University of Washington
Department of Atmospheric Sciences
Seattle, Washington 98195

CONTRIBUTIONS FROM
THE CLOUD PHYSICS GROUP

RESEARCH REPORT VI

Studies of Winter Cyclonic Storms
Over the Cascade Mountains (1970-71)

by

Peter V. Hobbs, L. F. Radke, A. B. Fraser,
J. D. Locatelli, C. E. Robertson, D. G. Atkinson,
R. J. Farber, R. R. Weiss, and R. C. Easter
(with an Appendix by K. R. Hardy)

December 1971
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td></td>
<td>i</td>
</tr>
<tr>
<td>Abstract</td>
<td></td>
<td>ii</td>
</tr>
<tr>
<td>Section 1</td>
<td>The B-23 Cloud Physics Research Aircraft and Airborne Instrumentation</td>
<td>1</td>
</tr>
<tr>
<td>Section 2</td>
<td>Ground Instrumentation and Procedures</td>
<td>35</td>
</tr>
<tr>
<td>Section 3</td>
<td>A Theoretical Model for Orographic Precipitation</td>
<td>48</td>
</tr>
<tr>
<td>Section 4</td>
<td>Airborne Observations and Measurements</td>
<td>92</td>
</tr>
<tr>
<td>Section 5</td>
<td>Some Results from the Ground Observations</td>
<td>142</td>
</tr>
<tr>
<td>Section 6</td>
<td>Some Case Studies of Artificial Seeding</td>
<td>191</td>
</tr>
<tr>
<td>Section 7</td>
<td>Radar Development and Studies</td>
<td>254</td>
</tr>
<tr>
<td>Appendix</td>
<td>Characteristics of a Weather Radar for the Investigation of Precipitation in the Pacific Northwest</td>
<td>268</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>301</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td></td>
<td>306</td>
</tr>
</tbody>
</table>
PREFACE

This report is the fourth in a series describing our studies of winter cyclonic storms, orographic clouds, and precipitation over the Cascade Mountains of Washington State (the "Cascade Project"). The present report covers work carried out during 1970-71. During this period simultaneous airborne, ground and radar observations were made in a number of different synoptic situations, and investigations into the effects on clouds and precipitation of seeding with artificial ice nuclei were continued. Progress was also made in developing a theoretical model to describe the flow of air over the Cascade Mountains and the growth and fall-out of precipitation from orographic clouds.

Peter V. Hobbs
Director, Cloud Physics Group
University of Washington
ABSTRACT

In the first section of this report a description is given of the research aircraft and airborne instrumentation used in the Cascade Project. This facility provides us with the capability of tracing cloud microphysical processes from the nucleation of cloud particles through to the production of precipitation. Of particular interest is a new instrument for the automatic counting of ice particles in mixed clouds, and devices for decelerating cloud and precipitation particles prior to collection in order to reduce fragmentation. With the aid of the latter devices we are able to collect and replicate intact ice crystals up to several millimeters in size from an aircraft flying at 120 mph.

The network of ground stations, instruments, and observations utilized in the Cascade Project is described in §2. The reliability of some of the ground techniques is also discussed in this section.

Section 3 of the report contains a detailed description of a theoretical model for the formation of orographic clouds and precipitation. Equations are derived for the flow of dry and cloudy air over a long (2 dimensional) ridge. The profile of the ridge can be changed, depending on the direction of the wind, to approximate to that of the Cascade Mountains. Using the airflow model, and equations for the growth of ice particles by deposition from the vapour phase and accretion, the trajectories of solid precipitation particles can be predicted from an upwind sounding of wind, temperature and humidity. The effects of changing the concentrations of ice particles on the trajectories of precipitation particles and the distribution of precipitation on the ground are considered.
The microstructure of the clouds and the types of cloud and precipitation particles observed in aircraft flights over the Cascade Mountains are summarized in §4. In pre-frontal conditions the winds near the surface over the western slopes of the Cascade Mountains are easterly and produce drying conditions, but from about 6000 to 12000 feet the air is moist and from the southwest. Over the eastern slopes, the low level easterly winds produce orographic clouds. Ice particles dominate over water droplets in the pre-frontal clouds and above the -10°C level riming is rare. However, the crystals often become rimed in falling from about 5,000 ft. to the ground. In post-frontal conditions the air is more unstable, the winds are westerly at all levels, and the cloud tops decrease in height. Rimming is common and graupel particles are observed. In the absence of frontal activity, but in strong westerly airstreams, extensive orographic clouds form over the Cascade Mountains. On average, the liquid water content in clouds over the Cascades reaches a peak value about 13 nautical miles west of the divide and a minimum value at about 15 nautical miles east of the divide. Details on the types of ice particles collected from the aircraft are also given in §4, and the role of ice crystal fragmentation in clouds is discussed.

Observations made at the ground stations in the Cascade Project during the winter of 1970-71 are described in §5 and details are given on the types, sizes and characteristics of the precipitation particles in different synoptic conditions. The observations indicate that most of the riming occurs below about 9,000 ft. and that riming is heavier in post-frontal than in pre-frontal situations. The degree of riming increases with increasing wind speed and water content at the 10,000 ft. level. At the crest of the Cascades the
rate of precipitation increased with increased riming but at stations on the eastern slopes the reverse may hold. Stations on the west side of the Cascades generally receive more precipitation than those on the east side but this difference is usually much greater in post-frontal conditions.

Trajectories are deduced for the solid precipitation particles in several situations. The smaller crystals often originate in clouds situated many tens of miles upwind of the point at which they eventually reach the ground. In the presence of strong easterly winds near the surface, but westerly winds at higher levels, the particles often originate west of the divide, are carried across the divide, and then return to near the divide on the easterly winds before reaching the ground. Some implications of these results on the possible effects of artificial seeding on precipitation are given.

In §6 four case studies are described in which clouds were seeded with silver iodide from the aircraft for short periods of time in an attempt to modify their structure and change the nature of the precipitation downwind over a small predetermined area. In two of the cases effects attributable to the artificial seeding were detected at ground level in the target area, in the third case the clouds appeared to be completely glaciated by the seeding, and in the fourth case no marked effects on precipitation were detected in the target area but at one of the ground stations there was a significant increase in the concentrations of freezing nuclei following the artificial seeding.

A small CW Doppler radar was built and operated in the Cascade Project during 1970-71. This radar is described in §7 and some of the data obtained are presented.
In an Appendix to the report, the characteristics of a suitable radar for general investigations of precipitation in the Pacific Northwest of the United States are described. Because of the nature of the precipitation and the requirement of high spatial resolution, it is suggested that a 5-cm radar with a beamwidth of about 0.5° is the best choice. Such a radar should be capable of providing quantitative information on radar reflectivity and could be used for synoptic, hydrological, cloud physics and weather modification investigations.
1.1 Introduction

After searching for several years for a suitable aircraft for cloud physics research, during which time we rented several aircraft currently being used for research of this kind and carefully assessed their capabilities (Hobbs and Ryan, 1969; Hobbs et al., 1970), we finally located what appeared to be the ideal aircraft for our purpose. This was a Douglas B-23 "Dragon" converted for civilian use by Hughes Aircraft Co. (Fig. 1.1).

A total of thirty-eight B-23's were built about thirty years ago and these received limited use during World War II. More than twenty of these were subsequently converted for civilian use and about ten of these are still flying. Our B-23 (N52327) was purchased from an oil company which had used it as an executive aircraft for many years and maintained it in excellent condition.

In appearance the B-23 is somewhat similar to the Douglas DC-3, however, its fuselage is much slimmer and it has a taller vertical stabilizer. The aircraft has two large R2600 engines. As a result, the B-23 has many of the outstanding features of the well-proven DC-3 but it is more rugged, can fly higher and faster, has a stall speed as low as 55 kts. The aircraft has complete navigational and communication equipment, propeller and leading edge de-icing gear, and a 5 cm weather radar. Further details on the aircraft are listed in Table 1.1.
TABLE 1.1
SOME TECHNICAL SPECIFICATIONS FOR THE B-23 AIRCRAFT

Engines:
Two Wright R2600-23
Take-off: 1,600 H.P. each
Meto: 1,350 H.P. each

Weight:
Empty: 21,500 lb.
Useful load: 6,000 lb.

Flight endurance:
Maximum: 10 hours
Typical: 6 "

Airspeeds:
Maximum: 250 kts
Cruise: 120 "
Minimum in level flight with no loss in altitude: 59 kts
Stall: 55 kts

Climb:
Meto power at gross weight: 1,600 ft/min.
Normal climb to 10,000 ft.: 350 " "

Ceilings:
With low blowers 25,000 ft.
With high blowers: 32,000 " (estimated)
Single engine with low blower: 13,000 ft.
TABLE 1.1 (continued)

**De-icing gear:**
- Hydraulic boots on all leading edges
- Alcohol de-icers on propellers

**Avionics:**
- Radios
- Dual very high frequency omnirange (VOR)
- Distance measuring equipment (DME)
- Sperry flight director
- Transponder
- Automatic direction finders (ADF)

**Electrical power:**
- For aircraft operation: 8400 W, 28V dc (300 A)
- 3000 W, 115V, 400 Hz (rotary inverter)
- For research instruments.
  - Total available: 8400 W, 28V dc (300 A)
  - May be distributed as follows: 1000 W, 115V, 60 Hz (rotary inverter)
  - 1000 W, 115V, 60 Hz (""
  - 1500 W, 115V, 400 Hz (""
  - 2600 W, 28V dc.
In extensive flying under severe conditions in cyclonic storms over the Cascade Mountains during the winter of 1970-71, the B-23 aircraft proved to be a reliable and excellent aircraft for cloud physics research.

1.2 Conversion of the B-23 Aircraft for Cloud Physics Research

The B-23 arrived in Seattle on September 2, 1970. Work began immediately on modifying the aircraft and instrumenting it for research purposes. The first stage of this work was finished by December 1, 1970, and from that time on the aircraft was available for research purposes. However, improvements and additions continued to be made throughout 1971. The description given below is of the aircraft research facility as it existed at the end of 1971.

To provide a large area for research equipment within the aircraft and reduce excess weight to a minimum, all excess items (e.g. galley, extra seats, tables, carpets, etc.) were removed. Two continuous, heavy duty seat tracks were then installed on one side of the aircraft, in both the front and rear cabins, on which equipment could be mounted and secured. Provision for sway bracing was provided by a single track attached to the wall just below the windows. With this system equipment could be placed at any position along the tracks and removed without tools.

The wall panelling beneath the windows was removed and replaced by a specially constructed panel which has two exterior trays with hinged lids, one beneath the other, which run the length of the cabin. These trays, which have outlet boxes every few feet, served both as conduit and electrical shields for the electrical wiring to the research instruments. One tray is used for power lines and the other for signal lines. The power lines provide 110V - 60Hz, 110V - 400Hz and 28Vdc to each outlet box. The outlets are not
Fig. 1.1 The University of Washington's B-23 research aircraft.
of the standard aircraft type, but are normal household outlets with grounded 3-pins for the 60Hz, grounded twist locks for the 400Hz and grounded 220V, 50A, 3-pin for the 28V dc. The 8.5 kW of power available for research purposes, and divided up as indicated in Table 1.1, is monitored and controlled from a distribution panel in the forward cabin. The panel contains a master switch enabling the pilot to switch off all research instrumentation. This system for the electrical wiring has proven to be very convenient and permits rapid changes in the instruments and equipment.

A number of research instruments need to be located well away from the region of disturbed air around the fuselage. For this purpose two bomb racks were attached under each wing and well removed from the fuselage. Each rack can support a load up to 70 kg. In addition, a substantial pylon and shackle assembly was installed on the belly on the plane forward of the wings. This can take a load of 230 kg and will accept any standard military fuel tank into which large instruments can be mounted.

1.3 Research Instrumentation System

1.3.1 Instruments and Data Recording

The location of the research instruments on the B-23 aircraft are indicated in Fig. 1.2. Detailed specifications on all of the instruments are given in Table 1.2. These instruments give us the capability of tracing cloud microphysical processes from nucleation through to the production of precipitation particles. Fig. 1.3 and Table 1.3 contain information on the methods which are used for recording and displaying the data. The data recording system is a combination of direct recording, FM recording, FM multiplexing and time-share multiplexing. This system (which was developed
Fig. 1.2 Location of men and research instruments on the B-29 aircraft. (caption on next page)
Fig. 1.2 Location of men and research instruments on the B-23 aircraft.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Pilot and Copilot</td>
<td>5</td>
<td>Instrumentation Monitor</td>
</tr>
<tr>
<td>3</td>
<td>Observer</td>
<td>6</td>
<td>Flight Director</td>
</tr>
<tr>
<td>4</td>
<td>Instrumentation Engineer</td>
<td>7</td>
<td>Observer</td>
</tr>
</tbody>
</table>

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 dewpoint thermometer.
E Time code generator and time display, WWV time standard receiver, TAS and To tool analog computers, signal conditioning amplifiers, audio signal mixers, FM and time share data multiplexers, 3-D electric field and turbulence analog read-outs.
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.
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 receiver.
K AgI flare rack (24 1.5 inch units).
L Twin burner "Skyfire" units suspended in bombracks under the wings. Alternately AgI flares in 17 unit racks or small instrument pods may be suspended here.
M Dry ice grinder and dispenser or urea-ammonium nitrate spray system (capacity 1000 lbs).
N Electric field mill sensor (fields along 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.
R MRI continuous particle replicator.
S AgI ejection flare racks (52 40 mm units).
T AgI ejection flare rack (24 1.5 inch units).
U Optical ice crystal counter.
V Radar altimeter, 3-D electric field mill electronics.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrument Type</th>
<th>Manufacturer and Model No.</th>
<th>Range</th>
<th>Error</th>
<th>Time Constant</th>
<th>On-Board Recorded?</th>
<th>Power Requirements</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total air Temperature ($T_{TOT}$)</td>
<td>Platinum wire resistance</td>
<td>Rosemont Eng. Co. 102CY2CG +414 L Bridge</td>
<td>-100 to +200°C</td>
<td>±0.1°C (Manuf. Spec.)</td>
<td>1 sec</td>
<td>Yes</td>
<td>1.4W/28VDC</td>
<td>Modified to give 0-5V output.</td>
</tr>
<tr>
<td>Static Air Temperature ($T_{STAT}$)</td>
<td>Platinum wire resistance</td>
<td>In House</td>
<td>-100 to +100°C</td>
<td>±0.5°C</td>
<td>1 sec</td>
<td>Yes</td>
<td>6W/28VDC</td>
<td>Minco resistance element in reverse flow housing (S1088) Recovery coefficient =0.2-0.3 Unreliable under heavy icing conditions</td>
</tr>
<tr>
<td>Dewpoint</td>
<td>Dew condensation type</td>
<td>Cambridge Model 880</td>
<td>-40 to +50°C</td>
<td>±1°C (Manuf. Spec.)</td>
<td>2°C/sec</td>
<td>Yes</td>
<td>50W/115Vac</td>
<td>Modified to give 0-5V output for linear output over -40 to +10°C.</td>
</tr>
<tr>
<td>Pressure Altitude</td>
<td>Absolute capacitance pressure</td>
<td>Rosemont Eng. Co. Model 830 BA</td>
<td>0-15 psi</td>
<td>±0.2% full scale (Manuf. Spec.)</td>
<td>No specs</td>
<td>Yes</td>
<td>3W/28VDC</td>
<td></td>
</tr>
<tr>
<td>True Air Speed (TAS)</td>
<td>Differential capacitance pressure sensor</td>
<td>Rosemont Eng. Co. Model 831 BA</td>
<td>0-1 psi</td>
<td>±0.2% full scale (Manuf. Spec.)</td>
<td>No specs</td>
<td>Yes</td>
<td>3W/28VDC</td>
<td>TAS derived by means of on-board in-house built analog computer.</td>
</tr>
<tr>
<td>Air Turbulence</td>
<td>Differential pressure sensor</td>
<td>Meteorology Research Inc.</td>
<td>0-10 cm/3 sec-1</td>
<td>±10%</td>
<td>3 sec.</td>
<td>Yes</td>
<td>20W/28VDC</td>
<td></td>
</tr>
<tr>
<td>Parameter</td>
<td>Instrument Type</td>
<td>Manufacturer and Model No.</td>
<td>Range</td>
<td>Error</td>
<td>Time Constant</td>
<td>On-Board Recorded?</td>
<td>Power Requirements</td>
<td>Remarks</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>----------------------------------</td>
<td>---------------------------</td>
<td>------------------------------</td>
<td>---------</td>
<td>---------------</td>
<td>---------------------</td>
<td>--------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Liquid Water</td>
<td>Hot wire resistance</td>
<td>Johnson Williams</td>
<td>0-2 g/m$^3$ 0-6 g/m$^3$</td>
<td>No specs</td>
<td>No specs</td>
<td>Yes</td>
<td>110W/115V/400Hz 40W/28VDC</td>
<td></td>
</tr>
<tr>
<td>Electric Field in Vertical Plane</td>
<td>Rotary field mill</td>
<td>Meteorology Research Inc. Model 611</td>
<td>0±100 kV m$^{-1}$</td>
<td>±10%</td>
<td>0.2 sec</td>
<td>Yes</td>
<td>20W/115V/400Hz 120W/28VDC</td>
<td>Modified for 0-5V output and calibration circuitry added for ±20kV m$^{-1}$</td>
</tr>
<tr>
<td>Electric Field in Horizontal Plane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical Conductivity of Air</td>
<td>Gerdien Ion Meter</td>
<td>In house</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Under development</td>
</tr>
<tr>
<td>Hydrometer Sampler</td>
<td>Metal foil impactor</td>
<td>Meteorology Research Inc. Model 1220A</td>
<td>Particles greater than 250 μm in size</td>
<td></td>
<td></td>
<td></td>
<td>300W/28VDC</td>
<td></td>
</tr>
<tr>
<td>Cloud Particle Sampler</td>
<td>Continuous particle replicator</td>
<td>Meteorology Research Inc. Model 1203D</td>
<td></td>
<td>No specs</td>
<td></td>
<td>Yes</td>
<td>300W/28VDC</td>
<td></td>
</tr>
<tr>
<td>Ice Crystal Counter</td>
<td>Optical polarization technique</td>
<td>In house</td>
<td>0-100 particles per liter</td>
<td>No specs</td>
<td>Immediate</td>
<td>Yes</td>
<td>180W/28VDC 50W/115V 160Hz</td>
<td>Under development</td>
</tr>
<tr>
<td>Electrical Hydrometer Counter</td>
<td>Charge detection device</td>
<td>In house</td>
<td>0-10,000 particles per liter</td>
<td>No specs</td>
<td>Immediate</td>
<td>Yes</td>
<td>50W/28VDC 1W/115V/60Hz</td>
<td>Under development</td>
</tr>
<tr>
<td>Parameter</td>
<td>Instrument Type</td>
<td>Manufacturer and Model No.</td>
<td>Range</td>
<td>Error</td>
<td>Time Constant</td>
<td>On-Board Recorded?</td>
<td>Power Requirements</td>
<td>Remarks</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------------</td>
<td>----------------------------</td>
<td>----------------------------</td>
<td>-------------</td>
<td>---------------</td>
<td>-------------------</td>
<td>---------------------------</td>
<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Cloud Condensation Nuclei</td>
<td>Optical counting by light scattering</td>
<td>In house</td>
<td>0-5,000 cloud condensation nuclei/cm³</td>
<td>±10%</td>
<td>1 Cycle per 15 sec</td>
<td>Yes</td>
<td>500W(Max)/115V/60Hz</td>
<td></td>
</tr>
<tr>
<td>Ice Nucleus Concentrations</td>
<td>NCAR acoustical counter</td>
<td>E. Bollay Assoc. (modified in house)</td>
<td>0.01-500 counts per liter</td>
<td>No specs</td>
<td>20 sec rise time several minutes delay</td>
<td>Yes</td>
<td>250W/115V/60Hz</td>
<td>Modified humidity control and aerosol generator. Compressor converted to 28VDC</td>
</tr>
<tr>
<td>Ice Nucleus Concentrations</td>
<td>Fast response polarizing technique</td>
<td>Mee Indust.</td>
<td>0.1-10,000 counts per liter</td>
<td>No specs</td>
<td>10 sec</td>
<td>Yes</td>
<td>175W/28VDC</td>
<td></td>
</tr>
<tr>
<td>Nephelometer</td>
<td>Optical light scattering</td>
<td>In house</td>
<td>Bscat = 1 x 10⁻⁵ m⁻¹ to 10⁻³ m⁻¹</td>
<td>±10%</td>
<td>5 sec</td>
<td>Yes</td>
<td>60W/115V/60Hz</td>
<td>Based on design by Alquist and Charlson.</td>
</tr>
<tr>
<td>Sodium Particle Counter</td>
<td>Flame spectrometer</td>
<td>In house</td>
<td>0-10,000 counts per liter</td>
<td>±1%</td>
<td>Immediate response</td>
<td>Yes</td>
<td>60W/115V/60Hz</td>
<td>Detects NaCl particles larger than 0.05 μm in diameter</td>
</tr>
<tr>
<td>Lithium Detector</td>
<td>Flame spectrometer</td>
<td>In house</td>
<td>0-100 counts per liter</td>
<td>Yes</td>
<td></td>
<td></td>
<td>5W/12VDC (powered by internal batteries)</td>
<td>Useful for plume tracing since the lithium aerosol background is essentially zero.</td>
</tr>
<tr>
<td>Parameter</td>
<td>Instrument Type</td>
<td>Manufacturer and Model No.</td>
<td>Range</td>
<td>Error</td>
<td>Time Constant</td>
<td>On-Board Recorded?</td>
<td>Power Requirements</td>
<td>Remarks</td>
</tr>
<tr>
<td>---------------------------------------</td>
<td>----------------------------</td>
<td>---------------------------</td>
<td>---------------------------</td>
<td>------------------------</td>
<td>---------------</td>
<td>--------------------</td>
<td>---------------------------</td>
<td>----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Altitude Above Terrain</td>
<td>Radar altimeter</td>
<td>AN/APN22</td>
<td>0-20,000 ft.</td>
<td>± 5% of indicated value</td>
<td>No specs</td>
<td>Yes</td>
<td>36W/28VDC 120W/115V/400Hz</td>
<td>Still being tested</td>
</tr>
<tr>
<td>Weather Radar</td>
<td>5 cm gyro stabilized</td>
<td>Radio Corp. America AVQ-1-</td>
<td>50 nautical miles</td>
<td>No specs</td>
<td>No</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft Position and Course Plotter</td>
<td>Works off DME and VOR</td>
<td>In house</td>
<td>80 miles</td>
<td>1 mile</td>
<td>10 sec</td>
<td>Yes</td>
<td>30W/28VDC</td>
<td>Gives real time plot on sectional map of area of position of aircraft.</td>
</tr>
<tr>
<td>Time</td>
<td>Time code generator</td>
<td>Systron Donner Model 8220</td>
<td>hrs, min, sec, (IRIG B code)</td>
<td>1 part in 10^5</td>
<td>Yes</td>
<td>12W/115V/60Hz</td>
<td>Modified for 28V dc operation. Hr, min, sec, display</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>Radio WWV</td>
<td>Gertsch RHF 1</td>
<td>min</td>
<td></td>
<td>Yes</td>
<td>1W/28VDC</td>
<td>2.5, 5, 10, 15 MHz Voice announcements are recorded on tape</td>
<td></td>
</tr>
<tr>
<td>Ground Communication</td>
<td>FM transceiver</td>
<td>Motorola</td>
<td>approx. 100 miles</td>
<td></td>
<td>No</td>
<td>Internal batteries</td>
<td>150 MHz band</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 1.3 Schematic of the instrumentation system on the B-23 aircraft.
<table>
<thead>
<tr>
<th>Type</th>
<th>Manufacturer and Model No.</th>
<th>Speed</th>
<th>Number of Channels</th>
<th>Information Recorded</th>
<th>Power Requirements</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Analog Magnetic Tape Recorder</td>
<td>Honeywell Model 5600</td>
<td>15/16 ips through to 60 ips capability. Normally operated at 3-3/4 ips.</td>
<td>7 tracks, 1/2&quot; tape, IRIG compatible. Normally operated with 5 FM and 2 direct tracks. 1 of the direct tracks is used to record the FM multiplex signal.</td>
<td>Capability for recording relevant information listed in Table 2.1</td>
<td>280W/115V/60Hz</td>
<td>Comments from front and rear observers and aircraft intercom. are also recorded.</td>
</tr>
<tr>
<td>Chart Recorder</td>
<td>Brush Model 260</td>
<td>1 through 125 mm min. Normally operated at 25 mm min.</td>
<td>6 tracks and 4 events.</td>
<td>Any instrument depending on requirements. Time pulse every odd minute on event channel.</td>
<td>200W/115V/60Hz</td>
<td>Normal chart speed 25 mm/min.</td>
</tr>
<tr>
<td>Digital Display</td>
<td>Assembly Products Inc. Model 3404</td>
<td></td>
<td></td>
<td>Ttot, Tstat, Dewpoint, Pressure, altitude, TAS, Liquid Water, Turbulence.</td>
<td>7W/115V/60Hz</td>
<td>2 Digital readouts: one in front cabin and one in rear cabin.</td>
</tr>
<tr>
<td>Time Code Reader</td>
<td>Systron Donner</td>
<td>up-dated on time.</td>
<td></td>
<td>Time code IRIGB from time code generator in front cabin</td>
<td>12W/115V/60Hz</td>
<td>Hrs, min, sec display.</td>
</tr>
</tbody>
</table>
by Mr. L. Engels of our research group) is designed around the Honeywell 5600 7-track analog tape recorder. The FM and time-share multiplexers are in-house designed and built. Overall accuracy is better than 1% full-scale deflection of the recorded parameter.

1.3.2 Basic Parameters

The basic parameters which are recorded routinely are total air temperature, static air temperature, dew point, pressure altitude, true airspeed and air turbulence. The sensors for these measurements are therefore located in semi-permanent positions on the fuselage. Real-time digital displays of these parameters are available at the push of a button in both the front and rear cabins. Most of the instrumentation associated with measuring basic parameters is standard, therefore, we describe below only a few in-house modifications.

Static air temperatures are measured with a platinum resistance thermometer protected by a reverse housing flow. The external parts of the probe are similar to that described in a report by NCAR (1970). The reverse housing forces the airflow into the reverse direction and at a reduced speed over the sensor; water droplets do not impact on the sensor due to their inertial separations. The diabatic flow and expansion into the region of lower pressure surrounding the sensor eliminates up to 70% of the dynamic heating. Provided icing conditions are not too severe (the reverse housing is not heated) the temperature recorded with this device should be within 1/2°C of the static air temperature at an aircraft speed of 125 knots and an altitude of 5,000 ft. Self-heating of a platinum resistance thermometer can introduce errors for the wire must be thin enough to have a time constant less than
about 1 sec. Also, the measurement of very small currents is difficult on an aircraft due to electrical noise. We have eliminated these problems by using a circuit (designed by Mr. H. West of our research group) which supplies pulsed currents to the platinum resistance thermometer (Fig. 1.4). Although the currents are fairly large and give a good signal to noise ratio, because of their short duration they do not cause much heating.

The true air speed (TAS) in meter sec\(^{-1}\) of the aircraft is given approximately by (Liepman and Roshko, 1957):

\[
TAS = \left[ 574 \left( T + 273 \right) \frac{\Delta P}{P_s} \right]^{1/2}
\]  

(1.1)

where, \(T\) is the total temperature (static plus dynamic heating) in °C, \(\Delta P\) the differential pressure due to ram air, and \(P_s\) the static pressure. The TAS is computed by means of a small analog computer on-board the aircraft from measurements of \(T\), \(\Delta P\) and \(P_s\) using eqn. (1.1). The method for doing this (designed by Mr. J. Russell of our research group) is shown in Fig. 1.5. The inputs from the sensors pass through a series of relays used for calibration purposes and are then scaled within three inverting amplifiers with appropriate gain. In addition, an offset of 273 mV is added to the total temperature to convert from °C to °K. The scaled temperature and \(\Delta P\) data are then multiplied together and divided by \(P_s\). The output is recorded and displayed in the aircraft in analog form. The calibration relays are used to periodically disconnect the sensors from the inputs and substitute two sets of known input voltages specifically chosen to produce readings of 50.0 and 200.0 m sec\(^{-1}\).
Fig. 1.4 Electrical circuit for supplying pulsed currents to a platinum resistance thermometer.
TAS = TRUE AIR SPEED

\( T_\text{oC} \) = TEMPERATURE IN DEGREES CENTIGRADE

\( \Delta P \) = DIFFERENTIAL PRESSURE

\( P_s \) = STATIC PRESSURE

\[
TAS = \left[ \frac{574 \times (T_\text{oC} + 273)}{\Delta P/P_s} \right]^{1/2} \text{ m/sec}
\]

From Sensors:

\( \Delta P \rightarrow 1 \text{ PSID} = 5 \text{ VOLTS}; 5.0 \text{ V/psid} \)

\( P_s \rightarrow 16 \text{ PSI} = 5 \text{ VOLTS}; 0.3125 \text{ V/psi} \)

\( T_\text{oC} \rightarrow 1.0 \text{ mV/°C} \)

Fig. 1-5 Method for computing true air speed from measurements of total temperature \( T \) in °C, differential ram pressure \( \Delta P \) and static pressure \( P_s \).
In addition to the basic instruments referred to above, about twenty other instruments are on-board as listed in Table 1.2. Those instruments developed or modified in our research group which have not been described previously are discussed below.

1.3.3 Continuous Particle Sampler: Decelerators

The continuous particle sampler (manufactured by Meteorology Research Incorporated) is used to obtain permanent records of ice crystals and water droplets in the clouds by means of Formvar replication. Several modifications and additions have been made to this device in order to improve its reliability and usefulness. The 16 mm mylar film, onto which the Formvar is applied, runs through a complicated system of sprockets and wheels and, on occasion, it would jump free. To reduce this possibility side flanges have been added to all of the sprocket wheels. The original single action peristaltic pump for the Formvar produced an uneven flow and an erratic coating of Formvar on the film. This problem has been partially solved by replacing the original pump with a quadruple action peristaltic pump which produces a wide uniform flow of Formvar.

The film is usually transported for periods of about 15 seconds at a speed between 0.5 and 0.85 feet sec\(^{-1}\), depending on the density of the cloud. In order to obtain some idea of the structure of the clouds between these runs without using up too much film, we have added a standby mode (designed by Mr. J. Pinnons of our research group) during which time the film is transported at about one-quarter of a foot per minute and the Formvar continues to flow but at a reduced rate. Since the Formvar is thicker during the standby mode, larger ice crystals and droplets can be replicated. The standby mode has the
additional important advantage that it allows the Formvar to flow continuously during a flight and this prevents clogging of the pen. During periods when the film is transported at higher speed (i.e. regular runs) a recognizable pulse is recorded on the event track of the tape recorder so that the data can be correlated with other parameters.

One of the main problems in sampling cloud particles from aircraft with a continuous particle replicator is that many of the fragile ice crystals break up when they impact on the Formvar coated film. In order to reduce this problem we have designed (with the help of Professor R. Joppa of the Department of Aeronautics and Astronautics, University of Washington) and built two decelerators which the particles pass through prior to impacting on the film and in which the velocity of the air with respect to the aircraft is reduced by a factor of five. The dimensions of the two decelerators, which are shown in Figs. 1.6 and 1.7, are carefully designed to minimize air turbulence within them. As the velocity of the air through the decelerator is reduced so are the velocities of the cloud particles in the air, however, if the particles are too large they will not experience the fullest possible reduction in relative velocity before they impact on the film. Wind tunnel tests have shown that the distances over which particles are decelerated in the small (Fig. 1.6) and large (Fig. 1.7) decelerators are 20 and 60 cm respectively. We have estimated by calculation the maximum sizes of stellar crystals, hexagonal plates and solid columns which can be fully decelerated (i.e. their relative velocity with respect to the aircraft reduced by a factor of 5) when they pass through the small decelerator or the large decelerator. These results are shown in Table 1.4 where it can be seen that both stellar
Fig. 1.6 Side view of the small decelerator. The decelerator is five inches deep and has a rectangular cross-section normal to this view.
Fig. 1.7 Side view of the large decelerator. The decelerator has a circular cross-section normal to this view.
TABLE 1.4

ESTIMATED MAXIMUM DIMENSIONS OF THREE TYPES OF ICE CRYSTAL IN ORDER THAT FULL VELOCITY DECELERATION (A FACTOR OF 5) BE ACHIEVED WITH THE SMALL AND LARGE DECELERATORS ATTACHED TO AN AIRCRAFT FLYING AT 80 AND 200 MPH AT AN ALTITUDE OF 13,000 FT.

<table>
<thead>
<tr>
<th>Airspeed (mph)</th>
<th>Small decelerator</th>
<th>Large decelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80</td>
<td>200</td>
</tr>
<tr>
<td>Stellar crystals</td>
<td>In excess of 3000 μm in diameter*</td>
<td>2800 μm in diameter</td>
</tr>
<tr>
<td>Hexagonal plates</td>
<td>In excess of 1000 μm in diameter†</td>
<td>In excess of 1000 μm in diameter†</td>
</tr>
<tr>
<td>Solid columns</td>
<td>325 μm in length</td>
<td>300 μm in length</td>
</tr>
</tbody>
</table>

* The width of the entrance slit to the continuous particle replicator is 3000 μm.

† Hexagonal plates with diameters greater than 1000 μm were seldom collected.
crystals and hexagonal plates up to about the maximum sizes of interest should be fully decelerated in both the small and large decelerators attached to aircraft flying at 80 or 200 mph. However, the small decelerator is only long enough to fully retard solid columns up to about 325 μm in length, whereas solid columns up to 2800 and 2500 μm in length will be fully retarded by the large decelerator at cruising speeds of 80 and 200 mph, respectively.

From observations of ice crystals collected after they had passed through decelerators attached to aircraft flying at different speeds, we have been able to deduce rough values for the maximum impact speeds which several different types of ice crystal can withstand without fragmentation when they collide with a film coated with a wet 4% solution of Formvar in chloroform (thickness of film about 150 μm). A summary of these results is contained in Table 1.5. It can be seen from these results, and those contained in Table 1.4, that with the large decelerator on the B-23 and at an aircraft speed of 120 mph, the impact speeds of most ice crystals on the Formvar coated film will be below that required for fragmentation of the crystals. Consequently, by the use of the large decelerator, we have been able to significantly reduce fragmentation of the crystals during collections, and have been able to collect intact large delicate ice crystals up to several millimeters in size (Fig. 1.8).

1.3.4 Optical Ice Crystal Counter

Preliminary airborne tests of a device for counting ice crystals in clouds, using an optical polarization technique (designed by Dr. L. Radke of our research group), were carried out during the 1968-69 Cascade Program (see Hobbs and Ryan, 1969). This prototype instrument consisted of two
TABLE 1.5

ESTIMATES OF MAXIMUM IMPACT SPEEDS WHICH NATURAL ICE CRYSTALS CAN WITHSTAND WITHOUT FRAGMENTATION WHEN THEY COLLIDE WITH A MYLAR FILM COATED WITH A WET 4% SOLUTION OF FORMVAR IN CHLOROFORM 150 µm THICK.

<table>
<thead>
<tr>
<th>Type of Crystal†</th>
<th>Maximum Dimensions of Crystal (µm)</th>
<th>Maximum Impact Speed in mph at which Crystal Remains Intact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellars and Dendrites (Pib, Plc, Pld, Ple, Plf)</td>
<td>3000</td>
<td>20</td>
</tr>
<tr>
<td>Thin hexagonal plates (Pla)</td>
<td>1000</td>
<td>30</td>
</tr>
<tr>
<td>Thick plates (Clg, Clh)</td>
<td>1500</td>
<td>160</td>
</tr>
<tr>
<td>Solid columns (Cle, Nle)</td>
<td>3000</td>
<td>60</td>
</tr>
<tr>
<td>Hollow columns (Clf)</td>
<td>3000</td>
<td>40</td>
</tr>
<tr>
<td>Needles (N1a, N1b, N2a)</td>
<td>3000</td>
<td>20</td>
</tr>
</tbody>
</table>

†Based on classification by Magono and Lee (1966)
Fig. 1.8 Examples of large delicate ice crystals collected intact from an aircraft by the use of a decelerator. (a) Stellar crystal 1700μm in diameter. (b) Crystal with sector-like branches 840μm in diameter. (c) Needle 1360μm long and 125μm wide. (d) Elementary sheath 1110μm long and 115μm wide.
crossed polaroids set for maximum extinction through which a narrow beam of light was passed. If an ice crystal passed between the polaroids, it caused a slight rotation of the plane of polarization of the light beam emerging from the first polaroid so that there was a momentary increase in the amount of light passing through the second polaroid. The increases in light intensity were detected by a photomultiplier tube. Water droplets are not detected because they do not rotate the plane of polarization. However, airborne testing of this device showed that the filament light source which was used was of insufficient intensity compared to the high ambient lights. Moreover, due to vibrations, the intensity of the light source was not steady.

In the fall of 1970 further developmental work on this instrument was started by Mr. F. Turner of our research group. The light source was changed to a mercury high pressure arc lamp which was physically very rigid. This eliminated vibrationally induced noise but inherent arc noise was still considered excessive. To eliminate this problem the mode of operation was changed from one of light transmission to forward scattering (Fig. 1.9). Tests in a cold room showed that this instrument was capable of detecting stellar ice crystals and hexagonal ice plates greater than 100 μm in diameter but that it was completely insensitive to even large quantities of liquid water. Wind tunnel tests showed that the velocity of air through the instrument was about 16% less than that in the face airstream. To compensate for this a venturi was added which raised the airflow through the instrument to that in the free airstream. At an aircraft speed of 70 m sec\(^{-1}\) the instrument views about 3 liter sec\(^{-1}\) of air.

A system of electronics provides control functions and two separate
Logarithmic Pulse Height Signal Power Supply

Photomultiplier

0.001% Ripple

Concentration Logarithmic 0.01-100 \text{µl}^{-1}

Analog Tape Recorder

Aircraft Skin

0.30 m

Sample Volume 3.14\text{µl}-sec^{-1} at 70 m sec^{-1}

Airflow

Isokinetic Airflow Corrector

Lamp Power 2% Regulation

Mercury Super Pressure Lamp Type Pek 107

Polaroid Filter

Collimating Lens

Photoelectric Multiplier Type Ip21

Polaroid-Ealing #22-9062-Extinction Ratio-5 parts in \text{10}^6

Light Black

Fig. 1.9 The University of Washington Optical Ice Crystal Counter (Schematic representation not to scale)
signal paths. The first path is a pulse circuit which processes the pulse signal from the ice crystal counter through a logarithmic amplifier and these are then recorded on magnetic tape. The second path consists of an integrating circuit which integrates the pulses and provides a visual indication of the rate at which ice crystals are detected. This signal is also recorded.

Initial airborne testing on the B-23 aircraft revealed the need for extensive light shielding against the effects of ambient light chopping and reflection from the aircraft propellers. Also, regulation of the power supply to the arc lamp was found to be necessary. These problems were overcome and subsequently several flights have been made with highly encouraging results.

The airborne tests have shown that this instrument can count ice particles in clouds above a certain threshold size (yet to be determined accurately) but that it does not "see" cloud droplets or even heavy rain. The device therefore provides a rather dramatic improvement over previous techniques for detecting ice particles in clouds. The most significant use of the device so far has been as an aid in determining in real-time the effects of artificial ice nuclei on increasing the concentrations of ice particles in clouds.

1.3.5 Electrical Particle Counter

Preliminary work on the development of a device for counting cloud particles from an aircraft by detecting the electrical charges they communicate to a metal wire with which they collide was described by Mach and Hobbs (1969). Further development and airborne testing of this device has been carried out by Mr. W. Mach of our research group.
In the latest version of this instrument, the particles in the air first pass through an induction ring and charges on individual particles are measured by an electrometer. The particles then collide with a copper sphere and any charges communicated to the sphere are counted individually by means of another electrometer. A logarithmic amplifier, capable of amplifying inputs between \( \pm 10 \text{ V} \), is connected to this electrometer so that the recordable dynamic range is \( \pm 3 \) orders of magnitude. A polarizing electric field can be applied in the vicinity of the copper sphere.

The voltage outputs from the two electrometers are recorded on magnetic tape (FM mode). These voltages are subsequently digitized and analyzed with a computer. The computer examines each voltage change and then counts and categorizes each change according to the characteristics of its height, slope and duration time. Data obtained with this device is being compared with simultaneous observations of the nature of the cloud particles obtained from the continuous particle sampler. In addition to its possible use as a particle counter, this device is providing useful information on charging mechanisms in clouds.

**1.3.6 Aircraft Position and Course Plotter**

Optimal use of an aircraft for cloud physics research requires a continuous on-board visual record of the position and course of the plane. At present this can be achieved by means of (in order of decreasing cost): an inertial navigator, a Doppler radar integrating navigator, and a radio navigational system. We describe in this section an inexpensive but highly successful radio navigational system (built by Mr. H. West of our research group) which is installed on the B-23 aircraft. This system converts the
angular bearing and radial distance of the aircraft from a transmitting station obtained from the Very High Frequency Omnirange (VOR) and the Distance Measuring Equipment (DME) respectively, into X-Y coordinates which are then automatically plotted on an airway's sectional map to provide a continuous trace of the flight route. (The same principle has been used by Berry and Chisholm, 1969.)

The device, which is shown schematically in Fig. 1.10, functions as follows. The VOR signal consisting of two 30 Hz sine waves, the phase angle of which represents the bearing, is filtered and squared. The reference wave is applied to two gates which are opened and shut in turn by the variable phase signal and a 90° shifted variable phase signal. The resulting linear output is proportional to the sine and cosine of the aircraft bearing and is switched synchronously to a sine-cosine converter. The sine and cosine of the bearing are then fed to an analog multiplier which has as its second input the DME output which is a DC voltage proportional to the distance of the aircraft from a reference station. The output is a square wave consisting of successive values proportional to the X and Y position of the aircraft. These values are synchronously switched into holding amplifiers which in turn drive an X-Y recorder over a map of the area.

Preliminary flight tests on the instrument revealed that on occasion the record could be interrupted by transitory signals and confused by the signals being reflected from mountains. These events produced a rapid movement of the pen. To prevent these movements being recorded, the position rate is sensed and when this exceeds the velocity of the aircraft the pen is automatically lifted from the map and the signal paths to the holding
Fig. 1.10 Schematic of the University of Washington's Automatic Aircraft Position Plotter
amplifiers opened. The pen remains in the last valid position until a stable signal is received when it lowers onto the map and continues to trace the flight path.

As an additional aid in post-flight data analysis, small recognizable pulses are applied to the pen every two minutes. The pulses are positive during even hours and negative during odd hours.

This aircraft position plotter has proven invaluable in our research work, particularly in the accurate positioning of the aircraft during cloud seeding.

1.3.7 Artificial Cloud Seeding Systems

The B-23 is equipped with a variety of systems for artificially seeding both cold and warm clouds (Fig. 1.2). A brief description of each system is given below.

(a.) Silver iodide pyrotechnic cartridge ejection flares.

A rack containing 52 cartridges is located beneath the instrument pod (S in Fig. 1.2). Up to 130 grams of silver iodide is contained in each cartridge and is ejected from the cartridge by a small electrically fired charge. The projectiles can be fused to dispense the silver iodide over a specified path length after falling freely for a certain distance. These delay units are extremely useful in the Cascade Program where often the clouds to be artificially seeded are below the permissible flight level in the mountains.

(b.) In situ silver iodide pyrotechnic flares.

This system provides a source of silver iodide particles generated pyrotechnically which is fixed to the aircraft. Two racks, each of which can carry 24 flares (each flare can contain up to 500 grams of silver iodide), are located permanently on the aircraft (K and T in Fig. 1.2). Two
additional racks which carry 17 flares each can be attached to the bomb racks under the wings (L in Fig. 1.2).

(c.) "Skyfire" silver iodide generator.

The bomb racks (L in Fig. 1.2) provide mountings for two "Skyfire" silver iodide-sodium iodide-acetone smoke generators. However, these systems have not been used in the Cascade Program.

(d.) "Dry ice" dispersing unit.

A rotary grinder and auger-feed dispersing unit for "dry ice" can be located in section M (Fig. 1.2). The unit is designed to crush 30 x 30 x 4 cm³ blocks at a maximum rate of about 20 kg min⁻¹. The crushing reduces about 60% of the block to irregular chunks from 0.5 to 1 cm across and leaves the remainder as a fine powder. If heavier seeding rates are required, the crusher feeds a hopper which can store 110 kg of "dry ice" which can then be dispensed at rates up to 30 kg min⁻¹.

(e.) Hygroscopic liquid spray system.

This system is designed to dispense a mixture of ammonium nitrate and urea in the form of small droplets at a rate of up to 20 liters per minute. Due to weight limitations the system is limited to 450 kg of solution. The unit is located in position M (Fig. 1.2) and the spray wand extends about 10 ft below the belly of the aircraft at that point. This system has been used for seeding cumulus clouds in Texas but has not been used in the Cascade Program.
SECTION 2

GROUND INSTRUMENTATION AND PROCEDURES

2.1 Network of Stations

During the winter of 1970-71, measurements were made at twelve ground stations straddling the Cascade Divide over an area which is shown in Fig. 2.1. Five of these stations (Alpental base, Keechelus Dam, Stampede Pass, Kachess Dam and Greenwater) were manned during designated "storm days." The other stations had automatic sensors which could run unattended for about a week. A small CW Doppler radar was operated at Keechelus Dam and rawinsondes were launched and tracked from Greenwater. The University of Washington in Seattle served as a control center to which data and information were relayed by radio from the manned stations as well as from the aircraft.

The types of measurements made at each of the ground stations are listed in Table 2.1 Comments on some of the instruments and techniques are given below.

2.2 Precipitation

Three different instruments were used to measure precipitation: weighing buckets, tipping buckets and optical snow-rate sensors. The most standard of these instruments is the weighing bucket precipitation gauge (Science Assoc., Model No. 551). These were equipped with a 24-hour clock drive and could run unattended for about a week. Solid precipitation is melted by an ethylene glycol-type anti-freeze. The instrument can resolve 0.02 inches of precipitated water and has a time resolution of about 5 minutes. The heated, tipping bucket precipitation gauge (manufactured by E. Bollay Assoc.) has an orifice 0.45 m² in area and, as supplied by the manufacturers, it can resolve...
Fig. 2.1 Region of the Cascade Mountains in which ground measurements were made. Stations where measurements were taken are underlined.
### TABLE 2.1

**MEASUREMENTS MADE AT GROUND STATIONS**

<table>
<thead>
<tr>
<th></th>
<th>North Bend</th>
<th>Bandera</th>
<th>Denny Creek</th>
<th>Alpental (1)</th>
<th>Hyak</th>
<th>Keechelus Dam (1)</th>
<th>Stampede Pass (1)</th>
<th>Cabin Creek</th>
<th>Kachess Dam (1)</th>
<th>Greenwater (1)</th>
<th>Univ. of Washington (Control Center)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighing Bucket</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Precipitation Gauge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heated Tipping Bucket</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Precipitation Gauge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical Snow Rate Sensor</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>(EG &amp; G)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow Crystal Replicas</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow Samples for</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentrations of</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freezing Nuclei &amp; Silver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ice Nucleus Counter (NCAR)</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermograph</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microbarograph</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind Speed and Direction</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radio</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radars</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(1) Manned station  
(2) National Weather Service measurement  
(3) Non-recording
1.5 \times 10^{-3} \text{ inches of water. However, the sensitivity of the tipping bucket located at Greenwater was increased to } 5.7 \times 10^{-4} \text{ inches of water.}

At higher elevations, where the precipitation was generally in the form of snow, optical snow-rate sensors (manufactured by E. Bollay Assoc., Model No. 2-004) were operated alongside the weighing buckets. These instruments detect individual airborne ice particles as they pass through a light beam 1 meter in length which is focused on a photo-resistor. The signal thus produced is conditioned electronically and recorded on a strip chart as an instantaneous value of the water equivalent of the snowfall rate. The instrument can resolve about 0.025 inches of water per hour with a time resolution of 2 minutes. Some saturation may occur with precipitation rates in excess of 0.2 inches per hour due to more than one ice particle being in the light beam at the same time. The instrument was modified by adding a black plate 23 cm in diameter behind the light source. This terminates the field of view of the photo-resistor and eliminates erroneous readings due to reflections from objects beyond the designated path (e.g. reflections from snowbanks, buildings, trees).

The original calibration of the optical snow-rate sensor was carried out in the Colorado Rockies where the following empirical relationship was derived (E. Bollay Assoc., Inc., 1968):

\[ r = 0.3 \, d \]  

(2.1)

where, \( r \) is the precipitation rate in inch hr\(^{-1} \) and \( d \) is the deflection of the optical snow-rate sensor expressed as a fraction of full-scale. From simultaneous measurements of \( r \) (from the weighing buckets) and \( d \) we have
reinvestigated the calibration of the optical snow-rate sensor for a wide variety of snow crystal types which occur in the Cascade Mountains. The results are shown in Figs. 2.2 and 2.3. It can be seen that the reading of the optical snow-rate sensor is linearly related to the precipitation rate only if the snow crystals are unrimed (Fig. 2.2), in which case our observations give

\[ r = 0.36 d \]  \hspace{1cm} (2.2)

As the amount of riming on the snow particles increases the relationship between \( r \) and \( d \) becomes more random until with graupel particles it is completely random. The actual habit of the crystal does not appear to affect the relationship between \( r \) and \( d \) (Fig. 2.3).

In view of the above observations it is clear that considerable caution must be used in interpreting the outputs from optical snow-rate sensors of the type described above in terms of a precipitation rate. However, they can be used as snow crystal counters. Also, if there is no wind blowing, the number of snowflakes which interrupt the light beam in a given period of time can be used in conjunction with a simultaneous measurement of the precipitation rate to give the average mass of the falling snow crystals. The average masses of snow crystals which fall in the Cascade Mountains, which we have deduced by using this technique, range from 1 to 2 milligrams. This is one to three orders of magnitude greater than the masses calculated from the size-mass relationships for ice crystals given by Nakaya and Terada (1934). The difference may be due to the large aggregates which are common in the Cascades.
Fig. 2.2 Simultaneous values of the integrated electrical output from optical snow rate sensors and weighing bucket precipitation gauges.
Fig. 2.3 Simultaneous values of the integrated snow rate sensors and weighing bucket precipitation gauges. G - graupel particles ● - rimed crystals ○ - unrimed crystals.
2.3 Crystal Types

At the manned stations plastic replicas were made of the snow crystals in the air using a 1% solution of Formvar in ethylene dichloride. Glass slides (2" x 2") were used as a substrate. If the evaporative cooling causes the temperature of the slide to fall below the dewpoint of the air, condensation occurs on the plastic replicas and this can be mistaken for natural riming. This problem was overcome by either placing the glass slide on a thermoelectric cooler surrounded by a supply of dry air or by placing the slide in a cold box at -20°C immediately after it had been exposed to the falling snow. Both techniques can also be used to obtain replicas even when the air temperature is a few degrees above the melting point.

2.4 Snow Sampling

Specially constructed polyethylene bags (60" x 50" in area and 0.00125" thick) were used to catch large quantities of snow. The bags were stretched over cylinders (40" in diameter and 24" high) and exposed to the snowfall for measured periods of time. The bags were then sealed, weighed and stored for subsequent analysis of the concentrations of freezing nuclei and silver in the snow as described below.

2.5 Freezing Nucleus Concentrations

The snow samples were used to determine the concentrations of freezing nuclei in the snow using the drop-freezing technique. The basic theory and instrumentation used in this technique have been described by Hobbs et al. (1970), therefore, we mention here only the improvements and changes which have been made during the past years.

Instead of using a circulating ice bath as the heat exchanger for the
thermoelectric cooler (see Fig. 4 in Hobbs et al., 1970), cold methanol was circulated in a closed system. The temperature of the methanol was controlled by pumping it through a refrigeration unit and then heating it to the desired temperature. In this way, the temperature of the methanol could be kept constant to within a few tenths of a degree for any period of time. Previously the temperature of the drops was determined by a thermocouple taped to a polyethylene film. This has now been replaced by a thermistor imbedded just below the surface of the aluminum plate in which the vacuum manifold is located. The thermistor is then used to control and observe the temperature of the plate. The temperature of the drops can now be set at any value between ±40°C with an accuracy of 0.2°C and the temperature measured to an accuracy of 0.1°C. The temperature can be increased or decreased at a rate from 0 to 5°C min⁻¹; a cooling rate of 2°C min⁻¹ was used in all the results described in this report.

During the middle of the 1970-71 program the volume of the individual water drops was changed from 0.001 cm³ to 0.017 cm³. This permitted the concentrations of freezing nuclei to be determined to higher temperatures, which corresponded more nearly to those of the natural cloud. Fig. 2.4 shows the measured spectra of freezing nuclei in the same samples of snow using two different drop sizes. It can be seen that when the volume of a drop was 0.017 cm³ the spectra could be extended to higher temperatures. However, with the larger drops the maximum concentrations of freezing nuclei per gram which could be measured were in the hundreds while with the smaller drops they were in the thousands.
Fig. 2.4 Freezing nucleus spectra for two different samples (solid and dashed lines) determined using drops of different volumes $v$. 
2.6 Silver Concentrations

Only a small portion of the snow collected in the polyethylene bags was needed for the determination of the concentrations of freezing nuclei by the drop-freezing technique. The bulk of the snow was analyzed with an atomic absorption spectrometer to determine the amount of silver it contained. This technique can detect concentrations down to about $3 \times 10^{-11}$ grams of silver per milliliter of water. A total of 323 samples of snow collected during the 1970-71 season were analyzed in this way.

2.7 Rawinsonde Measurements

Rawinsondes were launched and tracked from Greenwater (see Fig. 2.1) using a GMD-1 unit on loan from the National Center for Atmospheric Research. The sonde could generally be tracked up to the 100 mb level except when the winds were unusually strong. The raw data were transmitted to the University of Washington and then relayed for analysis via a computer terminus to the Bureau of Reclamation's RCA time sharing computer in Denver. The reduced data (temperature, dewpoint, wind speed and direction at standard altitudes) were then relayed back to the University of Washington where they were available while the aircraft and ground measurements were still in progress.

2.8 Radars

The objectives of the radar studies in the Cascade Program are to investigate the intensity of precipitation and the fall speeds of solid precipitation particles in winter storms over the Cascade Mountains and to relate these to simultaneous airborne and ground observations and, where appropriate, to artificial seeding. During the summer of 1970 a small CW mobile Doppler radar was built for this purpose and tested at Keechelus Dam.
through the winter of 1970-71. Details of this radar and some of the results obtained are described in §7.

In addition to the Doppler radar, data was available on the distribution of precipitation across the State from the powerful FAA L band (23 cm wavelength) radars located at Seattle, Spokane and Salem (Oregon). Also, arrangements were made to acquire vertically pointing radar data obtained with a TPQ-11 (0.86 cm wavelength) located at McChord Air Force Base which is situated about 50 miles SW of Snoqualmie Pass. This radar provides information of the heights of the bases and tops of all significant cloud layers above the radar.

2.9 Operational Procedures

"Storm days" were defined as those days for which the National Weather Service forecaster in Seattle predicted by 1600 hours on the preceding day that snow was likely to fall in the Cascade Mountains during daylight hours. On "storm days" ground crews were on station by 0800 hours at which time all instruments were checked and timed and observations begun. Complete weather observations were made at the ground stations every hour. Snow crystal replicas were taken every half-hour and snow samples collected over hourly intervals. Three rawinsondes were released from Greenwater at about two hourly intervals on a "storm day." The research aircraft generally left Seattle (Boeing Field) by mid-morning on a "storm day" and flew east across the Cascades passing over the ground stations. The aircraft then returned to the west side of the Cascade divide obtaining in-cloud measurements whenever possible. If the aircraft and ground observations indicated that there was a potential for modifying the precipitation over the Cascades by artificial seeding, this was carried out from the aircraft at a location
determined by the observations and theoretical calculations. During the period extending one hour before seeding started to two hours after the seeding was completed, snow crystal replicas were taken every ten minutes and snow samples collected every fifteen minutes at the ground stations.
3.1 Introduction

Concurrently with our field studies of the structure of winter orographic clouds over the Cascade Mountains, efforts are being made to develop a theoretical model which describes the essential features of the airflow over the mountain and the development of orographic clouds and precipitation. In this section we present an account of the state of the model at the end of 1971 and some of the theoretical predictions.

3.2 The Airflow Model

There are two main ways in which a mountain can modify the flow of air. Firstly, it acts as a barrier which deflects the air over and around it or blocks the air (the barrier effect). Secondly, a mountain can serve as a source or sink of heat (the diabatic effect). Since much of the precipitation which is deposited on the Cascade Mountains is produced by the stable overrunning of warm fronts, we have concentrated our attention on the barrier effect. Therefore, in the model described below, it is assumed that the atmosphere is stably stratified and that the only heat sources are due to the release of latent heat within the cloud.

The equations describing the flow of dry air over a mountain are considered first. These then serve as a guideline in developing equations to describe the flow of cloudy or partly-cloudy air over a mountain.

3.2.1 Airflow in a Dry Adiabatic Atmosphere

We consider first the two dimensional flow of dry air over a mountain in the form of a long ridge. The x-axis is taken perpendicular to the length of
the ridge and the z-axis vertically upwards.

For two dimensional, inviscid, steady flow the vorticity equation can be written in the form

$$a(v \cdot V)n + \alpha(n \cdot V) - a^3 \nabla p \times \nabla p = 0 \quad (3.1)$$

where, $\rho$ is the density of the air and $a = 1/\rho$, $v$ is the velocity of the air in the x-z plane ($= u + wk$), $n = (\frac{3u}{\partial z} - \frac{3w}{\partial x}) j = n j$ and $p$ is the pressure.

From the continuity equation $\nabla \cdot (\rho v) = 0$ we have:

$$\rho \nabla \cdot Vp = -\nabla \cdot v \quad (3.2)$$

so the first two terms in eqn. (3.1) become

$$a[(v \cdot V)n + n(v \cdot V)] = (v \cdot V)\alpha n \quad (3.3)$$

If the pressure is $p$ and the temperature $T$,

$$\rho p = RT \quad (3.4)$$

where $R$ is the gas constant for dry air, so that the baroclinic term in eqn. (3.1) can be written as

$$-a^3 \nabla p \times \nabla p = aRT \times \nabla (\ln p) \quad (3.5)$$

The potential temperature $\theta$ is defined as

$$\theta = T(p_p / p)^{R/c} \quad (3.6)$$
where \( p_r \) is a reference pressure, and \( c_p \) the specific heat of dry air at constant pressure. Therefore, from eqns. (3.5) and (3.6),

\[-\alpha \frac{\partial \rho}{\partial p} \times \frac{\partial p}{\partial x} = -\alpha \frac{\rho c_p}{c_p} T \times \partial \ln \theta \quad (3.7)\]

or,

\[-\alpha \frac{\partial \rho}{\partial p} \times \frac{\partial p}{\partial x} = -\alpha \frac{d(\ln \theta)}{dz} \frac{\rho c_p}{c_p} T \times \frac{\partial z}{\partial z} \quad (3.8)\]

where, \( z \) is the height of the streamline in the undisturbed flow well upstream of the mountain (i.e. at \( x = -\infty \)) and the adiabatic assumption, namely, that \( \theta \) is constant on a streamline, has been used.

In two dimensions, continuity in a stream tube gives

\[\frac{\partial v}{\partial x} = \frac{\rho}{\rho_0 u_0} v \times j \quad (3.9)\]

where the subscripts \( 0 \) indicate values at \( x = -\infty \). Therefore the baroclinic term becomes

\[-\alpha \frac{\partial \rho}{\partial p} \times \frac{\partial p}{\partial x} = \frac{\beta}{\rho_0 u_0} \frac{\partial \rho}{\partial p} \times \frac{\partial \left( c_p T \right)}{\partial x} \quad (3.10)\]

where,

\[\beta = \frac{d(\ln \theta)}{dz} = \frac{1}{\theta} \frac{d\theta}{dz} \quad (3.11)\]

is termed the upstream stability.

Substituting eqns. (3.3) and (3.10) into eqn. (3.1) we obtain
\[(v \cdot v)\alpha \eta + \left(\frac{-\theta}{\rho \rho_0 u_0^2} v \cdot \nabla c T\right) j = 0 \quad (3.12)\]

or

\[v \cdot \nabla \left(\alpha \eta + \frac{\beta c_0 T}{\rho \rho_0 u_0^2}\right) = 0 \quad (3.13)\]

which can be integrated. Bernoulli's equation can be written in the form

\[c_p T + g \zeta + \frac{q^2}{2} = A \quad (3.14)\]

where, \(g\) is the acceleration due to gravity, \(\zeta = z - z_o\) is the vertical displacement of a streamline, \(q^2 = u^2 + w^2\), and \(A\) is a constant on a streamline.

From eqns. (3.13) and (3.14)

\[\frac{\rho_0}{\rho} \eta - \frac{\beta}{u_0} (g \zeta + \frac{q^2}{2}) = C \quad (3.15)\]

where, \(C\) is a constant on a streamline and for fixed values of \(\beta\) and \(u_0\). For an incompressible fluid \(\beta = -d(\ln \rho)/dz_o\) and \(\rho_o = \rho\) and eqn. (3.15) reduces to the equation derived by Long (1953).

The transformation of eqn. (3.15) into the requisite differential equation has been carried out by Long (1953) and Scorer (1955) in a manner consistent with their particular assumptions. The differential equation is in general non-linear. Scorer and Klieforth (1959) have shown that under certain conditions a simplified linear form of eqn. (3.15) is

\[v^2 \zeta + \frac{g \beta}{u_0} \zeta = 0 \quad (3.16)\]
Since eqn. (3.16) has been used frequently in the literature, we will use it for comparing past results with those obtained here.

3.2.2 Airflow in a Wet Adiabatic Atmosphere

The restoring force which acts on a parcel of air when it is displaced by distance $\xi$ from its initial level as it flows over a mountain, is given by $-g\beta\xi$ where $\beta$ is the stability of the air. For a dry compressible fluid $\beta$ is defined by eqn. (3.11). Therefore, it is tempting to conclude by analogy that for cloudy air the appropriate stability factor is $\beta_w = \frac{d(ln \theta_w)}{dz}$, or perhaps $d(ln \theta_w)/dz$, where $\theta_w$ and $\theta_E$ are the wet-bulb potential temperature and the equivalent potential temperature respectively. However, as will be shown below, neither of these assumptions is correct.

The buoyancy of a parcel of air is defined as the acceleration (a) which it experiences which is given by

$$a = g(T' - T)/T$$

where, $T$ is the temperature of the environment and $T'$ that of the parcel of air. If the parcel is displaced from a level where it has the same temperature $T_o$ as that of the environment

$$T = T_o - \gamma_e \xi$$

$$T' = T_o - \gamma_p \xi$$

where, $\gamma_e$ is the lapse-rate of the environmental air and $\gamma_p$ the lapse-rate following the parcel. Therefore,
If the air is dry \( \gamma_p = \gamma_d = -g/c_p \) (the dry adiabatic lapse rate). Also, we have the general relationship

\[
\frac{d(\ln \theta)}{dz} = \frac{1}{T} (\gamma_d + \frac{dT}{dz})
\]

where the derivatives may be taken in the environment or following a parcel of air. If we assume that when we follow a parcel of dry air \( \frac{dT}{dz} = \gamma_e \), then

\[
a = -\frac{g}{T} (\gamma_d + \frac{dT}{dz}) \zeta = -g \frac{d(\ln \theta)}{dz} \zeta = -g \beta \zeta
\]

If we follow a parcel of moist air \( \frac{dT}{dz} = \gamma_m \) (the moist adiabatic lapse rate).

The equivalent potential temperature \( \theta_E \) is given by

\[
\theta_E = \theta \exp \left( \frac{Lw}{c_p T} \right)
\]

where, \( L \) is the latent heat of condensation and \( w_s \) the saturation mixing ratio. For the environment

\[
\frac{d(\ln \theta_E)}{dz} e = \frac{d(\ln \theta)}{dz} e + \frac{L}{c_p} \frac{d}{dz} \left( \frac{w_s}{T} \right) e
\]

where the subscript \( e \) indicates spatial derivatives in the environment. From eqns. (3.21) and (3.23)
\[
\frac{d(\ln \theta_E)}{dz} = \frac{1}{T} (\gamma_d - \gamma_e) + \frac{L}{c_p} \frac{d}{dz} \left( \frac{w_s}{T} \right)_e \tag{3.25}
\]

In following a parcel of moist air \( \theta_E \) is constant, therefore, from eqn. (3.23)

\[
0 = \frac{d(\ln \theta)}{dz} + \frac{L}{c_p} \frac{d}{dz} \left( \frac{w_s}{T} \right)_p \tag{3.26}
\]

where the subscript \( p \) indicates derivatives following the parcel. From eqns. (3.26) and (3.21), with \( \frac{dT}{dz} = \gamma_m \), we get

\[
0 = \frac{1}{T} (\gamma_d - \gamma_m) + \frac{L}{c_p} \frac{d}{dz} \left( \frac{w_s}{T} \right)_p \tag{3.27}
\]

Subtracting eqn. (3.27) from (3.25),

\[
\frac{d(\ln \theta_E)}{dz} = \frac{1}{T} (\gamma_m - \gamma_e) + \frac{L}{c_p} \left[ \frac{d}{dz} \left( \frac{w_s}{T} \right)_e - \frac{d}{dz} \left( \frac{w_s}{T} \right)_p \right] \tag{3.28}
\]

It follows from eqn. (3.28) that the acceleration of a rising parcel of moist air \( a = -\frac{g}{T} (\gamma_m - \gamma_e) \) is not equal to \( -g \frac{d(\ln \theta_E)}{dz} \). Therefore, \( \frac{d(\ln \theta_E)}{dz} \) is not the appropriate stability parameter for cloudy air.

If a similar procedure is followed with the wet bulb potential temperature \( \theta_w \), defined by

\[
\theta_w = \theta \exp \left[ \frac{L}{c_p} \left( \frac{w_s}{T} - \frac{w_{sr}}{T} \right)_r \right] \tag{3.29}
\]

where the subscript \( r \) refers to values at a reference level, then it is found that
\[
\frac{d(ln \theta_w)}{dz} = \frac{1}{T} (\gamma_m - \gamma_e) + \frac{L}{c_p} \left[ \frac{d}{dz} \frac{W_s}{T} + \frac{d}{dz} \frac{w_{sr}}{T} - \frac{d}{dz} \frac{w_s}{T} \right] (3.30)
\]

Therefore, \(d(ln \theta_w)/dz\) is also not the appropriate stability parameter for cloudy air.

To summarize: for an incompressible fluid the acceleration of a parcel is given by \(-g\frac{d(ln \rho)}{dz}\), where \(\rho\) is the density of the fluid. For a compressible adiabatic (dry) fluid the acceleration is \(-g\frac{d(ln \theta)}{dz}\), where \(\theta\) is the potential temperature. There are two analogous conservative quantities to \(\rho\) and \(\theta\) for a compressible diabatic fluid, namely, \(\theta_E\) and \(\theta_w\). However, neither of these quantities give the correct restoring force in the form \(-g\frac{d(ln \theta_E)}{dz}\) and \(-g\frac{d(ln \theta_w)}{dz}\). Consequently, we now return to first principles in order to derive an appropriate equation for the flow of cloudy air over a mountain.

From eqns. (3.6) and (3.23)

\[
\frac{p}{R/c_p} \frac{p}{T} \frac{Lw_s}{c_p T} (3.31)
\]

From eqn. (3.31)

\[
\nabla (ln \rho) = \frac{c_p}{R} \left[ \nabla (ln T) - \nabla (ln \theta_E) + \frac{L}{c_p} \nabla (\frac{w_s}{T}) \right] (3.32)
\]

Substituting eqn. (3.32) into eqn. (3.5), the baroclinic term becomes

\[
-\alpha^3 \nabla \theta \times \nabla \rho = \alpha c_p \nabla T \times \left[ -\nabla (ln \theta_E) + \frac{L}{c_p} \nabla (\frac{w_s}{T}) \right] (3.33)
\]

or
\[ -\alpha^3 V_P \times V_P = aV(ln \theta_E) \times V(c_p T) + aV(ln \theta) \times V(L_w) \] (3.34)

Substituting for \( V(ln T) \) from eqn. (3.32) into eqn. (3.34) gives

\[ -\alpha^3 V_P \times V_P = aV(ln \theta_E) \times V(c_p T + L_w) \]

\[ + \left[ \alpha \frac{R}{c_p} V(ln p) + aV(ln \theta_E) - \frac{L\alpha}{c_p} V(T) \right] \times V(L_w) \]

\[ - aV(ln \theta_E) \times V(L_w) \] (3.35)

or

\[ -\alpha^3 V_P \times V_P = aV(ln \theta_E) \times V(c_p T + L_w) \]

\[ + \left[ \alpha \frac{R}{c_p} V(ln p) + aV(ln \theta_E) - \frac{L\alpha}{c_p} V(T) \right] \times V(L_w) \]

\[ - aV(ln \theta_E) \times V(L_w) \] (3.36)

that is,

\[ -\alpha^3 V_P \times V_P = aV(ln \theta_E) \times V(c_p T + L_w) \]

\[ + a\left[ \frac{R}{c_p} V(ln p) + \frac{L_w}{c_p T^2} V(T) \right] \times V(L_w) \] (3.37)

Up to this point the air could be either cloudy or dry depending on the value of \( w_s \). We will now specify that the air is saturated with respect to
either water or ice. It follows from the definition of the saturation mixing ratio \( w_s \) that

\[ w_s = \frac{e e_s}{p - e_s} = \frac{e e_s}{p} \]  \hspace{1cm} (3.38)

where, \( e_s \) is the saturated vapour pressure and

\[ e = \frac{R}{R_v} \]  \hspace{1cm} (3.39)

where \( R_v \) is the gas constant for water vapour. From eqn. (3.38)

\[ \nabla (\ln w_s) = \nabla (\ln e_s) - \nabla (\ln p) \]  \hspace{1cm} (3.40)

Also from the Clausius-Clapeyron equation

\[ \frac{d(\ln e_s)}{dT} = \frac{L}{R_v T^2} \]  \hspace{1cm} (3.41)

therefore,

\[ \ln e_s = -\frac{L}{R_v T} + \text{(constant)} \]  \hspace{1cm} (3.42)

From eqns. (3.39), (3.40) and (3.42)

\[ \frac{L w_s}{RT^2} \nabla T = \frac{1}{\epsilon} \nabla w_s + \frac{w_s}{\epsilon} \nabla (\ln p) \]  \hspace{1cm} (3.43)
Using eqn. (3.43) the last term in eqn. (3.37) may be written as

\[
\alpha \frac{R}{c_p} \left(1 + \frac{w_s}{c}\right) \nabla (\ln p) \times \nabla (L_w) \tag{3.44}
\]

or, ignoring \(w_s/c\) compared to 1, substituting for \(\nabla (w_s)\) from eqn. (3.43) into expression (3.44), and using the gas equation, the last term in eqn. (3.37) becomes

\[
\alpha^3 \frac{1}{c_p} \frac{L_w}{T^2} \nabla \rho \times \nabla \rho \tag{3.45}
\]

Substituting (3.45) into eqn. (3.37) and rearranging gives

\[
-\alpha^3 \nabla \rho \times \nabla \rho = \alpha \left(1 + \frac{c_{RT^2}}{\epsilon L_w} \right)^{-1} \nabla (\ln \theta_s) \times \nabla (c_\rho T + L_w) \tag{3.46}
\]

where

\[
A = \left(1 + \frac{c_{RT^2}}{\epsilon L_w} \right)^{-1} \tag{3.47}
\]

Eqn. (3.46) is analogous to eqn. (3.7) but \(\nabla \ln(\theta)\) is replaced by \((1-A) \nabla \ln(\theta_s)\) and \(c_\rho T\) by \((c_\rho T + L_w)\). Therefore, the analogous equation to eqn. (3.10) for saturated air is
\[ -\sigma^2 \rho \times \nabla \rho = \beta_0 (1 - A) + \rho \frac{\beta_E}{u_o} \nabla (c_p T + Lw_s) \] (3.48)

where

\[ \beta_E = \frac{d(\ln \theta_E)}{dz_o} \] (3.49)

Substituting eqns. (3.3) and (3.48) into eqn. (3.1) gives

\[ \nabla \cdot \nabla v + (1 - A) \nabla \cdot \nabla \left[ \frac{\beta_E}{\rho u_o} (c_p T + Lw_s) \right] = 0 \] (3.50)

or,

\[ \rho \frac{\beta_E}{\rho u_o} \nabla \cdot \nabla v + \nabla \cdot \nabla \left( \frac{\rho u_o}{\beta_E} (c_p T + Lw_s) \right) - \nabla \cdot \nabla \left[ \frac{\beta_E}{u_o} (c_p T + Lw_s) \right] = 0 \] (3.51)

The Bernoulli equation can be written as

\[ c_p T + g_\xi + \frac{g_\xi^2}{2} + Lw_s = \text{constant (on a streamline)} \] (3.52)

Therefore, eqn. (3.51) becomes

\[ \frac{\rho}{\rho} \eta - \frac{\beta_E}{u_o} \left( \frac{g_\xi^2}{2} + g_\xi \right) - \frac{\beta_E}{u_o} \int_0^\xi \text{Ad}(c_p T + Lw_s) = K \] (3.53)

where \( K \) is a constant on a streamline, and the integral has been taken from zero displacement of the parcel to displacement \( \xi \).

Let us consider now the integral on the right hand side of eqn. (3.53). The 1st law of thermodynamics can be written as
\[ \begin{align*} c_p \, dT - \alpha dp &= -L \, dw_s \tag{3.54} \\
\end{align*} \]

Combining this with eqn. (3.43) yields

\[ \alpha \frac{dp}{d(Lw_s)} \left( 1 - \frac{Tc_p}{\epsilon L} \right) = 1 + \frac{RT^2 c_p}{\epsilon w_s L^2} \tag{3.55} \]

From eqns. (3.54) and (3.55)

\[ 1 + \frac{RT^2 c_p}{\epsilon w_s L^2} = \left( 1 - \frac{Tc_p}{\epsilon L} \right) \frac{d(c T + Lw_s)}{d(Lw_s)} \tag{3.56} \]

Using eqn. (3.56) the integral in eqn. (3.53) can be written as

\[ \int_0^\zeta \frac{d(c T + Lw_s)}{d(Lw_s)} = \int_0^\zeta \left( 1 - \frac{Tc_p}{\epsilon L} \right) \frac{d(Lw_s)}{RT^2 c_p \left( 1 - \frac{Tc_p}{\epsilon L} \right)} \tag{3.57} \]

From eqn. (3.52)

\[ d(Lw_s) = -d(c T + g\zeta + q^2/2) \]

or, since \( q^2/2 \) is small compared with the other terms,

\[ d(Lw_s) = -(c T + g\zeta) \tag{3.58} \]

Combining eqns. (3.57) and (3.58)
\[ \int_{0}^{\zeta} \text{Ad}(c_{p}T + Lw_{S}) = -\int_{0}^{\zeta} \left( \frac{d(c_{p}T + g\zeta)}{T_{c}p} \right) \] (3.59)

If it is assumed that the moist adiabatic lapse rate \( \gamma_{m} \) is constant along a streamline \( T = T_{o} - \gamma_{m}\zeta \) and eqn. (3.59) becomes

\[ \int_{0}^{\zeta} \text{Ad}(c_{p}T + Lw_{S}) = -\varepsilon L(\gamma_{m}c_{p} - g) \int_{0}^{\zeta} \frac{d\zeta}{\gamma_{m}c_{p} + (\varepsilon L - T_{o}c_{p})} \]

or

\[ \int_{0}^{\zeta} \text{Ad}(c_{p}T + Lw_{S}) = \frac{\varepsilon L(\gamma_{m} + \gamma_{d})}{\gamma_{m}} \ln \left( 1 - \frac{\gamma_{m}\zeta}{T_{o} - \varepsilon L} \right) \] (3.60)

where, \( \gamma_{d} = -\frac{g}{c_{p}} \) is the dry adiabatic lapse rate. Since \( \gamma_{m}\zeta \ll (T_{o} - \frac{\varepsilon L}{c_{p}}) \), eqn. (3.60) becomes

\[ \int_{0}^{\zeta} \text{Ad}(c_{p}T + Lw_{S}) = -g \frac{(1 + \gamma_{m}/\gamma_{d})\zeta}{(1 - c_{p}T_{o}/\varepsilon L)} \] (3.61)

Combining eqns. (3.53) and (3.61) gives

\[ \frac{\rho_{o}}{\rho} \frac{n}{u_{o}} \left[ \frac{g^{2}}{2} + bg\zeta \right] = K \] (3.62)

where,

\[ b = 1 - \frac{1 + \gamma_{m}}{1 - c_{p}T_{o}/\varepsilon L} \] (3.63)
Eqn. (3.62) is the appropriate equation for the flow of cloudy air over a mountain and it can be seen that it is of the same form as eqn. (3.15) for dry air. Therefore, within the limits of the assumptions, each solution of eqn. (3.15) also represents a solution for a variety of completely cloudy atmospheres.

3.2.3 Boundary Conditions and Assumptions

Since the equation for the flow of cloudy air over a mountain is of the same form as that for dry air, there should be no inherent difficulty in constructing a multi-layer model which contains both dry and cloudy air. This is, in fact, the case provided the layers are continuous in the x-direction. However, if the cloud layer is discontinuous (e.g. if it evaporates downwind) the superimposition technique fails. Since our main interest is in the details of the airflow upwind of the mountain (where in the case of the Cascade Mountains the cloudy air is extensive) rather than in lee waves (which are excluded anyway by the broad mountain assumption), this restriction is not serious.

In the present version of the model, the atmosphere is divided into three layers the middle layer of which is cloudy. The boundaries between these layers are determined from the upwind sounding of relative humidity. The boundary conditions, which are non-linear, are that $\zeta$ and $\partial\zeta/\partial z$ are continuous across the boundaries between the three layers. The positions of the bounding streamlines are determined by an iterative scheme.

In order to include some of the three dimensional features of the terrain into the two dimensional model, the profile of the Cascade Mountains is varied depending on the direction of the wind.
One difficulty which is encountered in a two dimensional model is that it is unable to handle the blocking of the air in a rigorous way. However, blocking can be simulated by either introducing a fluid sink on the upwind side of the mountain or by modifying the profile of the mountain. The latter approach has been adopted in this study, however, much more work remains to be done in order to make the simulation as realistic as possible. Fortunately, the two dimensional model appears to be capable of predicting the depth of air which is affected by blocking in the following manner. When the critical wave number $\frac{\sqrt{g\theta}}{u_o}$ exceeds a certain value (generally of the order 1 km$^{-1}$ for the Cascade Mountains), the individual streamlines possess multiple solutions in the vertical. While this may be a realistic result in the lee of a mountain, it is probably not realistic on the upwind side but instead indicates the presence of blocking.

3.2.4 Some Outputs from the Airflow Model

The three outputs of the airflow model included here demonstrate the effects of varying wind direction and simulated blocking. All three outputs were run with the same upstream wind and temperature profiles, which, together with the critical wavenumbers, are shown in Fig. 3.1. The divisions between dry and cloudy air are based on the vertical distribution of relative humidity as measured by the sounding. Since the wind speed is very small at the surface, the critical wavenumber becomes very large and this produces undesirable effects. In fact it is likely that the air below 1.1 km never passes over the crest of the mountain. Only in rare cases is the wavenumber near the surface small enough to be used in the airflow model. Generally, if one does not wish to consider blocking, the critical wavenumber at some height above the surface
Fig. 3.1 Upstream soundings of wind and temperature used as input data in calculating the streamlines shown in Figs. 3.2 and 3.3. Also shown is the critical wavenumber ($\sqrt{g\beta}/u_o$).
must be extrapolated down to the surface. In cases where the wind near the surface is reasonably high this will be a reasonable approximation. On calmer days, however, the procedure is questionable.

The actual critical wavenumbers used in the calculations which follow are shown as dashed lines in Fig. 3.1. Although the three layer model was originally devised to represent two dry layers and one cloudy layer, regions of dry and cloudy air may have the same critical wavenumber and thus obey the same differential equation. Therefore, it is often convenient to place the boundaries between the three layers at locations which differ from those which define the cloudy layer.

The information shown in Fig. 3.1 was used as input data for the theoretical model, and the critical wavenumber at 1.1 km was extrapolated to the surface. The streamlines predicted by the model when no account is taken of blocking are shown in Fig. 3.2. The sounding data shown in Fig. 3.1 were obtained from a station with elevation 0.55 km above MSL, located on the western slope of the Cascades. The wind and temperature profiles at $x = -\infty$ where the elevation is zero are required for calculating the critical wavenumbers for the model. The variation of the wind field above surface at $x = -\infty$ is assumed to be the same as its variation above surface at the sounding station. The temperature profile is obtained using the parcel method and assuming that the air at $x = -\infty$ is adiabatically lifted 0.55 km to reach the sounding station. Calculation of the critical wavenumbers at $x = -\infty$ simply results in a downward displacement by 0.55 km of the values shown in Fig. 3.1. The smoothed profile of the mountain shown in Fig. 3.2 corresponds to that for a westerly airflow over the Cascade Mountains. The winds over the
Fig. 3.2 Streamlines predicted by airflow model for a westerly flow over the Cascade Mountains when no account is taken of blocking. Input data is that shown in Fig. 3.1.
mountain are calculated from the continuity equation (see §3.4.2). It can be seen from the separations of the streamlines, that the maximum downstream winds occur just east of the crest and they are about 50% greater than the upstream velocities. The maximum updrafts and downdrafts are 0.5 and 1.2 m sec\(^{-1}\) respectively.

When blocking is simulated for a westerly airflow the results shown in Fig. 3.2 are obtained. The method used for simulating blocking is to modify the ground profile, keeping the height of the mountain peak and its half-width constant, but changing the ground level at \(x = -\infty\) so that the modified profile of the mountains corresponds to the top of the blocked layer. The true mountain profile and the simulated profile are both shown in Fig. 3.3. The effect of simulating blocking is, of course, to reduce the influence of the mountain on the upstream flow. Thus the maximum winds are now only 20% greater than the upstream winds. The maximum updrafts and downdrafts are now 0.2 and 0.4 m sec\(^{-1}\).

In the third case (Fig. 3.4), blocking has been simulated in the same manner as in Fig. 3.3, but the ground profile has been changed to correspond to southwesterly flow. In this case the Cascade Mountains present several high peaks at \(x > 0\). (The main west-east watershed divide is located at about \(x = -20\) km.) In the region \(x < 0\) the magnitude of the updraft and downdrafts are of the same magnitude as those shown in Fig. 3.3, and are significantly less than those shown in Fig. 3.2.

3.3 **Cloud Microphysics**

Our main interest in this section is to determine the origin of the precipitation particles which reach the ground as snow in the Cascade
Fig. 3.3 Streamlines predicted by airflow model for a westerly flow over the Cascade Mountains when blocking is simulated by modifying the profile of the Cascade Mountains. Input data is that shown in Fig. 3.1.
Fig. 3.4 Streamlines predicted by airflow model for a southwesterly flow over the Cascade Mountains when blocking is simulated by modifying the profile of the Cascade Mountains. Input data is that shown in Fig. 3.1.
Mountains, and to predict the effects which changes in the concentrations of ice particles (which may be accomplished, for example, by artificial seeding) will have on the trajectories of precipitation particles and the distribution of snowfall on the ground.

The trajectory of a cloud or precipitation particle can be determined if at each point in space the terminal fall speed of the particle and the magnitude and direction of the wind field is known. The latter is predicted by the airflow model previously described. In this section we present the equations which are used to determine the rates of increase in the masses and the fall speeds of ice particles. The particles are assumed to grow by diffusion from the vapor phase and by collecting supercooled cloud droplets (riming). Growth by aggregation with other ice particles is not considered at this time.

### 3.3.1 Growth by Diffusion from the Vapor Phase

The rate of increase in the mass $M$ of an ice particle due to deposition from the vapor phase is given by

$$\frac{dM}{dt} = 4\pi CGS_i$$

where, $C$ is the electrostatic capacity of the ice particle, $S_i$ the supersaturation of the air relative to ice and

$$G = \frac{D_{Dv}}{\rho_s^2} \left(1 + \frac{DL^2}{RT} \rho_o \right)^{-1}$$

where, $D$ is the diffusion coefficient of water vapor in air, $L$ the latent heat of deposition, $\rho_v$ and $\rho_s$ the densities of water vapor and ice respectively,
the molecular weight of water, \( R \) the gas constant, \( T \) the temperature in \( ^\circ \text{K} \), and \( k \) the thermal conductivity of air. If the ice particle is plate-like, it can be represented by a circular disc of radius \( r \) in which case

\[
C = \frac{2r}{\pi} \quad (3.66)
\]

and

\[
\frac{dM}{dt} = 6rG_{l} \quad (3.67)
\]

3.3.2 Growth by Rimeing

The rate of increase in the mass of an ice particle by rimeing can be written as

\[
\frac{dM}{dt} = A(V_{c} - V_{d})EX \quad (3.68)
\]

where, \( A \) is the effective cross-sectional area of the particle involved in the capture of droplets, \( V_{c} \) and \( V_{d} \) the terminal fall speeds of the ice particle and the cloud droplets respectively, \( E \) the collection efficiency, and \( X \) the liquid water content of the cloud. In the case of plate-like or spherical ice particles \( A = \pi r^{2} \), where \( r \) is the radius of the equivalent disc for a plate-like particle and it is equal to the radius of the particle if it is spherical. Therefore,

\[
\frac{dM}{dt} = \pi r^{2} (V_{c} - V_{d})EX \quad (3.69)
\]
3.3.3 Critical Concentrations of Ice Particles

The critical concentration $N_c$ of ice particles is defined as that concentration for which the total mass growth of the ice particles by deposition from the vapor phase is equal to the rate of supply of water vapor. Therefore,

$$N_c \frac{dM}{dt} = \frac{c_p}{L} (\gamma_d - \gamma_m)w$$  \hspace{1cm} (3.70)

where, $c_p$ is the specific heat of dry air at constant pressure, $\gamma_d$ and $\gamma_m$ the temperature lapse rates of dry air and moist air respectively, and $w$ the updraft velocity of the air. In the case of a plate-like ice particle $\frac{dM}{dt}$ is given by eqn. (3.67), and eqn. (3.70) becomes

$$N_c = \frac{c_p (\gamma_d - \gamma_m)w}{8Lr_{GS}}$$  \hspace{1cm} (3.71)

3.3.4 Terminal Velocities and Masses of Ice Particles

The functional dependence of the mass $M$ and the terminal fall speed $V_c$ of an ice particle on the radius $r$ are assumed to be of the form

$$M = a(r)^b$$  \hspace{1cm} (3.72)

and,

$$V_c = c(r)^d$$  \hspace{1cm} (3.73)
where the numerical values of \(a, b, c\) and \(d\) depend on the type of ice particle.

For graupel particles we take \(a = 0.52\) and \(b = 3\) for all values of \(r\) (Nakaya and Terada, 1934). For \(r > 0.12\) cm we take \(c = 640\) and \(d = 0.633\) (Nakaya and Terada, 1934), while for small graupel particles we assume that they fall with the same speed as a sphere of the same radius and mass.

Dendritic crystals are divided into three size ranges. The crystals which fall with a Reynolds number less than 0.1 \((r < 2.37 \times 10^{-3}\) cm\) have a density of 0.91 gm cm\(^{-3}\) and an axial ratio \((c\text{-axis}/a\text{-axis})\) of 4.08 (Auer and Veal, 1970). The terminal velocity of these crystals is computed from the equation for Stoke's flow. For large dendritic crystals \((r > 0.1\) cm\), the mass is related to the size by eqn. (3.72) with \(a = 1.51 \times 10^{-3}\) and \(b = 2\) (Nakaya and Terada, 1934), and the velocity relation used is an average of the results of Brown (1970) and Nakaya and Terada, namely, \(c = 77.0\) and \(d = 0.32\). For dendritic crystals with \(2.37 \times 10^{-3}\) cm < \(r < 0.1\) cm, the mass and velocity are obtained by interpolating logarithmically between the values at \(r = 2.37 \times 10^{-3}\) cm and \(r = 0.1\) cm.

The values of \(a, b, c\) and \(d\) for different crystal types and size ranges are summarized in Table 3.1.

3.4 Combination of Airflow Model with Microphysics

The wind, temperature, and liquid water fields at any point are predicted by the airflow model which requires wind, temperature, and humidity data from an upwind sounding. The starting locations and concentrations of ice particles are specified, and the growth and horizontal and vertical displacements of the ice particles with time are calculated.
### TABLE 3.1

MASS-SIZE AND FALL SPEED-SIZE RELATIONSHIPS USED IN NUMERICAL MODEL

<table>
<thead>
<tr>
<th>Crystal Radius (cm)</th>
<th>Crystal Mass (gm)</th>
<th>Crystal Terminal Velocity (cm sec&lt;sup&gt;-1&lt;/sup&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Graupel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r &lt; 0.12$</td>
<td>$M = 0.52 r^3$</td>
<td>$V_c = 1.73 \times 10^3 r^{1.1}$</td>
</tr>
<tr>
<td>$r &gt; 0.12$</td>
<td>$M = 0.52 r^3$</td>
<td>$V_c = 6.40 \times 10^2 r^{0.633}$</td>
</tr>
<tr>
<td><strong>Dendrites</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$r &lt; 2.37 \times 10^{-3}$</td>
<td>$M = 1.40 r^3$</td>
<td>$V_c = 5.37 \times 10^5 r^2$</td>
</tr>
<tr>
<td>$2.37 \times 10^{-3} &lt; r &lt; 0.1$</td>
<td>$M = 9.31 \times 10^{-4} r^{1.79}$</td>
<td>$V_c = 1.72 \times 10^2 r^{0.67}$</td>
</tr>
<tr>
<td>$r &gt; 0.1$</td>
<td>$M = 1.51 \times 10^{-3} r^2$</td>
<td>$V_c = 76.9 \times r^{0.32}$</td>
</tr>
</tbody>
</table>
3.4.1 Definition of Symbols

- **x, z** Coordinates of horizontal and vertical directions.
- **z_o** Vertical location at x = -∞ of streamline passing through (x, z).
- **Δz, Δz_o** Vertical separations between two streamlines at x = x and x = -∞.
- **u, u_o** Horizontal wind components at (x, z) and (-∞, z_o), respectively.
- **w** Vertical wind component at (x, z).
- **tan θ** Slope of streamline at (x, z).
- **T, T_o** Temperatures at (x, z) and (-∞, z_o), respectively.
- **X, X_o** Liquid water contents at (x, z) and (-∞, z_o), respectively.
- **c_p** Specific heat of dry air at constant pressure.
- **E** Collection efficiency.
- **H_c** Height of cloud base.
- **M** Mass of ice particle.
- **r** Radius of ice particle.
- **t** Time.
- **Δt** Time increment in calculating increase in mass of ice particle.
- **V_c, V_d** Terminal velocities of ice crystals and cloud droplets, respectively.
- **γ_d, γ_m** Temperature lapse rates of dry air and saturated air, respectively.
- **N_o** Concentration of ice particles.
- **N_c** Critical concentration of ice particles.
3.4.2 Equations for Wind, Temperature, and Liquid Water Fields

The horizontal wind velocity $u$ is obtained from the equation of continuity along a stream tube. The compressibility of air is ignored.

$$ u = \frac{\Delta z}{\Delta z} u_o $$  \hspace{1cm} (3.74)

The upstream wind velocity $u_o$ is obtained from the upwind sounding. The vertical wind component $w$ is then

$$ w = u \tan \theta $$ \hspace{1cm} (3.75)

where $\theta$ is calculated from the airflow model output.

Since adiabatic flow is a basic assumption of the airflow model, the temperature field is obtained from the upstream temperature profile using the parcel method. Therefore,

$$ T = T_o - \int_0^z \gamma(z') \, dz' $$ \hspace{1cm} (3.76)

The value of $\gamma(z')$ is either $\gamma_d$ or $\gamma_m$ depending on whether $z'$ is inside or outside of the cloudy layer. Hence

$$ T = T_o - \gamma_d(z - z_o) \hspace{1cm} (z, z_o < H_c) $$
$$ T = T_o - \gamma_d(H_c - z_o) - \gamma_m(z - H_c) \hspace{1cm} (z_o < H_c < z) $$
$$ T = T_o - \gamma_m(z - z_o) \hspace{1cm} (H_c < z, z_o) $$ \hspace{1cm} (3.77)
The liquid water content $X$ is also calculated using the parcel method. We have

$$
X = \begin{cases} 
\frac{c}{L} (\gamma_d - \gamma_m) (z - H_c) & (z_o < H_c) \\
X_o + \frac{c}{L} (\gamma_d - \gamma_m) (z - z_o) & (z_o > H_c)
\end{cases}
$$

(3.78)

3.4.3 Equations for Crystal Growth and Displacement

The positions and sizes of the ice particles are calculated at time increments $\Delta t$. The wind, temperature, and liquid water content when the particle is at $[x(t), z(t)]$ are also determined. These values are assumed constant over the path of the particle during the next time increment. The critical concentration of ice particles is calculated to determine the growth mode of the particle over the next time increment. Then the appropriate growth equation and the mass-radius and velocity-radius relations may be manipulated to obtain the particle position and radius at time $(t + \Delta t)$. The successive positions of the ice particles are calculated from the starting position until the particle reaches ground level. The program output consists of these successive positions, the particle size and precipitation rate at ground level, and the particle size and winds, temperature, and liquid water content at positions where the mode of growth of the particle changes.

(a) Glaciated Condition ($N_o > N_c$)

Under glaciated conditions the ice particles grow solely by diffusion, and their growth rate is limited by the rate of supply of water vapor due to the adiabatic lifting of the surrounding air. Thus
From eqns. (3.72) and (3.79)

\[
\frac{dr}{dt} = \frac{c_p w}{N_o La} \left( \gamma_d - \gamma_m \right) \quad (3.80)
\]

This is integrated to give

\[
r(t + \Delta t) = \left[ r(t)^b + c_p (\gamma_d - \gamma_m) \frac{w\Delta t}{N_o La} \right]^{1/b} \quad (3.81)
\]

The total vertical velocity of the particles is

\[
\frac{dz}{dt} = w - V_c \quad (3.82)
\]

and use of eqn. (3.73) gives

\[
\frac{dz}{dr} = \frac{w - cr^d}{dr/dt} \quad (3.83)
\]

Since \(dr/dt\) is a known function of \(r\) (eqn. 3.80) this may be integrated to yield

\[
z(t + \Delta t) = z(t) + w\Delta t - \frac{abcN L_0}{(b+d)c_p (\gamma_d - \gamma_m)w} \left[ r(t + \Delta t)^{b+d} - r(t)^{b+d} \right] \quad (3.84)
\]

The horizontal position is simply
\[ x(t + \Delta t) = x(t) + u\Delta t \]  \hspace{1cm} (3.85)

(b) Non-Glaciated Conditions \( (N_o < N_c) \)

In this case the ice particles may grow both by diffusion and riming. The growth equation from eqns. (3.67) and (3.69) is

\[ \frac{dM}{dt} = \pi r^2 (V_c - V_d)EX + 8rGS_i \]  \hspace{1cm} (3.86)

or using eqn. (3.72)

\[ \frac{dr}{dt} = \frac{r^{1-b}}{ab} \left[ \pi r^2 (V_c - V_d)EX + 8rGS_i \right] \]  \hspace{1cm} (3.87)

The total fall velocity of the ice particle is given by

\[ \frac{dz}{dt} = w - cr^d \]  \hspace{1cm} (3.88)

When the particles are small we may put \( E = 0 \), and

\[ r(t + \Delta t) = [r(t)^{b-1} + \frac{8GS_i}{ab} (b-1)\Delta t]^{1/b-1} \]  \hspace{1cm} (3.89)

\[ z(t + \Delta t) = z(t) + w\Delta t \]

\[ \frac{abc[r(t + \Delta t)^{b+d-1} - r(t)^{b+d-1}]}{8(b+d-1)GS_i} \]  \hspace{1cm} (3.90)
and,

\[ x(t + \Delta t) = x(t) + u\Delta t \]  \hspace{1cm} (3.91)

For larger particles \( E \neq 0 \), and eqns. (3.87) and (3.88) are simultaneously numerically integrated from \( t \) to \( (t + \Delta t) \) to yield \( r(t + \Delta t) \) and \( z(t + \Delta t) \) assuming \( E = 1 \). Eqn. (3.91) is used to evaluate \( x(t + \Delta t) \).

3.5 Some results from the Theoretical Model

In practise results are obtained from the theoretical model in the following manner. The airflow model (§3.2) is first run using an upwind sounding of temperature and winds and the results (i.e. streamlines) are stored on tape. Subsequently, any number of ice particle trajectories can be determined using either postulated or measured ice crystal concentrations \( (N_o) \).

Three sample outputs are shown in Figs. 3.5, 3.6, and 3.7. The airflows used to obtain these results correspond to Figs. 3.3, 3.2, and 3.4, respectively (see §3.2.4). The wind and temperature profiles in Fig. 3.1 correspond to the horizontal position \( x = -40 \) km. Figs. 3.5 and 3.6 show calculations for a west wind, while Fig. 3.7 is for a southwest wind. There is a marked difference in the terrain profile that is presented to the wind in these two cases but most of the difference is downwind of the target area. In both cases the target is the zero of the horizontal scale \( (x = 0) \). The water shed divide is the rise of land immediately upwind of the target. When the wind blows from the west the terrain downwind of the target area falls away.
Fig. 3.5 Predicted trajectories of growing precipitation particles as they fall out over the Cascade Mountains in a westerly airstream. The streamlines used in the calculations are those shown in Fig. 3.3 (simulated blocking). Number at end of each trajectory gives the precipitation rate of water equivalent in cm hr⁻¹ originating from indicated trajectory.
Fig. 3.6 Predicted trajectories of growing precipitation particles as they fall out over the Cascade Mountains in a westerly airstream. The streamlines used in the calculations are those shown in Fig. 2.2 (no blocking). Number at end of each trajectory gives the precipitation rate of water equivalent in cm hr⁻¹ originating from the indicated trajectory.
Fig. 3.7 Predicted trajectories of growing precipitation particles as they fall out over the Cascade Mountains in a southwesterly airstream. The streamlines used in the calculation are those shown in Fig. 3.4 (simulated blocking). Number at end of each trajectory gives the precipitation rate of water equivalent in cm hr⁻¹ originating from the indicated trajectory.
into the broad Ellensburg valley. To the north of this valley is a region of high mountains which is the downwind region for a southwesterly wind.

Fig. 3.5 shows six sample trajectories, all starting 50 km upwind of the target area. Blocking has been simulated in this case so that the mountain crest does not appear to be as high as it is in Fig. 3.6 where blocking is ignored. It should be noted that when blocking is simulated the trajectories predicted by the model terminate at the modified profile of the mountains. The trajectories of the particles below this level, which are not shown in Fig. 3.5 (or Fig. 3.7), will depend on the low level winds on the east side of the mountains. The trajectories start from both 1.5 km and 2.0 km above sea level. For each height three different concentrations of ice particles are assumed, $1 \times 10^{-3}$, $25 \times 10^{-3}$, and $100 \times 10^{-3}$ and the resulting trajectories calculated. Although the variation in the natural concentrations of ice particles is great, our observations indicate that a concentration of $1 \times 10^{-3}$ is typical in natural clouds over the Cascade Mountains. In the case of the particles which originate at 2.0 km, when the crystal concentration is increased the ice particles are carried further downwind and instead of reaching the ground to the west of the Cascade Divide they are carried over the crest and land east of the divide. However, the precipitation rate at the ground due to particles falling along this trajectory (which is shown in cm hr$^{-1}$ water equivalent in Fig. 3.5) decreases as the concentration of ice particles increases.

If we consider the ice particles which originate at an altitude of 1.5 km it is seen from Fig. 3.5 that an increase in the number concentration of ice particles from 1 to $25 \times 10^{-3}$ has no significant effect on the trajectory of the particles. It does, however increase the precipitation rate. An increase in
number concentration of ice particles to $100\text{lit}^{-1}$ lengthens the trajectory, so that the particles are carried over the Cascade crest, and decreases the precipitation rate.

The above results can be readily understood as follows. In the case of the particles which originate at an altitude of 1.5 km, when the concentration of ice particles is $1\text{lit}^{-1}$ the cloud does not convert the available water vapor into precipitation in the most efficient manner. An increase in the ice particles to $25\text{lit}^{-1}$ does not cause a reduction in the growth rate of an individual ice particle, therefore, all 25 ice particles per liter grow at a similar rate to the original one crystal per liter. Consequently, the trajectory does not change but the precipitation rate goes up by a factor of 25. (This result is, of course, somewhat unrealistic since the model does not take into account the effect which the growing ice particles will have on the liquid water content of the cloud if the concentration of ice particles is less than the critical concentration. This omission becomes increasingly serious as the ice particle concentration approaches the critical concentration.) When the ice particle concentration is increased to $100\text{lit}^{-1}$ the particles begin to compete for the available moisture. Roughly the same total mass of moisture is available as in the case of $25\text{lit}^{-1}$ but it is now divided between 100 particles per liter. The growth rates and fall speeds of the ice particles are therefore reduced so that the precipitation rate decreases and their trajectories lengthen.

Figure 3.6 shows a set of trajectories corresponding to the upper set of trajectories in Fig. 3.5 but in this case the air has not been blocked.
Instead the lower air was given a critical wave number which would enable it to flow over the mountain. It can be seen that the end points of the trajectories have been shifted upwind and the precipitation rate has increased. Although this is rather a crude test of the effect of blocking, it does indicate that the blocking should not be ignored. The abrupt changes in the trajectory for a concentration of 25 ice particles per liter near the point $x = -35$ km occur because the conditions change from non-glaciated to glaciated for a short period of time, back to non-glaciated due to strong uplift, and then return to glaciated.

Fig. 3.7 shows a simulated blocking run for a southwest wind. The primary difference between this case and that for a west wind can be seen at crystal concentration of $100$ $\text{cm}^{-1}$. The trajectory has been lengthened to the point that the ice particles are carried over the Cascade Divide and well downwind to reach the ground at about $x = +30$ km. Due to the mountains in this area and the enhanced lift which they produce, the ice particles undergo renewed growth and the precipitation rate again increases. This prediction might be difficult to verify in the field because of the rugged terrain of the Cascade Mountains and long trajectories of the ice particles. However, it is an interesting possibility that one of the best ways to increase precipitation on the east side of the divide might be to capitalize on the rise in terrain east of the Cascade Divide in this fashion.

The previous figures showed the results of a few sample trajectories. The subsequent figures show the results of a composite of many trajectories. Figs. 3.8 and 3.9 show the results of increasing the ice particle concentration beyond $1$ $\text{cm}^{-1}$. The results are therefore normalized to this
Fig. 3.8 Model predictions of the effects of ice particle concentration on precipitation rate and horizontal pathlength of precipitation for westerly flow (simulated blocking) over Cascade Mountains. "Artificial seeding" refers to a concentration of ice particles of 25 or 100 $\ell^{-1}$ and "natural" refers to a concentration of 1 $\ell^{-1}$.
Altitude above MSL at which precipitation originates

$\Delta = 1.5 \text{ km}$
$\square = 2.0 \text{ km}$
$\circ = 2.5 \text{ km}$

Fig. 3.9 Model predictions of the effects of ice particle concentration on precipitation rate and horizontal pathlength of precipitation for southwesterly flow (simulated blocking) over Cascade Mountains. "Artificial seeding" refers to a concentration of ice particles of 25 or 100\text{ L}^{-1} and "natural" refers to a concentration of 1\text{ L}^{-1}.
base concentration. Thus, if for a concentration of ice particles of $25l^{-1}$ the trajectory is increased in length by a factor of two and the precipitation increased by a factor of 10 over that for one ice particle per liter, this is indicated as a point with an abscissa of 2 and an ordinate of 10. Fig. 3.8 shows the results for a west wind and Fig. 3.9 for a southwest wind. The results for ice particle concentrations of 25 and 100$l^{-1}$ are essentially the same on these plots.

Although there is considerable scatter in the points shown in Fig. 3.8 a distinct trend can be discerned. The results indicate that precipitation can be increased by increasing the concentrations of ice particles provided that the trajectories are not lengthened by more than about a factor of 2 (i.e. 30 km). Also, the precipitation efficiency appears to be greater if the increase in ice particle concentration occurs at low elevations (as represented by the triangles) rather than at high elevations (as represented by the circles).

The last conclusion is also seen in the results shown in Fig. 3.9. However, in this case the decrease in precipitation which might otherwise accompany the long trajectories at high concentrations of ice particles is off-set by the continued growth of the ice particles caused by further lifting in the region downwind of the Cascade Divide.

Fig. 3.10 represents an entirely different way of presenting the same basic data. Here the distributions of precipitation across the mountain for the airflow corresponding to Figs. 3.3 and 3.5 are examined. The curve labeled "rimed" shows the calculated distribution of precipitation if the whole cloud had an ice crystal concentration of $1l^{-1}$. The curve labeled
Fig. 3.10 Model predictions of the distribution of precipitation across the Cascade Mountains in a westerly airflow (simulated blocking) when the particles grow (a) by riming (1 ice particle \( \text{m}^{-1} \)) and (b) by diffusion from vapor phase (25 or 100 ice particles \( \text{m}^{-1} \)).
"diffusion" shows the combined results for 25$\ell^{-1}$ and 100$\ell^{-1}$ (they did not differ significantly). These results indicate that increasing the ice particle concentration should decrease the precipitation rate over the mountain but increase it downwind. This last conclusion must be treated with caution if one wishes to equate the "rimed" precipitation with natural precipitation. For ice particle concentrations of the order of 1$\ell^{-1}$ or less, the precipitation rate predicted by the model will be linearly proportional to the ice particle concentration for nearly all cases. Thus if we had used an ice particle concentration of 0.1$\ell^{-1}$ or 10$\ell^{-1}$, which are within the observed variations of natural ice particles, the results would be quite different. This indicates the importance of establishing the background concentrations of ice particles in clouds under various conditions.
SECTION 4

AIRBORNE OBSERVATIONS AND MEASUREMENTS

4.1 Pacific Northwest Storms and Clouds

From observations and measurements made in aircraft flights across the Cascade Mountains during the winter of 1970-71 and previous winters, some general conclusions have emerged on the structure of clouds over the Cascade Mountains and these are summarized below.

4.1.1 Pre-frontal Conditions

In pre-frontal conditions the clouds over the Cascade Mountains are generally layered, ranging from stratus near the ground to cirrus at about 30,000 ft. There is often a deep layer of clear air between the tops of the orographic cloud and the base of the frontal clouds. Continuous cloud in the vertical direction is usually found only in the immediate vicinity of a front.

Well ahead of a front the air is normally sub-saturated with respect to water from the surface to 6,000 ft at Greenwater (Fig. 2.1). As a well-developed front approaches the Washington coast, dry easterly winds flow across the Cascade Mountains. These produce upslope winds on the eastern slopes of the Cascades and in this region the air is generally saturated from the surface up to about 6,000 ft. From about 6,000 to 12,000 ft the airflow over the Cascades is generally from the southwest and the air is near water saturation. As a consequence of this distribution of winds with height, solid precipitation particles which land near the Cascade crest often originate west of the Cascades but they may pass up to 40 miles east of the crest before reaching the ground (see §5.9).
The occluded fronts which pass over Washington State are often in their dying stages. Consequently, only a limited amount of moisture is advected upwards. Thus from about 12,000 to 30,000 ft the dewpoint depression increases; at 18,000 ft it usually is about 2 to 5°C. However, if the frontal system originates well to the southwest, water saturated conditions may extend up to 16,000 ft although this is not a common situation.

At temperatures between 0 and -10°C the types of ice particles collected from the aircraft varies with location. Over the Puget Sound the airflow is generally from the southwest and the air is close to water saturation. Sub-water saturated, warm region, solid slender columns are common, but sheaths and needles are also collected. Over the western slopes of the Cascades the low level easterly winds are usually strong and produce drying conditions, but at a few thousand feet above the surface the air is moist and from the southwest. However, this water-saturated layer of air is only a few thousand feet thick extending up to about the -10°C level. Solid columns and irregular ice particles are common in this region. Over the eastern slopes of the Cascades, the low level easterly winds produce orographic clouds and water saturated conditions. Needles, sheaths and irregular ice particles are dominant in this region although solid columns are also observed.

At temperatures between -10 and -20°C water saturation is not common in the pre-frontal portions of winter storms. Typical crystals observed are irregular ice particles, plates and sub-water saturated star-like crystals with broad branches and sector-like branches. However, over the Cascades the orographic effect occasionally produces ice crystals which have grown in water saturated air (e.g. dendrites).
Ice crystals which form at temperatures below $-20^\circ$C and in air close to water saturation are also common in pre-frontal conditions. These include solid and hollow bullets, solid and hollow columns, side planes, radiating assemblages of plates, sectors and dendrites.

A significant feature of the pre-frontal clouds is that ice particles dominate over water droplets. The liquid water content is generally between 0 and 0.5 g m$^{-3}$. Above the $-10^\circ$C the concentration of droplets falls off rapidly and riming is seldom observed on the ice crystals. The liquid water content below the $-10^\circ$C level over the western slopes of the Cascades increases with increasing wind speed from the southwest, and the ratio of ice to water decreases. Consequently, crystals at ground level in pre-frontal clouds near the crest of the Cascades, generally show some evidence of riming which probably occurs within 5,000 ft of the surface (see §5.5).

4.1.2 Transitional and Post-frontal Conditions

The differences in atmospheric conditions between pre-frontal and post-frontal conditions can be quite marked, particularly when cold air is being strongly advected into the region. In general, the air becomes increasingly unstable and the cloud tops begin to decrease in height as drier air moves in aloft. Convective clouds become more frequent but over the Cascades they are generally embedded in stratiform orographic clouds and are only detectable by their turbulence and the showery nature of the precipitation they produce. The orographic effect may be quite pronounced following the passage of the front since the winds tend to become westerly at all levels.

Due to the decrease in height of the cloud tops, low-temperature ice crystals become less common as the front passes through. Also, the ratio of
ice to water is less than in pre-frontal conditions and water droplets become increasingly common even at temperatures as low as -15°C. At temperatures above about -8°C the clouds frequently contain only supercooled water. Between -8 and -14°C frozen drops, irregular ice particles, dendrites and stellars are found. Rimming is common and graupel particles are collected on occasions. In post-frontal conditions the majority of the more fragile star-like crystals are fragmented both when collected from an aircraft and on the ground.

Turbulence readings are much higher in post-frontal than pre-frontal conditions and the distributions of liquid water and ice particles are more variable. Interestingly, the degree of irregularity of the ice crystals appears to increase with increasing turbulence.

A summary of the conditions in pre-frontal and post-frontal clouds over the Cascade Mountains is contained in Table 4.1.

4.1.3 Orographic Effect of the Cascade Mountains

The effects of the Cascade Mountains on clouds in frontal situations have been mentioned above. In the absence of frontal activity, but with a strong westerly airstream, extensive orographic clouds form over the western slopes of the Cascades which can give rise to light but steady precipitation. These clouds are generally layered with the lowest layer extending from the tops of the mountains to about 8,000 ft, with further layers up to 12,000 ft and sometimes higher layers. Clouds are thinner on the leeward slopes. There is often a thin haze of ice crystals which appear to originate from the denser clouds west of the Cascade divide. This haze is usually thin enough for the ground or sun to be seen through it. Water droplets predominate in the wave clouds,
<table>
<thead>
<tr>
<th></th>
<th>Clouds</th>
<th>Crystal Types</th>
<th>Relative Concentration of Ice Particles</th>
<th>Liquid Water Content (g m⁻³)</th>
<th>Turbulence</th>
<th>Relative Concentration of Aggregated Ice Particles</th>
<th>Precipitation Rate (in/hr)</th>
<th>Orographic Effect of Cascade Mountains</th>
<th>Special Features</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PRE-FRONTAL</strong></td>
<td>Layered from surface to 30,000 feet with clear layers.</td>
<td>Often water saturated crystals at temperatures &lt; -20°C (usually above 18,000 feet) e.g. hollow bullets, side planes, hollow columns, radiating assemblage of plates, sectors and dendrites, also solid columns and solid bullets, combinations of bullets. Usually sub-saturated at temperatures &gt; -20°C (usually below about 18,000 feet) e.g. plates, some crystals with broad branches and sector-like branches and warm region columns, thick plates.</td>
<td>Western slopes of Cascades: 1000 to 15,000 Eastern slopes of Cascades: 250 to 5,000 Puget Sound Basin: 500 to 10,000.</td>
<td>Western slopes of Cascades: 750 to 10,000. Eastern slopes of Cascades: 100 to 5,000. Puget Sound Basin: 200 to 7,500.</td>
<td>0 to 0.5. Some increase on western slopes of Cascades. Liquid water concentration near zero for temperatures &lt; -10°C (higher than about 13,000 feet).</td>
<td>0 to 100</td>
<td>Very little except near the surface in the Cascades. More riming on eastern slopes of Cascades.</td>
<td>Steady between 0.05 to 0.10</td>
<td>Increase in water saturated crystals such as dendrites, needles and sheaths. Increase in concentrations of aggregates on western slopes. Decrease in concentrations of ice crystals on the eastern slopes. Higher precipitation rate on western than eastern slopes.</td>
</tr>
<tr>
<td><strong>TRANSITIONAL</strong></td>
<td>Layered to 18,000 feet with embedded cumulus.</td>
<td>Water saturated crystal types at all levels, e.g. hollow bullets, side planes, hollow columns, combinations of bullets, dendrites, stellar some crystals with sector-like branches and broad branches, only a few plates many sheaths and needles, some warm columns.</td>
<td>Western slopes of Cascades: 10 to 100,000 Eastern slopes of Cascades: 0 to 15,000. Puget Sound Basin: 0 to 50,000.</td>
<td>Western slopes of Cascades: 20,000 to 350,000. Eastern slopes of Cascades: 80,000. Puget Sound Basin: 10,000 to 200,000.</td>
<td>Up to about 17,000 feet (about -20°C) 0.5 to 2.0</td>
<td>Moderate to severe, particularly for warm region crystals e.g. needles and sheaths.</td>
<td>Showery. 0 to 0.30.</td>
<td>Heavy showers on western slopes, often rapid clearing on eastern slopes. Heavy riming, particularly on western slopes of Cascades near surface.</td>
<td>Graupel and frozen drops common. Concentration of crystals variable. Heavy riming, particularly on western slopes of Cascades near surface.</td>
</tr>
<tr>
<td><strong>POST-FRONTAL</strong></td>
<td>Convective with tops to 18,000 feet.</td>
<td>Few crystals generally dendrites, a few plates and some needles and sheaths.</td>
<td>Western slopes of Cascades: 8 to 10,000. Eastern slopes of Cascades 0 to 1000. Puget Sound Basin: 0 to 2500.</td>
<td>Western slopes of Cascades: 25,000 to 300,000 (many small droplets average 10 um in diameter). Eastern slopes of Cascades: 100 to 5,000. Puget Sound Basin: 0 to 15,000.</td>
<td>0.1 to 1.0</td>
<td>Moderate to severe. Strong increase on western slopes of Cascades.</td>
<td>Showery. Scattered heavy showers on western slopes.</td>
<td>Heavy showers on western slopes, often rapid clearing on eastern slopes. More riming on western than on eastern slopes, also more graupel and frozen drops on western slopes.</td>
<td>Scattered heavy geographic showers on western slopes of Cascades.</td>
</tr>
</tbody>
</table>

### Table 4.1

**SUMMARY OF MICROPHYSICAL AND SYNOPTIC DIFFERENCES BETWEEN PRE-FRONTAL, TRANSITIONAL, AND POST-FRONTAL PORTIONS OF PACIFIC NORTHWEST STORMS OVER THE CASCADE MOUNTAINS**
lower level stratus and stratocumulus.

When cloud top temperatures are below about -8 and -12°C the following ice particles are observed in the orographic clouds (listed in order of predominance): irregular plate-like crystals, irregular particles, hexagonal plates, crystals with broad branches, sectored crystals, stellars, dendrites, and bullets. For cloud top temperatures above about -8 to -12°C the predominant ice particles are irregular, warm columns, needles and sheaths. When convective clouds are present frozen drops, often in groups, are common. On the eastern slopes of the Cascades a larger proportion of the ice particles are irregular in shape and the particles are frequently rounded rather than angular, indicating that they are evaporating. Needles and sheaths are rarely observed over the eastern slopes.

Fig. 4.1 and Fig. 4.2 show isopleths for the average liquid water content across the Cascade Mountains from measurements obtained with the Johnson-Williams meter. These curves are based on measurements made during seven flights (Jan. 8, Feb. 3, 18, 22, 25, March 28, and April 1, 1971) in which the prevailing wind was in the quadrant SW through NW. Three of the flights were in pre-frontal situations, one in a post-frontal situation, in two cases a front passed over the Cascades during the flight, and in the other flight there was a north-westerly airstream over the mountains. It can be seen that, on average, the liquid water content reaches a peak value at about 13 nautical miles west of the Cascade divide and a minimum value at about 15 miles east of the divide. (N.B. Peak values of the liquid water contents are, of course, much higher than those shown in Fig. 4.1 and 4.2.)
Fig. 4.1 Isopleths of average liquid water content (in g m$^{-3}$) in cloud across Cascade Mountains based on measurements taken during flights when winds were in the quadrant SW through NW.
Fig. 4.2 Isopleths of average liquid water content (in g m$^{-3}$) in cloud across Cascade Mountains based on measurements taken during flights when winds were in the quadrant SW through NW.
Fig. 4.3 shows isopleths of the percentages of occasions on which water droplets dominated over ice particles on the continuous particle sampler. The curves are based on 145 runs of the continuous particle sampler taken during nine flights (the same seven flights as those mentioned in above paragraph plus post-frontal situations on December 28, 1970, and March 11, 1971). These results provide general confirmation of the features shown in Fig. 4.1 and 4.2.

4.2 Characteristics of Ice Particles Collected in Clouds

Ice crystals in clouds were collected and replicated using the continuous particle sampler at temperatures between 0 and -40°C. The crystal types generally support the classification scheme for natural ice crystals proposed by Magono and Lee (1966), but some differences were noted. The principal results are summarized below. For completeness some of the observations on snow crystals collected at ground level in the Cascades are also mentioned although these are discussed at greater length in §5.

4.2.1 Needles (H1a, H1b, N2a)

According to Magono and Lee (1966) and Ono (1970) needles grow in the temperature range between -4 to -6°C under water-saturated conditions. The needles sampled by Ono (1970) had a limiting a-axis dimension of 60 μm. However, needles longer than about 500 μm were not recorded. The observations of Auer and Veal (1970) suggest that needles do not reach a limiting diameter, but continue to increase with increasing length.

†For reasons of economy we have not included photographs of the many different types of ice particles discussed in this section.

§ The symbols used for the different types of ice particles are those proposed by Magono and Lee (1966).
Fig. 4.3 Isopleths for percentages of occasions on which water dominated over ice in clouds over Cascade Mountains. Data is based on runs with continuous particle sampler during flights when winds were in the quadrant SW through NW.
Needles were collected from the aircraft flying at low levels over the Puget Sound Basin. The observations confirmed the conclusion of Magono and Lee (1966) and Ono (1970) that needles grow in the temperature region between \(-4\) to \(-6^\circ\)C under water-saturated conditions. The needles collected in the air were generally elementary needles (N1a), but bundles (N1b) and even a few combinations of needles (N2a) were observed. The needles ranged in length from about 350 to over 3000 \(\mu\)m, with an average length of 850 \(\mu\)m. The needles did not reach a limiting a-axis dimension of 60 \(\mu\)m as noted by Ono (1970). Needles with widths up to 160 \(\mu\)m were observed. The needles observed in the Pacific Northwest storms appear to have a smaller length to diameter ratio than that reported by Auer and Veal (1970).

At ground level in the Cascade Mountains, most of the needles occurred as parts of aggregates or in combinations. Needles up to 4000 \(\mu\)m long were collected, but the average length was 1500 \(\mu\)m. There appeared to be more low level moisture available for the growth of needles over the Cascades. However, due to the methods of collection, it was also possible to collect larger needles at the ground than from the aircraft.

Both the air and ground observations indicate that needles can be broken up in the air. Most easily broken were fragile knife-edge tips which protruded from the main body of the crystal.

4.2.2 Sheaths (N1c, N1d, N2b)

Differentiation between sheaths, warm slender columns, and needles was often extremely difficult. A more workable definition to differentiate between these crystals is needed.
Our aircraft observations confirm the deduction of Magono and Lee, and Ono, that sheaths grow between -6 to -8°C. It appeared from the aircraft observations that the sheaths are hexagonal in shape. This agrees with the findings of Ono. Ono states that sheaths reached a limiting a-axis dimension of 80 μm regardless of length, however, due to the limiting capabilities of his sampling apparatus, sheaths longer than about 500 μm may not have been recorded. In our airborne studies sheaths generally occurred as elementary sheaths (Nlc), although bundles (Nld) and a few combinations of sheaths (N2b) were also observed. The average length of the sheaths was about 800 μm with lengths varying from about 300 μm to 2000 μm. Limited ground observations indicated a similar trend in range of lengths of sheaths, and the average length was somewhat less than 1500 μm. Sheaths with an a-axis dimension as large as 140 μm were observed.

Both air and ground observations indicated that sheaths can undergo a limited amount of break-up in the air.

4.2.3 Solid and hollow Columns (Cle, Clf, N2c, C2b)

Magono and Lee state that columnar growth occurs between -5 to -10°C (warm region columns) and below -20°C (cold region columns). Ono (1970) states that columnar growth occurs between about -3.5 to -9.5°C and below -22°C. Ono's observations indicate that columns reach a limiting a-axis dimension of 100 μm, regardless of their length. However, Auer and Veal (1970) reported columns increasing in diameter with increasing length with no apparent limit to the diameter of a column.

Our aircraft observations confirm that warm region columns originate and grow at temperatures between -5 to -10°C and that the temperatures at which
cold temperature columns occur is below -20°C. Crystals were assumed to have formed within ± 1°C of the temperature at which they were collected if their length or diameter did not exceed 100 μm. However, warm region columns were also observed to form at temperatures above -4°C. Mossop et al. (1967) also observed columns forming and growing at temperatures above -4°C but Ono (1970) found only plates above -3.5°C. Columns were also found at temperatures above -20°C, in fact at temperatures near -18°C. This suggests that the transition from plate-like to columnar-like growth at -20°C is not sharp.

The aircraft observations indicated that columns were generally present as individual crystals (Cle, Clf) although combinations of columns (N2c and C2b) were observed. At the ground, columns often occurred in aggregates. The average lengths of the warm and cold region columns were about 500 μm and 350 μm respectively. Cold region columns seldom exceeded 600 μm in length whereas some warm region columns had lengths in excess of 2000 μm. Ground observations indicate that the average length of all columns was about 500 μm.

There appears to be a fundamental difference in shape between many warm region and cold region columns. Warm region columns were generally slender and had length to width ratios well in excess of three. By contrast, cold region solid and hollow columns were invariably stubbier, having length to width ratios of about three. C-axis growth appears to dominate more in the warmer region (-5 to -10°C) than in the cold region (below -20°C). Thus, only long, slender c-axis growth crystals are usually found between -5 to -10°C (e.g., sheath and needles) but other crystals (e.g., cold region plates) exhibiting a-axis growth are observed at temperatures below -20°C. At the ground both
slender and stubbier columns were observed. However, most of the stubbier columns resembled the typical cold region hollow columns.

Our aircraft observations indicated that columns did not reach a limiting a-axis dimension after a certain c-axis dimension was attained. Data collected suggests that columns continue to increase in the a-axis dimension, although at a decreasing rate, as the c-axis dimension increases. Columns with widths of at least 240 μm were observed.

4.2.4 Thin hexagonal Plates (Pla)

The aircraft observations confirmed the findings of Magono and Lee (1966) that hexagonal plates grow between -10 and -20°C.

In the air, hexagonal plates were often observed as part of aggregates, particularly when the concentrations of plates exceeded a critical value. Single hexagonal plates were commonly observed. Some adhesion of plates was also noted. At ground level most plates were observed as parts of aggregates.

Aircraft observations indicated that many hexagonal plates were not regular, but had sides of unequal length. Also, many of the plates collected on the ground were irregular in shape. This irregularity appeared more noticeable with the larger plates and near the transition temperatures of -10 and -20°C. Plates with trapezoidal shapes were commonly observed near these temperatures. Plates were often quite regular between -12 to -17°C. In addition, plates of unusual shape (for example, with extended sides) were observed and these appeared more commonly near the transition temperatures. This type of plate growth does not appear to have been reported in the literature.

Thin hexagonal plates ranged in diameter from under 100 μm to over
1000 μm. Aircraft observations indicated the average diameter was about 350 μm. At ground level, plates as large as 3000 μm in diameter, with the average somewhere near 700 μm, were observed. The discrepancy between air and ground observations appears to stem from the fact that larger plates could be collected more easily at the ground.

Many larger hexagonal plates, with diameters well in excess of 300 μm, did not show any sign of dendritic growth at their corners. At the ground plain hexagonal plates up to 3000 μm in diameter were observed without any indication of growth at their corners. Ono (1969), on the other hand, observed dendritic growth on all plates larger than 300 μm in diameter.

Some hexagonal plates collected from the aircraft had "double growth." Frozen droplets could not be detected at the centers of these crystals, therefore, the double growth may have been due to the nature of the ice nuclei. Few hexagonal plates with double growth were observed at ground level. However, this may be due to the smaller number of single plates collected at the ground. Double growth on hexagonal plates was not common even higher in the atmosphere, and most of the plates observed on the ground were parts of aggregates.

Air and ground observations indicated that thin hexagonal plates rarely broke up due to collisions with other crystals and aggregates.

4.2.5 Thick Plates (Clg and Clh)

Our aircraft observations confirmed the results of Ono (1970) that thick plates grow between about -10 to -20°C. The thick plates were usually present as individual crystals. Thin hexagonal plates were much more common than thick plates. Ground observations indicated that thick plates were not common, but those observed were individual crystals.
Thick plates were commonly observed to have multi-layered growth. These layers were of varying shapes and sizes. The layers consisted of hexagonal plates, often with ribs, small stellar germs, sectors and other features. Often these dissimilar layers were all part of one crystal. Seldom did thick plates have frozen drops at their center in spite of the double and multi-layered growth commonly present. Ribs were not observed on thick plates less than about 300 μm in diameter.

The shapes of the plates were often odd and irregular. The irregularities and peculiarities in the shape of the crystal appeared to be accentuated near the transition temperature of -10°C. V-shaped notches were commonly found in the largest two sides of these irregularly shaped crystals.

Aircraft observations indicated that riming was seldom present on these crystals. Thick plates were larger than plain plates and ranged in diameter from about 300 μm to over 1000 μm with an average diameter of about 555 μm. Thick plates were not observed to break up in the air.

4.2.6 Star-like Crystals (P1h, P1c, P1d, P1e, P1f)

Our aircraft observations confirmed the conclusion of Magono and Lee (1966) that star-like crystals grow between about -12 to -17°C in both water-saturated and sub-water saturated conditions. In the air, star-like crystals were generally observed as individual crystals, although these crystals interlaced with other star-like crystals and as part of aggregates were not uncommon. Ground observations indicated that most star-like crystals occurred as parts of aggregates and often these aggregates consisted entirely of star-like crystals.
Aircraft observations showed that the star-like crystals were irregular in many respects. A preliminary study was made of the centers of star-like crystals. Some had no centers at all, that is, the six arms tapered in thickness and width towards the center and met in a point. The arms of many of the crystals merged as they approached the center so that a large solid center was observed. In other cases, the branches of the crystals tapered to meet in a small hexagonal plate at the center of the crystal. Occasionally, solid columns were observed in the center. Fairly often, the center appeared to be simply an irregular piece of ice. Of the many star-like crystals studied, very few were observed to have frozen drops at their centers or double growth. Many combinations were observed: frozen drops with no double growth, double growth but no frozen drops, and crystals with double growth and a frozen drop at the center. Further studies are needed to investigate the causes of these different centers.

The shapes, lengths, and widths of the branches on star-like crystals varied considerably even within the same crystal. Perhaps the most symmetric crystal was the stellar (Pld) with long slender arms. Many crystals with sector-like branches, broad branches, and even stellars, had many peculiarities and irregularities within the crystal. Very few dendrites and fern-like crystals collected at ground level had six identical branches. The atmospheric conditions which accentuate these irregularities are not known.

Star-like crystals varied considerably in size. Aircraft observations indicated that dendritic and fern-like crystals were the largest of all star-like crystal types, with diameters up to 4500 μm. Ground observations indicated that dendrites were the most numerous of the individual crystals.
collected. Several were observed with diameters in excess of 5000 μm and the average size on the ground was about 3500 μm. Because of the limiting width of the continuous particle sampler these larger dendritic crystals could not be collected intact from the aircraft.

Aircraft and ground observations indicated that stellar crystals were the next largest star-like crystals. Several stellars over 3000 μm in diameter were observed and stellars as small as 250 μm in diameter were collected from the aircraft. The average diameter was about 1000 μm in the air and about the same on the ground. Crystals with broad branches ranged in diameter from about 300 μm to 2500 μm. The average size was about 800 μm in diameter. Crystals with sector-like branches rarely exceeded 2000 μm in diameter and their average size observed in the air was about 750 μm in diameter.

Air and ground observations indicated that star-like crystals undergo extensive break-up in the air. Isolated dendritic branches were very common. Ground observations indicate that even crystals with sector-like branches break-up in the air. However, larger percentages of star-like crystals were collected intact in the air compared to crystals collected at the ground.

4.2.7 Stellar Crystals with Plates at the Tips of Branches (P2a)

Our aircraft observations confirmed the findings of Magono and Lee (1966) that stellar crystals with plates at the tips of the branches grow between -12 to -17°C. These crystals generally occurred individually in the air, but they were also found as part of aggregates. When they were observed on the ground they were generally individual crystals.

Air observations indicated that this type of stellar crystal ranged in diameter from 1500 to 4000 μm. Thus, there was a tendency for only larger
stellar crystals to develop plates at the tips of their branches. Similar trends were noted at ground level.

Observations in the air and on the ground indicated that the arms of these stellar crystals were not as slender as the arms of true stellar crystals (P1d). They appeared intermediate in width between crystals with broad branches and stellar crystals. Air observations also indicated that the centers of the crystal were highly variable. The six arms of any one crystal appeared fairly uniform in length, shape, width and degree of dendritic growth. However, there were wide variations between crystals. Not uniform within each crystal was the degree of development of the plates at the tips of the branches. At some tips plates were completely developed, while at other tips end plates had barely started growing.

Air and ground observations indicate that these crystals can break up in the air.

4.2.8 Plates with Sector-like Extensions (P2f)

Our aircraft observations indicate that plates with sector-like extensions grow between -12 to -22°C. The upper temperature limit is in fair agreement with that found by other workers, but the lower limit is somewhat lower than reported previously. Ono (1970) found these crystals growing at temperatures between -14 to -17°C. The transition from planar to columnar growth at -20°C does not appear to be a sharp transition.

Our observations confirm the findings of Ono (1970) that plates need to exceed 300 μm in diameter for sector-like extensions to develop at their corners. Plates with sector-like extensions ranged in size from 400 μm to 3000 μm in diameter. Sector-like extensions were of all types from very small,
primitive shapes to well-defined, ribbed extensions. Occasionally, sector-like extensions varied on the same crystal and showed various stages of development.

Plates on which sector-like extensions emanated varied considerably. Some plates were plain while others were quite unusual, with double and even triple hexagonal plates, and sectoring of the plate. Plates on which sector-like extensions emanated were usually symmetrical with all six sides of equal length.

Both air and ground observations indicate that these crystals can undergo breakup in the air and the sector-like extensions generally become separated from the plate. However, surprisingly, these crystals were often captured with the extensions intact.

4.2.9 Plates with Dendritic Extensions (P2g)

The aircraft observations confirmed the findings of Magono and Lee (1966) that plates with dendritic extensions grow at temperatures between -12 and -17°C. In the air these crystals were observed as individual crystals and as parts of aggregates but they were not common either in the air or at ground level.

Hexagonal plates from which dendritic extensions originate are at least 300 µm in diameter. This result agrees with the findings of Ono (1970). The plates were usually plain and regular in shape with all six sides of equal length. Air observations indicated that the size range of these crystals was large with the crystal length generally between 1500 to 4500 µm.

Both air and ground observations showed that the crystals break up readily in the air particularly at the point of the extension to the plate, or within the delicate dendritic extensions.
According to Magono and Lee, scrolls grow only between -8 and -10°C. However, Ono (1970) observed scrolls only at temperatures below -22°C. Our aircraft observations indicate that scrolls grow in two distinct temperature regimes: -8 to -10°C, and below -19°C. They appeared more commonly at temperatures below -19°C. Further investigations are needed to clarify the differences between scrolls grown between -8 to -10°C and below -19°C.

Scrolls were commonly found as individual crystals, but were also observed as aggregates. They were not observed on the ground as individual crystals, although they could have been hidden in aggregates. Because of the nature of the continuous particle sampler scrolls were often too long to be fully replicated. Normally replicated was a portion of the columnar part of the crystal and one of the ends. Because of the shortness of the columnar part of the crystal, the scrolls often impacted on their ends. Thus, measurements of the widths of these crystals were possible. Air observations indicated that scrolls were wide, ranging in size from 100 μm to 600 μm. However, the shape and size of the scroll part of the crystal varied considerably from one crystal to another.

The observations indicated that scrolls do not break up readily in the air.

Nakaya (1954) observed that two-branched crystals grow in the temperature range -12 to -17°C. Our aircraft observations indicated that two-branched crystals were usually found in water-saturated conditions at temperatures between -12 to -17°C. These crystals generally were observed as individual
crystals and both air and ground observations indicated that they were fairly rare.

Magono and Lee (1966) indicate that the most common two-branched crystal has a separation of 180° between the two branches. Rarely are two-branched crystals with 60° or 120° angle of inclusions observed.

Both air and ground observations indicated that two-branched crystals are prone to break up in the air.

4.2.12 Dendritic Crystal with Twelve Branches (P4b)

The air observations indicated that dendritic crystals with twelve branches grow between -12 to -17°C under highly supersaturated conditions with respect to ice. Although generally observed as individual crystals, they are often embedded in aggregates both in the air and on the ground. They were observed more frequently on the ground than in the air but this most likely resulted from the sampling limitations of the continuous particle sampler.

These star-like crystals had all the irregularities associated with the more common six-branched star-like crystals. The nature of their centers varied from one crystal to another. Also, the lengths, widths, and shapes of the branches varied within individual crystals. Most noticeable was the difference in length of the branches. Nakaya (1954) noted that in many of these crystals six alternate branches were slightly larger than the other group of six between them. This alternation of length was not commonly seen in the crystals observed by us in the air or on the ground. The twelve-branched crystals observed in the air and on the ground were usually quite large. In the air the crystals ranged in size from 1400 to 4500 μm in
diameter with an average size of about 3000 μm. Larger crystals than this were observed on the ground.

Both air and ground observations indicated that these crystals may be readily broken up in the air.

4.2.13 Side Planes (S1), Combinations of Side Planes, Bullets and Columns (S3) and Radiating Assemblage of Plates (P7a)

According to Ono (1970), side planes (S1) form at temperatures below -22°C. Magono and Lee (1966) indicate that side planes (S1) grow at temperatures between -20 to -25°C and combinations of side plates, bullets, and columns (S3) at temperatures below -25°C. The growth region for radiating assemblage of plates is not mentioned by these workers.

Our aircraft observations confirmed that all these crystal types grew at temperatures below -18°C and at water saturated conditions. Preliminary results from ground measurements in this study indicate that cloud tops could have been warmer than -25°C when combinations of side plates, bullets, and columns (S3) were observed on the ground. Taken into account when considering temperature of the cloud tops was the origin and trajectory of these particles. Aircraft observations indicated that usually these crystal types occurred as single crystals but occasionally they were found in aggregates. At the ground these crystals were usually aggregated.

Side planes (S1) were numerous both in the air and on the ground. They were the most common cold region crystal to reach the surface. Radiating assemblages of plates were also commonly observed at ground level. Observed more commonly in the air than on the ground, but least common of all, was the combination of side planes, bullets, and columns.
Although the combinations of side planes, bullets, and columns (S3) occurred under water-saturated conditions, bullets and columns were not always indicative of water saturation. According to Magono and Lee (1966) hollow columns can grow at just ice saturation but water saturation is needed for hollow bullets. Further clarification and additional investigations are needed in order to determine the degree of hollowness and characteristics of columns and bullets as a function of humidity.

These crystal types were subject to break-up in the air when the individual crystals were attached to a central branch.

4.2.14 Solid and Hollow Bullets and Combinations of Bullets (C1c, C1d, and C2a)

According to Magono and Lee (1966), solid bullets grow at temperatures below -20°C in a sub-water saturated atmosphere, whereas, hollow bullets can only grow at temperatures below -25°C in a water-saturated environment. Magono and Lee state that combinations of bullets grow at temperatures below about -25°C in a water-saturated environment and that only hollow bullets are involved in combinations. Ono found that hollow bullets might grow at temperatures below -22°C.

Our aircraft observations indicated that solid and hollow bullets grow at temperatures below -19°C. Combinations of bullets were not observed at temperatures warmer than about -25°C under water-saturated conditions. Thus, our observations for solid bullets are in good agreement with those of Magono and Lee. Between -20 to -25°C there might be a gradual transition from a solid to a completely hollow bullet under water-saturated conditions. Further work is needed to determine the degree of hollowness of bullets as a function of
the ambient temperature. In contrast to the findings of Magono and Lee, our aircraft and ground observations showed that there were combinations of solid bullet-like crystals as well as combinations of hollow bullets.

Ground measurements indicated that hollow bullets occurred much more commonly than solid bullets. Combinations of hollow bullets were the most common crystal type of the three. In addition, many single bullets had aggregated by the time they reached the surface.

The shapes of the bullets were highly variable. Most of them had fairly flat bases and their sides tapered to a narrow pointed tip. However, the shape of the tip, its width in comparison to its base, and the manner in which the body of the crystal tapered toward the tip, were very variable. There were also some unique bullet-like crystals which have not previously been reported in the literature. These exhibited some of the characteristics of normal bullets, such as forming combinations, but the growth patterns were very unusual.

Observations from the air indicated that bullets ranged in size from 150 to about 750 μm in length. Measurements were not made of the other dimensions of the bullets (which appear to be highly variable) or of the dimensions of hollow bullets compared to solid bullets. Further work needs to be done to determine under what atmospheric conditions slender bullets and stubby bullets grow. Bullets as long as nearly 1500 μm were observed at the ground. However, the average size was about 500 μm. Again, cold region crystals remained shorter in length than crystals growing at temperatures above -20°C.

Bullets were not generally observed to fragment, although it was occasionally noticed that part of the tips were missing.
4.2.15 Capped Columns (CPla)

Our aircraft observations indicate that capped columns usually form by cold region columns falling through a region of active plate growth. The columnar portions of the crystals are typical cold region columns with length to width ratios of about three. Ground observations also indicated that the columnar part of the crystal was stubby. Air observations showed these crystals had lengths up to 800 µm. The end plates were often only partially replicated.

The nature of the capped part of the column was variable. Usually both ends were capped, but in some cases only one end of the column was capped. The end plates were not, in general, equal in diameter. Occasionally, riming was observed on these crystals and often the end plates collected other particles, both planar and columnar types. The accretion of particles at the end plates indicates that the column changed its original orientation to fall with the larger end plate leading. According to Ono (1969) this occurs when the diameter of the end plate exceeds the length of the column.

The air observations indicated that capped columns were usually present as individual crystals, although occasionally they were observed in aggregates. However, at the ground, the capped columns were usually parts of aggregates.

Capped columns were observed to suffer fragmentation in the air and this usually involved the end plates.

4.2.16 Frozen Drops

Air and ground observations indicated that frozen drops seldom made a large contribution to the total concentration of ice particles in the air. Those which were present were generally spherical in shape, although sometimes
they were distorted, but they often had cracks. The frozen drops were sometimes rimmed and on occasions had collected other ice particles.

The drops in any one storm were fairly uniform in size. Frozen drops were observed as large as about 1000 µm in diameter. However, most of them were between 250 to 500 µm in diameter on the ground and 50 to 400 µm in the air. In regions where there was an increase in air turbulence, there was also an increase in the concentration of frozen drops.

4.2.17 Frozen Droplets at the Centers of Crystals

The occurrence of a frozen drop at the center of a crystal may provide information on the mode of nucleation (Weickman, et al., 1970; Auer and Veal, 1970; Auer, 1971). Also, a frozen drop at the center of a crystal implies that the atmosphere was initially supersaturated with respect to water.

Very few crystals out of the many tens of thousands which we have examined had frozen drops at their centers. A rough estimate would indicate that of the crystals collected in the air less than one crystal in a thousand had a frozen drop at its center. The same extreme scarcity of crystals with frozen drops at their centers was also noted on the ground. Weickman, et al., Auer and Veal, and Auer have suggested that asymmetrical plates are more common with a frozen drop at their center and that a frozen drop is generally associated with double growth about the center of the crystal. Our observations to date do not lead to any such general conclusions. For example, double growth was often observed on both thick plates and isolated branches and yet no frozen droplet was observed at the centers of these crystals. Also, frozen droplets were rarely found at the centers of star-like crystals. Irregular blocks of ice, hexagonal plates and solid columns were sometimes at
the centers of these crystals, but in some cases the crystals did not have a distinct embryonic center. Also, many of the star-like crystals and thick plates were asymmetrical in shape although they did not have a frozen droplet at their center. Furthermore, frozen drops were sometimes observed at the centers of crystals which showed no evidence of double growth. However, in some cases frozen drops were present at the centers of crystals which exhibited double growth.

The fact that our observations do not confirm those of Weickman et al., Auer and Veal, and Auer could be due to differences in the nature of the clouds. The crystals observed by Weickmann et al. were grown in a cloud chamber, and Auer and Veal's and Auer's observations were made in cap clouds. Our results, on the other hand, are based on crystals collected in the relatively deep cloud systems associated with Pacific Northwest storms.

4.2.18 Isolated Branches

Branches may break away from star-like crystals at the points where the arms taper to join the center of the crystal. It appears that when a branch is fragmented from its parent star-like crystal, it is not well balanced. It may therefore undergo oscillations, rotations, and tumble as it falls through the air. As a consequence the branch often grows irregularly. A common characteristic of these isolated branches is their broad width. They often have a much smaller length to width ratio than similar branches connected to star-like crystals. This may be due to the fact that when a branch is part of a star-like crystal, its close proximity to neighboring branches results in preferential growth of the tip. In addition, many of the isolated branches appeared much thicker than comparable branches attached to star-like crystals.
However, the thick crystals were not always totally encapsulated by the Formvar so that this observation must remain tentative in nature. The growth on many of the isolated branches was unusual and often included multiple layers of ice of varying shapes on a single branch.

The isolated branches were observed both in aggregates and as individual isolated branches.

4.3 Aggregation of Ice Crystals

Aggregates play an important role in the total mass of ice observed in the Pacific Northwest storms. On the ground at least 60% of the total concentration of ice crystals are in the form of aggregates. The aggregates are often composed of needles and star-like crystals but side planes, columns, and bullets are common in aggregates composed of crystals formed below -20°C. Aggregates composed solely of plates were never found on the ground, although they were in the air. On the ground plates were combined with cold region crystals or often with dendrites. There were many aggregates composed of almost exclusively star-like crystals. The ground observations indicate that the shape of the aggregates resembled a large, flat but fairly thin disc.

Aggregates were also conspicuous in the particles collected from the aircraft, although they rarely exceeded about 1% of the total concentration of ice particles. As on the ground, aggregates in the air were composed of many different crystal types. Commonly observed were aggregates of plates and naturally fragmented star-like crystal branches, aggregates of primarily plates, aggregates of star-like crystals, aggregates of plates and columns, and aggregates of bullet-like crystals. Another common aggregate was a central branch composed of many individual crystals. Due to the large size of many of
the aggregates, and the delicate way in which the crystals were attached to each other, they were sometimes not replicated very well by the continuous particle sampler. Large aggregates generally left a circular impression in the Formvar.

There appeared to be a definite threshold concentration of individual crystals below which aggregation did not occur. Also, there was an increase in the concentration of aggregates as the concentration of large ice particles (greater than about 200 μm in maximum dimension) increased. The concentration of aggregates also increased as the temperature increased provided other atmospheric conditions remained constant. There was also an increase in the concentration of aggregates with a decrease in altitude and with increasing depth of the cloud. An increase in the concentration of aggregates with increases in air turbulence and with the relative strength of the orographic effect of the Cascades was also noted. Also noticeable was a decrease in the concentration of individual particles and aggregates on the east slopes of the Cascades compared to the west slopes. Often an increase in the concentrations of ice particles and aggregates was accompanied by a marked decrease in the concentration of water droplets.

4.4 Riming

Riming of ice particles was observed both in the aircraft and ground observations. Riming was more common on crystals which grew at temperatures above -20°C. Aircraft observations indicated the following trends. Cold region crystals such as bullets, columns, and side planes were generally not rimed. This was attributed to the large ratio of ice particles to water droplets at these low temperatures. Plates were only occasionally rimed but
there were never more than a few droplets on any one plate. Rimming was not observed on plates with diameters less than 300 μm. This is in reasonable agreement with the findings of Ono (1969). Rimming was not observed on star-like crystals.

Rimming was most common on warm region crystals. Thus needles, sheaths, and columns at temperatures above -10°C were generally rimed. It appeared that riming of these crystals occurred from the surface to about 5,000 feet above ground level. Rimming was not found on columnar crystals less than 50 μm in diameter. This also agrees with the field results of Ono (1969) and theoretical calculations of the collision efficiencies of droplets with cylinders. However, many columnar crystals with widths much greater than 90 μm were observed without any riming. Ono states that nearly all columnar crystals collected having widths greater than 90 μm were rimed. In the present study, the riming was often light, with seldom more than ten frozen droplets on a single crystal. However, heavier riming was observed on occasions.

Because of the light degree of riming, the size and locations of the droplets on the crystals were clearly observable. Airborne observations indicated that the frozen droplets on the crystals ranged from about 25 μm to 150 μm in diameter with an average diameter of about 50 μm. Ono found that frozen droplets on warm columnar crystals were 20 to 70 μm in diameter. However, the columns collected by Ono were much shorter in length, and therefore narrower, than the columns collected by us.

It appeared that in most cases, the droplets were sufficiently heavy to change the fall orientation of both hexagonal plates and columnar crystals. Thus, the edge on which riming occurred subsequently became the leading edge
and riming continued on that same face. For hexagonal plates, riming generally occurred on the prism faces or occasionally on the leading basal face. Since riming dominated in the lower levels, plate crystals had generally passed out of their diffusional growth regime prior to the onset of riming. Consequently, the riming was concentrated at the edges of the crystals. Occasionally, riming occurred below -10°C and the rimed droplets were then observed embedded in the crystals.

The observations of rimed crystals at the ground confirmed those made in the air. Cold region crystals such as columns, side planes, radiating assemblage of plates, sectors, dendrites, and bullets were not rimed to nearly the same degree as crystals formed at temperatures above -20°C. Dendrites, needles, sheaths, and warm columns were heavily rimed. Plain plates were often observed without much riming, as were other sub-water saturated crystals such as crystals with sector-like and broad branches. Thus, the crystals which were heavily rimed most commonly were those which formed at or above water saturation and above -20°C. Those crystals not heavily rimed were cold region crystals, both water saturated and sub-saturated types, and sub-water saturated crystals above -20°C such as hexagonal plates. At times aggregates of crystals were also heavily rimed. It was deduced from ground measurements and trajectory analyses that the crystals became rimed below about 9,000 feet above the Cascade Mountains and, in many cases, much closer to the surface than this (see §5.5).

In order for riming to occur water droplets must, of course, be present in the air. In general, the concentrations of droplets increased with decreasing altitude. In the first few thousand feet above the ground over the Cascades,
there are usually many more supercooled drops than at higher altitudes. This explains why the warm region crystals receive most of the riming. This observation also has important implications in the artificial modification of the clouds and precipitation which is discussed in §5.11. (It should be noted however that on occasions the concentrations of ice are greater at lower levels and aircraft icing is more severe at the higher and colder levels.)

Summaries of the principal conclusions described above concerning the nature of ice particles collected in the air in Pacific Northwest storms over the Cascade Mountains are contained in Tables 4.2 and 4.3. Some of the results are still tentative and must await confirmation from further observations.

4.5 Fragmentation of Ice Particles in Clouds

4.5.1 Observations

We have seen above that many of the ice crystals collected from the aircraft are fragmented even when the decelerators described in §1.3.2 are used and the impact speed of the crystals with the "Formvar" coated film is below that required to break the crystals. Isolated branches of ice crystals and crystals with branches missing were particularly common.

Fig. 4.4 shows some examples of broken ice crystals collected from the aircraft. The isolated branch shown in Fig. 4.4 (a) was collected in air super-saturated with respect to water at -14°C. It probably originated as one branch of a dendrite or stellar crystal and, after it became detached from its parent crystal, underwent further growth to produce the odd shape shown in the

---

*This section is based on a paper by Hobbs and Farber (1972)
<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>Observed Range of Temperatures (°C)</th>
<th>Form</th>
<th>Length of Crystal (μm)</th>
<th>Width of Crystal (μm)</th>
<th>Rimming</th>
<th>Subject to Breakup in the Air?</th>
<th>Special Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Needles (Nla, Nlb, N2a)</td>
<td>-4 to -6</td>
<td>Most commonly as single crystals (Nla)</td>
<td>350 to over 3000. Average length 850.</td>
<td>At least 160.</td>
<td>Yes, on leading prism face.</td>
<td>Yes, particularly the tips.</td>
<td>Cylindrical in shape.</td>
</tr>
<tr>
<td>Shafts (Nlc, Nld, N2b)</td>
<td>-6 to -8</td>
<td>Most commonly as single crystals (Nlc)</td>
<td>300 to 2000. Average length 800.</td>
<td>At least 140.</td>
<td>Yes, on leading prism face.</td>
<td>Yes, particularly at the ends.</td>
<td>Hexagonal in shape, hollow ends.</td>
</tr>
<tr>
<td>Solid and hollow columns (C1e, C1l, N2c, C2b)</td>
<td>Warm columns &gt; -3 to -10; Cold columns &lt; -18.</td>
<td>Most commonly as single crystals but combinations were observed.</td>
<td>Warm region 50 to over 2000; Cold region 50 to about 700. Average length warm region 500; average length cold region 350.</td>
<td>Up to 240</td>
<td>Yes, on leading prism face.</td>
<td>Very seldom.</td>
<td>Length to width ratio warm columns generally &gt; 3 to 1. Cold columns length to width ratio about 3 to 1.</td>
</tr>
<tr>
<td>Thin hexagonal plates (Pla)</td>
<td>-10 to -20</td>
<td>Often in aggregates but many single crystals.</td>
<td>60 to over 1000. Average diameter 350.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thick plates (C1g, C1h)</td>
<td>-10 to -20</td>
<td>Usually single crystals</td>
<td>300 - 1000 Average diameter 550.</td>
<td></td>
<td>Seldom</td>
<td>Seldom</td>
<td>Commonly multi-layered growth. ribs common on plates &gt; 400 μm diameter; odd shapes, V-notches.</td>
</tr>
</tbody>
</table>

*Thickness of planar crystal not determined.*
<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>Observed Range of Temperatures (°C)</th>
<th>Form</th>
<th>Length of Crystal (µm)</th>
<th>Width of Crystal* (µm)</th>
<th>Riming</th>
<th>Subject to Breakup in the Air?</th>
<th>Special Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Star-like crystals (P1b, P1c, P1d, P1e, P1f)</td>
<td>-12 to -17</td>
<td>Often single crystals but commonly as aggregates</td>
<td>250 - 4500</td>
<td></td>
<td>Seldom</td>
<td>Very common. Isolated branches observed frequently.</td>
<td>Many different centers. Many crystals non-symmetrical.</td>
</tr>
<tr>
<td>Stellar crystal with plates at the tips of branches (P2a)</td>
<td>-12 to -17</td>
<td>Usually single crystals</td>
<td>1500 to 4000</td>
<td>1500 to 4000</td>
<td>Seldom</td>
<td>Yes.</td>
<td>Plates were developed to varying degrees.</td>
</tr>
<tr>
<td>Plates with sector-like extensions (P2f)</td>
<td>-12 to -22</td>
<td>Usually single crystals</td>
<td>400 to 3000</td>
<td></td>
<td>Seldom</td>
<td>Yes, particularly the extensions.</td>
<td>Sector-like extensions varied considerably from crystal to crystal.</td>
</tr>
<tr>
<td>Plates with dendritic extensions (P2g)</td>
<td>-12 to -17</td>
<td>Usually single crystals but also aggregates</td>
<td>Up to 4500</td>
<td></td>
<td>Seldom</td>
<td>Yes, particularly the dendritic extensions.</td>
<td>Hexagonal plates were usually symmetrical.</td>
</tr>
<tr>
<td>Scrolls (C11)</td>
<td>-8 to -10 &lt; -19</td>
<td>Often single crystals, but also aggregates.</td>
<td>Undetermined</td>
<td>100 to 600</td>
<td>Seldom</td>
<td>Seldom</td>
<td>Scroll part of crystal varied in shape.</td>
</tr>
<tr>
<td>Two- branched crystals (P3a)</td>
<td>-12 to -17</td>
<td>Single crystals</td>
<td>Variable</td>
<td></td>
<td>Seldom</td>
<td>Occasionally at the centers.</td>
<td>Angular separation between branches generally 180°.</td>
</tr>
<tr>
<td>Dendritic crystal with 12 branches (P4b)</td>
<td>-12 to -17</td>
<td>Single crystals but also aggregates.</td>
<td>Large up to 4500. Average length 3000.</td>
<td></td>
<td>Seldom</td>
<td>Yes, quite often.</td>
<td>Branches varied in length within the crystal. Associated with high humidities.</td>
</tr>
</tbody>
</table>

* Thickness of planar crystal not determined.
<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>Observed Range of Temperatures (°C)</th>
<th>Form</th>
<th>Length of Crystal (μm)</th>
<th>Width of Crystal* (μm)</th>
<th>Rimming</th>
<th>Subject to Breakup in the Air?</th>
<th>Special Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side planes (S1), combination of side plates bullets and columns (S3) and radiating assemblage of plates (P7a)</td>
<td>&lt; -18</td>
<td>Single crystals and occasionally aggregates.</td>
<td>Variable</td>
<td>Very seldom.</td>
<td>Quite often at the point of crystal attachment to the branch.</td>
<td>Side planes most common. Combination of side planes, bullets and columns least common.</td>
<td></td>
</tr>
<tr>
<td>Solid, hollow and combination of bullets (C1c, C1d, and C2a)</td>
<td>Solid and hollow bullets &lt; -19; combination of bullets &lt; -25.</td>
<td>Usually single crystals occasionally aggregates and combinations.</td>
<td>150 to 750. Average length.400.</td>
<td>Very seldom.</td>
<td>Very seldom.</td>
<td>Many different shapes. Hollow bullets more common than solid. Combinations of solid bullet-like crystals were observed. Unique, bullet-like crystals were observed at &lt; -25.</td>
<td></td>
</tr>
<tr>
<td>Capped columns (CP1a)</td>
<td>-10 to -20</td>
<td>Single crystals and aggregates.</td>
<td>Up to 800</td>
<td>Occasionally</td>
<td>Yes, particularly the capped portion of the column.</td>
<td>Capped portion was rimed and collected other particles. Often the end plates were not equal in diameter. Occasionally only one end was capped.</td>
<td></td>
</tr>
</tbody>
</table>

* Thickness of planar crystal not determined.
<table>
<thead>
<tr>
<th>Crystal Type</th>
<th>Threshold Crystal Diameter for Riming (µm)</th>
<th>Degree of Riming</th>
<th>Location of Riming</th>
<th>Diameter of Droplets (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bullet (Clc, Cld, C2a)</td>
<td>Not known</td>
<td>Usually none, occasionally on C2a.</td>
<td>On the main body</td>
<td>Not known</td>
</tr>
<tr>
<td>Cold column (solid and hollow)</td>
<td>&gt; 50</td>
<td>Very light</td>
<td>On the leading prism face.</td>
<td>25 to 140</td>
</tr>
<tr>
<td>Star-like crystals (Plb, Plc, Pld, Ple, Plf)</td>
<td>&gt; 100 (width of individual crystal arm)</td>
<td>Very light. Occasionally on Plb and Plc.</td>
<td>On the leading face near the edge of the branches.</td>
<td>25 to 100</td>
</tr>
<tr>
<td>Plates</td>
<td>&gt; 300</td>
<td>Light</td>
<td>On the leading prism face and adjacent two prism faces. Occasionally at the edges of the basal faces.</td>
<td>25 to 115</td>
</tr>
<tr>
<td>Warm region crystals, needles, columns and sheaths (N1a, N1b, N1c, N1d, N1e, N2a, N2b, N2c, Cle, Clf, and C2b)</td>
<td>&gt; 50</td>
<td>Generally moderate up to 10 drops per crystal. Occasionally heavy.</td>
<td>On the leading prism face of the crystal. Occasionally on the basal faces.</td>
<td>25 to 150</td>
</tr>
</tbody>
</table>
Fig. 4.4  (a) Isolated branch of an ice crystal. Length of branch 700\(\mu\)m.
(b) Isolated branch of an ice crystal. Length of branch 700\(\mu\)m.
(c) Stellar ice crystal with part of one branch missing. Diameter of stellar is 400\(\mu\)m.
(d) Needle with broken ends. Needle is 1450\(\mu\)m long and 120\(\mu\)m wide.
photograph. The fact that the branch is fairly broad at its tip indicates that it entered a region of lower saturation than during the initial stage of its growth. The isolated branch shown in Fig. 4.4 (b) has secondary growth on one side only, probably as a result of the mode of fall after becoming detached from its parent crystal. Also of interest are the two large dendritic extensions adjacent to each other near one end of the branch and the third extension at the opposite end. This fragment was collected at -12°C.

Fig. 4.4 (c) shows a stellar crystal with one branch severely stunted. It seems likely that the original branch at this point broke off in the air and some further growth from the vapor phase then took place at this point to produce the stunted branch. Isolated branches of the type shown in Fig. 4.4 (a) and 4.4 (b) were the most readily identifiable fragments of symmetrical ice crystals. Portions of other crystals (e.g. columns and needles) were more difficult to identify but they were observed. Fig. 4.4 (d) shows a needle both ends of which have undergone fragmentation. The needle is rimed along one side.

It might be argued that the crystals described above could have fragmented whilst being collected rather than in the free air. We do not think that this was the case for the following reasons. Fragmentation of ice crystals due to impact on the "Formvar" coated film was generally quite obvious because the fragments were clumped together on the film. The fragments referred to above, on the other hand, were isolated on the film without any evidence of nearby related fragments. Fragmentation due to collision with the entrance slit of the cloud particle sampler, or within the decelerator, is also unlikely since the isolated branches often showed considerable asymmetrical secondary growth
which must have taken place in the air after the branches were detached from their parent crystals. Finally, observations made on the ground, in which ice particles in the air were collected by allowing them to settle gently onto a horizontal surface, also revealed that many ice fragments were present in the air (see §5.3).

Some of the conclusions which we have drawn on the fragmentation of ice crystals in clouds over the Pacific Northwest are summarized in one of the columns in Table 4.2. The results are based on data collected from aircraft over a period of three years.

4.5.2 Fragmentation of Ice Crystals Due to Collision

Perhaps the most obvious way in which ice particles might undergo fragmentation in the air is simply by colliding with one another. However, there does not appear to be any information available on the speeds of impact which are required to fragment different types of ice crystal. From observations of ice crystals collected after they have passed through a decelerator attached to aircraft flying at different speeds, we have been able to deduce rough values for the maximum impact speeds which several types of ice crystal can withstand without fragmentation when they collide with a mylar film coated with a wet 4% solution of "Formvar" in chloroform (thickness of the "Formvar" solution about 150 μm). These results, which are shown in Table 1.5, give some idea of the relative strengths of different types of ice crystal. We see, for example, that stellar, dendritic and needle crystals fragment at about one-half the impact speed of hollow columns and at one-third the impact speed of solid columns with the same maximum dimensions. Thick plates appear to be particularly strong. However, due to differences in the
nature of the impact when ice crystals collide with a film coated with wet "Formvar" and when they collide with each other in the air, the threshold impact speeds listed in Table 1.5 cannot be applied a priori to the latter case.

We can estimate whether, say, a stellar ice crystal is likely to lose an arm when it collides with water droplets or ice particles in the air in the following way. Let us assume that the water droplet or ice particle hits the tip of the arm of a stellar crystal and that the arm then bends like a cantilever, with the center of the stellar crystal remaining unmoved due to the collision and the tip of the arm undergoing maximum displacement. The energy $E_{BS}$ required to break the arm is then given by

$$E_{BS} = \frac{\sigma^2 l b t}{18 Y}$$

where, $\sigma_m$ is the tensile strength of ice (about $1.5 \times 10^7$ dyne cm$^{-2}$ and not strongly temperature dependent between 0 and -30°C, $l$ the length of the arm, $b$ the average width of the arm, $t$ the average thickness of the arm, and Young's modulus for ice (about $6 \times 10^{10}$ dyne cm$^{-2}$ and not strongly temperature dependent). Therefore, for a stellar crystal 1 mm in diameter, $l = 500$ μm, $b = 100$ μm and $t = 40$ μm (Auer and Veal, 1970) and, from eqn. (4.1), $E_{BS} = 4 \times 10^{-4}$ ergs.

The kinetic energy with respect to the stellar crystal of a water droplet of mass $m_d$ is $\frac{1}{2} m_d (V_d - V_s)^2$ where, $V_d$ is the fall speed of the droplet and
that of the stellar \( (30 \text{ cm s}^{-1}) \). This kinetic energy is equal to \( E_{\text{BS}} \) for a droplet of diameter 150 \( \mu \text{m} \). Therefore, droplets in excess of this size should, under the most favorable circumstances, have sufficient energy to break the arm of a stellar crystal 1 mm in diameter if they collide with it in free fall.

Consider next a graupel particle of mass \( m_g \) which collides with a stellar crystal. The kinetic energy \( E_g \) of this particle with respect to the stellar crystal is given by

\[
E_g = \frac{1}{2} m_g (v_g - v_s)^2 \tag{4.2}
\]

where, \( v_g \) is the fall speed of the graupel particle. If the diameter of the graupel particle is \( d \text{ cm} \), its mass \( m_g \) (in gm) and its fall speed are given by (Nakaya and Terada, 1934):

\[
m_g = 0.065 d^3 \tag{4.3}
\]

and

\[
v_g = 500 d \tag{4.4'}
\]

Therefore,

\[
E_g = 0.0325 d^3 (500d - 30)^2 \tag{4.5}
\]
The variation of $E_g$ with $d$ is shown in Fig. 4.5. It can be seen that $E_g$ exceeds $E_{BS}$ when the diameter of the graupel particle exceeds about 700 μm (shown as a shaded area in Fig. 4.5). Therefore, according to our model, if a stellar crystal 1 mm in diameter collides with a graupel particle with diameter greater than 700 μm an arm of the stellar crystal may be broken off. If the magnitude of $E_{BS}$ were somewhat less than that calculated above, it can be seen from Fig. 4.5 that in addition to large graupel particles there would be a group of smaller graupel particles that would be capable of fragmenting this stellar crystal.

We turn now to the fragmentation of columnar ice crystals. In this case we will assume that when a particle hits the column the latter is acted upon by a system of non-uniform forces which have a maximum value at the point of impact and taper off to zero at the end points of the column (i.e. triangular loading). If a solid columnar crystal is represented by a cylinder of length $l$ and radius $r$, the energy $E_{BC}$ required to break the column if it is struck at its center is given by

$$E_{BC} = \frac{11 \pi}{320} \frac{\sigma}{Y} l^2 r^2$$

(4.6)

Therefore, for a solid needle of length 1 mm and radius 75 μm, $E_{BC} = 2.4 \times 10^{-3}$ erg. It should be noted that the calculated value for $E_{BC}$ is not very sensitive to the exact model which is assumed for the break-up of the crystal. If for example the loading is assumed to act as a point at the center of the needle, the energy required to break the column is found to be $1.9 \times 10^{-3}$ erg.
Fig. 4.5 Solid curve shows the kinetic energy $E_g$ of a graupel particle with respect to a stellar crystal (falling at 30 cm s$^{-1}$) as a function of the diameter of the graupel particle. The dotted line indicates the estimated energy $E_{BS}$ required to break off the stellar crystal.
Proceeding as before we can now estimate the likelihood of, say, a solid column of length 1 mm breaking when it collides with other particles in the air. For example, the kinetic energy of a water droplet with respect to the column is \( \frac{1}{2} m_d (V_d - V_c)^2 \) where \( V_c \) is the fall speed of the column (60 cm s\(^{-1}\)). This energy is greater than \( E_{BC} \) for droplets with diameters in excess of about 225 \( \mu m \). Therefore, these droplets should be capable of breaking the column.

The kinetic energy \( E_g \) of a graupel particle with respect to the column considered above is given by

\[
E_g = 0.0325 d^3 (500d - 60)^2
\]

This function is shown in Fig. 4.6 where it can be seen that \( E_g \) exceeds \( E_{BC} \) for graupel particles with diameters between about 340 and 1040 \( \mu m \) and in excess of 1310 \( \mu m \). These two regions are shown as shaded areas in Fig. 4.6. Therefore, according to our model calculations, if an ice crystal in the form of a solid column 1 mm in length collides with a graupel particle with a diameter lying within the shaded areas, the column could be broken. The smaller graupel particles (340 to 1040 \( \mu m \) in diameter) are overtaken by the column, while graupel particles greater than 1310 \( \mu m \) in diameter catch up with the column. For graupel particles with diameter between 1040 and 1310 \( \mu m \), the relative velocities between the column and the graupel particles are too small to break the column even if collision occurs.

The likelihood of stellars and columns of different sizes, and also other types of ice crystals, being broken due to in-air collisions can be estimated in a similar way to the methods described above. However, the examples which
Solid curve shows the kinetic energy $E_g$ of a graupel particle with respect to a columnar ice crystal (falling at 60 cm s$^{-1}$) as a function of the diameter of the graupel particle. The dotted line indicates the estimated energy $E_{BC}$ required to break a needle. Graupel particles with diameters lying within the shaded areas can, in principle, break the needle during a collision.
have been given are sufficient to illustrate that under appropriate conditions certain types of ice crystals are likely to be broken when they collide with other particles in the air.

4.5.3 Fragmentation of Ice Crystals Due to Thermal Shock

When an ice crystal in the air collides with a supercooled drop it will receive a sudden thermal shock due to the release of the latent heat of freezing of the drop. This will cause differential expansion of the crystal and may result in its fragmentation.

Dye and Hobbs (1968) noted in laboratory experiments that when a supercooled water drop, about 1 mm in diameter, was brought gently into contact with an ice crystal, the crystal often fragmented into 5 or 10 visible pieces. More recently, the following further observations of this phenomenon have been made in our laboratory. Ice crystals were grown from the vapor phase on a fine fiber suspended vertically along the center of a diffusion cloud chamber. Water drops, about 2 mm in diameter, were then lowered to the level in the chamber where dendrites were growing. After the drops had supercooled and reached equilibrium with the environmental air at this level, they were brought gently into contact with the dendrites. A short time after a drop was nucleated by contact with a dendritic crystal, the dendrite fragmented into several pieces.

It seems likely that some ice crystals in the atmosphere will be fragmented by thermal shock due to collisions with supercooled drops. However, an assessment of the importance of this phenomenon must await careful studies to determine the sizes of drops required to fragment different types of ice crystal and the numbers of ice fragments produced. It appears that fairly
large drops are necessary to cause fragmentation of even delicate ice crystals by thermal shock since unbroken ice crystals which are rimed with small cloud droplets are commonly observed.

4.5.6 Fragmentation of Ice Crystals and Ice Multiplication

A number of observers have reported that the concentrations of ice particles in some clouds are very much greater than would be expected from ice nucleus measurements. In order to explain these observations it has commonly been assumed that once a few ice crystals are nucleated in a cloud their numbers may, under suitable conditions, be enhanced by a multiplication process.

Many mechanisms have been suggested by which ice particles might multiply in clouds. However, only two of these mechanisms, the splintering of isolated drops during freezing and the splintering of drops during riming, have been investigated carefully under conditions similar to those in natural clouds. In neither case was a powerful ice multiplication process detected (Hobbs and Alkezweeny, 1968; Brownscombe and Thorndike, 1968; D. Johnson and A. N. Aufdermauer*).

The observations of ice fragments in clouds, which have been discussed in the first section of this paper, indicate that the break-up of ice crystals in the air will contribute to ice multiplication. Of the ice particles collected in clouds using a continuous particle sampler, over 50% are commonly ice fragments which appear to have originated by break-up in the air. On some occasions, the concentrations of ice fragments are several orders of magnitude greater than the concentrations of regular ice crystals.

* Personal communication, 1971.
We have shown that the collision of comparatively large water drops or graupel particles with stellar or columnar ice crystals should be capable of breaking up the ice crystals by virtue of the energy of impact. In addition, large water drops may fragment ice crystals with which they collide by thermal shock. In this connection, we note that most of the field observations of large concentrations of ice particles in clouds noted by other workers occurred in the presence of millimeter-sized water drops and/or heavily rimed crystals or graupel particles. These are just the conditions which favor fragmentation due to collision and thermal shock.

The question now arises as to whether the fragmentation of ice crystals due to collisions or thermal shock can generate sufficient numbers of ice crystals to explain the high concentrations of ice particles which are produced when a crystal breaks up. Many small ice particles may be produced when a crystal snaps in one place. We note, however, that if those water drops or graupel particles in a cloud which are sufficiently large to cause fragmentation when they collide with an ice crystal are present in concentrations of 1 per liter, a stellar crystal 1 mm in diameter would have to fall through a distance of about 1.5 km in order to collide with such a particle and suffer fragmentation. If we assume that the stellar crystals undergo only one such collision in their fall through a cloud, then the ice multiplication factor would be equal to the number of fragments produced in one collision. For example, if each stellar crystal in a cloud collided with a supercooled droplet 250 μm in diameter which knocked one arm of the stellar and the arm was fragmented into ten pieces by thermal shock due to the
nucleation of the drop, the ice multiplication factor would be ten. In the case of a columnar ice crystal 1 mm in length and 150 μm in diameter, the particles responsible for fragmentation would have to be present in concentrations of about 6 per liter in order for a collision to occur in 1.5 km of fall. Of course, other mechanisms not mentioned above (e.g., air drag and turbulence) might cause fragile ice crystals to fragment in clouds.
SECTION 5

SOME RESULTS FROM THE GROUND OBSERVATIONS

5.1 Introduction

The replicas of snow particles which are made at the ground stations contain a wealth of information both on the structure of the clouds in which they grew and the temperatures which they experienced. In this section the replicas which were collected at Alpental, Keechelus Dam and Kachess Dam during the 1970-71 season are analyzed and some conclusions are drawn concerning the microstructure of the clouds at various stages during the history of a storm, the trajectories of the precipitation particles, and their potential for modification by artificial seeding. Some of the conclusions are necessarily tentative at this time and must await confirmation from further field studies.

5.2 Types of Precipitation Particles at the Three Ground Stations

The glass slides on which the snow particles were replicated were studied carefully under a stereo-microscope. The particles were then classified using a simplified version of the scheme suggested by Magono and Lee (1966). This classification is shown in Table 5.1, and photographs illustrating the various types of particles are shown in Figs. 5.1 - 5.4.

If one type of particle occupied more than three-quarters of the area of a slide it was termed the "dominant slide particle." If several particles were present in approximately equal numbers on the slide they were all termed "dominant slide particles."

Fig. 5.5 shows the number of times a particular type of ice particle was the "dominant slide particle" at the three ground stations using all the data
### TABLE 5.1

**CLASSIFICATION AND SYMBOLS FOR SNOW PARTICLES**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
<th>Conditions under which Particles Grow</th>
</tr>
</thead>
<tbody>
<tr>
<td>←→</td>
<td>Includes both needles &amp; sheaths (separate, bundles &amp; combinations)</td>
<td>-4 to -6°C. Above water saturation</td>
</tr>
<tr>
<td>⬇</td>
<td>Sheaths (separate, bundles &amp; combinations)</td>
<td>-6 to -8°C. Above water saturation</td>
</tr>
<tr>
<td>⬆</td>
<td>Dendrites &amp; radiating assemblages of dendrites</td>
<td>-13 to -17°C. Above water saturation</td>
</tr>
<tr>
<td>⋆</td>
<td>Stellars</td>
<td>-13 to -17°C. Above water saturation</td>
</tr>
<tr>
<td>□</td>
<td>Side planes</td>
<td>-20 to -25°C. Above water saturation</td>
</tr>
<tr>
<td>⬤</td>
<td>Assemblages of plates</td>
<td>-18 to -22°C. Above water saturation</td>
</tr>
<tr>
<td>○</td>
<td>Plates</td>
<td>Several temperature ranges</td>
</tr>
<tr>
<td>⬤</td>
<td>Assemblages of sectors</td>
<td>-18 to -22°C. Above water saturation</td>
</tr>
<tr>
<td>⬤</td>
<td>Bullets</td>
<td>-25 to -30°C. Above water saturation</td>
</tr>
<tr>
<td>□</td>
<td>Columns</td>
<td>Several temperature ranges</td>
</tr>
<tr>
<td>⬤</td>
<td>Plates with extensions</td>
<td>Several temperature ranges</td>
</tr>
<tr>
<td>⬤</td>
<td>Frozen water drops</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Graupel (hexagonal, cone-like &amp; graupel)</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Irregular</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Undetermined</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Nothing on slide</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Melted crystals</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Unrimed - no frozen drops on particle</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Light riming - few frozen drops on particle</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Moderate riming - about one-half of particle covered with frozen drops</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Densely rimed - particle completely covered with frozen drops</td>
<td></td>
</tr>
<tr>
<td>⬤</td>
<td>Aggregates of ice crystals (due to difficulties in replications the absence of an &quot;A&quot; does not necessarily mean there were no aggregates at that time)</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 5.1 Examples of snow particles collected on the ground in the Cascade Mountains. 
(a) Needle (b) Sheaths (c) Dendrite (d) Stellar with end plates. The scaled line on each photograph represents 1 mm.
Fig. 5.2 Examples of snow particles collected on the ground in the Cascade Mountains. (a) Side planes (b) Assemblages of plates and sectors (c) Plate with extensions (d) Bullets. The scaled line on each photograph represents 1 mm.
Fig. 5.3 Examples of snow particles collected on the ground in the Cascade Mountains. (a) Column (b) Frozen water drops (c) Lump graupel (d) Conelike graupel. The scaled line on each photograph represents 1 mm.
Fig. 5.4 Examples of various degrees of rime of snow particles collected in the Cascade Mountains. (a) Lightly rimed dendrite (b) Densely rimed stellar (c) Densely rimed hexagonal plate (d) Graupel-like snow of hexagonal type. The scaled line on each photograph represents 1 mm.
Fig. 5.5 Occurrence of "dominant slide particles" (For comparing one station with another)
available from the 1970-71 season. It should be noted that the number of slides exposed varied from day to day, but at all three stations approximately the same number of replicas were taken on any one day. Therefore, the results shown in Fig. 5.5 probably do not give a true representation of the relative frequency of occurrence of particle types at one station but they should give a good indication of the differences in the frequencies of occurrence of particles between stations. For example, at Alpental needles and sheaths were more common than at Keechelus Dam and these crystals were more common at Keechelus Dam than at Kachess Dam. Also, graupel was more common at Alpental than at the other two stations. Conversely, there were more bullets, side planes, assemblages of sectors and assemblages of plates at Kachess Dam and Keechelus Dam than at Alpental. These differences reflect the locations of the stations. Alpental is situated near the crest of the Cascades at an altitude of 2940 ft., while Keechelus Dam and Kachess Dam are on the eastern slopes of the Cascades at altitudes of 2480 and 2330 ft., respectively. Consequently, local clouds commonly form immediately over Alpental out of which needles and sheaths often fall. The bullets, side planes and assemblages of sectors and plates, form in higher level and colder clouds. The position of Alpental near the crest of the Cascades is also reflected in the higher incidence of graupel at this station, which indicates higher liquid water contents than at the two stations at lower elevations.

The dominant type of ice particle which occurred throughout each day (rather than on each slide) was also determined for each station. The frequency of occurrence of these "dominant day particles" are shown in Fig. 5.6. Unlike Fig. 5.5, this diagram can be used to compare the relative
Fig. 5.6 Occurrence of "dominant day particles" (Gives relative frequency of occurrence for each station.)
frequency of occurrence of different types of particles at any one station but it is not as accurate as Fig. 5.5 for comparing one station with another because of the smaller amount of data used. It can be seen that more dendrites than other type of particles fell at Keechelus Dam and Kachess Dam but at Alpental dendrites and graupel occurred with equally high frequencies. It should be noted that even though plates and columns were rarely the dominant particles, they were often present on the slides. Crystals which were sometimes seen on the slides but which were never "dominant slide particles" or "dominant day particles" were: sectors, double and triple stellars, scrolls, broad-branched crystals, columns and bullets capped with plates, stellars or dendrites, and plates with sector-like dendritic simple extensions. It was not possible to discern if the double and triple stellars had frozen droplets at their centers.

5.3 Aggregation and Fracturing

Aggregates of snow crystals were very common. On more than 60 per cent of the slides the dominant crystal (excluding graupel) was present in aggregates.

Dendrites were more often than not fractured. Also, crystals with sector-like branches were often short of one or more arms and needles were often fractured, particularly at their tips. Portions of ice crystals with spatial extensions and radiating assemblages of various crystal types were often missing. Miscellaneous irregular fragments of ice were also common.

5.4 Sizes of Particles

The solid precipitation particles were divided according to their maximum dimension into the following eight groups: less than 0.25 mm, 0.25 - 0.5 mm,
0.5 - 1.0 mm, 1.0 - 1.5 mm, 1.5 - 2.0 mm, 2.0 - 3.0 mm, 3.0 - 5.0 mm and greater than 5.0 mm. Only those particles with regular shapes were classified in this way (side planes, assemblages of plates, assemblages of sectors were excluded). However, if a crystal had irregular branches it was classified according to the average diameter of its branches.

The size distributions of the particles collected at Alpental, Keechelus Dam, and Kachess Dam showed no significant differences. Fig. 5.7 shows the relative frequency of occurrence of solid particles of different sizes based on replicas taken at all three stations. A noticeable feature of the results in the large sizes of the dendrites compared to other crystals. Fig. 5.8 shows size spectra for frozen drops based on particles collected on three different occasions. It can be seen that the frozen drops were fairly uniform in size.

5.5 Rimming

The degree of riming of the solid precipitation particles is shown in Figs. 5.9 and 5.10. The data has been analyzed in the same way as that described in §5.2, therefore, the results shown in Fig. 5.9 are for comparing one station with another, while those in Fig. 5.10 show the relative frequency of occurrence of different degrees of riming at each station. It should be emphasized that these results are based on a limited quantity of data collected during the winter of 1970-71. It can be seen from Fig. 5.9 that heavy riming and graupel was far more common at Alpental (the station at the highest elevation) than elsewhere. Fig. 5.10 shows that at Alpental moderately and heavily rimed particles were more frequent than unrimed or lightly rimed particles, but at the other two stations the frequencies of occurrence of the different degrees of riming were similar.
Fig. 5.7 Size distributions of solid precipitation particles.
Fig. 5.8 Size distributions of frozen drops collected on three occasions.
Fig. 5.9 Occurrence of dominant degree of riming from individual slides. (For comparing one station with another)
Fig. 5.10 Number of days various degrees of rime were dominant at each station.
Variations in the degree of riming with the type of particle are indicated in Fig. 5.11 where each dot shows the degree of riming of a "dominant slide particle." Needles, sheaths and dendrites were more often densely rimed than unrimed; plates, sectors, side planes and bullets were generally unrimed or lightly rimed; plates and columns occurred on an about the same number of occasions rimed and unrimed; and frozen drops ranged from lightly rimed to densely rimed. Hence, those crystals which originated in the colder regions of the atmosphere (side planes, etc.) are generally unrimed or lightly rimed, while crystal which form in the warmer layers are unrimed to densely rimed.

Since most of the "dominant slide particles" grew under water-saturated conditions and the temperatures at which these particles form and grow by diffusion is known, it was possible to deduce from the Greenwater radiosonde data the approximate levels in the atmosphere between which each particle must have originated and completed their diffusional growth. (These levels were generally 2000 or 3000 feet apart.) We will refer to the region between these layers as the "diffusional growth layer" of the particle. In Fig. 5.12 the degree of riming of each "dominant slide particle" is shown as a dot located at the middle of the "diffusional growth layer" for the particle. It can be seen that most of the densely rimed particles formed in "diffusional growth layers" located around 11,000 ft. above mean sea level, while most of the unrimed crystals formed around 15,000 ft. Since even the densely rimed crystals had distinguishable habits (other than graupel which has been excluded from the present analysis) it appears that most of the riming occurs after the crystals have passed through the base of the "diffusional growth layer." We will therefore assume that a crystal grows in two distinct
Fig. 5.11 Degree of riming of dominant slide particles (see Table 5.1 for key to symbols)
Fig. 5.12 Degree of riming of dominant slide particles against the median height of the diffusional growth layer for the particle.
layers, namely, a "diffusional growth layer" followed by a "riming growth layer." It follows from the results shown in Fig. 5.12 that most of the heavy riming occurs in layers which are below about 9,000 ft. above mean sea level, and in some cases below 5,000 ft. The reason why crystals such as side planes and bullets, which form at low temperatures, are generally unrimed is that they commonly form in pre-frontal conditions where liquid water contents are low.

5.6 Pre-frontal and Post-frontal Precipitation

In Fig. 5.13 frequency histograms are shown for the degree of riming, types of particles, and the median height of the "diffusional growth layer," for precipitation at Alpental in pre-frontal and post-frontal conditions. It can be seen from these results that in pre-frontal conditions the particles were more often unrimed or lightly rimed while in post-frontal conditions densely rimed particles and graupel dominated. Also, the "diffusional growth layers" were generally higher in pre-frontal than in post-frontal conditions. Several reasons can be suggested to explain these observations:

(a) In pre-frontal conditions the winds at lower levels tend to be easterly and relatively dry so that riming in the lower layers is inhibited.

(b) In post-frontal conditions the low level winds tend to be westerly (i.e. from the Pacific Ocean) and therefore moist, consequently, riming is more likely to occur.

(c) In pre-frontal conditions the atmosphere is generally moister to higher altitudes than in post-frontal conditions, therefore, crystals which form at lower temperatures (e.g., bullets, assemblages of sectors and plates) are more likely to form.
Fig. 5.13 Degree of riming, types of particles, and median height of "diffusional growth layer" for precipitation at Alpental in pre-frontal and post-frontal conditions.
There does not appear to be any significant correlation between the types of ice crystals which reach the ground in the Cascade Mountains and the temperatures of the storm (e.g., as represented by the temperature at 700 mb). This indicates that the distribution of moisture in a storm plays a greater role in determining the nature of the precipitation than does temperature.

5.7 Correlations Between Rimming, Winds, Moisture Content and Precipitation

It is reasonable to expect that due to the orographic effect, the degree of riming of the precipitation particles at Alpental will vary with the wind speed and direction. Correlations of this kind were sought using winds from the Greenwater soundings at the 3,000, 7,000 and 10,000 ft. levels. The best correlations were found using the 10,000 ft. data. It can be seen from Fig. 5.14 that the degree of riming of the precipitation particles at Alpental increased with increasing wind speed at 10,000 ft. but it did not change in any systematic way as the wind varied in direction around 270°. Fig. 5.15 shows that the degree of riming of precipitation at Alpental also tends to increase as the water vapor content at 10,000 ft. increases.

Fig. 5.16 shows that when the wind speed and water vapor content at 10,000 ft. are high the precipitation rate at Alpental tends to be high.

It should be noted that the general correlations referred to above can be violated under some conditions. For example, the highest precipitation rate which was recorded at Alpental during 1970-71 occurred when the wind speed and moisture content at 10,000 ft. were only moderate, while on another occasion, when the wind speed and water content were both very high, the precipitation rate was only light.
Fig. 5.14 Degree of riming of precipitation at Alpental against the wind speed at 10,000 feet and the deviation of its direction from 270°.
Fig. 5.15 Degree of riming of precipitation at Alpental against the wind speed and water vapor content at 10,000 feet
Fig. 5.15 Effects of wind speed and water vapor content at 10,000 feet on the intensity of precipitation at Alpental.
We turn now to the relationship between the rate of snowfall or precipitation and the degree of riming of the solid precipitation particles. It was found at Alpental (on the crest of the Cascades) that a wide range of instantaneous precipitation rates could occur with any degree of riming. However, the average rates of precipitation at Alpental which were associated with particular degrees of riming throughout the winter of 1970-71 correlated fairly well with the degree of riming (Fig. 5.17). Also shown in Fig. 5.17 are two points from the 1968-69 winter season. It can be seen that, on average, the rate of precipitation at Alpental increased as the riming of the particles increased. However, the same plot for Kachess Dam (which is on the eastern slopes of the Cascade Mountains) does not show this correlation (Fig. 5.18). It can be seen that at Kachess Dam the heaviest riming produced a very light precipitation rate.

A comparison of the mean precipitation at four stations to the west of the Cascade divide with that at four stations to the east of the divide in a number of synoptic storms throughout the winter of 1970-71 reveals that the stations on the west side generally receive more precipitation than those on the east side but that this difference is usually much greater in post-frontal than in pre-frontal conditions (some of this data is contained in Tables in §6). Several factors may be responsible for this effect. Firstly, the air is drier in post-frontal conditions so that subsidence over the eastern slopes of the Cascades dissipates the clouds more readily than in pre-frontal conditions. Secondly, in pre-frontal conditions there is often an easterly wind near the surface which may produce orographic precipitation over the eastern slopes. Thirdly, as we have seen above, the precipitation particles in post-frontal
Fig. 5.17 Average precipitation rates at Alpental against the degree of riming of the precipitation.
Fig. 5.18 Average precipitation rates at Kachess Dam against the degree of riming of the precipitation.
conditions are heavily rimed and therefore have comparatively high fall speeds. Consequently, in a westerly wind they tend to be deposited further west than unrimed particles (see §3).

5.8 An Illustrative Example

Most of the general conclusions referred to above can be illustrated by reference to the measurements made during the passage of an occluded front across the Cascade Mountains on February 18, 1971. A description of the synoptic situation and the aircraft measurements made during this storm is given in §6.4. Here we are concerned primarily with the ground observations at Alpental and related phenomena.

Fig. 5.19 contains a synopsis of the relevant data for February 18, 1971. The following information is contained in this figure:

(a) At the top of the figure the water vapor content of the air (in grams per kg of dry air) at 3000, 5000, 10,000, and 15,000 ft. The data for 1000, 1300 and 1500 hours PST is for the radiosondes launched from Greenwater while that at 1650 PST was estimated from a time cross-section based on the Quillayute radiosonde.

(b) Barometric pressure (mb) at Stampede Pass.

(c) Wind speed and direction at Stampede Pass.

(d) Heights of the "diffusional growth layers" for the solid precipitation particles falling at Alpental.

(e) The types of solid precipitation particles and their degree of riming at Alpental (see Table 5.1 for key to symbols).
Fig. 5.19 Summary of observations for February 18, 1971 (See text for further explanation.)
(f) The precipitation rate at Alpental as determined from the weights of snow collected in the sampling bags (histogram) and from the optical snow rate sensor (curve).

It can be seen from the fluctuations of the barometric pressure, the wind shift from SE to WSW, and in the increase in precipitation, that the occluded front passed over the Cascade Mountains between 1400 and 1500 PST. The variations in the water vapor content show that the upper levels (10,000 to 15,000 ft.) dried out more than the lower layers (3,000 ft.) following the passage of the front. As a consequence, in the pre-frontal portion of the storm the "diffusional growth layers" were around 15,000 ft. but in the post-frontal portion they fell to about 5000 ft. In the pre-frontal region the crystals were mostly unrimed and appropriate to cold temperatures (assemblages of sectors and plates, side planes and bullets), while in the post-frontal region the crystals were moderately to densely rimed needles, sheaths and graupel. It will be noticed that in this storm the precipitation at Alpental was generally lower when the crystals were heavily rimed; clearly the sharp decrease in precipitation following the passage of the front more than compensated for the increase in precipitation which might have been expected at Alpental due to the higher level of riming.

5.9 Trajectories of Precipitation Particles

The trajectories through the atmosphere of solid precipitation particles, which reached the ground in the Cascade Mountains were estimated using the following assumptions:

(a) The particles originated and developed their primary habit while falling through their "diffusional growth layer" (see §5.5).
(b) If the particles were rimed the timing occurred uniformly between the base of the "diffusional growth layer" and the ground (see §5.5).

(c) The particles fell as individual crystals with a fall-speed in the range listed in Table 5.2. (The effects of vertical air motions on the fall-speeds were ignored.)

(d) The wind and temperature fields through which the particles fell were those given by the radiosonde launched from Greenwater (see Fig. 3.1).

Two trajectories were computed for each "dominant slide crystal", one based on the smallest fall-speed listed in Table 5.2 and the other on the largest fall-speed. The atmosphere through which the particle fell was divided up into layers 1000 ft. thick, each with an average wind speed and direction determined from the Greenwater sounding. The trajectories of precipitation particle determined in this way for four "storm days" in 1971 (February 3, February 22, March 2 and March 11) are described below.

Solid precipitation particles were collected at Alpental, Keechelus Dam and Kachess Dam during daylight hours on February 3, 1971, ahead of a weak surface warm front. (A full description of the synoptic conditions, airborne and ground measurements for this storm is given in §6.3.) At 1515 PST densely rimed dendrites were falling at Alpental and Keechelus Dam and somewhat less heavily rimed dendrites at Kachess Dam. The computed trajectories of these particles are shown in Fig. 5.20. The trajectories are shown originating at the point where they pass out of the base of their "diffusional growth layer" which, on this occasion, was at 10,000 ft. For example, the largest densely rimed dendrites (fall-velocity 6.6 ft. sec\(^{-1}\)), which arrived at Alpental at 1515 PST, left the 10,000 ft. level at about 1450 PST at a distance of about
**TABLE 5.2**

**ASSUMED FALL SPEEDS OF PRECIPITATION PARTICLES FOR TRAJECTORY CALCULATIONS**

<table>
<thead>
<tr>
<th>Type of Particle</th>
<th>Range of Fall-Speed (Meters per Second)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Unrimed dendrites</td>
<td>0.25 - 1.0 (0.8 - 3.3 ft sec(^{-1}))</td>
</tr>
<tr>
<td>&quot; stellars</td>
<td></td>
</tr>
<tr>
<td>2. Densely rimed dendrites</td>
<td>0.48 - 2.0 (1.6 - 6.6 ft sec(^{-1}))</td>
</tr>
<tr>
<td>&quot; stellars</td>
<td></td>
</tr>
<tr>
<td>3. Unrimed side planes</td>
<td>0.25 - 0.5 (0.8 - 1.6 ft sec(^{-1}))</td>
</tr>
<tr>
<td>&quot; assemblages of plates</td>
<td></td>
</tr>
<tr>
<td>&quot; &quot; sectors</td>
<td></td>
</tr>
<tr>
<td>&quot; bullets</td>
<td></td>
</tr>
<tr>
<td>4. Unrimed needles</td>
<td>0.5 - 1.0 (0.8 - 3.3 ft sec(^{-1}))</td>
</tr>
<tr>
<td>&quot; sheaths</td>
<td></td>
</tr>
<tr>
<td>5. Densely rimed needles</td>
<td>0.5 - 2.0 (1.6 - 6.6 ft sec(^{-1}))</td>
</tr>
<tr>
<td>&quot; sheaths</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 5.20 Trajectories of precipitation particles which fell on the Cascade Mountains at 1515 PST on February 3, 1971. (Numbers against points give the altitude of the particle in thousands of feet.)
15 miles upwind; the smallest densely rimed dendrite (fall-velocity 1.6 ft. sec\(^{-1}\)) left the 10,000 ft. level about 64 miles upwind at 1345 PST. Fig. 5.21 shows a cross-section along the line EF (indicated in Fig. 5.20) of the trajectories for the particles falling at Keechelus Dam and Kachess Dam.

It can be seen from Fig. 5.21 that the crystals arriving at Kachess Dam at 1515 PST on February 3, 1971, had travelled through almost the same riming layer as the crystals which were falling at Keechelus Dam. However, the former crystals were less heavily rimed than the latter. This observation suggests that the riming growth layer, instead of being evenly distributed between the base of the diffusional growth layer and the ground as assumed previously, might be concentrated in regions closer to the ground west of the Cascade crest. This riming growth layer might also be responsible for Alpental receiving more precipitation during the winter months than Keechelus Dam or Kachess Dam, since our observations indicate that in southwesterly winds the crystals which fall on the west and east sides of the Cascades originate in the same general area west of the Cascades and the main difference between the precipitation particles at these three stations is in their degree of riming.

We consider next the trajectories of particles on February 22, 1971. On the morning of this day, a very weak front was lying just off the Pacific Coast of Washington State. Surface winds were E - SSE and mostly light. Light precipitation was falling over most of Western Washington. At Stampede Pass the temperature was in the upper 20's, light snow was falling, and there was a light easterly wind. Winds up to 10,000 ft. were light and variable. The wind at 500 mb, computed from the 1038 PST sounding at Greenwater, was
Fig. 5.21 Cross-section of trajectories for dendrites falling at Keechelus Dam and Kachess Dam at 1515 PST on February 3, 1971. (\[\ldots\]\ Densely rimed dendrites; \[\ldots\]\ Moderate to densely rimed dendrites)
only 10 mph. The 500 mb map for 0400 PST showed very little upper level frontal activity with wind speeds decreasing rapidly ahead of the trough.

At 0800 PST on February 22, 1971, unrimed sideplanes, assemblages of plates and sectors, and bullets were falling at Alpental, Keechelus Dam and Kachess Dam, in addition, unrimed needles were falling at Alpental. At 1000 PST lightly rimed dendrites and moderately to densely rimed dendrites were falling at all three stations and the winds were light and variable. Figs. 5.22 and 5.23 show the trajectories for 0800 and 1000 PST, respectively. Figs. 5.24 and 5.25 show the corresponding cross-sections for these trajectories. The results for 0800 PST illustrate how the easterly upslope wind, which was confined to below 7000 ft., caused needles and sheaths to form in a layer between 6,000 and 7,000 ft. near the Cascade Crest. By 1000 PST the air between 11,000 and 13,000 ft. became saturated, dendrites then formed in this layer and rimed as they fell towards the ground.

On March 2, 1971, at 1500 PST an occluded front extended north-south over the Cascade Mountains just west of the crest. At the 500 mb level the trough, which contained the coldest upper level air, was still off of the Pacific coast. Behind the front in Western Washington the temperatures were in the lower 40's, winds were from the SW, and it was precipitating. At Stampede Pass winds were light and from the east and light snow was falling. Pre-frontal winds in Eastern Washington were mainly from the SSE.

Fig. 5.26 shows the trajectories of the precipitation particles which fell on the Cascade Mountains at 1500 PST on March 2, 1971. Densely rimed dendrites and needles were falling at Alpental, moderately to densely rimed dendrites and needles at Keechelus Dam and moderately to densely rimed dendrites at Kachess
Fig. 5.22 Trajectories of precipitation particles which fell on the Cascade Mountains at 0800 PST on February 22, 1971. (Numbers against points give altitude of particle in thousands of feet.)
Fig. 5.23 Trajectories of precipitation particles which fell on the Cascade Mountains at 1000 PST on February 22, 1971. (Numbers against points give altitude of particle in thousands of feet.)
Cross-section of trajectories for precipitation particles falling on the Cascade Mountains at 0800 PST on February 22, 1971. ( □□□□ Unrimed sideplanes, assemblages of plates and sectors, bullets. ▪▪▪▪ Unrimed needles and sheaths.)
Fig. 5.25 Cross-section of trajectories for precipitation particles falling on the Cascade Mountains at 1000 PST on February 22, 1971 (lightly to heavily rimed dendrites.)
Fig. 5.26 Trajectories of precipitation particles which fell on the Cascade Mountains at 1500 PST on March 2, 1971. (Numbers against points give altitude of particle in thousands of feet.)
Dam. Fig. 5.27 (a) shows cross-sections of these trajectories for Alpental along the lines A - B (which is indicated in Fig. 5.26) and Fig. 5.27 (b) shows a cross-section of the trajectories for the precipitation at all three stations along line C - D (which is also indicated in Fig. 5.26). These observations again indicate that the riming growth layer may be confined to layers close to the ground, rather than being distributed between the base of the diffusional growth layer and the ground. For example, densely rimed needles and sheaths were falling from a layer around 6,000 ft., therefore, it is likely that the dendrites received a substantial amount of their riming below this level.

On March 11, 1971, the winds below 5,000 ft. were strong from the south-east. Fig. 5.28 shows the trajectories of the precipitation particles which reached the ground in the Cascade Mountains at 1900 PST. At this time densely rimed dendrites were falling at Alpental but at Keechelus Dam and Kachess Dam the precipitation consisted of unrimed side planes. Fig. 5.29 shows a cross-section of the trajectories along line GH (which is indicated in Fig. 5.28). The crystals were reaching the ground stations from the east side of the Cascade Crest, and it can be seen that the unrimed sideplanes had less steep trajectories than the densely rimed dendrites.

Why were dendrites observed at Alpental but not at Keechelus Dam or Kachess Dam on this occasion? Fig. 5.30 suggests a possible answer to this question. Shown in this figure are the trajectories for large densely rimed dendrites which reached Alpental at 1900 PST, the diffusion growth layer for these dendrites (cross-hatched area) lies west of Mt. Rainier (14,000 ft.). However, if large rimed dendrites were to have reached the ground at Keechelus
Fig. 5.27 Cross-section of trajectories for precipitation particles falling on the Cascade Mountains at 1500 PST on March 2, 1971. ( Densely rimed dendrites Densely rimed needles and sheaths Moderately to densely rimed dendrites Moderately rimed dendrites Moderately rimed needles and sheaths.)
Fig. 5.28 Trajectories of precipitation particles which fell on the Cascade Mountains at 1900 PST on March 11, 1971. (Numbers against points give altitude of particle in thousands of feet.)
Fig. 5.29 Cross-section of trajectories for precipitation particles falling on Cascade Mountains at 1900 PST on March 11, 1971. ( Densely rimed dendrites Unrimed sideplanes Rising growth layer for dendrites.)
Fig. 5.35 Regions where dendrites formed and did not form on March 11, 1971.
Dam or Kachess Dam they would have had to originate between about 13,500 to
12,000 ft. in the lee of Mt. Rainier. It seems likely that this did not occur
because of the disruption to the air flow caused by Mt. Rainier. It can be
seen from Fig. 5.28 that the trajectories for the sideplanes which fell at
Keechelus Dam and Kachess Dam passed southeast of Mt. Rainier. Sideplanes were
not detected at Alpental but this was probably due to the fact that they were
obscured by the much heavier (x4) precipitation rate of the rimed dendrites.

5.10 Freezing Nuclei and Precipitation

The concentrations of freezing nuclei in the snowfall were measured as
described in §2.5. The results for Alpental did not show any direct relation-
ship between snowfall rate and the concentrations of freezing nuclei active at
-15°C (it is emphasized that only freezing nuclei were measured).

Graupel particles contained an average of 36 freezing nuclei per gram
active at -15°C and unrimed crystals 13 freezing nuclei per gram at -15°C.
This observation supports our previous deduction (see §5.9) that a large amount
of riming occurs in the lower regions of the atmosphere.

The numbers of graupel particles and unrimed crystals per freezing nucleus
(active at the minimum temperatures of formation) were estimated as indicated
in Table 5.3. In both cases, it can be seen that there were about two orders
of magnitude more ice particles than freezing nuclei. This result indicates
that either deposition or contact nuclei were dominating the formation of
these ice particles or that ice crystal multiplication was occurring.

5.11 Conclusions Pertaining to Artificial Seeding

One of the objectives of the Cascade Project is to test the feasibility
of changing the trajectories of ice particles in the air by reducing their
<table>
<thead>
<tr>
<th>Quantity</th>
<th>Graupel Particles</th>
<th>Unrimed Side Planes and Assemblages of Plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured Mean Diameter $d$(mm)</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Derived Mean Mass $m^\dagger$(mg)</td>
<td>$m = 0.065d^3 = 0.11$</td>
<td>$m = 0.010d^2 = 4.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Minimum Temperature of Formation$^\star$(°C)</td>
<td>-15</td>
<td>-25</td>
</tr>
<tr>
<td>Measured Mean Concentration of Freezing Nuclei Per Gram at Minimum Temperature of Formation.</td>
<td>30</td>
<td>500</td>
</tr>
<tr>
<td>Derived Number of Ice Particles per Freezing Nucleus</td>
<td>300</td>
<td>490</td>
</tr>
</tbody>
</table>

$^\dagger$Nakaya and Terada (1934)

$^\star$Magono and Lee (1966)
growth by riming by artificial seeding with ice nuclei (Hobbs and Ryan, 1969; Hobbs et al., 1970). The following conclusions which have been arrived at in the above sections, are relevant to this project:

(a) The crystal types which are most susceptible to riming are dendrites, stellars, needles and sheaths. These crystals are often moderately densely rimed when they reach the ground in the Cascades.

(b) The diffusional growth layers for these crystals generally lie between 5,000 and 13,000 ft.

(c) These crystals increase in mass by riming after they pass out of the base of their diffusional growth layer. Most of the riming probably occurs within a few thousand feet of the top of the Cascades.

(d) At the crest of the Cascades (Alpental) riming is denser and more common in post-frontal than in pre-frontal conditions.

During the 1969-70 and 1970-71 winter seasons [see Hobbs et al., (1970) and §6 of this report, respectively] attempts were made to reduce the riming of ice particles forming in clouds to the west of the Cascades by seeding in those regions which calculations indicated to be the origin of the ice particles reaching our manned ground stations in the Cascades. Since these regions were generally many tens of miles upwind of the ground stations, the targeting of the effects of seeding to a comparatively small area on the ground was extremely difficult. In the light of the conclusions listed above it now appears that it might be possible to eliminate most of the riming growth by glaciating those clouds lying below about 8,000 ft. which are immediately upwind of the ground stations. Moreover, post-frontal conditions appear to offer a greater potential for artificial modification of this kind than do pre-frontal conditions. These ideas will be tested next winter (1971-72).
SECTION 6

SOME CASE STUDIES OF ARTIFICIAL SEEDING

6.1 Introduction

During the winter of 1970-71 artificial seeding from the research aircraft over the Cascade range was carried out for short periods of time on seventeen occasions. The purpose of this seeding was to see whether it is possible to predict where clouds must be seeded in order to target the precipitation affected by the seeding to a predetermined area on the ground. The methods used to predict the location for the artificial seeding was the same as that described by Hobbs et al. (1970). The target area on the ground straddled the Cascade divide in the vicinity of Alpental, Keechelus Dam and Kachess Dam.

Prior to seeding, measurements were made at the ground stations (see Fig. 2.1) and in-cloud measurements were made from the aircraft on the west and east side of the Cascades. In addition, radiosondes were released from Greenwater at regular intervals during the day. Based on these observations the potential for precipitation modification by artificial seeding was evaluated and the location for the seeding determined. Artificial seeding was then carried out from the aircraft at this location for a period of about an hour. Depending on the altitudes at which it was required to seed the clouds and the air temperatures, either silver iodide pyrotechnic units or dry ice was dispersed directly into the clouds at the flight level or silver iodide pyrotechnics with delayed ignition (2,000 ft. of fall before silver iodide is dispersed over next 3,000 ft.) were released from the aircraft.
Following the seeding the research aircraft would attempt to fly downwind into the region predicted to be affected by the seeding in order to obtain in-cloud measurements. Intensive measurements were also made at the ground stations to determine whether precipitation in the target area was changed by the artificial seeding upwind.

Four case studies have been selected below to illustrate the results obtained in several different synoptic situations in 1970-71 when artificial seeding was carried out.

6.2 December 31, 1970

Ground, airborne and radar observations were made on December 31, 1970 when orographic precipitation was being produced over the Cascade Mountains in the absence of frontal activity. Artificial seeding with silver iodide pyrotechnics was carried out for about 1-1/2 hours west of the Cascade divide and some effects attributable to seeding were detected in the target area 20 miles downwind.

6.2.1 Synoptic Situation

A time cross-section based on radiosondes launched from Quillayute between December 28, 1970 and January 1, 1971 is shown in Fig. 6.1. It can be seen that on December 31 the area was free of any frontal activity although a surface cold front of moderate intensity had passed over the Cascades about twenty-four hours earlier. The sounding from Quillayute for 0400 PST on December 31 showed that the greatest dewpoint depression was 2°C, which occurred near the 850 mb level, and corresponded to a relative humidity of 86%. The surface synoptic map for 1300 PST on December 31 (Fig. 6.2) shows the conditions which prevailed during the period of measurements. Higher
Fig. 6.1 Time cross-section for soundings at Quillayute between February 2 and February 4, 1971. (Hours refer to Pacific Standard Time. Temperatures in °C.)
Fig. 6.2 Surface synoptic situation at 1300 PST on December 31, 1970.
pressure was beginning to spread across the State and the winds were generally light. Precipitation was light and showery. However, continuous light snow fell at some higher elevations. Dewpoints were generally low. Stampede Pass was the only station reporting fog.

6.2.2 Aircraft Observations

The research aircraft left Boeing Field just before 1100 PST on December 31, 1970. Sketches of the flight route and the cloud conditions observed along airway V2 between Sea-Tac Airport and Ellensburg are shown in Figs. 6.3 and 6.4, respectively. The clouds over the western slopes of the Cascades were orographic with embedded cumulus; wave clouds were also common. There appeared to be little ice in the clouds but liquid water contents up to 1 g m⁻³ were measured. Although the continuous particle sampler was operated during this flight it malfunctioned so that no record was obtained of the cloud particles.

From the airborne and ground observations and the radiosonde sounding from Greenwater, it was determined that if the clouds were seeded with artificial ice nuclei at an altitude of about 12,000 ft. over the Howard Hanson Reservoir, this should modify the precipitation at the ground stations near the Cascade crest (Alpental, Keechelus Dam and Kachess Dam) which are situated about 20 nautical miles ENE of the Howard Hanson Reservoir (Fig. 2.1). Therefore, the aircraft cruised in a circle about 8 nautical miles in diameter at an altitude of 14,000 ft. above the Howard Hanson Reservoir and delay pyrotechnic flares each containing 40 grams of silver iodide were dropped every 2 minutes between about 1206 and 1333 PST (however, no flares were ignited between 1209 and 1221 PST) into the clouds. Between about 1230
Fig. 6.3 Sketch of flight route on December 31, 1970. (Four figure numbers give local time.)
Fig. 6.4 Cloud conditions along the V2 airway between Sea-Tac airport and Ellensburg during research flight on December 31, 1970. The temperature and winds shown are based on the 1244 PST radiosonde launched from Greenwater which is situated about 10 miles southwest of the point where the V2 airway crosses the Cascade Crest.
and 1315 PST very high ice nucleus counts were recorded on the aircraft, which indicates that some of the silver iodide was being carried upwards at least 2,000 ft. above the point at which it was dispersed into the cloud.

6.2.3 Ground Observations

The precipitation rates and types of snow crystals observed at Alpental, Keechelus Dam and Kachess Dam between 1000 and 1630 PST on December 31 are shown in Fig. 6.5. At Alpental graupel particles fell and these were mixed on occasions with densely rimed dendrites. At Keechelus Dam it was noted that graupel particles were bouncing off the slides and were not replicated, only small irregular particles were replicated. At Kachess Dam graupel fell during the whole period of sampling.

Calculations based on the fastest wind speeds between the ground stations and the level at which artificial seeding was carried out, indicate that the time intervals at which the direct effects of the artificial seeding should have been experienced at the ground stations (Alpental, Keechelus Dam and Kachess Dam) was from about 1220 to 1400 PST. It can be seen from Fig. 6.5 that there were peaks in either the precipitation rate or the optical snow-rate sensor during this period at all three stations. However, in view of the variability of the precipitation at other times during the day, it is not possible to definitely attribute these peaks to the artificial seeding upwind. Interestingly, there was a change from graupel to densely rimed dendrites at Alpental between 1340 and 1420 PST indicating a decrease in the amount of riming which might also have been produced by the seeding. However, similar subtle variations in the types of snow particles also occurred later in the day at Alpental.
Fig. 6.5 Types of snow particles and precipitation rates on December 31, 1970.
The concentrations of freezing nuclei measured in snow samples collected at Alpental are shown in Fig. 6.6. It can be seen that there was a peak in the concentrations between 1230 and 1245 PST which is in the period of the predicted time of arrival of the direct effects of the silver iodide seeding. Fig. 6.7 shows that it was the freezing nuclei active above about -20°C which increased in concentration during the period 1230 to 1245 PST. The concentrations of freezing nuclei in the snow samples collected at Kachess Dam are shown in Fig. 6.8. These concentrations showed several peaks between about 1230 and 1600 PST during which period the plume from the artificial seeding upwind were predicted to arrive in the target area. Moreover, the concentration of silver in the snow collected at Kachess Dam on December 31 only exceeded the minimum detectable level between 1230 - 1245 PST when it reached a concentration of $3 \times 10^{-11}$ grams of Ag per ml of water.

It appears from the above observations that on December 31, 1970, some effects due to artificial seeding from the aircraft 20 miles upwind were detected at the ground stations in the target area during the period when the plume from the seeding was predicted to be in the target area.

6.3 February 3, 1971

Ground, airborne and radar observations were made on and over the Cascade Mountains on February 3, 1971, ahead of a weak surface warm front. Artificial seeding with silver iodide pyrotechnics was carried out for a period of 40 minutes west of the Cascade divide and effects attributable to the seeding were observed in the target area 11 miles downwind.
Fig. 6.6 Differential spectra of freezing nuclei in snow samples collected at Alpental on December 31, 1970.
Fig. 6.7 Concentrations of freezing nuclei active at four temperatures in snow samples collected at Alpental on December 31, 1970.
Fig. 6.8 Concentrations of freezing nuclei active at five different temperatures in snow samples collected at Kachess Dam on December 31, 1970.
6.3.1 **Synoptic Situation**

On February 3, 1971 a low pressure system was moving southeastward toward the State of Washington. A very weak surface warm front moved slowly through the western portion of the state as shown in Fig. 6.9. The surface synoptic map for 1300 PST (Fig. 6.10) shows the conditions across the state during the most intensive period of observations. Figs. 6.11 and 6.12 show the areas over which precipitation was falling at 1230 and 1330 PST as detected by the radar at Seattle. A time cross-section based on radiosondes launched from Quillayute between February 2 and 4 is shown in Fig. 6.13. In the vicinity of the warm front there was light to moderate precipitation throughout February 3. Winds were generally light for the entire period.

Table 6.1 summarizes the spatial and temporal distribution of precipitation associated with the weak occlusion which passed through Alpental at about 0400 PST on February 4, 1970.

6.3.2 **Aircraft Observations**

The research aircraft left Boeing Field at about 1125 PST on February 3 and followed the flight path shown in Fig. 6.14. Figs. 6.15 and 6.16 indicate the cloud conditions along the V2 airway from 1205 to 1237 PST and from 1418 to 1454 PST, respectively. A summary of the particles collected in the clouds with the continuous particle sampler is contained in Table 6.2; the position where each sample was collected is shown in Fig. 6.14 and Fig. 6.15 or 6.16. Moderate icing occurred on climb out (and descent to) Seattle. On the first profile across the Cascade crest, cloud droplets 30 to 40 μm in diameter were collected in densities up to 10 cm\(^{-3}\) with an average density of 4 cm\(^{-3}\) over
Fig. 6.9  Frontal sequence for February 3, 1971.
Fig. 6.10 Surface synoptic situation at 1300 PST on February 3, 1971.
Fig. 6.11 Radar observations at Auburn, Washington on February 3, 1971 at 1230 PST.
Fig. 6.12 Radar observations at Auburn, Washington on February 3, 1971 at 1330 PST.
Fig. 6.13  Time cross-section for soundings at Quillayute between February 2 and February 4, 1971. (Hours refer to Pacific Standard Time. Temperatures in °C.)
Pre-frontal and post-frontal precipitation analysis for February 3, 1971

Weak occluded front passed through Alpental at about 0400 PST on February 3, 1971.

<table>
<thead>
<tr>
<th>Station</th>
<th>Location with respect to Cascade Divide</th>
<th>Total precip. in inches during 18-hr. period</th>
<th>Station pre-frontal precip. in inches</th>
<th>Fraction of 18-hr. precip. which was pre-frontal (%)</th>
<th>Station post-frontal precip. in inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Bend</td>
<td>West</td>
<td>0.91</td>
<td>0.61</td>
<td>67.1</td>
<td>0.30</td>
</tr>
<tr>
<td>Bandera</td>
<td>West</td>
<td>1.06</td>
<td>0.75</td>
<td>70.7</td>
<td>0.31</td>
</tr>
<tr>
<td>Denny Creek</td>
<td>West</td>
<td>0.92</td>
<td>0.69</td>
<td>75.2</td>
<td>0.23</td>
</tr>
<tr>
<td>Alpental Base</td>
<td>West</td>
<td>0.83</td>
<td>0.54</td>
<td>65.0</td>
<td>0.29</td>
</tr>
<tr>
<td>Hyak</td>
<td>East</td>
<td>0.73</td>
<td>0.52</td>
<td>71.2</td>
<td>0.21</td>
</tr>
<tr>
<td>Keechelus Dam</td>
<td>East</td>
<td>0.70</td>
<td>0.60</td>
<td>85.7</td>
<td>0.10</td>
</tr>
<tr>
<td>Cabin Creek</td>
<td>East</td>
<td>0.72</td>
<td>0.63</td>
<td>87.6</td>
<td>0.09</td>
</tr>
<tr>
<td>Kachess Dam</td>
<td>East</td>
<td>0.69</td>
<td>0.56</td>
<td>81.2</td>
<td>0.13</td>
</tr>
<tr>
<td>Stampede Pass</td>
<td>On divide</td>
<td>1.07</td>
<td>0.72</td>
<td>67.3</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Total precipitation for all stations, 18-hour period: 7.63 inches

Percent of total precipitation, pre-frontal: 73.6
" " " " post-frontal: 26.4

Mean precipitation per station, pre-frontal: 0.62 inches
" " " " post-frontal: 0.22 "

Mean precipitation per east station, pre-frontal: 0.58 inches
" " " " west station, pre-frontal: 0.65 "
" " " " east station, post-frontal: 0.13 "
" " " " west station, post-frontal: 0.28 "

The west stations accounted for 46.1% of the pre-frontal precipitation.
The east stations accounted for 41.1% of the pre-frontal precipitation.
The west stations accounted for 56.2% of the post-frontal precipitation.
The east stations accounted for 26.3% of the post-frontal precipitation.

Number of hours of measurable precipitation, pre-frontal, east stations: 34
" " " " pre-frontal, west stations: 35
" " " " post-frontal, east stations: 18
" " " " post-frontal, west stations: 30

---

1. The 18-hour period extends from 9 hours prior to passage of front to 9 hours after passage of front.
2. Pre-frontal precipitation is defined as the cumulative amount in the 9-hour period prior to the passage of the front.
3. Post-frontal precipitation is defined as the cumulative amount in the 9-hour period after the passage of the front.
Fig. 6.14 Sketch of flight route on February 3, 1971. (Cloud particles were replicated at positions along the flight route indicated by the run numbers 1 through 21. Four figure numbers give local time.)
Cloud conditions along the V-2 airway between 1205 and 1237 PST on February 3, 1971. Temperatures and winds from the 1223 PST radiosonde from Greenwater. Run numbers refer to the cloud particle sampler. LWC = Liquid water content in gram m⁻³. T = Turbulence in cm²/s sec⁻¹.
Fig. 6.16 ‘Cloud’ conditions along the V-2 airway between 1418 and 1454 PST on February 3, 1971. Temperatures and winds from the 1515 PST radiosonde from Greenwater. Run numbers refer to cloud particle sampler. LWC = Liquid water content in m$^{-3}$. 
TABLE 6.2

SUMMARY OF CLOUD PARTICLES COLLECTED WITH CONTINUOUS PARTICLE SAMPLER ON FEBRUARY 3, 1971

(The position of each run is indicated in Fig. 6.14 and Fig. 6.15 or Fig. 6.16.)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Water Drops</th>
<th>Ice Particles</th>
<th>Number Ratio of Water to Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (µm)</td>
<td>Concentration (cm⁻³)</td>
<td>Type &amp; Maximum Dimension (µm)</td>
</tr>
<tr>
<td>1</td>
<td>15-60</td>
<td>1-11</td>
<td>Irregular 20-80. Columns up to 200µ.</td>
</tr>
<tr>
<td></td>
<td>Average 30</td>
<td>Average 4</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20-50</td>
<td>1-6</td>
<td>Isolated crystals at beginning. Irregular and hexagonal plates. Toward end of run 2 or 3 broken aggregates up to 300µ.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Toward end of run fewer drops)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Up to 120.</td>
<td>0.6-6</td>
<td>2 aggregates of hexagonal plates &amp; some single crystals up to 80µ.</td>
</tr>
<tr>
<td></td>
<td>Average 40.</td>
<td>(Some splashing)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Concentration low in last half of run)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>Hexagonal plates up to 40µ &amp; irregulars.</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>Irregulars up to 40µ.</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-50</td>
<td>Only two drops observed.</td>
<td>Irregular ~20µ. Hexagonal plates up to 100µ.</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td>Irregulars and hexagonal plates 20-150µ.</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>Irregulars and hexagonal plates 50-200µ.</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>Irregulars 15-50µ</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td>Fragments of plates or dendrites up to 200µ. (Some shattered crystals)</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>Plate-like - 150µ. Some smaller fragments.</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>Up to 30</td>
</tr>
</tbody>
</table>
### TABLE 6.2 (continued)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Water Drops</th>
<th>Ice Particles</th>
<th>Number Ratio of Water to Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (µm)</td>
<td>Concentration (cm⁻³)</td>
<td>Type &amp; Maximum Dimension (µm)</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Possibly 30.</td>
<td>Up to 30.</td>
<td>Irregular plates 20-120µm. (Average 40µm)</td>
</tr>
<tr>
<td>17</td>
<td>One drop ~25</td>
<td></td>
<td>Irregular plates 30-120µm. (Average 40µm)</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td></td>
<td>Irregular 40-120µm, possibly one arm from a dendrite 300µm x 80µm.</td>
</tr>
<tr>
<td>19</td>
<td>Few drops 10-40. Possibly one 180µm frozen drop.</td>
<td>Irregular plates 10-50µm.</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the western slopes, and the liquid water reached sustained levels of 0.32 g m\(^{-3}\). Isolated ice particles and aggregates were also observed over the western slopes but the ratio of water droplets to ice particles was about 100 to 1. Over the eastern slopes of the Cascades only ice particles were collected by the continuous particle sampler, although liquid water readings up to 0.18 g m\(^{-3}\) were occasionally recorded by the Johnson-Williams meter. Subsequent profiles across the Cascade crest indicated that the transition from predominantly water to predominantly ice clouds was variable but occurred in the vicinity of the Cascade crest.

Calculations based on the observed conditions indicated that in order to modify precipitation on the ground at Alpental, Keechelus and Kachess by artificial seeding the clouds would have to be seeded 11 nautical miles northwest of the ground target area at an altitude of about 8,500 ft. Therefore, the aircraft flew in a circle about 8 nautical miles in diameter around this location (Fig. 6.14) at an altitude of 12,000 ft. (which was near cloud tops), and pyrotechnic delay ejection flares each containing 10 grams of AgI were released every two minutes between 1334 and 1414 PST. The delay time of these flares was such that the AgI was dispersed in the air between 10,000 and 7,000 ft.

Following the first few circles of seeding a subsun -- indicating the presence of plate-like ice crystals -- was observed downwind of the aircraft but not upwind. When the seeding was completed, the aircraft headed downwind toward the target area. Large ice crystals were visible in the clouds, although on an earlier traverse made prior to seeding, crystals were not seen. Moreover, the continuous particle sampler showed that in the predicted
plume-of-effect produced by the artificial seeding the cloud particles were almost entirely ice (irregular and plate-like fragments predominated), whereas, prior to seeding the clouds in this region were predominantly liquid water. These observations show that the artificial seeding produced large numbers of ice particles in the clouds in a region extending toward the target area on the ground.

6.3.4 Ground Observations

The precipitation rates and types of snow particles observed at Alpental, Keechelus Dam and Kachess Dam between 0800 and 1730 PST on February 3, 1971, are shown in Fig. 6.17. At all three ground stations similar trends occurred in the types of particles and the degree of riming. The particles changed from unrimed to moderately rimed side-planes, assemblages of plates and sectors in the morning, to moderately or heavily rimed dendrites around midday, graupel from midday to 1400 PST, and then back to moderately or densely rimed dendrites after about 1400 PST.

The periods for which the direct effects of the artificial seeding upwind were predicted to affect precipitation at the ground stations are indicated by the hatched areas in Fig. 6.17. At each of the three stations the rates of snowfall as indicated by direct weighing and the optical snow-rate sensor showed marked increases during the predicted period of the plume-of-effect from the artificial seeding. Also, at all three stations the solid precipitation changed from graupel to heavily and moderately rimed dendrites during this period. These results suggest that the artificial seeding increased precipitation rates and decreased riming in the target area, however, the natural variability in the type and rate of snowfall precludes a
Fig. 6.17 Types of snow particles and precipitation rates at ground stations on February 3, 1971. (The predicted times of arrival of the direct effects from the airborne seeding are shown by the hatched areas.)
definite conclusion based on this evidence alone. Interestingly, the higher precipitation rates and dendritic crystals persisted for at least two hours after the direct effects of the artificial seeding were predicted to have passed through the ground stations.

The measured concentrations of freezing nuclei in snow samples collected at the three ground stations are shown in Fig. 6.18. It can be seen that these concentrations reached absolute maxima at Alpental and Keechelus Dam during the predicted periods at these stations of the plume-of-effect produced by the artificial seeding, but at Kachess Dam a pronounced effect attributable to the seeding was not observed.

Seventy-six snow samples, collected at four ground stations on February 3 were analyzed for silver. Only ten of the samples contained concentrations of silver in excess of the minimum detectable level. At Keechelus Dam, Kachess Dam and Stampede Pass, the silver in the snow reached measurable values of $6 \times 10^{-11}$, $4 \times 10^{-11}$ and $6 \times 10^{-11}$ gram of Ag per ml of water, respectively, during the predicted periods at these stations of the plume-of-effect from the artificial seeding.

CW Doppler radar measurements were made through the day at Keechelus Dam on February 3. Although the data on this occasion were subject to some uncertainties due to poor sensitivity they showed some interesting features (Fig. 6.19). In the pre-seeded period around 1030 PST well-defined fall speeds located at about 1 and 2 m s$^{-1}$ were detected (Fig. 6.19a), but later on during this period the higher fall speed split into two components (Fig. 6.19b, c). During the period when the plume-of-effect produced by the artificial seeding was predicted to be at Keechelus Dam (1355 to 1450 PST),
Fig. 6.18 Measured concentrations of freezing nuclei at -21°C at Alpental, Keechelus and Kachess on February 3, 1971. The predicted period of the plume-of-effect from the artificial seeding is indicated by the hatched area.
Fig. 6.19 Spectra of fall speeds of precipitation particles at Keechelus Dam on February 3, 1971, with CW Doppler radar before seeding (a, b and c) and during the predicted period at Keechelus Dam of the plume-of-effect produced by airborne seeding 11 miles upwind (d, e, and f).
the spectra showed more variability and more spectral lines (Fig. 6.19d, e, f). A noticeable feature during this period was the appearance of a strong signal corresponding to particles with much smaller fall speeds than were present prior to seeding; these particles may have been produced by the silver iodide seeding upwind.

When considered collectively the above observations provide strong evidence that the artificial seeding carried out from the aircraft on February 3, 1971, caused modifications in the intensity and the nature of the precipitation at three ground stations situated over 10 miles downwind which were defined as the target area prior to seeding.

6.4 February 18, 1971

Airborne and ground measurements were made during the passage of an occluded front on February 18, 1971. Artificial seeding with silver iodide pyrotechnics was carried out from the aircraft for about one hour and probably produced complete glaciation of the cloud. However, any effects of the seeding at ground level were probably obscured by the passage of the front.

6.4.1 Synoptic Situation

An occluded front passed through Washington on February 18, 1971. The 0400 PST upper air sounding from Quillayute (Fig. 6.20) shows backing winds (cold air) to about 3,000 ft. and veering winds (warm air) above this level. Twelve hours later the Quillayute sounding indicates that the cold air wedge has risen to about 11,000 ft. with some warm air above the frontal surface. The 850 and 700 mb maps show this cold air advection (Figs. 6.21 and 6.22). The post-frontal air mass was dry; at 800 mb and above the dewpoint depressions were all greater than 10°C.
Fig. 6.20 Time cross-section for soundings at Quillayute between February 17 and February 19, 1971. (Hours refer to Pacific Standard Time. Temperatures in °C.)
Fig. 6.21 850 mb synoptic map for 1600 PST on February 18, 1971

- Temperature (°C)
- Height in 10's of geopotential meters of 850 mb surface
Fig. 6.22  700 mb synoptic map for 1600 PST on February 18, 1971
The frontal sequence map (Fig. 6.23) shows the progression of the occlusion across Washington on February 18. The front passed through Quillayute at 0842 PST, and through Stampede Pass at the crest of the Cascades at about 1430 PST. The 1300 PST surface map (Fig. 6.24) shows conditions at a time when intensive aircraft and ground measurements were being made. Precipitation and winds were generally light, however, between 1800 and 2300 heavier precipitation was observed in the Cascades. North Bend (situated about 20 miles west of the Cascade crest) had 0.22 inches of precipitation between 1800 and 1900 PST. An analysis of the pre-frontal and post-frontal precipitation for February 18 is shown in Table 6.3.

6.4.2 Aircraft Observations

The research aircraft left Boeing Field Airport at about 1245 PST and headed east on vector 2 across the Cascade Mountains. The flight route is shown in Fig. 6.25. Summaries of some of the observations made on the flight are shown in Figs. 6.26 and 6.27. Table 6.4 lists the particles collected on the continuous particle sampler in the various runs.

Climbing out of Seattle just behind the front moderate icing was experienced. The mean diameter of the cloud droplets was 30 \( \mu \text{m} \) and the concentrations were less than 100 cm\(^{-3} \). The aircraft probably passed through the front about 15 nautical miles east of Seattle. Ahead of the front ice crystals dominated in the clouds. The crystals were mainly irregular or plate-like at altitudes between 8,000 and 10,000 ft. (-10 to -14\(^\circ\)C) but some needles were collected at lower altitudes at -4\(^\circ\)C. Frozen drops were collected in many of the runs.

Between 1409 and 1500 PST the aircraft flew at 12,000 ft. in a circle of
Fig. 6.23 Frontal sequence for February 18, 1971
Fig. 6.24  Surface synoptic situation at 1300 PST on February 18, 1971
TABLE 6.3
PRE-FRONTAL AND POST-FRONTAL PRECIPITATION ANALYSIS FOR FEBRUARY 18, 1971

Front passed through Alpental at about 1400 PST on February 18, 1971.

<table>
<thead>
<tr>
<th>Station</th>
<th>Location with respect to Cascade Divide</th>
<th>Total precip. in inches during 18-hr. period(1)</th>
<th>Station pre-frontal precip. in inches(2)</th>
<th>Fraction of 18-hr. precip. which was pre-frontal (%)</th>
<th>Station post-frontal precip. in inches(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Bend</td>
<td>West</td>
<td>1.32</td>
<td>0.52</td>
<td>39.4</td>
<td>0.80</td>
</tr>
<tr>
<td>Bandera</td>
<td>West</td>
<td>1.01</td>
<td>0.27</td>
<td>26.7</td>
<td>0.74</td>
</tr>
<tr>
<td>Denny Creek</td>
<td>West</td>
<td>0.79</td>
<td>0.24</td>
<td>30.4</td>
<td>0.55</td>
</tr>
<tr>
<td>Alpental Base</td>
<td>West</td>
<td>1.07</td>
<td>0.30</td>
<td>28.1</td>
<td>0.77</td>
</tr>
<tr>
<td>Hyak</td>
<td>East</td>
<td>0.85</td>
<td>0.18</td>
<td>21.2</td>
<td>0.67</td>
</tr>
<tr>
<td>Keechelus Dam</td>
<td>East</td>
<td>0.63</td>
<td>0.15</td>
<td>23.8</td>
<td>0.48</td>
</tr>
<tr>
<td>Cabin Creek</td>
<td>East</td>
<td>0.45</td>
<td>0.15</td>
<td>33.3</td>
<td>0.30</td>
</tr>
<tr>
<td>Kachess Dam</td>
<td>East</td>
<td>0.22</td>
<td>0.06</td>
<td>27.3</td>
<td>0.16</td>
</tr>
<tr>
<td>Stampede Pass</td>
<td>On divide</td>
<td>0.35</td>
<td>0.13</td>
<td>37.3</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.00</td>
<td></td>
</tr>
</tbody>
</table>

Total precipitation for all stations, 18-hour period - -- - -- -- 6.69 inches

Percent of total precipitation, pre-frontal - -- - -- -- 29.9
" " " " " post-frontal - -- - -- -- 70.1

Mean precipitation per station, pre-frontal - -- - -- -- 0.22 inches
" " " " " post-frontal - -- - -- -- 0.52 "

Mean precipitation per east station, pre-frontal - -- - -- -- 0.13 inches
" " " " west station, pre-frontal - -- - -- -- 0.33 "
" " " west station, post-frontal - -- - -- -- 0.40 "
" " west station, post-frontal - -- - -- -- 0.71 "

The west stations accounted for 66.5% of the pre-frontal precipitation.
The east stations accounted for 27.0% of the pre-frontal precipitation.
The west stations accounted for 60.9% of the post-frontal precipitation.
The east stations accounted for 34.3% of the post-frontal precipitation.

Number of hours of measurable precipitation, pre-frontal, east stations -- 17
" " " " " " " " west stations -- 27
" " " " " " west station, post-frontal, east stations -- 26
" " " " " post-frontal, west stations -- 34

The west stations had an unusually high percentage of pre-frontal precipitation in this storm.

(1) The 18-hour period extends from 9 hours prior to passage of front to 9 hours after passage of front.
(2) Pre-frontal precipitation is defined as the cumulative amount in the 9-hour period prior to the passage of the front.
(3) Post-frontal precipitation is defined as the cumulative amount in the 9-hour period after the passage of the front.
Fig. 6.25 Sketch of flight route on February 18, 1971. (Cloud particles were replicated at positions along the flight route indicated by the run numbers 1 through 23. Four figure numbers give local time.)
Fig. 6.26 Cloud conditions between 1245 and 1340 PST along the V-2 airway between Sea-Tac airport and Ellensburg during research flight on February 18, 1971. The temperatures and winds shown are based on the 1253 PST radiosonde launched from Greenwater which is situated about 10 miles southwest of the point where the V-2 airway crosses the Cascade Crest. Run numbers refer to cloud particle sampler. "LWC = Liquid water content in gm·s⁻³."
Fig. 6.27  Cloud conditions between 1510 and 1600 PST along the V-2 airway between Sea-Tac Airport and Ellensburg during research flight on February 18, 1971. The temperature and winds shown are based on the 1501 PST radiosonde launched from Greenwater which is situated about 10 miles southwest of point where the V-2 airway crosses the Cascade Crest. Run numbers refer to cloud particle sampler. LWC = Liquid water content in gm⁻³. T = Turbulence in cm²/3 sec⁻¹.
### TABLE 6.4

**SUMMARY OF CLOUD PARTICLES COLLECTED WITH CONTINUOUS PARTICLE SAMPLER ON FEBRUARY 18, 1971**

(The position of each run is indicated in Fig. 6.24 and Fig. 6.25 or Fig. 6.26.)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Water Drops</th>
<th>Ice Particles</th>
<th>Number Ratio of Water to Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (µm)</td>
<td>Concentration (cm⁻³)</td>
<td>Type &amp; Maximum Dimension (µm)</td>
</tr>
<tr>
<td>1</td>
<td>10-80. Many frozen drops.</td>
<td>11-110</td>
<td>Mainly irregular. Some columns or needles. Some melting aggregates. 50-500</td>
</tr>
<tr>
<td>2</td>
<td>10-30</td>
<td>Isolated</td>
<td>Mainly irregular. 10-250</td>
</tr>
<tr>
<td>3</td>
<td>15-30</td>
<td>Isolated</td>
<td>Some hexagonal plates. Mainly irregular. Some aggregates. Shattering. 20-300</td>
</tr>
<tr>
<td>4</td>
<td>A few drops</td>
<td></td>
<td>Aggregate &amp; shattered larger crystals. 20-200</td>
</tr>
<tr>
<td>5</td>
<td>15-40</td>
<td>A few towards end</td>
<td>A few aggregates. 20-200</td>
</tr>
<tr>
<td>6</td>
<td>15-25. Some frozen.</td>
<td>Isolated</td>
<td>A few shattered larger crystals. 10-150</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Isolated</td>
<td>Some hexagonal plates, most irregular. Shattered larger crystals &amp; aggregates. 15-250</td>
</tr>
<tr>
<td>8</td>
<td>Similar to Run #7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>15-30</td>
<td>Isolated</td>
<td>Aggregate &amp; shattering plates &amp; irregulars. 20-200</td>
</tr>
<tr>
<td>10</td>
<td>15-35</td>
<td>Isolated</td>
<td>Irregular &amp; plate fragments. Shattered larger crystals. 20-200</td>
</tr>
<tr>
<td>11</td>
<td>15-40 (A few larger) Many frozen. Some groups of cemented frozen drops.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>20-120 Frozen</td>
<td></td>
<td>Aggregate &amp; shattered larger crystals.</td>
</tr>
</tbody>
</table>
TABLE 6.4 (continued)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Water Drops</th>
<th>Ice Particles</th>
<th>Number Ratio of Water to Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (μm)</td>
<td>Concentration (cm⁻³)</td>
<td>Type &amp; Maximum Dimension (μm)</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td>Some columns. Shattering. Some aggregates.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Up to 150; occ. to 250</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td>20-80</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Almost clear air.</td>
</tr>
<tr>
<td>15</td>
<td>Up to 40. Mainly frozen.</td>
<td>Isolated</td>
<td>Mainly platelike fragments. Aggregates.</td>
</tr>
<tr>
<td>16</td>
<td>20-50 Many frozen droplets. Many double frozen drops.</td>
<td>Isolated</td>
<td>Small irregulars. 20-90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mainly platelike fragments. Aggregates. Up to 250.</td>
</tr>
<tr>
<td>17</td>
<td>Similar to Run #17. Fewer frozen drops.</td>
<td>Isolated</td>
<td>Shattering frozen drops. Irregular. A few hexagonal plates. 20-80</td>
</tr>
<tr>
<td>19</td>
<td>10-70 Mean 50.</td>
<td>10-41</td>
<td>Mainly irregulars. Some aggregates. 20-200; mainly &lt;100</td>
</tr>
<tr>
<td>20</td>
<td>10-40</td>
<td>1-10</td>
<td>20-100</td>
</tr>
<tr>
<td>21</td>
<td>~20</td>
<td>Isolated</td>
<td>Irregular 25-70</td>
</tr>
<tr>
<td>22</td>
<td>Almost clear air.</td>
<td>20-50</td>
<td>Isolated</td>
</tr>
</tbody>
</table>
diameter 8 nautical miles centered at a point 17 nautical miles from Keechelus Dam on a bearing of 215° (Fig. 6.25). Artificial seeding with AgI delay pyrotechnics was carried out during this time. The AgI from these units was dispersed between 10,000 and 7,000 ft. From 1409 to 1429 PST the pyrotechnics were released every 2 minutes and each contained 40 gm of AgI. From 1430 to 1500 pyrotechnics were released every minute, on the even minutes the units contained 10 gm of AgI and on the odd minutes 40 gm of AgI. A total of twenty-six 40 gm and fifteen 10 gm silver iodide units were dispersed.

It was observed from the aircraft that some clearing occurred in the region that was seeded. Moreover, as mentioned above, subsequent inspection of the particles collected ahead of the front showed that even prior to seeding ice particles dominated in the clouds. It seems likely therefore that the introduction of AgI in the pre-frontal region of this storm produced over-seeding and confirms the conclusions arrived at in §5.6 and §5.7.

Winds in and below the seeding levels were from 244° to 134° and between 12.5 and 5.7 m s⁻¹, below 5,000 ft. the winds had a westerly component. Therefore, the seeding should not have affected the ground stations in the target area before about 1500 PST.

6.4.3 Ground Observations

Some of the observations of precipitation which were made at ground level on February 18, 1971, have already been described in §5.8. The passage of the occluded front across the Cascades between about 1400 and 1500 PST produced increases in precipitation at most of the ground stations (Fig. 6.28) which probably masked any direct effects on the precipitation which the artificial
Fig. 6.28 Precipitation from weighing buckets on February 18, 1971.
seeding upwind might have produced. However, the concentrations of freezing nuclei active at \(-15^\circ C\) in the precipitation samples collected at Keechelus Dam (Fig. 6.29) show a marked increase in concentrations from about 1530 to 1700 PST which might well have been due to the artificial seeding upwind.

**6.5 March 28, 1971**

Airborne and ground observations were made in a frontal situation on March 28, 1971. Artificial seeding with silver iodide was carried out 40 miles upwind of the target area. There was an increase in freezing nucleus concentrations at Alpental following seeding, but no other marked effects attributable to the seeding were observed in the target area. However, post-analysis showed that any effects due to the seeding would probably have been carried southeast of the target.

**6.5.1 Synoptic Situation**

Fig. 6.30 shows the movement of a frontal system across the State of Washington on March 28, 1971. Both the cold and warm fronts were weak, but rapid occlusion did not occur until they were well east of the Cascade Range. The 850 mb map for 1600 PST indicated some cold air advection to the west of Washington, but the higher level map showed little or no advection. The Quillayute radiosonde sounding for 1600 PST (Fig. 6.31) shows that the air mass was very moist from the surface to 750 mb. There are backing winds from the surface to about 5,000 ft. indicating the advance of the wedge of cold air. Above the frontal surface the winds veer to the maximum height of the sounding. The 1600 PST sounding at Spokane Airport in Eastern Washington showed veering winds throughout, indicating warm air advection.
Fig. 6.29 Concentrations of freezing nuclei active at -15°C in snow samples at Keechelus Dam on February 18, 1971.
Fig. 6.30 Frontal sequence for March 28, 1971
Fig. 6.31 Time cross-section for soundings at Quillayute between March 27 and March 29, 1971.
(Hours refer to Pacific Standard Time. Temperatures in °C.)
The surface synoptic map for 1300 PST (Fig. 6.32) shows the conditions which prevailed close to the time when artificial seeding was carried out. Precipitation and winds were generally light. Stampede Pass had an easterly wind until the passage of the cold front when the wind was calm for two hours. Fog was prevalent throughout Washington during the day.

An analysis of the distribution of precipitation associated with this system is contained in Table 6.5.

6.5.2 Aircraft Observations

The flight route of the research aircraft over the Cascades between about 1100 and 1515 PST is shown in Fig. 6.33. Schematics of the conditions encountered between 1105 to 1150 PST and 1425 to 1515 PST are shown in Figs. 6.34 and 6.35, respectively, and the particles collected on the continuous particle sampler are described in Table 6.6.

At 8,000 ft. (-5°C) the clouds consisted mainly of water droplets, but some large ice particles were present. The concentrations of droplets as indicated by the continuous particle sampler and the Johnson-Williams liquid water meter were highest on the western slopes and decreased to the east. The ice crystals were irregular or needles. Samples made in cumulus clouds east of the Cascades contained almost entirely water droplets. However, regions where ice particles (irregular, plate-like and fragments of stellars) were precipitating out of the clouds were encountered to the east of the Cascade divide. A cap-cloud over Mt. Rainier contained mainly droplets with a few isolated ice crystals. The drop sizes were generally fairly uniform within any one sample with diameters ranged from 10 to 40 μm. The greatest
Fig. 6.32 Surface synoptic situation at 1300 PST on March 28, 1971.
### TABLE 6.5

**PRE-FRONTAL AND POST-FRONTAL PRECIPITATION ANALYSIS FOR MARCH 28, 1971**

Front passed through Alpental at about 1500 PST on March 28, 1971.

<table>
<thead>
<tr>
<th>Station</th>
<th>Location with respect to Cascade Divide</th>
<th>Total precip. in inches during 18-hr. period(1)</th>
<th>Station pre-frontal precip. in inches(2)</th>
<th>Fraction of 18-hr. precip. which was pre-frontal (%)</th>
<th>Station post-frontal precip. in inches(3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Bend</td>
<td>West</td>
<td>0.95</td>
<td>0.31</td>
<td>32.6</td>
<td>0.64</td>
</tr>
<tr>
<td>Bandera</td>
<td>West</td>
<td>1.05</td>
<td>0.33</td>
<td>31.4</td>
<td>0.72</td>
</tr>
<tr>
<td>Denny Creek</td>
<td>West</td>
<td>0.84</td>
<td>0.24</td>
<td>28.6</td>
<td>0.60</td>
</tr>
<tr>
<td>Alpental Base</td>
<td>West</td>
<td>1.43</td>
<td>0.65</td>
<td>45.5</td>
<td>0.78</td>
</tr>
<tr>
<td>Hyak</td>
<td>East</td>
<td>0.82</td>
<td>0.39</td>
<td>47.6</td>
<td>0.43</td>
</tr>
<tr>
<td>Keechelus Dam</td>
<td>East</td>
<td>0.56</td>
<td>0.28</td>
<td>50.0</td>
<td>0.28</td>
</tr>
<tr>
<td>Cabin Creek</td>
<td>East</td>
<td>0.53</td>
<td>0.32</td>
<td>60.3</td>
<td>0.21</td>
</tr>
<tr>
<td>Kachess Dam</td>
<td>East</td>
<td>0.27</td>
<td>0.18</td>
<td>66.7</td>
<td>0.09</td>
</tr>
<tr>
<td>Snoqualmie Pass</td>
<td>On divide</td>
<td>0.43</td>
<td>0.26</td>
<td>60.4</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Total precipitation for all stations, 18-hour period = 6.88 inches

Percent of total precipitation, pre-frontal = 43.0

Mean precipitation per station, pre-frontal = 0.33 inches

Mean precipitation per east station, pre-frontal = 0.29 inches

The west stations accounted for 51.7% of the pre-frontal precipitation.

The east stations accounted for 48.3% of the pre-frontal precipitation.

The west stations accounted for 70.0% of the post-frontal precipitation.

The east stations accounted for 25.8% of the post-frontal precipitation.

Number of hours of measurable precipitation, pre-frontal, east stations = 32

Number of hours of measurable precipitation, pre-frontal, west stations = 33

Number of hours of measurable precipitation, post-frontal, east stations = 22

Number of hours of measurable precipitation, post-frontal, west stations = 36

---

(1) The 18-hour period extends from 9 hours prior to passage of front to 9 hours after passage of front.

(2) Pre-frontal precipitation is defined as the cumulative amount in the 9-hour period prior to the passage of the front.

(3) Post-frontal precipitation is defined as the cumulative amount in the 9-hour period after the passage of the front.
Fig. 6.3 Sketch of flight route on March 28, 1971. (Cloud particles were replicated at positions along the flight route indicated by the run numbers 1 through 33. Four figure numbers give local time.)
Fig. 6.34 Cloud conditions along V2 airway between 1105 and 1150 PST on March 28, 1971. The temperature and winds shown are based on the 1002 PST radiosonde launched from Greenwater. Run numbers refer to cloud particle sampler. LWC = Liquid water content in gm⁻³.
Fig. 6.35 Cloud conditions along the V2 airway between 1425 and 1515 PST on March 28, 1971. The temperature and winds shown are based on the 1519 PST radiosonde launched from Greenwater. Run numbers refer to cloud particle sampler. LWC = Liquid water content in gm-3.
TABLE 6.6
SUMMARY OF CLOUD PARTICLES COLLECTED WITH CONTINUOUS PARTICLE SAMPLER ON MARCH 28, 1971
(The position of each run is indicated in Fig. 6.32 and Fig. 6.33 or Fig. 6.34. Decelerator used.)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>Water Drops</th>
<th>Ice Particles</th>
<th>Number Ratio of Water to Ice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diameter (μm)</td>
<td>Concentration (cm⁻³)</td>
<td>Type &amp; Maximum Dimension (μm)</td>
</tr>
<tr>
<td>1</td>
<td>10-40</td>
<td>21-115</td>
<td>All water (+2⁰)</td>
</tr>
<tr>
<td></td>
<td>Some to 150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20-50</td>
<td>14-72</td>
<td>All water (+2⁰)</td>
</tr>
<tr>
<td></td>
<td>Some to 150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>15-50.</td>
<td>14-68</td>
<td>&gt;50:1</td>
</tr>
<tr>
<td></td>
<td>Some to 200.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Melting ice in some larger drops.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>15-60</td>
<td>Up to 38.</td>
<td>50-300 (Some melting)</td>
</tr>
<tr>
<td></td>
<td>Some clear areas.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>15-100</td>
<td>6-38</td>
<td>50-250 (Mainly melting)</td>
</tr>
<tr>
<td></td>
<td>Some to 250.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Melting ice in larger drops.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>10-50</td>
<td>7-40</td>
<td>Mainly irregular. Some needles or sheaths.</td>
</tr>
<tr>
<td></td>
<td>Some to 100.</td>
<td></td>
<td>50-500</td>
</tr>
<tr>
<td>7</td>
<td>10-40</td>
<td>3-13</td>
<td>Mainly irregular. Some needles or columns.</td>
</tr>
<tr>
<td></td>
<td>Some to 120.</td>
<td></td>
<td>50-300</td>
</tr>
<tr>
<td>8</td>
<td>15-60</td>
<td>7-35</td>
<td>No ice during run. Some columns after run.</td>
</tr>
<tr>
<td></td>
<td>Some to 120.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>15-50</td>
<td>7 (Decreasing to 0.7)</td>
<td>Small irregular ice near beginning. &lt;70</td>
</tr>
<tr>
<td>10</td>
<td>Slow Speed</td>
<td></td>
<td>Irregular &amp; plate-like. Possibly subliming. Some riming. 1200μm stellar remnant near end.</td>
</tr>
<tr>
<td></td>
<td>30-70</td>
<td></td>
<td>50-300</td>
</tr>
<tr>
<td>Run No.</td>
<td>Water Drops</td>
<td>Ice Particles</td>
<td>Number Ratio of Water to Ice</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>---------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td></td>
<td>Diameter (µm)</td>
<td>Concentration (cm⁻³)</td>
<td>Type &amp; Maximum Dimension (µm)</td>
</tr>
<tr>
<td>11 1st half Slow Speed</td>
<td>20-100</td>
<td>20-100</td>
<td>Plate-like &amp; rimed. Some subliming.</td>
</tr>
<tr>
<td>11 2nd half Slow Speed</td>
<td>10-60</td>
<td>12-30</td>
<td>Isolated ice. Some small aggregates</td>
</tr>
<tr>
<td>12</td>
<td>15-30</td>
<td>25-75</td>
<td>Irregular small aggregates.</td>
</tr>
<tr>
<td>13 Slow Speed</td>
<td>50-100</td>
<td>Isolated</td>
<td>A few rimed stellar fragments.</td>
</tr>
<tr>
<td>14</td>
<td>15-60</td>
<td>&lt;1:3</td>
<td>Plate-like &amp; branch fragments. Stellar fragment from 1000µm crystal.</td>
</tr>
<tr>
<td>15</td>
<td>30-60</td>
<td>Inc. to 4</td>
<td>Irregular, hexagonal plates, branch fragments.</td>
</tr>
<tr>
<td>16</td>
<td>30-70</td>
<td>Occasional some frozen</td>
<td>Irregular &amp; hexagonal plates. Some riming.</td>
</tr>
<tr>
<td>17 Clear air</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 Slow Speed</td>
<td></td>
<td></td>
<td>Plate, branch &amp; sector fragments. A few columns.</td>
</tr>
<tr>
<td>19</td>
<td>15-30</td>
<td>Up to 50</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>~10</td>
<td>~34</td>
<td>Isolated irregulars. 100-200</td>
</tr>
<tr>
<td>21</td>
<td>15-30</td>
<td>Up to 24</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>15-30</td>
<td>13-40</td>
<td>Occasional irregulars. 20-200</td>
</tr>
<tr>
<td>23</td>
<td>20-40</td>
<td>12-36</td>
<td>50-100</td>
</tr>
<tr>
<td>24</td>
<td>10-20</td>
<td>6-24</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>10-60</td>
<td>Up to 38</td>
<td>Irregulars &amp; plate-like. Shattering. Some aggregates. 40-200</td>
</tr>
<tr>
<td>Run No.</td>
<td>Water Drops</td>
<td>Ice Particles</td>
<td>Number Ratio of Water to Ice</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td>---------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td></td>
<td>Diameter (µm)</td>
<td>Concentration (cm⁻³)</td>
<td>Type &amp; Maximum Dimension (µm)</td>
</tr>
<tr>
<td>26</td>
<td>10-50</td>
<td>Up to 90</td>
<td>Irregulars and hexagonal plates 40-250</td>
</tr>
<tr>
<td></td>
<td>(A few frozen)</td>
<td>Mainly -11</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>15-40</td>
<td>50-250</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Occasional at beginning.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>15-40</td>
<td>10-31</td>
<td>Melting. A few small aggregates. 50-250</td>
</tr>
<tr>
<td></td>
<td>Some to 150.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>15-50</td>
<td></td>
<td>Melting. Mainly irregular sheath or needle aggregates. 50-250</td>
</tr>
<tr>
<td>30</td>
<td>15-50</td>
<td>1.2-6</td>
<td>Sheaths, columns, irregular. 50-400</td>
</tr>
<tr>
<td>31</td>
<td>20-80</td>
<td>1.2-5 at first, 2.4-12 later.</td>
<td>Columnar 60-400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td>10-50</td>
<td>6-60</td>
<td>Small melting aggregates. To 400µm</td>
</tr>
<tr>
<td></td>
<td>Some to 200. (with melting ice?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>10-250</td>
<td>5.5-28</td>
<td>Melting hexagonal plates near beginning to 250. Melting to 1400µm.</td>
</tr>
</tbody>
</table>
concentration recorded was 84 cm$^{-3}$, but due to the use of the decelerator the derived concentrations are not reliable.

Artificial seeding was carried out from the research aircraft from two locations (Fig. 6.33). From 1227 to 1236 PST fifteen 10 gm end-burning AgI pyrotechnics were ignited at approximately 1-minute intervals at an altitude of 10,000 ft. over Bumping Lake which is situated 30 miles south of Keechelus Dam. The second location for seeding was at an altitude of 17,000 ft. over Mt. Rainier (about 40 miles southwest of Keechelus Dam). From 1317 to 1340 PST twenty-six delay pyrotechnic units each containing 40 gm of AgI were released at this location. The time interval between the release of each unit was about 1 minute. From 1345 to 1358 PST another twenty-five delay pyrotechnic units each containing 40 gm of AgI were released every 1/2 minute at 17,000 ft. over Mt. Rainier.

6.5.3 Ground Observations

The intensity and nature of the precipitation observed at Alpental, Keechelus Dam and Kachess Dam on March 28, 1971, are shown in Fig. 6.36. Many of the ice particles collected at ground level were melting so that their detailed structure was obscured. From 1000 to 1100 PST at Alpental the crystals were moderately rimed needles and sheaths, from 1100 to 1400 PST graupel and densely rimed sheaths were falling, but after 1400 most of the crystals were melted.

The direction of the winds (245$^{\circ}$) were such that any effects from the artificial seeding described above would probably have been carried southeast of the ground stations in the Cascade Mountains. It can be seen from Fig. 6.36 that the precipitation rates showed no significant changes during the
Fig. 6.36 Types of snow particles and precipitation rates at ground stations on March 28, 1971. (The predicted times of arrival of the direct effects from the airborne seeding are shown by the hatched areas.)
period following seeding. However, Fig. 6.37 shows some pulses of high freezing nucleus concentrations at Alpental during the period following seeding. This suggests that some of the snow which fell at Alpental during this period had silver iodide in it.

It is obvious that when the winds are strong, as they were on this occasion, so that seeding has to be carried out many miles (40) upwind, small fluctuations in the directions of the winds below the level of seeding make it extremely difficult to target the effects of the seeding to a small area on the ground. As we have mentioned in §5.11, it now appears from the observations collected during the 1970-71 season that it should be possible to appreciably modify the growth rate and trajectories of precipitation particles by glaciating those clouds which form within a few thousand feet of the tops of the mountains and lie immediately upwind of the Cascade crest. This idea will be tested next winter.
Fig. 6.37 Concentrations of freezing nuclei active at five temperatures in snow samples collected at Alpental on March 28, 1971.
SECTION 7
RADAR DEVELOPMENT AND STUDIES

7.1 Introduction

Radar studies of clouds and precipitation in the Cascade Program were initially confined to reflectivity measurements with 3 cm radars (Hobbs and Ryan, 1969; Wilson and Hobbs, 1969; Hobbs et al., 1970). However, in the spring of 1970 work began on building a mobile, vertically-pointing, CW Doppler radar for obtaining information on the fall speeds of precipitation particles. In this section we describe the radar which was developed during 1970-71 and present some of the results which were obtained during this period.

7.2 The CW Doppler Radar

Details of the CW Doppler radar are shown in schematic form in Fig. 7.1. The radar was mounted in a 2-1/2 ton truck which also served as a working area. Two parabolic antennas, eight feet in diameter, were mounted on the roof and over the cab at different levels to enhance electromagnetic isolation between transmitter and receiver. Calculations of side lobe levels placed these signals well below the dynamic range of the receiver although antenna patterns could not be measured.

The stable local oscillator is a commercial X band radio frequency generator the frequency of which is stabilized in a double, closed loop, cavity feedback locking arrangement. The stability of the system depends upon the short term variations of the STALO and the crystal controled 30MHz reference oscillator. The overall performance is limited by this stability
Fig. 7.1 The CW Doppler Radar
and the radio frequency coupling between the transmitter and the receiver.

Most of the 400 mW of the STALO power is dissipated in the dummy load causing a minimum of phase noise from loading effects.

Energy is tapped off into two paths using -20 db couplers. The transmitter path is passed through a mechanical phase shifter. The phase shift allows the operator to minimize the effect of the feed through radio frequency in quieting the receiver. The phase stable information passing through the phase shifter is fed into a balanced mixer where it is translated with the 30MHz crystal controlled oscillator (hereafter called COHO) located in the phase detector. In this way the stable signal at 9300MHz is converted to 9270 and 9330MHz with phase information intact. A double cavity filter removes the 9270MHz and a signal of about 1 mW level can be viewed on a spectrum analyzer for purity. The remainder of the 9330MHz drives a 15 W traveling wave tube to near saturation. The traveling wave tube is protected from antenna load variation with an isolator. Provision for power monitoring is supplied through a -40 db coupler. A mechanical wave guide switch allows the operator to compare signal return when all transmitter power is dissipated in a high power dummy load. The switch also allows an independent voltage standing wave ratio (VSWR) measurement to be made, which is indicative of antenna icing. The 9330MHz phase stable signal is radiated into a conical volume intersected by the beam of the receiving antenna. The phase and frequency of the transmitted energy is shifted on the order of $10^2$ Hz in $10^{-10}$ Hz. The 9330MHz plus the small Doppler shift passes through the receiver antenna and into a receiver balanced mixer. Here it is translated to 30MHz
by mixing it with a part of the original 9300MHz from the STALO. Because the
time of an energy packet from the transmitter to the receiver is less
than 10 μ sec, the short term stability of the STALO was the critical
parameter. This could be checked at one delay time (about 0.1 μ sec) by
connecting a 33 m coaxial cable from the transmitter to the receiver using the
wave guide switches below the antennas.

The 30MHz energy which carries the tiny Doppler shift passes through two
stages of intermediate frequency amplification. The phase is then compared
with the phase of the COHO in the phase detector and further amplified in a
low noise instrumentation amplifier. The output is recorded on 1/4 inch
magnetic tape at 1.5 ips. In this way 6 hours of Doppler data can be stored
on one roll of 0.5 mil tape.

The non-standard items in this radar were the phase detector and the
tape recorder. The phase detector was designed for the Doppler phase shifts
expected below 5kHz, and the tape recorder had modified electronics to accept
the Doppler band at 1.5 ips. Great care had to be exercised in the radio
frequency plumbing and the physical location of units as this made a
significant difference in the amount of signal directly coupled into the
receiver. The coupling problem was the limit to the sensitivity rather than
the minimum detectable signal of the receiver.

Fig. 7.1 shows the final form of the CW Doppler radar used in the 1970-71
season. (Prior to March 1971, a slightly different configuration was used in
which the 400 mW from the STALO was radiated and the high powered travelling
wave tube was missing.)
The radar performed reliably under severe weather conditions in the Cascade Mountains during the winter of 1970-71. Interpretation of the data was limited of course by the inherent range ambiguities associated with CW radars. However, spectra data on the fall speeds of precipitation particles collected during the latter part of the 1970-71 winter program appeared to be reliable.

The minimum amount of detectable precipitation was not known precisely, however, Doppler signals were often observed several minutes before any precipitation reached the ground and, on occasions, weak signals were recorded in the absence of any precipitation at ground level. The dynamic range of the strongest to the weakest signal was about 40 db. The range of fall speeds which could be measured was from 0.2 to 8 m sec\(^{-1}\); this covers needles with masses of $4 \times 10^{-2}$ mg (full speed about 0.4 m sec\(^{-1}\)) to large graupel particles with masses in excess of $9 \times 10^{-1}$ mg (full speed 2 m sec\(^{-1}\)).

### 7.3 Data Processing

The spectral characteristics of fall speeds can be highly variable and this dictates careful data processing.

Spectral measurements were recorded using a HP 302A wave analyzer and a dual channel Brush recorder. The analyzer scan consists of a single band pass filter with a center frequency which is mechanically driven at a slow rate over the data of interest. Ideally, for good fidelity, the scan rate should be set to just cover the time interval for which the meteorological data can be considered stationary and this rate must be very slow with respect to the "phase noise" produced by the shuffling of the scatterers in the radar beam. The latter requirement was easily met but the former was not. For this reason
the only data which produced acceptable spectral characteristics were ones where the precipitation and atmospheric conditions were very steady. The spectra obtained under these conditions are very reliable because of the large number of independent statistical estimates which are made with each scan.

7.4 Measurements in Rainfall

In the case of rainfall the drop size distribution can be determined from the spectrum of fall speeds because the fall speed of a drop is a single-valued function of its size. Therefore, as an initial test of the CW Doppler radar, it was planned to make a comparison between raindrop size distributions determined from measurements of the fall speeds of raindrops with the radar and those determined using a raindrop distrometer (Joss and Waldvogel, 1967). The latter instrument transforms the vertical momentum of an impacting raindrop into a pulse the amplitude of which is a function of the diameter of the drop. The raindrop size distribution can be determined from the Doppler spectrum using the relation (Atlas, 1964):

\[ S(v) = kN(D)D^6 \frac{dD}{dv} \]  

(7.1)

where, \( S(v)dv \) is the spectral power measured in the velocity interval between \( v \) and \( v + dv \), \( N(D)dD \) is the number of raindrops with diameter between \( D \) and \( D + dD \) and \( k \) is a constant determined from the radar characteristics. Therefore, using values of \( \frac{dD}{dv} \) derived from previous work (Gunn and Kunger, 1949), \( N(D) \) can be derived from eqn. (7.1) for various values of \( D \).

Unfortunately, during the short time that a distrometer was on loan from Dr. Joss no rain fell when both the radar and distrometer were operating in
the same location. However, Fig. 7.2 shows the results of measurements, made on two different occasions, of raindrop size distributions obtained from radar measurements, and from the distrometer. It can be seen that the two distributions are similar.

7.5 Measurements in Snowfall

In the case of solid precipitation there is not a unique relationship between the fall speed of a particle and its size. Consequently, the measured spectral characteristics of the fall speeds are used as basic data.

In the winter of 1970-71 the CW Doppler radar was located at Keechelus Dam and measurements were obtained in twelve storms. The results of two sets of measurements are described briefly below.

7.5.1 December 29, 1970

Simultaneous measurements between 1610 and 1810 PST on December 29, 1970, of the mean vertical velocities of precipitation particles, measured with the CW Doppler radar, and snowfall rates obtained from 10 minute averages of an optical snow rate sensor located on the ground close to the radar, are shown in Fig. 7.3. Also shown is an estimate of the spectral width of the Doppler signals. It can be seen that the mean Doppler velocity correlates with the snowfall rate fairly well. However, there is a tendency for the Doppler velocity to lead the surface measurements of snowfall rates; this is to be expected since the particles sensed by the radar extended from 300 to 1000 m above the location of the snow rate sensor.

Artificial seeding with silver iodide was carried out upwind of the radar site between 1710 and 1725 PST on December 29; the effects of seeding were predicted to reach the radar site between about 1735 and 1750 PST. It is
Fig. 7.2 Measurements of raindrop size distributions on two occasions using the CW Doppler radar and a raindrop distrometer.
Simultaneous observations of fall speed of solid precipitation and spectral width from CW Doppler radar, snowfall rate from optical snow rate sensor and types of precipitation particles on December 29, 1970.
interesting to note that both the snow rate and the mean Doppler velocity reached maximum values between about 1730 and 1750 PST (Fig. 7.3). The spectral activity of the fall speeds between 1735 and 1800 are shown in Fig. 7.4, where it can be seen that during the period 1745 to 1750 PST precipitation particles with fall speeds less than 1 m sec\(^{-1}\) started to show up on the spectrograms.

### 7.5.2 March 28, 1971

Good spectral data on the fall speeds of snow particles were obtained with the CW Doppler radar on March 28, 1971. By this time the travelling wave tube had been installed and this increased the sensitivity of the radar by about a factor of 100. Also, the recording techniques had been improved to the point that the data could be partially analyzed in real-time. However, the day was marginal as far as snowfall at ground level was concerned so that good additional ground support measurements (e.g. replicas of snow particles, snow rates, etc.) were not available.

Fig. 7.5 shows a spectrogram for the fall speeds of the precipitation particles between 1028 and 1045 PST on March 28, 1971. It can be seen that there is a sharp spectral peak at a fall speed of 1.8 m sec\(^{-1}\) (this corresponds to the fall speed of a graupel particle 2.5 mm in diameter). A loop was made of a three minute segment of the data shown in Fig. 7.5 and this loop was run through a spectrum analyzer with a very slow scan rate for 90 minutes. This procedure greatly increases the statistical significance of the output although it blurs the fine details. The results are shown in Fig. 7.6 where it can be seen that the major spectral features of Fig. 7.5 are preserved.
Fig. 7.4 Spectrograms showing the relative intensities of Doppler signals as a function of fall-speed of precipitation particle producing the signal from 1735-1800 PST on December 29, 1970.
Fig. 7.5 Spectrogram showing relative intensities of Doppler signals as function of fall-speed of precipitation particle producing the signal from 1028 to 1045 PST on March 28, 1971, at Keechelus Dam.
Fig. 7.6 Loop made from a three-minute segment of the spectrogram shown in Fig. 7.5. Note that the essential shape is preserved. The small oscillations are due to variations in the total snowfall rate over the three-minute interval. Total scan time 90 minutes.
Data similar to that shown in Fig. 7.5, was obtained over a period of six hours on March 28, 1971. During this period the precipitation near the ground fluctuated between snow and rain. The fall speeds of the snow particles extended up to about 2 m sec\(^{-1}\) and the raindrops had an average fall speed of 3.5 m sec\(^{-1}\).

7.6 Pulsed Doppler Radar

The Doppler radar data collected during the latter half of the 1970-71 winter program were of reasonably good quality for CW measurements. However, the scan outputs were an integrated effect over a presumably non-homogeneous volume. In order to overcome this problem it is necessary to use pulsed Doppler radar. By adding range information to the Doppler velocities the ambiguity in the spectral information is reduced and hydrometeor velocities at specified heights may be obtained. Work has already begun on building a vertically pointing pulsed Doppler radar for use in the Cascade Program and it is expected that this will be available for the 1971-72 winter program.

Improvements in our methods of data analysis are also being considered. Ideally, we would like to use an analyzer with a 1 - 10 sec sweep and a 7Hz bandwidth. These sweeps should be recorded on digital tape which is computer-compatible. A large number of scans could then be averaged with appropriate weighting functions to give a clear picture of the variations in the spectra with time.
A.1 Introduction

Although weather radars have been operated extensively and routinely over most regions of the United States for many years, they have been used rather infrequently in the Pacific Northwest. Kreitzberg (1963) and Reed (1961) have described precipitation patterns over Seattle which were obtained with a vertically pointing 1.87-cm radar. They found that the storm systems in the Northwest were highly variable and contained numerous small-scale features. A 3-cm CPS-9 radar has been operated occasionally near Corvallis by Oregon State University, but the primary work apparently was concerned with improving radar instrumentation techniques rather than the investigation of precipitation systems (Decker, et al., 1960; Mendenhall and Decker, 1968). Also, a new weather surveillance radar to aid in predicting precipitation for flood control has recently been installed on the summit of Mt. Ashland in southern Oregon. Wilson and Hobbs (1969) have considered how radar may be utilized for the study of winter storms over the Cascade Mountains. They propose a two Doppler radar facility which would be employed in a manner

*Visiting Associate Professor, Atmospheric Sciences Department, University of Washington, 1970-71. On leave of absence from the Air Force Cambridge Research Laboratories, Bedford, Massachusetts.
such that the two dimensional field of motion could be derived. As demonstrated by Browning, et al. (1968) and Lhermitte (1970), two Doppler radars which observe the same storm system from different locations can provide detailed information on the horizontal or vertical motion fields. Two Doppler radars, however, complicate an already difficult data handling problem. Thus, in spite of the obvious advantages of a two-Doppler radar system, the complexity and expense involved in acquiring and utilizing the system may be prohibitive at the present time. The intent of this report is to present some of the characteristics of a weather radar and to demonstrate how such a radar might be exploited for meteorological purposes in the Pacific Northwest.

A.2 Applications of a Weather Radar

A.2.1 Synoptic Purposes

The most obvious use of a weather radar is for the detection and mapping of precipitation. For synoptic purposes, it is desirable to detect the precipitation out to the maximum range possible. Because of the earth's curvature, the radar beam is above the significant storm structure beyond a certain range. For example, under average atmospheric conditions, the height of the beam axis when directed at 0° elevation angle will be 9.4 km at a range of 400 km. Thus, unless the storms are unusually intense, it will normally be impossible to detect them beyond about 400 km. Of equal significance is whether the radar will be sensitive enough to detect the precipitation which is within its beam. This point will be considered in more detail
later, but for now it will suffice to mention that there is little difficulty in fabricating a radar system which could detect very light precipitation out to ranges of at least 300 km.

Once the precipitation is detected, the next step is to determine its intensity or, as a minimum, its relative intensity. For many years, the usual practice was to observe the plan position indicator scope when the radar was set at maximum gain. During the next scan of the antenna, the gain would be reduced and only the more intense regions of the echo would be displayed. This procedure was repeated until no further echoes were detected. In this way, the storm structure could be mapped qualitatively. Throughout the past 15 years, many attempts have been made to display the relative echo intensities with only one scan of the antenna (Marshall, 1960; Wein and Gunn, 1964; Joss, 1968; Shreeve, 1969). Although an optimum system for handling the large data rates of a weather radar is still not available, recent advances by Schaffner (1968) and Works and Groginsky (1970) demonstrate that the development of an efficient, reliable, and economical digital processor is possible, and within a few years radar meteorologists can look forward to the existence of a nearly ideal system for the storage and display of radar data.

A.2.2. Hydrological Purposes

The requirements of a weather radar for hydrological studies are similar to those for synoptic use. It is necessary to map the precipitation rate or amount over the area of interest. In the Pacific Northwest, a primary problem
is to determine the amount of snow pack over large areas throughout the winter months. In addition, it is necessary to assess the magnitude of heavier rains accompanied by pronounced warmings which may occur throughout the winter and result in a potential for serious flooding. Thus, compared to synoptic uses, it is much more important that accurate quantitative measurements be available if radar is to be of real value for hydrological investigations. The requirement for these quantitative measurements places restraints on the type of system which can be used, and, as discussed in practically every one of the 14 Radar Meteorology Conference Proceedings, there are also some uncertainties with regard to the relationships between the radar measured quantities and precipitation rate and amount which are of interest to the hydrologist. Thus, weather radars at present cannot provide highly accurate maps of snow pack, but in general, a skillful use of weather radar will provide hydrological data which will be more accurate and of greater benefit than data obtained by other means.

A.2.3. Research in Cloud and Precipitation Physics

If small-scale features of cloud and precipitation systems are to be investigated, then ideally the radar should (1) acquire data rapidly (one complete scan every 15-30 sec.), (2) have high resolution of the radar beam (probably less than 1 km at the maximum range of interest), (3) have a large dynamic range with great sensitivity so that early stages of precipitation could be detected, (4) operate at a wavelength in which the attenuation is small, and (5) have a means of data storage and reduction
which keeps the analysis time within manageable limits. It is likely that a radar which satisfies the above requirements for cloud physics research would also be more than adequate for synoptic and hydrological purposes.

In the Pacific Northwest severe thunderstorms are a rarity. Instead, the precipitation tends to be stratiform in its gross features, but small and complex convective elements are nearly always present. Often these convective elements are aligned in rather broad bands, but the patterns are also greatly affected by the pronounced orographic features in the Pacific Northwest. If these smaller features of the precipitation patterns are to be investigated, then emphasis should be placed on a radar which, as a minimum, is capable of resolving the features at reasonable ranges from the radar. As we shall see in § A.3, a radar which has the required resolution will probably also be sufficiently sensitive to detect the precipitation out to ranges of 100 km or more.

A.3 Radar Parameters for Meteorological Investigation

A.3.1 The Radar Equation for Distributed Targets

The radar equation relates the echo power received by the radar to the parameters of the radar and to the target's range and scattering characteristics. It has been derived rigorously by Probert-Jones (1962), but it can be approximated by the convenient expression:

\[ P_r = 2 \times 10^{-4} P_t \tau d^2 \frac{n}{r^2} k \]  \hspace{1cm} (A.1)
where $P_r$ is the received power in watts,

- $P_t$ is the peak transmitted power in watts,
- $\tau$ is the pulse duration in $\mu$ sec ($10^{-6}$ sec),
- $d$ is the antenna diameter in m,
- $n$ is the radar reflectivity (backscattering cross-section per unit volume) in cm$^{-1}$,
- $r$ is the range to the target in km, and
- $k$ is the attenuation factor.

For particles which are somewhat smaller than the radar wavelength (e.g., $D/\lambda \ll 0.3$ where $D$ is the particle diameter and $\lambda$ is the radar wavelength) the radar reflectivity can be expressed as

$$n = \frac{\pi^5}{4} \frac{|k|^2}{\lambda^6} \sum_{\text{Unit Vol.}} D^6$$  \hspace{1cm} (A.2)

where $|k| = \frac{m^2 - 1}{m^2 + 2}$ and $m$ is the complex index of refraction of the atmospheric particles. Since the sum of the sixth powers of the drop diameters over a unit volume is a characteristic only of the atmosphere, it is customary to express this quantity by $Z$, the radar reflectivity factor. That is

$$Z = \sum_{\text{Unit Vol.}} D^6$$  \hspace{1cm} (A.3)

Substituting eqns. (A.2) and (A.3) into eqn. (A.1), the radar equation becomes

$$P_r = 6 \times 10^{-14} P_t \tau d^2 \frac{|k|^2}{\lambda^4 r^2} Z k$$  \hspace{1cm} (A.4)
where all the units are similar to those given in eqn. (A.1), \( Z \) is in \( \text{mm}^6 \text{ m}^{-3} \), and \( \lambda \) is in cm. For water, \( |K|^2 \approx 0.93 \) and for ice \( |K|^2 \approx 0.2 \) at radar wavelengths longer than 3 cm and for the range of temperatures encountered in the atmosphere. The constants given in eqns. (A.1) and (A.4) are based on some important assumptions about the radar antenna. First it is assumed that the antenna is a circular paraboloid, and the "antenna efficiency" is 55%. This factor takes into account the effects of non-uniform illumination of the aperture and any actual losses in the antenna. The value of 55% is fairly typical of the efficiency attained in practice for antennas operating at wavelengths between 1 and 10 cm. Eqns. (A.1) and (A.4) also assume that \( \theta \), the 3-dB beamwidth of the antenna (i.e. twice the angle from the beam axis to the position where the gain of the antenna has dropped to 0.5 of its maximum value), is given by

\[
\theta = 1.25 \frac{\lambda}{d} \quad \text{(radians)},
\]

(A.5)

where \( d \) is the diameter of the antenna aperture.

Although for an individual radar, eqns. (A.1) and (A.4) may lead to an estimate of \( P_r \) which is incorrect by a factor of about 2, their simplicity outweighs their inaccuracies for our purposes. For a given value of \( Z \) for ice or water at a particular range and neglecting attenuation for the moment, eqn. (A.4) shows that the received power scattered from the particles is proportional only to the peak power transmitted, the pulse duration, and the square of the antenna diameter and is inversely proportional to the fourth power of the radar wavelength. The maximum peak transmitted
power is limited because of the breakdown of the energy within the waveguide, and, in general, the pulse duration should not be increased beyond about 2 \( \mu \) sec because this determines the range resolution (i.e. a 1 \( \mu \) sec pulse duration is equivalent to a range resolution of 150 m). Thus, the remaining factors which determine the strength of the received power are the antenna diameter and the radar wavelength. The wavelength has a strong influence, and for a given \( Z \), increased power will be received for the shorter wavelengths. However, the wavelength cannot be decreased beyond a certain value or otherwise the attenuation becomes excessive. This topic will be covered in § A.3.3. Increasing the antenna diameter has two advantages. First, it increases the received power and secondly, it decreases the beamwidth (eqn. A.5). Thus, in general, it is desirable to use as large an antenna as is practical.

The one factor which has not been considered thus far is the minimum detectable received power. A radar is essentially useless if the anticipated scattered power will result in a power returned to the radar which is less than the minimum detectable power. Radar receivers can detect power down to some rather broad limit without much difficulty. Fortunately, the minimum detectable power which is characteristic of most weather radars is sufficiently below the expected scattered power from precipitation that useful information can be obtained. Beyond certain lower limits, however, improved receiver sensitivity is only achieved with considerable effort and expense. Examples of the application of eqn. (A.4) to the detection of cloud and precipitation will be given later in this section.
A.3.2 Rain Characteristics in Western Washington

Before a decision can be made on the radar which would be most suitable for use in a given area, it is necessary to consider the character of the precipitation which is to be observed. For example, severe thunderstorms will cause excessive attenuation of the radar energy at wavelengths below about 6 cm, whereas light stratiform rain can be mapped to long ranges with radar wavelengths of about 3 cm. Consequently, some of the features of the precipitation in the Pacific Northwest are included in this section.

Much of the important precipitation which falls in the Pacific Northwest is of a general stratiform character. That is, the regions of growth are characterized by relatively small vertical upward velocities, and the precipitation is quite light. An indication of the distribution of the rainfall intensity for the Seattle area and for the Stampede Pass area, which is about 80 km southeast of Seattle near the summit of the Cascades (see Fig. 2.1), is shown in Fig. A.1. The cumulative percentage of either rainfall amount or duration is plotted as a function of precipitation rate. As an example of how to interpret Fig. A.1, consider a precipitation rate of 5 mm hr\(^{-1}\); the curve for Seattle amount shows that about 95% of the total rainfall amount observed in Seattle falls at a rate of less than 5 mm hr\(^{-1}\); the corresponding percentage for Stampede Pass is about 90%. For the duration curves at a rate of 5 mm hr\(^{-1}\), it is found that about 99% of the time that it is raining in Seattle, the rate is less than 5 mm hr\(^{-1}\). Also note that, for Seattle, 70% of the time that it is raining the rate is
Fig. A.1 Cumulative percentage of rainfall amount and duration for Stampede Pass (80 km southeast of Seattle) and Seattle, Washington as a function of precipitation rate. For Seattle, 95% of the total rainfall amount falls at a rate of less than 5 mm hr\(^{-1}\) and also 99% of the time that it is raining, the rate is less than 5 mm hr\(^{-1}\).
less than 1 mm hr\(^{-1}\). It is this abundant light rain of the winter months which has led visitors and even some natives of Seattle to remark that it rains all the time. However, for our purposes it is sufficient to note that, during the winter months, precipitation rates in excess of 11 mm hr\(^{-1}\) for Stampede Pass and 7 mm hr\(^{-1}\) for Seattle are relatively rare. This information will be used to derive some estimates of the attenuation of microwave energy which is likely to be encountered in the Pacific Northwest.

A.3.3 Attenuation of Microwaves by Precipitation

The attenuation by hydrometeors has received considerable attention over the past 25 years. The subject is rather complex because of the variability of the hydrometeors which can occur in the atmosphere. For our purposes, however, it will be sufficient to provide rough estimates of the attenuation to be expected for the precipitation in the Pacific Northwest.

Attenuation is dependent on the wavelength of the radio waves as well as the size, shape, state, concentration and temperature of the hydrometeors. The attenuation is usually expressed as the reduction of the electromagnetic energy in decibels (dB) per unit distance and will be designated as \(Y\), the specific attenuation. Then the total attenuation in dB will be defined by

\[
A = 2 \int_0^r Y \, dr. \tag{A.6}
\]

The factor 2 is required because of the two-way path over the distance \(r\) from the radar to the precipitation which is being observed. The quantity \(k\) in eqns. (A.1) and (A.4) is related to \(A\) by

\[
k = 10^{-0.1} A \tag{A.7}
\]
Thus, for $A = 10$ dB, the energy received at the radar is reduced by a factor of 10 because of attenuation.

Estimates of attenuation are often given in terms of the precipitation rate. The problems arise because of the variability of the attenuation on the type and size distribution of the hydrometeors for the same rate of precipitation. This variability for rain is illustrated in Fig. A.2 which is taken from Dyer (1970). Note that the ordinate is the specific attenuation per mm hr$^{-1}$ of rain. The limits shown in Fig. A.2 are based on experimental results; generally, the results of theoretical computations fall near or below the lower limit. For our purposes, it will be assumed that the specific attenuation for rain in Western Washington will be given by $2 \times 10^{-2}$ and $3 \times 10^{-3}$ dB km$^{-1}$/mm hr$^{-1}$ at wavelengths of 3.2 and 5.4 cm, respectively. These values are slightly greater than the lower limit in Fig. A.2 and are close to the mean attenuations which have resulted from theoretical computations. Attenuation at a wavelength of 10 cm is only about $3 \times 10^{-4}$ dB km$^{-1}$/mm hr$^{-1}$. Joss has recently analyzed the data from a carefully conducted experiment and concluded that observed attenuations in rain are in close agreement with those expected from theory.

It is now necessary to determine the rainfall rate and its horizontal extent for the heaviest rain which is likely to occur in Western Washington. From Fig. A.1 it is seen that rainfall rates during the winter months rarely exceed 7 mm hr$^{-1}$ in Seattle and about 11 mm hr$^{-1}$ at Stampede Pass. These

---

*Private communication from Dr. Jürg Joss*
Attenuation of microwaves by rain as a function of radar wavelength. The two curves define the range of results for 12 different experiments. The mean attenuation determined by theoretical computations gives a relation which is close to the lower limit of the experimental results, and also recent careful experiments give results which are in agreement with theory. (From Dyer, 1970.)
maximum rates may extend over distances of about 100 km (i.e., a band of precipitation characterized by a rate of 10 mm hr$^{-1}$ would have to extend over a distance of 100 km if the band were advected at a speed of 100 km hr$^{-1}$). Shumway$^*$ has analyzed some of the storms which have produced the largest amounts of precipitation in the Pacific Northwest. For the storm of 19 November 1962, the isohyet of maximum hourly precipitation recorded at 1400 GMT was 10 mm, and this isohyet had a maximum dimension of about 200 km and a width of about 60 km. The storm of 20 November 1959 had a maximum isohyet of hourly precipitation of 30 mm at 0200 GMT which extended along the western slope of the Olympic Mountains for almost 100 km. However, for a radar located near Seattle, there would have been no path through the storm longer than about 40 km in which the rainfall rate exceeded 30 mm hr$^{-1}$. Using these past storms as a guide, a rainfall rate of 10 mm hr$^{-1}$ over a path of 100 km is considered to be representative of the maximum which is likely to be observed with a radar located near Seattle.

Fig. A.3 is a plot of the total attenuation which could be expected at various wavelengths if rain of 10 mm hr$^{-1}$ extends for 100 km. The value plotted is $A$ in eqn. (A.6) which is the attenuation in dB for the two-way path through the precipitation. Note that the total attenuation will be 40 dB at 3.2-cm wavelength and it drops to about 6 and 0.6 dB at wavelengths of 5.4 and 10 cm respectively. It is seen that attenuation near a wavelength

---

$^*$Private communication from Mr. Stewart Shumway
Fig. A.3 Total attenuation as a function of radar wavelength for the heaviest rains which may occur in the Pacific Northwest. The total attenuation is about 40 dB at 3.2-cm wavelength and falls to 6 and 0.6 dB at wavelengths of 5.4 and 10 cm respectively.
of 10 cm is negligible, but at wavelengths near 3 cm the attenuation becomes excessive. Fig. A.3 can also be used to approximate the attenuation to be expected for other rainfall rates or distances. For example, if the rain of 10 mm hr$^{-1}$ only extended for 10 km rather than 100 km, then the total attenuation would be a factor 10 less than shown in Fig. A.3.

As suggested earlier, the attenuation estimates should only be used as rough guidelines. The attenuation could be somewhat higher for the same surface rainfall rate if a significant fraction of the radar beam traversed the melting layer rather than the rain area just above the surface. Within this region the water-coated snowflakes lead to increased attenuation compared to the completely melted raindrops. On the other hand, attenuation in dry snow is very much less than for rain of comparable intensity. For example, the maximum attenuation which can be expected in any snowstorm is only about 2 dB at a wavelength of 3.2 cm and is correspondingly less at longer wavelengths (Dyer, 1970). The main point, however, is that attenuation must be considered if one is to determine the performance of a radar in the Pacific Northwest.

A.3.4 A Radar for the Pacific Northwest

Let us suppose that we wish to resolve small-scale features of the precipitation with a resolution of 1 km at a range of 100 km. This might be reasonable if one were interested in studying the detailed structure of the precipitation over the Cascade Mountains with a radar located in Seattle. The beamwidth which would be required for this radar is $\theta = 10^{-2}$ radians or
0.57 deg. From eqn. (A.5) a beamwidth of 0.57 deg. could be attained with an antenna of about 4 m diameter at a wavelength of 3.2 cm. For a 5.4 cm wavelength radar the antenna diameter increases to 6.8 m and is 12.5 m in diameter for a 10-cm radar. The cost of antennas and their supporting 2-axes mount and pedestal increases greatly as the size of the antenna increases. Consequently, it would be desirable to work at smaller wavelengths if high resolution is to be acquired at reasonable costs.

For a given antenna size at each wavelength, eqn. (A.4) provides an indication of how sensitive the radar would be for the detection of cloud and precipitation. The variables remaining are the peak transmitted power and the pulse duration. A nominal pulse duration is 1 µ sec and peak transmitted powers of $2 \times 10^5$ watts are easily attainable at wavelengths greater than 3 cm. From eqn. (A.4), the minimum detectable radar reflectivity factor, $Z_{\text{min}}$, is given by

$$Z_{\text{min}} = \frac{1.7 \times 10^{13} (P_r)_{\text{min}} \lambda^4 r^2}{P_t \tau d^2 |k|^2}$$  \hspace{1cm} (A.7)$$

where $(P_r)_{\text{min}}$ is the minimum detectable power of the radar receiver and attenuation has been neglected. From eqn. (A.7) it is possible to compute $Z_{\text{min}}$ for various values of the radar parameters and this is tabulated in Table A.1. The three wavelengths tabulated are those which are most widely used in weather radars.
### Table A.1

Possible Performance Characteristics of Weather Radars

<table>
<thead>
<tr>
<th>WAVE LENGTH (cm)</th>
<th>BEAM WIDTH (deg)</th>
<th>ANTENNA DIA. (m)</th>
<th>PEAK POWER (watts)</th>
<th>PULSE DURATION (µ sec)</th>
<th>($P_r$) MIN. (watts)</th>
<th></th>
<th></th>
<th>RANGE (km)</th>
<th>$Z_{MIN} \cdot 6^{-3}$</th>
<th>$R_{MIN} \cdot 10^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2</td>
<td>.57</td>
<td>4</td>
<td>$2 \times 10^5$</td>
<td>1</td>
<td>$10^{-13}$</td>
<td>.93</td>
<td>100</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.4</td>
<td>.57</td>
<td>6.8</td>
<td>$2 \times 10^5$</td>
<td>1</td>
<td>$3.2 \times 10^{-14}$</td>
<td>.93</td>
<td>100</td>
<td>0.5</td>
<td>$\approx 2.6 \times 10^{-2}$</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>.57</td>
<td>12.5</td>
<td>$5 \times 10^5$</td>
<td>1</td>
<td>$3.2 \times 10^{-14}$</td>
<td>.93</td>
<td>100</td>
<td>0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Note that if the beamwidth is kept constant and the peak powers and minimum detectable powers are kept consistent with what can easily be attained at the appropriate wavelength, then the minimum detectable reflectivity factor is about the same regardless of the radar wavelength. Of course, at a wavelength of 10 cm, a 12.5 m diameter antenna is required to give a beamwidth of 0.57 deg, and this is a fairly massive and expensive structure.

An overall reasonable relationship between the radar reflectivity factor, $Z$ (mm$^6$ m$^{-3}$), and the rainfall rate, $R$ (mm hr$^{-1}$), is:

$$Z = 200 R^{1.6}$$  \hspace{1cm} (A.8)

Using eqn. (A.8), the minimum detectable rainfall rate corresponding to the minimum detectable $Z$ can be computed, and these values are shown in the last column of Table A.1. Note that all of the radars can detect rainfall rates as low as $2 \times 10^{-2}$ mm hr$^{-1}$ at a range of 100 km. It should be emphasized that the values given in Table A.1 are for a range of 100 km. At lesser ranges, the radars would be able to detect smaller rainfall rates but the reverse would be true at greater ranges.

Although each of the possible radars listed in Table A.1 would be excellent candidates for the investigation of light precipitation, only the 10-cm radar is essentially unaffected by attenuation. As mentioned previously, for near record storms, up to 40 dB of attenuation could be expected with a 3.2-cm radar, whereas the maximum attenuation approaches acceptable values of about 6dB at a radar wavelength of 5.4 cm. Thus, for most purposes, a 5.4-cm radar would be capable of providing reliable
quantitative data, and it has the advantage of having a manageable antenna
diameter provided that the beamwidth is greater than 0.5 deg (Table A.1).
In general, 3.2-cm radar sets are more readily available than radars operating
near 5.4-cm wavelength. If a 3.2-cm radar is used in the Pacific Northwest,
however, then there will be occasions when reliable quantitative measurements
will be very difficult or impossible to obtain. Unfortunately, the
attenuation is severe in just those situations which are of most interest to
investigate and which may be most hazardous for hydrological purposes. Thus,
there is considerable merit in using wavelengths of more than 5 cm. On the
other hand, in the vast majority of the storms which occur in the Puget
Sound area, a 3.2-cm radar may provide an adequate record of the
distribution of precipitation and its intensity. For example, if a 10 mm hr\(^{-1}\)
rainfall occurs over a range of only 10 km, then the attenuation will be
about 4 dB, and it may be possible to make appropriate corrections for
attenuation effects. Generally, however, it is best to avoid any significant
attenuation if possible, and, consequently, weather radars with wavelengths
of more than 5 cm should be used in the Pacific Northwest.

A.4 Location of a Weather Radar

The ideal location for a weather radar will usually be in the center of
a slight depression in the ground. Such a position is sketched in Fig. A.4.
Some of the desirable features of the radar location are: (1) the hills
surrounding the radar are about 2 km distance and are at an elevation angle
of 0° from the center of the antenna, and (2) there are no obstructions
Fig. A.4 Sketch of the best location for a weather radar. The radar is placed in a slight depression and is surrounded by hills or ridges at a distance of about 2 km. The height of the hills is such that energy is blocked below an elevation angle of 0°.
extending above 0° elevation angle at ranges beyond 2 km. The above two
features insure that radar echoes will rarely be caused by ground targets
within the side lobes of the radar beam because the side lobe energy will be
trapped within a range of 2 km when the antenna is at 0°. Consequently, for
a location as sketched in Fig. A.4, and for usual gradients of reflectivity,
the power scattered from precipitation can be interpreted as coming from the
main lobe of the antenna. Locating a weather radar is of prime importance
if reliable information is to be obtained at close ranges and at low
observation angles. An example of the difficulties which arise with a poor
location is illustrated by Unthank and Barton (1966). They described the
problems associated with the scattering and reflection from ground targets
for a radar located on top of a prominent tall building in Melbourne,
Australia.

In an effort to determine the suitability of the top of the Atmospheric
Sciences Building, University of Washington, as a possible site for a sensitive
weather radar, a survey of the surrounding terrain was made. The optical
horizon was measured with a theodolite which was placed about 3 m above the
roof of the Atmospheric Sciences Building. The results of this survey are
shown in Fig. A.5. In contrast to the detrimental effects common to most
roof top locations, the top of the Atmospheric Sciences Building is a reasona-
bly acceptable site. This arises because of the shielding afforded by the
hills in Laurelhurst or Bellevue to the east, Capital Hill and Queen Ann in
the southwest quadrant, and a rise in the general horizon toward the northwest.
Fig. A.5 The elevation angle of the optical horizon from a position about 3 m above the roof of the Atmospheric Sciences Building, University of Washington. The high elevation angles toward the north-northeast are caused by buildings on the campus. The elevation angles of the mountain ridges to the east and west are indicated by dashed curves.
Excluding the horizon of the mountains, the optical horizon is within a range of 4 km except for the hills of Bellevue which are about 10 km from the University of Washington. Of course, there are some buildings on the campus which effectively block the view in some directions. This is the cause of the high elevation angles of the horizon toward the north-northeast. The undesirable blocking effects of these nearby buildings can be considerably reduced if the antenna were raised about 10 m above the roof top of the Atmospheric Sciences Building. In fact, raising the antenna would generally improve the horizon for radar purposes because smaller elevation angles would be realized. It should also be noted that the Cascades to the east and the Olympics to the west have optical horizons of about 1.5°. This is the minimum angle that can give any information on precipitation at ranges beyond the mountains. If 10 km is taken as the maximum height of any significant precipitation or cloud, then for elevation angles of 1.5°, the radar beam will be at a height of 10 km at a range of about 250 km. Consequently, any weather radar in the Seattle area will usually not be able to obtain any useful information on precipitation which is beyond a range of 250 km either toward the west (Olympic Range) or toward the east (Cascade Range).

The range to the optical horizon (excluding the horizon of the Cascade and Olympic Mountains) is indicated in Fig. A.6. The data in Fig. A.6 essentially indicate the range and azimuth of ground clutter (echoes received from ground targets) which would likely exist for a radar located on top of the Atmospheric Sciences Building. In general, the anticipated ground
The range to the optical horizon (excluding the horizon of the mountains to the east and west) from the roof of the Atmospheric Sciences Building. The region within the curve is where scattered energy from ground targets in the side lobes will probably mask the scattering from precipitation in the main beam of the antenna.
clutter is not excessive and should not seriously degrade the performance of the radar.

To summarize the information in Figs. A.5 and A.6, it is noted that the minimum elevation angle for a radar on top of the Atmospheric Sciences Building would be generally near 1° and the ground clutter would be confined within a range of 10 km. With these limitations, useful data could be obtained at any higher elevation angles out to the range of the Cascade or Olympic Mountains. Beyond the ranges of the Cascades and the Olympics, the minimum useful elevation angle is increased to about 1.5°. Raising the antenna about 10 m above the roof top would reduce significantly the blocking by some of the nearby buildings and would improve slightly the minimum elevation angle for radar observations. Lastly, it is suggested that a survey similar to the one described here be carried out prior to making a final decision on the location of any sensitive radar system.

A.5 Data Recording and Processing

One of the outstanding problems of using weather radars is the present limited data handling capabilities which are generally utilized. Radars generate a huge quantity of data. For example, if a radar with a 0.5°-beam rotates at 10° sec⁻¹ (20 beamwidths sec⁻¹), has 1000 independent range elements, and has a pulse repetition rate of 1000 sec⁻¹, then the maximum data rate is $20 \times 10^6$ words sec⁻¹. Not all of these words are independent, however, and it is desirable to do some time averaging of the signal from each range element. If we limit our data samples to an average value at
each range for each beam width of rotation, then our data rate is reduced to $20 \times 10^3$ words sec$^{-1}$. This rate is becoming manageable, especially if one considers that not all ranges will contain useful information. As an estimate, perhaps 20% of the ranges on the average will contain signals from precipitation. Thus, an average data rate for possible storage might be more like $4 \times 10^3$ words sec$^{-1}$. Even this rate is high, but it is a value which should be considered if data are to be available at a resolution comparable to the limit of the radar.

Because of the excessive data rate which is characteristic of weather radars, the usual practice has been to record the information on photographic film. If signal averaging (either in time or range) and some type of contouring circuitry is used to display relative echo intensity, then the photographic medium provides a useful type of display. An example of integrated and contoured radar echoes is given in Fig. A.7 which is a photograph of the plan position indicator (PPI) scope. The radar is a 3.2-cm CPS-9, and the outer range mark is at 50 n.mi. The contours start at a received power level of -105 dBm and the difference in power level between the inner and outer portion of a contour is 10 dB. The showers in the southwest quadrant about 25 n.mi. from the radar are relatively small and intense. In one of the showers, the power level varies by at least 50 dB in a distance of about 3 n.mi. from the periphery of the storm to its center. On the other hand, the precipitation to the north at ranges beyond 20 n.mi. is fairly weak (only one 10 dB contour) but its areal extent is relatively large.
Although the depiction of radar data in Fig. A.7 is acceptable, there remains the problem of what should be the next step in the data analysis. Since the radar beam is at increasing heights above the surface with increasing range, it is often difficult to interpret the storm structure from PPI photographs. An improved display is the constant altitude plan position indicator (CAPPI) system developed at McGill University (Marshall, 1957). The CAPPI display is generated from a series of PPI's taken at increasing elevation angles and then the data are rearranged and presented as reflectivity maps at constant altitude. The altitude spacing of the maps is either 5,000 or 10,000 ft. depending on the characteristics of the storm which is observed. At McGill, the intensity of the storm is indicated by a stepped grey scale; each step of the scale represents an increase in signal power of 10 dB. Thus, with about six constant altitude PPI's of stepped grey scale power levels, it is possible to display the three-dimensional structure of precipitation systems.

The shortcoming of CAPPI displays or any other type of basic data which are stored on photographic film is the relative inflexibility and difficulty of additional analysis. With the rapid advances in digital techniques, it is apparent that radar data in the future will be partially or entirely processed by computers. Today, only a few weather radar groups are utilizing digital methods for the processing and display of the data. However, it is anticipated that the equipment and techniques will soon be available which will make it possible to store all the significant radar
Fig. A.7  Plan position indicator (PPI) scope photograph of a 3.2-cm radar. The range marks are at 25 n.mi. intervals. The photo shows contour levels of received power at 10 dB intervals and illustrates the fine-scale structure of convective showers particularly in the southwest quadrant. (From Lamkin and Atlas, 1965.)
information in a digital form. Once stored, the data can be processed in a variety of ways and displays can be generated which are optimum for either operational or research purposes. For example, in operational configurations, it is now conceivable that radar data which have been stored over the past few hours could be displayed as a movie which would depict the movement and development of the significant storms within the range of the radar. For research purposes, the basic radar data, once stored in digital form, can be processed and displayed in a form determined by the analyst. Thus, within the next few years, radar meteorologists can look forward to the availability of processing and display techniques which are commensurate with the high data rates generated by the radar.

Wilson and Hobbs (1969) have presented an analysis of the use of Doppler radars for the investigation of winter storms over the Cascade Mountains. They correctly recognize the advantages of obtaining information on the fields of motion within the storm systems. This added information, however, is only acquired with an increase in the complexity of both the radar and the data recording and processing equipment. Since the report by Wilson and Hobbs (1969) is quite complete, the comments which follow should be considered as a brief supplement to their study.

Just as the use of non-Doppler radars is limited by the generally inadequate data handling capabilities, the techniques to process and display Doppler information fall short of being able to keep up with the high data rates of a Doppler radar. Essentially two methods are adopted to circumvent the difficulty. Either the entire spectrum is recorded at a relatively few
A.7 Summary and Conclusions

After consideration of the characteristics of the precipitation in the Pacific Northwest, it is concluded that a radar having a wavelength of about 5 cm is entirely adequate for research in precipitation physics. The received power of a 5-cm wavelength radar will seldom be attenuated significantly by rain in the Pacific Northwest, and the wavelength is a good compromise between the requirements for little attenuation and an antenna size which would result in the resolution needed to observe the small scale features of precipitation. A sensitive 3-cm radar may satisfy the requirements to investigate most storms in the Pacific Northwest, but the received power will be seriously attenuated in the more severe storms, and thereby the effectiveness of the radar will be diminished in the most interesting and dangerous situations.

The ideal location of a weather radar is in the middle of a slight depression about 2 km in radius, and the radar beam should be blocked below 0 deg. elevation. Such a location minimizes the effect of ground targets in the side lobes of the antenna. The roof of the Atmospheric Sciences Building is a reasonable site for a weather radar because of the natural shielding provided by the numerous low hills or ridges surrounding the campus of the University of Washington. Prior to the final decision of the radar location, however, it is recommended that a careful survey of the site be carried out.

One of the outstanding problems in radar meteorology is inadequate data
processing techniques. Digital methods are being developed to alleviate this problem, and in the next few years, it is anticipated that efficient and economical means will be available to record and store all the significant radar information. The data can then be processed and displayed in a format which would be of most benefit to the user. The display may be quite different depending on whether it is to be used for synoptic, hydrological, or research purposes.

Although there is an urgent need to map the velocity field in precipitation, it is suggested that initial efforts be concentrated on the acquisition and operation of a sensitive non-Doppler radar. If possible, the radar would have a coherent transmitter in order that a Doppler capability could be added at a later date when experience has already been acquired with the use of high resolution reflectivity data.

Acknowledgments: I wish to thank Mr. Stewart E. Shumway, State of Washington, and Prof. Phil E. Church, University of Washington, for tabulating and providing the data on precipitation for Stampede Pass and Seattle. Many of the ideas expressed in this report are the result of interesting discussions on the use of weather radars with Dr. Richard R. Weiss, University of Washington, and Dr. Jurg Joss, Meteorological Service of Switzerland, and I greatly appreciate their help.
REFERENCES


We wish to express our appreciation to the following members of our research team who made substantial contributions to the work reported herein: L. Engels, J. Frost, W. Havener, Y. Huang, W. Mach, J. Pinnons, J. Russell, B. Simon, F. Turner and H. West. Additional help was received from S. E. Shumway, L. Guimond, Mrs. K. Moore and Mrs. G. Goodman.

Special thanks must go to our pilot, Mr. R. Spurling, for his extraordinary efforts during the field program. The cooperation of the Federal Aviation Authority in the conversion of the B-23, day-to-day flight operations, and radar data, is also gratefully acknowledged. Thanks are also extended to the Officer in Charge of radar at McChord Air Force Base, Wn., for providing us with useful radar data, and to the National Weather Service Office in Seattle for daily weather briefings.

This research was supported by U. S. Dept. of Interior, Bureau of Reclamation, under Contract No. 14-06-D-6999 (administered through the Dept. of Ecology, State of Washington) and the Atmospheric Sciences Section of the National Sciences Foundation under Grants GA-17381 and GA-27637.