

**Influence of surface morphology on ice nucleation**

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# Influence of surface morphology on the immersion mode ice nucleation efficiency of hematite articles

N. Hiranuma<sup>1</sup>, N. Hoffmann<sup>1</sup>, A. Kiselev<sup>1</sup>, A. Dreyer<sup>2,\*</sup>, K. Zhang<sup>3</sup>, G. Kulkarni<sup>3</sup>, T. Koop<sup>2</sup>, and O. Möhler<sup>1</sup>

<sup>1</sup>Institute for Meteorology and Climate Research – Atmospheric Aerosol Research, Karlsruhe Institute of Technology, Karlsruhe, Germany

<sup>2</sup>Faculty of Chemistry, Bielefeld University, Bielefeld, Germany

<sup>3</sup>Atmospheric Science and Global Change Division, Pacific Northwest National Laboratory, Richland, Washington, USA

\*now at: Institute Advanced Ceramics, Hamburg University of Technology, Hamburg, Germany

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Correspondence to: N. Hiranuma (seong.moon@kit.edu)

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## Abstract

In this paper, the effect of the morphological modification of aerosol particles with respect to heterogeneous ice nucleation is comprehensively investigated for laboratory-generated hematite particles as a model substrate for atmospheric dust particles.

5 The surface area-scaled ice nucleation efficiencies of monodisperse cubic hematite particles and milled hematite particles were measured with a series of expansion cooling experiments using the Aerosol Interaction and Dynamics in the Atmosphere (AIDA) cloud simulation chamber. Complementary off-line characterization of physico-chemical properties of both hematite subsets were also carried out with scanning electron microscopy (SEM), energy dispersive X-ray (EDX) spectroscopy, dynamic light scattering (DLS), and an electro-kinetic particle charge detector to further constrain droplet-freezing measurements of hematite particles. Additionally, an empirical parameterization derived from our laboratory measurements was implemented in the single-column version of the Community Atmospheric Model version 5 (CAM5) to investigate

15 the model sensitivity in simulated ice crystal number concentration on different ice nucleation efficiencies. From an experimental perspective, our results show that the immersion mode ice nucleation efficiency of milled hematite particles is almost an order of magnitude higher at  $-35.2^{\circ}\text{C} < T < -33.5^{\circ}\text{C}$  than that of the cubic hematite particles, indicating a substantial effect of morphological irregularities on immersion mode freezing. Our modeling results similarly show that the increased droplet-freezing rates of milled hematite particles lead to about one order magnitude higher ice crystal number in the upper troposphere than cubic hematite particles. Overall, our results suggest that the surface irregularities and associated active sites lead to greater ice activation through droplet-freezing.

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## 1 Introduction

The chemical and physical surface structure of an aerosol particle can greatly influence its microphysical characteristics such as hygroscopicity (e.g., Twohy and Anderson, 2008; Shilling et al., 2007), chemical reactivity (e.g., Di Cosimo et al., 1998), optical properties (Linke et al., 2006), and ice nucleation efficiency (e.g., Schill and Tolbert, 2013; Pruppacher and Klett, 1997). More specifically on ice nucleation properties, Möhler et al. (2006) and Kulkarni and Dobbie (2010) postulated that surface roughness and irregularities may lead to an enhancement of ice nucleation rate of dust particles by water vapor deposition on dust surface. It has been known that surfaces that show a structural match to the crystal lattice of hexagonal ice (e.g. AgI with  $\text{NH}_4\text{I}$ ) may facilitate nonpolar proton-disordered ice propagation and ice formation (Jacquemain et al., 1991). It has been also discussed that the surface's physical and chemical properties may play a major role in the initiation of ice crystals in mixed-phase clouds and ice clouds (Mason, 1971; Cziczo et al., 2013), yet our current understanding of ice nucleation properties of various aerosols is still rudimentary, in part due to the fact that changes in composition, size, and surface morphology are often inherently related during an aerosol's atmospheric lifetime and aging process (Hiranuma et al., 2013).

Previous laboratory studies have revealed that electric fields promote the formation of ice-like aggregates and eventually induce ice nucleation (Ehre et al., 2010; Anim-Danso et al., 2013; Gavish et al., 1992). For instance, upon cooling water freezes preferentially on positively charged pyroelectric surfaces due to the prevalent interaction between lone electron pairs of water's oxygen atoms and the charged surface (Ehre et al., 2010). In contrast, negatively charged surfaces may coincide with a disrupted ice-like structural match, resulting in deteriorated freezing activity (Anim-Danso et al., 2013). In addition, Gavish et al. (1992) observed that artificially polarized crevices on hydrophobic surfaces induce an orientation of water molecules into ice-like clusters at a higher temperature than nonpolar crevices.

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Importance of surface structure and defects towards ice nucleation were recently investigated by Croteau et al. (2010). The authors performed molecular dynamic simulations to investigate water adsorption on an irregularly-shaped clay mineral surface, which includes a series of narrowly spaced trench-like defects. The results indicated that strong water affinity and apparent multilayers of water at the edges of these trenches where ice onset may preferentially occur may be due to the interaction between water and clay lattice compared to flat surface. These simulations helps to understand the surface structures that may assist in ice nucleation; however, systematic laboratory studies performed under controlled conditions that can be used to further constrain and verify these molecular simulations are missing. In conjunction with aerosol-cloud interactions, ice nucleation enhancement in the presence of abundant water vapor would lead to more but smaller ice crystals, exerting higher albedo (Lohmann and Feichter, 2005). Hence, a surface morphology-dependent parameterization that accurately describes experimental results may be important to improve our climate change models.

In this study, we took an integrated approach that consists of experimental and cloud modeling investigations, to determine ice nucleation properties on hematite particles, with and without the presence of surface irregularities. We assumed hematite particles as surrogate for the natural mineral dust particles. Surface area-scaled ice nucleation activities of different types of hematite particles were determined experimentally at atmospherically relevant conditions using the Aerosol Interaction and Dynamics in the Atmosphere (AIDA) cloud chamber. The degree of morphological irregularities, both in terms of size and surface charge, was assessed by in situ light scattering instruments as well as off-line microscopy and spectroscopy techniques. In addition, a modeling sensitivity evaluation was performed with the simplified one-column version of the Community Atmospheric Model version 5, CAM5 (Neale et al., 2010), which allowed assessing the role of surface modification upon the overall ice nucleation efficiency of the dust proxy in upper tropospheric ice clouds.

## 2 Method

### 2.1 Sample preparation

Chemically homogeneous cubic hematite ( $\text{Fe}_2\text{O}_3$ ) particles were produced following the procedure prescribed in Sugimoto and Sakata (1992). Briefly, iron hydroxide [ $\text{Fe}(\text{OH})_3$ ] was initially produced by agitating a mixture of sodium hydroxide ( $\text{NaOH}$ ) and ferric chloride ( $\text{FeCl}_3$ ) solutions (100 mL of 5.6 M and 100 mL of 2.0 M, respectively). The resulting highly viscous gel form of  $\text{Fe}(\text{OH})_3$  with an excess of  $\text{Fe}^{+3}$  was subsequently aged and freeze-dried to form a powder of equally sized hematite particles ( $\sim 1 \mu\text{m}$  diameter, see Fig. 1a). Next, a subset of these original cubic hematite particles was milled by agitating them with immiscible  $100 \mu\text{m}$  diameter bronze beads, resulting in surface irregularities (cracks and/or edges, see Fig. 1b).

To assess the degree of surface modification, we measured the specific surface area of these hematite particles by  $\text{N}_2$ -absorption using the Brunauer, Emmett and Teller (BET) gas adsorption technique (Brunauer et al., 1938). Additionally, surface charge properties and dynamic light scattering size of suspended hematite particles (1 to 10 mg hematite in 1 mL of triple-distilled water) were investigated using a StabiSizer<sup>®</sup> instrument (Microtrac Europe GmbH, PMX 200CS) to examine a possible relation between surface morphology and charge properties. The StabiSizer<sup>®</sup> has been widely used for many applications in particle analysis (e.g., Gaware et al., 2013; Titze et al., 2010). The detailed methods and its applications are described elsewhere for studying particle size using dynamic light scattering (DLS, Ukhatskaya et al., 2013) and surface charge properties as an electro-kinetic particle charge detector (Biver and Shotyky, 2013), so only a brief description will be given here. The hydrodynamic diameter of hematite particles was measured at a scattering angle of  $180^\circ$  at a temperature of  $25^\circ\text{C}$ . A  $750 \text{ nm}$  laser beam was focused onto a  $10 \text{ mg mL}^{-1}$  hematite suspension through a sapphire window, and the scattered light intensity was recorded and directly related to colloidal size distribution from the intensity fluctuations induced by the par-

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articles' Brownian motion. The particles' interfacial potential was electro-kinetically characterized by charge-pH titration based on the creation or extinction of surface charges (i.e., Brønsted-Lowry acid-base reaction) by incrementally adding 0.01 M aqueous HCl or NaOH solutions to the hematite suspension. The measurement of the charge properties is based on the particle adsorption to the PTFE-Teflon vessel wall. A swaying piston in the vessel creates an alternating solvent stream over these immobilized particles that deforms their flexible space-charge cloud and generates oscillating dipoles. These dipoles are detected as an oscillating streaming potential between two electrodes. In addition, the absolute number of charges can be determined by titration to zero potential with  $10^{-5}$  to  $10^{-4}$  mol L<sup>-1</sup> solution of oppositely charged polyelectrolyte particles of anionic poly-vinyl sulfate (PVS) or cationic poly-diallyl dimethyl ammonium chloride (PDADMAC).

## 2.2 AIDA immersion mode freezing experiments

To investigate the immersion mode ice nucleation efficiency of hematite particles, we conducted a series of controlled expansion cooling experiments using the AIDA cloud simulation chamber. Detailed experimental procedures of the immersion mode AIDA runs are described elsewhere (e.g., Steinke et al., 2011; Niemand et al., 2012), and only a concise discussion is provided here. The AIDA chamber consists of a 84 m<sup>3</sup> aluminum vessel in a thermally insulated housing and is outfitted with instruments for heterogeneous ice nucleation studies of a wide variety of aerosols (e.g., Möhler et al., 2003, 2006; Mangold et al., 2005). Continuous cooling is simulated within the vessel by mechanically pumping and expanding the air in the vessel. During a typical expansion, constant pumping speed results in cooling rates decreasing from initially about 5 °C min<sup>-1</sup> to below 0.1 °C min<sup>-1</sup> while the chamber pressure reduces from 1000 mb to 800 mb. Part of the chamber walls is coated with an ice layer, maintaining almost ice saturated conditions in the stirred chamber before the start of the pumping expansion. Thus, water supersaturation conditions occur shortly after pumping expansion begins, which is directly accessible from in situ tunable diode laser (TDL) water va-

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por absorption and gas temperature measurements. As soon as water saturation is exceeded, presumably the majority of the aerosol particles in the chamber acts as cloud condensation nuclei in our experiments and, therefore, become immersed into water droplets. From that point on, immersion mode ice nucleation of specific aerosol particles can be measured solely as a function of the temperature along with water saturation line (Connolly et al., 2009). An in situ scattering intensity measurement for the optical detection of ice was also conducted by the SIMONE (i.e., German acronym for Streulicht-intensitätsmessungen zum optischen Nachweis von Eispartikeln) throughout the experiments. The instrument-performance and technical details are described in Schnaiter et al. (2012). Briefly, a horizontally aligned continuous wave semiconductor laser is used to probe light scattering of particles at the center location of the AIDA at a wavelength of 488 nm. By changing the scattering plane at the laser head, scattering signals either in forward or backward direction can be detected. At the backward direction, scattering intensities perpendicular and parallel to the linear polarisation state are evaluated and counted per second. At droplet- or ice-activation in the AIDA, quick response in intensities can be observed. Further, an apparent increase in depolarisation ratio (the ratio of those two intensities i.e., perpendicular/parallel) is a direct indicator of the appearance of non-spherical components and their contribution to enhanced light scattering. Hence, the precise timing for the formation of aspherical ice crystals can be recognized based on the depolarisation ratio, and the simulated cloud phase (pure ice, mix phase, or liquid phase) in the AIDA is quantitatively identified. For our study, a depolarisation ratio below 0.05 denoted the presence of unactivated aerosols (Fig. S1). During expansion cooling, the WhitE-Light Aerosol Spectrometer (WELAS) and optical particle counters (PALAS, Sensor series 2300 and 2500) were operated at a vertical sampling tube from the AIDA vessel in order to measure the number and size distribution of ice crystals. WELAS instrument has been routinely used in previous studies at the AIDA facility, and a full description of the WELAS probe is available in Benz et al. (2005).



geometric total surface area,  $A_{\text{total,geo}}$  (Peters et al., 2006). To obtain the latter one, the geometric total mass concentration ( $\text{g cm}^{-3}$ ) is multiplied by BET specific surface ( $\text{m}^2 \text{g}^{-1}$ ). Thus, we obtained two different INAS densities, namely geometric area-based  $n_{\text{s,geo}} (= N_{\text{ice}}/A_{\text{total,geo}})$  and BET-inferred  $n_{\text{s,BET}} (= N_{\text{ice}}/A_{\text{total,BET}})$ .

## 2.3 Model and simulation

For the modeling study, we used the single-column mode of the CAM5 model (Neale et al., 2010) to examine the sensitivity of simulated ice crystal number to the two aforementioned types of hematites as ice nucleating particles. One advantage of using a single-column model is that the performance of the physical parameterizations at a certain column over 100 km horizontal length-scales can be evaluated in isolation from other columns. To drive the single-column model, ECMWF (i.e., acronym for European Centre for Medium Range Forecasts) analyses were used to derive the large scale forcing terms, including vertical profiles of the horizontal advective tendencies of atmospheric state variables as well as the large scale vertical velocity (Zhang et al., 2001). The model consists of 30 vertical layers and the time step is set to 10 min. The cloud case observed from the United States Department of Energy's Atmospheric Radiation Measurement facility located at the Southern Great Plain (SGP) site near Lamont, Oklahoma was chosen to test INAS parameterizations. The simulation was performed for the period of 29 March to 1 May 2010. Only model outputs in April are included in the analysis. In a pair of two idealized simulations, cubic and milled hematite particle concentrations are prescribed as  $200 \text{ L}^{-1}$ , which is the average dust concentration simulated by CAM5 model over SGP in springtime. The size and surface area of both types of hematite particles are prescribed with the mean surface area of hematite particles, which is equivalent to having the mean particle diameter of  $1 \mu\text{m}$  based on the spherical assumption. The ice nucleation rate is derived from experimentally determined INAS densities as a function temperature (see Eqs. 1, 2, and 3) and is only applied in the limited temperature range ( $-35.2^\circ\text{C} < T < -33.5^\circ\text{C}$ ) for mixed phase clouds. In order to

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towards slightly higher pH when compared to cubic hematite particles. This implies that the surface of milled hematite particles is more basic than that of cubic ones, probably due to the presence of a relatively higher fraction of the basic groups (i.e., Fe-O-Fe) and/or due to a change in the coordinative environment of the functional groups and their enhanced chemical activity at surface kinks and edges (Schindler and Stumm, 1987). To conclude, a distinct difference in the surface chemical properties of milled and cubic hematite particles was found and ice might have nucleated at the deprotonated active sites on the surface of milled hematite particles (Mazeina and Navrotsky, 2007). These results may support previous molecular dynamic simulations such as Croteau et al. (2010). A more quantitative analysis is required for relating surface chemical and physical properties of atmospherically relevant dust (e.g., natural dust) to ice nucleation activity.

### 3.2 Influence of surface morphology from AIDA experiments

The results of a total four expansion cooling experiments are presented and interpreted in the context of contribution of surface irregularities towards ice nucleation. Two sets of AIDA experiments were analyzed, including two expansions for each cubic and milled hematite particles. Figure 3 summarizes all four AIDA experiments and illustrates the effect of surface irregularities by milling on ice nucleation properties expressed in INAS density. We observed the immersion mode ice nucleation activity,  $n_{s,geo}$ , of hematite to be dependent on temperature, i.e.,  $n_{s,geo}$  increases with decreases in temperature as previously observed (e.g., Steinke et al., 2011; Niemand et al., 2012). We note that  $n_{s,geo}$  of hematite is generally about two orders of magnitude smaller than that of natural dusts (Niemand et al., 2012). We also observed that, as postulated in Möhler et al. (2006), the milling process significantly enhances the overall ability of ice nucleation by more than an order of magnitude at  $-35^{\circ}\text{C}$ . The observed differences may be attributed to the role of various surface features, such as BET measured surface area (a factor of two higher  $A_{total,BET}$  of milled samples than that of cubic ones), highly chargeable components on milled surface, and active sites (cracks and steps). Among these

features, the importance of surface area influence seems not to be significant, as the comparison of  $n_{s,BET}$  still exhibits an order magnitude gap between milled and cubic hematite particles, similar to that of  $n_{s,geo}$  (Fig. 3). More importantly, our overall results suggest that the active sites (cracks and steps) and elevated charge densities on milled surface may be the main reasons of enhanced freezing ability of milled hematite particles.

We note that quantitatively small contribution of early deposition mode ice nucleation (i.e., ice formation due to the direct deposition of water vapor) before the spontaneous formation of droplets is routinely observed for both cubic and milled subset (Fig. S1). For clarity, these minor contributions of deposition mode ice crystals (up to 27 % of total ice crystals formed in an expansion) were excluded from the INAS density estimation. We also limit our analyses to the temperature range of heterogeneous ice nucleation and the measurement-period where the ice probes were operated above their minimum detection limit. Hence, the contributions from homogeneous ice nucleation observed below  $-35^{\circ}\text{C}$  (Figs. S1 and S2) and the time interval coinciding with measured ice crystal concentration below WELAS detection limit ( $< 0.1 \text{ cm}^{-3}$ ) were excluded.

### 3.3 Influence of surface morphology from modeling perspective

Figure 4 shows the simulated ice crystal number concentration at SGP site during April 2010. The ice nucleation rates used in our modeling simulations ( $j_{het}^c$  for cubic hematite particles and  $j_{het}^m$  for milled ones in  $\text{s}^{-1}$ ) are derived from experimentally determined temperature-dependent geometric area-based INAS densities as

$$\begin{bmatrix} j_{het}^c(T) \\ j_{het}^m(T) \end{bmatrix} = \begin{bmatrix} n_{s,geo}^c(T) \\ n_{s,geo}^m(T) \end{bmatrix} \times A_{mean} / \Delta t \quad (1)$$

$$n_{s,geo}^c(T) = 1.072 \times 10^8 + 1.777 \times 10^{-6} \times \exp(-0.969 \times T) \quad (2)$$

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$$n_{s,\text{geo}}^m(T) = 2.523 \times 10^9 + 2.605 \times 10^{-4} \times \exp(-0.889 \times T) \quad (3)$$

where  $T$  is the temperature ( $^{\circ}\text{C}$ ),  $n_{s,\text{geo}}^c(T)$  is the geometric area-based INAS density of cubic hematite particles ( $\text{m}^{-2}$ ),  $n_{s,\text{geo}}^m(T)$  is the geometric area-based INAS density of milled hematite particles ( $\text{m}^{-2}$ ),  $A_{\text{mean}}$  is the mean surface area of single hematite particle ( $\sim 3.1 \times 10^{-12} \text{m}^2$ ), and  $\Delta t$  is the evaluated time step. Ice nucleation induced by hematite particles appears mostly at around 400 hPa, because it can only happen in the limited temperature range  $-35.2^{\circ}\text{C} < T < -33.5^{\circ}\text{C}$ . Ice number predicted in the cubic hematite case varies from less than one per liter to a few per liter. During most of the time, the milled hematite case predicts much higher ice number concentrations than the cubic case, due to its higher INAS density, owing probably from surface morphology (cracks and steps) or charging state. Due to the convective transport and sedimentation processes, ice crystals can be redistributed higher than 250 hPa and lower than 700 hPa before they evaporate or converted to snow. Between 200 hPa and 500 hPa, the simulated ice number for the milled hematite case is on average one order of magnitude higher than for the cubic hematite particles. As a result, the ice water path increases significantly in the milled hematite case (not shown). It should be noted that in these idealized model simulations we intentionally switched off all other ice formation processes, so the simulated ice number concentrations are not realistic and cannot be compared to observations. We also note that the model application in this study only demonstrates the effect of using different INAS densities for a given aerosol population on the ice crystal number concentration. Nevertheless, the sensitivity shown in Fig. 4 indicates that the change of nucleation rate due to the properties of the surface in the milled particles is fully confirmed, and can further lead to significant changes of ice cloud formation process in the upper troposphere. In the future, we suggest modeling study examining the effect of milling or other characteristic surface morphology on the ice nucleation efficiency of atmospherically relevant clay mineral particles (e.g., il-

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lite, kaolinite, and feldspar) and comparison of simulated INAS densities to the AIDA measurements with ground powder samples.

## 4 Conclusions

Laboratory and modeling studies were performed to examine the role of surface morphology upon ice nucleation on hematite particles that heterogeneously freeze at  $-35.2^{\circ}\text{C} < T < -33.5^{\circ}\text{C}$ . Two different forms of laboratory-generated hematite particles were used in this study. Milled hematite particles were generated by mechanically agitating  $1\ \mu\text{m}$  diameter cubic hematite particles with  $100\ \mu\text{m}$  diameter bronze beads, and its immersion mode ice onset was first quantitatively measured using the AIDA cloud simulation chamber at the temperature below  $-28^{\circ}\text{C}$ . An isometric experiment was conducted on cubic hematite particles. The observed ice nucleation activity of milled hematite particles inferred by the INAS density was almost an order of magnitude higher than that of the original cubic hematite particles. Thus, the characteristics of the surface as a result of milling appear to have a substantial effect on the immersion mode ice nucleation efficiency.

We also estimated the specific surface area and interfacial potential independently. The contribution of specific surface area to observed enhancement in ice nucleation ability inferred by the INAS density appeared not to be substantial (up to a factor of two). Interestingly, our charge-pH titration measurements showed a qualitative but reasonable (about a factor of two) difference in surface chemistry. For instance, the milled hematite particles contained more chemically active functional groups that can store charges and exhibited higher charge potential than the original cubic hematite particles. This difference may contribute to form stable multiple layers of water molecules at the surface and may enhance freezing at these sites. This observation may also imply that the active sites (e.g., localized surface features such as cracks and edges) of morphologically complex aerosols may have plausible and quantitative relevance to

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heterogeneous freezing mechanisms in the atmosphere, but also in laboratory experiments.

Additionally, the results from the laboratory experiments were adapted in the computationally efficient version of CAM5 model to simulate ice crystal number concentration in cirrus clouds during April 2010 at the SGP site. We performed a set of simulations that include one with INAS densities for cubic hematite particles and another with INAS densities for milled hematite particles. The ice nucleation in both cases is considered as heterogeneous droplet-freezing in mixed phase clouds (i.e., only happens when cloud droplets exist). The comparison of these two simulations suggested that the surface irregularities and associated active sites lead to greater ice activation through droplet-freezing.

Overall, the influence of surface morphology of hematite particles upon the ice nucleation efficiency was verified by an experimental study, and the influence of enhanced ice nucleation activity was demonstrated by a modeling approach. We note that the conclusions from the current study are limited to the idealized droplet-freezing of known composition and size, and a quantitative analysis for a wide range of different particle types and experimental conditions are required for a complete understanding of the relative importance of active sites over aerosol size and chemistry. The modeling studies further beyond the single-column analysis presented in this study, specifically estimating corresponding longwave cloud forcings, are needed to examine the influence of active sites on overall heterogeneous ice-nucleating properties, constrain the aerosol cloud interactions and cloud model parameterizations.

**Supplementary material related to this article is available online at**  
**[http://www.atmos-chem-phys-discuss.net/13/23757/2013/  
acpd-13-23757-2013-supplement.pdf](http://www.atmos-chem-phys-discuss.net/13/23757/2013/acpd-13-23757-2013-supplement.pdf)**

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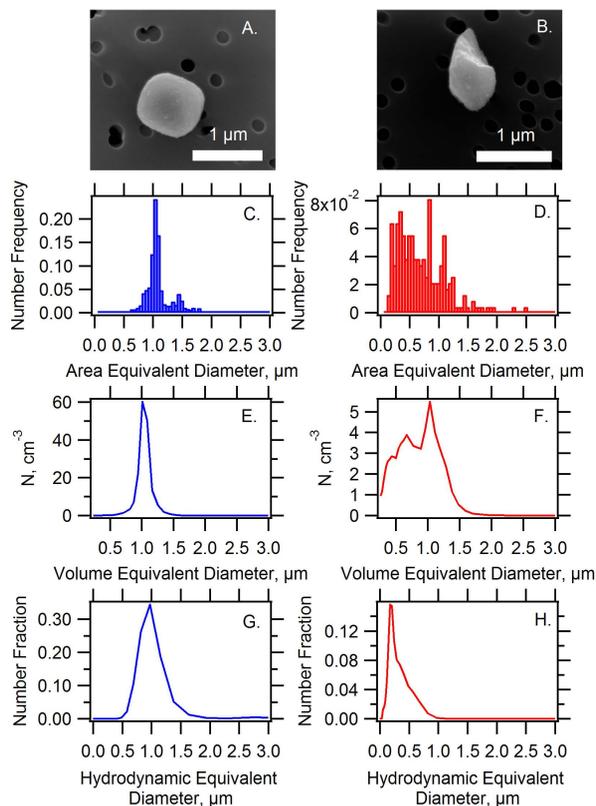
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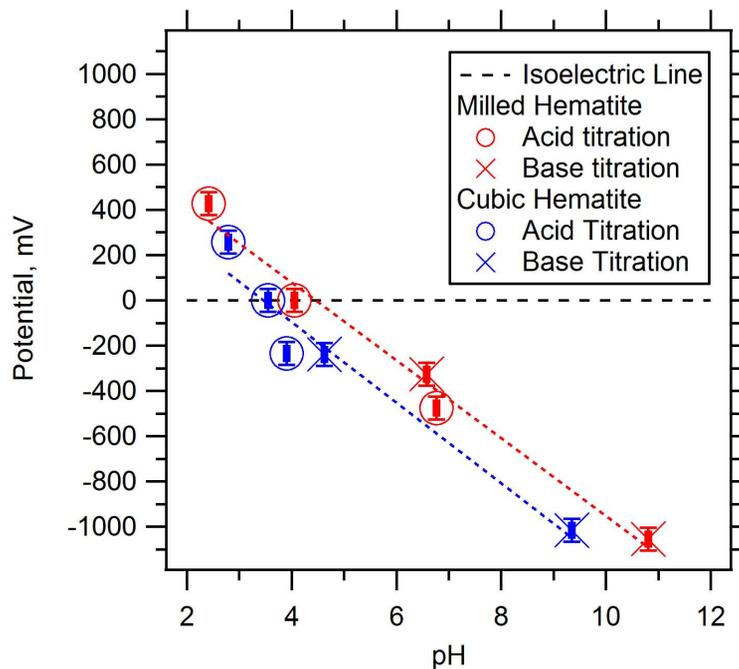


**Fig. 1.** SEM images of (A) a cubic hematite particle and (B) a milled hematite particle. Number frequencies estimated by SEM for each subset of hematite particles are shown in (C) and (D). Particle size distributions measured in the AIDA chamber are shown in (E) and (F). DLS measured size distributions are also shown in (G) and (H).

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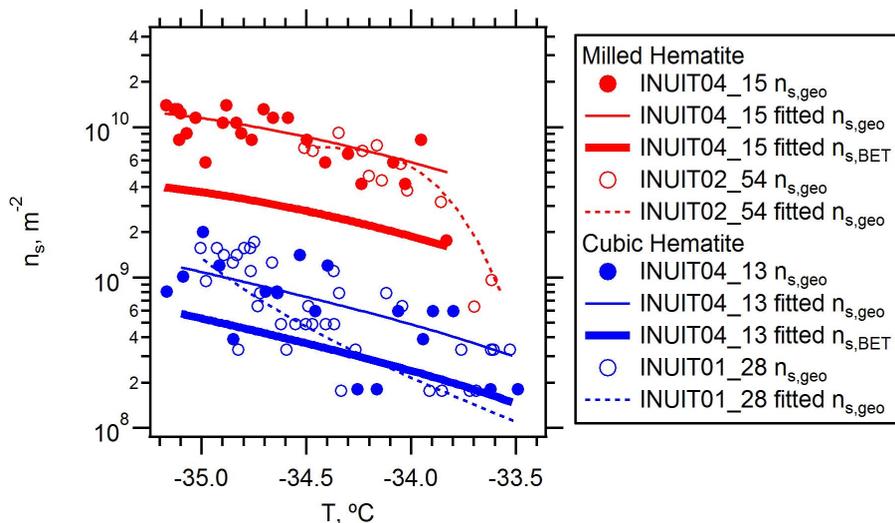


**Fig. 2.** Generation of charged particles by acid-base titration. Isoelectric line (black dashed) represents the pH, at which hematite particle surfaces show zero charge potential. The colored dashed lines represent fits for each hematite particle subset. Error bars represent our experimental uncertainties  $\pm 0.05$  for the pH values and  $\pm 50$  mV for the potential.

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**Fig. 3.** INAS densities, geometric area-based  $n_{s,geo}$  and BET-inferred  $n_{s,BET}$ , for immersion freezing of cubic and milled hematite particles as a function of temperature,  $T$ . The thin solid lines correspond to fitted  $n_{s,geo}$  of INUIT04\_15 and INUIT04\_13 and the thin dashed lines correspond to fitted  $n_{s,geo}$  of INUIT02\_54 and INUIT01\_28. The bold solid lines represent the BET-inferred  $n_{s,BET}$  of INUIT04\_15 and INUIT04\_13. Note that experimental uncertainties are  $T \pm 0.3^\circ\text{C}$  and  $n_s \pm 35\%$  (Steinke et al., 2011).

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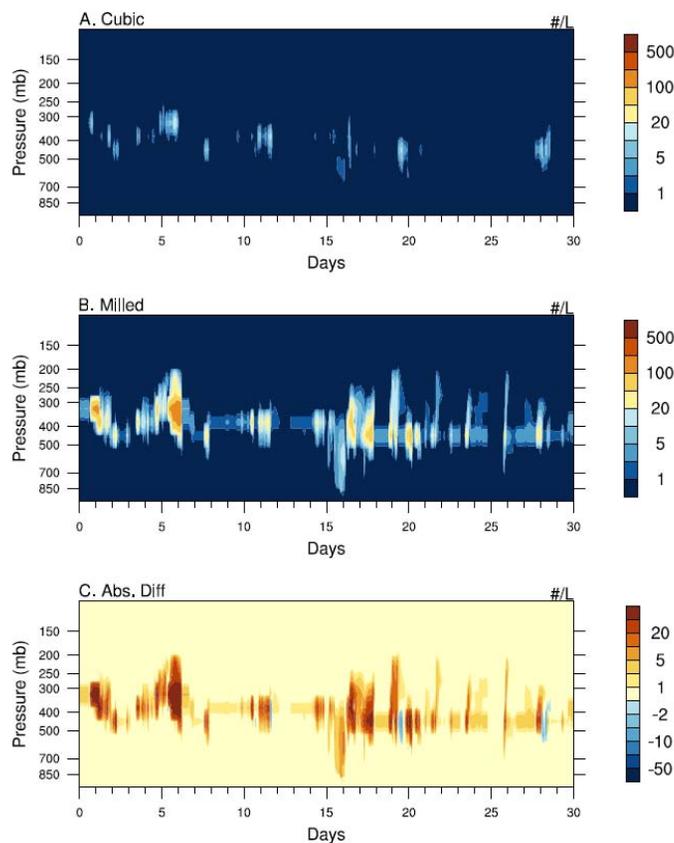
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**Fig. 4.** Simulated time evolution of ice crystal number concentration (color-scaled in  $L^{-1}$ ) over the ARM-SGP site in April 2010. Top panel shows the result of simulation with cubic hematite particles and middle panel shows that of the milled hematite particles. Bottom panel shows the absolute difference between these two simulations.