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montmorillonite as
ice nuclei**

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Ice nucleation of ammonia gas exposed montmorillonite mineral dust particles

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The ice nucleation characteristics of montmorillonite mineral dust aerosols with and without exposure to ammonia gas were measured at different atmospheric temperatures and relative humidities with a continuous flow diffusion chamber. The montmorillonite particles were exposed to pure (100%) and diluted ammonia gas (25 ppm) at room temperature in a stainless steel chamber. There was no significant change in the mineral dust particle size distribution due to the ammonia gas exposure. 100% pure ammonia gas exposure enhanced the ice nucleating fraction of montmorillonite mineral dust particles 3 to 8 times at 90% relative humidity with respect to water (RH_w) and 5 to 8 times at 100% RH_w for 120 min exposure time within our experimental conditions. The percentages of active ice nuclei were 2 to 9 times higher at 90% RH_w and 2 to 13 times higher at 100% RH_w in 25 ppm ammonia exposed montmorillonite compared to unexposed montmorillonite. All montmorillonite particles are more efficient as ice nuclei with increasing relative humidities and decreasing temperatures. The activation temperature of montmorillonite exposed to 100% pure ammonia was 12°C higher than for unexposed montmorillonite particles at 90% RH_w and 10°C higher at 100% RH_w. In the 25 ppm ammonia exposed montmorillonite experiments, the activation temperature was 7°C warmer than unexposed montmorillonite at 100% RH_w. Degassing does not reverse the ice nucleating ability of ammonia exposed montmorillonite mineral dust particles. This is the first experimental evidence that ammonia gas exposed montmorillonite mineral dust particles can enhance its activation as ice nuclei and that the activation can occur at temperatures warmer than -10°C where natural atmospheric ice nuclei are very scarce.

1 Introduction

Atmospheric aerosols are important for direct climate forcing due to their effect on scattering and absorption of solar radiation (Ramaswamy, 2001). Aerosol particles can

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modify the radiative properties of clouds by acting as cloud condensation nuclei (CCN) and ice nuclei (IN) (Knopf and Koop, 2006; Ramanathan et al., 2001; Pruppacher and Klett, 1997; Twomey, 1974). Understanding atmospheric ice formation processes is important in predicting precipitation and cloud radiative properties, both major concerns related to the uncertainties in contemporary climate change (Bailey and Hallett, 2002; Lohmann et al., 2000). Ice particle formation in the atmosphere is usually inefficient since there are relatively few natural ice nuclei especially at temperatures above -20°C . Heterogeneous ice nucleation involving atmospheric aerosols is the first step in the formation of ice crystals in supercooled liquid water clouds (Hobbs, 1974). This paper presents experimental results where the ice nucleation occurs in the deposition or condensation/freezing mode.

Laboratory studies have indicated good ice nucleating properties associated with some types of dust aerosols in the atmosphere (Isono et al., 1959), especially clay minerals (Zuberi et al., 2002; Roberts and Hallett, 1968) and many of the metal oxide components of dust (Hung, et al., 2003). Montmorillonite is frequently used as a surrogate for atmospheric dust particles in laboratory experiments because it is considered one of the main components of ice nucleating tropospheric mineral dust in the submicron range (Lohmann and Diehl, 2006; Schaller and Fukuta, 1979; Kumai, 1961; Kumai and Francis, 1962). In studies with a continuous flow diffusion chamber (Salam et al., 2006) and in a large cloud chamber (Möhler et al., 2006) it was found that montmorillonite mineral dust particles act as effective ice nuclei in deposition/condensation nucleation modes.

Chemical and physical interactions can take place between atmospheric trace gases and aerosol particles which may potentially change their ice activation properties (Dymarska et al., 2006; Dontsova et al., 2005; Umann et al., 2005; Russell, 1965). Ammonia is one such trace gas that is produced mainly from anthropogenic sources. In a recent study the interaction of mineral dust particles with gaseous nitric acid, sulfur dioxide and ozone were investigated (Umann et al., 2005). Gaseous nitric acid and ozone were adsorbed on the mineral dust surface, whereas no interaction was

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observed between sulfur dioxide and mineral dust aerosols (Umann et al., 2005). Dymarska et al. (2006) studied the ice nucleation of soot that was exposed to ozone and found no significant effect of ozone. However, the ice nucleating behavior of mineral dust aerosols due to exposure to ammonia gas has not been studied until now.

5 In this paper we study the ice nucleation characteristics of ammonia exposed versus non-exposed montmorillonite mineral dust aerosols at temperatures between -5°C and -35°C at different relative humidity conditions with the Continuous Flow Diffusion Chamber (CFDC) at Dalhousie University, Canada.

2 Experimental methods

10 2.1 Aerosol aging

A stainless steel cylindrical chamber 45 cm long with a diameter of 20 cm was used to hold the mineral dust particles while being aged in the presence of ammonia gas. About five grams of montmorillonite K10 (Sigma-Aldrich, Powder) mineral dust particles were placed into the bottom of the cylindrical chamber for each aging session. Ammonia gas (100% pure, or 25 ppm diluted in N_2 gas), with a pressure of 0.5 atmospheres at room temperature was allowed to pass into the chamber with occasional stirring so that ammonia exposure would be uniform on the dust particles for different exposure times 15 varying from 0 to 2.5 h for 100% ammonia and from 0 to 70 h for 25 ppm ammonia.

2.2 Degassing experiment

20 Ammonia exposed montmorillonite mineral dust particles were degassed at room temperature under a vacuum pressure of 1.3×10^{-4} atmospheres. About 2.0 g of ammonia exposed montmorillonite dust particles were placed in an aluminum container which was placed into a vacuum jar and maintained at vacuum for about 24 h. The degassed montmorillonite was used in FT-IR analyses and also for ice nucleation experiments.

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2.3 Aerosol surface characteristics

The Fourier transform infrared spectra (FT-IR) using the potassium bromide (KBr) pressed disk technique (e.g., Ogloza and Malhotra, 1989) was conducted using a Bruker FT-IR spectrometer (Model Vector 22). About 1.0 mg mineral dust and 100 mg KBr were weighted and ground in an agate mortar prior to pellet making under a load of 1.0×10^4 kg of pressure for 2 min. The pellet was transferred into the sample holder and the FT-IR spectra were measured at room temperature over a wavenumber range of 500–4000 cm^{-1} .

2.4 Aerosol generation and impaction

The montmorillonite mineral dust particles were placed into the aerosol generator of the CFDC. The aerosol generator is an airtight reservoir with a vibrating membrane at its base (Salam et al., 2006). The reservoir consists of an aluminum container with a thin, conductive Mylar bottom. The Mylar bottom is held in place with an aluminum collar with an o-ring seal, and is vibrated using a 40 W, 4 Ω speaker. The speaker is driven at 5 V using a square wave generator at 1000 Hz. The aerosol particles levitated by the generator were introduced to the flow entering the diffusion chamber. Before entering the chamber the aerosol particles passed through an inertial impactor (Salam et al., 2006; Marple and Willeke, 1976) to remove particles larger than $5 \mu\text{m}$ allowing only montmorillonite mineral dust particles smaller than $5 \mu\text{m}$ to enter the CFDC.

2.5 Continuous Flow Diffusion Chamber (CFDC) System

The ice nucleation experiments were carried out with the Dalhousie University CFDC (Salam et al., 2006). The CFDC (Fig. 1) is a vertically oriented flow chamber consisting of two concentric circular copper cylinders. The length of the chamber is 161 cm, the top 123 cm is cooled while the bottom 38 cm has no active cooling. The region without cooling is needed to evaporate any water droplets that might have potentially formed

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and could be misinterpreted as ice crystals by the particle counter at the exit of the CFDC. The annular gap between the two cylinders, in which the ice crystals grow, is 0.45 cm and this results in a Reynolds Number of about 20, indicative of laminar flow in the annulus gap. Prior to each experiment the annulus gap of the chamber was flooded with water for about 2 s in order to freeze a thin film of ice on the inside walls. During the experiment the two walls are held at two different temperatures at ice saturation which by the diffusion of heat and water vapor creates a steady-state supersaturation with respect to ice near the center of the annulus gap through which the aerosols are carried and, if activated, will grow by water vapor deposition to ice crystals. The air stream containing the aerosols is surrounded by two clean sheath air streams which confines all the aerosols to the center of the annulus gap where the ice supersaturation conditions exist. Typical operating conditions of the chamber are temperatures between -2°C and -45°C ; temperature differences between the two walls of 0°C to 20°C ; supersaturation with respect to water (SSw) -30% to $+10\%$; supersaturation with respect to ice (SSi) 0% to $+50\%$; total air flow 2.83 liters per minute (lpm) and the residence time for the aerosol particles in the actively cooled portion of the chamber is 20 seconds. Further details of the CFDC can be found in Salam et al. (2006).

2.6 Detection of Ice Crystals

Aerosol particles smaller than $5\ \mu\text{m}$ in diameter produced by the aerosol generator were injected into the center of the gap near the location of the maximum supersaturation. Ice crystals were activated, grew in the chamber while being carried by the air stream and were identified with a MetOne (Model 278B) optical particle counter at the outlet of the CFDC with a flow rate of 2.83 lpm (Salam et al., 2006). The MetOne particle counter can measure particles with sizes from 0.3 to $20\ \mu\text{m}$ using 6 size bins. Since the impactor at the input to the CFDC removes all aerosol particles larger than $5\ \mu\text{m}$ we can assume, after performing the quality controls described in the next subsection, that all particles greater than $5\ \mu\text{m}$ detected by the MetOne are ice crystals.

The activated ice nuclei fraction ($IC_{>5}/APS_{<5}$) was calculated from the ratio of the total number of ice crystals larger than $5\ \mu\text{m}$ detected by the MetOne during the growth experiment ($IC_{>5}$) to the average of the total number of aerosol particles smaller than $5\ \mu\text{m}$ ($APS_{<5}$) measured before and after each ice nucleation experiment.

5 2.7 Quality Control of the CFDC Measurements

All experiments used filtered and dried air for both the sheath and aerosol flows. An ULPA air filter preceded by a HEPA air filter removed 99.97% of the ambient aerosols larger than $0.1\ \mu\text{m}$. The air streams were dried down to a dew point of -73°C with anhydrous calcium sulfate Drierite (W. A. Hammond Drierite Co). To check the presence of any ice particle artifacts both blank and dry experiments were conducted. In a blank experiment no aerosol particles are input into the chamber flow but the chamber walls are coated with ice. In a dry experiment aerosol particles are input into the chamber but there is no ice coating on the chamber walls. Before running any blank experiment we passed dried and filtered air into the CFDC for about eight hours to remove all particles that may have remained inside the system from the previous experiment.

We used the total aerosol particle number concentrations smaller than $5\ \mu\text{m}$ ($APS_{<5}$) before and after the ice nucleation experiments in the calculation of the percentage of ice activation because it was not possible to measure the input aerosol number concentrations during the actual ice nucleation experiment. This is not a problem because of the high reproducibility ($\pm 5\%$) that was obtainable for the input aerosol number concentration. Moreover, we are unable to differentiate between aerosol and ice particles below $5\ \mu\text{m}$ and so we had to use particles greater than $5\ \mu\text{m}$ as the criterion for ice particles. Hence we are unable to report the total ice nucleation rate, but rather report the ice nucleation percentage based on the ratio of ice crystals that grew to sizes larger than $5\ \mu\text{m}$ to the pre-nucleation particle concentration.

To rule out the possibility of hygroscopic growth by the aerosol particles within the CFDC it was checked whether montmorillonite adsorbed enough water vapor to grow larger than $5\ \mu\text{m}$. The test was done by setting the temperature of both ice-covered

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walls of the chamber to -2°C . The relatively warm temperature of -2°C was picked to get very close to water saturation conditions (98.1% RHw) in the chamber. The ice crystal fraction ($\text{IC}_{>5}/\text{APS}_{<5}$) was only 0.04% at the outlet of the chamber, which is within the noise level as determined by the blank as well as the dry experiments.

We also carried out ice nucleation experiments using water vapor instead of ammonia to age the montmorillonite dust aerosols. The percentage of the active ice nuclei of montmorillonite dust aerosols due to the exposure to water vapor for 24 h instead of ammonia gas was 1.02% at 90% RHw at -30°C . However, the percentages of activated ice nuclei of water vapor exposed montmorillonite were similar to that of the pure montmorillonite, which indicates that water vapor exposure alone has no significant effect on the ice nucleation ability of the montmorillonite dust aerosol particles.

3 Results and discussion

3.1 Aerosol size distributions

The initial size distributions of the mineral dust aerosol particles before injection into the CFDC were determined with an aerodynamic particle sizer (APS), Model TSI 3321 (Peters and Leith, 2003) both with and without ammonia exposure (Fig. 2). The size distribution curve shows the variation of aerodynamic diameter versus number concentration (dN/dlogD_a) between 0.5 and $20\ \mu\text{m}$. The total number concentration of aerosol particles smaller than $5\ \mu\text{m}$ in diameter that are input into the CFDC is almost the same (about $1.05 \times 10^4\ \text{cm}^{-3}$) for both ammonia-exposed and non-exposed montmorillonite. Only 0.03% of all particles ($3.2\ \text{cm}^{-3}$) were found to be larger than $5\ \mu\text{m}$ in diameter, which is below the noise level as shown in Fig. 2. The noise level was determined from particle artifacts measured during the blank and dry experiments described in Sect. 2.7.

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3.2 Fourier Transform Infrared (FT-IR) Analysis

The spectra of montmorillonite, ammonia exposed montmorillonite and degassed (after ammonia exposure) montmorillonite mineral dust particles at room temperature are given in Fig. 3. The FT-IR spectrum of pure montmorillonite is shown in Fig. 3a. It shows the typical absorption bands of montmorillonite (Farmer, 1974), for example Al-OH-Al (Ogloza and Malhotra, 1989) stretching at 3625 cm^{-1} , OH (Ogloza and Malhotra, 1989; Russell, 1965) stretching of water at 3434 cm^{-1} and Si-O (Ogloza and Malhotra, 1989; Russell, 1965) bending at 1059 cm^{-1} . However, there is a broad peak at the band position of about 3220 cm^{-1} in Figs. 3b and 3c, which is absent in Fig. 3a. Hydroxyl and amino groups show characteristic absorption bands (Coates, 2000; Ogloza and Malhotra, 1989) in the region from 3650 to 3200 cm^{-1} . The 3220 cm^{-1} absorption band in ammonia exposed (Fig. 3b) and degassed (Fig. 3c) montmorillonite dust particles is likely due to the N-H stretching of ammonia (Russell, 1965). There is another small IR signature peak for ammonium at around 1400 cm^{-1} in Figs. 3b and 3c, which is also less dominant in Fig. 3a. Thus, the similarity of the peak positions between ammonia exposed and degassed montmorillonite mineral dust indicates the retention of ammonia into the montmorillonite interlayer space and/or that ammonia is adsorbed chemically (Russell, 1965).

3.3 Ice nucleation experiments with varying exposure times

Ice nucleation experiments of aged montmorillonite dust particles were performed by varying the ammonia gas exposure times from 0 to 2.5 h for 100% pure ammonia (Fig. 4 top), and 0 to 70 h for 25 ppm ammonia (Fig. 4 bottom) before injecting them into the CFDC at 100% and 90% relative humidities at a temperature of -20°C . About 0.7% of the 100% pure ammonia aged montmorillonite particles were activated as ice nuclei at 90% RHw, and 2.7% at 100% RHw with only one minute of ammonia gas exposure. In contrast, only about 0.4% and 0.7% of the non-aged montmorillonite particles were activated as ice nuclei at 90% RHw and 100% RHw, respectively (Fig. 4 top). The

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percentage of activated aged montmorillonite ice nuclei increases with exposure times up to 2 h and then reaches a saturation level at about 1.5% at 90% RHw and at about 7.8% at 100% RHw (Fig. 4 top). In the case of 25 ppm ammonia exposed montmorillonite (Fig. 4 bottom), the active ice nuclei (%) increases below 20 hours exposure time and then attains a saturation level with increasing exposure times. The higher fractions of activation in the case of aged montmorillonite at 100% RHw in Fig. 4 are caused by either condensation freezing or enhanced deposition nucleation. It should be pointed out that our percentages of ice activation may be underestimated since we are unable to detect ice crystals smaller than $5\ \mu\text{m}$ exiting the CFDC.

3.4 Ice nucleation experiments with varying temperatures

3.4.1 With 100% Pure Ammonia Gas

In this series of experiments the 100% pure ammonia exposure time was fixed at 2 h at each temperature. The air temperature was varied between -5°C and -35°C at 90 to 100% RHw in 5°C temperature intervals. There was a set of 15 experiments at each temperature including blank and dry experiments. The active ice nuclei fraction ($IC_{>5}/APS_{<5}$), expressed as a percentage, versus temperature for montmorillonite mineral dust aerosols with and without exposure to ammonia gas at 90% and 100% RHw is shown in Fig. 5. The fraction of montmorillonite dust particles that act as ice nuclei increased 3 to 8 times due to exposure to 100% ammonia gas at 90% RHw, and 5 to 8 times at 100% RHw within the temperature range of -15°C and -35°C (Fig. 5). All montmorillonite aerosol particles are more efficient as ice nuclei with increasing relative humidities and decreasing temperatures. Ice nucleation activity was observed at a temperature of -5°C and -10°C for the ammonia aged montmorillonite mineral dust at 100% and 90% RHw, respectively, whereas no ice nucleation activity was observed at temperatures above -15°C at 100% RHw and above -27°C at 90% RHw (Fig. 5) for pure montmorillonite mineral dust aerosol particles.

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3.4.2 With 25 ppm diluted Ammonia gas

Ice nucleation experiments of montmorillonite mineral dust particles were also carried out with 25 ppm ammonia gas at temperatures between -5°C and -35°C at 90% and 100% RHw with an 18 h exposure time (Fig. 5). The concentration of the diluted ammonia used in these series of experiments is still significantly higher than the concentration of atmospheric ammonia in polluted regions (e.g., Godish, 2003). Our experimental setup prevented further dilution of the gas. However the effect of the ammonia gas on ice nucleation will also be determined by the exposure time which can be longer in the atmosphere and help to compensate for the lower concentrations found in the real atmosphere. The fraction of montmorillonite dust particles that act as ice nuclei increased 2 to 13 times at 100% RHw and 2 to 9 times at 90% RHw due to the modification of the montmorillonite dust surface by 25 ppm ammonia from temperatures of -15°C to -35°C . Our finding shows an effect that is opposite to the previous studies on ice nucleation of gas-aged dust aerosols. For example, the investigations on the chemisorption of trace gases on the surface of silver iodide particles by Birstein (1957, 1960) reported that the presence of ammonia gas lowers the threshold nucleation temperature of silver iodide particles considerably. Georgh (1963) also found that NO_2 and NH_3 are more effective in deactivating freezing nuclei. The concentration of ammonia necessary to cause an appreciable effect is 4 to 5 orders of magnitude larger than the NH_3 concentration generally found in the atmosphere (Georgh, 1963). Our study shows enhanced ice nucleation of montmorillonite dust particles aged with 25 ppm ammonia gas exposure, which is 3 orders of magnitude larger than found in highly polluted situations (e.g., Godish, 2003). The activation temperature of 25 ppm ammonia exposed montmorillonite mineral dust aerosols was -8°C at 100% RHw (108% RH_i) (Fig. 5); whereas the activation temperature of unexposed montmorillonite was -15°C at 109% RH_i (Salam et al., 2006). This is a significant finding since natural ice nuclei that are active at temperatures warmer than -10°C are very scarce (e.g., Schaller and Fukuta, 1979). This is the first experimental evidence that diluted ammonia gas exposure to

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montmorillonite mineral dust particles can raise the heterogeneous ice nucleation activation temperature to warmer than -10°C .

Some possible mechanisms for the ammonia adsorption or retention on the montmorillonite surface include coordination of ammonia to the exchangeable cations, formation of ammonium cations, hydrogen bonding of NH_3 to the montmorillonite surface and trapping of NH_3 molecules in the interlayer space (e.g., Dontsova et al., 2005; Russell, 1965; Mortland, et al., 1963). A likely scenario is that ammonia molecules replace water in the interlayer space of montmorillonite in an atmosphere of ammonia (Russell, 1965). In the current study the FT-IR measurements suggest that the ammonia is chemically adsorbed in the montmorillonite. It is possible that the addition of ammonia enables liquid water uptake so that ammonia-aged montmorillonite mineral dust aerosols are activated in condensation freezing mode first, and followed by deposition mode, which enhanced the heterogeneous ice nucleation ability of ammonia gas exposed montmorillonite mineral dust aerosol particles.

3.5 Ice nucleation experiments using degassed Montmorillonite

The ice nucleation experiments using degassed montmorillonite (after 100% ammonia exposure for 24 h) were carried out in the CFDC system and compared to 100% ammonia exposed montmorillonite for the same duration without degassing. The experimental conditions for this comparison were at -30°C and 90% RHw. Enhanced ice nucleation was observed in both non-degassed and degassed ammonia exposed montmorillonite mineral dust aerosols with 4.90% active ice nuclei in the 100% ammonia exposed and 4.89% active ice nuclei in the degassed experiment. This result indicates that degassing does not reverse the ice nucleating ability of ammonia exposed montmorillonite. This is expected if the ammonia molecules are chemically adsorbed into the montmorillonite as suggested by the FT-IR spectra.

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The importance of ammonia on the aging of montmorillonite mineral dust particles for ice nucleation was studied for different exposure times, air temperatures and relative humidity conditions with the Dalhousie University Continuous Flow Diffusion Chamber.

5 The ice nucleation increases with increasing ammonia gas exposure time and relative humidity. Only 1.5% of the 100% pure ammonia aged montmorillonite particles were activated as ice nuclei that eventually grew to a size larger than $5\ \mu\text{m}$ at 90% RHw at -20°C . The ice nucleating fraction of montmorillonite dust particles increased 3 to 8 times at 90% RHw due to the exposure to 100% ammonia and 2 to 9 times at 90%
10 RHw due to the exposure to 25 ppm ammonia compared to nonexposed particles. The activation temperature of 100% pure ammonia aged montmorillonite mineral dust particles was found to be 10°C warmer than that of the non-aged montmorillonite at 100% RHw and 12°C warmer at 90% RHw. The activation temperature of 25 ppm ammonia exposed montmorillonite mineral dust aerosols was -8°C at 100% RHw, which is 7°C
15 warmer than pure montmorillonite. Ammonia exposed and then degassed montmorillonite dust aerosols have similar ice nucleation efficiencies. This along with the infrared transmission spectra suggests that the ammonia is chemi-adsorbed in the montmorillonite.

This is the first experimental evidence for an enhancement of ice nucleation by mineral dust aerosols exposed to ammonia gas. Although the ammonia concentrations used are higher than those found in the polluted atmosphere the effect has been demonstrated and future experiments will be performed using lower concentrations. Not only was there an increase in the activated fraction of montmorillonite aerosols for the temperatures and relative humidities used in this study, but the aged aerosols were
20 able to initiate ice nucleation at temperatures warmer than -10°C where very few natural ice nuclei are found. This is potentially an important way that anthropogenic trace gases can change the atmospheric cloud properties and precipitation development by the ice particle phase with significant climate change implications.

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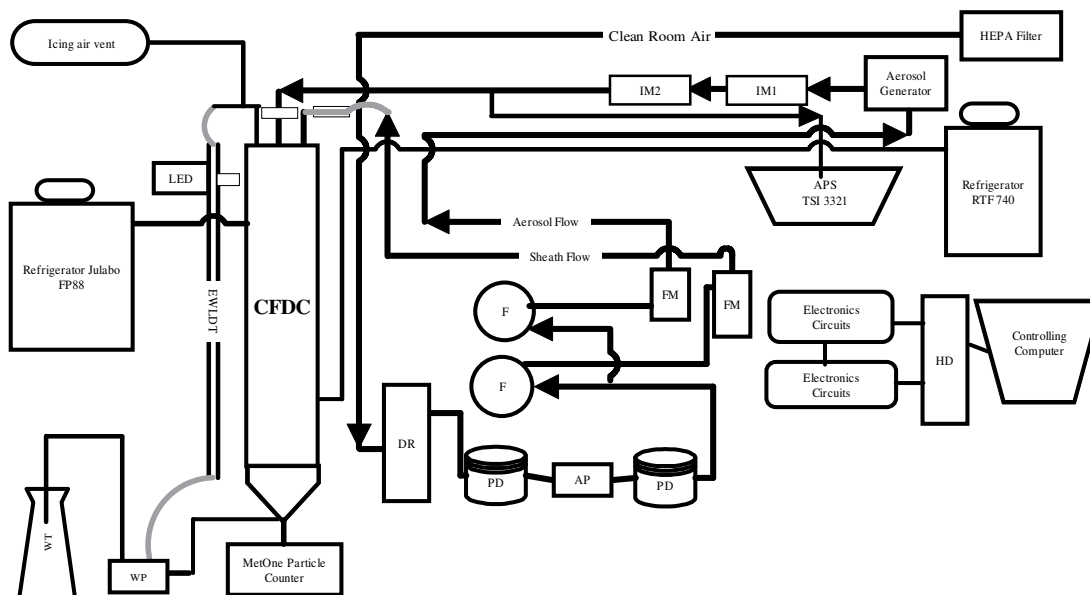


Fig. 1. Schematic Diagram of the Continuous Flow Diffusion Chamber (CFDC) at Dalhousie University, Canada. Arrows indicate the airflow in the CFDC system. EWLDT = External Water Level Detection Tube, WT = Water Tank, WP = Water Pump, DR = Drierite holder, F = Inline Filter, FM = Flow Meter, PD = Pulse Dampeners, AP = Air Pump, IM = Impactor, and HD = Computer Hard Disk.

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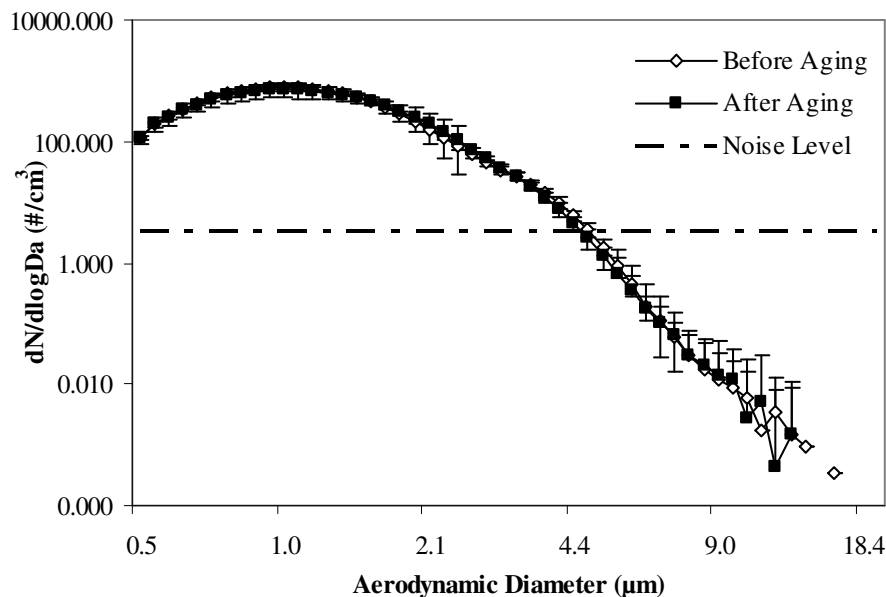


Fig. 2. Aerosol particle size distributions of montmorillonite mineral dust before and after aging with ammonia gas as measured with an Aerodynamic Particle Sizer (TSI 3321) exiting the aerosol generation of the CFDC. The dashed line indicates the noise level of the measurements determined by blank and dry experiments. The vertical bars are the error bars equal to the standard deviation of the 20 samples (duration of each sample is 60 s).

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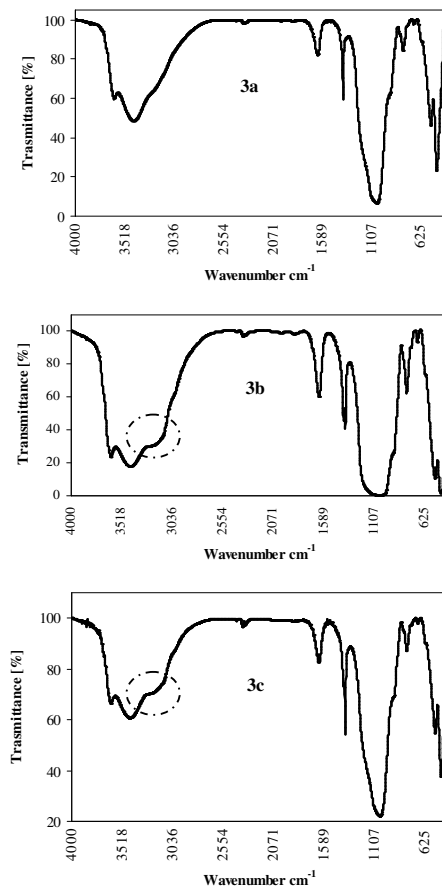


Fig. 3. The Fourier transform infrared (FT-IR) spectra of pure montmorillonite Fig. 3a, ammonia exposed montmorillonite Fig. 3b, degassed (after ammonia exposure) montmorillonite Fig. 3c with Bruker FTIR instruments, Model Vector 22. The absorption band at 3220 cm^{-1} suggests chemi-adsorbed ammonia indicated by the dashed circle in Figs. 3b and 3c.

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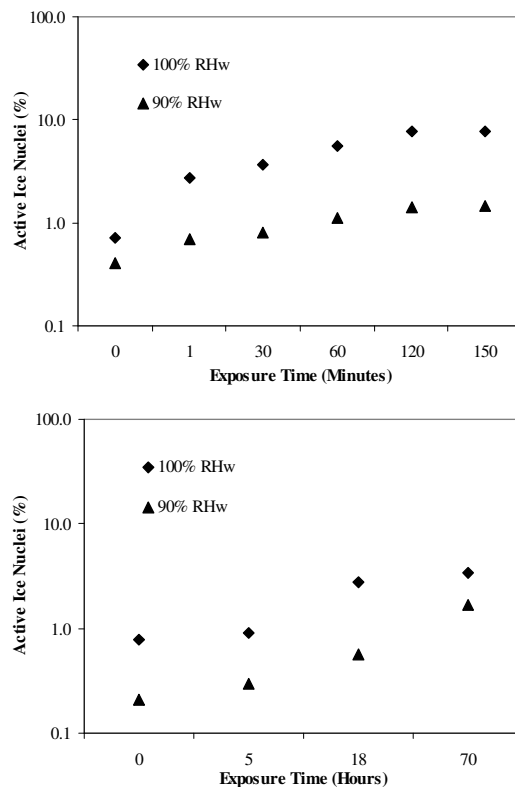


Fig. 4. Percentage of activated ice nuclei versus 100% pure (top) and 25 ppm (bottom) ammonia gas exposure time of montmorillonite mineral dust particles at 100% and 90% relative humidity with respect to water (RHw) at -20°C . The percentage of activated ice nuclei ($\text{IC}_{>5}/\text{APS}_{<5}$) was calculated from the ratio of the total number of ice crystals larger than $5\ \mu\text{m}$ ($\text{IC}_{>5}$) to the average of the total number of aerosol particles smaller than $5\ \mu\text{m}$ ($\text{APS}_{<5}$) before and after of each ice nucleation experiments. Results at 0 min exposure time stem from the non-aged experiments.

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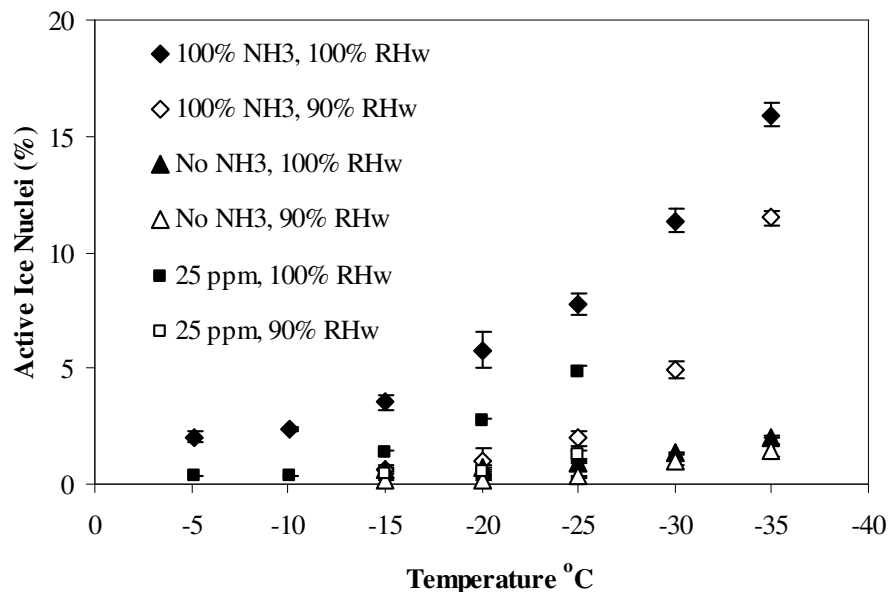


Fig. 5. Percentage of activated ice nuclei (as defined in Fig. 4) versus temperature (°C) of montmorillonite mineral dust particle exposed to 100% pure or 25 ppm ammonia gas and without ammonia gas exposure at 90% and 100% relative humidity with respect to water (RHw). The exposure time was 2 h for 100% pure ammonia and 18 h for 25 ppm ammonia. The vertical bars are the error bars equal to the standard deviation of the 15 measurements conducted at each temperature.

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