Anthropogenic Modulation of Dust-Dominated Ice Nucleation in an Urban Dryland City of China during Winter and Spring

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Abstract. Ice-nucleating particles (INPs) are crucial for cloud and precipitation modulation, yet their variability and sources or properties in urban dryland regions remain poorly understood. While natural dust is recognized as substantial INPs, interactions between dust and anthropogenic pollutants, and how they alter INP abundance remain insufficiently quantified. Here, we present online observations of INPs (−15 to −35 °C), together with co-located aerosol size distribution and chemical composition in Lanzhou from winter 2024 to spring 2025. We show that long-range dust transport boosts INP concentrations by ×15 at −30 °C. Elevated secondary inorganic aerosol during pollution in winter was enhanced and negatively correlated with INP activity (R = −0.71). We further refine an INP parameterization based on aerosol size (1–2.5 μm) and freezing temperature, which reproduces 83% of observations within a factor of 5. These findings underscore the need to include local aerosol heterogeneity and dust-pollution interactions in INPs parameterizations for more accurate regional climate simulations.

1. Introduction

Ice-nucleating particles (INPs) significantly reduce the energy barrier for ice crystal formation on water-insoluble aerosol surfaces by inducing heterogeneous nucleation at temperatures above −38°C (Pruppacher et al., 1998; Hoose and Möhler, 2012). Despite their extremely low atmospheric concentrations, INPs are critical for initiating ice-phase processes that govern cloud phase partitioning (Wang et al., 2015) and precipitation efficiency (Murray et al., 2012; Hawker et al., 2021). Owing to this microphysical sensitivity, cloud-seeding experiments have shown that artificially enhancing INP concentrations in supercooled clouds can shift the timing and spatial distribution of precipitation (French et al., 2018). It has been well established that most terrestrial precipitation originates from ice-phase processes, which are strongly influenced by the abundance and properties of INPs (Field and Heymsfield, 2015; Kärcher, 2022). Therefore, by regulating ice crystal number concentrations, INPs subsequently affect cloud microstructure, lifetime, and radiative properties, thereby contributing to aerosol indirect radiative forcing and posing a major source of uncertainty in climate modeling (Morrison et al., 2020; Gjelsvik et al., 2025).

INP concentrations commonly span about seven orders of magnitude across the typical temperature range in mixed-phase

clouds, and can differ by up to three orders of magnitude even at the same temperature (Petters and Wright, 2015; DeMott et al., 2010). These variations are influenced by multiple factors, including particle source, chemical composition, and surface morphology (Kanji et al., 2017). Mineral dust is considered the abundant natural source of INPs in mixed-phase clouds, with East Asian dust being particularly effective due to its relatively high ice-nucleating activity (Chatziparaschos et al., 2023; Kawai et al., 2021). Biogenic particles, such as pollen, bacteria, and fungal spores, can also contribute significantly in warm (> −10°C) and biologically active environments (Pereira Freitas et al., 2023). Marine sea spray aerosols are a major source of INPs in remote oceanic regions (McCluskey et al., 2023). On a global scale, the contribution of biomass burning aerosols (BBAs), mainly emitted by wildfires, to atmospheric INPs remains uncertain and highly variable. Although some field observations report elevated INP concentrations under biomass-burning-influenced conditions (Zhao et al., 2024), this association may partly reflect the presence of co-lofted materials such as mineral dust rather than a direct contribution from BBAs themselves (Chen et al., 2025).

Urban aerosols, shaped by diverse natural and anthropogenic sources, exhibit complex INPs characteristics: concentrations are strongly influenced by the long-range transport of desert dust (Bi et al., 2019), while black carbon (BC) from anthropogenic emissions generally exhibits low ice-nucleating efficiency under immersion freezing conditions (Kanji et al., 2020). The ice-nucleating efficiency of metal and metal-oxide particles varies strongly with chemical composition, and many pure metals and metal oxides exhibit poor ice-nucleating ability (Yakobi-Hancock et al., 2013); however, metal elements are widely used as tracers of fine mineral dust (Liu et al., 2022) and thus provide useful information on mineral-related contributions to atmospheric INPs. In suburban regions heavily affected by human activity, organic aerosols and anthropogenic dust (e.g., road dust from traffic emissions) have been identified as effective INP sources (Tian et al., 2022; Chen et al., 2024b). Moreover, anthropogenic pollution may influence cloud glaciation processes. Elevated cloud freezing temperatures have been reported under polluted conditions (Pan et al., 2024). INP number concentrations have been observed to differ between clean and polluted environments (Ren et al., 2023). However, some studies report that severe urban pollution does not lead to significant changes in INP concentrations(Chen et al., 2018; Zhang et al., 2022). These conflicting observations highlight the limited understanding of the mechanisms underlying pollution-related INPs variability, further contributing to the uncertainties in INP parameterizations within current climate models (Burrows et al., 2022; Herbert et al., 2025).

Most weather and climate models employ simplified empirical parameterization methods, one of the most representative being the scheme introduced by DeMott et al. (2010), commonly referred to as D10, which is widely integrated into global climate models and high-resolution cloud-resolving models (Burrows et al., 2022). As an empirical, size-based approach, the D10 scheme primarily relates INP number to particles larger than 0.5 μm in diameter, offering a practical proxy for INP-relevant aerosols. However, it does not explicitly account for mixing-state effects or aerosol compositions as emphasized in Phillips et al. (2008). This simplification introduces additional uncertainty in polluted environments, where mineral dust-pollution interactions and abundant pollution-derived aerosols may alter INP activity and complicate size-based representations. These challenges are not limited to polluted regions and have motivated recent efforts to develop source-aware parameterizations that explicitly include multiple aerosol types for improved regional applicability of INPs simulations

(DeMott et al., 2015; McCluskey et al., 2019).

The stagnant and compositionally complex aerosols in Lanzhou, an inland major city close to the Tibetan Plateau, shaped by its arid climate and enclosed terrain, provide a valuable setting for studying INPs behavior under mixed aerosol regimes (Tan et al., 2017). While winter heating promotes the buildup of fine-particle pollution dominated by organics and secondary inorganics (Du et al., 2020), springtime dust transport and construction activity enhance coarse particle resuspension, leading to a higher contribution from crustal materials (Cheng et al., 2022). Road dust, as a persistent local resuspension source, significantly contributes to $PM_{2.5}$, accounting for up to 51.7% of emissions in developing urban areas (Chen et al., 2019). Concurrently, the rising fraction of organic components in Lanzhou aerosols underscores the influence of traffic emissions and secondary photochemical processes (Xu et al., 2014; Wang et al., 2021). Despite these complex aerosol regimes, systematic INP observations in the region remain scarce, and hence the applicability of parameterization schemes developed in other environments under such an aerosol regime remains uncertain.

This study focuses on Lanzhou, a typical semi-arid inland city in northwest China, where systematic observations of INPs and concurrent measurements of aerosol physical and chemical properties were conducted during winter and spring. These efforts provide valuable additions to long-term INP datasets under atmospheric conditions affected by both anthropogenic pollution and dust events. Building on these observations, we investigated the inter-seasonal differences of INP concentrations in the urban atmosphere, compared nucleation efficiency across different aerosol pollution events, and developed an empirical parameterization applicable to urban background in Northwest China. This research contributes to a better understanding of INP formation mechanisms in complex source environments and provides theoretical support for improving the parameterization of INP concentrations in regional climate models.

2. Data and Methods

2.1 Overview of field campaign

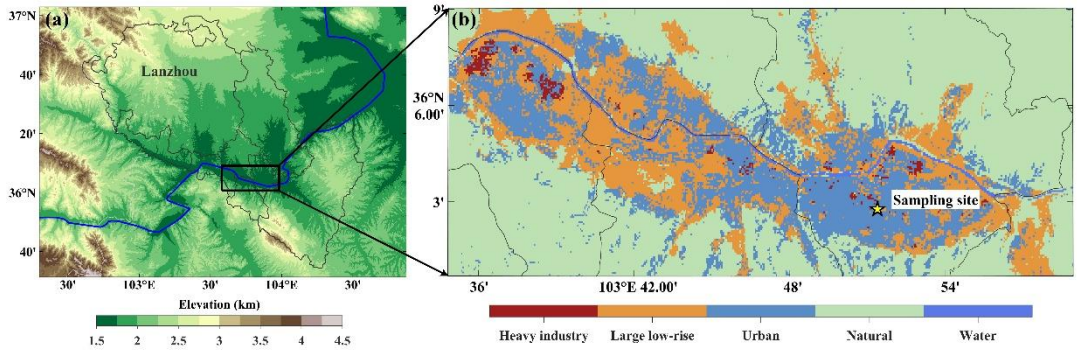

Fig.1. Overview of the location of observations. (a) Regional topography of Lanzhou. black box denotes the urban area shown in panel (b). (b) Local-scale Local Climate Zone classification of the Lanzhou urban area, with the sampling site marked by a star.

This study conducted atmospheric INPs observations during the winter and spring from 12 December 2024 to 21 April 2025. The sampling site was located on the campus of Lanzhou University (103°51′E, 36°2′N, 3m above ground level, AGL) in Lanzhou City, Northwest China, which represents a typical semi-arid inland urban environment (Fig. S1). Lanzhou is situated in a narrow river valley along the upper reaches of the Yellow River and is surrounded by complex terrain (Fig. 1). This enclosed topographic setting frequently suppresses atmospheric dispersion and favors the accumulation and interaction of aerosols within the urban boundary layer (Chen et al., 2019). As a result, the sampling site is influenced by both regional dust transport and local anthropogenic activities.

The observation was conducted using a container-type mobile station, where key monitoring parameters, including INP concentration and aerosol particle number size distribution ($N(D)$), and black carbon (BC) mass concentration, were continuously measured. Ambient aerosols were sampled using the same container-based mobile observation system as described in Wang et al. (2025), without an external size-selective inlet. The CFDC instrument is equipped with two size-selective inlets connected in series, and details are provided in Sect. 2.5. Additionally, a National Atmospheric Super Monitoring Station is co-located on the campus and provides supporting measurements of aerosol chemical composition. A detailed description of the monitoring station can be found elsewhere (Du et al., 2020; Li et al., 2023).

2.2 Aerosol size distribution measurements

A Scanning Mobility Particle Sizer (SMPS; Model 3082, TSI Inc.) was employed to measure the electrical mobility diameter in the size range of 13.6 nm to 532.8 nm, divided into 103 bins, with a complete scan conducted every two minutes. The Stokes diameter is denoted as D and is approximately equal to the electrical mobility diameter (Hinds, 1999; Baron and Willeke, 2011). An Aerodynamic Particle Sizer (APS; Model 3321, TSI Inc.) was used to measure the aerodynamic diameter (D_a) in the range of 0.542 to 19.81 μm, divided into 51 size bins, with a full scan performed every five minutes. To minimize humidity-related measurement errors, which could lead to size overestimation due to particle growth, the particle stream was dried using a silica gel diffusion dryer. The D_a distribution obtained by the APS was converted to D distribution by assuming an effective particle density of 1.5 g cm^{-3}, a typical value for urban aerosol environments (Zhang et al., 2022), so that the size distributions from different instruments could be merged.

All particle size distribution data were averaged to 10-minute intervals to enable temporal alignment and reduce short-term statistical fluctuations before merging. After combining the data from both instruments, several particle size distribution parameters were calculated, including the $N(D)$, surface area concentration distribution, and volume concentration distribution. The attached diagram (Fig. S2) shows the combined particle size results for the entire sampling period, which exhibited no significant biases and acceptable levels of precision.

2.3 Aerosol chemical composition and reconstructed tracers

Aerosol chemical composition data were used to characterize particulate matter properties relevant to INP variability. A seven-wavelength Aethalometer (AE33, Magee Scientific Inc.) was employed to measure aerosol absorption coefficients and

derive equivalent BC mass concentration (Wang et al., 2024a). BC mass concentration was measured at a native time resolution of 1 min at 370, 470, 520, 590, 660, 880, and 950 nm. The BC mass concentrations were calculated by the light absorption coefficients at 880 nm (Li et al., 2023) and a 10 min moving average was applied before analysis. In addition, The National Atmospheric Super Monitoring Station, provided $PM_{2.5}$ measurements of major water-soluble inorganic ions (NH_4^+, NO_3^-, SO_4^{2-}, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, and K^+) as mass concentrations (μg m^{-3}) from an online ion chromatograph (IC) and elemental mass concentrations (μg m^{-3}; e.g., Ca, Al, Fe, Ti, Si) from a heavy-metal analyzer (XHAM-2000), offering essential support for the aerosol composition analysis (Tian et al.,2023). Both ion and elemental composition data were recorded at an hourly time resolution.

Reconstructed chemical tracers, including Fine mineral dust (FMD) and secondary inorganic ions (SNA), were derived to represent major aerosol types and processes. To further elucidate the drivers of the observed differences in INP activity among the event types, we focused on −30 °C for detailed analysis, because it is a characteristic temperature at which immersion freezing is most frequently examined. FMD in $PM_{2.5}$ was determined following Malm et al. (1994), and was used as a mineral dust tracer representing both locally resuspended urban dust and transported mineral dust. Specifically, FMD was estimated from the major crustal elements measured in $PM_{2.5}$ using the following mass reconstruction equation:

$$FMD = 2.20\ Al + 2.49\ Si + 1.63\ Ca + 2.42\ Fe + 1.94\ Ti \quad (1)$$

where Al, Si, Ca, Fe, and Ti denote the measured elemental concentrations. The coefficients account for the contribution of associated oxides and represent the typical stoichiometric ratios of aluminosilicate mineral dust.

SNA was quantified as the summed concentration of SO_4^{2-}, NO_3^-, NH_4^+, a commonly used formulation that reflects the overall loading of secondary inorganic aerosol and serves as an indicator of pollution processing (Hu et al., 2017). Specifically, SNA was calculated as:

$$SNA = SO_4^{2-} + NO_3^- + NH_4^+ \quad (2)$$

with all components expressed as $PM_{2.5}$ mass concentrations. It should be noted that these reconstructed tracers are used here as empirical proxies to characterize relative variations in major aerosol components rather than exact mass apportionment.

2.4 Aerosol event categorization

Since the sampling site lacked an online mass concentration monitoring instrument, hourly $PM_{2.5}$ mass concentration data were obtained from the National Environmental Monitoring Station at the Railway Design Institute, located approximately 1.7 km away. To investigate how different aerosol regimes influence INP activity, we categorized the observation period into four event types (Fig. S3). Dust events were identified by $PM_{10} \geq 150$ μg m^{-3}, while non-dust conditions were further separated into Clean, Moderate, and $PM_{2.5}$ High categories according to $PM_{2.5}$ thresholds of 35 and 75 μg m^{-3}. The PM_{10} can effectively capture the arrival of dust intrusions and has been used in previous studies to identify periods of coarse-mode aerosol enhancement (Lei et al., 2014; Wang et al., 2024b), while $PM_{2.5}$ serves as a useful indicator of pollution severity (Ren et al., 2023). In combination, these two indicators offer a representative and widely comparable basis for separating dust events from

varying levels of pollution. The occurrence frequencies and INP characteristics associated with the different aerosol event types are presented in Sect. 3.2.

2.5 INPs observations

INP measurements in this study were performed using a commercial Continuous Flow Diffusion Chamber–Ice Activation Spectrometer (CFDC-IAS), which is based on the well-established CSU-CFDC design (Rogers et al., 2001; DeMott et al., 2015) and is capable of autonomous operation with minimal in-person handling and full remote access (Bi et al., 2019). Hereafter, this instrument is referred to as CFDC. Detailed technical specifications and theoretical descriptions have been comprehensively documented in previous instrument publications (Lacher et al., 2024; DeMott et al., 2017, 2025). The chamber comprises two concentric cylindrical walls, each maintained at different temperatures through an ethanol circulation system. The inner surfaces are coated with ice, creating a temperature and humidity gradient in the upper growth region of simulated cloud particles, where aerosol particles activate, nucleate, and grow as ice crystals. In the lower evaporation region, liquid droplets rapidly evaporate, leaving only ice crystals for optical particle counter (OPC) detection. The sheath gas flow rate and sample flow rate were set at 7.5 L min^{-1} and 1.5 L min^{-1}, respectively, to ensure stable delivery of both the gas flow and sample. Water supersaturation conditions (typically 4–6% SS_w), consistent with those reported by Moore et al. (2024) for immersion freezing, were maintained in the growth section. Here, SS_w denotes supersaturation with respect to liquid water and is defined as $SS_w = RH_w - 100\%$.

Before the experimental observations, the performance of the CFDC was assessed using ammonium sulfate and illite-NX under representative temperature and supersaturation conditions (Fig. S4–S5). These tests were intended to verify stable OPC-based ice crystal detection and chamber operation under immersion-freezing conditions. Illite-NX and ammonium sulfate are standard reference materials widely used in CSU-CFDC studies to characterize heterogeneous and homogeneous freezing (Richardson et al., 2010; Hiranuma et al.,2015). The thermodynamic freezing onset characteristics of these materials have been systematically documented for the standard CSU-CFDC configuration over comparable temperature and supersaturation ranges (e.g., Rogers et al., 2001; Kanji et al., 2011; Levin et al., 2014). To ensure accurate measurements, the aerosol stream was dried below the frost point using silica gel and molecular sieves. Aerosol particles that could interfere with the optical detection of ice crystals were removed by passing the aerosol stream through two identical single-jet impactors in series (D50 = 2.5 μm), where D50 denotes the aerodynamic particle diameter at which 50% of particles are transmitted through the impactor. The CFDC is serviced weekly, with the diffusion desiccant replaced, O-rings sealed, the water tank replaced when necessary, and the nitrogen tank changed as needed. The experimental temperature ranged from −15°C to −35°C, with a 5°C interval, to fully investigate ice nucleation activity under varying temperature conditions. The measurement cycle was 5 minutes, alternating with a 5-minute HEPA-filtered air cycle to provide background counts for the instrument. During this process, the INP concentration was background-corrected using data from the adjacent filtered air cycle (Barry et al., 2021). The effective detection limit of the CFDC is not a fixed instrumental constant but depends, for example, on the sampling flow rate, integration time, and background ice counts (Demott et al., 2017). Under the operating conditions applied here, the

effective lower detection limit is estimated to be ~0.13 INP sL^{-1}. In this study, INPs and $N(D)$ results are reported under standard conditions (STP: 0°C, 101.325 kPa).

To ensure temporal consistency across datasets, all aerosol measurements, including $N(D)$, particle mass concentration, BC, and aerosol chemical composition, were temporally matched to INP observations using the same nearest-neighbor approach. For each INP measurement, the closest-in-time data point from each aerosol dataset was selected, provided that the time difference did not exceed 30 min. This time window was chosen to avoid using aerosol data that are temporally too distant from the corresponding INP measurements.

2.6 Back trajectory models

Backward air-mass trajectories were calculated using the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT), developed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory (Hofer et al., 2024). The model was driven by the GDAS 1° × 1° meteorological dataset. To determine an appropriate arrival height for trajectory analysis over the entire sampling period, 72 h backward trajectories were first calculated at 1 h intervals for four arrival heights (100, 500, 1000, and 1500 m AGL). The backward trajectory frequency patterns show broadly similar dominant source regions across the four starting heights, with air masses mainly originating from western and northwestern continental regions (Fig. S6). Despite these differences, the associated land-cover fractions remain relatively consistent among heights. We therefore focus on trajectories arriving at 100 m AGL in the following analyses as representative of near-surface air masses influencing the INP measurements. The resulting trajectories were then used to infer the potential influence of regional dust sources and anthropogenic pollution on the observed INP variability. This approach is commonly applied in field-based INP studies to provide source-context information complementary to in situ aerosol chemical measurements.

The land cover types were obtained from the MODIS Land Cover Type product (MCD12C1 v061) for the year 2024, based on the International Geosphere–Biosphere Programme (IGBP) classification scheme at a spatial resolution of 0.05°. The original 17 IGBP classes were further aggregated into seven major land-cover categories (barren, grass and shrubland, cropland, forest, urban, water and wetland, and snow and ice). To further characterize the underlying surface types along transport pathways, each trajectory was overlaid with a gridded land-cover dataset, and the fractional contributions of major land-cover classes were calculated. This combined trajectory–land-cover analysis is commonly applied in field-based INP studies as a complement to in situ aerosol chemical measurements (Chen et al., 2024a).

3. Results and Discussion

3.1 Dust predominates over pollution in INP bursts

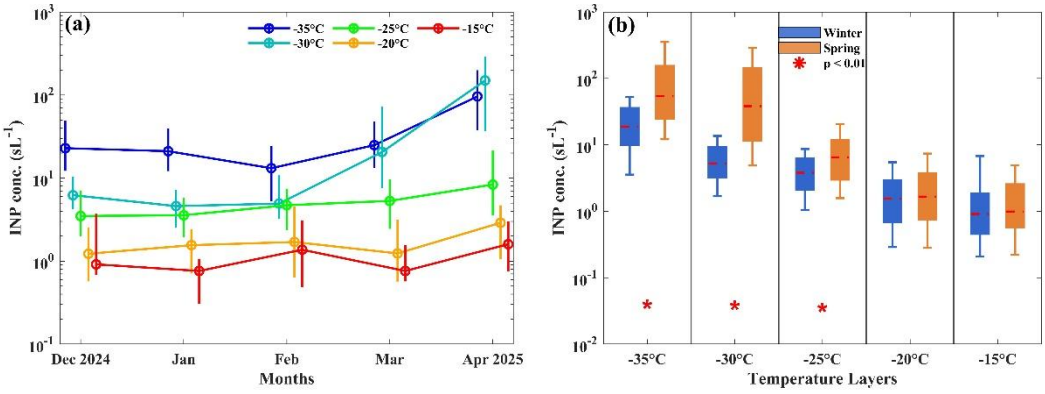

Fig. 2. Monthly variations and Seasonal differences in INPs. (a) Monthly median INP concentrations. (b) Seasonal box plots of INP concentrations in winter (December–February) and spring (March–April); boxes indicate the interquartile range, whiskers the 10th–90th percentiles, and red asterisks denote significant differences.

In most months and in both seasons, the median INP concentrations decreased as the activation temperature increased from −15 °C to −35 °C (Fig. 2), reflecting the expected temperature dependence of immersion freezing. From December to April, INP concentrations at −15 °C and −20 °C remained relatively stable. In contrast, INPs at −25 °C, −30 °C, and −35 °C showed little variation from December to February, followed by a pronounced increase in March that persisted through April. Over the same period, coarse-mode aerosol (1 μm < D < 2.5 μm) number concentrations showed a similar increase. In addition, mass concentrations of water-soluble mineral-related ions, such as Ca^{2+}, and crustal trace metals were also higher during this period (Fig. S7; Table S1). This linkage suggests that the seasonal rise in INPs was closely tied to the intensification of the coarse mineral-dust component during spring.

Seasonal comparisons further confirmed the significance of these differences: spring INP concentrations were a factor of 1.4–2.2 higher than winter levels (Mann–Whitney U test; Fig. 2b). These increases coincided with enhanced coarse-mode aerosol and Ca^{2+}, as well as elevated crustal trace metals (Table S1), whereas $PM_{2.5}$, BC, SO_4^{2-}, NO_3^-, NH_4^+, and Cl^- were all higher in winter (Fig. S7). Overall, these results indicate a clear redistribution in aerosol composition, with coarse dust dominating in spring and fine particle pollution prevailing in winter, consistent with the enhanced heating-related coal combustion in northwestern China (Du et al., 2020). Such shifts in the dominant aerosol sources are often the main driver of seasonal variations in INPs (Creamean et al., 2022), explaining the substantially higher cold-temperature INP activity observed during spring.

Indeed, a Spring dust intrusion coincided with enhanced coarse-mode aerosol, PM_{10}, FMD, and Ca^{2+}, accompanied by a pronounced increase in INP concentrations at −25 °C, −30 °C, and −35 °C (Fig. S8). Such behavior reflects the high immersion-freezing efficiency of mineral dust, particularly its abundance in the coarse mode during dust intrusions. In contrast, the wintertime $PM_{2.5}$ pollution episode during the Lantern Festival showed no marked change in INP concentrations at most activation temperatures, with only fluctuations observed at −35 °C. This indicates that pollution-derived fine particles, although abundant in winter, have intrinsically low immersion-freezing ability and exert only a minor influence on INPs compared with

mineral dust. As meteorological parameters were generally stable (Fig. S9) and INPs were measured under fixed temperature and humidity conditions, the observed variability was predominantly driven by aerosol influences rather than changes in meteorological conditions. To summarize, the springtime predominance of coarse dust, overriding the wintertime $PM_{2.5}$ pollution, establishes the requisite conditions for the episodic INP bursts (i.e., episodic and pronounced increases in INP concentrations) that characterize the ice nucleation regime in the inland basin.

3.2 INP Characteristics under Different Aerosol Events

The observations are categorized into four aerosol event types (Clean, Moderate, PM2.5 High, and Dust). These event types e exhibit distinct seasonal preferences, with Dust and Clean events occurring mainly in spring, while PM2.5 High events are predominantly observed in winter (Fig. S10). The four categories showed distinct physicochemical characteristics, further confirming the representativeness of this classification (Fig. 3a–3c). Dust events were characterized by markedly high PM_{10} levels and a low $PM_{2.5}/PM_{10}$ ratio (~0.25), indicative of the coarse-mode particles' dominance (Yu et al., 2024). In contrast, $PM_{2.5}$ High events show elevated $PM_{2.5}$ concentrations and higher ratios (0.5–1.0). This divergence was further unequivocally reflected in $N(D)$ (Fig. 3b). Dust events uniquely exhibit a pronounced coarse-mode aerosol concentration with enhanced number concentrations in the $0.5 < D < 1.0$ μm range, indicative of mineral dust input. Finally, chemical composition indicators, including major ions, BC, and FMD, provided conclusive evidence for distinct particle sources (Fig. 3c). Dust events were marked by abundant mineral ions, whereas $PM_{2.5}$ High events were enriched with BC and secondary inorganic ions, along with additional fine-mode species such as Cl^- and K^+. Moderate events displayed mixed ion characteristics, with concentrations falling between conditions of Dust and $PM_{2.5}$ High events, and Clean events consistently registered the lowest ion concentrations across all species.

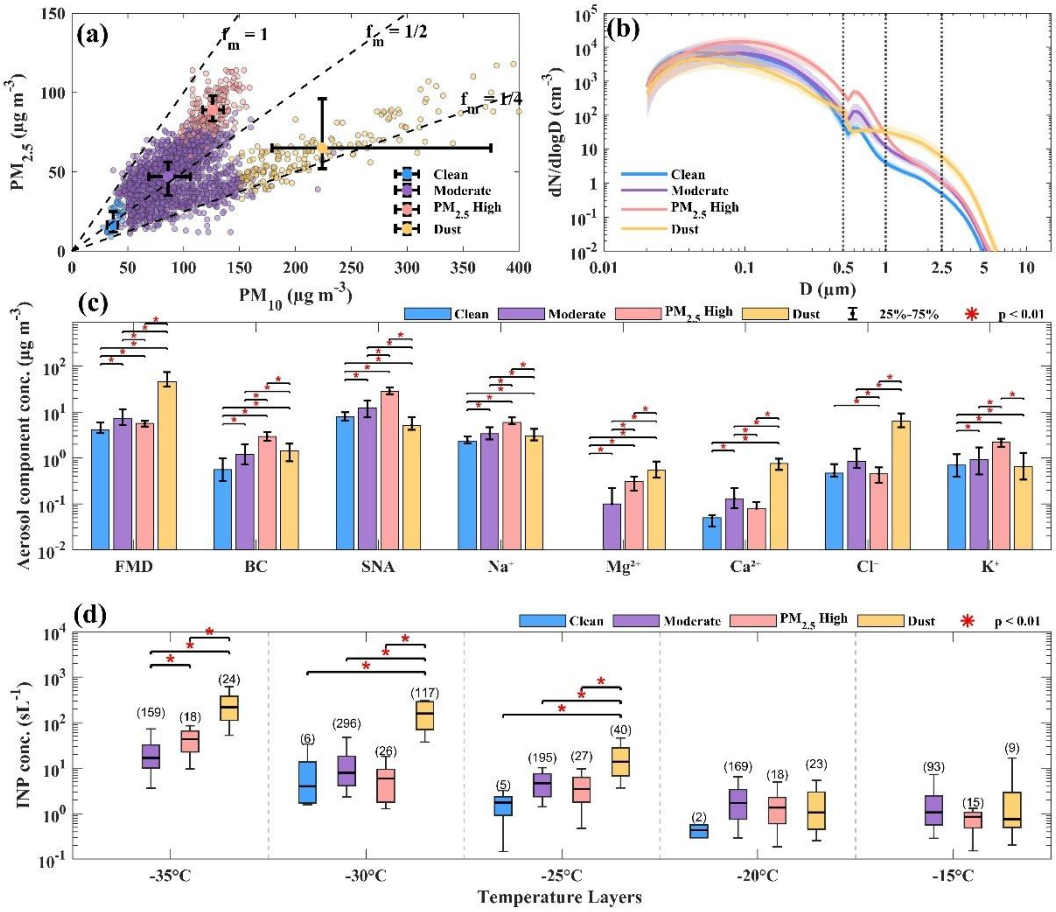

Fig. 3. Comparative analysis of physicochemical characteristics and INP concentrations across different aerosol event types. (a) Mass concentrations of $PM_{2.5}$ and PM_{10}. Solid markers indicate the median, error bars represent the 25th and 75th percentiles, and dashed lines show the $PM_{2.5}/PM_{10}$ ratio (f_m). (b) Particle number size distribution. The solid line indicates the median, and the gray shading represents the 25th–75th percentile range. (c) Mass concentrations of water-soluble ions, shown as median values for different event types. (d) INP concentrations at different temperatures. Boxes represent the 25th–75th percentiles, red lines inside the boxes indicate the median, and whiskers extend to the 10th and 90th percentiles. Numbers in brackets indicate the number of samples corresponding to combinations of aerosol event types and temperature layers. Red asterisks above the brackets indicate significant differences ($p < 0.01$) between groups based on median tests.

A stark temperature-dependent contrast in INP activity was observed between dust and pollution events (Fig. 3d). INP concentrations in $PM_{2.5}$ High and Moderate events were similar above −30 °C, indicating that pollution-derived fine particles exert limited freezing influence under these conditions. In contrast, dust events diverged sharply at colder temperatures: at −30 °C, INP concentrations during dust events were 15.2 times higher than in Moderate events, and the enhancement further amplified at −35 °C. This strong temperature sensitivity reflects the well-established efficiency of mineral-dust particles in

supplying abundant immersion-freezing-active sites. Notably, A significant divergence emerged only at −35 °C, where fine particles in $PM_{2.5}$ High events also showed significant ice-nucleating ability at −35 °C, implying that small particles can still contain active ice-nucleating sites for ice formation at very low temperatures (Zhao et al., 2019; Tian et al., 2022). Nevertheless, their activity remained substantially weaker than that of dust aerosols. As expected, Clean events consistently exhibited the lowest INP concentrations across all temperatures, aligning with the overall low aerosol loading and reduced abundance of coarse-mode particles. The coherent ordering of the four event types across activation temperatures highlights the strong modulating influence of aerosol source and size distribution on INP activity.

To compare the ice-nucleating activity among aerosol types, activity parameters normalized by particle number ($N_{D>0.5}$, $N_{D>1.0}$) and surface area (N_s) were calculated (definitions in Appendix Text S1). Dust events consistently exhibit the highest activation fractions and site densities at −25 °C and below, confirming their strong nucleation efficiency of mineral dust particles (Fig. 4). Conversely, $PM_{2.5}$ High events displayed the weakest activity from −15 to −30 °C, consistently lower than Moderate and Clean events, yet showed a marked increase at −35 °C, indicating enhanced nucleation potential only under the coldest conditions and likely a very low threshold temperature for appreciable nucleation by $PM_{2.5}$ pollution particles. The consistent pattern across all normalization approaches demonstrates that dust was the dominant ice-nucleating aerosol type during the observation period, particularly in spring.

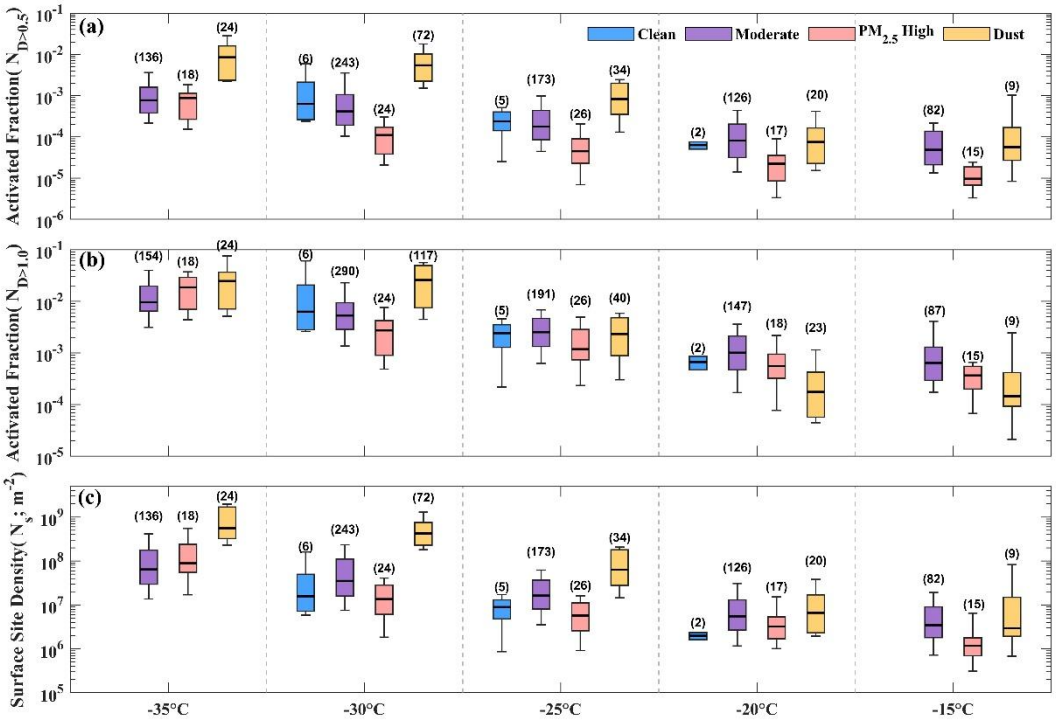

Fig. 4. Distributions of ice nucleation activity parameters. Each box shows the 25th–75th percentile range, with the center line indicating the median and the whiskers extending to the 10th and 90th percentiles. Numbers above the boxes indicate the number of samples for each

event type at each temperature.

3.3 Backward trajectory and source region analysis

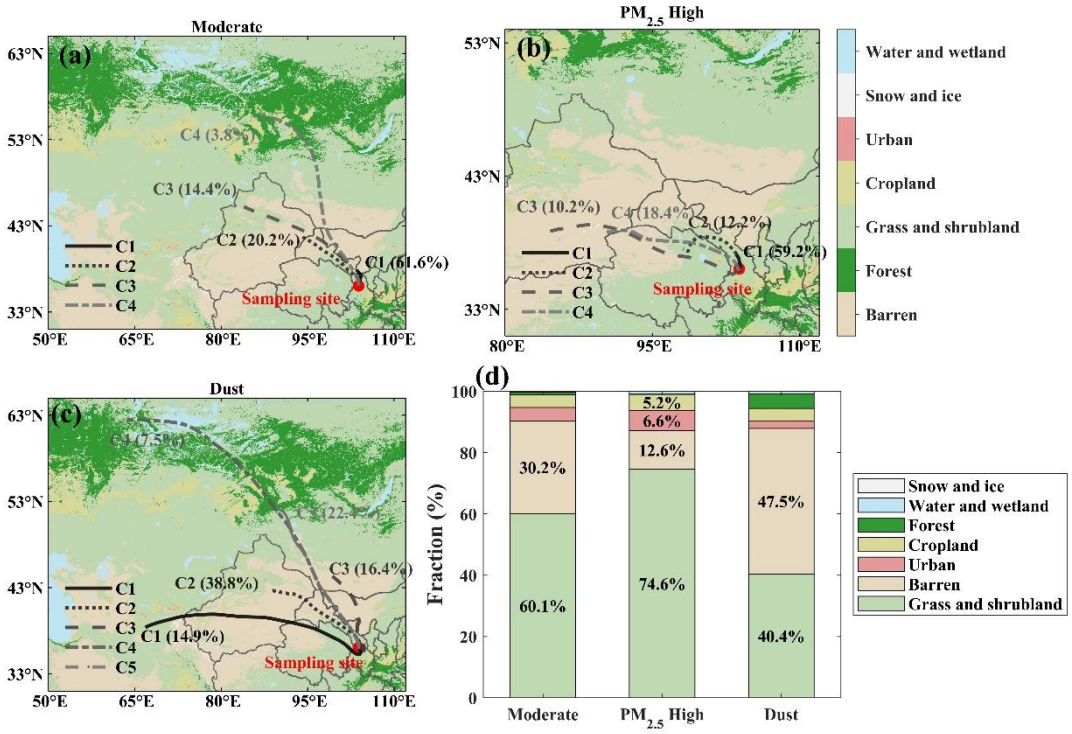

Fig. 5. Spatial distributions of 72-h backward air-mass trajectories and associated land-cover characteristics for different aerosol event events. Panels (a–c) show clustered backward trajectories for (a) Moderate, (b) $PM_{2.5}$ High, and (c) Dust events, overlaid on MODIS land-cover data. The red star indicates the sampling site, and the percentages denote the fraction of trajectories in each cluster. Panel (d) shows the fractional contributions of major land-cover types sampled by trajectories for each event type. Land-cover categories include barren, forest, grass and shrubland, cropland, urban, snow and ice, and water and wetland.

To place the observed contrasts in INP activity into a transport context, we examined air-mass pathways and potential source regions using 72-h HYSPLIT backward trajectory clustering combined with land-cover statistics along the transport pathways (Fig. 5). Dust events were characterized by a pronounced shift toward long-range transport, with clusters C2 (38.8%) and C5 (22.4%) accounting for more than 60% of all trajectories. These trajectories predominantly originated from northwestern inland Asia and frequently crossed extensive desert and semi-arid regions before reaching Lanzhou. Correspondingly, land-cover analysis shows a substantially higher fraction of barren surfaces (47.5%) along Dust trajectories, together with a reduced contribution from grassland and shrubland (40.4%). This coherent pattern between long-range transport pathways and enhanced traversal of arid land surfaces highlights the distinct upstream environments associated with Dust events. Furthermore, near-surface wind fields and synoptic-scale meteorological processes may also modulate INP

observations. Existing research indicates that dust events in mid-latitude regions often co-occur with convective systems, gusty winds, and precipitation processes, which can simultaneously influence dust transport, removal, and resuspension of surface sediments (Rivera Rivera et al., 2008). Although this study did not quantitatively analyze the relevant weather processes, under the Dust scenario, the long-range transport characteristics indicated by the trajectory and the significant increase in the proportion of bare ground surface are consistent with the enhanced performance of INP in the low-temperature segment, and synoptic-scale processes may play a further modulating role.

In contrast, during $PM_{2.5}$ High events, the trajectories were dominated by short-range clusters with limited horizontal displacement (C1: 59.2%), with most air masses remaining within the broader vicinity of Lanzhou. Consistent with this transport pattern, the associated trajectories predominantly traversed grassland and shrubland surfaces (74.6%), with relatively minor contributions from barren land (12.6%) and other land-cover types, indicating that air masses during $PM_{2.5}$ High events were largely confined to near-regional environments rather than originating from remote arid source regions. Moderate events exhibited intermediate transport characteristics, with trajectories distributed among near-regional and regional-scale clusters (C1: 61.6%; C2: 20.2%; C3: 14.4%). The associated land-cover composition was likewise transitional, with trajectories sampling both grassland/shrubland (60.1%) and barren land (30.2%), reflecting a mixture of regional background air masses and episodic inputs from drier source areas. Owing to the limited number of Clean events, trajectory clustering was not performed; backward trajectories for Clean conditions are shown in Fig. S11, and they generally indicate short-range transport within northwestern China. Overall, significant differences in transport path length and the types of land surfaces traversed provide direct transport-level evidence for contrasting INP concentration levels and temperature dependence between Dust and $PM_{2.5}$ High scenarios.

3.4 Contrasting correlations of dust and SNA with INP activity

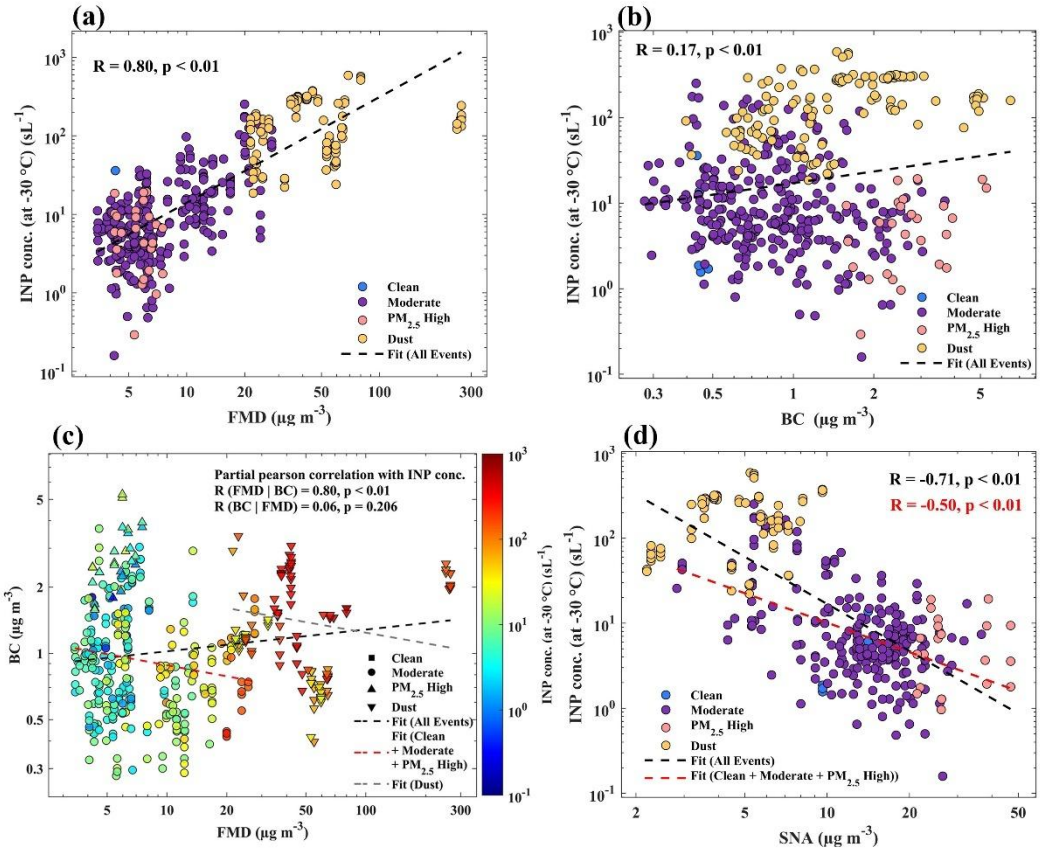

Fig. 6. Associations between -30 °C INP concentrations and aerosol ion components. (a), (b), (d) Scatter plots of INP concentrations versus FMD, BC and SNA mass concentrations, respectively. *R* denotes the Pearson correlation coefficient, and *p* denotes the significance level, calculated in the natural log space. (c) Bivariate plots with FMD and BC on the axes, where the color scale represents INPs. *R* and *p* denote the partial correlation coefficient and significance level, also calculated in the natural log space.

To further elucidate the drivers of the observed differences in INP activity among the event types, we focused on −30 °C for detailed analysis, because it is a characteristic temperature at which immersion freezing is most frequently examined (Fig.6). INPs increased with the concentration of FMD (R = 0.80, Fig. 6a), consistent with the important role of mineral dust, particularly feldspar-bearing particles, in immersion freezing (Kiselev et al., 2017). As part of the compositional analysis, we also examined the behavior of BC. Although BC showed a weak positive correlation with INPs (R = 0.17, Fig. 6b), this relationship became statistically insignificant once FMD was accounted for in a partial correlation analysis (Fig. 6c). This is consistent with laboratory studies showing that BC may nucleate ice mainly under cirrus conditions through deposition freezing (Nichman et al., 2019), while its potential role in immersion freezing warrants further investigation.

Across all events, INP concentrations decreased with increasing SNA (R = −0.71), whereas this relationship reversed during dust events, where SNA instead showed a positive association with INPs (Fig. 6d). To further investigate this divergence,

we examined the ratio of soluble Ca^{2+} to elemental Ca, an indicator of dust dissolution. SNA was positively correlated with this Ca^{2+}/Ca ratio during dust events but showed no relationship in non-dust periods (Fig.7a), indicating that SNA in dust events is linked to the chemical aging of transported mineral particles rather than to local urban pollution. This interpretation is consistent with the low local pollution in Lanzhou and with evidence that SNA on Asian dust is primarily controlled by chemical aging along its transport pathway (Li et al., 2015). Notably, the Ca^{2+}/Ca ratio itself shows little association with INP concentrations (Fig. 7b). This agrees with field evidence showing that increases in water-soluble ions through pollution-induced aging do not necessarily translate into stronger ice-nucleating activity (Chen et al., 2023). Instead, the positive SNA–INP relationship observed during dust events (Fig. 7c) likely reflects their joint increase with dust intrusion intensity: stronger dust episodes elevate both mineral dust loading and SNA levels.

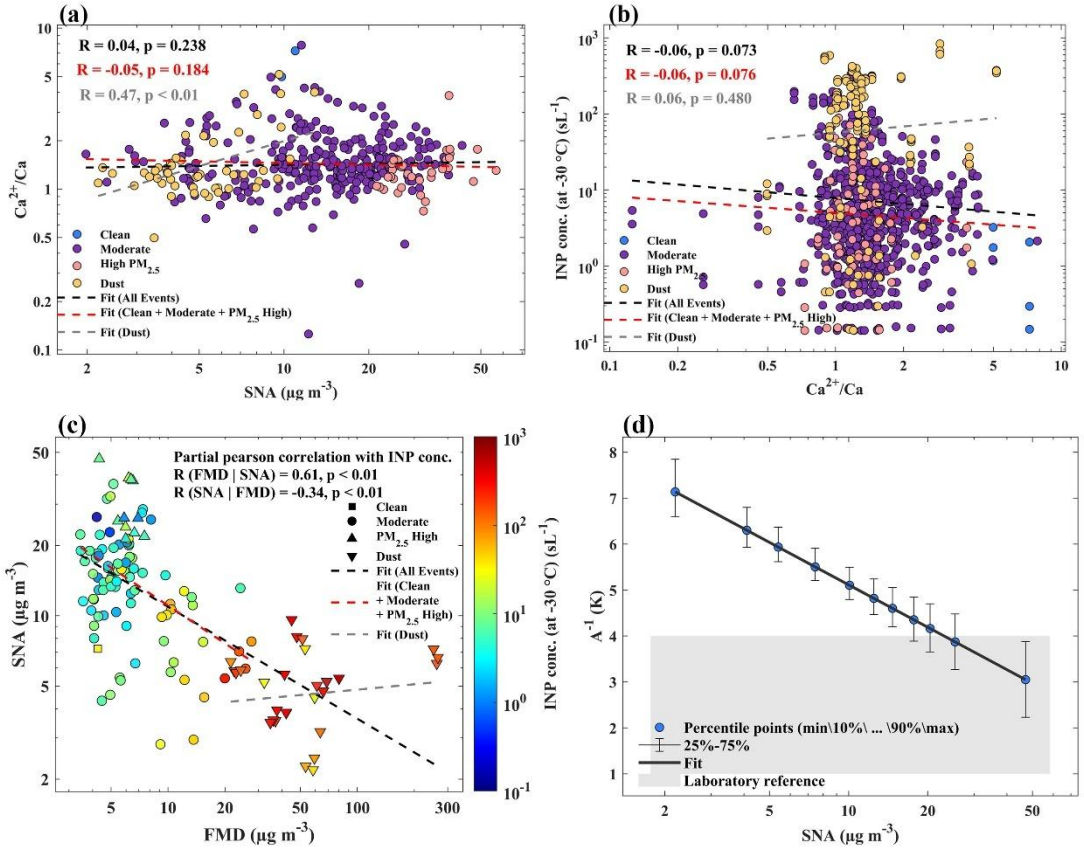

Fig. 7. Associations between -30 °C INP concentrations and SNA. (a) Scatter plots of SNA versus Ca^{2+}/Ca. (b) Scatter plots of Ca^{2+}/Ca versus INP concentrations. *R* denotes the Pearson correlation coefficient and *p* the significance level, calculated in the natural log space. (c) Bivariate plots with FMD and SNA on the axes, where the color scale represents INP concentrations. *R* and *p* denote the partial correlation coefficient and significance level, also calculated in the natural log space. (d) Dependence of the sensitivity metric A^{-1} on SNA concentrations (−25 °C to −35 °C). The shaded area indicates the laboratory reference range reported by Villanueva et al. (2025).

A key issue, however, is that the negative SNA–INP relationship persists even after transported-dust events are removed, and even in partial correlation analyses that control for FMD to account for the temporal mismatch (Fig. 7c). This indicates that, under non-dust-transport conditions, elevated SNA corresponds to an aerosol regime in which efficient mineral-dust INPs are relatively scarce. Consistent with this interpretation, INP concentrations during $PM_{2.5}$ High conditions tend to be lower than those during Moderate conditions, although the difference is not statistically significant (Fig. 3d). This slight decrease may suggest that mineral dust present under polluted conditions has experienced physicochemical modification, which in turn modulates its ice-nucleating efficiency. Secondary inorganic coatings (e.g., $(NH_4)_2SO_4$) can increase the effective contact angles on mineral surfaces, thereby requiring higher supersaturation for activation (Eastwood et al., 2009; Chernoff and Bertram, 2010). H_2SO_4 coatings can even irreversibly suppress the ice-nucleating activity of mineral dust (Sullivan et al., 2010), indicating that anthropogenic SO_2 and NH_3 emissions can substantially alter the immersion-freezing efficiency of dust particles. At the same time, other studies have reported that the ice-nucleating activity of mineral dust is not necessarily reduced after atmospheric aging, and in some cases remains largely unchanged or even partially enhanced, depending on the chemical composition and extent of surface processing (Kanji et al., 2019; Bertozzi et al., 2021; Chen et al.,2023; Huang et al.,2025). For example, field observations in Beijing reported no systematic difference in mineral-dust-related INP activity between polluted and clean conditions (Chen et al., 2018; Zhang et al., 2022). Taken together, these results indicate that, although pollution aerosols are not efficient immersion freezing INPs, they may still influence the observed INP abundance indirectly when pollution loading is high and mineral dust is scarce.

Beyond the correlation analysis, this study further evaluated the sensitivity of INPs to dust under different levels of SNA loading. We use the sensitivity metric A^{-1} from Villanueva et al. (2025), defined as the ratio of dust to temperature sensitivity, with a slight modification here to include SNA (see Appendix Text S3). At the median SNA level (12.47 μg m^{-3}), A^{-1} equals 4.82 K, meaning that increasing dust by e-fold (i.e., based on the natural exponential e) would produce the same INP enhancement as lowering the temperature by approximately 4.82 K (Fig. 7d). As SNA concentrations increase, this A^{-1} declines from about 6.30 K at the 10th percentile of SNA (4.10 μg m^{-3}) to about 3.87 K at the 90th percentile (25.41 μg m^{-3}), corresponding to a reduction of ~39%.

3.5 $n_{1.0}$-based INP parameterizations

INP concentrations decrease systematically with increasing temperature and exhibit pronounced variability across different aerosol regimes. These features indicate the need for a quantitative framework describing the relationships between INP concentrations, thermodynamic conditions, and aerosol properties. Following established temperature-based parameterization approaches (Meyers et al., 1992; Demott et al.,2010), empirical relationships are fitted and evaluated using the present dataset. A temperature-only formulation is first examined, followed by an extension of the framework that incorporates coarse-mode particle concentrations as an additional predictor (see Appendix Text S2).

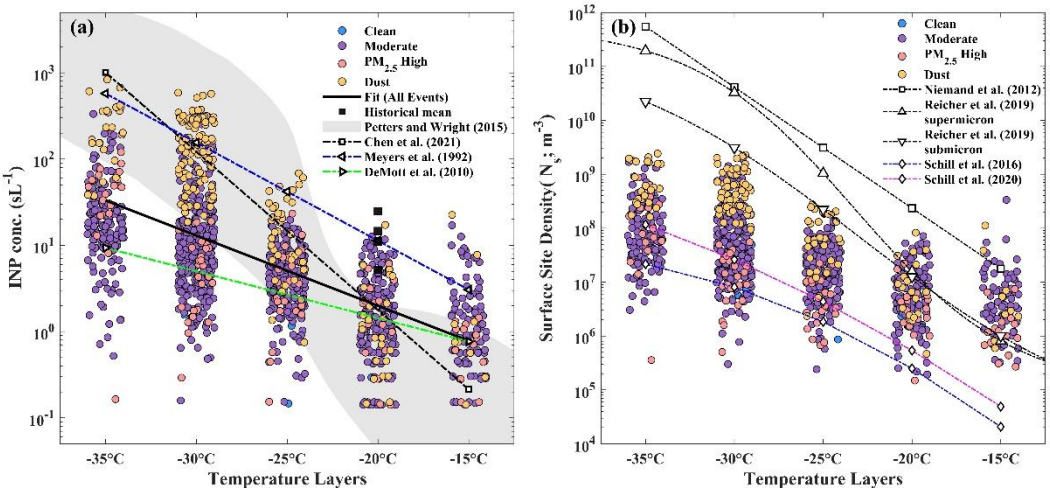

Fig. 8. Construction of single-parameter INPs parameterizations and comparison with existing parameterization schemes. (a) Temperature dependence of INP concentrations. The black solid line shows the overall fit from all events, and representative literature parameterizations are included for comparison. The gray shaded region denotes the range reported by Petters and Wright (2015). The black square indicates the historical mean INP concentration in Lanzhou (Ge et al., 1986).

A temperature-only parameterization was fitted at the five temperature layers (Fig. 8a). The fitted exponential relationship captures the systematic decrease of INP concentrations with increasing temperature and reproduces the overall magnitude of the observations. Substantial dispersion remains at each temperature layer, and the spread increases toward colder temperatures, with INP concentrations spanning about two orders of magnitude at −25 °C and warmer and approaching three orders of magnitude at colder temperatures. This enhanced dispersion is consistent with increasingly distinct INP activities among different aerosol regimes. Dust events occupy the upper range of observed INP concentrations and display steeper temperature dependences than non-dust regimes, consistent with typical mineral dust behavior (Beall et al., 2022). In contrast, Clean, Moderate, and $PM_{2.5}$ High events largely overlap and collectively exhibit lower INP concentrations. Several widely used temperature-based parameterizations are also shown. The shaded envelope representing precipitation-derived INP concentrations reported by Petters and Wright (2015) overlaps with many of the observations, placing the Lanzhou dataset within the typical global range. The fitted curve for dust events aligns with the Beijing dust scheme proposed by Chen et al. (2021) under the 1.0 μm cutoff, but lies below those based on 1.8 μm and 3.2 μm thresholds In contrast, non-dust types closely match the global mean parameterization of DeMott et al. (2010), reflecting background-like nucleation behavior. This apparent consistency based on temperature alone does not necessarily imply common sources or nucleation efficiencies. Historical INPs observations at −30 °C from Lanzhou (1960s–1980s) also fall within the same order of magnitude, though slightly higher than present results, likely due to methodological differences and subsequent improvements in data quality. A complete summary of all fitted parameters is provided in Table S2.

Temperature-dependent N_s relationships are also presented in Fig. 8b. During Dust events, the derived N_s values are systematically lower than mineral-dust-based parameterizations (Niemand et al., 2012), typically by about 1–2 orders of

magnitude. Such discrepancies are expected, as laboratory-derived schemes are known to represent fresh mineral surfaces and tend to overestimate ambient N_s (Connolly et al., 2009; Ullrich et al., 2017). In comparison, the observed Dust-event N_s values are closer to the lower bound of the size-segregated parameterizations proposed by Reicher et al. (2019), particularly the submicron scheme. For Clean, Moderate, and $PM_{2.5}$ High events, the observed N_s values fall largely within the range predicted by combustion-related parameterizations for vehicle exhaust and biomass-burning aerosols (Schill et al., 2016; 2020), while remaining substantially lower than mineral-dust-based schemes. The pronounced variability in ice-nucleating efficiency across aerosol regimes indicates that temperature-only parameterizations are insufficient. An improved framework should either adopt aerosol-type-specific parameterizations or incorporate aerosol-related indicators that distinguish between dust-influenced and pollution-influenced conditions.

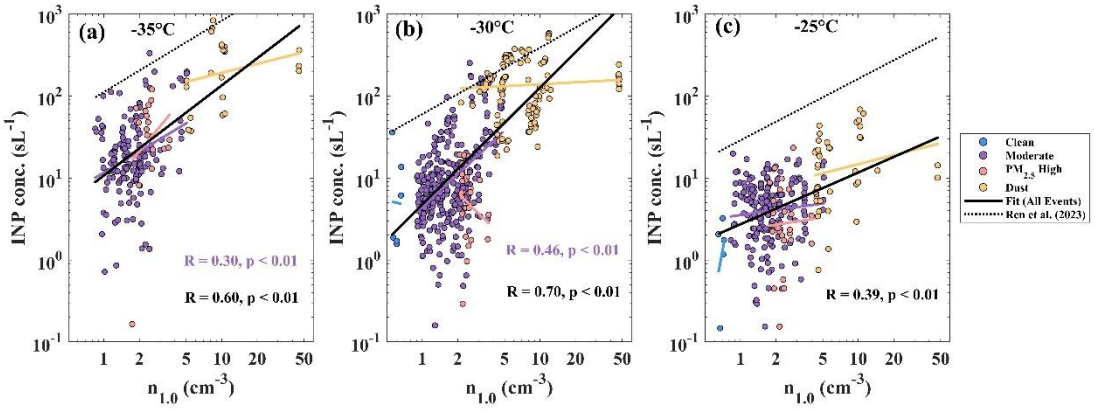

Fig. 9. Relationships between INPs and aerosol number concentrations. (a–c) show the relationships between INP concentrations and $n_{1.0}$. The black dashed line indicates the prediction from existing parameterization schemes. The R and p values represent the Pearson correlation coefficient and its significance, and only results with $p < 0.01$ are shown.

When all aerosol event types are combined (Fig. 9), INP concentrations at colder temperatures (−25 °C to −35 °C) show a significant positive correlation with $n_{1.0}$ (particle number concentration with D = 1.0–2.5 μm), which is generally stronger than with $n_{0.5}$ (particle number concentration with D = 0.5–2.5 μm, Fig. S12). Because FMD, which represents an important contributor to active sites, shows a strong positive correlation with $n_{1.0}$ (R = 0.90, Fig. S13) but a negative correlation with $n_{0.5}$ (R = −0.19), using $n_{1.0}$ simply provides a size metric that better matches the dust characteristics in this region. This agrees with earlier urban observations indicating that $n_{0.5}$ is not a reliable predictor of INPs because it reflects background aerosols rather than the larger particles typically responsible for ice nucleation in polluted regions (Chen et al., 2018; Wagh et al., 2021). At warmer temperatures (−15 °C and −20 °C), INP concentrations were near the detection limit, and correlations with $n_{1.0}$ and $n_{0.5}$ were weak (Fig. S14); thus, the parameterizations at these temperatures should be interpreted with caution. Nevertheless, data from all temperatures were retained to ensure full representativeness in this study (see Table S3 for the specific formulae).

We further examined the relationships between INP concentrations and particle number concentrations across different size intervals within each aerosol event type (Fig. S15). Across all five activation temperatures, no particle-size range showed

a statistically significant association with INPs in either Clean or $PM_{2.5}$ High events. For Dust events, significant positive correlations emerged only at −30 °C, and only for particles in the 0.25–0.5 μm and 0.5–1.0 μm intervals. Accordingly, we did not extend the temperature-based fits with an additional size-dependent predictor within individual event categories.

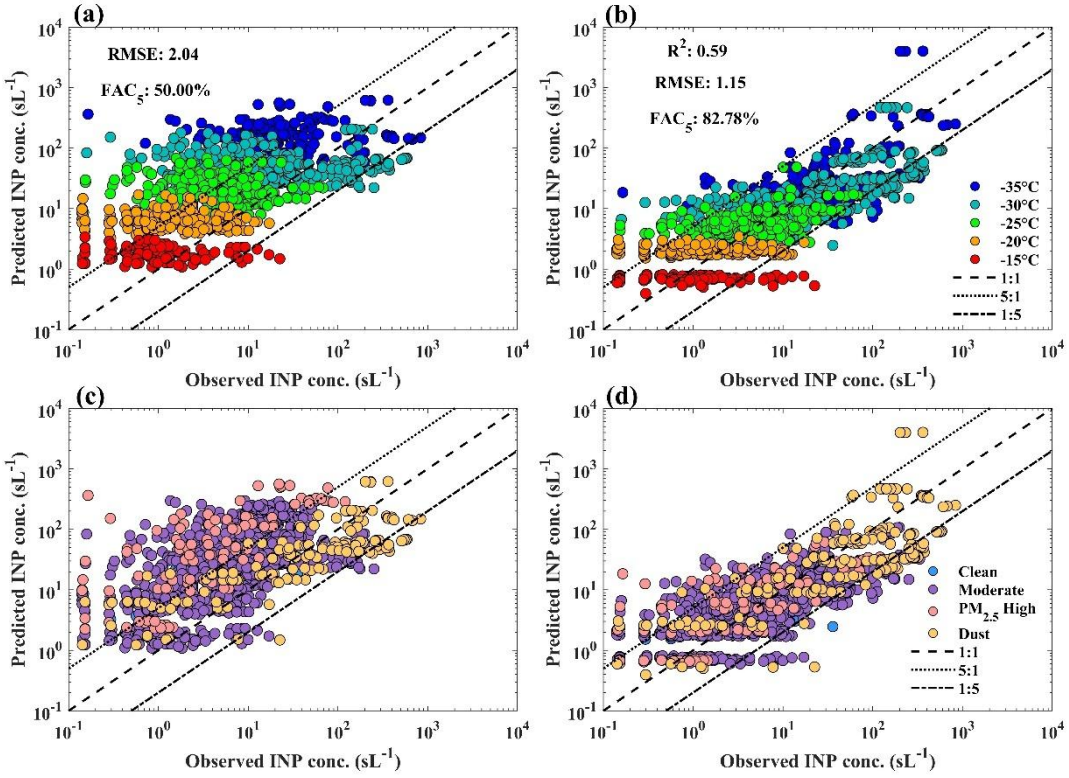

Fig. 10. Comparison between predicted and observed INP concentrations. (a) and (c) show the prediction results of the D10 parameterization scheme using $n_{0.5}$ as input across different temperature conditions, while (b) and (d) present the corresponding predictions from the exponential model developed in this study based on $n_{1.0}$. The black solid line denotes the 1:1 reference line, and the gray dashed lines indicate the ±5-fold error bounds.

To evaluate the performance of the parameterizations, three metrics were applied: RMSE, FAC_5 (fraction of data points falling within the ±5-fold error range), and R^2 (definitions in Appendix Text S4). The global mean parameterization dual-parameter scheme systematically overestimates INP concentrations, yielding an RMSE of 2.04 and an FAC_5 of 50% (Fig. 10). These biases were most evident at colder activation temperatures and during pollution-dominated periods, underscoring the importance of accounting for urban aerosol event types when applying global INP parameterizations. By comparison, the locally derived $n_{1.0}$-based model achieves markedly improved skill (R^2 = 0.59, RMSE = 1.15, FAC_5 = 82.8%), providing higher predictive accuracy and greater consistency across both temperature regimes and aerosol event types. Nevertheless, certain limitations remain. The vertical alignment of observed INP concentrations at approximately 0.13 sL^{-1} reflects the instrumental detection limit of the CFDC measurements. At −15 °C, the current parameterization does not capture aerosol-related variability

and effectively yields a single representative value. Despite these limitations, the overall improvement mainly reflects a regional optimization that better suits the urban environment, suggesting that parameterizations may benefit from incorporating region-specific aerosol characteristics when applied to complex environments. In addition, future coordinated online CFDC and offline droplet-freezing measurements may help better constrain low-level INP concentrations.

4. Conclusion

Based on the first winter-spring, high-time-resolution online INP measurements in Lanzhou, this study investigated the temporal variability and controlling factors of INPs in an urban inland environment. Springtime dust storms elevate INP concentrations at −30 °C by a factor of ~15, making episodic dust plumes the primary driver of urban INP bursts. In contrast, $PM_{2.5}$-rich pollution episodes only contribute significant ice-nucleating ability below −35 °C, revealing a clear "dust-warm vs pollutant-cold" temperature threshold that can be used to flag dominant INP sources in operational forecasts. Normalized activation fractions and surface site densities confirm that the elevated INP concentrations during dust events are attributable to intrinsically higher ice-nucleating efficiency of mineral dust, rather than merely increased particle abundance. Backward trajectory and land-cover analyses further show that elevated INPs are linked to long-range transport from arid source regions, while $PM_{2.5}$ High events are mainly associated with near-regional air masses.

Urban-inland INP bursts are driven by episodic dust plumes, not persistent $PM_{2.5}$. Fine mineral dust (FMD) provides a robust indicator of dust-related INP contributions, whereas secondary inorganic aerosol accumulated during pollution events correlates negatively with INP activity. While our −30 °C observations show a strong negative correlation between SNA mass and INP number (R = −0.71), this consistency is circumstantial. Ambient RH, coating thickness, and dust mineralogy were not constrained, and the relationship emerged only under conditions where pollution levels were high and dust influence was relatively weak. Therefore, the degree to which coatings suppress INPs in the real atmosphere remains an open question requiring targeted follow-up studies.

Although a temperature-only scheme reproduces the overall thermal trend of INPs, the pronounced dispersion, particularly at colder temperatures, and the clear separation between dust and non-dust regimes indicate that temperature alone cannot account for urban INP variability. temperature-dependent N_s comparisons further reveal strong aerosol-type dependence of ice-nucleating efficiency, highlighting the limitation of temperature-only parameterizations. Because FMD is closely associated with $n_{1.0}$ ($R = 0.90$), using $n_{1.0}$ as the size indicator provides a more regionally representative basis for INP estimation in this urban environment. Building on this, the two-parameter framework demonstrates stable performance across different aerosol event types and temperatures, achieving RMSE = 1.15, FAC_5 = 82.78%, and $R^2 = 0.59$. Overall, the scheme benefits from the fact that particle size can partially reflect aerosol types and, in turn, their associated ice-nucleating activity, providing a practical approach for estimating regional INP concentrations.

This study could provide region-specific constraints on aerosol–ice-cloud interactions in arid North-West China and offer observational insights that can inform parameterizations for other dryland cities where urban air interacts with transported dust.

We demonstrate that particle size alone can distinguish dust-dominated from pollution-dominated INP sources in a dryland city. However, extending the scheme to humid subtropical or marine-coastal regions will require multi-site validation and inclusion of additional parameters (e.g., mineralogical composition, organic-mass fraction). Such coordinated efforts will enable more accurate INP representation in regional and global models that presently overlook non-marine, non-pure-desert ice-nucleating sources, ultimately improving our ability to simulate cloud formation and climate feedbacks across diverse atmospheric environments.

Data availability

Datasets used to generate the figures in this study are available on Zenodo (https://doi.org/10.5281/zenodo.17775917). Other measurement datasets used in this study can be obtained from the corresponding author on reasonable request. Meteorological fields used for the HYSPLIT simulations are publicly available from the NOAA Air Resources Laboratory (https://www.ready.noaa.gov).

Author Contribution.

C.C. designed the study, performed the field INP measurements, and conducted the analysis of the related aerosol observational datasets. Ya.W. and J.L. supervised the research and provided guidance on methodology and interpretation. L.F. and T.C. assisted with aerosol instrumentation maintenance and data preprocessing. Z.J. contributed to the ion chromatography and heavy-metal data acquisition. J.W. and Yu.W. provided model support and contributed to the discussion of the parameterization framework. J.H. offered conceptual guidance on regional aerosol–cloud interactions and contributed to interpretation of the results. C.C. wrote the manuscript with input from all authors. All authors reviewed and approved the final manuscript.

Competing interests.

The authors declare that they have no conflict of interest.

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