



Supplement of

Immersion freezing of surface dust particles from Tengger Desert in China: effects of mineral composition and aging treatments on ice nucleating activity

Jiao Xue et al.

Correspondence to: Bingbing Wang (bingbing.wang@xmu.edu.cn)

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S1 Temperature calibration and freezing temperature at different heating/cooling rates.

Following Budke and Koop (2015), temperature calibration was performed using the melting points of decane (243.45 K) and dodecane (263.55 K) (Knopf and Lopez, 2009) at heating rates of 0.5–10 K min⁻¹. These reference temperatures span much of the freezing temperature range investigated in this study (245–265 K). Calibration was conducted in heating mode because the thermal lag of an organic crystal above its melting temperature is usually negligible (Budke and Koop, 2015). In contrast, using the temperature of liquid to solid phase transition (e.g, freezing of water droplets) in cooling mode for calibration will lead to supercooling of a liquid. In addition to the variability of freezing temperature due to the stochastic nature of crystallization, even minor supercooling and the stochastic nature would bias a calibration in cooling mode. The reference substances were deposited on hydrophobic glass slides prepared in the same manner as those used for the droplet freezing experiments. The measured melting temperatures were compared with literature values to establish the calibration, which was then applied to the raw freezing temperatures. Applying the heating mode calibration to the cooling mode freezing measurements assumes comparable thermal lag during heating and cooling at the same temperature change rate. At a heating rate of 10 K min⁻¹, the deviations from the literature melting points were approximately 2.1 K for decane and 1.6 K for dodecane (Fig. S2). The absolute difference between the calibrated temperatures and the literature values was determined for individual calibration. We reported a conservative temperature uncertainty of ± 0.5 K as the higher values of standard deviations of these absolute differences at 243 and 263 K, as shown as error bars in Fig. S2 which is smaller than 0.5 K at 243 K and 0.3 K at 263 K.

We conducted additional freezing experiments using water droplets and Tengger Desert dust suspensions at different cooling rates. T_{50} showed little variation at cooling rate between 0.5 and 2 K min⁻¹, whereas the differences in T_{50} between 10 and 1 K min⁻¹ were +1.1 K at 255 K and -0.9 K at 245 K (Fig. S3). Previous studies have demonstrated that immersion freezing can exhibit cooling rate dependence due to the time dependent nature of nucleation, although the magnitude of this effect varies among ice nucleating materials and with particle surface area (Broadley et al., 2012; Wright et al., 2013). Studies of kaolinite containing droplets reported an approximately 2 K decrease in freezing temperature when the cooling rate increased from 1 to 10 K min⁻¹, whereas smaller shifts have been reported for pure water droplets (Murray et al., 2011, 2012). Taken together, these studies indicate that the approximately 1 K difference observed here is consistent with previously reported cooling rate effects, although it cannot be attributed exclusively to time dependent nucleation, and potential contributions from temperature uncertainties cannot be excluded.

S2 Particle size distribution and surface area.

To independently assess the particle surface area in the dust suspensions, additional measurements were performed using dynamic light scattering (DLS), and the

corresponding geometric surface area per 1 μL droplet was estimated from the measured size distributions. The particle size distributions of suspended dust particles were measured using a DLS instrument (Zetasizer Lab, Malvern Panalytical, UK). The refractive index of the dust particles was set to 1.46, and water was used as the dispersant. The measurement temperature was maintained at 25 $^{\circ}\text{C}$. For each sample, 1 mL of S-dust or Us-dust suspension was transferred into a quartz cuvette and analyzed. At least, three replicate measurements were performed for each sample. The scattered light intensity data were processed using the instrument software to obtain volume-weighted and number-weighted particle size distributions. The surface area was subsequently calculated from the volume-weighted particle size distribution.

For 0.1 wt% suspension, the estimated surface areas per droplet obtained from DLS and CCSEM were $1.0 \times 10^6 \mu\text{m}^2$ and $2.4 \times 10^6 \mu\text{m}^2$ for Us-dust, and $8.2 \times 10^5 \mu\text{m}^2$ and $2.5 \times 10^6 \mu\text{m}^2$ for S-dust, respectively. These two methods yielded estimates within the same order of magnitude, with the CCSEM-derived values approximately 2–3 times higher. These differences may reflect differences in particle size characterization and the underlying measurement principles. The original dust was sieved to $<74 \mu\text{m}$ and only the upper portion ($\sim 10 \text{ mL}$) of each 20 mL suspension was used for both ice nucleation experiments and CCSEM/EDX analysis. Larger particles and aggregates may have settled toward the bottom of the vial before sampling, potentially reducing their representation in the upper suspension and contributing to the smaller particle size range ($\sim 0.2\text{--}2 \mu\text{m}$) observed in the CCSEM/EDX measurements. As shown in Fig. S4, the size range determined by CCSEM/EDX is generally consistent with the DLS measurements, which indicate that the majority of particles have hydrodynamic diameter below $3 \mu\text{m}$. Nebulization, aerosol transport, and impaction may introduce size dependent biases in the particles collected for CCSEM/EDX analysis. Nevertheless, the agreement between the DLS- and CCSEM-derived surface area estimates suggests that these differences did not result in an order of magnitude discrepancy in the estimated surface area under the conditions examined.

91 Table S1. Sample information for ice nucleation parameterization of compositionally
 92 complex dust in Fig. 6b from previous studies.

Reference of parameterization	Sample description
Hader et al., 2014	Commercial ATD
Niemand et al., 2012	(1) Soil sample collected in the eastern parts of the Takla Makan Desert in China (2) Soil sample collected about 50 km north of Cairo, Egypt (3) Soil sample collected near the town of Mala on the Canary Island of Lanzarote (4) Sedimented particles after a dust storm in Israel (5) Milled reference dust material, Powder Technology, Inc., Minnesota
Ullrich et al., 2017	(1) Asian desert dust collected from the ground in the eastern parts of the Takla Makan desert in China, east of the Dalimu basin between Kuerle and Ruoquiang (2) Canary Island dust collected from the ground near Mala, Lanzarote, Canary Islands (3) Israel desert dust collected as sediment particles after a Saharan dust storm event in Tel Aviv, Israel (4) Saharan desert dust collected from a hole of 1.5-m depth about 70 km northeast of Cairo, Egypt (5) Saharan desert dust collected 50 km north of Cairo, Egypt as sediment particle after sand storm event (6) Saharan desert dust collected in Morocco (7) Saharan desert dust collected as soil sample in southern Tunisia near Tozeur
Reicher et al., 2019	Airborne aerosol in dust events collected in Rehovot, Israel
Chen et al., 2021	Airborne aerosol in dust events collected in Beijing, China

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94 Table S2 The m and n values for the parameterizations of N_s as a function of T , J_{het} as a
95 function of Δa_w , and J_{het} as a function of T .

Parameterization	Samples	m	LCL_m	UCL_m	n	LCL_n	UCL_n	RMSE	R^2
$\log_{10}(N_s)$	Us-dust (0.0187 wt%)	-0.46	-0.49	-0.43	123.67	115.31	132.03	0.11	0.99
$= m_1 \times T + n_1$	Add 5×10^{-5} M AS	-0.44	-0.48	-0.41	119.94	110.65	129.23	0.12	0.99
	Add 5×10^{-4} M AS	-0.33	-0.37	-0.28	90.39	79.14	101.65	0.18	0.95
	Add 1×10^{-3} M AS	-0.54	-0.59	-0.49	145.79	132.25	159.33	0.10	0.99
	Add 2×10^{-3} M AS	-0.47	-0.57	-0.37	128.85	101.82	155.87	0.28	0.91
	Add 5×10^{-3} M AS	-0.45	-0.50	-0.40	124.32	111.48	137.16	0.16	0.97
	Add 5×10^{-2} M AS	-0.40	-0.41	-0.39	110.34	106.98	113.71	0.04	1.00
	Add 5×10^{-4} M NaCl	-0.38	-0.42	-0.34	103.68	93.31	114.05	0.14	0.97
	Add 5×10^{-3} M NaCl	-0.46	-0.49	-0.42	123.51	114.95	132.07	0.09	0.99
	Add 5×10^{-2} M NaCl	-0.52	-0.59	-0.45	139.47	121.63	157.31	0.20	0.97
	Add 2.5×10^{-4} M H ₂ SO ₄	-0.63	-0.68	-0.58	167.13	154.03	180.23	0.11	0.99
	Add 2.5×10^{-3} M H ₂ SO ₄	-0.57	-0.64	-0.50	152.81	134.89	170.72	0.11	0.98
	Add 2.5×10^{-2} M H ₂ SO ₄	-0.50	-0.60	-0.41	135.65	112.09	159.22	0.21	0.95
	Add 5×10^{-3} M HNO ₃	-0.35	-0.40	-0.30	95.78	82.45	109.11	0.21	0.94
	Add 5×10^{-3} M HNO ₃	-0.32	-0.36	-0.28	88.72	77.80	99.63	0.17	0.96
	Add 5×10^{-2} M HNO ₃	-0.55	-0.61	-0.49	146.82	130.80	162.84	0.14	0.98
	Heating treatment	-0.55	-0.59	-0.50	146.34	134.81	157.88	0.10	0.99
$\log_{10}(J_{\text{het}})$	Us-dust	54.75	51.21	58.29	-6.40	-6.92	-5.88	0.36	0.94
$= m_2 \times \Delta a_w$ $+ n_2$	S-dust	42.49	37.08	47.91	-5.49	-6.43	-4.56	0.36	0.85
	Us-dust (0.0187 wt%)	47.48	40.62	54.34	-5.82	-6.78	-4.85	0.22	0.95
	Add 5×10^{-5} M AS	46.77	39.41	54.12	-5.43	-6.41	-4.45	0.24	0.94
	Add 5×10^{-4} M AS	37.64	28.65	46.63	-3.74	-4.80	-2.69	0.35	0.85
	Add 1×10^{-3} M AS	52.27	44.76	59.79	-5.16	-6.05	-4.26	0.15	0.96
	Add 2×10^{-3} M AS	40.86	31.24	50.47	-3.54	-4.64	-2.44	0.26	0.89
	Add 5×10^{-3} M AS	38.99	33.20	44.79	-2.98	-3.58	-2.38	0.18	0.95
	Add 5×10^{-2} M AS	36.75	30.64	42.86	-2.85	-3.49	-2.21	0.19	0.93
$\log_{10}(J_{\text{het}})$ $= m_3 \times T + n_3$	Us-dust	-0.46	-0.49	-0.43	120.02	112.63	127.41	0.34	0.94
	S-dust	-0.34	-0.39	-0.30	88.84	77.66	100.02	0.35	0.85
	Us-dust (0.0187wt%)	-0.40	-0.46	-0.34	103.57	88.56	118.57	0.21	0.94
	Add 5×10^{-5} M AS	-0.40	-0.46	-0.34	103.72	87.93	119.50	0.21	0.94
	Add 5×10^{-4} M AS	-0.33	-0.40	-0.25	85.86	65.90	105.82	0.33	0.86
	Add 1×10^{-3} M AS	-0.45	-0.52	-0.39	118.37	101.47	135.27	0.14	0.96
	Add 2×10^{-3} M AS	-0.35	-0.44	-0.27	93.32	71.36	115.28	0.24	0.89
	Add 5×10^{-3} M AS	-0.34	-0.39	-0.29	90.58	76.88	104.28	0.17	0.94
	Add 5×10^{-2} M AS	-0.32	-0.38	-0.27	85.50	71.53	99.47	0.18	0.94

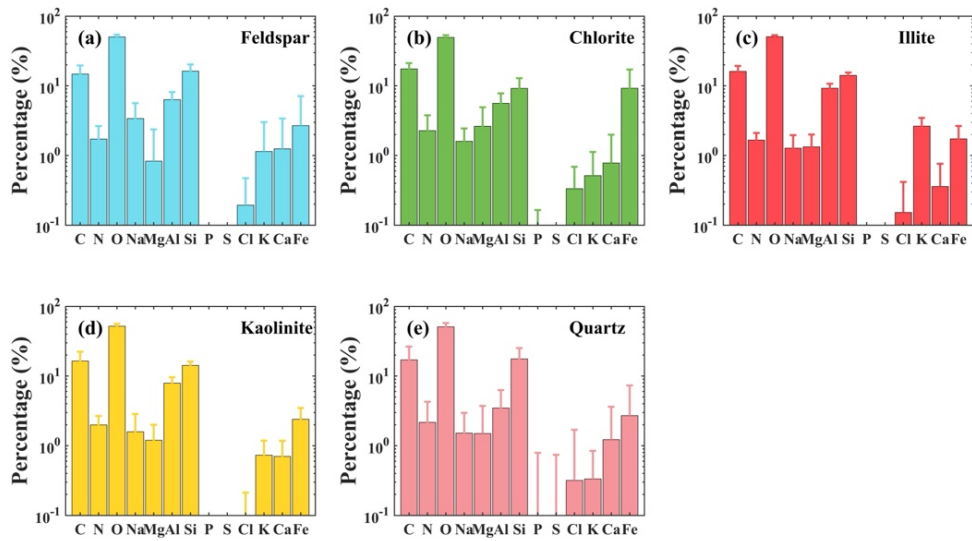


Figure S1. Mean atomic percentages of elements for each dust type from CCSEM/EDX analysis. Overall, all particles exhibit high abundances of O, Si, and Al, reflecting the typical elemental characteristics of silicate minerals. In addition to Si and Al, Feldspar contains non-negligible proportions of Na, K, and Ca. Chlorite is characterized by notably higher proportions of Fe and Mg, whereas illite exhibits a prominent K peak. For Kaolinite, apart from the major elements (O, Si, and Al), the abundances of other metallic elements (e.g., Fe, K, Ca, and Mg) are relatively low. Quartz is dominated by Si and O, with a relatively low Al content lower than Si.

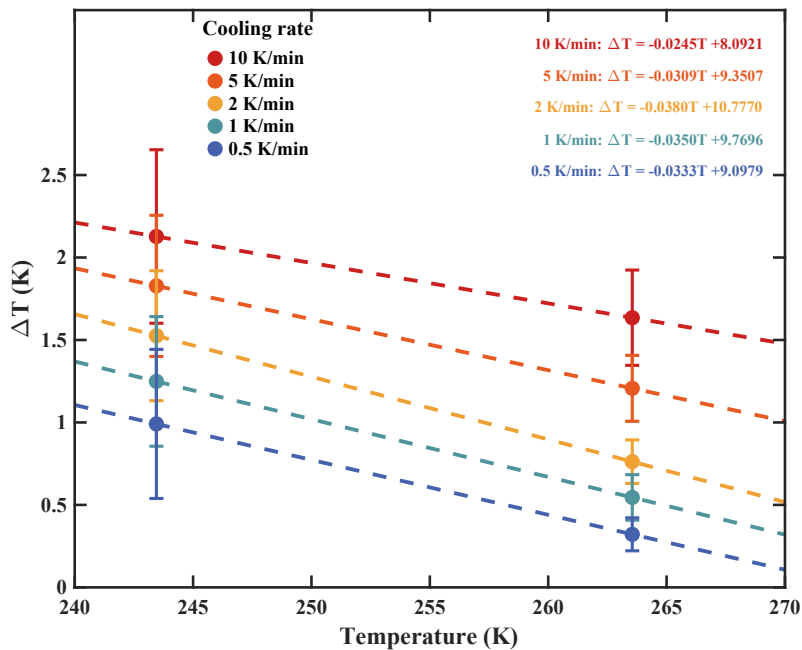
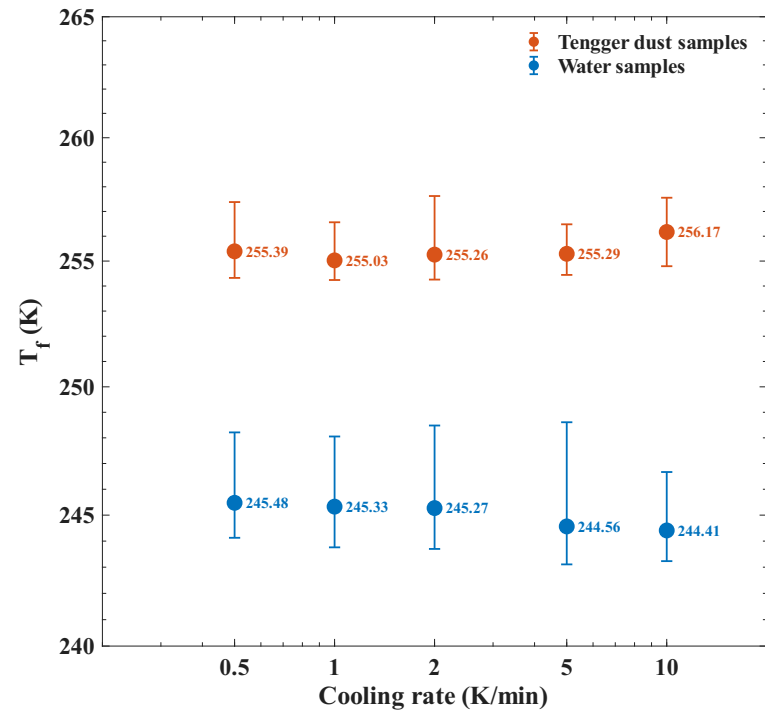


Figure S2. Temperature calibration based on the differences between the experimentally measured melting temperatures of decane and dodecane droplets and their respective literature values at heating rate of 0.5-10 K min⁻¹. Error bars indicate the standard deviations of the absolute deviations from the reference values.

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Figure S3. Median freezing temperatures of water droplets and Tengger Desert dust suspensions measured at different cooling rates. Error bars indicate the 25th and 75th percentiles.

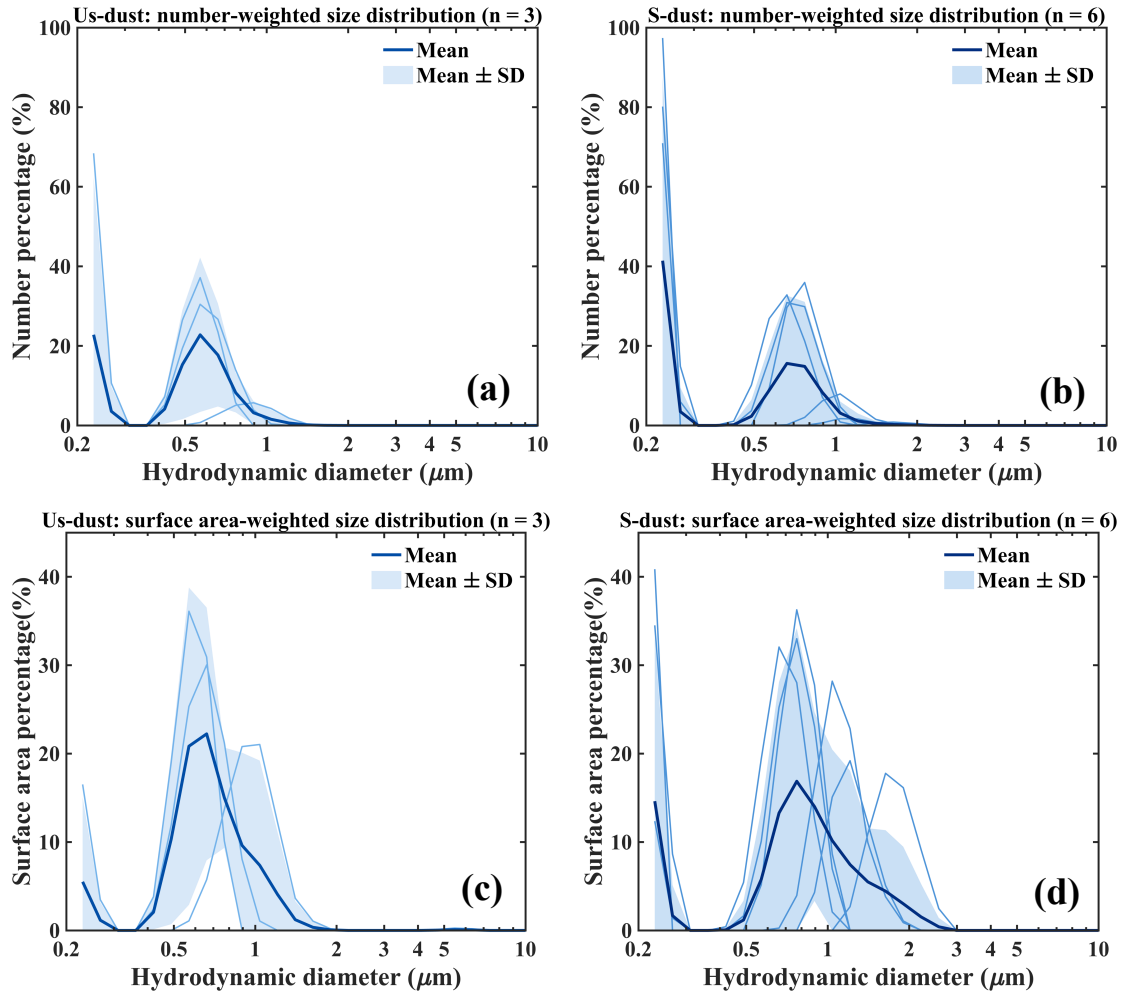


Figure S4. The number-weighted (a, b) and surface area-weighted (c, d) particle size distribution determined by DLS for Us-dust (a, c) and S-dust (b, d) suspensions. Light blue lines show individual replicate measurements; n denotes the number of replicates. Dark blue lines indicate the mean, and shaded regions indicate ± 1 standard deviation (SD).

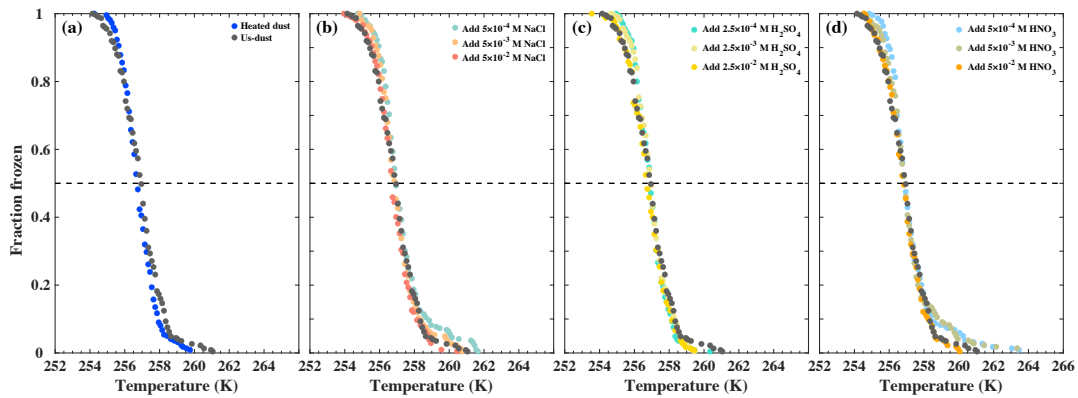


Figure S5. Frozen fraction for droplets with Us-dust (gray dots) and Us-dust treated by heating (a) and added to NaCl (b), H_2SO_4 (c), and HNO_3 (d) (dots with different colors).

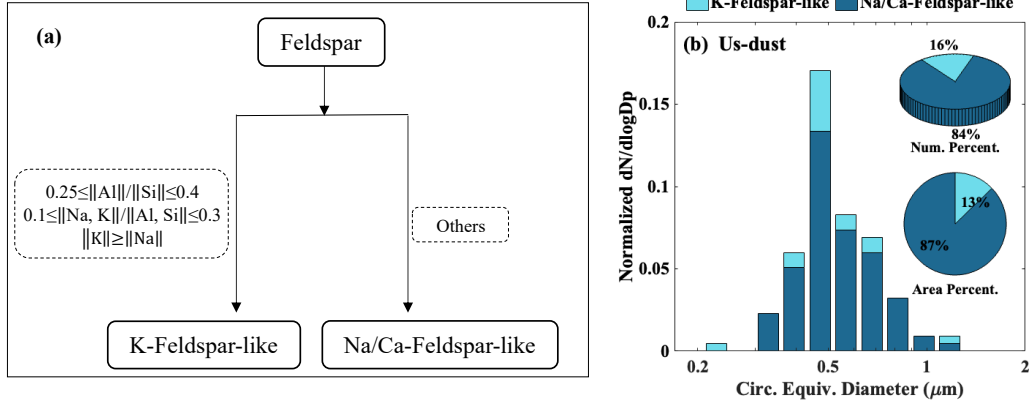


Figure S6. Separation of feldspar in Us-dust into K-feldspar and Na/Ca-feldspar. (a) Classification scheme; (b) Classification results, including normalized particle size distribution, number percentage and surface area percentage of K-feldspar and Na/Ca-feldspar in feldspar particles.

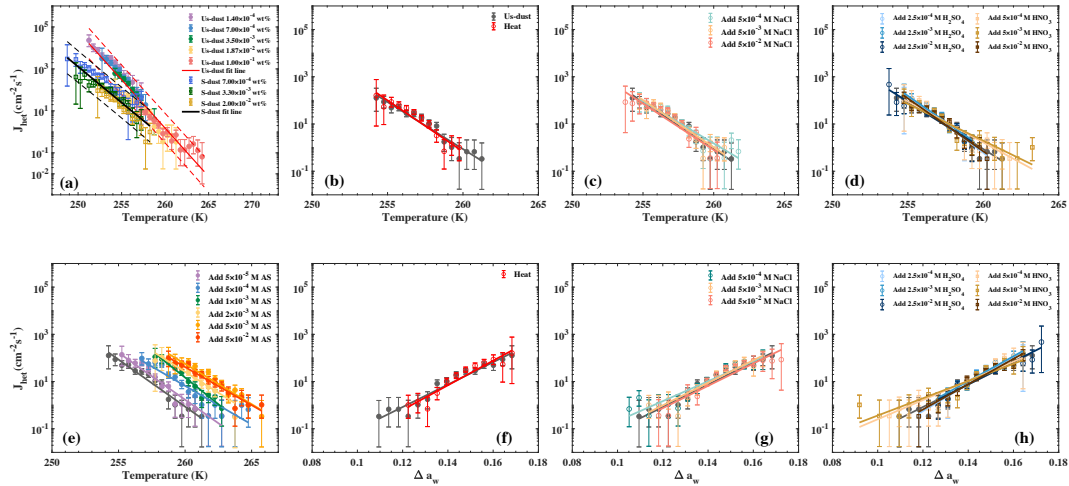


Figure S7. Heterogeneous ice nucleation rate coefficient (J_{het}) as a function of temperature (a-e) and Δa_w (f-h) for Us-dust, S-dust, and Us-Dust (1.87×10⁻² wt%) treated by heating and added to NaCl, H₂SO₄ HNO₃, and AS solution. The gray lines (b-h) are fitted lines to the Us-dust (1.87×10⁻² wt%). Solid fitting lines (a, e) are parameterizations according to $\log_{10}(J_{het}) = m \times T + n$, and the values of m and n parameters are listed in Table S2.

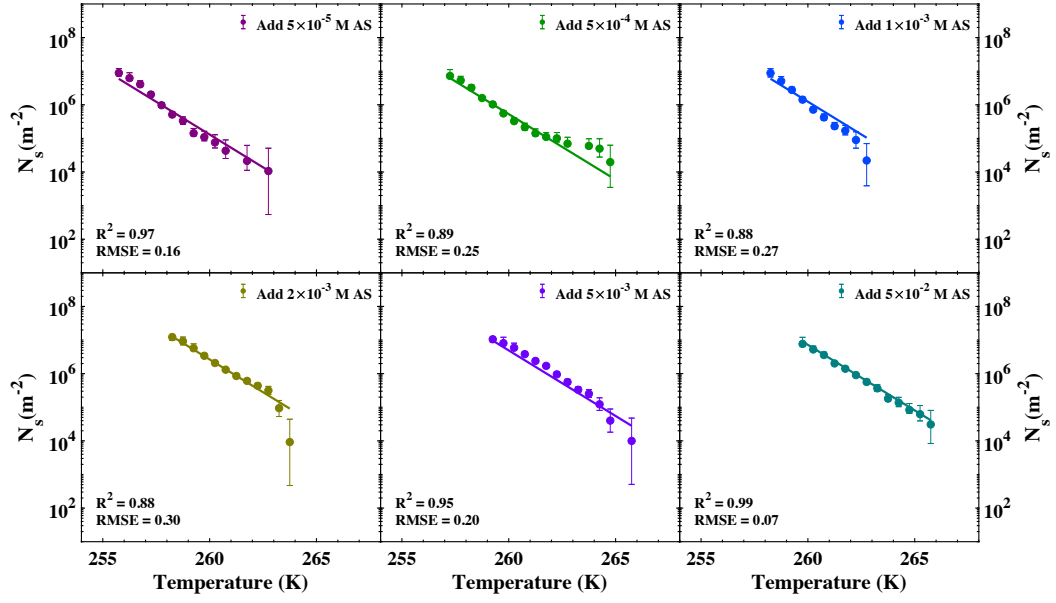


Figure S8. Comparison of the parameterized $N_s(T, r)$ with experimental data. Solid lines represent the parameterizations of $N_s(T, r)$ according with Eq.8. Colored dots represent the experimental data.

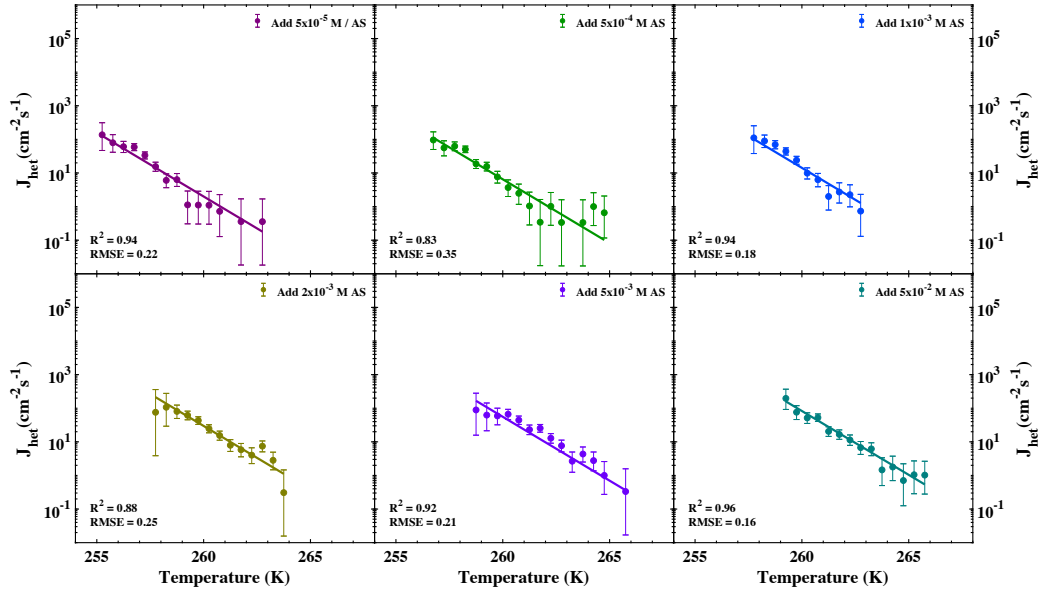


Figure S9. Comparison of the parameterized $J_{\text{het}}(T, r)$ with experimental data. Solid lines represent the parameterizations of $J_{\text{het}}(T, r)$ according with Eq.9. Colored dots represent the experimental data.

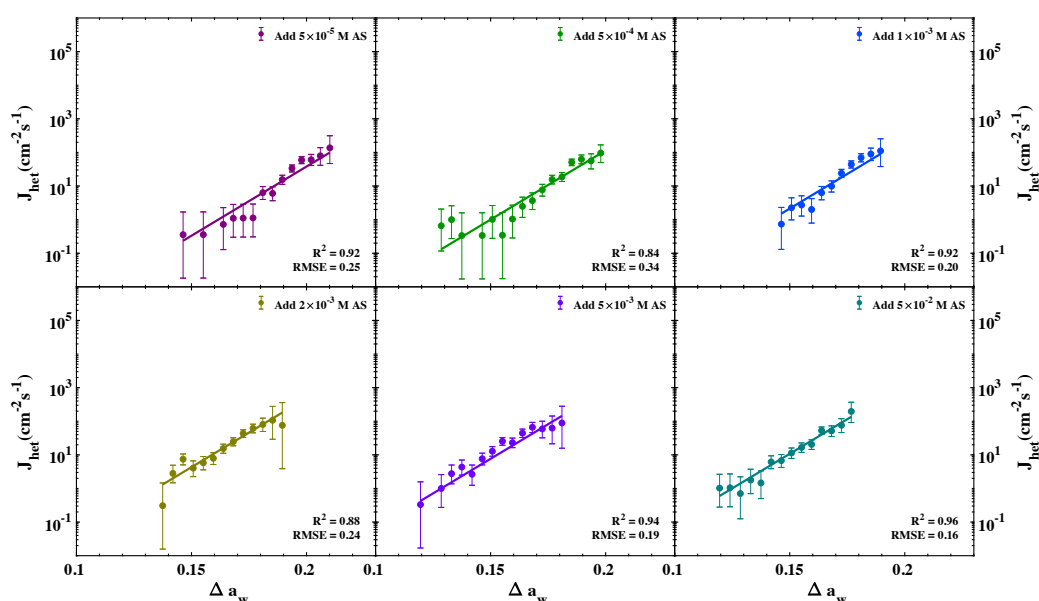


Figure S10. Comparison of the parameterized $J_{\text{het}}(\Delta a_w, r)$ with experimental data. Solid lines represent the parameterizations of $J_{\text{het}}(\Delta a_w, r)$ according to Eq.10. Colored dots represent the experimental data.

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