Supplementary Information

S1. Statistical analysis

All statistical analyses and graphical visualisations were performed using Python (SciPy and Matplotlib) and OriginPro 2024. Data are presented as mean ± one standard deviation (SD) unless otherwise stated. The normality of seasonal datasets was evaluated using the Shapiro–Wilk test. Because several variables exhibited non-normal distributions and unequal variances, both parametric and non-parametric statistical tests were applied.

Seasonal differences between the northeast monsoon (NEM) and southwest monsoon (SWM) were evaluated using Welch's two-sample t-test and the Mann–Whitney U test, with the latter used as the primary test for variables that did not meet the normality assumption. Differences among the four seasonal periods (NEM, pre-transition, SWM, and post-transition) were evaluated using the Kruskal–Wallis test, with one-way ANOVA also calculated for comparison. Statistical significance was defined as $p < 0.05$.

Relationships among aerosol chemical components were examined using Pearson correlation coefficients (r), calculated separately for the NEM, SWM, pre-transition, and post-transition periods. Correlation strength was interpreted as strong ($|r| \geq 0.70$), moderate ($0.40 \leq |r| < 0.70$), and weak ($|r| < 0.40$). The resulting seasonal correlation matrices are presented in Figure S4.

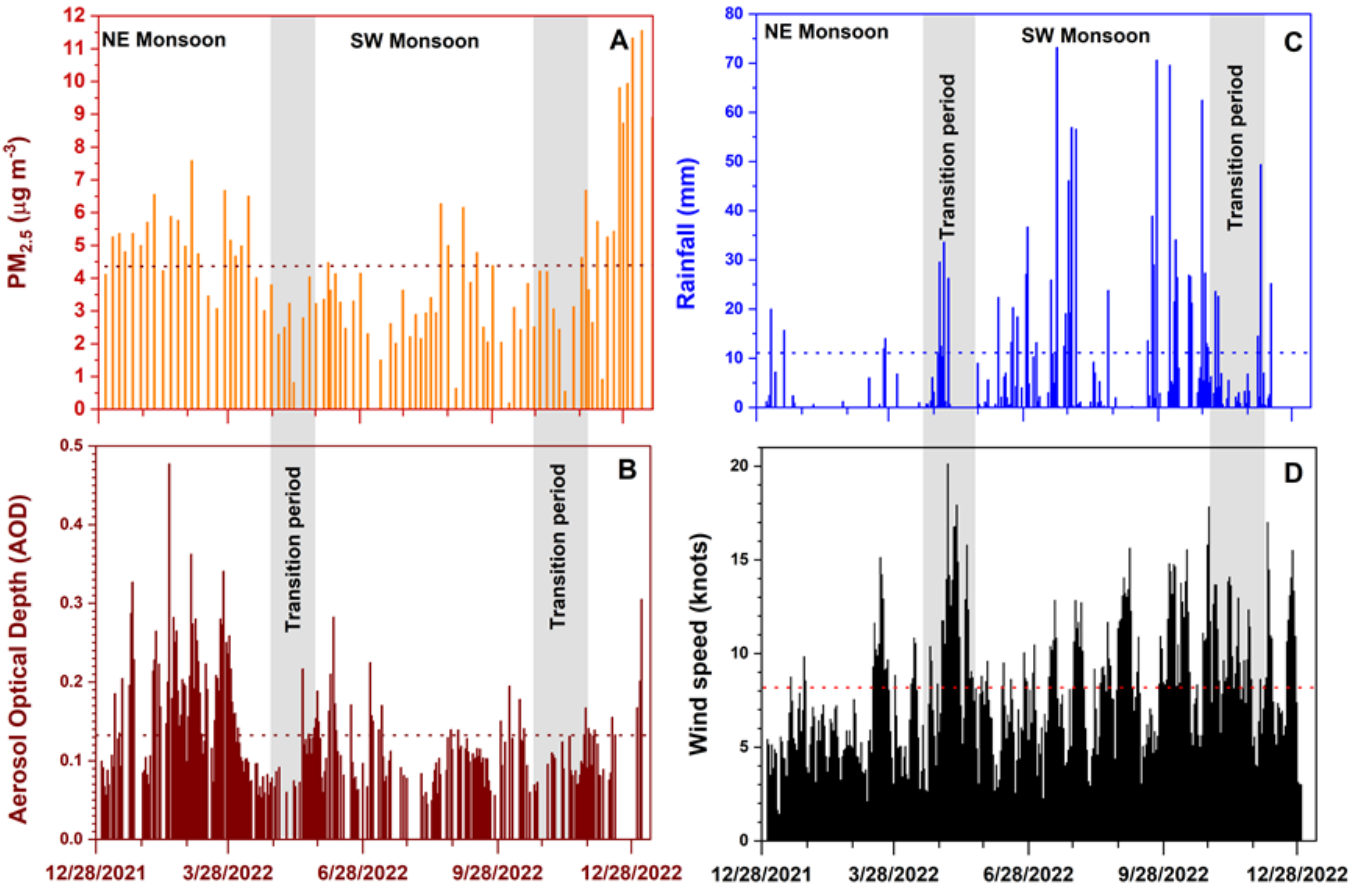

Figure S1: Temporal variations in (A) $PM_{2.5}$ mass concentration measured over variable-duration integrated sampling periods, and daily observations of (B) aerosol optical depth (AOD_{500}), (C) precipitation, and (D) wind speed at the Maldives Climate Observatory at Gan (MCOG), Maldives, from December 2021 to December 2022. Shaded regions indicate the northeast monsoon (NEM), southwest monsoon (SWM), and intervening transition periods. Dotted lines indicate the corresponding mean values.

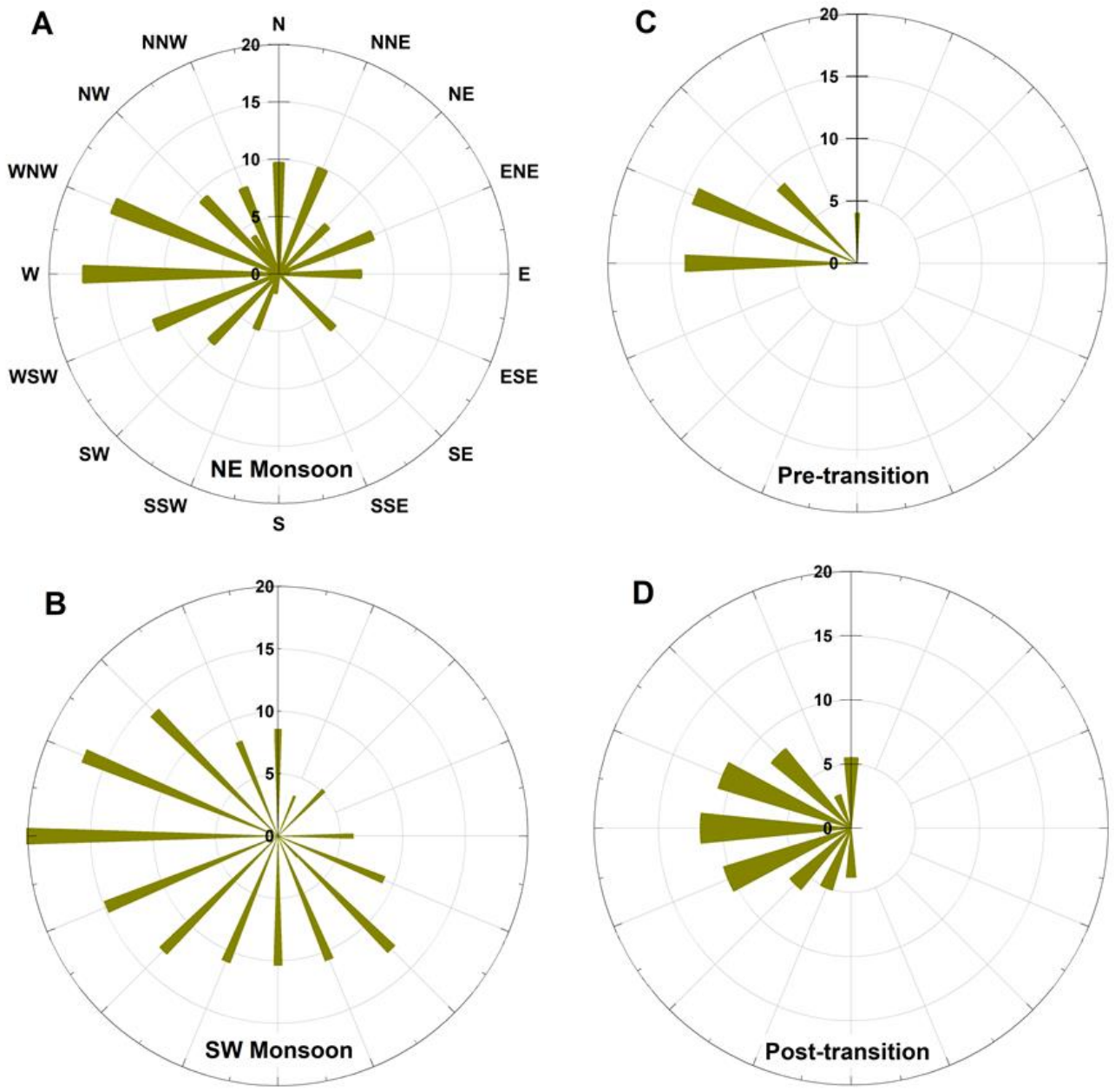

Figure S2: Wind rose diagrams showing the frequency distribution of wind directions observed at the Maldives Climate Observatory at Gan (MCOG), Maldives, during December 2021–January 2023 for (A) the northeast monsoon (NEM), (B) the southwest monsoon (SWM), (C) the pre-transition period, and (D) the post-transition period. Values represent the percentage frequency of occurrence in each wind-direction sector.

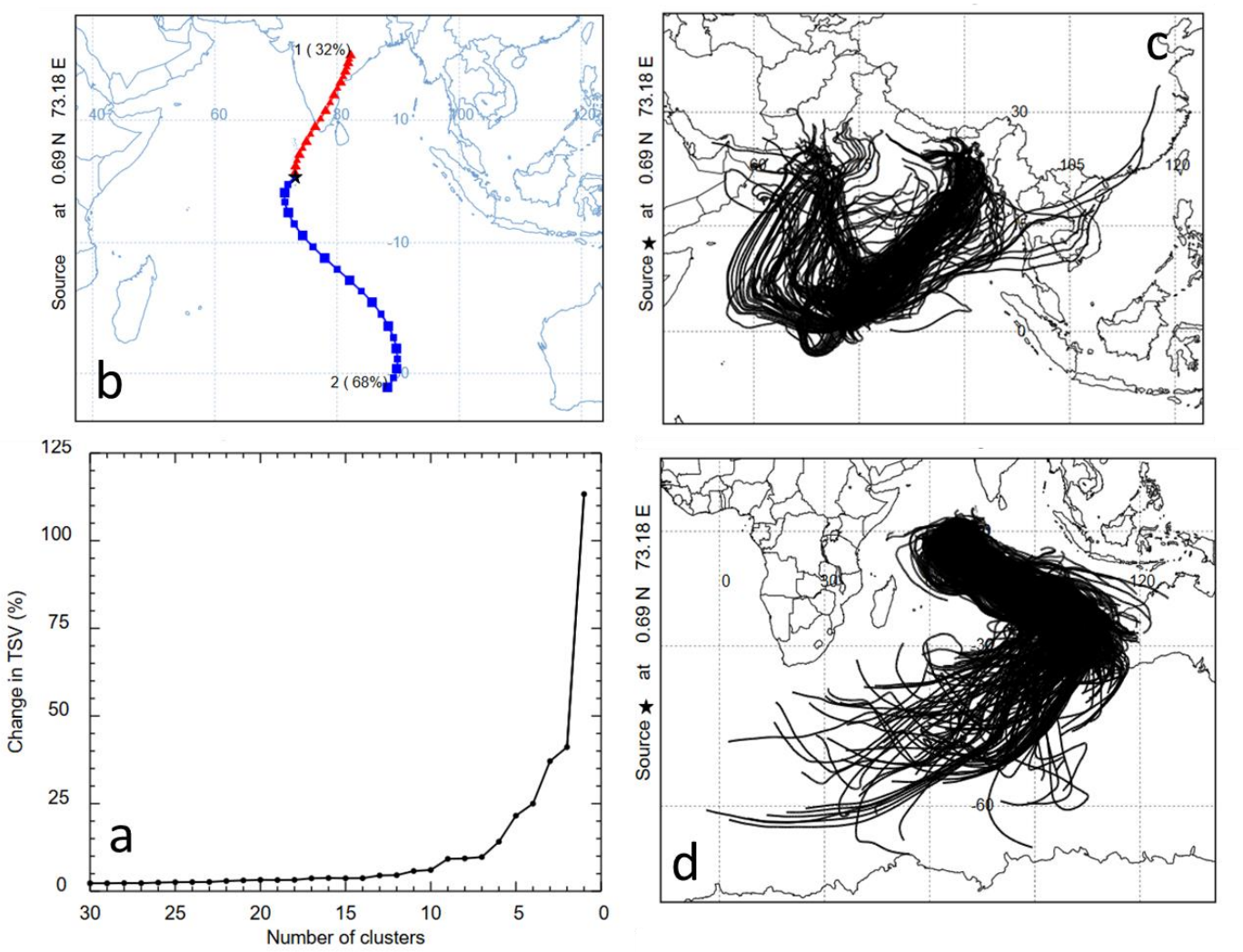

Figure S3: HYSPLIT 10-day backward-trajectory analysis of air masses arriving at the Maldives Climate Observatory at Gan (MCOG) during 2022. (A) Total spatial variance (TSV) as a function of the number of trajectory clusters, used to identify the optimal clustering solution. (B) Clustered backward trajectories arriving at MCOG (star), showing two dominant transport regimes: Cluster 1 (red; 32 %), representing predominantly continental transport, and Cluster 2 (blue; 68 %), representing predominantly marine transport. (C) Composite 10-day backward trajectories during the northeast monsoon (NEM), showing predominant transport from South and Southeast Asia across the northern Indian Ocean. (D) Composite 10-day backward trajectories during the southwest monsoon (SWM), showing predominantly marine transport from the southern Indian Ocean.

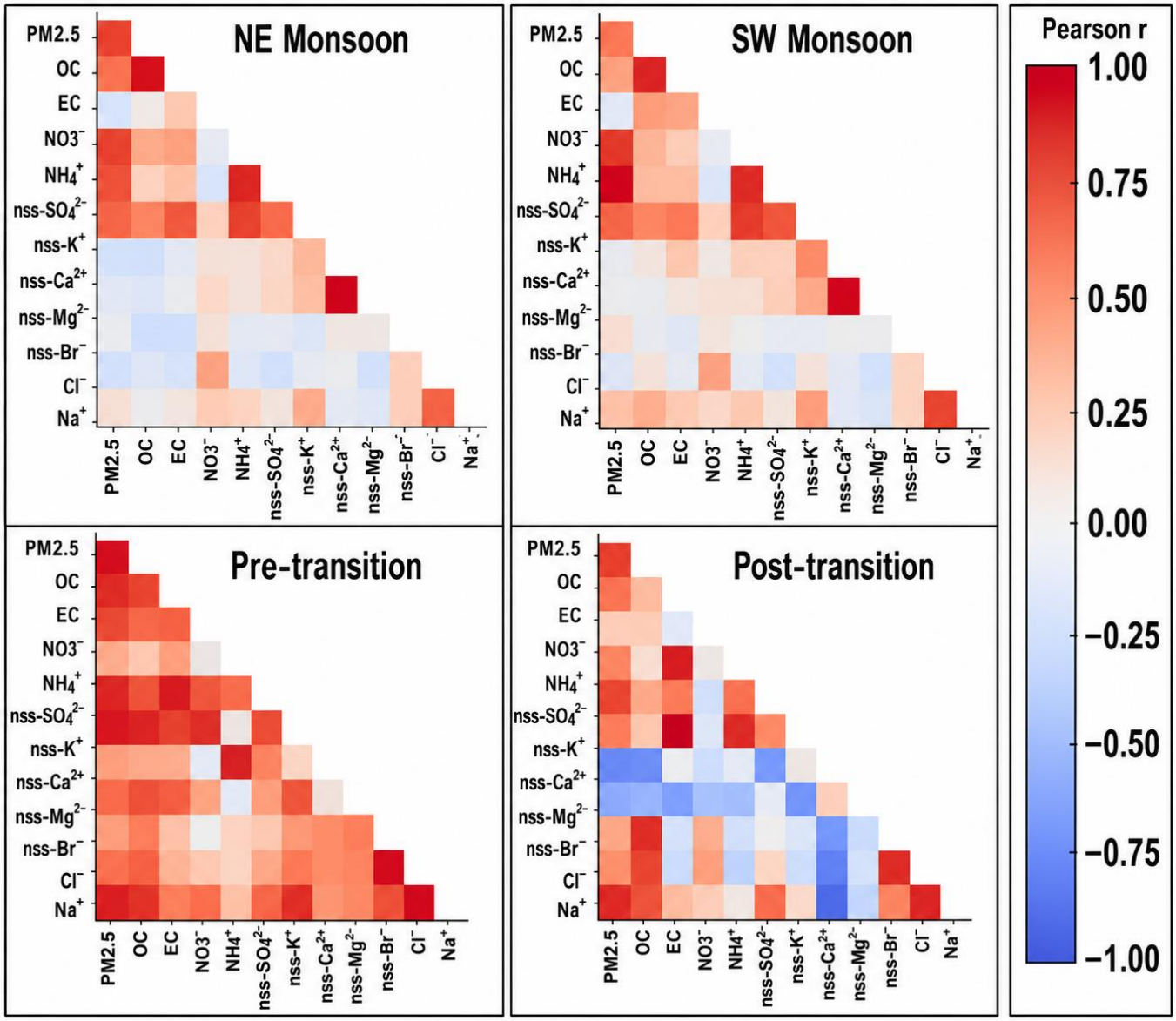

Figure S4: Pearson correlation heatmaps showing relationships among major $PM_{2.5}$ chemical components measured at the Maldives Climate Observatory at Gan (MCOG) during December 2021–January 2023 for (A) the northeast monsoon (NEM), (B) the southwest monsoon (SWM), (C) the pre-transition period, and (D) the post-transition period. The matrices include $PM_{2.5}$, organic carbon (OC), elemental carbon (EC, used as a proxy for BC), NO_3^-, NH_4^+, nss-SO_4^{2-}, nss-Ca^{2+}, nss-Mg^{2+}, nss-K^+, nss-Br^-, Cl^-, and Na^+. Colours represent Pearson correlation coefficients (r), with red indicating positive correlations, blue indicating negative correlations, and white indicating weak or no linear correlation.

Table S1. Statistical summary of seasonal differences in selected aerosol physical, chemical, and optical parameters measured at the Maldives Climate Observatory at Gan (MCOG). Differences between the northeast monsoon (NEM) and southwest monsoon (SWM) were evaluated using Welch's t-test and the Mann–Whitney U test, while differences among all four seasonal periods were assessed using one-way ANOVA and the Kruskal–Wallis test. Statistical significance was defined as $p < 0.05$.

Parameter/comparison	Statistical result	Interpretation
$BC\text{-}MAC_{658}$: NEM vs SWM	Welch $p = 0.103$; Mann–Whitney $p = 0.064$	No statistically significant seasonal difference
$BC\text{-}MAC_{658}$: all four periods	ANOVA $p = 0.305$; Kruskal–Wallis $p = 0.208$	No significant difference among NEM, pre-transition, SWM, and post-transition periods
$PM_{2.5}$	$p < 0.001$	Significantly lower during SWM
AOD_{500}	$p < 0.001$	Significantly lower during SWM
BC	$p < 0.001$	Significantly lower during SWM
OC	$p < 0.001$	Significantly lower during SWM
nss-SO_4^{2-}	$p < 0.001$	Significantly lower during SWM
NH_4^+	$p < 0.001$	Significantly lower during SWM
OC/BC	Significant ($p < 0.05$)	Higher during SWM
Na^+	Significant ($p < 0.05$)	Significantly higher during SWM
Cl^-	Significant ($p < 0.05$)	Significantly higher during SWM
$BC\text{-}MAC_{658}$ correlations during SWM	No significant correlations with RH, precipitation, nss-SO_4^{2-}, OC, or BC	No clear evidence that seasonal $BC\text{-}MAC_{658}$ variability during SWM is directly associated with these individual parameters

Note: Unless otherwise stated, NEM–SWM p-values are from the Mann–Whitney U test. Welch's t-test was also used for comparison, and both tests are reported for $BC\text{-}MAC_{658}$. Statistical significance was defined as $p < 0.05$.

Table S2. Dual-carbon isotope signatures of black carbon (BC) in selected $PM_{2.5}$ samples collected at the Maldives Climate Observatory at Gan (MCOG), together with the estimated contributions of contemporary biomass-derived and fossil carbon. Because only five samples were analysed, the source fractions are interpreted as sample-specific constraints rather than as quantitative seasonal source apportionment.

Sampling date	Period	$\delta^{13}C$ (‰,V-PDB)	$\Delta^{14}C$ (‰)	$f_{biomass}$	f_{fossil}
14 Feb 2022	NEM	−27.6	−990.33	0.01	0.99
01 Mar 2022	NEM	−21.1	−228.11	0.64	0.36
07 Jul 2022	SWM	−22.9	−993.40	0.01	0.99
11 Sep 2022	SWM	−18.7	−272.52	0.61	0.39
02 Jan 2023	NEM	−21.0	−533.95	0.39	0.61

Note: Sampling dates denote the end of the 72-h filter collection period; therefore, the sample dated 02 January 2023 includes measurements from the final days of December 2022.