AIRBORNE MEASUREMENTS AND OBSERVATIONS IN CIRRUS CLOUDS

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Qualified requestors may obtain additional copies from the Defense Documentation Center. All others should apply to the National Technical Information Service.
Fourteen case studies of airborne measurements in cirrus clouds are described. For each case information is given on the location of the flight, the synoptic situation (with accompanying satellite IR and visible photographs), the types, sizes and mass concentrations of ice particles in the clouds, and the distribution of the ice mass concentration among particle sizes at different altitudes.

From simultaneous measurements of ice mass concentrations and ice particle
number concentrations, mean ice particle masses are derived: they range from about 0.3 to 30 μg. Low number concentrations of ice particles are generally associated with low ice mass concentrations and high number concentrations with high mass concentrations.

The total ice mass concentrations in cirrus clouds generally increase with increasing temperature. Maximum values of the total ice mass concentration did not exceed the atmospheric water vapor content for water saturated conditions (about 0.1 and 1.0 g m$^{-3}$ at -45 and -20°C respectively) except when the cirrus originated from cumulonimbus tops.
Preface

This research was supported by the Space and Missiles Systems Organization under the technical direction of the Air Force Cambridge Research Laboratories, Air Force Systems Command, USAF, under Contract F19628-74-C-0066 with the Atmospheric Sciences Dept., University of Washington.

The effort of Dr. Cunningham and Mr. Bunting in support of this work is gratefully acknowledged.
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1. INTRODUCTION

In this report we describe the results of a series of aircraft flights in cirrus clouds carried out in Washington State and Colorado during the period November, 1973, to July, 1974. The principal objectives of these flights were to explore the distribution of ice in cirrus clouds, to obtain measurements of the mass concentrations of ice as a function of particle size, and to seek predictor variables for the total ice mass concentration in cirrus clouds.

Table 1 lists the fifteen flights that were made. Good quality data were obtained in eleven of these flights, fair quality data in three flights, and poor quality data in the remaining flight. Following descriptions of the aircraft instrumentation and the methods of data analysis, the results obtained in each of the fourteen flights on which good or fair quality data were obtained are described. This is followed by a presentation of the relationship between total ice mass concentration and air temperature.
### TABLE 1. CHRONOLOGY OF FLIGHTS MADE IN CIRRUS CLOUDS

<table>
<thead>
<tr>
<th>Date of Flight</th>
<th>Location of Flight</th>
<th>Synoptic Situation</th>
<th>Distribution of Cloud Layers (in 1000's of ft.)</th>
<th>Maximum Flight Altitude (in 1000's of ft.)</th>
<th>Quality of Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>November 30, 1973</td>
<td>Washington State</td>
<td>Upper Trough</td>
<td>10 to 23</td>
<td>22</td>
<td>Good</td>
</tr>
<tr>
<td>December 4, 1973</td>
<td>&quot;</td>
<td>Pre-Frontal</td>
<td>14 to 24</td>
<td>22</td>
<td>&quot;</td>
</tr>
<tr>
<td>December 18, 1973</td>
<td>&quot;</td>
<td>&quot;</td>
<td>17 to 22</td>
<td>22</td>
<td>&quot;</td>
</tr>
<tr>
<td>January 2, 1974</td>
<td>&quot;</td>
<td>Upper Trough</td>
<td>10 to 18</td>
<td>19</td>
<td>&quot;</td>
</tr>
<tr>
<td>January 8, 1974</td>
<td>&quot;</td>
<td>&quot;</td>
<td>13 to 21</td>
<td>21</td>
<td>&quot;</td>
</tr>
<tr>
<td>January 23, 1974</td>
<td>&quot;</td>
<td>Dying Front</td>
<td>15 to 20</td>
<td>20</td>
<td>&quot;</td>
</tr>
<tr>
<td>January 30, 1974</td>
<td>&quot;</td>
<td>Westerly Airstream</td>
<td>{10 to 18, 20 to 25}</td>
<td>23</td>
<td>Fair</td>
</tr>
<tr>
<td>February 20, 1974</td>
<td>Colorado</td>
<td>Pre-Frontal</td>
<td>8 to 19</td>
<td>18.5</td>
<td>Good</td>
</tr>
<tr>
<td>March 12, 1974</td>
<td>&quot;</td>
<td>&quot;</td>
<td>21 to 26</td>
<td>24</td>
<td>&quot;</td>
</tr>
<tr>
<td>March 17, 1974</td>
<td>&quot;</td>
<td>&quot;</td>
<td>19 to 21</td>
<td>21</td>
<td>Poor</td>
</tr>
<tr>
<td>March 26, 1974</td>
<td>&quot;</td>
<td>&quot;</td>
<td>23 to 26</td>
<td>25</td>
<td>Good</td>
</tr>
<tr>
<td>April 4, 1974</td>
<td>Washington State</td>
<td>&quot;</td>
<td>6.5 to 23</td>
<td>23</td>
<td>Fair</td>
</tr>
<tr>
<td>April 17, 1974</td>
<td>&quot;</td>
<td>&quot;</td>
<td>13.5 to 23</td>
<td>24</td>
<td>&quot;</td>
</tr>
<tr>
<td>May 17, 1974</td>
<td>&quot;</td>
<td>Cb anvils</td>
<td>15 to 23</td>
<td>22</td>
<td>Good</td>
</tr>
<tr>
<td>July 15, 1974</td>
<td>&quot;</td>
<td>Upper Trough</td>
<td>19.5 to 23</td>
<td>23</td>
<td>&quot;</td>
</tr>
</tbody>
</table>

#### 2. AIRCRAFT AND INSTRUMENTATION

The aircraft used in these studies was the University of Washington's Douglas B-23. This is a twin-engine aircraft which can cruise at 100 mph and has an altitude capability of 30,000 ft. The low cruising speed is particularly advantageous in that it reduces the fragmentation of delicate ice particles on collection. The B-23 is equipped for all-weather operations, it has complete
navigational and communication equipment, de-icing facilities and a 5-cm weather radar.

Some of the specialized instruments for cloud physics research which are on the aircraft are indicated in Figure 1. In addition to the state parameters (temperature, humidity, pressure altitude), automatic instrumentation is available for measuring air turbulence, cloud condensation nuclei (in-house\textsuperscript{1,2}), cloud droplet size distributions (Knollenberg axially scattering spectrometer and Keilly disdrometer), liquid water content (Johnson-Williams), the concentrations of ice particles (in-house\textsuperscript{3,4}) and electric fields. The outputs from these instruments are displayed digitally in the aircraft and recorded on a 25-channel tape recorder for subsequent computer analysis. Cloud and precipitation particles can be collected and replicated with a continuous (Formvar) particle sampler (CPS) and a metal foil impactor. Decelerators can be attached to the CPS in order to reduce the speed of impact of the ice particles with the Formvar-coated film and thereby reduce their fragmentation.\textsuperscript{5} Further details on the aircraft instrumentation have been given by Hobbs et al.\textsuperscript{3}

3. PROCEDURES OF DATA ANALYSIS

3.1 Concentrations of Ice Particles

Three of the instruments on board the aircraft gave data on the number concentrations of ice particles in the air. Namely, the CPS, the metal foil

\begin{itemize}
  \item 3. Hobbs, P. V. et al. (1971) Contributions from the Cloud Physics Group, University of Washington, Research Report VI.
\end{itemize}
Figure 1. Schematic of instrumentation on board the University of Washington's Cloud Physics Research Aircraft. Caption on following page.
Caption for Figure 1. Location of men and research instruments on the B-23 aircraft.

1-2 Pilot and copilot
3 Observer
4 Instrumentation Engineer
5 Instrumentation Monitor
6 Flight Director
7 Observer

A 5 cm gyrostabilized weather radar
B Rosemount airspeed, pressure altitude and total temperature probes, MRI-turbulence probe and electronics, J-W liquid water probe
C VOR-DME slaved position plotter; research power panel (2 KW 110V 60 Hz; 1.5 KW 110V 400 Hz; 150 amps 28V dc)
D Electronic controls for J-W liquid water indicator, reverse housing thermometer, electrical cloud particle counter and dew point thermometer, time code generator and time display, WWV time standard receiver, TAS and Ttot analog computers, signal conditioning amplifiers, audio signal mixers, FM and time-share data multiplexers, 3-D electric field and turbulence analog read-outs
E Minicomputer (16 bit word 16K word capacity), computer interface to instrumentation, remote A-D converter, keyboard and printer (scheduled for completion Sept. 1974)
F Analog tape recorder (7 track, 1/2") and high speed, 6-channel analog strip chart recorder
G Inlet aerosol sampling
H Aircraft oxygen, digital readout of all flight parameters, dew point sensor, time code reader and time display, heated aerosol plenum chamber, vertical velocity, Millipore filter
I Controls for metal foil impactor and continuous particle replicator
J Aerosol analysis section, generally contains: modified NCAR ice nucleus counter or MEE fast ice nucleus counter, integrating nephelometer, sodium particle flame photometer, automatic cloud condensation nucleus counter, VHF air-to-ground transceiver, Whitby aerosol analyzer, Royco particle counter
K Optical droplet counter (Knollenberg) vertically mounted
L Bomb rack hard points suitable for small instrument pods, AgI flare racks, or "Skyfire" generators
M Proposed location of lidar system
N Electric field mill sensor (vertical and horizontally perpendicular to the aircraft axes)
O Electric field mill sensor (vertical and horizontal field)
P Reverse flow static temperature probe
Q Electrical cloud particle counter (NCAR Electrostatic Disdrometer)
R MRI continuous particle replicator
S AgI ejection flare racks (52 40 mm units)
T AgI flare rack (24 1.5" units)
U Radar repeater
V Radar altimeter, 3-D electric field mill electronics, 20-channel telemetry transmitter
W Instrument vacuum system (consists of three high capacity vacuum pumps connected individually to the cabin)
X Storage oscilloscope monitor for the aircraft weather radar
Y Optical ice crystal counter and metal foil hydrometeor impactor
imacter and the University of Washington's optical ice particle counter.\textsuperscript{3,4} Fragmentation of crystals is the major problem with the CPS data. Counting all crystals except those that obviously appear to be fragments gives results that seem to overestimate the concentrations by about a factor of 10. On the other hand, counting only large smashed and intact regular crystals appears to underestimate the concentrations (compared with the optical ice particle counter) by about the same factor.

The foil sampler gives good data for precipitation sized particles but, in the normal speed range of the B-23, many crystals below 1 mm in maximum dimension do not leave recognizable imprints. The threshold of detection for drops and graupel-type particles is about 0.25 mm. However, as the ratio of mass-to-maximum dimension decreases, the threshold rises, to about 1 mm for dendrites and stellar type crystals. Even at this threshold, it appears that only a fraction of the crystals leave imprints. These factors limit the effectiveness of the foil sampler in cirrus studies.

The optical ice particle counter appears to give the best estimates of ice crystal concentrations. However, this counter was undergoing a series of modifications during these studies and as a result the threshold sensitivity (the ice particle size at which 100 per cent counting occurs) varied considerably as the optimal configuration was sought. In addition, an undetected intermittent component failure caused occasional spurious counting on some flights.\textsuperscript{†}

Generally, however, the optical ice particle counter detected all of the ice particles larger than 100 \textmu{}m and a decreasing fraction to sizes down to 30 \textmu{}m.

3.2 Ice Mass Concentrations

Ice mass concentrations were derived from the types and dimensions of the ice particles collected on the CPS using the data shown in Table 2. These data are based both on calculation and on the measured masses of ice particles of various types and sizes.\textsuperscript{6}

\textsuperscript{†}These problems have now been resolved and the optical ice particle counter is now an operational device which provides excellent measurements of ice particle concentrations in clouds.

TABLE 2. MASSES (in μg) OF ICE PARTICLES OF VARIOUS TYPES AS A FUNCTION OF THEIR MAXIMUM DIMENSIONS

<table>
<thead>
<tr>
<th>Maximum Dimensions (μm)</th>
<th>Hexagonal Plates and Plate-like Fragments</th>
<th>Short Columns and Columnar Fragments</th>
<th>Long Columns and Needles</th>
<th>Assemblages of Columns</th>
<th>Assemblages of Plates and Columns</th>
<th>Assemblages of Plates or Side-Planes</th>
<th>Graupel</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-32</td>
<td>0.003</td>
<td>0.005</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32-56</td>
<td>0.012</td>
<td>0.020</td>
<td>0.004</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>56-100</td>
<td>0.055</td>
<td>0.075</td>
<td>0.020</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>100-178</td>
<td>0.22</td>
<td>0.27</td>
<td>0.10</td>
<td>0.08</td>
<td>0.13</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>178-320</td>
<td>0.95</td>
<td>1.0</td>
<td>0.38</td>
<td>0.42</td>
<td>0.52</td>
<td>0.62</td>
<td></td>
</tr>
<tr>
<td>320-560</td>
<td>3.5</td>
<td>3.5</td>
<td>1.5</td>
<td>2.4</td>
<td>2.3</td>
<td>2.2</td>
<td>3.5</td>
</tr>
<tr>
<td>560-1,000</td>
<td>15.0</td>
<td>12.5</td>
<td>6.0</td>
<td>12.0</td>
<td>10.0</td>
<td>8.0</td>
<td>18.0</td>
</tr>
<tr>
<td>1,000-1,780</td>
<td>60</td>
<td>65</td>
<td>25</td>
<td>40</td>
<td>34</td>
<td>28</td>
<td>100</td>
</tr>
<tr>
<td>1,780-3,200</td>
<td>---</td>
<td>---</td>
<td>100</td>
<td>150</td>
<td>125</td>
<td>100</td>
<td>400</td>
</tr>
</tbody>
</table>

Because of the cubic relation of mass to dimension, the largest particles encountered in any significant quantity usually contributed most to the total mass concentration of ice. Consequently, our estimates of the total ice mass concentration from the CPS are more reliable than our estimates of the number concentration of ice particles which tend to be dominated by the large number of small ice fragments collected on the CPS.

4. RESULTS FROM FOURTEEN CASE STUDIES

4.1 November 30, 1973

(a) Flight location and time: The flight was made over the northeastern corner of the Olympic Mountains in Washington State. The period of the flight was 1540 to 1809 Pacific Standard Time (PST) on November 30, 1973.

(b) Synoptic situation (Figures 2 and 3): A depression and associated upper trough were off the Washington-Oregon coast and moving slowly east. The 500 mb winds were southwesterly tending to southerly at 40 to 70 knots.
Figure 2. Surface synoptic map for 1600 PST on November 30, 1973. Location of flight (-----). Period of flight 1540 to 1809 PST.
Figure 3. 500 mb map for 1600 PST on November 30, 1973. Location of flight (□□□□). Period of flight 1540 to 1800 PST.
Temperatures were rising.

The morning and evening NOAA-2 satellite photographs (Figure 4 and 5) showed a slow-moving, wide (about 300 nautical miles) frontal cloud band over Washington State. The flight was probably made just west of the center of this band.

(c) **Airborne data:** The cloud system consisted of altostratus layers merging into a cirrostratus layer (cirrostratus nebulosus). The main cloud deck was entered at 10,000 ft. Some clear areas were encountered between 13,000 and 15,000 ft. Tops were at 22,000 ft. (-31°C). On descent, the cloud base had lowered to about 7,000 ft.

The experimental data collected from the aircraft are summarized in Figures 6 and 7. The predominant crystals collected were assemblages of columns and single columns. The mass concentration of ice reached 0.28 g m⁻³ in the lower regions of the cloud layer but fluctuated about 0.05 g m⁻³ in the cirrostratus. Crystal sizes were smallest (all less than 0.3 mm) near the cloud tops, and grew steadily toward cloud base where some were in the range 1.0 to 1.5 mm.

4.2 **December 4, 1973**

(a) **Flight location and time:** The aircraft climbed to 23,000 ft. over Hoquiam on the Washington Coast and then flew to Seattle. The period of the flight was 0743 to 1008 PST.

(b) **Synoptic situation (Figures 8 and 9):** An upper level ridge was over the Western United States with a weakening short-wave trough approaching the Washington Coast which caused cirrostratus to thicken over Western Washington.

It should be noted that in the cross-sections the vertical exaggeration (usually 15:1) makes the clouds appear less stratified than they actually were. Also since the atmosphere varies in space and time, some inconsistencies show up when trying to illustrate the data collected on a flight in a two-dimensional diagram.

†Sizes refer to maximum linear dimension.
Figure 4. Satellite mosaic photograph (visible) for November 30, 1973. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 5. Satellite mosaic photograph (IR night) on November 30, 1973. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
Figure 6. Cross-section of flight path (---) from 1540 to 1809 PST on November 30, 1973. Shown are areas of cloud (-----), sizes of largest particles collected (+ = 0.1 to 0.3 mm; X = 0.4 to 0.7 mm; * = 0.8 to 1.5 mm) and ice mass concentrations (in g m\(^{-3}\)) in boxes. The presence of liquid water is indicated by cross bars on the flight track (---) with the value (in g m\(^{-3}\)) shown alongside. Temperatures (in °C) shown on the right hand side were measured from the aircraft.
Figure 7. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on November 30, 1973. M is the total ice mass concentration at each altitude.
Figure 8. Surface synoptic map for 1600 PST on December 4, 1973. Flight location (HHHH). Period of flight 0743 to 1008 PST.
Figure 9. 500 mb map for 1600 PST on December 4, 1973. Flight location (11111111'). Period of flight 0743 to 1008 PST.
The satellite photographs (Figures 10 and 11) show a cirrus band moving over Washington State. The aircraft flight was made in the eastern third of this band and bracketed the time the satellite photographs were taken. Both the visual and IR photographs show less dense clouds over the Puget Sound Basin than over the Olympics.

(c) **Airborne data:** The upper cloud layer had thickened to altostratus at the time of the flight, with a base at about 14,000 ft. over the coast but higher inland. The tops of the clouds were not well defined but they were well above the highest flight level of 22,000 ft. The altostratus gradually merged into a uniform cirrostratus layer. Crystal types were predominantly assemblages of plates and columns, irregular particles and single columns. Ice mass concentrations ranged from 0.13 to 0.25 g m\(^{-3}\), with one sample showing 0.06 g m\(^{-3}\) in fall-streaks below the main cloud base. Maximum crystal sizes were generally about 0.5 mm, but reached 1 mm near cloud base.

This flight was part of a cyclonic storm study and is presented as a time cross-section in Figure 12. Ice mass concentration spectra are shown in Figure 13.

4.3 **December 18, 1973**

(a) **Flight location and time:** Airborne measurements were made from the northeast corner of the Olympic Mountains in Washington State to Paine Field which is situated twenty nautical miles north of Seattle. The period of the flight was 1455 to 1720 PST.

(b) **Synoptic situation (Figures 14 and 15):** A weakening front was situated off the Pacific Coast and was moving slowly west toward an upper ridge over Washington State. The 500 mb winds were variable but tending to southwesterly and strengthening.

The morning satellite cloud mosaic (Figure 16) shows cirrus bands ahead of the front but still off-shore. The evening mosaic (Figure 17) shows the leading bands to have moved into Eastern Washington. The measurements described below were probably made in the leading cirrus band ahead of the front.
Figure 10. Satellite mosaic photograph (IR day) for December 4, 1973. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 11. Satellite mosaic photograph (visible) for December 4, 1973. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 12. Cross-section for flight path (---) on December 4, 1973, based on system movement of 20 knots, showing distribution of cloud (........), ice mass concentrations (in g m\(^{-3}\)) in boxes, and sizes of largest crystals collected (+ = 0.1 to 0.3 mm; \(\times\) = 0.4 to 0.7 mm; \(\ast\) = 0.8 to 1.5 mm). Isotherms are shown by (----). The presence of liquid water is shown by cross bars on the flight track (----------), with values in g m\(^{-3}\) alongside. The flight track was from Seattle to the Pacific coast at Hoquiam, and return.
Figure 13. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes on December 4, 1973. M is the total ice mass concentration at each altitude.
Figure 14. Surface synoptic map for 1600 PST on December 18, 1973. Location of flight (- - -). Period of flight 1455 to 1720 PST.
Figure 15. 500 mb map for 1600 PST on December 18, 1973. Location of flight (/////). Period of flight 1455 to 1720 PST.
Figure 16. Satellite mosaic photograph (visible) for December 18, 1973. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 17. Satellite mosaic photograph (IR night) for December 18, 1973. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
(c) **Airborne data:** A layer of cirrostratus (cirrostratus fibratus) was advancing from the west and lowering. The first airborne samples were taken at 17,000 ft. near the western end of the flight path in what appeared to be fall-streaks below the main cloud base of 18,000 ft. Tops were about 22,000 ft. at this location but were higher to the north and east. The cloud base was also rising in this direction.

Predominant crystals were bullets and columns. The ice mass concentration was highest in the fall-streaks (0.048 g m\(^{-3}\)); occasional droplets were sampled in the fall-streaks. In the main cirrostratus layer, ice mass concentrations ranged from 0.014 to 0.032 g m\(^{-3}\). The data are shown in Figures 18 and 19.

4.4 **January 2, 1974**

(a) **Flight location and time:** Airborne data was taken on a gradual climb from Seattle to Astoria (located at the mouth of the Columbia River) and on the return flight to Seattle. The period of the flight was 1124 to 1309 PST on January 2, 1974.

(b) **Synoptic situation (Figures 20 and 21):** A blocking ridge was situated off the Pacific Coast with a short-wave trough moving south in the northerly airstream. As the trough passed over Washington State it developed a closed circulation and the winds at 500 mb switched from northerly to easterly. The flight was made just ahead of the trough.

The visual satellite photograph taken at about 0900 PST over Washington (Figure 22) shows the bulk of the cloud east of the Cascade Mountains but there are some thin bands, oriented east-west, which extend west of the Cascades just ahead of the upper trough which was situated over the Washington-British Columbia border at the time of the satellite scan. By evening the infrared satellite photograph (Figure 23) shows the east-west bands had dissipated over Western Washington and moved off-shore.

(c) **Airborne data:** The flight consisted of a long climbing traverse to the southwest, almost perpendicular to the axis of the upper trough, and a descent back in the reverse direction. The cloud system had many layers,
Figure 18. Cross-section of flight path (→) from 1455 to 1720 PST on December 18, 1973, showing distribution of cloud (-----), sizes of largest particles collected (+ = 0.1 to 0.3 mm; X = 0.4 to 0.7 mm) and ice mass concentrations (in g m$^{-3}$) shown in boxes. Temperatures (in °C) and winds shown on the right-hand side are from the 1600 PST Quillayute rawinsonde. The presence of liquid water is shown by cross bars (-----) on the flight track.
Figure 19. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on December 18, 1973. M is the total ice mass concentration at each altitude.
Figure 20. Surface synoptic map for 1600 PST on January 2, 1974. Location of flight (\textbullet\textbullet\textbullet\textbullet\textbullet\textbullet\textbullet\textbullet\textbullet\textbullet). Period of flight 1124 to 1309 PST.
Figure 21. 500 mb map for 1600 PST on January 2, 1974. Location of flight (solid line). Period of flight 1124 to 1309 PST.
Figure 22. Satellite mosaic photograph (visible) for January 2, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 23. Satellite mosaic photograph (IR night) for January 2, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
generally increasing in height to the southwest. Although cloud tops were only 18,700 ft., temperatures were much lower than average (-34°C at tops) and the higher layers had the appearance of cirrostratus and occasionally cirrocumulus. The predominant crystal type was assemblages of columns.

Ice mass concentrations in the higher layers were in the range 0.02 to 0.08 g m⁻³. In the lower layers, a sample of 0.12 g m⁻³ was taken. No significant changes in crystal type were noticed between the cirrocumulus and stratified sections of the cloud. The data are shown in Figures 24 and 25.

4.5 January 8, 1974

(a) Flight location and time: This flight was from Seattle to Hoquiam, on the Pacific Coast, and back again to Seattle. The period of flight was 1204 to 1346 PST on January 8, 1974.

(b) Synoptic situation (Figures 26 and 27): A deep, almost stationary, upper ridge was situated off the Pacific Coast of Washington with a NNW airstream of 30 to 50 knots at 500 mb over Washington. A weak, short-wave trough moving south in the northerly airstream caused a series of upper level cloud bands to cross the State.

The morning visual satellite mosaic (Figure 28) shows widespread cloud east of the Cascades and a thin cloud layer (probably cirrus) over Western Washington. The evening infrared mosaic (Figure 29) does not show cirrus over Western Washington but some bands can be seen over Oregon, indicating that the cirrus was moving south fairly fast. The measurements described below were obtained near the northern edge of this band.

(c) Airborne data: The cloud bands consisted of cirrus, cirrostratus fibratus and then altostratus. Late in the day, a clearing occurred from the north. The first cloud encountered on the flight was thin altostratus at 13,000 to 15,500 ft. Further south, this cloud merged into the cirrostratus layers, which continued from 19,000 to 20,000 ft. The cirrostratus had ice mass concentrations in the range 0.12 to 0.026 g m⁻³.
Figure 24. Cross-section of flight path (---) from 1124 to 1309 PST on January 2, 1974, showing distribution of cloud (---), sizes of largest particles collected (+ = 0.1 to 0.3 mm; X = 0.4 to 0.7 mm) and ice mass concentration (in g m\(^{-3}\)) shown in boxes. No liquid water was detected. Temperatures (in °C) and winds shown on the right-hand side are from the 1600 PST Quillayute rawinsonde.
Figure 25. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on January 2, 1974. M is the total ice mass concentration at each altitude.
Figure 26. Surface synoptic map for 1600 PST on January 8, 1974. Location of flight (III...). Period of flight 1204 to 1346 PST.
Figure 27. 500 mb map for 1600 PST on January 8, 1974. Location of flight (H). Period of flight 1204 to 1346 PST.
Figure 28. Satellite mosaic photograph (visible) for January 8, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 29. Satellite mosaic photograph (IR night) for January 8, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
Above the cirrostratus was a thinner cirrus layer (cirrus fibratus) from 20,000 to 21,000 ft. Ice mass concentrations were lower in this layer (0.04 to 0.07 g m\(^{-3}\)). Thin scattered cirrus uncinus was observed above at about 23,000 ft. In both the cirrus fibratus and cirrus uncinus the predominant crystals were assemblages of columns which were up to 1 mm in maximum dimensions in the lower cirrostratus layer and 0.5 mm in the cirrus layer. The data are displayed in Figures 30 and 31.

4.6 **January 23, 1974**

(a) **Flight location and time**: An orbiting climb was made over the northern slopes of the Olympic Mountains followed by a traverse back to Seattle. The period of the flight was 1243 to 1417 PST on January 23, 1974.

(b) **Synoptic situation** (Figures 32 and 33): A strong west to northwest airstream was over the State of Washington with remnants of an occluded front over the northwestern portion of the State.

The morning visual satellite mosaic (Figure 34) shows that the dying front still had an extensive cloud band associated with it. The measurements described below were made in this band quite close to the surface front. By evening the infrared satellite mosaic (Figure 35) shows that the frontal band had weakened and merged with another band of cloud to the north associated with a strong WSW flow.

(c) **Airborne data**: The clouds sampled were more a deep altostratus layer, rather than cirrostratus. Tops were at 19,500 ft. (-16°C) and water droplets were occasionally present. Thin wisps of cirrus (cirrus fibratus) were visible above the main layer. A CPS sample taken near the cloud top showed 0.07 g m\(^{-3}\) liquid water and 0.3 g m\(^{-3}\) of ice. The ice was mainly in the form of heavily-rimed particles (0.5 to 1.7 mm in diameter). The accuracy of these measurements is probably not very good due to the small number of particles counted. However, the liquid water value agrees well with that recorded by the Johnson-Williams hot-wire liquid water meter which was fluctuating about 0.05 g m\(^{-3}\). Rimed particles and aggregates to 4 mm in maximum dimensions were present in the lower parts of the cloud deck. The results are summarized in Figures 36, 37 and 38.
Figure 30. Cross-section of flight path (→→) from 1204 to 1346 PST on January 8, 1974, showing distribution of cloud (►►►), sizes of largest particles collected (+ = 0.1 to 0.3 mm; X = 0.4 to 0.7 mm; * = 0.8 to 1.5 mm) and ice mass concentration (in g m⁻³) shown in boxes. No liquid water was detected. Temperatures (in °C) and winds shown on the right-hand side are from the 1600 PST Quillayute rawinsonde.
Figure 31. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on January 8, 1974. \( M \) is the total ice mass concentration at each altitude.
Figure 32. Surface synoptic map for 1600 PST January 23, 1974. Location of flight (□□□□□). Period of flight 1243 to 1417 PST.
Figure 33. 500 mb map for 1600 PST January 23, 1974. Location of flight ( ). Period of flight 1243 to 1417 PST.
Figure 34. Satellite mosaic photograph (visible) for January 23, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 0300 PST.
Figure 35. Satellite mosaic photograph (IR night) for January 23, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
Figure 36. Cross-section of ascending part of flight path (---) from 1243 to 1415 PST on January 23, 1974, showing areas of cloud (****), sizes of largest particles collected (\( \pm \) = 0.1 to 0.3 mm; \( \times \) = 0.4 to 0.7 mm; \( \star \) = 0.8 to 1.5 mm; \( \star \star \) = > 1.5 mm). The presence of liquid water is shown by cross bars on the flight track (-----), with values (in g m\(^{-3}\)) shown alongside temperatures (in °C) and winds shown on the right-hand side are from the 1600 PST Quillayute rawinsonde.
Figure 37. Cross-section of descending part of flight path (-----) from 1417 to 1500 PST on January 23, 1974, showing areas of cloud (-----) and sizes of largest particles collected (X = 0.4 to 0.7 mm; * = 0.8 to 1.5 mm; ** = > 1.5 mm). The presence of liquid water is shown by cross bars on the flight track (-----) with values (in g m\(^{-3}\)) shown alongside.
Figure 38. Plot of ice mass concentrations (×) and liquid water concentrations (○) against particle maximum dimensions for January 23, 1974 at 19,500 ft. (-16°C). Total ice mass M and total liquid water content L are also shown.
4.7 January 30, 1974

(a) **Flight location and time:** The climb to altitude was made sixty nautical miles north of Seattle. This was followed by a seventy-five nautical mile traverse to the south over the crest of the Cascade Mountains. The period of the flight was 1021 to 1242 PST on January 30, 1974.

(b) **Synoptic situation (Figures 39 and 40):** A strong (50 to 90 knots at 500 mb) westerly airstream was present as a fast-moving, short-wave ridge approached Washington State. A weak cold front was aligned almost east-west over Oregon. Thicker cloud was present to the south and east of the flight track.

The morning visual satellite mosaic (Figure 41) shows a cloud deck over Washington State with some breaks over the Cascade Mountains south of Snoqualmie Pass. However, at the time of the flight, conditions had changed considerably and breaks were observed in the clouds to the north with thicker clouds to the south and east. The evening satellite mosaic (Figure 42) shows breaks in the clouds in different positions again. The main cloud mass was advecting from west to east but the smaller clear patches showed no regular movements.

(c) **Airborne data:** The clouds consisted of lower stratocumulus layers and an altostratus deck with the cloud base rising to the north. The altostratus merged into a cirrostratus deck and layers of thin cirrus and cirrostratus were present above 25,000 ft. Water droplets predominated in the tops of the altostratus with one CPS sample showing a liquid water content of 0.036 g m⁻³ and an ice mass concentration of 0.012 g m⁻³. Ice crystals in this layer were mainly rimed assemblages of columns. In the higher cirrostratus layer, the ice crystals were almost all below 200 μm in maximum dimension. Single columns predominated. Two samples showed ice mass concentrations of 0.014 and 0.031 g m⁻³. In the lower levels the ice crystals were still predominantly single columns but some assemblages of plates and columns were observed. The ice mass concentration had risen to 0.18 g m⁻³ at 19,000 ft. The data are shown in Figures 43 and 44.
Figure 39. Surface synoptic map for 1600 PST on January 30, 1974. Location of flight ( ). Period of flight 1021 to 1242 PST.
Figure 40. 500 mb map for 1600 PST on January 30, 1974. Location of flight (□□□□). Period of flight 1021 to 1242 PST.
Figure 41. Satellite mosaic photograph (visible) for January 30, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 42. Satellite mosaic photograph (IR night) for January 30, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
Figure 43. Cross-section of flight path (---) from 1021 to 1202 PST on January 30, 1974, showing areas of cloud (-----), sizes of largest ice particles collected (+ = 0.1 to 0.3 mm; \( \times \) = 0.4 to 0.7 mm) and ice mass concentrations (in g m\(^{-3}\)) in boxes. The presence of liquid water is shown by cross bars on the flight track (-----), values (in g m\(^{-3}\)) are shown alongside. Temperatures (in °C) and winds shown on the right-hand side are from the 1600 PST Quillayute rawinsonde.
Figure 44. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on January 30, 1974. M is the total ice mass concentration at each altitude.
4.8 February 20, 1974

(a) Flight location and time: This flight was made near Durango, Colorado, over the southern slopes of the San Juan Mountains. The period of flight was 1139 to 1300 Mountain Standard Time (MST) on February 20, 1974.

(b) Synoptic situation (Figures 45 and 46): A deep upper-level trough was passing over Colorado with the 500 mb winds switching from southwest to northwest during the day. The surface depression was moving rapidly into Texas at the time of the flight. The morning visible satellite mosaic (Figure 47) showed an extensive layer of cloud over Colorado. By evening the cloud was broken with the main band over Texas and Oklahoma (Figure 48).

(c) Airborne data: The lower cloud to the south of the San Juan Mountains was breaking up at the time of the flight as winds backed to northwesterly leaving broken layers at various altitudes. The cloud top temperature was -25°C. Ice crystal types included assemblages of columns and plates and some aggregates. Ice mass concentrations were fairly high, reaching to 0.9 g m⁻³, mainly because of the existence of large crystals or aggregates in significant concentrations. The experimental data are summarized in Figures 49 and 50.

4.9 March 2, 1974

(a) Flight location and time: The aircraft flew southeast from Durango, Colorado, and then passed over the crest of the Chuska Mountains in northwestern New Mexico. The period of the flight was 1029 to 1243 MST on March 12, 1974.

(b) Synoptic situation (Figures 51 and 52): An upper level ridge was present over the Western States; a weak, short-wave trough moved through this ridge over Utah and Arizona. Winds at the 500 mb level, in the vicinity of the flight path, were WSW at 20-25 knots. The evening infrared satellite photograph shows scattered cirrus clouds over Colorado (Figure 53).

(c) Airborne data: Radiosonde data showed a very dry atmosphere up to 450 mb (21,000 ft.) with a fairly deep moist layer above. Clouds were sampled from the aircraft over the Chuska Mountains; the latter apparently
Figure 45. Surface synoptic map for 1700 MST February 20, 1974. Location of flight (H). Period of flight 1139 to 1300 MST.
Figure 46. 500 mb map for 1700 MST February 20, 1974. Location of flight (■ ■ ■ ■). Period of flight 1139 to 1300 MST.
Figure 47. Satellite mosaic photograph (visible) for February 20, 1974. The segment of mosaic which includes Colorado was taken at approximately 0900 MST.
Figure 48. Satellite mosaic photograph (IR night) for February 20, 1974. The segment of the mosaic which includes Colorado was taken at approximately 2200 MST.
Figure 49. Cross-section of flight path (—) from 1139 to 1300 MST on February 20, 1974, showing areas of cloud ([][][]), sizes of largest particles collected (+0.1 to 0.3 mm; X 0.4 to 0.7 mm; @ 0.8 to 1.5 mm) and ice mass concentrations (in g m⁻³) in boxes. The presence of liquid water is shown by cross bars on the flight track (—). Values (in g m⁻³) are shown alongside. The temperatures shown on the right-hand side are from the Durango 1150 MST radiosonde.
Figure 50. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on February 20, 1974. M is the total ice mass concentration at each altitude.
Figure 51. Surface synoptic map for 1700 MST March 12, 1974. Location of flight (H H H). Period of flight 1029 to 1243 MST.
Figure 52. 500 mb map for 1700 MST March 12, 1974. Location of flight (■■■■). Period of flight 1029 to 1243 MST.
Figure 53. Satellite mosaic photograph (IR night) for March 12, 1974. The segment of the mosaic which includes Colorado was taken at approximately 2200 MST.
enhanced cloud development by orographic lifting. The satellite mosaic that evening (Figure 53) showed cloud patches generally aligned NE to SW over the flight path. A wave cloud, possibly with some water droplets but largely glaciated, was encountered at 21,300 ft. and showed the highest ice mass concentration of $0.12 \text{ g m}^{-3}$ (see Figure 54). Samples in higher layers showed much lower ice mass concentration. The almost singular concentration of ice mass in the 500 to 1500 $\mu$m size range in the lowest-level sample (Figure 55) is also worthy of note. The predominant types of ice crystals were assemblages of columns and plates and single columns.

4.10 March 26, 1974

(a) **Flight location and time:** The aircraft climbed to altitude over the crest of the San Juan Mountains in Southern Colorado. The period of the flight was 1414 to 1630 MST on March 26, 1974.

(b) **Synoptic situation (Figures 56 and 57):** A broad upper-level ridge was present over the Mountain States, with a weak short-wave trough approaching Colorado from the west. Bands of cirrus and cirrostratus developed and appeared to be enhanced by wave motion over the San Juan Mountains. Winds at the 500 mb level were southwesterly at 30 knots.

The evening infrared satellite mosaic (Figure 58) shows scattered cirrus clouds over Colorado ahead of a well-defined cloud band over the western part of the State. This band was associated with a dying surface front which had been dropped from the surface synoptic chart that morning. The flight was made in the broken bands ahead of the main cloud band.

(c) **Airborne data:** The thickest cloud was found near the crest of the San Juan Mountains. Fall streaks extended down to 22,000 ft. with thicker cloud above 23,000 ft. Ice crystals were predominantly assemblages of columns. Ice mass concentrations were in the range $0.22$ to $0.29 \text{ g m}^{-3}$. The data are summarized in Figures 59 and 60.
Figure 54. Cross-section of flight path (----) across wind direction between 1029 and 1243 MST on March 12, 1974, showing areas of cloud (**********), sizes of largest particles sampled, (+ = 0.1 to 0.3 mm; X = 0.4 to 0.7 mm), and ice mass concentrations (in g m\(^{-3}\)) in boxes. The presence of liquid water is shown by cross bars on the flight track (---). Temperatures and winds shown on the right-hand side are from the Durango 1100 MST rawinsonde.
Figure 55. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on March 12, 1974. M is the total ice mass concentration at each altitude.
Figure 56. Surface synoptic situation at 1700 MST on March 26, 1974. Location of flight (---). Period of flight 1414 to 1630 MST.
Figure 57. 500 mb map for 1700 MST on March 26, 1974. Location of flight (H H H H). Period of flight 1414 to 1630 MST.
Figure 58. Satellite mosaic photograph (IR night) for March 26, 1974. The segment of the mosaic which includes Colorado was taken at approximately 2200 MST.
Figure 59. Cross-section of flight path (--->) from 1414 to 1630 MST on March 26, 1974, showing areas of cloud (-----), sizes of largest particles (\( \times \) = 0.8 to 1.5 mm) and ice mass concentrations (in g m\(^{-3}\)) in boxes. The presence of liquid water is shown by cross bars on the flight track (----), with values (in g m\(^{-3}\)) shown alongside. Temperatures and winds shown on the right-hand side are from the Durango 1710 MST rawinsonde.
Figure 60. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on March 26, 1974. M is the total ice mass concentration at each altitude.
4.11 April 4, 1974

(a) **Flight location and time:** The aircraft climbed west of Seattle, Washington, over the Olympic Mountains. The period of the flight was 1326 to 1639 PST.

(b) **Synoptic situation (Figures 61 and 62):** An upper ridge was situated over Washington State with a depression well-off the Pacific Coast and a dissipating surface warm front approaching from the southwest. Winds at the 500 mb level were about 50 knots from the southwest. Satellite photographs were not available for this day.

(c) **Airborne data:** Samples of cloud particles were collected over the Olympic Mountains. The cloud was continuous from about 6,000 ft. to diffuse tops at 23,000 ft. (-30°C), with wispy higher cirrus above (see Figure 63). Ice crystals in the higher clouds included assemblages of columns, combinations of columns and plates, and individual columns and bullets. Lower cloud layers contained mainly plate-like ice crystals. Ice mass concentrations generally decreased with increasing altitude (see Figure 64). The highest ice mass concentration above 600 mb was 0.12 g m⁻³.

4.12 April 17, 1974

(a) **Flight location and time:** The aircraft climbed to cloud tops over the western slopes of the Olympic Mountains and then made a slow descent to Seattle. The period of the flight was 1449 to 1715 PST on April 17, 1974.

(b) **Synoptic situation (Figures 65 and 66):** A deepening upper trough was situated off the Pacific Coast with a dissipating cold front about 300 miles off-shore. Winds at the 500 mb level were south-westerly at 20 to 40 knots. Satellite photographs were not available for this day.

(c) **Airborne data:** Layers of altostratus and cirrostratus clouds were sampled over the Olympic Mountains. Falling ice crystals were encountered at about 13,000 ft. with more solid cloud at about 18,000 ft. (see Figure 67). Stellar ice crystals were encountered in the lower ice fall but the upper part of the cloud consisted of columns, bullets and assemblages of columns. Cloud tops were at 24,000 ft. (-36°C). Ice
Figure 61. Surface synoptic situation for 1600 PST on April 4, 1974. Location of flight ( ). Period of flight 1326 to 1639 PST.
Figure 62. 500 mb map for 1600 PST on April 4, 1974. Location of flight ( ). Period of flight 1326 to 1639 PST.
Figure 63. Cross-section of flight path (→←→) from 1326 to 1639 PST on April 4, 1974, showing areas of cloud (●●●●●●), sizes of largest particles (+ = 0.1 to 0.3 mm; X = 0.4 to 0.7 mm; * = 0.8 to 1.5 mm, * = > 1.5 mm) and ice mass concentrations (in g m⁻³) in boxes. The presence of liquid water is shown by cross bars (↔↔↔) on the flight track, with values (in g m⁻³) alongside. Temperatures shown on the right-hand side (in °C) are from the Quillayute 1600 PST rawinsonde.
Figure 64. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on April 4, 1974. M is the total ice mass concentration at each altitude.
Figure 65. Surface synoptic situation for 1600 PST on April 17, 1974. Location of flight (H). Period of flight 1449 to 1715 PST.
Figure 66. 500 mb map for 1600 PST on April 17, 1974. Location of flight (□□□□□□). Period of flight 1449 to 1715 PST.
Figure 67. Cross-section of flight path (---) from 1449 to 1715 PST on April 17, 1974, showing areas of cloud (****), sizes of largest particles collected (+ = 0.1 to 0.3 mm; \( \times \) = 0.4 to 0.7 mm; \( \ast \) = 0.8 to 1.5 mm; \( \# \) = > 1.5 mm) and ice mass concentrations (in g m\(^{-3}\)) in boxes. No liquid water was detected on this flight. Temperatures (in \( ^{\circ}\)C) and winds on the right-hand side are from the Quillayute 1600 PST rawinsonde.
mass concentrations were generally low, the highest being 0.08 g m$^{-3}$ (see Figure 68). Ice mass concentrations may have been greater in the falling ice region but the CPS data were unsatisfactory in this region.

4.13 May 17, 1974

(a) **Flight location and time:** The aircraft climbed to altitude over the western slopes of the Cascade Mountains, Washington, and then traversed west to Seattle. The period of the flight was 1203 to 1442 PST on May 17, 1974.

(b) **Synoptic situation (Figures 69 and 70):** An upper-level cold low was over the Pacific Northwest with east to northeast winds over Washington State. Cumulus clouds developed predominantly over the eastern slopes of the Cascade Mountains. The cellular cloud is apparent in the morning satellite mosaic (Figure 71); a clearer area is apparent over Western Washington. The evening infrared mosaic (Fig. 72) shows what are probably spread out cumulonimbus tops.

(c) **Airborne data:** Some smaller cumulus clouds were penetrated during the ascent followed by a layer of altostratus and then cirrostratus which was apparently blowing over from cumulominbus clouds on the eastern side of the Cascade Mountains. Embedded cumulus were also encountered while climbing. Some patches of frozen droplets were sampled at temperatures of -34 to -35°C. Crystal types included columns, bullets, assemblages of plates and columns, and isolated stellaris. Occasional riming occurred. Ice mass concentrations were variable but frequently high, up to 0.9 g m$^{-3}$. The data are shown in Figures 73 and 74.

4.14 July 15, 1974

(a) **Flight location and time:** The aircraft climbed out of Seattle on an easterly heading and reached cirrus clouds about 120 nautical miles east of Seattle just east of the Columbia River. The period of the flight was 1317 to 1537 PST on July 15, 1974.

(b) **Synoptic situation (Figures 75 and 76):** A deep upper-level trough was located off the Pacific Coast of Washington with a southwesterly airstream of 50 to 70 knots over Washington State. A band of cirrus-cloud,
Figure 68. Plot of ice concentrations against maximum dimensions of ice particles at different altitudes for flight made on April 17, 1974. $M$ is the total ice mass concentration at each altitude.
Figure 69. Surface synoptic map for 1600 PST on May 17, 1974. Location of flight (□□□□□). Period of flight 1203 to 1442 PST.
Figure 70. 500 mb map for 1600 PST on May 17, 1974. Location of flight ( ). Period of flight 1203 to 1442 PST.
Figure 7. Satellite mosaic photograph (visible) for May 17, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 72. Satellite mosaic photograph (IR night) for May 17, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
Figure 73. Cross-section of flight path (—→—) from 1203 to 1442 PST on May 17, 1974, showing areas of cloud (⊗⊗⊗⊗), sizes of largest particles collected (+ = 0.1 to 0.3 mm; X = 0.4 to 0.7 mm; X = 0.8 to 1.5 mm) and ice mass concentrations (in g m⁻³) in boxes. The presence of liquid water is denoted by cross bars on the flight track (—-nil—), with values (in g m⁻³) alongside. Temperatures (in °C) shown on the right-hand side are from aircraft data.
Figure 74. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on May 17, 1974. M is the total ice mass concentration at each altitude.
Figure 75. Surface synoptic map for 1600 PST on July 15, 1974. Location of flight (-----). Period of flight 1317 to 1537 PST.
Figure 76. 500 mb map for 1600 PST on July 15, 1974. Location of flight ( ). Period of flight 1317 to 1537 PST.
thickening into altostratus, crossed Western Washington during the morning. Some precipitation occurred. This band can be seen in the morning visible satellite mosaic (Figure 77). The cloud band was intercepted by the aircraft over Eastern Washington where it had dissipated considerably and consisted of a cirrus band from 20,000 to 24,000 ft. The evening infrared mosaic (Figure 78) does not contain this band.

(c) **Airborne data:** Measurements were obtained in the cirrus uncinus cloud. The lower CPS samples were taken in fall streaks. The highest ice mass concentration was $0.12 \text{ g m}^{-3}$ which occurred in one of the generating cells. The predominant ice crystal types were plate-like assemblages with some assemblages of columns and some single columns. The data are shown in Figures 79 and 80.

5. **TOTAL ICE MASS CONCENTRATIONS, ICE PARTICLE NUMBER CONCENTRATIONS AND AVERAGE ICE PARTICLE MASSES IN CIRRUS CLOUDS**

The continuous Formvar particle sampler provides fairly reliable measurements on the total ice mass concentration but less reliable data on the number concentrations of ice particles (see §3). On the other hand, the University of Washington's optical ice particle counter provides fairly reliable measurements on the number concentration of ice particles in the air but no information on the sizes or masses of the ice particles. By combining simultaneous data obtained from these two instruments, the average mass of the ice particles in a cloud sample may be deduced.

Listed in Table 3 are the measurements of ice mass concentrations and ice particle number concentrations obtained in the present study. Shown in Figure 81 are the datum points for those cases where simultaneous measurements were made of ice mass concentration and ice particle number concentration. The corresponding values of the average ice particle masses appear as a set of straight lines on this plot. If it is assumed that the ice particles consist of solid columns, a mean column length can be associated with each mean mass; these values are shown in brackets in Figure 81. While the data show considerable scatter, it is interesting to note that low number concentrations of ice particles are generally associated with low ice mass concentrations and high number concentrations with high mass concentrations. In other words,
Figure 77. Satellite mosaic photograph (visible) for July 15, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 0900 PST.
Figure 78. Satellite mosaic photograph (IR night) for July 15, 1974. The segment of the mosaic which includes Western Washington was taken at approximately 2200 PST.
Figure 79. Cross-section of flight path (---) from 1317 to 1537 PST on July 15, 1974, showing areas of cloud (::::::), sizes of largest particles sampled (+ = 0.1 to 0.3 mm; \(X\) = 0.4 to 0.7 mm; \(\bigtriangleup\) = 0.8 to 1.5 mm) and ice mass concentrations (in g m\(^{-3}\)) in boxes. No liquid water was detected on this flight. Temperatures shown on the right-hand side are from the Spokane 1600 PST rawinsonde.
Figure 80. Plot of ice mass concentrations against maximum dimensions of ice particles at different altitudes for flight made on July 15, 1974. M is the total ice mass concentration at each altitude.
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<th>CPS Run Number</th>
<th>Altitude (in 1000's of feet)</th>
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ₕ On April 4 and April 17, a decelerator was used on the CPS, therefore, ice masses are probably underestimated.
Figure 81. Ice mass concentrations (from CPS data) and ice particle number concentrations (from optical particle counter data) for all available cirrus samples. The mean ice particle masses (in µg) are shown together with their mean length (assuming the particles are solid columns).
extreme cases of very many very small ice particles or a few very massive ice particles appear to be uncommon in cirrus clouds.

6. RELATIONSHIP BETWEEN ICE MASS CONCENTRATIONS IN CIRRUS CLOUDS AND AIR TEMPERATURES

Shown in Figure 82 are measurements of total ice mass concentrations in clouds plotted against the air temperature at which the particles were collected. Despite the wide scatter in the results (and the lower limit values for the total ice mass concentration in fact extend down to zero), the following important points can be seen from these results:

(i) The total ice mass concentration tends to increase with increasing cloud temperature.

(ii) The upper limit to the total ice mass concentration at any temperature generally does not exceed the saturated water vapor content. (The only significant exception to this rule was a case where the cirrus originated from a cumulonimbus cloud.) The maximum value of the total ice mass concentration $M_{\text{max}}$ (in g m$^{-3}$) in cirrus clouds based on this result is given approximately by:

$$\log_{10} M_{\text{max}} = 1 + 0.045 t_c$$

where, $t_c$ is the air temperature in °C.

The variations in total ice mass concentration at any given temperature, from near zero to the upper limit value given by the above equation, is no doubt due to variations in vertical air velocities. It can be seen, for example, that the maximum measured total ice mass concentrations tend to fall away from the water saturation curve at lower temperatures. This is probably because the vertical velocities in these low temperature and high altitude clouds were not as great as in the lower (warmer) clouds. The addition of vertical air motion measurements should lead to an empirical equation which gives the actual ice mass concentration in a cirrus cloud as a function of the cloud temperature and the vertical velocity of the air. Work is now underway to obtain these measurements.

* Obtained by replacing the slightly curved solid line in Figure 82 by a straight line (shown dotted in Figure 82).
Figure 82. Measurements of total ice mass concentrations in clouds against temperature at which sample was collected (+ - University of Washington results; O - Meteorology Research Inc. results).
References


Appendix

The Utility of the Knollenberg Axially Scattering Spectrometer Probe in Cirrus Cloud Studies

Since November 1973 a Knollenberg Axially Scattering Spectrometer Probe (ASSP)* has been mounted on the University of Washington's B-23 aircraft. The probe is essentially a laser forward-scattering device designed to measure the number/size distribution of cloud droplets between 3 and 45 μm in diameter. The droplets are size discriminated into 15 ranges (channels) plus one channel for the total number of particles larger than 45 μm.

It was hoped that this device might have some utility in counting the total concentration of ice particles in cirrus clouds (the size discriminating ability of the device would not, in general, be applicable to ice particles). However, comparisons of the data with those from the continuous Formvar particle sampler (CPS) and the University of Washington's optical ice particle counter have shown the ASSP may give substantial overestimates of the total concentrations of ice particles in clouds.

Figure A.1 shows histograms of particle size distributions from the ASSP

Figure A.1 A comparison of the Axially Scattering Spectrometer Probe (ASSP), the Continuous Particle Sampler (CPS), and the Optical Ice Particle Counter (OIPC) in cirrus clouds on April 4, 1974. Column A is the concentration ($cm^{-3}$) of particles 3 to 45 $\mu$m from the ASSP, column B is the concentration ($\mu^{-1}$) of particles > 45 $\mu$m from the ASSP, column C is the concentration ($\mu^{-1}$) of particles from the CPS, column D is the concentration ($\mu^{-1}$) of particles from the OIPC. The data suggest that the ASSP gave erroneous results under these conditions.
(together with measurements of the total concentrations of particles from this
device), the CPS and the optical ice particle counter, obtained in one study of
pre-frontal cirrus. The histograms were taken over a twenty-three minute
period at cloud top temperatures from -23 to -29°C. In examining this figure
the CPS record should be noted first. CPS samples were taken simultaneously
with the 3rd and 5th histogram. Both of these samples show the cirrus cloud
to be composed entirely of ice particles up to 300 μm in maximum dimensions
and with a lower-size limit of from 50 to 80 μm. The concentrations deduced
from the CPS are in good agreement with those measured by the optical ice
particle counter and are on the order of a few tens per liter. By contrast
the ASSP recorded a total concentration on the order of several thousands per
liter with an over-range (> 45 μm) count of several hundred per liter.

Our experience with the ASSP suggests that these erroneous results are a
special-case failure and do not invalidate the use of the ASSP for its intended
purpose, namely, the counting of droplets from 3 to 45 μm. Indeed, our own
in-house calibration of the ASSP with uniform glass spheres shows good
correspondence with the manufacturer's specifications. Also, measurements we
have obtained with the ASSP in droplet clouds and in aerosol measurements show
satisfactory agreement with other techniques.

It appears that the ASSP fails to provide a reliable measurement of the
concentration of ice particles in cirrus clouds because large irregular particles
(~200 μm) cause scintillations which, coupled with the counter's short dead-
time, result in multiple counting. This would produce spurious data whenever
large particles are present. However, the error only becomes significant when
the concentration of small particles is low (less than 50 cm⁻³). Fig. A.1
shows that the total spurious count (on the order of 1 cm⁻³) would be
insignificant compared to the normal droplet concentrations in warm phase clouds.