



Investigating the discrepancy between wet-suspension- and dry-dispersion-derived ice nucleation efficiency of mineral particles

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Abstract. Cloud chamber investigations into ice nucleation by mineral particles were compared with results from cold-stage droplet freezing experiments. Kaolinite, NX-illite, and K-feldspar were examined, and K-feldspar was revealed to be the most ice-active mineral particle sample, in agreement with recent cold-stage studies. The ice nucleation efficiencies, as quantified using the *ice-active surface site density* method, were found to be in agreement with previous studies for the lower temperatures; however, at higher temperatures the efficiency was between a factor of 10 and 1000 higher than those inferred from cold-stage experiments. Numerical process modelling of cloud formation during the experiments, using the cold-stage-derived parameterisations to initiate the ice phase, revealed the cold-stage-derived parameterisations to consistently underpredict the number of ice crystals relative to that observed. We suggest the reason for the underestimation of ice in the model is that the slope of the cold-stage-derived ice-active surface site density vs. temperature curves are too steep, which results in an underestimation of the number of ice crystals at higher temperatures during the expansion. These ice crystals suppress further freezing due to the Bergeron–Findeison process. A coagulation model was used to investigate the idea that the mineral particles coagulate in suspension. This model suggests that coagulation during the experiments may be sufficient to significantly remove the particles for the suspension by sedimentation or reduce the total particle surface area available for ice nucleation to take place. Aggregation was confirmed to take place in mineral suspensions using dynamic light-scattering measurements. However, it is not proven that aggregation of the mineral particles is able to reduce the surface area avail-

able for ice nucleation. The implication is that the mineral particles may be more important at nucleating ice at high temperatures than previously thought.

1 Introduction

Atmospheric mineral dust particles are comprised of several different minerals (e.g. Glaccum and Prospero, 1980; Kandler et al., 2007), and it is possible to determine their ice nucleation activity (e.g. Connolly et al., 2009, and others). However, there is much to be learned by investigating the ice nucleating ability of less complex “pure minerals”. Using a technique originally described by Vali (1971), kaolinite (KGa-1b from the Clay Minerals Society) and NX-illite have been examined in the immersion freezing nucleation mode (Murray et al., 2011; Broadley et al., 2012), and parameterisations of the ice-active surface site density have been put forward, as have those for K-feldspar (Atkinson et al., 2013). These studies used “wet suspensions” of mineral powders to investigate ice nucleation by immersion freezing. They quantified the ice nucleation ability of pure minerals using the ice-active surface site density concept, described as the number of ice-active sites per unit surface area of dust, n_s , as presented by Connolly et al. (2009).

Recently Hiranuma et al. (2015) determined ice nucleation efficiency of the NX-illite dust sample using a variety of methods. The methods were broadly classed as “wet-suspension” methods, where mineral particles were put into water suspension before droplets of the suspension were cooled and frozen, or “dry-dispersion” methods, where the

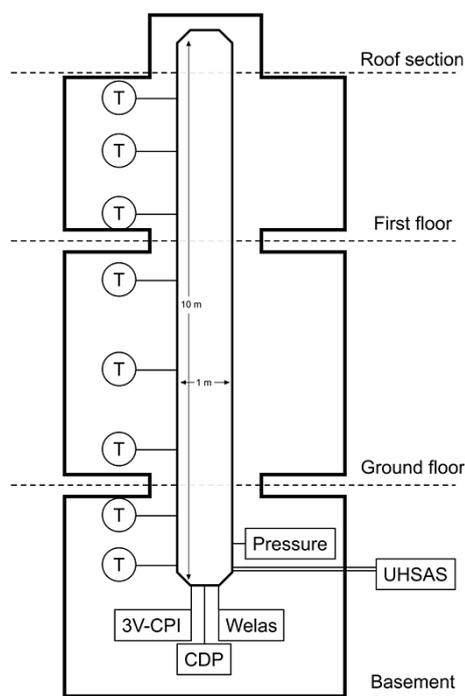


Figure 1. A schematic of the MICC cold rooms and chamber. Outer lines mark the outline of the outer wall of the cold rooms, with the MICC tube inside. Temperature probes are labelled with a “T”. Pressure and cloud properties are monitored in the bottom section of the chamber.

mineral particles act as cloud condensation nuclei followed by freezing. Hiranuma et al. suggested that there was a discrepancy between the dry-dispersion methods and the wet-suspension methods at high temperatures, which they suggested may be due to a change in chemical composition of the NX-illite mineral during dissolution in water. They also discussed the potential effect of agglomeration of the mineral particles in suspension to reduce the available surface area for ice nucleation and also the possibility of the powders having multiple nucleation “modes”. They concluded that further work was needed to better understand instrumental differences.

Several papers (e.g. Murray et al., 2011; Broadley et al., 2012) have shown that the number of ice-active sites on mineral powders scales with the total surface area of powder in a drop; however, in these papers, the total surface area available in the drops was, in some instances, relatively large due to high particle number concentrations in the suspension. The typical range of particle number concentrations was between 10^{15} and 10^{17} m^{-3} . The higher value, 10^{17} m^{-3} , equates to an inter-particle spacing of $\sim 2 \mu\text{m}$, if one assumes equal spacing between the particles. At these high particle concentrations one might expect some interaction between neighbouring particles if they are able to come together and adhere due to the van der Waals interaction.

In nature, it is unlikely such high dust concentrations will be present in supercooled cloud drops. Hence, the aim of this paper is to use a combination of laboratory experiments, data analysis and modelling to reconcile two different approaches for determining ice nucleation efficiency. This paper focusses on the condensation/immersion freezing mode of ice nucleation, which was the dominant mode observed in our experiments.

2 Experimental set-up

Experiments were conducted in the Manchester Ice Cloud Chamber (MICC) fall tube, which has a diameter of 1 m and height of 10 m (additional details of the general facility are described in Connolly et al., 2012). The MICC and experimental set-up are shown in Fig. 1. Initially, the chamber was pressure-sealed and evacuated to 200 hPa using two scroll pumps, capable of reducing the pressure at a rate of approximately 1.4 hPa s^{-1} , before refilling with filtered air. The filtered air had $10\text{--}20 \text{ cm}^{-3} > 5 \text{ nm}$ particles, with a total particle mass concentration $< 0.01 \mu\text{g m}^{-3}$. Volatile organic carbon, VOC, measurements by the Leicester proton transfer reaction mass spectrometer indicated VOC levels below detection limits of approximately 1 ppb. This cleaning process was repeated a total of three times to reduce background aerosol concentration inside MICC to typically 20 cm^{-3} . The chamber was then cooled to the desired temperature, ranging from -12 to $-27 \text{ }^\circ\text{C}$ depending on the experiment, and allowed to thermally equilibrate.

Prior to conducting the cloud formation experiments, a background experiment was performed in which the pressure was reduced to 700 hPa to check that the remaining background aerosol in the chamber post-cleaning were not ice nuclei. Ice was only ever observed in low concentrations of a few per cubic centimetres (cm^{-3}) at the lowest temperatures and was attributed to homogeneous nucleation when the temperature during the pressure reduction process approached $-35 \text{ }^\circ\text{C}$. In the case where this was observed, the ice crystal concentration was substantially lower than the resulting concentration in the later experiments where mineral dust particles were present. Several of these background experiments are shown in Figures S1 and S2 of the Supplement, where it is seen that very low background ice crystal number concentrations were achieved.

Following the background experiment, a selected mineral dust was inserted into the chamber using a PALAS dust generator (RBG 1000 ID). This instrument uses particle-free compressed air to separate and insert dust particles from a rotating brush which collects them from a reservoir. The dust was inserted into the top of the chamber and allowed to homogenise; an initial measurement was taken using an Ultra High Sensitivity Aerosol Spectrometer (UHSAS), which uses an intracavity laser to measure aerosols in the size range (50–1000 nm) and a PALAS WELAS (White Light Aerosol

Table 1. Table showing summary of experimental results. Ice crystal concentrations are determined from the CPI number concentration of ice crystals, unless stated otherwise. The two values listed within the $[\dots]$ are the parameters for the two log-normal modes of the size distribution. Multiple rows indicate the expansion number on the same mineral particle sample after refilling to 1000 hPa. Geometric surface areas were obtained through integration of the size distribution assuming spherical particles. Errors in ice crystal concentration were calculated using Poisson counting statistics at the 0.05 level of significance.

Mineral sample	Ice conc. (cm^{-3})	N (cm^{-3})	D_m (μm)	$\ln\sigma_g$	Geometric surface area (m^{-1})
K-feldspar @ -12°C	8.96 ± 0.15	[1700, 45]	[0.32, 2.8]	[0.3, 0.55]	1.99×10^{-3}
	6.31 ± 0.13	[1200, 15]	[0.32, 2.8]	[0.5, 0.55]	1.25×10^{-3}
	4.53 ± 0.11	[800, 4]	[0.32, 2.8]	[0.5, 0.45]	5.75×10^{-4}
	2.56 ± 0.08	[400, 3]	[0.32, 2.8]	[0.5, 0.65]	3.44×10^{-4}
K-feldspar @ -21°C ^a	47.16 ± 0.35	[1000, 20]	[0.32, 2.8]	[0.5, 0.8]	1.41×10^{-3}
	53.39 ± 0.38	[600, 20]	[0.33, 1.0]	[0.45, 1.5]	7.03×10^{-4}
	32.56 ± 0.29	[300, 20]	[0.33, 1.0]	[0.45, 1.4]	5.42×10^{-4}
	27.05 ± 0.27	[200, 1]	[0.33, 1.0]	[0.45, 0.8]	1.10×10^{-4}
Kaolinite @ -19°C	9.51 ± 0.16	[500, 90]	[0.45, 2.8]	[0.4, 0.6]	4.35×10^{-3}
	1.52 ± 0.06	[300, 20]	[0.45, 2.8]	[0.4, 0.5]	1.13×10^{-3}
	0.34 ± 0.03	[200, 8]	[0.45, 2.8]	[0.4, 0.5]	5.50×10^{-4}
	0.20 ± 0.02	[100, 15]	[0.45, 2.8]	[0.4, 0.55]	7.23×10^{-4}
	0.06 ± 0.01	[50, 5]	[0.45, 2.8]	[0.4, 0.8]	2.81×10^{-4}
Kaolinite @ -25°C	5.29 ± 0.12	[500, 90]	[0.4, 3]	[0.4, 0.6]	4.55×10^{-3}
	8.43 ± 0.15	[375, 60]	[0.45, 3]	[0.4, 0.6]	3.21×10^{-3}
	8.59 ± 0.15	[250, 40]	[0.5, 2.8]	[0.4, 0.65]	2.11×10^{-3}
	8.78 ± 0.15	[150, 25]	[0.45, 2.8]	[0.4, 0.8]	1.28×10^{-3}
	4.69 ± 0.11	[50, 15]	[0.45, 2.8]	[0.5, 0.8]	7.26×10^{-4}
Illite @ -15°C	1.59 ± 0.07	[1400, 15]	[0.28, 2.6]	[0.25, 0.5]	5.10×10^{-4}
	0.182 ± 0.02	[700, 5]	[0.27, 2.6]	[0.28, 1.3]	1.92×10^{-4}
	0.037 ± 0.01	[400, 2]	[0.27, 2.6]	[0.48, 0.5]	1.73×10^{-4}
	0.021 ± 0.03	[250, 3]	[0.27, 2.6]	[0.48, 2]	1.50×10^{-4}
Illite @ -25°C	8.04 ± 0.15	[1700, 25]	[0.28, 3]	[0.45, 0.5]	1.51×10^{-3}
	10.36 ± 0.17	[1500, 20]	[0.28, 3]	[0.45, 1]	1.27×10^{-3}
	10.92 ± 0.17	[800, 15]	[0.28, 3]	[0.45, 1.6]	7.14×10^{-4}

^a Ice concentrations determined from particles greater than $20\mu\text{m}$ as measured with the CDP for this experiment because the concentrations were high and hence the ice crystal sizes were small.

Spectrometer) 2000 aerosol probe ($0.4 < D_p < 90\mu\text{m}$) indicating total initial concentrations of approximately $1000\text{--}2000\text{ cm}^{-3}$. Size distributions from the UHSAS and WELAS were used to derive log-normal mode fit parameters to approximate the size distributions and also the aerosol particle surface area, assuming a spherical particle geometry.

Liquid cloud drops formed as the pressure was reduced to 700 hPa from ice-saturated conditions, and this was sampled with cloud probes, including the PALAS WELAS 2000, Droplet Measurement Technologies Cloud Droplet Probe (CDP), and the Stratton Park Engineering Company Cloud Particle Imager 3V (3V-CPI). Briefly, the WELAS infers the size of particles from the intensity of the light they scatter at 90° . The CDP operates on a similar principle to the WELAS, but it uses a solid-state laser (658 nm) and detects light scat-

tered by particles ($3 < D < 50\mu\text{m}$) in the forward direction ($4\text{--}12^\circ$).

The 3V-CPI acquires images of particles ($20 < D < 2000\mu\text{m}$) that pass through its sample volume, using a pulsed infrared laser incident on a CCD (Charge-Coupled Device) array. 3V-CPI images that are greater than $35\mu\text{m}$ in length are analysed via their shape to determine if they are ice crystals or not; if they have a roundness parameter¹ of less than 0.9, they are classified as ice crystals. For these large shapes visual inspection of the images allows us to be confident in discriminating between drops and ice crystals; hence, the remaining errors are due to Poisson counting, which are presented in Table 1.

¹ defined as the area of the particle divided by the area of a circle with the same maximum dimension of the particle.

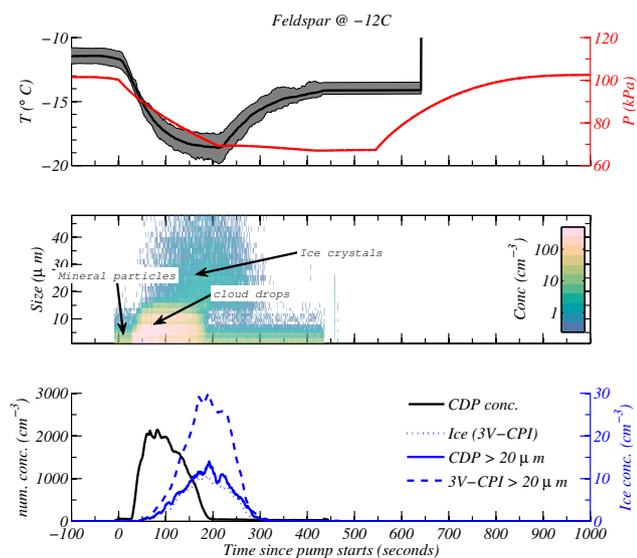


Figure 2. Feldspar mineral particles at -12°C . Top shows the temperature in the chamber (black line, left axis) and the pressure (red line, right axis). The black line is the mean of temperature probes, while the grey shading demarks the range in measured temperatures across all probes. The middle plot shows the size distribution as measured with the CDP instrument. Bottom plot shows (1) the drop concentration measured with the CDP (black line, left axis); (2) the concentration of particles larger than the main droplet mode (solid blue line, right axis); (3) the ice crystal concentration measured with the 3V-CPI (blue dotted line, right axis); and (4) the concentration of particles larger than 20 microns with the 3V-CPI (dashed blue, right axis).

Internal chamber pressure was measured using a KELLER LEX 1 pressure probe, and the air temperature was measured using calibrated type K thermocouples arranged along the height of and in the centre of the cloud chamber. Several repeat pressure reduction cycles were performed on the same dust (referred to as an experimental “run”): after each experimental run, the chamber was filled back to ambient pressure using the clean-air system so that a total of \sim four similar experimental runs could take place – the collection of experimental runs was referred to as a “set” of experimental runs. Two sets of experimental runs were performed for each of the three dust samples (kaolinite, feldspar, and illite), one at high temperature and one at low temperature. As stated, there were \sim four runs per set, yielding a total of \sim 24 depressurisations, not including background runs.

3 Observations

Our observations generally showed that ice nucleation took place following the formation of drops; hence, this study focusses on the condensation/immersion freezing mechanism of ice nucleation.

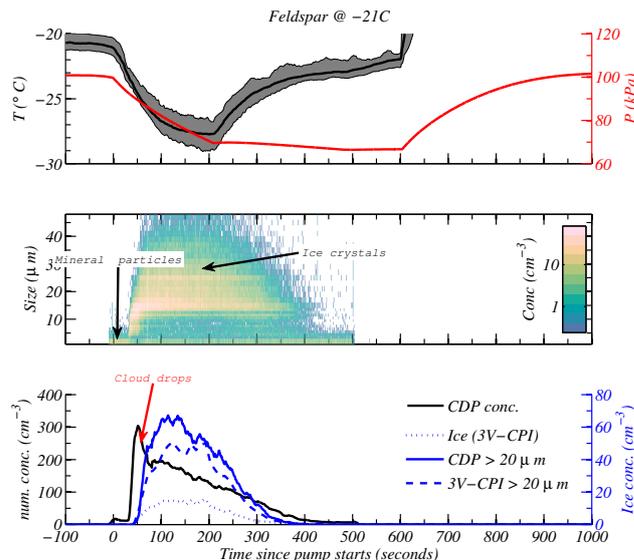


Figure 3. Same as Fig. 2 but for feldspar at -21°C .

In the high-temperature experimental runs few ice crystals formed, which enabled them to grow to large sizes observable with the 3V-CPI. Fewer ice crystals allows for supercooled droplets to grow to appreciable sizes, similar to the sizes of ice crystals, which were in general $> 20\mu\text{m}$ in size. Hence, in these experiments, we could not reliably use the measurement of size, from the CDP, as a means to discriminate ice crystals from drops. In this case the best method was to use the 3V-CPI to determine the ice crystal concentrations.

For the lower-temperature experimental runs many more ice crystals formed, resulting in smaller ice crystals that were difficult to observe with the 3V-CPI. The supercooled drops that formed were small in size and clearly separated from the ice crystals. Thus, in this kind of experiment, it was preferable to use the CDP to determine the ice crystal concentrations (the cut size between liquid and ice was $13\mu\text{m}$). We now show two examples highlighting this.

Figures 2 and 3 show the results of the two first experimental runs on K-feldspar – the same sample used in the Atkinson et al. (2013) study. Figure 2 was conducted with the initial temperature equal to -12°C , and expansion of the air to 700 hPa resulted in the temperature decreasing to $\sim -19^{\circ}\text{C}$. The middle plot of Fig. 2 shows the time evolution of the measured size distribution from the CDP. Mineral particles are visible at the start of the experiment at sizes up to $\sim 10\mu\text{m}$, whereas $\sim 25\text{ s}$ into the experiment a cloud of droplets grows as noted from the brighter colours. Following the formation of drops, ice crystals are formed and grow to large sizes.

The cloud of drops evaporates at $\sim 200\text{ s}$ due to the Bergeron–Findeison process, following which the ice crystals are able to persist to $\sim 300\text{ s}$. The bottom plot of Fig. 2 shows that the drop concentration measured with the CDP

reaches $\sim 2000 \text{ cm}^{-3}$. The ice concentration determined by the 3V-CPI (blue dotted line) agrees very well with the concentrations of particles greater than $20 \mu\text{m}$ as measured with the CDP (blue line), thus giving confidence in our measurements of ice crystal concentration. The blue dashed line is the concentration of particles greater than $20 \mu\text{m}$ measured with the 3V-CPI. It should be noted that the reason this is greater than the concentrations of particles greater than $20 \mu\text{m}$ measured with the CDP is because the 3V-CPI often over-sizes out-of-focus images of droplets (Connolly et al., 2007).

Figure 3 shows the results of the first run of K-feldspar at an initial temperature of $-21 \text{ }^\circ\text{C}$. During the expansion the air temperature reduced to $\sim -28 \text{ }^\circ\text{C}$. The CDP showed evidence of droplets forming for a brief period at $\sim 40 \text{ s}$ into the experiment (middle plot and black line on bottom plot). However, the droplets only lasted for a brief period (less than $\sim 40 \text{ s}$). The 3V-CPI ice concentration is lower than the CDP concentration of particles greater than $20 \mu\text{m}$ (blue line); however in this experiment, because there were so many ice crystals nucleated, it was difficult to discriminate the ice crystals on shape alone because the ice crystals appeared somewhat rounded due to the lack of vapour growth. Furthermore, the concentrations of particles greater than $20 \mu\text{m}$, measured with the CDP, and those measured with the 3V-CPI greater than $20 \mu\text{m}$ are in good agreement. For this experiment it was more accurate to use the CDP concentrations greater than $13 \mu\text{m}$, rather than the 3V-CPI, for the ice crystal concentrations so that the smallest ice crystals were not missed.

4 Analysis

To compare our dry-dispersion chamber observations with wet-suspension cold-stage methods (e.g. Murray et al., 2011; Broadley et al., 2012; Atkinson et al., 2013), we used two main approaches. Firstly we calculated values of the ice-active surface site density, or n_s , using our data and plotted them on the same graph as existing data taken using cold stages (see Sect. 4.1). Secondly the Aerosol–Cloud Interactions Model (ACPIM) (Connolly et al., 2012) was used to simulate the MICC cloud chamber experiments. In this model, the freezing parameterisations of Murray et al. (2011), Broadley et al. (2012) and Atkinson et al. (2013) have been implemented and were used to compare ice concentrations expected with those observed. Results from ACPIM are presented in Sect. 4.2.1.

4.1 Calculating n_s directly from the data

We calculated n_s directly from the data in the following way. The result of the n_s concept is that the fraction of drops, f , containing surface area, A , that are frozen at temperature, T , is described by the factor

$$f = 1 - \exp(-An_s[T]). \quad (1)$$

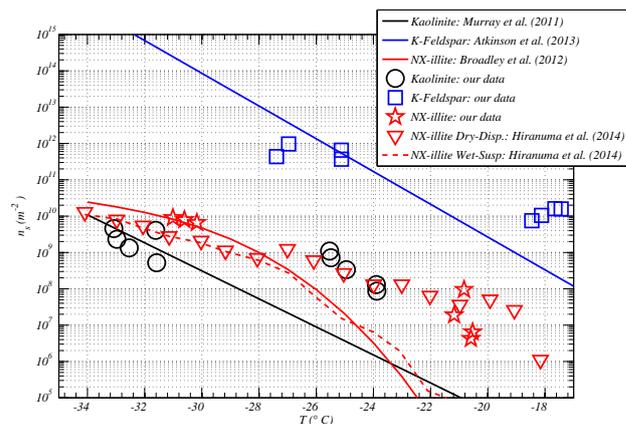


Figure 4. n_s values from the literature using wet-suspension methods are shown via the line plots: black line is for kaolinite from Murray et al. (2011); blue line is for K-feldspar from Atkinson et al. (2013); red solid line is for NX-illite from Broadley et al. (2012); red dashed line is for NX-illite from Hiranuma et al. (2015). The open symbols correspond to n_s values derived using dry dispersion: black circles are our data for kaolinite; blue squares are our data for K-feldspar; and stars are our data for NX-illite. Downward-pointing triangles are for the NX-illite data derived using dry dispersions from Hiranuma et al. (2015). For our data, measurement errors are typically the size of the symbols or less (see Table 1)

Hence, for an input dust particle size distribution, $\frac{dN}{dD}$, where all particles are hygroscopic, or take up at least a mono-layer of water, we write the number of ice crystals that are nucleated as

$$N_{\text{ice}} = \int_{D_{\text{min}}}^{D_{\text{max}}} \frac{dN(D)}{dD} (1 - \exp(-An_s[T])) dD. \quad (2)$$

Here D_{min} and D_{max} are the minimum and maximum particle size in the mineral particle size distribution.

The value used for A in Eq. (2) is the surface area of a sphere multiplied by a factor to yield the BET (Brunauer–Emmett–Teller) specific surface area (SSA; see Table 3). We calculate n_s iteratively using data and Eq. (2) as follows. Firstly, we use an initial guess of n_s and evaluate the integral in Eq. (2). We then compare the calculated value of N_{ice} with the measured value. This process is repeated with updates to n_s until the integral is equal to the measured value of N_{ice} , at which point the method has converged.

Another way of estimating n_s (e.g. Niemand et al., 2012; Hiranuma et al., 2015) has been to divide the measured ice crystal number concentration by the surface area of the aerosol size distribution, as measured at the start of the experiment (with a pressure correction for dilution during the expansion):

$$n_s \cong \frac{N_{\text{ice}}}{\pi \int_{D_{\text{min}}}^{D_{\text{max}}} D^2 \frac{dN(D)}{dD} dD}. \quad (3)$$

However, this method can lead to an underestimation of n_s because it does not take into account the removal of surface area from the dust size distribution as its nucleates ice.

The values of n_s derived using the iterative method are shown in Fig. 4. We have chosen to plot each experimental run as a single data point. Note that the spread in n_s values, for data points that are close together in temperature, arises because experiments were repeated for several expansions, which allowed the most efficient ice nuclei to be depleted from subsequent expansions. Since the ice crystal concentrations are measured with time, we could use a single experiment to derive multiple data points as is typically done in other studies (e.g. Niemand et al., 2012; Hiranuma et al., 2015); however, we have more confidence in the accuracy of the averaged data from each experimental run.

Figure 4 shows that the results from MICC for NX-illite (red stars) closely match those for the dry dispersions by Hiranuma et al. (2015) (red triangles), which validates our approach. Furthermore, it is seen that, at the higher temperatures, values from the chamber (using dry dispersion) are significantly larger than those taken from cold stages (using wet suspension). This corroborates the discrepancy noted in the recent study by Hiranuma et al. (2015) for NX-illite.

4.2 Process modelling

The application of ACPIM to understand and interpret the observations is described in Sect. 4.2.1, below. The discrepancies noted in Fig. 4 prompted us to investigate the reason for differences between dry-dispersion and wet-suspension techniques; hence, coagulation model calculations are presented in Sect. 4.2.2.

4.2.1 Chamber modelling

We operated ACPIM as a cloud parcel model with bin microphysics (see Connolly et al., 2012, for a description of the model). The aerosol size distributions were specified as log-normal fits to the observed data from the UHSAS and the WELAS probes (see Table 1). The curves were manually fitted to the data. Since the background aerosol particles were not ice nuclei, we assumed them to be hygroscopic aerosol particles (ammonium sulfate). A single log-normal mode of ammonium sulfate aerosol was used to describe the background aerosol measured during the background experiment, while two log-normal modes were used to describe the mineral particle size distribution that was measured prior to the experiment. The background aerosol could be clearly distinguished from the mineral particle size distribution by size: the background distribution was narrow and had a median diameter of ~ 40 nm whereas the mineral particle distribution was broad and had a median diameter of ~ 400 nm. It was assumed that the mineral dust particles had a small amount of soluble material on them, to enable them to act as cloud condensation nuclei (as well as ice nuclei). The model was

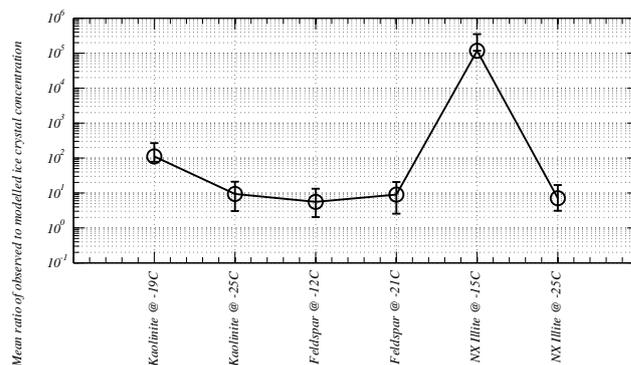


Figure 5. Figure summarising the results of the ACPIM simulations. The metric shown is the ratio of observed to modelled ice crystal number concentrations averaged over all expansions in a set of experiments. Error bars are 25th and 75th percentiles. The ACPIM model used the parameterisations from Murray et al. (2011), Broadley et al. (2012) and Atkinson et al. (2013) for kaolinite, illite and K-feldspar particles respectively.

relatively insensitive to the fraction of soluble material assumed in the range 1–5 % (by mass). The parcel model was forced with the observed pressure drop rate, and the temperature rate of change was calculated from the conservation of energy (first law of thermodynamics) for moist air with the addition of a first-order derivative that depends on the temperature difference between the gas and the chamber walls to account for the wall effect. In the model, total water content remained constant during an experiment (which was consistent with the condensed mass inferred from the CDP measurements and water vapour concentration measured by a tunable diode laser).

The condensation process was described by the droplet growth equation (Pruppacher and Klett, 1997), with equilibrium vapour pressures described by Köhler theory. Ice nucleation was modelled using the parameterisation of Koop et al. (2000) for homogeneous freezing or Murray et al. (2011), Broadley et al. (2012) or Atkinson et al. (2013) for heterogeneous freezing by the kaolinite, illite or feldspar mineral dust respectively. A criterion was added that a dust particle had to have 5×10^{-14} kg of water condensed before it could act in the immersion/condensation mode – this prevented ice nucleation at conditions that were sub-saturated with respect to water in the model, consistent with the chamber data (to within error). Once nucleated, ice crystals grew according to the ice crystal growth equation (Pruppacher and Klett, 1997), and in this work crystals were assumed to be quasi-spherical with a variable effective density (see Connolly et al., 2012, for details). All derivatives form a large set of coupled ODEs (Ordinary Differential Equations), which were solved using the DVODE (Double Precision Variable coefficient ODE solver) solver from Netlib.

ACPIM was run for every experiment in Table 1, and the results are summarised as ratios of observed to simulated ice

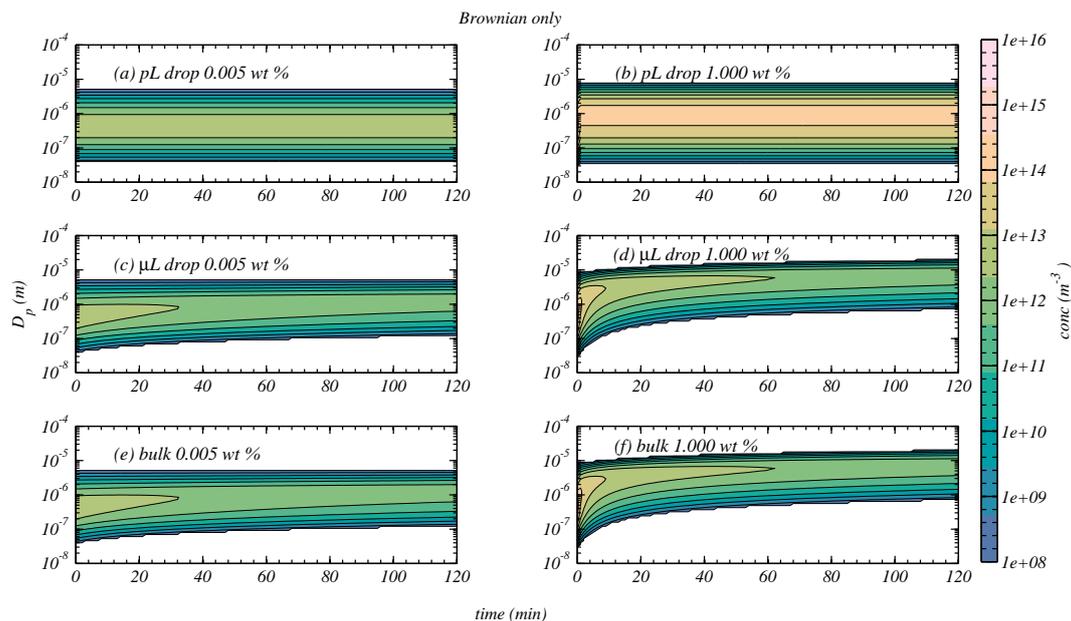


Figure 6. Numerical model simulations of the coagulation of mineral particles within suspension showing the size distribution evolution vs. time. (a) is for a 0.005 wt% suspension inside a pico-litre drop; (b) is the same as (a) but for 1.000 wt%; (c) is for a 0.005 wt% suspension inside a micro-litre drop; (d) is the same as (c) but for 1.000 wt%; (e) and (f) are the same as (c) and (d) respectively but for an infinite volume.

crystal concentrations in Fig. 5. The statistics in Fig. 5 were calculated from each of the experimental runs for a particular set of experiments. In general it is shown that the parameterisations, which are all based on particle surface area, underestimate the ice crystal concentrations at all temperatures, whereas from Fig. 4 one would expect the parameterisations to do reasonably well at the lower temperatures. The reason the parameterisations do not do well at low temperatures is because the dry-dispersion data suggest that the slope of the n_s vs. temperatures curves should be shallower, thus yielding higher values of n_s at the start of the expansion.

4.2.2 Coagulation modelling

In previous experimental approaches relying on wet suspension, mineral particles are generally added to a large volume of water, and then small droplet samples of this suspension are deposited on a cold stage. The droplets are deposited either by spraying (in which case pico-litre drops are produced) or by pipetting onto a glass slide (in which case micro-litre drops are produced). A few minutes may then elapse before commencing the cooling of drops. Hence, in this approach, it is possible that coagulation of the mineral particles occurs – either in the large volume of water or in the droplets before and during the cooling cycle.

In addition, while on the cooling cold stage, droplets are subject to a temperature gradient; therefore, coagulation may be further enhanced over Brownian coagulation by thermophoretic forces. However, the following argument sug-

gests that this is a small effect: we note that the timescale for heat energy to travel through a droplet,

$$\tau = \frac{L^2}{\kappa}, \quad (4)$$

where $L \sim 10^{-3}$ m is the size of the drop and $\kappa \sim 0.6 \text{ W m}^{-1} \text{ K}^{-1}$ is the thermal conductivity, is of the order of a microsecond. Hence, we expect thermophoresis to be a small effect and do not consider it further.

We modelled the coagulation of particles within wet suspensions using the model described in Appendix A. We present the results here, neglecting the electric double charge layer that is commonly used to describe inter-particle forces in a colloid (our justification for this is discussed in Sect. 5.1.1).

Simulations with the coagulation model were performed for a 2 h run time. We performed simulations for two weight percents (0.005 and 1.000) and also used three assumptions for the size of the water drops that the mineral particles were suspended in. The first was to assume a pico-litre volume drop ($1 \times 10^{-15} \text{ m}^3$), the second was to assume a micro-litre volume drop ($1 \times 10^{-9} \text{ m}^3$) and the third was to assume an infinite volume of water. The reason for these choices was that they span the range of conditions encountered in the cold-stage experiments. We also used different coagulation kernels: one where forces due to Brownian motion were the only forces governing the motion of the particles, and another where Brownian and gravitational settling forces were acting.

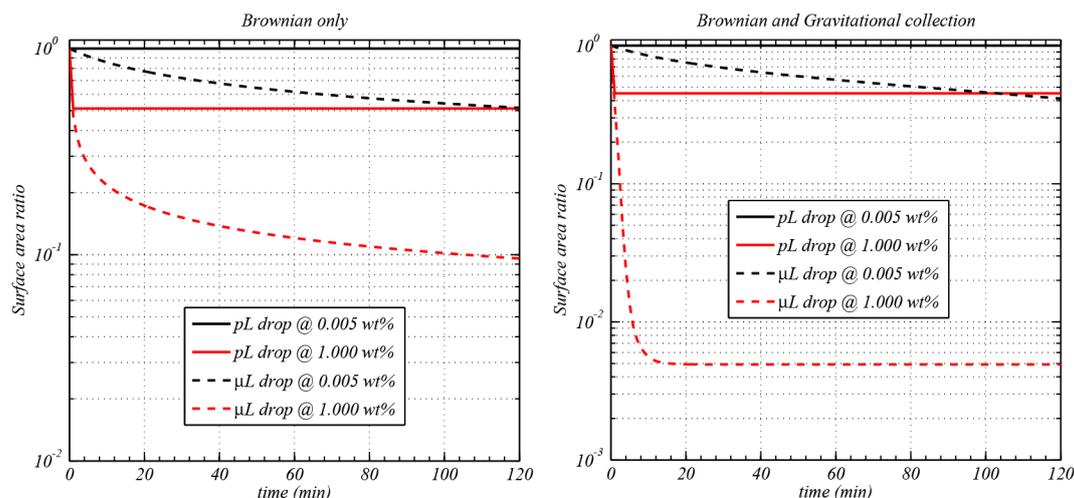


Figure 7. Left: the evolution of the ratio of particle surface area to initial particle surface area for mineral particles undergoing coagulation in water suspension. The coagulation kernel assumed is that due to collisions arising from Brownian motion only. Right: same but with the coagulation due to Brownian motion and gravitational settling.

Figure 6 shows results from the coagulation model, assuming that the forces governing the movement of mineral particles are those due to Brownian motion only. Figure 6a and b show that hardly any coagulation occurs within the pico-litre drops at the weight percents assumed in the calculations. This is evident from the fact that the particle sizes do not change with time. There are just too few particles present for coagulation to be efficient. When micro-litre drops are used (Fig. 6c and d), we see that the size of the mode shifts to larger sizes. This is significant for the larger weight percent drops where the median size shifts from sub-micron to tens of microns. The assumption of an infinite volume of water in Fig. 6e and f yields similar results to the micro-litre model run.

From the results in Fig. 6 we have calculated the ratio of mineral particle surface area to the initial mineral particle surface area. These calculations are shown in Fig. 7, left panel. We have assumed that a collision between two mineral particles yields a mineral particle with the same volume as the other two and that they produce quasi-spherical particles with a fractal dimension of ~ 2 (as shown by Vaezi G et al., 2011). Figure 7, left panel, shows that, at the highest weight percent in the micro-litre drop, the surface area of the mineral particles quickly drops to ~ 0.1 of the initial value. For the highest weight percent in the pico-litre drop and for the lowest weight percent of the micro-litre drop we see that the surface area available for nucleation is ~ 0.5 of the initial value. Finally, for the lowest weight percent in the pico-litre drop we see no reduction in the available surface area.

Figure 7, right panel, shows the same calculation of available surface area vs. time when both Brownian motion and gravitational settling influence the coagulation kernel. Similar results to those for the Brownian-only kernel are shown for the pico-litre drops and also for the micro-litre at low

weight percent; however, for the micro-litre drop at high weight percent we see that the available surface area quickly drops to 0.005 of the initial value.

It should be noted that our simulations of coagulation offer a rough calculation of the reduction in surface area due to coagulation. However, another important process to consider is the fact that, once aggregated, large particles will sediment out of the suspension, therefore further reducing the available surface area for nucleation. The subsequent calculations of n_s will be biased low because the surface area used to calculate n_s (the original surface area added to the suspension) will be too high.

4.3 Colloid experiments

In order to support our calculations, we have conducted experiments where we prepare colloidal suspensions at 0.1 to 1 wt % solids (either K-feldspar, kaolinite or NX-illite) in ultrapure (18.2 M Ω cm) water.

We stirred the suspensions for 12 h using a magnetic stirrer to reproduce the methods of previous ice nucleation studies and then passed them through either 1 or 5 μ m filters (22 mm Cellulose nitrate membrane, Whatman, UK). We found in all cases that this process reduced the absorbance of UV and visible light to that of ultrapure water (UV-Vis spectrometer, Stellarnet, FL, USA) and, therefore, removed the particles completely to within error of the absorbance measurements. Less than 2 mL of suspension was passed through the filter membranes, and their effective pore size would have remained unaltered. This therefore suggests that the sub-micron sizes initially present in the mineral particle sample had aggregated to super-micron sizes. We also monitored the absorbance of the suspension vs. time across the spectrum; at 567 nm, the optimum wavelength with respect to signal-to-

Table 2. Table showing results from dynamic light-scattering experiments for the kaolinite sample. Standard deviations are given in parentheses.

In water			
pH	Diameter for 0.1 mg mL ⁻¹ (nm)	Diameter for 0.33 mg mL ⁻¹ (nm)	diameter for 1 mg mL ⁻¹ (nm)
3.0	692.4 (51.8)	1143.0 (101.65)	1777.0 (151.25)
5.1	652.1 (54.05)	741.9 (76.25)	753.2 (76.95)
7.0	695.0 (49.56)	742.4 (100.5)	792.8 (96.1)
9.0	449.4 (58.75)	418.0 (81.65)	721.6 (83.45)
11.0	467.7 (61.55)	448.0 (70.95)	693.2 (66.75)
100 mM NaCl			
pH	Diameter for 0.1 mg mL ⁻¹ (nm)	Diameter for 0.33 mg mL ⁻¹ (nm)	
3.0	1241.5 (51.8)	1585.0 (175.72)	
5.1	913.0 (54.05)	1318.5 (120.22)	
7.0	740.1 (49.56)	1533.5 (155.55)	
9.1	674.6 (58.75)	1350.0 (153.82)	
11.0	618.2 (61.55)	997.85 (173.90)	

Table 3. Table showing BET specific surface area of the different mineral samples used in this study.

Mineral sample	BET SSA m ² kg ⁻¹	Bulk density (kg m ⁻³)	SSA underestimation factor
Kaolinite	11 800	2650	~ 2.1
NX-illite	104 200	2770	~ 19.2
K-feldspar	3115 ^a	2570	~ 0.53

^a 3.5 times that of 890.

noise ratio decreased by a factor of 10 within 90 min of sample preparation. This also suggests that sedimentation and aggregation had occurred.

Dynamic light scattering (DLS) measurements were performed using a Malvern Zetasizer Nano ZS at The University of Manchester, UK. DLS is a technique to measure the size of small particulates in suspension. A laser is used to illuminate the particles in a sample of water, which gives a scattered signal containing a speckle that fluctuates in time due to the movement of the particles by Brownian motion. Theory is used to relate this fluctuating signal to the size of the particles in suspension.

Kaolinite suspensions were prepared (MilliQ H₂O and 100 mM NaCl) to study the effect of electrolytes on particle aggregation. The water was filtered with a 0.2 μm PTFE filter to eliminate possible dust particles. Measurements of the kaolinite samples were conducted with concentrations of 0.1, 0.33 and 1 mg mL⁻¹ (0.01, 0.033 and 0.1 wt %) prepared by mild sonication for 5 min at 60 °C and then immediately cooled to room temperature and measured within minutes. Note that in the absence of heating to 60 °C the particles remained in an aggregated state. The pH was varied between 3 and 11 by addition of the minimum amount of diluted HCl and NaOH respectively, and the results are summarised in Table 2.

Measurements in MilliQ water show an increase in particle size with increasing kaolinite concentration. It is notable that at pH ~ 9.0 there is a factor-of-2 increase in particle size, going from 0.33 mg mL⁻¹ concentration to 1 mg mL⁻¹, since the pH of kaolinite in MilliQ water was measured to be ~ 8.2 in the aggregated sample, thus suggesting that aggregation is important. The effect of electrolytes is clearly seen in the lower half of Table 2. At high NaCl concentrations aggregation is enhanced, as expected, since charges on the clay minerals are neutralised by the mobile charges in solution. It is not clear whether this enhancement in aggregation is due to a reduction in like–like charge repulsion or an enhancement in the attraction of particles with different zeta potential in the heterogeneous mineral particle sample (see Appendix C, Fig. 10).

5 Discussion

Hiranuma et al. (2015) suggested that there is a discrepancy between the dry-dispersion and wet-suspension methods of determining the ice nucleation efficiency of the clay mineral NX-illite. They explained that the mineral surface is chemically altered during reaction with water, which may affect the ice nucleating activity. Their measurements of ion concentrations in water containing NX-illite supported this finding;

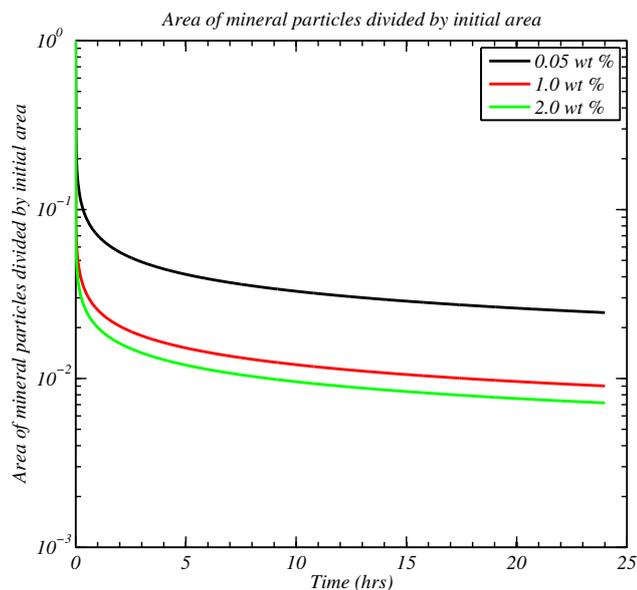


Figure 8. Model calculations of the surface area of mineral particles divided by the initial surface area, in micro-litre-sized drops, for three different weight percentages (wt %): 0.05, 1.0 and 2.0. The calculations assumed the only forces were due to Brownian motion.

however, since ion concentrations are able to screen surface charge on colloidal particles, these charges may significantly enhance the ability of the particles to coagulate (see Appendix B and C).

Although Hiranuma et al. (2015) state that dry dispersions lead to higher n_s values than wet suspensions, this was not true of all data they presented. For example some of the CFDC (Continuous Flow Diffusion Chamber) data showed lower values of n_s , more consistent with the wet-suspension methods. However, one possible reason to account for this was presented by the same authors, who stated that the lower n_s of the CSU-CFDC (Colorado State University-Continuous Flow Diffusion Chamber) may be a consequence of the underestimation of the number of ice crystals, possibly due to its constrained RHw (Relative Humidity with respect to water) (when operating at 105 %) and the disturbance of aerosol laminar between two plates in a CFDC. Indeed, more recently DeMott et al. (2015) found that the CSU-CFDC typically underestimated cloud chamber measurements by a factor of 3 when operating at RHw = 105 % but agreed well at higher RHw, thus confirming Hiranuma et al. (2015).

We confirm that our dry-dispersion method, using the MICC, predicts higher values of n_s at high temperatures than the previously published results using wet suspensions, but the two methods are in close agreement at the lower temperatures. We explore an alternate explanation to that of Hiranuma et al. (2015), which is that the mineral particles may coagulate together in suspension and reduce the surface area available for nucleation.

This explanation is also consistent with the discrepancy found at high temperatures: in the wet-suspension methods, the high-temperature results use the highest mineral particle weight percents, which are more likely to coagulate. However, Atkinson et al. (2013) show high weight percents (0.8 %) in pico-litre drops at lower temperatures that are in agreement with our dry-dispersion measurements. We suggest a possible reason is that the K-feldspar particles form relatively weak aggregates, which can be disrupted and broken up by energetic spraying into pico-litre size drops (diameter $\sim 10 \mu\text{m}$), but not by pipetting into micro-litre drops. Furthermore, once the aggregates are broken up, there are too few mineral particles, even at high weight percentage, contained in pico-litre drops for aggregation to occur within them (as suggested by the modelling in Fig. 7, right panel). This is not the case for micro-litre drops.

Naturally, the question arises of why some unpublished measurements of NX-illite in micro-litre drops do not show large sensitivity to the mineral particle weight percentage (B. Murray, personal communication, 2015). In order to investigate this, we have run the aggregation model (described in Appendix A) to show that the fractional surface area left in micro-litre drops is relatively insensitive to the initial weight percentage. The results are shown in Fig. 8, where it is demonstrated that an increase by a factor of 20 in weight percentage (0.05 to 1.0) results in only a factor-of-2 decrease in fractional surface area. It should be noted that these model results are subject to other uncertainties, such as the assumed packing geometry of the aggregates and any ions available in the suspension.

The real test of our laboratory results is whether they can better describe observations. Atkinson et al. (2013, Fig. S8 in their Supplement) present a comparison between observed IN (Ice Nuclei) from field experiments and their cold-stage-derived parameterisation. This showed the parameterisation to underestimate observations at high temperatures and overestimate at low temperatures. One can do a similar comparison by taking the data from the plot and multiplying the parameterised ice concentrations by the ratio of our n_s curve (fitted to our data for K-feldspar in Fig. 4) to the Atkinson curve for K-feldspar (both adjusted to take into account the weight percentage of K-feldspar present in natural dust as in the original study). This is shown in Fig. 9. While such a comparison is crude, it arguably shows that there is better agreement when using the chamber-derived parameterisation, which supports a shallower n_s vs. temperature curve than the cold-stage-derived curves.

5.1 Does the assumption of spherical particles affect our findings?

We note that Fig. 4 is adjusted so that we take account of the specific surface area; however, the process modelling (Fig. 5) assumes the surface area of spherical mineral particles. Here we assess whether this affects the main findings. The quoted

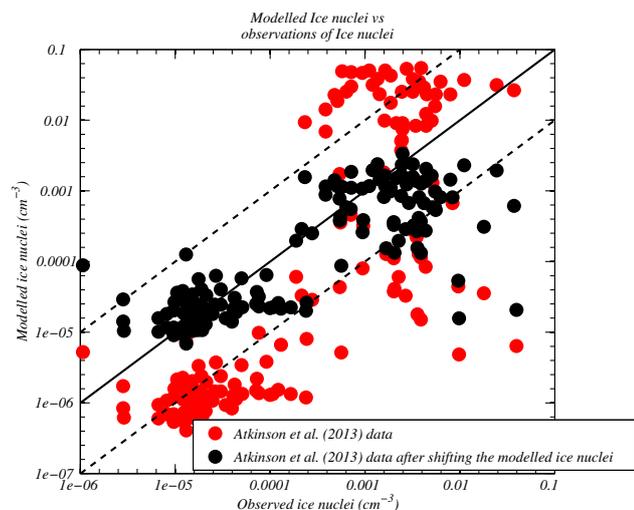


Figure 9. A comparison of the Atkinson et al. (2013) cold-stage-derived parameterisation to observations and a similar comparison using our data. Red dots are taken directly from Atkinson et al. (Fig. S8 of Supplement, 2013); black dots are the same data but multiplied by the ratio of the n_s data for feldspar taken from our data (multiplied by 25 % to take into account the weight percentage of K-feldspar present in natural dust) to the n_s data derived from cold-stage studies (again reduced to take into account the composition of natural dust).

values for BET specific surface areas of the three samples are shown in Table 3.

We estimate the discrepancy in the assumption that the particles are spherical. The median diameter for the three samples when introduced into the chamber was approximately $D_m = 0.4 \times 10^{-6}$ m. The calculated surface-area-to-mass ratio is then S :

$$S = \frac{6D_m^2}{\rho D_m^3} \quad (5)$$

$$= \frac{6}{\rho D_m}. \quad (6)$$

We may then calculate the SSA underestimation factor, which is the ratio of the SSA to the value of S . Table 3 shows that the assumption of spherical particles likely underestimates the surface area for the kaolinite and NX-illite samples by factors of ~ 2 and ~ 20 respectively. For the K-feldspar the assumption of sphericity overestimates the surface area by a factor of ~ 2 . The underestimation is because the particles are platelets so their measured optical size is closer to $\frac{\pi D^2}{2}$ (area of a disk) instead of πD^2 (area of a sphere). It should be noted that these values are not large enough to significantly affect the conclusions from Fig. 5.

5.1.1 Colloidal forces in suspensions

The coagulation modelling in Sect. 4.2.2 neglected the force of repulsion due to the electric double charge layer (see Ap-

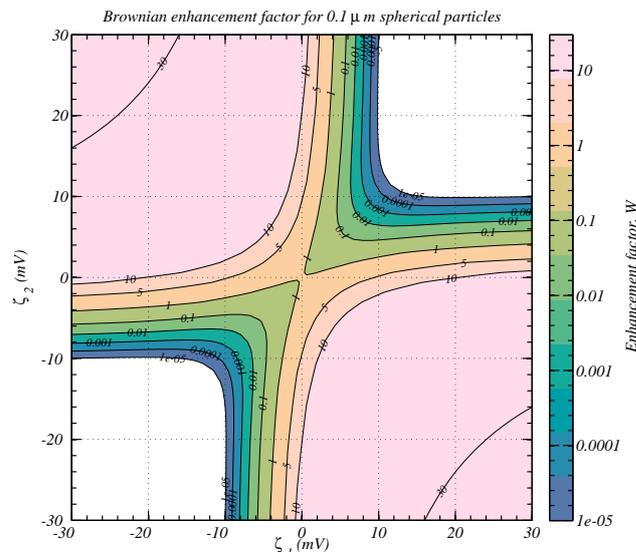


Figure 10. The enhancement factor of the Brownian collision kernel for two spherical particles in pure water as a function of the zeta potential of both particles.

pendix B and C for details). Kaolinite is a 1 : 1 layer clay consisting of alternating silica (tetrahedral) and alumina (octahedral) layers, which are bonded together. The tetrahedral faces have a net negative charge due to isomorphous substitution of silicon ions by ions with a lower charge, whereas the edges and octahedral faces have charges that depend on the pH of the solution.

When placed in suspension, the minerals develop a double charge layer by attracting positive ions (counter ions) to the surface. The double charge layer can result in the particles being colloidally stable because of the effective like-charge Coulomb interaction between two particles. The sign and magnitude of the charge layer can be quantified by inferring the zeta potential from measurements of electrophoresis.

We now provide some justification for the decision to neglect the suppression of coagulation due to the double charge layer. Elimelech et al. (2000) have shown that the zeta potential, ζ , is a relatively insignificant factor in predicting the transport/sedimentation of particles when there is heterogeneity in the surface of the colloidal material. This is reasonable since the ζ potential is only a bulk measurement of the charge on a population of particles.

Tombácz and Szekeres (2006) have since shown that kaolinite has surface charge heterogeneity due to the mineral having permanent charges on the tetrahedral silica faces and pH-dependent charges on the crystal edges and also the octahedral alumina faces. In the paper by Tombácz and Szekeres (2006), kaolinite samples were heavily processed to remove the large particle sizes and any other contamination; however, surface charge heterogeneity still persisted.

The faces of alumina and edges of the kaolinite crystal may undergo hydrolysis and hence carry pH-dependent

charges (Tombácz and Szekeres, 2006). Tombácz and Szekeres (2006, their Fig. 7) show that, at pH 7, these alumina and silica groups (as inferred through a linear combination of their zeta potential) may have an overall charge close to 0. Hence, there is surface charge heterogeneity in clay minerals. Indeed Schofield and Samson (1954) had noted previously that “edge-to-face” coagulation (or flocculation) occurs in kaolinite samples.

Berka and Rice (2005) have shown that kaolinite can be colloidally stabilised at particle concentrations similar to those under consideration here ($\sim 10^{16} \text{ m}^{-3}$); however, their results are at pH of 9.5, where the alumina also carries a high negative charge; hence, it should be expected that kaolinite will be colloidally stabilised to some extent at pH 9.5. Our own dynamic light-scattering measurements confirm that high pH does cause some colloidal stability, but they also show that this can be overcome at higher concentrations (Table 2).

6 Conclusions

Experiments were conducted in the Manchester Ice Cloud Chamber facility to look at ice nucleation in the condensation-freezing mode. Three mineral powders were investigated: kaolinite (KGa-1b), NX-illite, and K-feldspar; each mineral powder was examined at two temperatures: referred to as “high” and “low” temperatures. The primary goal of this study was to reconcile dry-dispersion methods of quantifying ice nucleation on mineral dusts with those using wet suspension.

Results from MICC for NX-illite were demonstrated to agree well with previously published results for dry dispersions (see Fig. 4, red triangles vs. red stars), thus serving as a validation of MICC.

Observations revealed K-feldspar to be the most efficient at nucleating ice (Fig. 4) in agreement with Atkinson et al. (2013), followed by illite, then kaolinite. Thus our data are qualitatively in agreement with previous findings. However, they all showed a discrepancy at the higher temperatures: our data showed higher values of n_s than previously published wet-suspension methods.

Using the ACPIM numerical model to simulate the cloud chamber with ice nucleation parameterisations provided by Murray et al. (2011), Broadley et al. (2012) and Atkinson et al. (2013), ice concentrations for all mineral powders were underestimated relative to observations. The reason for this was that the slope of the n_s vs. temperature curves were determined to be less steep in our measurements than the published wet-suspension methods. Hence, the reason the model underpredicted the ice crystal concentration at lower temperatures was because the values of n_s from the parameterisations were too low at the start of the experiment. Thus too few ice crystals were nucleated and, by the time the lower

temperatures were reached, the Bergeron–Findeison process had led to evaporation of the drops.

Modelling of coagulation in the suspension showed that it may be a pathway to reduce the surface area of mineral particles, and hence, although not proven in this study, we consider it may reduce the effective n_s calculated from experimental data. Aggregation was confirmed by separate experiments passing the suspensions through filters after initial dispersion and also through measurements using dynamic light scattering.

To explain the discrepancy between dry dispersions and wet suspensions, we put forward the following suggestions:

- During the stirring process K-feldspar particles do not adhere strongly to each other. These weak aggregates may thus be easily disrupted when pico-litre drops of the suspension are sprayed. The reason for this is that pico-litre drops are a similar size to the aggregate particles so that forcing the aggregates through a small nozzle can disrupt them, causing them to be broken up. The clay mineral powders (illite and kaolinite) are platelets and, under high weight percentage, tend to clump together when forced through a small nozzle (as in the pico-litre drop case), whereas the K-feldspar particles are more three-dimensional and more likely to break up when forced through a small nozzle.
- Illite and kaolinite particles, due to their platelet morphology, form stronger, more tightly packed, aggregates.
- As the drops are either sprayed or pipetted onto the glass slide, the possibility of further coagulation of the mineral particles within the drops should be considered.
- However, in the pico-litre drops insufficient numbers of mineral particles are present, even at 1.000 wt %, to result in significant coagulation.
- In micro-litre drops there are enough mineral particles to result in significant coagulation, and there is a reduction of surface area in the drops. This reduction increases with increasing weight percentage of mineral particles.
- The fractional surface area left in the drops after aggregation can be relatively insensitive to the weight percentage under some circumstances (see Fig. 8).
- The slopes of the n_s vs. temperature curves derived from our dry-dispersion experiments more closely agree with those derived for natural dusts by Niemand et al. (2012).
- The dry-dispersion techniques suggest that mineral particles are more efficient than the wet-suspension-derived parameterisations suggest, especially at relatively high temperatures.

Appendix A: Modelling coagulation in suspension

We adopted the semi-implicit numerical algorithm for treating the coagulation process (Jacobson, 1999, p. 438). This method conserves total particle volume and approximately conserves the monomer concentration. The algorithm is written as follows:

$$v_{k,t} = \frac{v_{k,t-1} + dt \sum_{j=1}^k \left(\sum_{i=1}^{k-1} f_{i,j,k} \beta_{i,j} v_{i,t} n_{j,t-1} \right)}{1 + dt \sum_{j=1}^{N_B} (1 - f_{k,j,k}) \beta_{k,j} n_{j,t-1}}, \quad (\text{A1})$$

with $n_k = \frac{v_k}{v_k}$ and

$$f_{i,j,k} = \begin{cases} \left(\frac{v_{k+1} - V_{i,j}}{v_{k+1} - v_k} \right) \frac{v_k}{V_{i,j}} & v_k \leq V_{i,j} < v_{k+1} \text{ if } k < N_B \\ 1 - f_{i,j,k-1} & v_{k-1} < V_{i,j} < v_k \text{ if } k > 1 \\ 1 & V_{i,j} \geq v_k \text{ if } k = N_B \\ 0 & \text{all other cases} \end{cases}. \quad (\text{A2})$$

Equation (A1) shows that the solution at the next time step depends on the solution at that time step; hence, the method is an “implicit” method; however, the algorithm is solved sequentially in discrete bins such that the solution at the next time step is always known.

The variable β is the coagulation kernel of two interacting particles ($\text{m}^3 \text{particle}^{-1} \text{s}^{-1}$). When multiplied by the concentration of particles in a discrete bin, it gives the rate of the number of particle interactions. We assume it can be described by the sum of a kernel due to Brownian diffusion and that due to gravitational settling. For Brownian the diffusion the kernel takes the form

$$\beta(i, j) = 4\pi (r_i + r_j) (D_{p,i} + D_{p,j}), \quad (\text{A3})$$

where $D_{p,i}$ and $D_{p,j}$ are particle diffusion coefficients:

$$D_{p,i} = \frac{k_B T}{6\pi r_i \eta_w} \quad (\text{A4})$$

following Einstein (1956). This model assumes that each Brownian collision results in a sticking event.

For gravitational settling the kernel takes the form

$$\beta(i, j) = E_{i,j} \pi (r_i + r_j)^2 |u_{t,i} - u_{t,j}|. \quad (\text{A5})$$

Appendix B: Interaction potential of minerals in suspension

A particle suspended in water will generally form a double charge layer by accumulation of ions.

The potential energy of the electrical double layer interaction between two spheres may be written

$$V_R = \left(\frac{\pi \epsilon R_1 R_2}{R_1 + R_2} \right) \left(\zeta_1^2 + \zeta_2^2 \right) \left(\frac{2\zeta_1 \zeta_2}{\zeta_1^2 + \zeta_2^2} p + q \right), \quad (\text{B1})$$

where R_1 and R_2 are the radii of the two interacting particles; ϵ is the electric permittivity; and $\zeta_{1,2}$ are the zeta potentials of the interacting particles.

$$p = \ln \left(\frac{1 + \exp(-\kappa x)}{1 - \exp(-\kappa x)} \right), \quad (\text{B2})$$

$$q = \ln(1 - \exp(-2\kappa x)), \quad (\text{B3})$$

where x is the shortest distance between to particles and κ^{-1} is the Debye length:

$$\kappa^{-1} = \sqrt{\frac{\epsilon k_B T}{N_A e^2 \sum Z^2 m_i}}, \quad (\text{B4})$$

where k_B is Boltzmann’s constant; N_A is Avogadro’s number; $e = 1.6 \times 10^{-19} \text{ C}$ is the charge on an electron; Z and m_i are the valence and molar concentration (moles per cubic metre) of ions; and T is the temperature.

In addition to the electrical double layer potential we also consider the van der Waals interaction, which is given by London’s equation:

$$V_A = -\frac{A_{132}}{6} \left(\frac{2R_1 R_2}{[R_1 + R_2 + x]^2 + [R_1 + R_2]^2} + \frac{2R_1 R_2}{[R_1 + R_2 + x]^2 + [R_1 - R_2]^2} + \ln \left[\frac{[R_1 + R_2 + x]^2 + [R_1 + R_2]^2}{[R_1 + R_2 + x]^2 + [R_1 - R_2]^2} \right] \right). \quad (\text{B5})$$

Here, A_{132} is the Hamaker constant for interaction between particle 1 and particle 2 in medium 3. Individual Hamaker constants are as follows: for mineral particles we use A_1 and $A_2 = 6.8 \times 10^{-19} \text{ J}$; whereas for pure water we use $A_3 = 7 \times 10^{-21} \text{ J}$. A_{132} can be estimated (Elimelech et al., 1995, p. 45) from the Hamaker constants for pure components:

$$A_{132} \cong \left(\sqrt{A_1} - \sqrt{A_3} \right) \left(\sqrt{A_2} - \sqrt{A_3} \right). \quad (\text{B6})$$

The total potential for the interaction is given by the sum of van der Waals and the double electric charge layer: $V_T = V_A + V_R$.

Appendix C: Coagulation kernel with interaction potential

As described in Housiadas and Drossinos (2005, Sect. 6.3.1.2), the coagulation kernel can be corrected for the effect of an external, conservative force field. Here, “external” refers to the force field being external to the process considered in the uncorrected kernel. The correction is to divide the kernel by the factor

$$Q = (R_i + R_j) \int_0^\infty \frac{\exp \left[\frac{V_T(x)}{k_B T} \right]}{x^2} dx. \quad (\text{C1})$$

We define the enhancement factor over the Brownian kernel, W , as the ratio of Q calculated with the interaction potential in Eqs. (B1) and (B5) to that calculated by van der Waals alone (B5). This enhancement factor is shown in Fig. 10 for two spherical, $0.1\ \mu\text{m}$ diameter particles having different values of the zeta potential.

Figure 10 shows that two particles may come together if the zeta potential of one of the particles has a magnitude less than a threshold of $\sim 10\ \text{mV}$. However, mineral particles are not spheres and exhibit patch-wise heterogeneity in their surface potential (see Sect. 5.1.1). Hence, we argue that for measured bulk zeta potentials of $-20\ \text{mV}$ there may be enough heterogeneity in the sample, in addition to patch-wise heterogeneity, to lead to colloidal instability.

In addition Fig. 10 also shows that the enhancement factor may be greater than unity even when the particles have like charge. This is seen most clearly at values of $\zeta_1 \cong -20$ and $\zeta_2 \cong 0\ \text{mV}$, where the enhancement factor is ~ 5 . This behaviour is because the interaction between the two spheres leads to induced charge, and it has been observed experimentally in other studies.

Appendix D

Table D1. Nomenclature.

β	Coagulation kernel ($\text{m}^3 \text{particle}^{-1} \text{s}^{-1}$)	Eq. (A1)
ϵ	Permittivity of water (F m^{-1})	Eq. (B4)
η_w	Viscosity of water $\sim 8.9 \times 10^{-4} \text{ Pa s}$	Eq. (A4)
κ	Reciprocal of Debye length (m^{-1})	Eq. (B2)
v	The volume of a single particle in a bin (m^3)	Eq. (A1)
ζ_1	Zeta potential of particle 1 (V)	Eq. (B1)
ζ_2	Zeta potential of particle 2 (V)	Eq. (B1)
A_1, A_2	Hamaker constant for particles 1 and 2 ($6.8 \times 10^{-19} \text{ J}$)	Eq. (B5)
A_3	Hamaker constant for water ($7 \times 10^{-21} \text{ J}$)	Eq. (B5)
A_{132}	Hamaker constant for interaction between particle 1 and 2 in medium 3	Eq. (B5)
$D_{p,i}$	Particle diffusion coefficient (Stokes–Einstein coefficient) for bin i ($\text{m}^2 \text{s}^{-1}$)	Eq. (A3)
e	Charge on electron ($\sim 1.6 \times 10^{-19} \text{ C}$)	Eq. (B4)
k_B	Boltzmann's constant, $1.381 \times 10^{-23} \text{ m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$	Eq. (A3)
m_i	Molar concentration of ions (mol m^{-3})	Eq. (B4)
N_A	Avogadro's number (6.02×10^{23})	Eq. (B4)
N_B	The number of bins	Eq. (A2)
R_1	Radius of particle 1 (m)	Eq. (B1)
R_2	Radius of particle 2 (m)	Eq. (B1)
$r_{i,j}$	The radius of a particle in bin i or j (m)	Eq. (A3)
T	Temperature (K)	Eq. (B4)
u	Terminal velocity of particle in fluid (m s^{-1})	Eq. (A5)
V	The volume of the bin edges (m^3)	Eq. (A2)
n	The number concentration of a particle in a bin (m^{-3})	Eq. (A1)
v	The total volume of all particles in a bin ($\text{m}^3 \text{m}^{-3}$)	Eq. (A1)
V_A	van der Waals interaction potential (V)	Eq. (B5)
V_R	Interaction potential between two particles (V)	Eq. (B1)
V_T	Sum of all interaction potentials (V)	Eq. (C1)
W	Correction factor for particles interacting with potential	Eq. (C1)
Z	Valence of dissociation	Eq. (B4)
x	Distance between two particles (m)	Eq. (B2)

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