the Arctic deployment from 21 June to 11 October 2023 (16,124 records). A prespecified quality-control rule excluded 50 Antarctic unit-70 records with nonzero instrument status codes, leaving 27,292 valid Antarctic pairs; unit 71 and the Arctic unit-70 dataset contained no flagged records. Across PM_{1.0}, PM_{2.5}, PM_{4.0}, and PM₁₀, Antarctic inter-unit correlations were 0.995–0.997, equal-variance Deming slopes were 0.992–1.033, and relative mean biases were –1.1 % to +2.1 %. Paired relative precision was 9.0–9.8 % for PM_{2.5}–PM₁₀ and 16.3 % for PM_{1.0}, for which the route-wide mean was only about 1.53 µg m^{–3}. In the polar subsets, TAC reduced mean ambient RH from 54.0 % to 32.2 % in the Antarctic and from 73.7 % to 34.5 % in the Arctic; internal RH was at or below 40 % for 99.99 % and 100 % of valid records, respectively. These results provide evidence of timebase continuity, inter-unit comparability, and repeatable humidity control across two extreme marine deployments. They do not establish absolute accuracy, inlet efficiency, or freedom from ship-exhaust contamination, which require a collocated reference instrument and ship-relative wind or exhaust-tracer measurements.

1 Introduction

Continuous observations of atmospheric particulate matter over remote oceans and polar regions are important for evaluating marine aerosol processes and for constraining aerosol–climate interactions. Optical PM measurements in these environments are difficult because hygroscopic particles grow as RH increases, altering particle size and light scattering. Physics-based evaluations and field studies have identified aerosol composition, refractive index, size distribution, and humidity as major sources of uncertainty in optical particle sensing (Hagan and Kroll, 2020; Chacón-Mateos et al., 2022).



30 A moving ship adds sampling challenges. Inlet aspiration can change with relative wind and vessel motion, and exhaust may be recirculated to a sampling point. Forward placement reduces but does not eliminate platform contamination; robust screening normally requires ship-relative wind or exhaust-sensitive measurements (Humphries et al., 2019; Welti et al., 2020). These limitations must be separated from the performance of an upstream humidity conditioner.

35 TAM/TAC conditions the aerosol stream before optical sizing. The instrument architecture, low-power conditioner, upward-flow arrangement, repeatability, and a stationary comparison with a governmental beta-attenuation monitor were described by Baek (2022). That study reported 3.25 % relative precision between two TAM units, a reference-comparison slope of 0.986 and correlation of 0.979, and substantial RH-dependent overestimation when the conditioner was disabled. The present study addresses a different, field-oriented question: whether the system maintains data continuity, inter-unit comparability, and controlled internal RH during long shipboard deployments.

40 Two features of the supplied dataset strengthen that assessment. First, two instruments (units 70 and 71) were operated concurrently throughout the Antarctic deployment, enabling a paired comparison over a wide concentration range. Second, unit 70 was subsequently used for the Arctic deployment without hardware substitution, allowing performance in the two polar campaigns to be compared without changing instrument identity. The objectives were therefore to (1) quantify record continuity and status-code-defined data availability, (2) evaluate Antarctic inter-unit agreement, (3) characterize humidity conditioning in GPS-defined polar subsets, and (4) place the observed PM variation in spatial context while stating the limitations imposed by the absence of a collocated field reference, relative wind, and chemical composition.



45 2 Instrumentation, deployment, and analysis

2.1 Instrument and shipboard installation

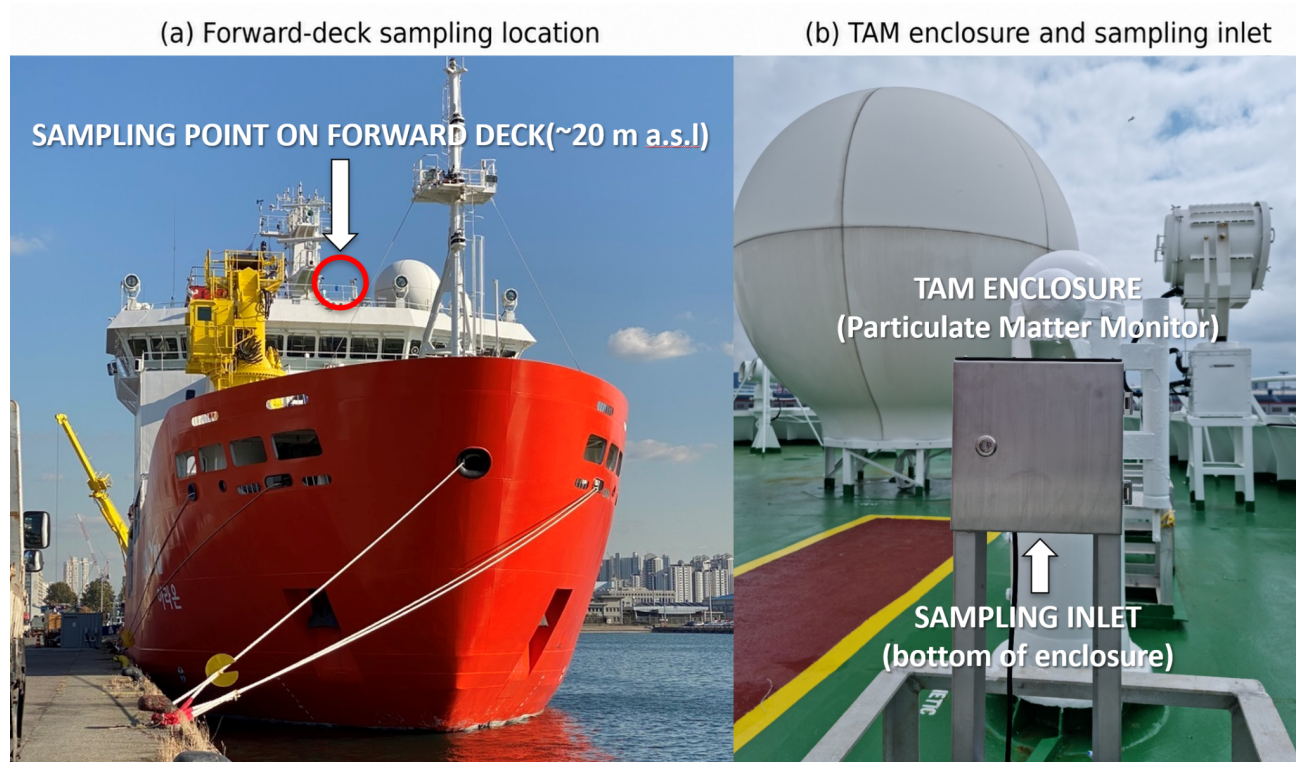


Figure 1: TAM/TAC installation aboard the R/V ARAON: (a) forward-deck sampling location, approximately 20 m above sea level; (b) TAM enclosure and bottom sampling inlet. Photographs and annotations were supplied by the authors. Forward placement reduces, but cannot exclude, platform-exhaust influence.

The integrated TAM/TAC systems were installed on the forward top deck of the research icebreaker R/V ARAON, approximately 20 m above sea level and forward of the primary exhaust stack (Fig. 1). TAC performs active dehumidification upstream of optical particle sizing, with a nominal internal-RH target near 35 %. The upward-flow configuration follows thermal buoyancy, and the inlet and outlet orientation was designed to reduce dynamic-pressure perturbations. No dedicated inlet-efficiency or dynamic-pressure experiment was performed during the voyages.

Units 70 and 71 were co-deployed during the Antarctic campaign. The same physical instrument, unit 70, was subsequently transferred to the Arctic campaign without hardware substitution. Physical measurements were acquired at 1 s intervals, averaged to 5 s within the TAM operating system, and aggregated to 10 min records. Each record therefore represents an integrated interval rather than an instantaneous observation. The logger stored PM_{1.0}, PM_{2.5}, PM_{4.0}, PM₁₀, ambient temperature and RH, TAC temperature and RH, pressure, instrument status, and GPS position. Logger timestamps were recorded in UTC+9; UTC was obtained by subtracting 9 h.



2.2 Timebase completeness and quality control

Expected record counts were calculated from the first and last timestamps at the nominal 600 s interval, inclusive. A record was considered valid for quantitative analysis when the instrument status field (Error) equalled zero. Nonzero status codes were retained in the source files but excluded before paired or environmental statistics were calculated. This rule excluded 44 unit-70 Antarctic records with code 1 and six with code 49. The files do not define the physical meaning of those codes; consequently, no mechanism is assigned to them here. Zero PM values with status code zero were retained. No concentration-based outlier deletion or wind-sector masking was applied.

The Antarctic streams were joined one-to-one by timestamp. Regional and humidity analyses used unit 70 for both deployments so that instrument identity did not confound the Antarctic–Arctic comparison; unit 71 was used only for the Antarctic intercomparison. Polar subsets were defined from GPS latitude as $\leq 60^\circ$ S and $\geq 60^\circ$ N. The remaining unit-70 records were grouped into northern mid-latitudes ($20\text{--}60^\circ$ N) and low/southern mid-latitudes (60° S– 20° N). These are route-based observation sectors, not area-representative climatologies.

2.3 Inter-unit and environmental statistics

Inter-unit agreement was summarized using the Pearson correlation coefficient, ordinary descriptive statistics, equal-variance Deming regression, mean bias (unit 71 minus unit 70), relative mean bias, mean absolute error, root-mean-square error, and descriptive 95 % limits of agreement. Paired relative precision was calculated as $100 \times \{\text{mean}[(x - y)^2]/2\}^{1/2} / \text{mean}[(x + y)/2]$. Because concentrations were strongly serially correlated, the analysis emphasizes effect sizes rather than formal p values or confidence intervals that would treat all 10 min observations as independent.

Humidity-control performance was summarized from valid polar records using the ambient and internal RH means, the fraction of internal-RH records at or below 40 %, and the Pearson correlations of ambient RH with PM_{2.5} and PM₁₀. Regional PM values are reported as arithmetic mean $\pm$ 1 standard deviation and median. Size-fraction ratios were calculated as ratios of regional mean concentrations. This definition is explicitly used because averaging record-level ratios is unstable when the denominator is near zero. All computations used the original concentration scale; the $0.1 \mu\text{g m}^{-3}$ offset and logarithmic coordinates in Fig. 2 are used only for visualization.



3 Results

3.1 Record continuity and valid-data yield

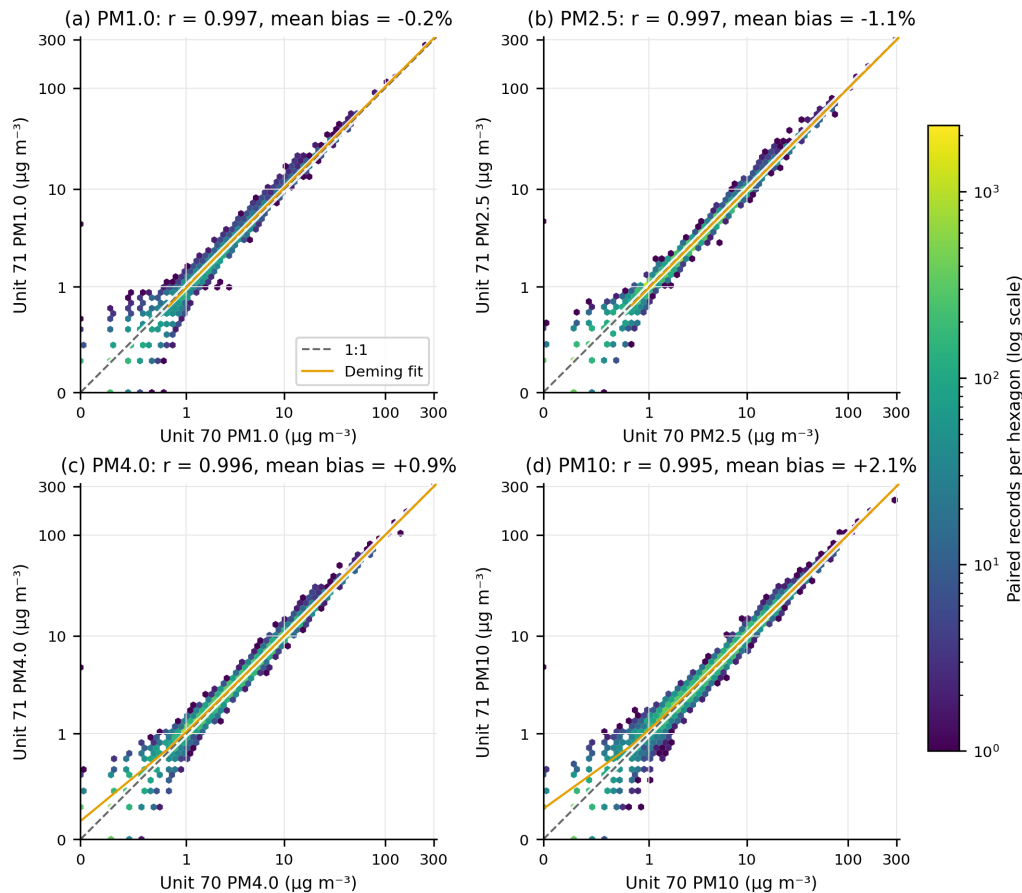
Table 1: Deployment record continuity and status-code-defined data availability.

Deployment / instrument	Logger period (UTC+9)	Scheduled and logged records	Status = 0 records	Result
Antarctic / unit 70	25 Oct 2022 13:19 – 3 May 2023 10:09	27,342 / 27,342	27,292 (99.817 %)	No missing time steps; 50 records excluded by status code
Antarctic / unit 71	25 Oct 2022 13:19 – 3 May 2023 10:09	27,342 / 27,342	27,342 (100 %)	No missing or flagged records
Arctic / unit 70	21 Jun 2023 14:19 – 11 Oct 2023 13:29	16,124 / 16,124	16,124 (100 %)	No missing or flagged records

90 All three logger streams contained the exact number of 10 min timestamps expected from their start and end times, and every adjacent timestamp differed by 600 s (Table 1). This establishes timebase completeness but is not equivalent to 100 % valid measurement yield. The Antarctic unit-70 status flags reduced its valid yield to 99.817 %, whereas Antarctic unit 71 and Arctic unit 70 had 100 % status-code-defined availability. Unit 70 contributed 43,466 logged records across the two campaigns, representing approximately 302 d of observation time and demonstrating successful redeployment of the same instrument after the Antarctic campaign.



95 3.2 Antarctic inter-unit agreement



100 **Figure 2:** Agreement between Antarctic units 70 and 71 for (a) PM_{1.0}, (b) PM_{2.5}, (c) PM_{4.0}, and (d) PM₁₀ (n = 27,292 valid paired 10 min records). Hexagon colour shows record density. The dashed line is 1:1 and the orange line is the equal-variance Deming fit. Axes display log₁₀(0.1 + PM) coordinates so that zero and low values remain visible; agreement metrics were calculated on the untransformed concentrations.

Table 2: Route-wide Antarctic inter-unit agreement (unit 71 relative to unit 70; n = 27,292).

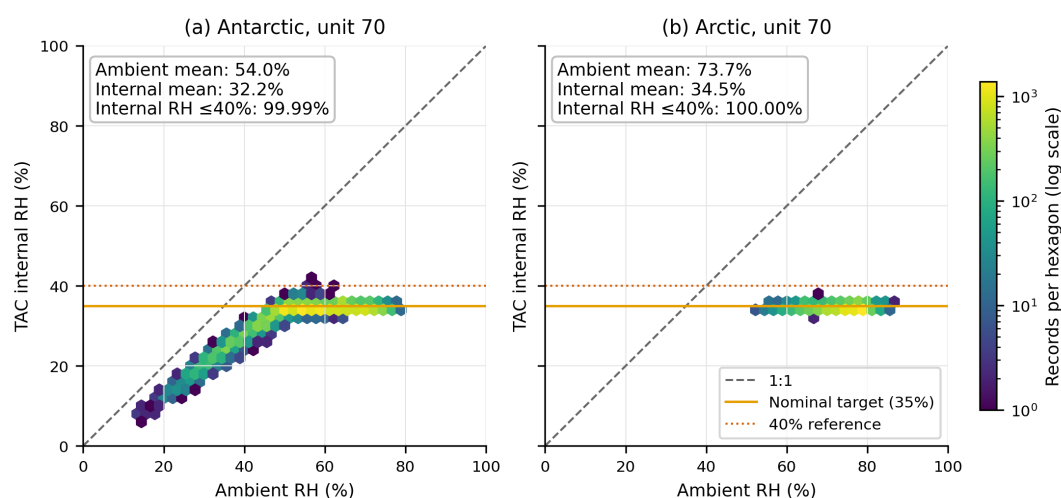
Fraction	Mean, unit 70 / 71 (µg m ⁻³)	r	Deming slope	Intercept (µg m ⁻³)	Mean bias (relative)	Paired relative precision
PM _{1.0}	1.531 / 1.528	0.997	1.033	-0.053	-0.003 (-0.2 %)	16.3 %
PM _{2.5}	3.307 / 3.270	0.997	0.992	-0.011	-0.037 (-1.1 %)	9.0 %
PM _{4.0}	4.152 / 4.187	0.996	0.996	+0.051	+0.035 (+0.9 %)	9.8 %
PM ₁₀	5.616 / 5.732	0.995	1.003	+0.100	+0.116 (+2.1 %)	9.5 %

105 Agreement was high across the route-wide dynamic range (Fig. 2 and Table 2). Pearson r ranged from 0.995 to 0.997, Deming slopes from 0.992 to 1.033, and relative mean biases from -1.1 % to +2.1 %. Paired relative precision was 9.0–9.8 % for PM_{2.5}, PM_{4.0}, and PM₁₀. The PM_{1.0} value was 16.3 %, despite a relative mean bias of only -0.2 %, because the route-wide mean was approximately 1.53 µg m⁻³ and many measurements were at the 0.1 µg m⁻³ reporting increment.



The high correlations were not solely a consequence of high-concentration port observations. Within the Antarctic polar subset, r remained 0.981 for $PM_{1.0}$, 0.990 for $PM_{2.5}$, 0.994 for $PM_{4.0}$, and 0.996 for PM_{10} . Unit 71 was higher than unit 70 by 5.3 % for $PM_{2.5}$ and 12.8 % for PM_{10} in that low-concentration subset, but the median paired differences were 0.0 and 0.1 $\mu g m^{-3}$, respectively. Relative metrics therefore become sensitive to quantization and small absolute offsets under near-
 110 background conditions. The paired results establish comparability between units, not absolute accuracy, because common-mode optical or inlet biases would not be detected.

3.3 Humidity conditioning in the polar subsets



115 **Figure 3: TAC internal RH versus ambient RH for valid unit-70 records in the (a) Antarctic polar subset ($\leq 60^\circ S$; $n = 11,212$) and (b) Arctic polar subset ($\geq 60^\circ N$; $n = 8,060$). The dashed line is 1:1; horizontal lines mark the nominal 35 % target and a 40 % operational reference. Hexagon colour shows record density.**

Table 3: Humidity-conditioning statistics for GPS-defined polar subsets using unit 70.

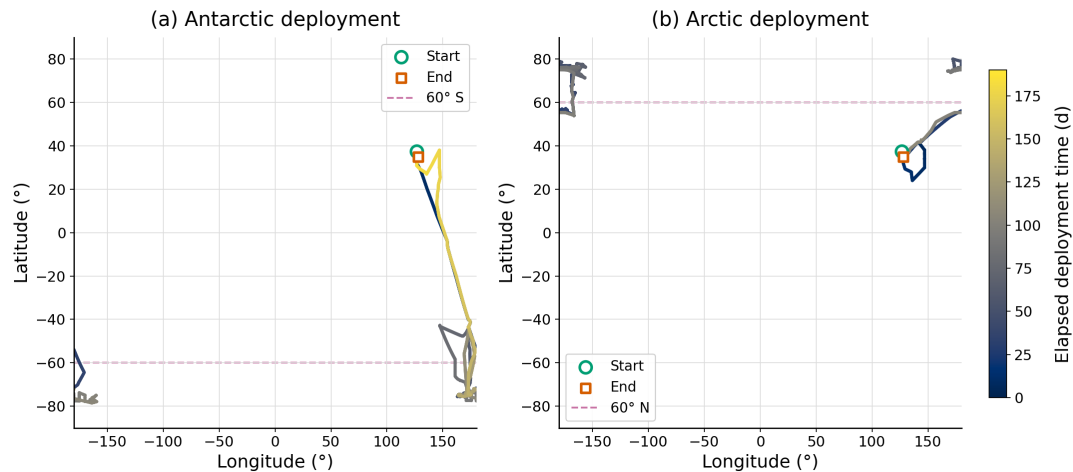
Polar subset	N	Ambient RH, mean $\pm$ SD (%)	Internal RH, mean $\pm$ SD (%)	Mean reduction (percentage points)	Internal RH ≤ 40 %	Ambient RH correlation with $PM_{2.5} / PM_{10}$
Antarctic ($\leq 60^\circ S$)	11,212	54.0 $\pm$ 12.4	32.2 $\pm$ 4.7	21.8	99.99 %	0.322 / 0.351
Arctic ($\geq 60^\circ N$)	8,060	73.7 $\pm$ 5.7	34.5 $\pm$ 0.5	39.2	100.00 %	0.086 / 0.038

TAC maintained internal RH near its nominal target under both polar conditions (Fig. 3 and Table 3). Mean ambient-to-internal reductions were 21.8 percentage points in the Antarctic and 39.2 percentage points in the Arctic. Internal RH
 120 exceeded 40 % in only one valid Antarctic record and in no Arctic polar record. The Arctic internal-RH standard deviation was 0.51 %, compared with 5.75 % for ambient RH, indicating a pronounced plateau near 35 %.

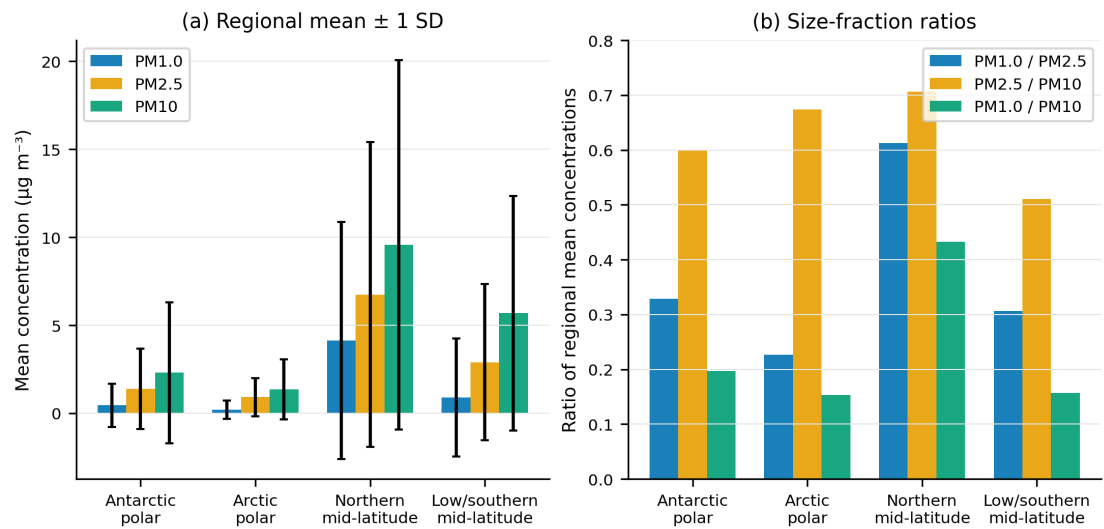
Ambient RH was weakly correlated with $PM_{2.5}$ and PM_{10} in the Arctic ($r = 0.086$ and 0.038) and moderately correlated in the Antarctic ($r = 0.322$ and 0.351). The low Arctic correlations are consistent with successful suppression of RH-driven variability, but correlation alone cannot demonstrate dry-equivalent mass accuracy. The Antarctic co-variation may reflect
 125 changes in aerosol production, transport, or residual humidity response. Southern Ocean aerosol optical properties are known

to covary with RH and wind-driven sea-salt production (Thomas et al., 2022), but wind and chemical measurements were unavailable here; a causal assignment is therefore not possible.

3.4 Spatial context of the unit-70 observations



130 **Figure 4: GPS trajectories for unit 70 during the (a) Antarctic and (b) Arctic deployments. Hourly positions are shown for clarity and coloured by elapsed deployment time; all 10 min records were used in the numerical analyses. The Start and End markers represent the first and last raw records; both deployments ended near 34.922° N, 127.697° E. Dashed lines mark the latitude thresholds used to define the polar subsets. The plots show geographic coordinates without a cartographic base layer.**



135 **Figure 5: Unit-70 particulate matter observations by GPS latitude sector: (a) regional mean ± 1 standard deviation for PM_{1.0}, PM_{2.5}, and PM₁₀; (b) ratios of regional mean concentrations. Sectors follow Sect. 2.2. These route-based summaries are not area-weighted climatologies.**



Table 4: Unit-70 PM concentrations by GPS latitude sector. Values are mean $\pm$ 1 SD, with median in parentheses; ratios are ratios of regional means.

Latitude sector	N	PM _{1.0} ($\mu\text{g m}^{-3}$)	PM _{2.5} ($\mu\text{g m}^{-3}$)	PM ₁₀ ($\mu\text{g m}^{-3}$)	PM _{1.0} / PM _{2.5}
Antarctic polar ($\leq 60^\circ$ S)	11,212	0.45 $\pm$ 1.24 (0.0)	1.38 $\pm$ 2.29 (0.7)	2.30 $\pm$ 4.00 (1.0)	0.329
Arctic polar ($\geq 60^\circ$ N)	8,060	0.21 $\pm$ 0.51 (0.0)	0.91 $\pm$ 1.08 (0.7)	1.35 $\pm$ 1.71 (0.9)	0.227
Northern mid-latitude (20–60° N)	11,909	4.13 $\pm$ 6.74 (1.6)	6.75 $\pm$ 8.66 (3.7)	9.56 $\pm$ 10.50 (5.9)	0.612
Low/southern mid-latitude (60° S–20° N)	12,235	0.89 $\pm$ 3.36 (0.4)	2.90 $\pm$ 4.43 (2.2)	5.68 $\pm$ 6.66 (4.3)	0.307

140 Using the same instrument for both deployments removes instrument identity as an explanation for the broad Antarctic–Arctic contrast, but it does not control for season, route, meteorology, or platform influence. Mean PM_{2.5} was 1.38 $\mu\text{g m}^{-3}$ in the Antarctic polar subset and 0.91 $\mu\text{g m}^{-3}$ in the Arctic polar subset, compared with 6.75 $\mu\text{g m}^{-3}$ in the northern mid-latitude sector. The corresponding mean PM₁₀ values were 2.30, 1.35, and 9.56 $\mu\text{g m}^{-3}$. These results document low polar mass relative to the mid-latitude portions of the observed routes; they should not be interpreted as a hemispheric
 145 climatology or as evidence that one polar region is intrinsically more polluted.

Ratios of regional means were used to maintain numerical consistency with the reported mass concentrations. PM_{1.0}/PM_{2.5} increased from 0.329 in the Antarctic polar subset and 0.227 in the Arctic polar subset to 0.612 in the northern mid-latitude sector. This shift demonstrates a larger submicrometre contribution along the observed mid-latitude route. It is qualitatively compatible with stronger combustion and secondary-aerosol influence near populated shipping regions, while marine sea salt
 150 can contribute to PM concentrations over a broad size range (Murphy et al., 2019; Bian et al., 2019). Because no composition or exhaust tracer was measured, the ratios are descriptive size fingerprints and cannot support source apportionment.

4 Measurement implications and limitations

The paired Antarctic deployment adds an independent field-performance dimension to the stationary evaluation of Baek
 155 (2022). Route-wide slopes close to unity, small mean biases, and high correlations show that two units tracked the same rapidly changing aerosol field over approximately 190 d. The same unit then operated with a complete unflagged timebase in the Arctic, supporting operational redeployability. These are important attributes for distributed or expeditionary observations, where data loss and unit-to-unit discontinuity can be as consequential as short-term precision.

Several uncertainties limit the claims. First, inter-unit agreement cannot reveal common-mode calibration bias. No collocated
 160 gravimetric, beta-attenuation, or research-grade optical reference was operated during the cruises; therefore, the present data do not establish field accuracy or traceability. Second, the study did not include a simultaneous unconditioned channel or dry-reference measurement. Internal RH demonstrates conditioner control, but not complete removal of composition-dependent hygroscopic or optical effects.



Third, inlet efficiency was not characterized as a function of wind speed, direction, vessel speed, or particle size. The forward-deck location reduced the probability of exhaust sampling, but the absence of ship-relative wind, black carbon, carbon monoxide, nitrogen oxides, or particle-number data prevented an exhaust filter of the type used in dedicated shipboard studies (Humphries et al., 2019). Retaining all concentration values with status code zero avoids subjective outlier deletion but also means that unidentified exhaust encounters may remain in the route summaries.

Fourth, the PM fractions are optically inferred mass concentrations and depend on the instrument response model. Chemical composition, density, refractive index, and particle shape were not measured. The regional results must therefore be treated as instrument observations rather than chemically resolved aerosol mass. Finally, the 10 min records are temporally autocorrelated and spatially clustered along nonrandom ship tracks. The large record count improves descriptive resolution but does not convert the routes into independent or area-representative samples.

5 Conclusions

Two TAM/TAC units completed a timestamp-complete Antarctic co-deployment, and the same unit 70 subsequently completed a timestamp-complete Arctic deployment. After status-code quality control, 27,292 Antarctic pairs were available. Across four PM fractions, route-wide correlations were at least 0.995, Deming slopes were within 3.3 % of unity, and relative mean biases were within ± 2.1 %. Unit 70 provided approximately 302 d of logged observations across the two deployments, with 99.817 % valid yield in the Antarctic and 100 % in the Arctic.

TAC maintained mean internal RH at 32.2 % in the Antarctic and 34.5 % in the Arctic despite higher and more variable ambient RH. The results support long-duration operational continuity, unit comparability, and repeatable humidity conditioning in extreme marine environments. A future validation campaign should combine paired TAM/TAC units with a traceable reference PM instrument, an unconditioned or independently dried comparison channel, size-dependent inlet testing, ship-relative wind, and exhaust-sensitive tracers. Those additions are necessary to convert the present operational evidence into a complete field-accuracy and uncertainty assessment.

Code availability

The calculations use standard descriptive statistics, equal-variance Deming regression, and direct plotting of the supplied 10 min records. The analysis script needed to reproduce the tables and figures is available from the corresponding author upon reasonable request.



190 **Data availability**

The 10 min PM, instrument-status, humidity, pressure, and GPS records underlying the reported results are available from the corresponding author upon reasonable request. The raw exports form part of an ongoing commercial instrument-development and validation programme and are not currently deposited in a public repository. De-identified variables necessary to reproduce the reported tables and figures can be provided for scientific review subject to protection of
195 proprietary device information.

Author contributions

MS conceptualized the study, curated the data, performed the formal analysis, and prepared the manuscript. SHB designed and developed the TAM/TAC hardware architecture, managed the data-logging systems, and supervised the field deployments. Both authors hold doctoral degrees in engineering, reviewed the scientific content and numerical results, and
200 approved the manuscript.

Competing interests

MS and SHB are affiliated with Gonggam Sensors Co., Ltd., the developer of the TAM/TAC system evaluated in this study, and therefore have a commercial interest in the technology. The authors declare no other competing interests.

Acknowledgements

205 The authors thank Korea University, Chungnam National University, and the Korea Polar Research Institute (KOPRI) for facilitating installation and operational support aboard the R/V ARAON. OpenAI ChatGPT (GPT-5.6, accessed 2 September 2026) was used to assist with language editing, numerical cross-checking against the author-supplied CSV files, figure preparation, and document formatting. The authors are responsible for independently verifying and, where necessary, revising all calculations, interpretations, citations, and final wording before submission.

210 **Financial support**

This study was conducted using internal resources of Gonggam Sensors Co., Ltd.; no external funding was received for the work reported here.



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