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# Preliminary Analysis of University of North Dakota Aircraft Data from the FIRE Cirrus IFO-II

Final Report

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## 1.0 Introduction

This report describes the work performed by the University of North Dakota (UND) under NASA Research Award NAG-1-1351 - "Preliminary Analysis of University of North Dakota Aircraft Data from the FIRE Cirrus IFO-II," during the period October 29, 1991 to March 31, 1995. The funding for this work was provided under the second phase of the First International Satellite Cloud Climatology Program (ISCCP) Regional Experiment (FIRE). The stated goals of FIRE are "to promote the development of improved cloud and radiation prameterization for use in climate models, and to provide for assessment and improvement of ISCCP products" (FIRE Project Office, 1990). FIRE Phase II has focused on the formation, maintenance and dissipation of cirrus and marine stratocumulus cloud systems. These objectives have been approached through a combination of modeling, extended-time observations and intensive field observation (IFO) periods.

The work under this grant was associated with the FIRE Cirrus IFO II. This field measurement program was conducted to obtain observations of cirrus cloud systems on a range of scales from the synoptic to the microscale, utilizing simultaneous measurements from a variety of ground-based, satellite and airborne platforms. By combining these remote and in situ measurements a more-complete picture of cirrus systems can be obtained. The role of the University of North Dakota in Phase II was three-fold: to collect in situ microphysical data during the Cirrus IFO II; to process and archive these data; and to collaborate in analyses of IFO data. This report will summarize the activities and findings of the work performed under this grant; detailed descriptions of the data sets available and of the analyses are contained in the Semi-annual Status Reports submitted to NASA.

## 2.0 Field Operations

UND participated in the FIRE Cirrus IFO - II through operations of its Citation II research aircraft. This is a twin-engine fanjet aircraft that has been modified for weather research and equipped for cloud microphysical and other measurements. A list of the instrumentation and observed parameters for the IFO is given in Table 1.

Two additional instruments from other investigators were flown on this project. Special modifications were made to the Citation to accommodate the mounting of a continuous formvar replicator from Dr. John Hallett of the Desert Research Institute (DRI). This instrument was included to obtain measurements of size distributions and habits for small cloud ice particles. Prior to this IFO, most observations of cirrus clouds had been made with probes which could not resolve

**Table 1.** **University of North Dakota**
**Cessna Citation II Research Aircraft**
**Summary of Measurement Capabilities**

| | |
|---|---|
| **State Parameters** | |
| Temperature | Rosemount Total |
| Temperature | |
| | Reverse Flow, Resistance |
| Dew Point Temperature | EG&G Cooled Mirror |
| Pressure | Rosemount |
| **Cloud Microphysics** | |
| Cloud Droplet Spectrum | PMS FSSP |
| Cloud Particles | PMS Optical Array 1D-C |
| Cloud Particles | PMS Optical Array 2D-C |
| Large Particles | PMS Optical Array 1D-P |
| Liquid Water Content | J-W |
| Supercooled LWC | Rosemount Icing Rate |
| Meter | |
| **Air Chemistry and Aerosols** | |
| $O_3$ | Scintrix Chemiluminescent |
| $NO_x$ | Scintrix Chemuluminescent |
| CN Counter | TSI Alcohol Condensing |
| **Air Motion and Turbulence** | |
| Horizontal, Vertical Wind | Flow Angle Probe, Inertial Navigation System |
| Attack and Sideslip Angles, Differential Airspeed | Flow Angle Probe, Pressure Transducers |
| **Aircraft Parameters** | |
| Heading, Pitch, Roll, Ground Speed, Position, Vertical Acceleration | Litton LTN-76 Inertial Navigation System |
| Position | VOR/DME |
| Position, Ground Speed | GPS |
| Longitudinal and Lateral Acceleration | Schaevitz |
| Engine Fan Speed | Tach Generator |
| Cabin Pressure | Setra |

particles smaller than about 50 μm. Furthermore, there was little or no detail regarding the characteristics of these particles with diameters smaller than about 150 μm. However, other measurements, both remote and in situ, had suggested that there may be significant numbers of smaller ice crystals in many cirrus cloud systems. The DRI replicator is able to collect particles as small as 7 μm and could therefore extend our knowledge of typical size spectra and remove some of the uncertainty in cirrus cloud composition. The other instrument was an aerosol cascade impactor from Dr. Donald Hagen of the University of Missouri - Rolla. The impactor was operated for a portion of each flight to collect samples of airborne particulates.

During the IFO, the Citation was based in Coffeyville, Kansas, for the period 12 November through 7 December, 1991. In that time, ten research missions were flown for a total of 35 flight hours (see Table 2). Flight operations were coordinated with the FIRE mission scientist in concert with the operations of the other project aircraft and the ground-based remote sensors at the hub site. The flight profiles consisted primarily of step climbs and descents to obtain time-averaged profiles of the cirrus cloud systems passing over the hub. There were also several ramp and spiral-type flight segments flown.

## 3.0 Data Processing and Archival

### 3.1 Data Processing

The data collected during the missions were recorded in essentially a raw format; that is, in units of volts for most analog probes and other unprocessed units for most other instruments. Subsequent processing of these data was required to convert the raw numbers into meteorological values, to derive certain parameters, and to apply calibration factors. During this process the data were also checked for quality and consistency. Initial processing of the data was done in the field after each flight to look for problems with the instrumentation.

In a parallel activity, mission summaries were compiled to help in analysis of the data. These summaries break each flight down into legs or flight segments that correspond to portions of the flight profiles. They were determined from voice notes taken by the flight scientist and from the data itself. There were a total of 148 flight segments noted for the IFO.

To help with interpretation of the data collected by the Particle Measuring Systems 2D-C Optical Array Probe (PMS 2D-C), two automatic particle habit classification schemes were made available. One is an adaptation of a scheme

**Table 2.** **FIRE Cirrus IFO-II**
**UND Citation Flight Summary**

| Date (UTC) | Flight Times (UTC) | Comments |
|---|---|---|
| 11/14 | 1341-1740 | Supercooled water |
| 11/22-1 | 0050-0426 | Small ice crystals |
| 11/22-2 | 1803-2140 | Supercooled water in wave |
| 11/25 | 1350-1826 | Deep deck of small ice particles |
| 11/26 | 1629-1958 | Deepening cirrus, contrail penetrations |
| 11/28 | 1633-2118 | High cirrus |
| 11/30 | 1500-1715 | High cirrus, all small particles. Off hub |
| 12/5-1 | 0612-0847 | Two layers, lower quite dense. Good hub mission |
| 12/5-2 | 1756-2021 | Cirrus profile, Coffeyville-Parsons |
| 12/7 | 1922-2228 | Cirrus band, coordinated with aircraft, satellite. Spectacular optical effects. |

developed by Holroyd (1987), where classification is attempted on particles with a maximum dimension of at least 200 μm and not shadowing either of the array end elements. A linear regression is performed on accepted particles to determine orientation and linear fit. Particles not classified as linear or columnar are typed according to a factor that considers the perimeter, length and area of the particle image. Modifications were made to the threshold values of Holroyd which were derived for particles found at warmer temperatures.

The other algorithm was developed by Dr. Andy Heymsfield of NCAR and was ported to the UND Cray X-MP for processing of this data set. This scheme looks at particles larger than 150 μm and determines their habit by the area ratio of each image. This is the ratio of image area to the equivalent area of a circle with diameter equal to the maximum dimension of the image. The algorithm uses the derived particle habits and sizes to compute the cloud ice water content, using appropriate mass-dimensional relationships. This is the same algorithm used to process the data collected by similar probes on the NCAR Sabreliner and King Air aircraft also flown in the IFO. This will allow for comparison and integration of the data sets, particularly for cloud systems sampled by more than one aircraft.

### 3.2 Data Archival

The data collected by the Citation during the IFO, except those produced by the DRI replicator and the U. Missouri-Rolla impactor, were processed into several different formats for archival at the NASA Langley DAAC. (The data obtained with those two additional probes was turned over to the principal scientists after each flight.) This archival occurred in three steps. As mentioned, the data needed to be checked and calibrations applied before archival. During the period of time when this processing was taking place, before any data were submitted to the DAAC, a number of requests for data were received from other FIRE principal investigators. These were requests for either data from certain missions or just certain parameters from each flight; these requests were filled as they were received.

The first submission of data to the DAAC included three data types. One consisted of one-second average values of 51 parameters that were either sampled directly by the instrumentation or were derived from these measurements. These were submitted in ASCII data format with one file for each flight. This set did not include any of the cloud microphysical data obtained by any of the four PMS particle probes mounted on the aircraft. These were submitted in two additional, separate files because of the nature of these data. A number of schemes have been devised for reducing PMS data, and many investigators who are familiar with these data prefer to apply their own algorithms to derive parameters of interest.

Therefore, these were provided in a standard raw format. One set contains the data collected by the "1-D" probes: the 1D-C, 1D-P and FSSP instruments. The other consists of the particle images generated by the 2D-C probe mentioned previously.

Following this initial archival, another type of data set was generated from the raw Citation data. Since a number of FIRE investigators either did not wish to or were not able to reduce the PMS data, a file type was created that included cloud microphysical parameters derived from the PMS probes in addition to the other direct and derived measurements. A total of 114 variables were computed and averaged over 5-second intervals. These were stored as scaled 32-bit integer values in one file per flight mission.

The final data set produced for the FIRE archive was the output of the PMS 2D-C data reduction algorithm of Heymsfield discussed earlier. These data were also processed with a 5-second averaging time. The output of this routine was submitted to the DAAC in ASCII format with one file per flight. There were no 2D-C data for the 28 November mission because of a probe malfunction.

Documentation concerning the file structure and how to read all of the above data sets was submitted to the Langley DAAC All data are available from the FIRE archive at the DAAC.

## 4.0 Data Analysis

Analysis of the Citation data was given a primary emphasis of collaboration with other FIRE investigators in case studies of several of the cirrus cloud systems observed during the IFO. The UND contribution to these studies focused on the cloud microphysical and aerosol data. Additional effort was directed toward the study of aerosol scavenging by cirrus ice particles and measurements of small ice particles with the FSSP probe.

### 4.1 The 5 December 1991 Case Study

This case study investigated the possible effects of volcanic aerosols on cirrus cloud morphology. In June of 1991, Mount Pinatubo in the Philippines erupted and injected a massive amount of aerosol into the troposphere and lower stratosphere. Much of this material was still in circulation around the globe at the time of the Cirrus IFO; its presence in the atmosphere over the FIRE site was noted by lidar measurements and by the occurrence of spectacular sunsets. Remote and in situ measurements made during the nighttime hours and a subsequent daytime flight of 5 December 1991 are included in this study. The Citation microphysical and aerosol data show a high likelihood that this cirrus system existed within an airmass recently affected by a stratospheric intrusion. Pinatubo aerosols appear to have been brought down into the upper troposphere; coincidentally, the sampled cirrus cloud particle concentrations were the highest of the project. These data helped support the preliminary findings of Sassen (1992) concerning a mechanism for volcanic influence on cirrus. The results of this case study have been published in the Journal of the Atmospheric Sciences (Sassen, et al, 1995).

### 4.2 The Radiative Effects of Small Ice Particles

Data collected in situ on 21 November 1995 were used to compare the performance of the DRI replicator and the PMS 2D-C probe and to examine the role of small ice crystals in radiative transfer through cirrus. The replicator showed the presence of large numbers of ice crystals smaller than the minimum detection threshold (66 μm) of the 2D-C. The measurements showed good overlap for concentrations and sizes of particles with diameters of 100-200 μm, and some oversizing by the replicator of the larger particles.

Calculations based on these data showed that small particles can contribute significantly to the solar extinction and infrared emission and at times exceed the effects of the larger particles. The combined spectra had a bimodal character, suggesting a two-stage nucleation process that is a result of varying supersaturations which result from varying updraft speeds and the fallout of larger crystals. It will be important to include the effects of the smaller particles in cloud and climate models and in remote sensing algorithms. The results of this study have been published in the Journal of Geophysical Research (Arnott, et al, 1994).

### 4.3 Satellite Remote Sensing of Multiple Cloud Layers

This study focused on the application and validation of a method for remotely sensing cloud top heights from satellite when more than one cloud layer is present. Cirrus often occur in combination with other cloud types at different altitudes. The data collected on 28 November 1991 from rawinsonde, active surface-based remote sensors (radar and lidar) and the Citation were used to test the cloud-top values derived from the polar-orbiting satellites. The PMS 1D-C and FSSP probe data were used to determine cloud boundaries in conjunction with GPS altitude data. The cloud top heights derived from the satellite data compared favorably with the aircraft data. These results have been accepted for publication in the Journal of the Atmospheric Sciences (Baum, et al, 1995).

## 4.4 Scavenging of Aerosols by Cirrus Ice Particles

It was planned to measure the rate at which the aerosol particles were being removed by the ice particles at the cirrus cloud levels. From the rate of change of the aerosol concentration and the size spectrum of the ice particles, the washout coefficients for scavenging by cirrus ice particles could be determined in a manner similar to that done near the surface by Graedel and Franey (1975). In order to determine the washout coefficients, the information required is the aerosol concentrations from the TSI condensation nucleus counter and the ice particle size and concentration from the PMS 2D-C probe. These data needed to be available at different times when the same volume elements of the cirrus clouds were penetrated as those volume elements were advected downwind.

The condensation nucleus counter was not operational early in the 1991 field season and data were not collected with this instrument until 11/26/91. The 2D-C probe was not functioning properly during a portion of the flight on 11/26/91 and on the next flight on 11/28/91. Early in the flight on 11/26/91, there were consecutive legs flown at the same altitude, but on the first pair (legs 1 and 2), there were very few ice particles and on the second pair(legs 6 and 7) the only ice encountered was at the end of leg 6 and the beginning of leg 7. The time between the two measurements was only about 5 minutes and was not long enough to see a significant decrease in the CN concentrations.

There were four flights made after 11/28/91 with both instruments working properly. Unfortunately, on all these flights there were no consecutive legs flown at the same altitude, with one exception. This exception was on the second flight of 12/05/91, when there were two consecutive legs flown, but not along reverse tracks or headings. As the winds were relatively strong during this flight (greater than 60 m/s), the air sampled during the first leg was blown past the intersection point of the two legs long before the Citation arrived at the intersection point. Due to the fact that the winds were strong during the last four flights, it was mandatory that the measurements be made at the same level for consecutive legs.

There were flights when the flight profiles were appropriate for this analysis. In particular, the flight of 11/26/91 had at least two pairs of legs flown where consecutive passes through the same sample volume were made. The 2D-C data were not available for these legs but there are replicator data. These have yet to be analyzed, but if they are analyzed, it would be possible to determine the washout coefficients for this day. The same is true for the flight of 11/28/91. This day is not quite as good as the first for this analysis because the wind velocities were somewhat higher on the 28th than they were on the 26th ( the wind velocities at the altitudes of interest were about 40 m/s on the 28th and less than 20 m/s on the 26th).

4.5 Use of the PMS FSSP to Detect Small Ice Particles

There were several instances noted during the IFO when the FSSP probe was detecting small particles at temperatures colder than -40° C but nothing was observed on the optical array probes. The FSSP probe is designed to count and size small (0.5-47 μm diameter) spherical particles and has been used primarily for the study of liquid water clouds. However, given the apparent importance of small ice crystal and their relative lack of measurements, it would be useful to be able to derive quantitative information about them from FSSP data. FSSP measurements are based on Mie scattering theory; since Mie theory applies to spherical particles, the use of the FSSP for measurements where non-spherical ice crystals are present is problematic.

The primary problem is that complex scattering and reflection increases the effective sample area of the probe to some unknown value. Gardiner and Hallett (1985) noted that errors in particle concentrations may be as great as 2-3 orders of magnitude. This and other studies noted the difficulties in using FSSP data to measure cloud droplet spectra in mixed phase clouds due to the uncertainty introduced by the relatively large ice crystals. The errors may be acceptably small, however, in clouds composed entirely of small, quasi-spherical ice particles. In their parameterization of cirrus particle size spectra, Heymsfield and Platt (1984) considered the FSSP data in the 10-20 μm size range to be valid, based on comparison with a 1D-C probe.

Additional evidence for the utility of the data can be seen in spectra derived from a preliminary analysis of the Citation FIRE data. Figure 1 shows an average FSSP spectrum from a period when the aircraft was sampling near the top of a cirrus layer at an altitude of 12.4 km and temperature of -63.5 °C. During this time, the 2D-C was not sensing any particles. Notice that the spectrum has a sharp peak at approximately 20 μm and is not flattened as reported in the studies mentioned previously. Total number concentrations were running on the order of 100-600 $l^{-1}$. During FIRE, the Citation also carried a continuous formvar replicator operated by the Desert Research Institute. This instrument is capable of capturing particles as small as 7 μm in the form of replicas which can be counted, sized and analyzed for crystal habit. A preliminary analysis of the replicator data during the time of the FSSP measurements indicates particle sizes of <50 μm (most much smaller than 50 μm) and concentrations of 100-400 $l^{-1}$ (Arnott, personal communication). This corroborates the FSSP observations and shows that with further analysis it may be possible to quantify these and other such cirrus measurements.

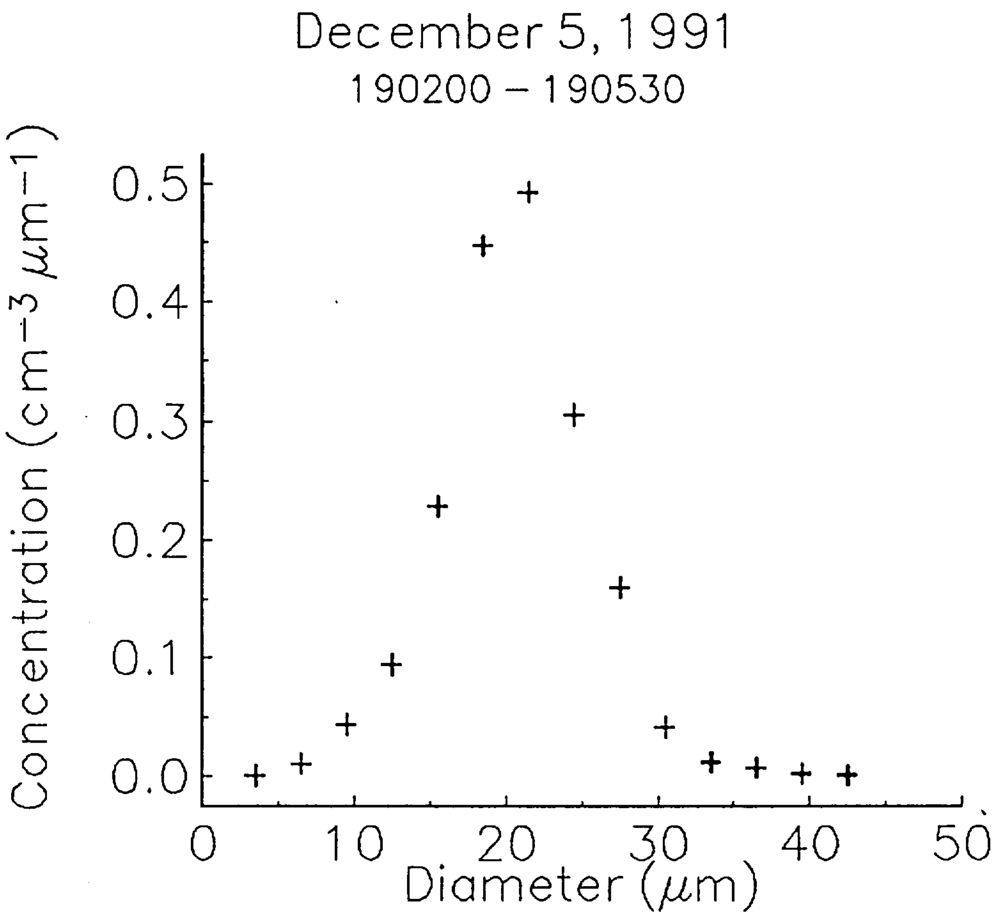


Figure 1. Average FSSP spectrum from 5 December 1991, 19:02:00 - 19:05:30

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