

Supplement of Drivers of ice-nucleating particle variability at urban and high-mountain environments of the Western Mediterranean

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Table S1: Summary of atmospheric ice-nucleating particle (INP) measurements in the mixed-phase cloud range performed at high-altitude mountain stations.

Station	Coordinates	Instrument	Temperature	Measurement period	Reference
Jungfraujoch (JFJ), Switzerland	(46.548° N, 7.984° E, 3580 m)	PINC (online)	−31 °C	Mar. and June 2009	(Chou et al., 2011)
		DFA (offline)	−4 to −12 °C	Jun. 2012 – May 2013	(Conen et al., 2015)
		PINC (online)	−25, −26, −32 °C	Jan. 2012; Jan. – Feb. 2013 and 2014	(Boose et al., 2016a)
		HINC (online)	−31 °C	Jan. – Feb. 2015; Jan. – Mar. 2016	(Lacher et al., 2017)
		PINC + HINC (online)	−31, −32 °C	2014–2017 (9 campaigns)	(Lacher et al., 2018)
		HINC (online)	−31 °C	Jan. – Feb. 2017	(Lacher et al., 2021)
		HINC-Auto (online)	−30 °C	Feb. – Dec. 2020	(Brunner et al., 2021)
		HINC-Auto (online)	−30 °C	Feb. 2020 – Jan. 2021	(Brunner et al., 2022)
		DFA (offline)	−5 to −15 °C	Jan. 2019 – Mar. 2021	(Conen et al., 2022)
Weissfluhjoch (WFJ), Switzerland	(46.833° N, 9.806° E, 2671 m)	LINDA (offline)	−15 °C	Feb. – Mar. 2019	(Mignani et al., 2021)
Sonnblick (SON), Austria	(47.054° N, 12.958° E, 3106 m)	INSEKT + PINE (offline + online)	−5 to −30 °C	Aug. 2019 – Oct. 2022	(Bogert, 2024)
Izaña (IZO), Spain	(28.309° N, 16.499° W, 2373 m)	DFA (offline)	−4 to −12 °C	Jun. 2012 – June 2013	(Conen et al., 2015)
		PINC (online)	−15 to −40 °C	July – Aug. 2013 and 2014	(Boose et al., 2016b)
Montsec d’Ares (MSA), Spain	(42.050° N, 0.733° E, 1570 m)	LINDA (offline)	−4 to −16 °C	Oct. 2018	(Bras et al., 2024)
Puy de Dôme (PUY), France	(45.77° N, 2.95° E, 1465 m)	LINDA (offline)	−5 to −18 °C	Oct. 2018 – May 2019	(Bras et al., 2024)
		PINE (online)	−22 to −33 °C	Dec. 2022 – Mar. 2023	(Canzi et al., 2025)

Station	Coordinates	Instrument	Temperature	Measurement period	Reference
Mt. Cimone (MTC), Italy	(44.11° N, 10.42° E, 2165 m)	DFPC (offline)	−18 °C	May 2014 and Oct. 2015	(Rinaldi et al., 2017)
Mt. Helmos (HAC) ² , Greece	(37.984° N, 22.196° E, 2314 m)	INSEKT + PINE (offline + online)	−7 to −28 °C	Oct. – Nov. 2021	(Gao et al., 2024)
Pico Mountain Observatory (PMO), Azores Islands, Portugal	(38.47° N, 28.40° W, 2225 m)	Vapor-controlled cryo-cooling stage (offline)	−25 to −35 °C	Aug. – Sep. 2013	(China et al., 2017)
Storm Peak Laboratory (SPL), USA	(40.455° N, 106.744° W, 3200 m)	CSU-CFDC (online)	−30 to −55 °C	Nov. 2001	(DeMott et al., 2003)
		CSU-CFDC (online)	−15 to −50 °C	Apr. – May 2004	(Richardson et al., 2007)
		PINE (online)	−22 to −32 °C	Oct. 2021 – May 2022 and Jan. – May 2025	(Lacher et al., 2026)
Rocky Mountains (DOE ARM, AMF-2), USA	(38.898° N, 106.943° W, 3137 m) and (38.956° N, 106.988° W, 2885 m)	CSU-INS (offline)	−7.5 to −27.5 °C	Sep. 2021 – June 2023	(Zhou et al., 2026)
Whistler Mountain, Canada	(50.09° N, 122.96° W, 2182 m)	MOUDI-DFT (offline)	−10, −15, −25 °C	Mar. – Apr. 2014	(Mason et al., 2016)
Altzomoni (AAO), Mexico	(19.118° N, 98.655° W, 4000 m)	UNAM-MOUDI-DFT (offline)	−10 to −25 °C	2019 (4 aerosol samples)	(Pereira et al., 2021)
		UNAM-MOUDI-DFT (offline)	−18 to −38 °C	2022 (5 aerosol samples)	(Negrete-Harper et al., 2026)
Haituo Mountain (HT), China	(40.52° N, 115.78° E, 1344 m)	INSEKT (offline)	−5 to −30 °C	Apr. – May 2019	(Hu et al., 2023)

Station	Coordinates	Instrument	Temperature	Measurement period	Reference
Central Tianshan Mountains (Ulasitai), China	(43.28° N, 87.12° E, 2169 m)	Static water vapor diffusion chamber (offline)	−15, −20, −25 °C	Aug. – Sep. 2019 and Jan. 2020	(Jiang et al., 2023)
Guangmingding peak, Huangshan Mountains, China	(30.08° N, 118.09° E, 1840 m)	Portable mixing cloud chamber and static diffusion chamber (online)	−10 to −25 °C	May. – Sep. 2011	(Jiang et al., 2014)
		Static water vapor diffusion chamber (offline)	−15, −17, −20, −23 °C	Sep. – Oct. 2012	(Jiang et al., 2015)
Huangshan Mountains, China	(30.07° N, 118.09° E, 1351 m)	Portable mixing cloud chamber and static diffusion chamber (online)	−10 to −25 °C	May. – Sep. 2011	(Jiang et al., 2014)
Mt. Tai, China	(36.25° N, 117.10° E, 1534 m)	Static water vapor diffusion chamber (offline)	−20, −25 °C	May. – June 2017	(Chen et al., 2021)
Changbai Mountains, China	(42.03° N, 128.07° E, 2623 m)	GIGINA (offline)	−5 to −30 °C	July – Aug. 2021	(Sun et al., 2024)
Mt. Fuji (MFRS), Japan	(35.36° N, 138.73° E, 3776 m)	SNICS (offline)	−6 to −32 °C	July – Aug. 2021	(Murata et al., 2026)
Radio Astronomy Centre (RAC), Ooty, India	(11.38° N, 76.66° E, 2240 m)	Thermal gradient diffusion chamber (offline)	−17.6 to −22 °C	Jan. 2013 and Jan. 2014	(Wagh et al., 2017)
High Altitude Cloud Physics Laboratory (HACPL) at Mahabaleshwar, India	(17.92° N, 73.66° E, 1348 m)	SPIN (online)	−25, −30, −34 °C	Aug. – Dec. 2018	(Kumar et al., 2020)

Table S2. Summary of atmospheric ice-nucleating particle (INP) measurements in the mixed-phase cloud range performed at urban stations.

Station	Coordinates	Instrument	Temperature	Measurement period	Reference
Beijing (BJ), China	(39.956° N, 116.988° E)	INDA + LINA (offline)	−6 to −25 °C	Nov. – Dec. 2016	(Chen et al., 2018)
		Bigg's cloud chamber (online)	−10 to −30 °C (every 5 °C)	Mar. – Apr. 2017	(Che et al., 2019)
		CFDC-IAS (online)	−20, −25, −30 °C	May – June 2018	(Bi et al., 2019) and (Li et al., 2026)
		INSEKT (offline)	−5 to −30 °C	Apr. – May 2019	(Hu et al., 2023)
		HINC (online)	−30 °C	Feb. 2021	(Zhang et al., 2022)
		PKU-INA (offline)	−5 to −21 °C	June – July 2020	(Chen et al., 2024)
Lanzhou, China	(36.033° N, 103.850° E)	CFDC-IAS (online)	−15 to −35 °C	Dec. 2024 – Apr. 2025	(Chen et al., 2026)
Taiyuan, China	(37.88° N, 112.55° E)	PKU-INA (offline)	−5 to −35 °C	Dec. 2023 – Jan. 2024	(Yang et al., 2026)
Tai'an, China	(36.19° N, 117.17° E)	Static vacuum water vapor diffusion chamber (offline)	−15, −20, −25 °C	June 2018	(Jiang et al., 2020)
Tokyo, Japan	(35.71° N, 139.81° E, 458 m a.g.l.)	CRAFT (offline)	−5 to −25 °C	Aug. 2016 – July 2017	(Tobo et al., 2020)
Yokohama, Japan	(35.56° N, 139.66° E)	DFA (offline)	−5 to −25 °C	Mar. – June 2021 and Oct. 2021 – Feb. 2022	(Iwata et al., 2026)
New Delhi, India	(28.55° N, 77.10° E, 237 m)	NP-TGDC chamber (online)	−18 °C	Dec. 2016 – Jan. 2017	(Wagh et al., 2021)
Bologna, Italy	(44.517° N, 11.333° E)	DFPC chamber (offline)	−22 °C	9 Feb. 2017	(Belosi et al., 2018)
Mexico City, Mexico	(19.326° N, 99.176° W, 2240 m)	UNAM-MOUDI-DFT (offline)	−10 to −35 °C	Feb. – May. 2018 and 2019	(Cabrera- Segoviano et al., 2022)
		UNAM-MOUDI-DFT (offline)	−13 to −38 °C	2022 (5 samples)	(Negrete-Harper et al., 2026)
		(CU: 19.326° N, 99.176° W; CS: 19.484° N, 99.147° W) (offline)	−12 to −38 °C	16–20 May 2022	(Mendoza-Téllez et al., 2026)
Mérida, Mexico	(20.98° N, 89.64° W)	UNAM-MOUDI-DFT (offline)	−5 to −31 °C	Jan. 2017 – July. 2018 (5 campaigns)	(Córdoba et al., 2021)
Houston, USA	(29.670° N, 95.059° W, 8 m)	DFA (offline)	−13 to −30 °C	Aug. – Sept. 2022	(Thompson et al., 2025)

S1 Measurements at UGR and SNS

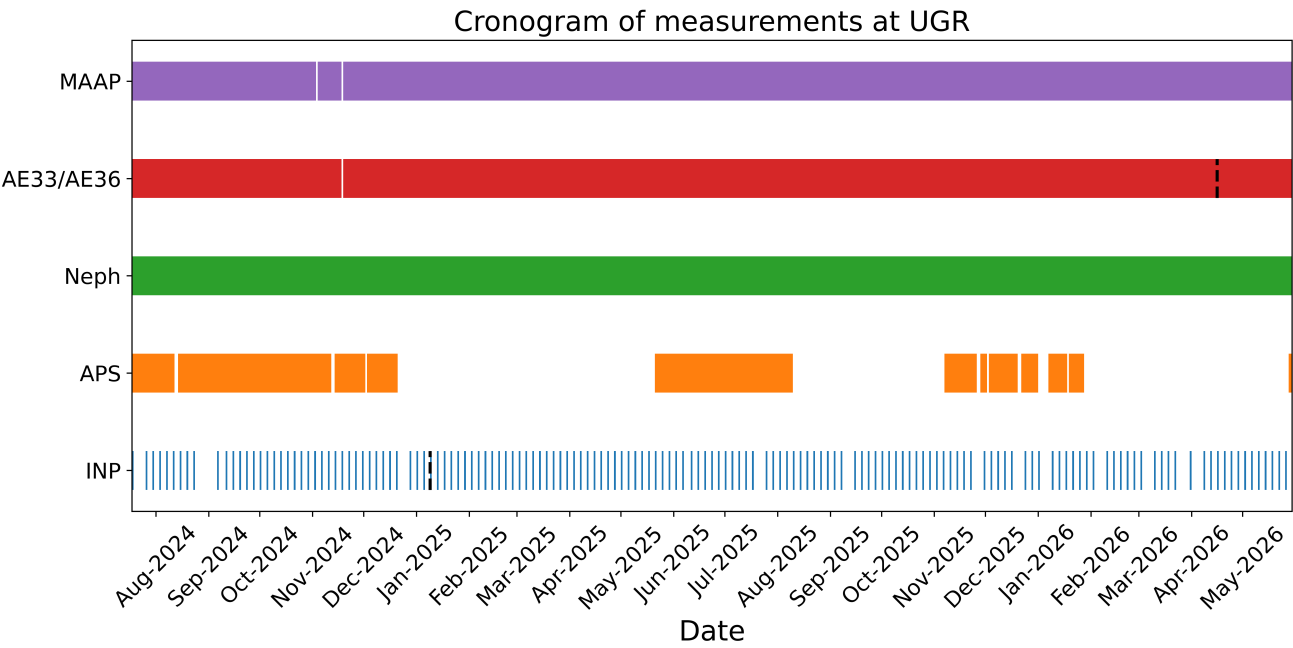


Figure S1. Cronogram of measurements at UGR station. Black dashed line in the AE33/AE36 bar marks the day when AE33 was replaced by AE36 at the station. Black dashed line in the INP bar marks the switch from CAV-A/Mb to GRASS.

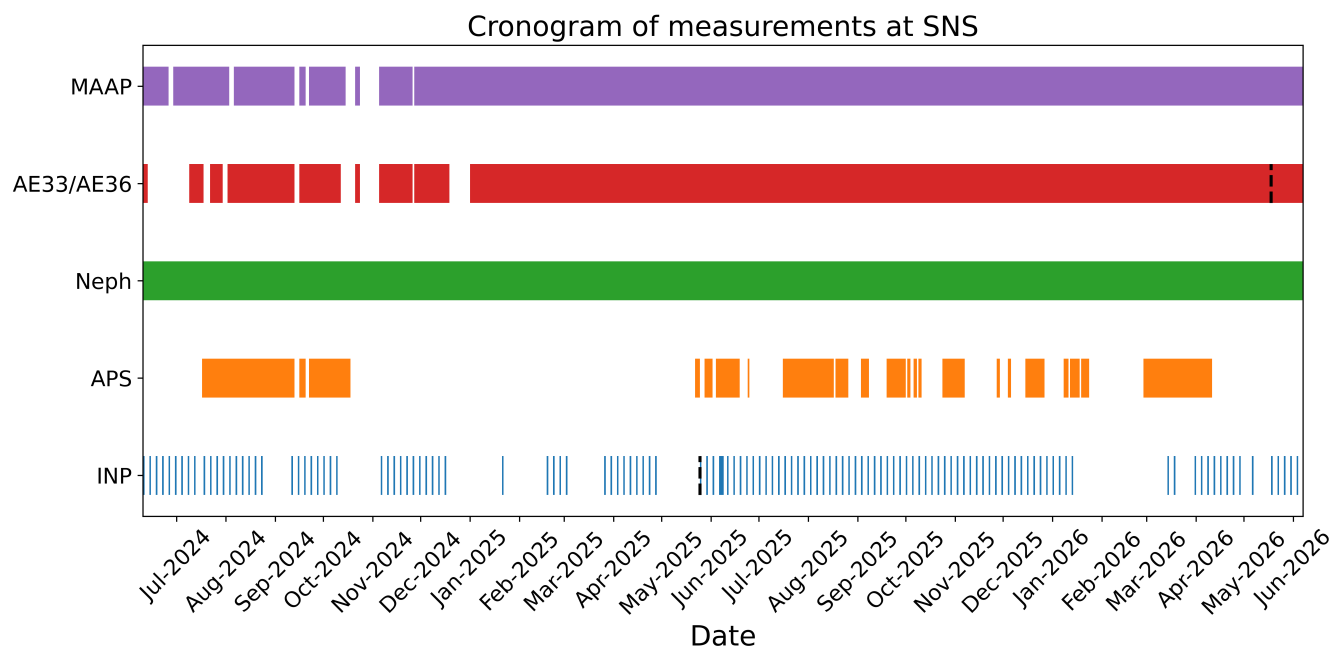


Figure S2. Cronogram of measurements at SNS station. Black dashed line in the AE33/AE36 bar marks the day when AE33 was replaced by AE36 at the station. Black dashed line in the INP bar marks the switch from CAV-A/Msb to GRASS.

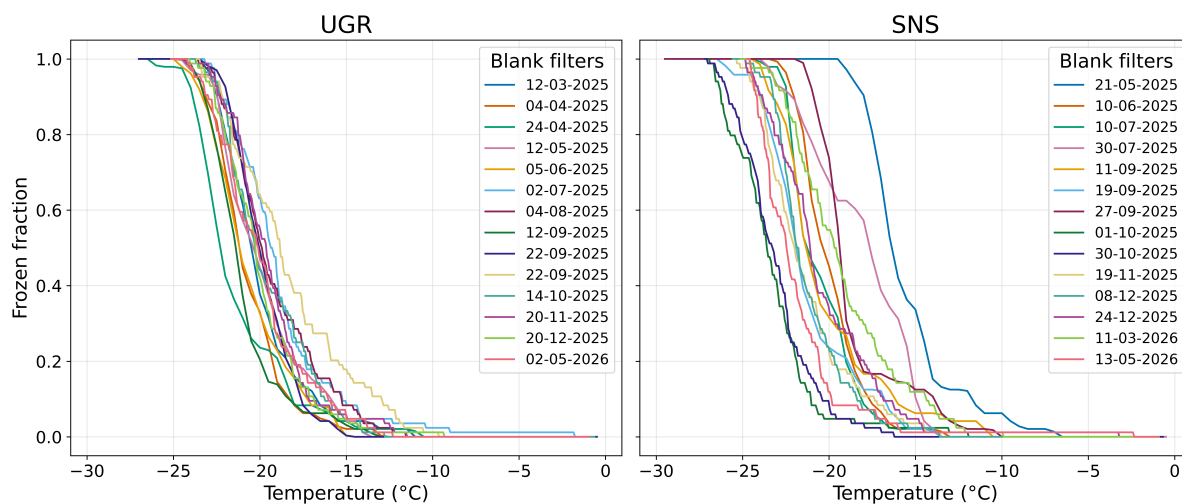


Figure S3. Frozen fraction of the field blank filters at UGR and SNS.

S2 Obtention of the total surface area with aerosol optical properties

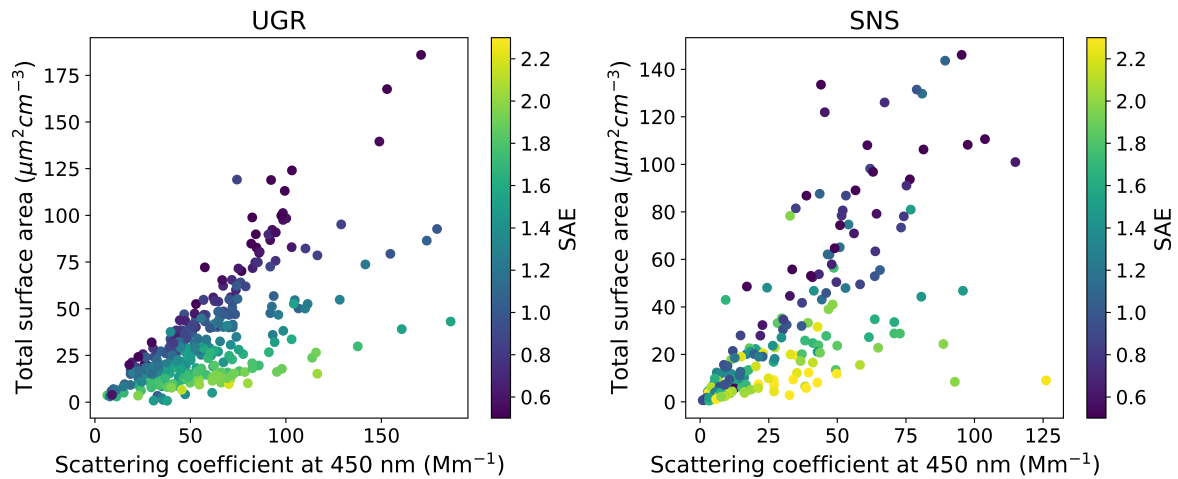


Figure S4. Relationship between the total surface area from APS size distribution measurements and the scattering coefficient at 450 nm measured by the integrating nephelometer, colored by the SAE.

S3 Overview of INP at UGR and SNS

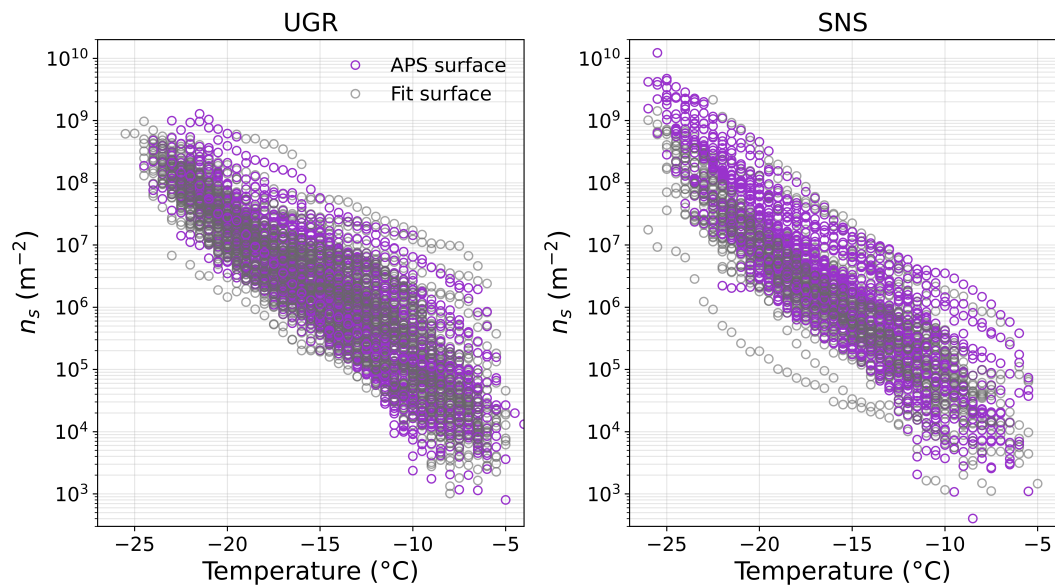


Figure S5. INAS densities at UGR (left) and SNS (right) for the entire measurement period.

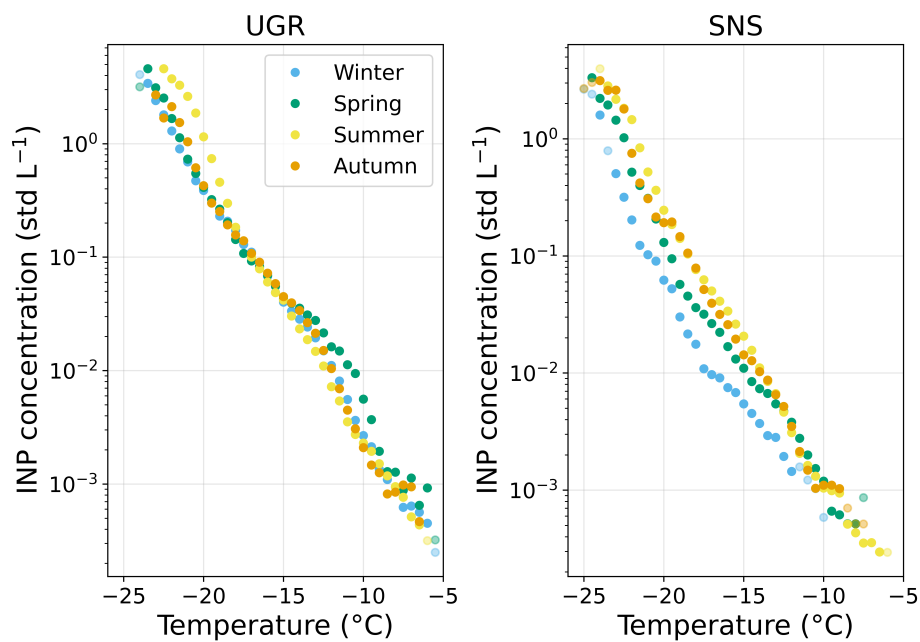


Figure S6. Seasonal median of the INP concentrations at UGR (left) and SNS (right).

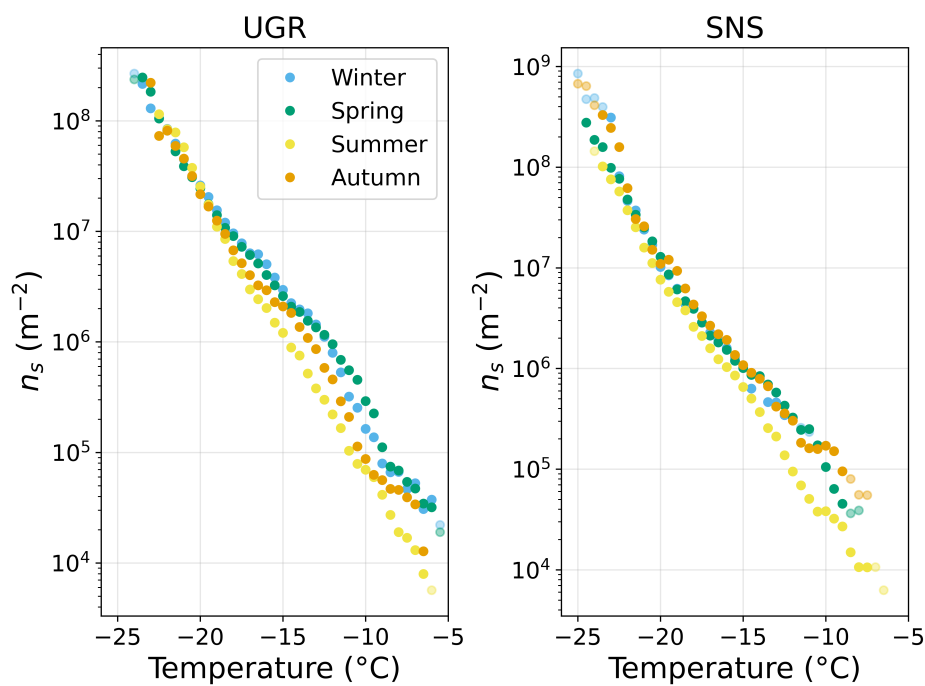


Figure S7. Seasonal median of the INAS densities at UGR (left) and SNS (right).

S4 Relationship of INP concentrations and aerosol optical properties

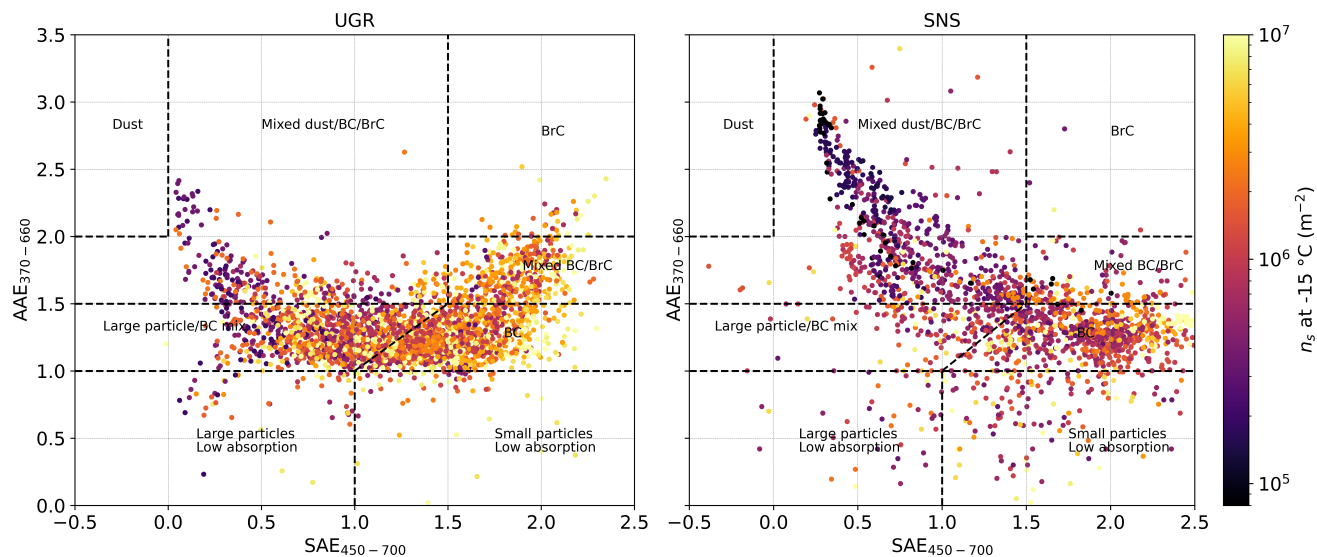


Figure S8. Absorption Ångström exponent (AAE) versus scattering Ångström exponent (SAE) for the entire measurement period. Data points represent daily averages of the optical properties and are colored by the INAS densities at -15°C . The classification shown was proposed by Cappa et al. (2016).

5 S5 Predicting INP concentrations at UGR and SNS using aerosol properties

Table S3. Permutation feature importance (PFI) of the aerosol variables included in the Random Forest models at SNS for three different temperatures (-12, -15 and -18 °C). Values are reported as mean $\pm$ standard deviation from 100 permutations.

Model	Variable	-12 °C	-15 °C	-18 °C
σ_{sp}	σ_{sp}	0.275 ± 0.132	0.375 ± 0.176	0.220 ± 0.182
	SAE	0.039 ± 0.046	0.095 ± 0.059	-0.071 ± 0.034
	AAE	-0.008 ± 0.055	0.037 ± 0.030	-0.005 ± 0.036
	SSA	-0.079 ± 0.093	-0.004 ± 0.057	-0.093 ± 0.034
N_{500}	N_{500}	-0.174 ± 0.161	0.466 ± 0.249	0.512 ± 0.224
	SAE	-0.401 ± 0.325	0.027 ± 0.061	0.093 ± 0.106
	AAE	-0.382 ± 0.342	-0.013 ± 0.040	-0.003 ± 0.024
	SSA	0.428 ± 0.300	0.062 ± 0.142	0.010 ± 0.048
σ_{ap}	σ_{ap}	0.232 ± 0.114	0.377 ± 0.176	0.232 ± 0.181
	SAE	0.071 ± 0.049	0.075 ± 0.060	-0.101 ± 0.055
	AAE	-0.022 ± 0.073	0.021 ± 0.033	0.002 ± 0.036
	SSA	-0.087 ± 0.084	0.015 ± 0.091	-0.075 ± 0.052

Table S4. Permutation feature importance (PFI) of the aerosol variables included in the Random Forest models at UGR for three different temperatures (-12, -15 and -18 °C). Values are reported as mean $\pm$ standard deviation from 100 permutations.

Model	Variable	-12 °C	-15 °C	-18 °C
σ_{sp}	σ_{sp}	0.030 ± 0.070	-0.018 ± 0.033	0.021 ± 0.111
	SAE	0.099 ± 0.078	0.047 ± 0.099	0.138 ± 0.074
	AAE	0.058 ± 0.054	0.243 ± 0.096	-0.011 ± 0.056
	SSA	0.016 ± 0.096	0.036 ± 0.106	0.133 ± 0.081
N_{500}	N_{500}	-0.063 ± 0.048	-0.075 ± 0.045	0.062 ± 0.065
	SAE	0.076 ± 0.069	-0.012 ± 0.085	0.043 ± 0.056
	AAE	0.069 ± 0.043	0.157 ± 0.066	-0.021 ± 0.059
	SSA	-0.006 ± 0.176	-0.188 ± 0.153	0.041 ± 0.075
σ_{ap}	σ_{ap}	0.063 ± 0.070	0.091 ± 0.066	0.072 ± 0.073
	SAE	0.070 ± 0.071	0.024 ± 0.069	0.124 ± 0.067
	AAE	0.054 ± 0.058	0.156 ± 0.076	-0.011 ± 0.067
	SSA	0.091 ± 0.112	0.033 ± 0.081	0.024 ± 0.047

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