P1.16 ICE CRYSTAL FORMATION IN WAVE CLOUDS, AIRBORNE STUDIES -10 TO –35°C

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1. INTRODUCTION

The initial formation of ice is a long-standing problem in cloud physics. Ice particle numbers, sizes, and growth habits determine a cloud's microphysical and radiative properties. For many mid-latitude clouds, ice is crucial for precipitation. Processes involved in the initial formation of ice are not well understood because there are a number of primary and secondary production processes (Cooper 1991; Rasmussen 1995; Baker 1997).

Past field studies have been performed used instrumented aircraft to examine ice formation, although simultaneous measurements of cloud microphysics and ice nuclei (IN) were usually not obtained. Attempts to correlate IN and ice crystal concentrations often had cloud observations from one location and time, aerosol samples at a different location and time, and processing of aerosol collections still later, at a laboratory. In some cases, IN measurements addressed temperature dependencies but did not include equally important variations in humidity. Basic questions remain about the significance of aerosol particles in natural ice formation.

This paper describes some results from a field project to measure ice nuclei and cloud microphysical properties from instrumented aircraft. Studies of ice formation in altocumulus standing lenticular wave clouds were conducted in Colorado and Wyoming during March 2000 using the University of Wyoming King Air and aerosol instrumentation from Colorado State University. Ten flights were made, and measurements were obtained for microphysical, thermodynamic, and kinematic properties. Cloud temperatures ranged from -10 to -37°C. Aerosol properties (IN, CN and CCN) were measured upwind, within, and downwind of the clouds. Observations from selected case studies are presented. Exploratory modeling results are presented for two cases, using inputs based on the observations. The emphasis of this research is testing the potential to improve predictions of ice particle concentrations by using measurements of ice nuclei and CCN.

2. INSTRUMENTATION

Primary measurements included thermodynamics, kinematics, position keeping, water and ice cloud particles, and aerosol particles. Cloud particles were measured with four PMS probes: FSSP-100, FSSP-300, OAP-2DC, and OAP-200X. At selected times snow crystals were collected using a NCAR device. These samples were stored on dry ice and photographed later.

Instruments for measuring ice nuclei, cloud condensation nuclei, and condensation nuclei were located inside the aircraft cabin and shared a common air inlet. The inlet ingested air at ~700 L min^{-1} and the tip was heated to 5°C to avoid blocking from rime ice accumulating in regions of supercooled water.

Measurements of IN were made with a continuous flow thermal gradient diffusion (CFD) chamber [Rogers et al. 2001]. This technique detects ice nuclei that activate through deposition or condensation-freezing mechanisms. Nucleation mechanisms that require times >~1 s are not detected (contact-freezing and immersion-freezing). The CFD chamber exposes particles to one temperature (T) and one supersaturation (SS). These can be adjusted over time to produce ice nuclei activation spectra. Measurements were made both above and below water saturation, with the maximum water supersaturation (SSw) typically about +5%, and the minimum typically -10%. The general strategy was to try to match (T,SS) that were expected in the target wave cloud and to maintain constant (T,SS) conditions during vertical profiles. Occasionally, samples were made at very high SSw (>10%) for short time periods.

CCN were measured with a static thermal gradient cloud chamber (Delene et al., 2000) at 0.5, 1, 1.5, and 2.0% supersaturation to produce CCN activation spectra. CN concentration was measured with a butanol type instrument (TSI-3010).

3. FIELD PROJECT

Operations were based out of Laramie, Wyoming, and wave cloud flights were conducted in March 2000. The weather presented a wide range of sampling conditions during these flights, with cloud temperatures –10 to -40°C. Ice nuclei measurements ranged from -10 to -35°C and humidities from ice saturation to ~10% water supersaturation. Ice nuclei data were averaged to 10 s, corresponding to ~1 km distance and ~0.17 L volume.

After a cloud was selected for study, a number of cloud penetrations were made parallel to the wind in vertical steps of ~150 m. Sampling was also done in the on the upwind (updraft) region below water cloud base, between ice and water saturation, where crystals could form by a deposition mechanism. Likewise, passes were made on the downwind (downdraft) side to characterize the final state of snow crystals that formed in the clouds. For most "level" penetrations of clouds, the aircraft ascended and descended with the vertical wind and did not track along streamlines. Vertical excursions of the aircraft were ~65 m during a cloud pass. Although the aircraft was not able to follow air parcel trajectories, one of our analysis goals is to construct vertical cross sections of clouds by combining the overlying penetrations.

CCN, CN and IN measurements were made continuously. The interpretation of the in-cloud aerosol data is not straightforward because some fraction of cloud droplets or snow crystals entered the inlet, and their evaporated residues were measured by the aerosol instruments. This fraction is not known quantitatively.

suggesting that cloud processes were quite repeatable as the air flowed from one cloud to the next. There is some indication in the top panel that fewer ice particles formed on the downwind (left) end of the series where there were fewer ice nuclei. The air parcel transit time can be estimated as

*aircraft time * (true airspeed – wind)/wind*

For the fifteen minutes in Figure 1, the parcel transit time is ~4.5X larger, or ~68 minutes.

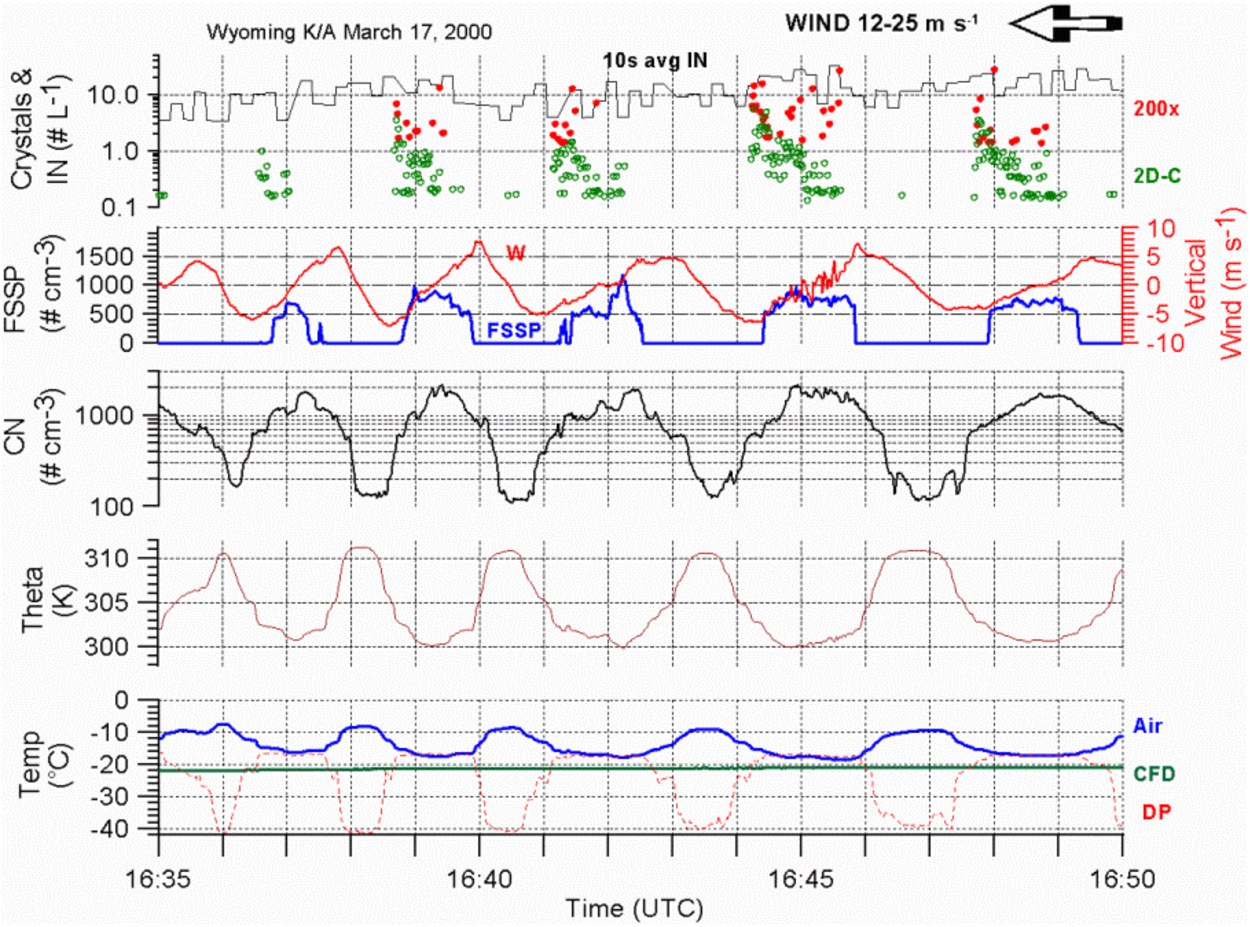

Figure 1. Measurements during fifteen minutes of continuous upwind flight at 4.5 km altitude. This flight segment was into the wind and penetrated a series of five wave clouds.

4. RESULTS

Observations from two flight days are shown to illustrate the kind of data that were obtained. Cloud model simulations are being done to assess the utility of aerosol particle measurements for predicting the formation of water and ice particles. Results from one simulation case are shown as an example.

4.1 March 17 case

A series of wave clouds formed downwind of the mountain ridge on this day. Enroute to the most upstream cloud, the aircraft passed through the middle of four other clouds, as shown in Figure 1. Notice the regular periodic appearance of the data,

The blue FSSP trace shows the water droplet cloud regions. Average droplet concentrations were ~700 cm^{-3} with peaks >1000 cm^{-3}. Vertical wind speeds were +5 to –5 m s-1 and were 90° out of phase with other oscillatory data. Snow crystal concentrations (top panel) measured by the 2D-C probe were ~0.1-3 L^{-1}, whereas the 200-X probe (red) measured ~1-20 L^{-1}. This discrepancy is due to the 2D-C's low detection efficiency for particles smaller than ~100 µm. Ice nuclei (black trace) were measured at –22°C and 4 to 5.5% water supersaturation. In this case, the IN concentration is roughly comparable to the 200-X snow crystal concentration.

CN concentrations (middle panel) and dew point (bottom panel) indicate two different air masses.

Higher concentrations of CN and water vapor were in the boundary layer.

Thirty-five cloud penetrations were made on this day. The summary of crystal concentrations is shown versus temperature in Figure 2. The number label of each point identifies the cloud pass and is plotted at the mean value. Error bars are 1 standard deviation. These data are based on the 200-X probe which covers the size range 12.5-186 µm. Note the general trend of higher concentrations at colder temperatures, as expected. There is a concentration spread of ~10X at any one temperature.

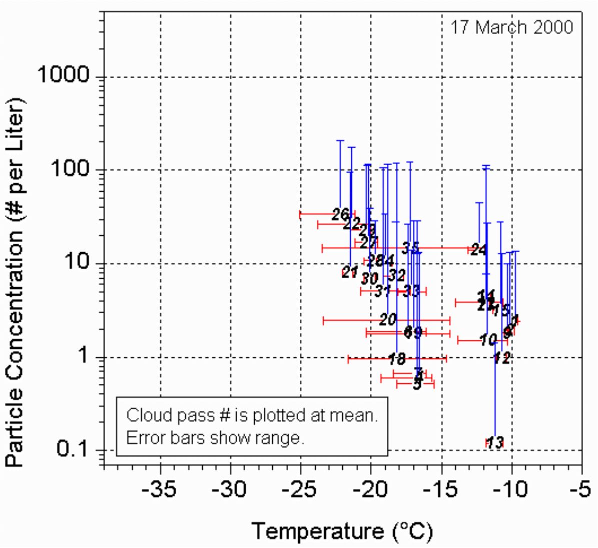

Figure 2. Summary crystal concentrations from 200X probe for thirty-five cloud penetrations - March 17.

CCN concentration were much smaller in the overlying air mass, similar to the difference exhibited by CN in Figure 1. Boundary layer air was identified as having potential temperature, Θ < 303K. The CCN data were grouped by Θ in Figure 3 and fell into two classes. Recall that athe observed droplet concentrations were ~700cm^{-3} on average. Since cloud formed in boundary layer air, the CCN data suggest peak supersaturations of 1.8% occurred.

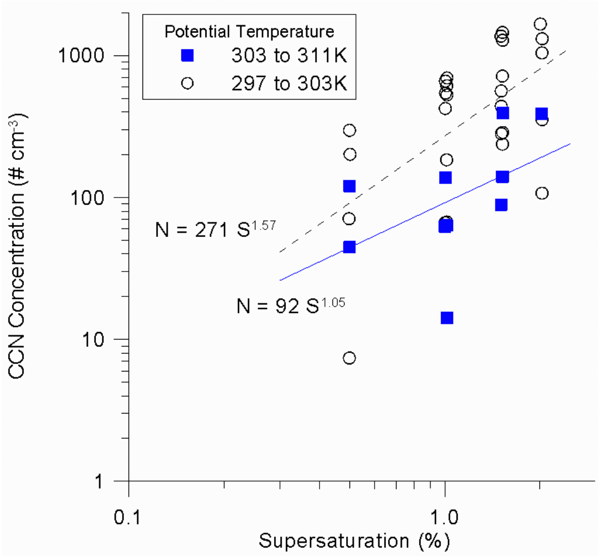

Figure 3. CCN activation spectra for the same time period as Figure 1, separated according to potential temperature.

4.2 Simulation for 17 March case

Our simulation studies are based on an adiabatic parcel model of Young (1974), with modifications by several later users. It has explicit treatment of ice and water droplet nucleation mechanisms. In comparing the simulations with observations it should be remembered that the aircraft does not follow streamlines or particle trajectories. Furthermore, the measured CCN spectra were tried in the model but did not produce high enough droplet concentration, so the number was fudged from 271 to 1000 in order to obtain agreement. Measurements of contact-freezing IN were not available, so we used what was already in the model. For this case, the model predicts the contribution of contact IN to ice production as relatively minor (~4%). The parcel motion was taken as a sine wave with peak 6 m s^{-1} updraft and period of 1000 s. It produced ~600 m lift above cloud base at -20°C.

Ice nuclei were described as a function of ice supersaturation, N (per liter) = 1.6x10^{-6} SS$_i^5$. The equation provides a general representation of the measurements for deposition + condensation-freezing nucleation, and it is useable in the model. It does not represent the variability that was observed.

The simulation for cloud #22 on this day is shown in Figure 4. The basic features of this cloud are reproduced reasonably by the model. The predicted droplet and crystal concentrations are approximately correct.

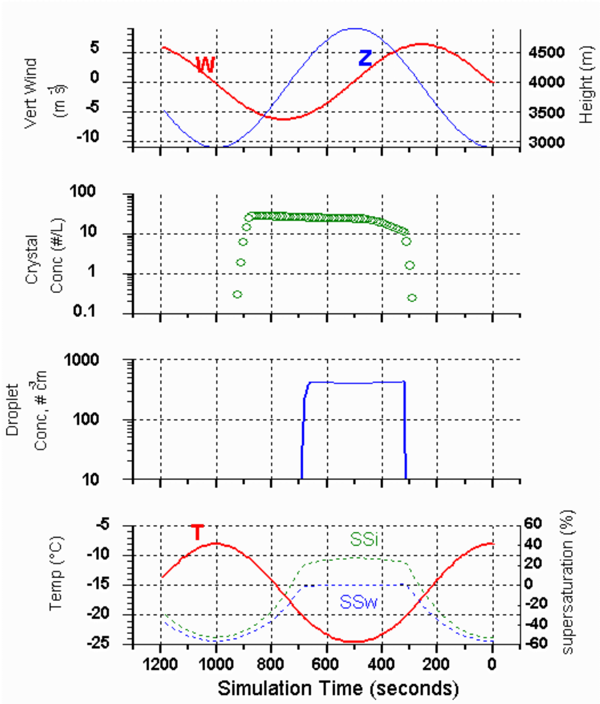

Figure 4. Parcel model simulation of cloud #22 for March 17 case.

4.3 March 25 case

Forty cloud penetrations were made on this day, and the summary of crystal concentrations is shown versus temperature in Figure 5. The general trend of higher concentrations at colder temperatures was observed, and the 10X (or greater) spread of concentrations was also apparent.

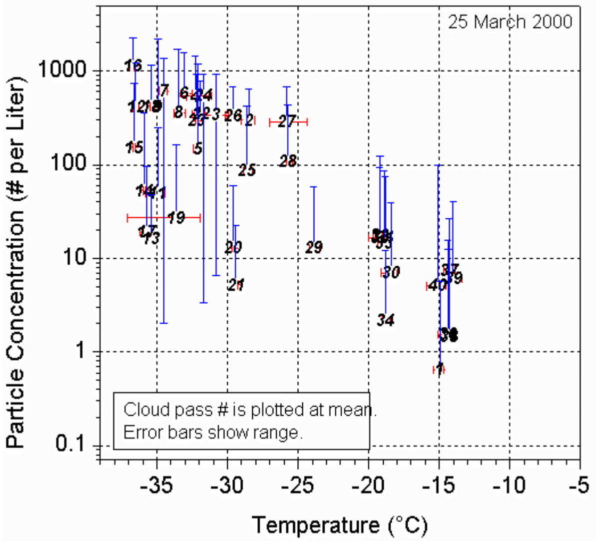

Figure 5. Summary crystal concentrations from 200X probe for forty cloud penetrations - March 25.

4.4 Discussion

The crystal concentration observations on 17 and 25 March yielded similar temperature trends. Using a reference point of –20°C, the concentration was ~10 L^{-1} on both days, with the March 17 data generally warmer and the March 25 data colder.

The relatively well defined vertical motions and simple air trajectories in these wave clouds can be used for estimating parcel trajectories and will serve as a basis for microphysical parcel modeling to examine the formation of ice crystals and cloud droplets. Our analyses are continuing on flight data from the other days and on incorporating the aerosol measurements with the goal of testing the ability of such data to improve the prediction of ice formation.

5. ACKNOWLEDGEMENTS

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