This study examines in detail a continuous drop-size distribution recorder and selected data gathered with this recorder at various locations on 6, 15, and 31 May 1966. The drop-size distribution recorder consists of a self-contained, mobile unit able to operate without electric power. This recorder utilizes "Ozalid 105 SZ" filter paper cut in rolls three inches wide and 150 feet long. Before using the ASB recorder, problems concerning smearing, underdevelopment, and splashing required a solution. A portion of the data used in this study came from the AN/TPS-10D weather radar located atop McCulloch Peak. Several comparisons between the radar data and the drop-size data demonstrate a tendency for a relationship between the average mean drop diameter and the average height of the echo top, averaging both values throughout a shower. A tendency for a relationship also occurs between the variance of the drop diameter and the average height of the echo top. The average mean
echo intensity exhibits a possible correlation with both the mean of the parameter

$$\left( D_{\text{max}} - D_{\text{min}} \right) \left( D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_{5} \right)$$

and the mean range of drop sizes. Student's t-test demonstrates a significant difference between the average mean drop diameter and the average range of the drop diameters gathered at different locations under the same synoptic conditions; however, it shows no significant difference at the same location even under different synoptic conditions. The difficulty of calculating the length of time required for a raindrop to fall from that region viewed by the radar to the ground makes a minute-to-minute comparison of drop-size data to radar data nearly impossible.
VARIATIONS IN DROP-SIZE DISTRIBUTIONS AS MEASURED WITH A CONTINUOUS RAINDROP RECORDER AND COMPARED TO RADAR ECHO CHARACTERISTICS

by

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VARIATIONS IN DROP-SIZE DISTRIBUTIONS AS MEASURED WITH A CONTINUOUS RAINDROP RECORDER AND COMPARED TO RADAR ECHO CHARACTERISTICS

INTRODUCTION

Why should researchers study raindrop sizes? Far from a purely academic subject of an esoteric nature, this subject has emerged as one in demand because of its significant potentialities for related subjects. Weather radar, weather modification, rainfall simulation, soil-erosion control, and other aspects of precipitation physics depend upon drop-size distribution data. Blanchard (1953) suggests that a study of drop-size distributions may help in the understanding of precipitation mechanisms. Drop-size distributions present very important characteristics of rain and might tell something of its formation.

The need for reliable raindrop-size distribution measurements increases with each advance in radar meteorology. Raindrop size greatly affects the intensity of a received radar signal. The power, $\overline{P}_r$, received by a radar from a beam-filling precipitation target relates to the radar and precipitation characteristics as follows:

$$\overline{P}_r = \frac{\pi}{72} \left( \frac{P_c \phi \theta h A^2}{\lambda^6 \bar{P}} \right) |K| \left( \frac{Z}{r^2} \right)$$
where

\[ P_t = \text{power transmitted by radar} \]
\[ \theta = \text{angular width of beam} \]
\[ \phi = \text{angular height of beam} \]
\[ h = \text{pulse length} \]
\[ A_p = \text{aperture of antenna} \]
\[ \lambda = \text{wavelength of electromagnetic radiation transmitted} \]
\[ |K|^2 = \text{constant dependent upon type of precipitation} \]

For observations at a fixed point the range, \( r \), equals a constant; therefore,

\[ \bar{P}_r = CZ \]

where \( C = \text{constant} \).

The variable

\[ Z = \sum N_i D_i^6 \]

where \( N_i \) equals the number of drops having diameters \( D_i \) and
where \( \sum \) extends over the whole sampling volume (Sarmah, 1963).

According to this relationship, the average power received by a radar varies in proportion to the sixth power of the drop diameter. Therefore, only knowledge of raindrop size allows the power received by a radar to determine precipitation rate.
This study covers the following two analyses:

1. Examination of a continuous drop-size distribution recorder including a detailed discussion of its construction, its operation, the sensitized paper used, the calibration of this paper, and all problems confronted.

2. Examination of drop-size data collected with this recorder on 6, 15 and 31 May and compared to changes in time, changes in the synoptic situation and topographic conditions, and changes in the radar echo.
DEVELOPMENT OF DROP-SIZE SPECTRA

Formation of Precipitation

Growth of Cloud Droplets

When lifted, a mass of air cools by expansion. As the temperature decreases the relative humidity* increases, and in the absence of foreign particles the relative humidity may increase to seven or eight times that necessary for saturation (Mason, 1963). Of course, the air does contain numerous particles. These particles, commonly called condensation nuclei, range in size from $10^{-7}$ centimeters to greater than $10^{-3}$ centimeters. When the mass of air cools nearly to saturation, water vapor condenses on these nuclei.

The growth rate of an individual droplet depends on surface tension and hygroscopic forces, the humidity of the air, and the rate at which heat of condensation transfers from the water vapor to a droplet. When dealing with a large number of droplets, these factors make the process extremely complicated. With all the droplets competing for the available water vapor, their rate of growth depends

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*The relative humidity equals the vapor pressure divided by the saturation vapor pressure times 100. The saturation vapor pressure depends solely upon the temperature of the air, so that as the temperature of the air decreases, the saturation vapor decreases causing the relative humidity to increase.
upon the size, concentration, and the rate of cooling of the air
(Mason, 1963).

Mason (1963) states two processes by which droplets may grow
to form clouds: (1) diffusion of water vapor to the surface of a droplet and condensation upon it; and (2) growth of a droplet
through collision and coalescence caused by the relative motion of
the droplets to one another. Electrical forces, small-scale turbulent
motions, Brownian motion, and different fall velocities under the
force of gravity all contribute to the relative motion of the droplets.

Growth of Raindrops

At present two theories successfully describe the growth of
cloud droplets to raindrop size. One theory considers mechanisms
in the clouds which produce drops of different sizes. The other
theory examines the situation in which supercooled water droplets
and ice crystals coexist in a cloud.

Measurements show that clouds contain a considerable range
of drop sizes in any given region (Houghton, 1950). The fall velocities
of various size drops differ to the degree that larger drops will
"sweep out" the smaller, slower-falling ones. Some of the smaller
drops in the volume swept out escape collection, however. The pro-
toportion of the drops collected, called the "collection efficiency",
depends upon the size of the collecting and collected drops and their
relative velocity (Houghton, 1950). The growth rate of a droplet by this method, called coalescence, depends on the mass of the particle, the median cloud drop diameter and the liquid-water content of the cloud, and the breadth of the cloud drop-size spectra (Houghton, 1950). Also, the electrical charge on the drop appears important in the coalescence process (Fujiwara and Mueller, 1961).

Favorable conditions for condensation-coalescence growth of raindrops include moderately strong updraft velocities, large liquid-water content, and cloud dimensions and wind fields such that the larger drops will not be carried out the top or sides of the cloud (Hardy and Dingle, 1962). A minimum cloud depth for shower production by coalescence exists which increases with the speed of the updrafts and decreases with a rise in the temperature of the cloud base (Ludlam, 1951). Giant hygroscopic nuclei in unstable maritime air masses evidently cause rain showers when cloud tops do not reach the freezing level (Fujiwara, 1961). However, in the middle latitudes, especially over land, most clouds in general could not release drops larger than drizzle by the coalescence process (Houghton, 1950).

In the early 1930's Tor Bergeron proposed a theory for the growth of raindrops. He recognized the importance of the difference between saturation vapor pressures over supercooled water and ice at temperatures below freezing. For example, measurements show
the vapor pressure over supercooled water at -20°C exceeds by 22 percent that of ice at the same temperature (Langmuir, 1948). Therefore, upon the introduction of ice crystals into a cloud of supercooled water droplets, the ice crystals will grow by deposition from the super-saturated environment at the expense of evaporation of the water droplets for which the same environmental air appears sub-saturated. Battan (1962, p. 61) describes the process in steps:

Assume now that some ice-crystal nuclei are suddenly introduced into the cloud and that a small number of ice crystals are formed. As soon as this occurs, the cloud system becomes unstable. The air is saturated with respect to water, but it is supersaturated with respect to ice crystals. As a result, water-vapor molecules deposit on the ice crystals. As soon as this happens, the air is no longer saturated with respect to water. Consequently, some water evaporates from the cloud droplets to make up for the losses to the crystals. This evaporation again leads to super-saturation with respect to the ice, the crystals grow larger, and the cycle continues.

These steps occur continuously in the cloud, and under proper conditions snowflakes grow thousands of times faster than water droplets.

Although clouds which lie below the freezing level can grow only through the coalescence process, the frozen particles of a mixed cloud of ice crystals and supercooled cloud droplets above the freezing level can grow through the Bergeron-Findeisen process and also through the coalescence process. Houghton (1950) states that ice-crystal growth begins rapidly and then slows down, while the reverse situation occurs in growth by coalescence. In typical mid-latitude
conditions neither the ice-crystal process nor the coalescence process acting alone produces raindrops of one to five millimeters in diameter. Some combination of these two processes leads to optimum growth. Rigby and Marshall (1952) state that in most cases of continuous rain in the mid-latitudes the precipitation begins as ice crystals which aggregate to form flakes, then melt and fall as rain. After melting, the drops continue to grow by coalescence.

**Changes in Raindrops Between Cloud and Ground**

Methods of measurement of raindrop-size distributions restrict observations almost entirely to ground locations because of the nature of the equipment used. A knowledge of the mechanisms which alter the raindrops provides an understanding of changes in the spectrum that occur as the drops fall from the region viewed by a radar and reach the ground recording equipment. This knowledge also contributes to understanding the factors which cause the growth and evaporation of raindrops (Hardy, 1962).

The average distribution high in a cloud may differ from that at the base of the cloud (Blanchard, 1953). Also, the distribution at the ground may differ radically from the distribution at the base of the cloud, as seen in its most extreme example by the occurrence of virga.

Numerous processes work together in altering raindrops as
they fall. The raindrop diameters change, either growing by coalescence or shrinking by evaporation; this change in size causes a continual change in fall velocity (Rigby and Marshall, 1952). In addition, turbulence may cause large drops to break up forming numerous smaller ones. A horizontal wind also tends to affect the distribution by sorting smaller drops from larger ones.

**Evaporation**

Evaporation from a freely falling raindrop depends on the temperature and relative humidity of the atmosphere and on the drop diameter (Hardy and Dingle, 1962). For example, at a relative humidity of 90 percent in an isothermal atmosphere of 20°C small drops can completely evaporate in a fall of about 1000 meters. A 1.5 millimeter drop will evaporate to only 1.42 millimeters in a fall of 2000 meters, while a 0.5 millimeter drop will evaporate completely in a fall of 1000 meters (Blanchard, 1953). The evaporation of small drops deprives researchers of any knowledge of their distribution, which appears important to the question of rain formation mechanisms. Users of data on drop-size spectra should exercise care in their interpretation of the effects of evaporation. Evaporation from falling rain affects the atmosphere in two ways: (1) increasing the moisture content of the air and (2) cooling of the air (which must supply latent heat for the evaporation) and consequently
changing the atmospheric stability (Hardy and Dingle, 1962). Both of these factors effect changes in the drop-size distribution.

**Raindrop Breakup**

The maximum size of raindrops depends on the turbulence of the air through which they fall. In still air drops as large as ten millimeters in diameter can be produced, but in the free atmosphere drops of six millimeters appear rarely (Hardy and Dingle, 1962). If the speed of updrafts exceeds three to four meters per second, raindrop breaking occurs (Ludlam, 1951).

A water drop, if it has no appreciable motion relative to the air, will assume a spherical shape due to surface tension (Spilhaus, 1948). As a raindrop falls through the air, unequal pressures develop over its surface producing pressure deficits on the top and sides and an excess of pressure on the bottom. This out-of-balance drag and pressure excess on the bottom will be offset by the weight of the steadily falling drop, thus causing it to deform by flattening on the bottom and spreading sideways (Spilhaus, 1948). Aerodynamic forces deform a droplet as it falls through the air. Observations have shown the drop to vibrate strongly and to spin. These vibrations and deformations frequently break up a large drop (Gunn and Kinzer, 1949).

Under a constant velocity air stream a drop will oscillate until
it exceeds its surface tension, forming a narrow neck in its middle and eventually separating into two or more drops (Blanchard, 1950). Blanchard (1950) performed numerous experiments on the stability of water droplets. He found that by interrupting the flow of air supporting the drop for 0.1 second the drop will begin to fall; as the air stream strikes the drop, extreme flattening occurs which causes a typical shock break up resulting in 20 or so drops of various sizes. Although any sudden change in the velocity of the air stream will affect drop stability, drop behavior varies depending on whether the air velocity increases or decreases. A sudden increase in the air speed, which corresponds to a downdraft, will not cause disintegration (Blanchard, 1950).

Extreme turbulence occurs often in convective showers. As previously shown, turbulence plays an important role in the changing of the character of the drop-size distribution. Therefore, the distribution found under convective showers depends on the character of the turbulence.

Coalescence

A description of coalescence appeared earlier in connection with rain formation. It may be thought of as the collision of larger drops with smaller drops brought about by the differences in fall velocities. These collisions, and subsequent absorptions of the
smaller drops, modify raindrop distributions. Coalescence increases the size of large drops while eliminating smaller drops. In most cases when small drops collide with larger ones coalescence occurs instantly. In some instances, however, the small drop falls or slides across the undersurface of the large drop. Electrostatic changes may cause this type of behavior (Blanchard, 1950).

If a drop at 8000 feet has a diameter of 1.2 millimeters, a combination of growth by coalescence and slight decay by evaporation could result in a 1.8 millimeter drop at the ground (Atlas and Plank, 1953). Although coalescence can seriously affect drop-size distribution, the process remains poorly understood. Some studies of coalescence, however, appear nascent at UCLA (Pruppacher, 1966).

Wind Effect

A constant horizontal wind blowing between the base of a cloud and the ground will sort the raindrops according to size. Larger drops fall nearly straight, while smaller ones blow horizontally. Therefore, the drop-size distribution observed on the ground depends on the observer's position with respect to both cloud and wind. Significant changes in the distribution may occur between the cloud base and the ground on the windward or lee edge of a shower.
Formation of Different Drop-Size Distributions

The raindrop spectrum observed at the ground depends upon (1) the distribution formed in the cloud, and (2) the changes which occur between the cloud and the ground. Raindrops may form by different processes such as the melting of snowflakes, the melting of hailstones, and the coalescence of water droplets. Furthermore, because of the modification of the drops by such factors as coalescence, breakup, evaporation, and wind sorting, the characteristics of the spectrum will markedly differ, depending on whether widespread frontal or cyclonic rainfall, showers, or thunderstorms produce the rain (Mason and Andrews, 1960).
METHODS OF RECORDING DROP-SIZE DISTRIBUTIONS

Many difficulties arise in obtaining meaningful raindrop-size spectra. Achieving representativeness by making the sample very large produces the difficulty of measuring an unreasonable number of drops. The raindrop sampler must not alter the rain field in any way. In addition, it must consist of a rugged, all-weather unit with the sensitivity and accuracy of a delicate laboratory instrument.

Early Research

Blanchard (1953) reports that Lowe, in 1892, apparently made the first study on raindrop-size measurements. He observed diameters of spots produced by drops falling on sheets of slate, but he did not attempt to relate these "slate" diameters to the actual drop diameters. A number of other papers published over the next 13 years generally laid a foundation for the study of drop-size spectra.

Wiesner, report Laws and Parsons (1943), first published the detailed results of exposing chemically treated filter paper in 1895. The "filter-paper method", that most frequently used for determining drop-size distributions, consists of exposing water-sensitive paper to rain for a given period of time. A comparison of raindrops with spots made by drops of various known sizes permits the measurement of natural rain.
Blanchard (1950) cites an interesting approach to raindrop-size measurements used by Bentley in 1904. Bentley's "flour technique" consists of allowing raindrops to fall into an inch-deep layer of flour; they remain in the flour until the dough pellets formed by the water drops become hard and dry. The dough pellets correspond roughly in size to the raindrops.

According to Hardy and Dingle (1962), Lenard, in 1904, used Wiesner's method and improved it by dusting the spots on the blotting paper with eosin in order to obtain a permanent record of the drops. He obtained samples of raindrop sizes in natural rains from 1898 to 1899 at Kiel, Germany and also in Switzerland. Lenard appears as the first investigator to show interest in the frequency distribution of raindrop sizes (Laws and Parsons, 1943).

In a review Neuberger (1942) reports that in 1905 Defant used the filter-paper method to observe drop-size distributions. Defant noted that the most frequently occurring sizes of drops appear in the proportion 1:2:4:8, etc., with 3, 5, and 7 appearing rarely. Becker (1907) and Schmidth (1908) confirmed Defant's findings. Later works by many investigators proved Defant's theory false.

Interest in drop-size research lapsed during the period 1908-1930, but in 1932 papers by Houghton, Findeisen, and Neiderdorfer appeared, showing renewed interest (Neuberger, 1942).
Recent Work

The development of radar as a weather-observing device during World War II greatly stimulated the study of raindrop spectra. However, water and soil conservationists, as well as cloud and rain physicists, continued making numerous studies.

In recent years methods of making drop-size measurements have grown through advances in electronic techniques. Mason and Ramanadham (1953) used optical methods for measuring raindrop sizes. Hardy and Dingle (1962) recently implemented a photoelectric raindrop-size spectrometer to determine time-integrated drop-size distributions. This spectrometer consists of two main components: a light source which produces a beam of nearly collimated light 0.5 centimeters wide and four centimeters high, and photometer which "views" a segment of the light beam. Mounted on arms, the light source and photometer extend from a central hub, and when the components rotate the photometer observes a volume of 9330 cubic centimeters. Raindrops in the path of the rotation sensitive field scatter an amount of light proportional to their cross sectional area.

Caton (1966) presents observations of a distribution in the free atmosphere during continuous frontal rains using a vertically-looking 3.2 centimeter pulsed Doppler radar. This radar observes a volume in excess of $3 \times 10^4$ cubic meters. Dependence of echo intensity on the
sixth power of drop diameter assists in the detection of large drops.

Hardy and Dingle (1962) describe an instrument devised in 1951 by Cooper which measured the amplitude of the pulses produced by raindrops impinging upon a microphone diaphragm. A similar instrument was developed by Schindelhauer (Neuberger, 1942). Numerous difficulties prevent the collection of meaningful data by these devices.

Bowen and Davison (1951) describe a raindrop spectrograph which takes the form of a mass spectrograph. This device uses a horizontal air current to deflect the falling raindrops. An inversely proportional relationship exists between the distance deflected and the mass of the drop.

Several photographic techniques apply to the study of drop-size distributions. For instance, Neuberger (1942) cites a study done by Mache who photographed raindrops in front of a black background. The trace length produced by a falling raindrop on the picture and the shutter speed of the camera permitted him to determine the fall velocity. A direct proportionality exists between the velocity and the drop size.

Hardy and Dingle (1962) cite a photographic technique developed by Jones and Dean in 1953. They took a series of pictures of a volume of atmosphere and then counted and sized the drops photographed. A volume greater than one cubic meter per minute was
examined by this sampling method. However, errors occurred in the measurement of drops less than 1.0 millimeters in diameter.

Sims, et al. (1964) used a raindrop camera to determine drop-size distributions at different locations throughout the country. The raindrop camera they employed sampled one cubic meter of air space in about 13 seconds at intervals of 60 seconds. All raindrops in this volume with diameters larger than 1.5 millimeters were measured by means of semi-automatic calipers. The film, projected on a screen, enlarged the raindrop image to twice its actual size. The distance across the ends of the calipers, adjusted to the size of the image, was automatically entered on punch cards with each depression of a foot switch.

Laws and Parsons (1943) did significant work during the early 1940's using a refined version of Bentley's flour-pellet method. Their data related the median-volume diameter, $D_0$, (defined as the drop diameter which divides the distribution of liquid water exactly in half) to rainfall intensity, $R$, by

$$D_0 = 1.24 R^{0.182}$$

This represents one of the first attempts to describe a property of the drop-size distribution quantitatively.

Blanchard (1950) experimented with soot-coated 100- and 50-mesh brass screens. Raindrops passing through these screens
removed a circular area of soot, thereby giving a measure of drop size.

The "filter-paper" method still remains the most common means of obtaining drop-size distributions. In this technique raindrops moisten a chemically treated paper and, after drying, leave circular stains whose diameters relate to the diameters of the drops. Many workers have examined spots produced on absorbent filter paper and have thus determined empirical relationships between spot diameter and drop diameter which now serve as a basis for laboratory experiments and for studies of the size spectrum of natural raindrops. A consideration of simple theory suggests a relationship of the form

\[ D = aS^b \]

where \( D \) and \( S \) equal drop and spot diameter, respectively, and \( a \) and \( b \) equal constants which depend on the type of paper used (Magarvey, 1957).

In his study of Hawaiian rains, Blanchard (1950) used Whatman No. 1 filter paper dusted with methylene blue dye. He held the paper between two brass rings and exposed it to rain with the aid of a small aluminum cover and a stop-watch. Mason and Andrews (1960) also used Whatman No. 1 filter paper treated either with a solution of bromo-cresol green or rhodamine dye.
Anderson (1948), in his study of oreigenic rain, used ordinary ink blotters, nine and one-half inches by four inches, dusted with powdered potassium permanganate. He exposed these in long-handled trays equipped with a sliding lid. Anderson calibrated the blotters by weighing a one-inch square piece on an analytical balance, placing a drop on the square, and then reweighing. Assuming a spherical shaped drop, he calculated the drop diameter from its weight.

Engelmann (1962) designed and successfully used a continuous drop-size distribution recorder which exposed a sheet of blue-print paper to the rain. The paper develops when exposed to ammonia fumes. If properly developed, black rings on a yellow-gray background will outline the yellow-orange drop stains. An instrument of the type designed by Engelmann fulfills an important requirement for investigation of the physics of rain formation; namely that, while very simple, it allows a continuous and accurate record of raindrops. The implementation of water-sensitive paper excels as a direct, accurate, versatile, and economic means of sampling in light rainfall.
THE ASB\textsuperscript{*} RAINDROP RECORDER

Construction

This study required a self-contained, mobile recorder able to operate without electric power. In 1962 at Oregon State University Meland constructed a continuous drop-size distribution recorder similar to the Hanford Raindrop Sampler designed and built by Engelmann (1962). Meland's recorder demanded several modifications in order to fulfill the requirements of this study.

The shell of the ASB raindrop recorder consists of a box constructed of one-half inch plywood 14 inches wide, 30 inches high, and 54 inches long. A partition divides this box into two chambers, one 18 inches long and the other 36 inches long. Exposed paper dries and develops in the larger chamber; the smaller contains a roll of unexposed paper and a spool on which to wind the paper after development. Rollers allow the paper to proceed smoothly from the unexposed paper roll through the drying and developing chamber and back onto the take-up spool. A four by five-inch window located on top of the recorder exposes the paper to rain.

A modified "camp stove" which burns white gasoline composes the heating element, and it adjusts to any desired heat. A

\textsuperscript{*}Atmospheric Science Branch, Oregon State University.
Figure 1. Observer operating ASB Recorder.

Figure 2. Observer making time marks on record.
Figure 3. View inside ASB Recorder. Note pan in bottom of picture which catches water that passes through the window but past the paper.

Figure 4. View inside ASB Recorder. Note heating element in bottom of picture with gasoline tank connected outside the recorder.
Figure 5. ASB Raindrop Recorder.
Figure 6. Typical record of raindrops obtained with the ASB Recorder.
hand-operated crank moves the paper, thereby allowing the operator to manipulate the paper speed according to the intensity of the rain.

Using a felt-tip pen, the operator makes time marks on the paper. This process permits him further control in adjusting the frequency of time marks to the intensity of the rain.

Paper

Ozalid, a division of General Aniline and Film Corporation, manufactures the sampling paper under the brand name "Ozalid 105 SZ". This paper consists of a sulfite paper base coated with a thin layer of polyvinyl acetate, which gives the paper a very smooth surface. An aqueous-alcohol solution of diazonium salts, stabilizers and couplers applied to the polymer layer finishes it. Ammonia fumes develop the paper. When fully developed, the paper appears black with light yellow spots where drops have dried.

Engelmann (1962) found that partial development gives the best contrast for sizing work. When only partially developed, the raindrops appear on the paper as yellow spots, clearly outlined with black rings, generally on a gray or lavender background. A 28 percent solution of aqua ammonia poured in a 50 milliliter beaker and placed in the bottom of the recorder provides enough fumes to partially develop the paper.

The ASB recorder uses three-inch wide paper on rolls 150 feet
Chapter 5 presents a discussion of the narrow width of the paper.

Calibration

In any raindrop recorder which utilizes the "filter-paper" technique, a relationship must be derived between the raindrop diameter and the diameter of the spot on the paper. Determining this relationship requires a series of tests, of which a complete description appears in Appendix A. The results of the calibration tests show that a drop 0.56 millimeters in diameter produces a spot 1.5 millimeters in diameter; a drop 0.64 millimeters in diameter produces a spot 2.0 millimeters in diameter; a drop 2.2 millimeters in diameter produces a spot 9.0 millimeters in diameter; and a drop 4.3 millimeters in diameter produces a spot 24 millimeters in diameter.

The Hanford recorder used the same type paper as this study. In addition, Engelmann used a similar method to calibrate his paper. He plotted a graph of the logarithm of drop diameter versus the logarithm of spot diameter using 23 points.

Ten to thirty drops and about as many spots were sized to provide each of the 23 points from which the calibration curve was obtained. The least squares fit was

\[ D = 0.434 S^{0.7413} \]

The 95% confidence interval estimates for the logarithm of the equivalent drop diameter, \( D \), given the spot diameter, \( S \), were 0.918 and 1.091. (Engelmann, 1962, p. 10)
The four points obtained above fall along his curve (see Figure 7). It therefore appears that similar characteristics of the two batches of paper exist. The equation developed by Engelmann relating spot size to drop size also gives the proper relationship for this study.

Operation

The ASB raindrop recorder operates quite simply. (1) Light the burner on the heating element, turning the flame up fairly high. (2) Pour ammonia into the 50 milliliter beaker and place it next to the burner on the floor of the recorder. (3) Position a roll of paper on the feed-off spool, threading it through the slits in the partition, over the rollers and taping it to the take-up spool. (4) Put the water-catching pan below the window to collect any rain that passes by the paper. (5) Turn the flame down to the desired heat and close the cover of the recorder. (6) Place a sheet of one-half-inch thick spongy material around the window to reduce splashing. This completes preparation of the ASB raindrop recorder.
Figure 7. Calibration Curve. Engelmann's (1962, p. 11) calibration curve (O) with the four additional points calculated in this study (Δ).
PROBLEMS WITH THE ASB RAINDROP RECORDER

The collection of data with this recorder required solving several easily overcome problems.

**Smearing**

It appears necessary for the raindrops to dry while the paper remains in a horizontal position. If the raindrops stay wet and beaded up on the paper when it goes over the roller at the end of the recorder, the drops will run. Also, if the paper remains wet as it goes onto the take-up spool, the drops will soak through the overlapping turns of the paper. These complications make analysis of the data extremely difficult. The solution of this problem occurs quite easily in light or moderate rains by keeping the air in the chamber very warm and making sure the drops dry before the paper goes over the roller at the end of the chamber. Rolling the paper as slowly as possible also helps eliminate running and smearing. Unfortunately, the heavier rains contain more larger drops, which take longer to dry, and also more total drops. Therefore, to avoid overlapping the drops the paper must be rolled faster than in light rains. This allows the heavier rain and large drops less time to dry than the light rains.
Underdevelopment

Occasionally the concentration of ammonia fumes falls below the amount required to develop the raindrops on the filter paper. This usually occurs when all the ammonia evaporates from the container. Running the paper through ammonia fumes at some later time solves this problem; paper developed in this manner appears the same as paper developed in the chamber.

Splashing

Splashing from the Paper

Splashing may occur when a raindrop strikes the paper. Engelmann (1962, p. 8) states:

The paper has a hard surface and large drops will splash upon contact if the paper is backed with a solid material. By suspending the paper under a minimum tension the splashing is reduced. Under these conditions, only drops larger than 1.2 millimeters show splash lines radiating outward from the spot. Small droplets from this type of splash can be later associated with the parent drop as a rule.

The present study found that by holding the paper under minimum tension a single drop, up to 4.3 millimeters in diameter, will not produce any splashes. Further, this study found that splashes only occur when a drop directly strikes the wet area on the paper made by another drop. Splashes which occur in this manner cannot
be distinguished from raindrops (see Figures 8 and 9). This part of
the study utilizes the equipment and procedure discussed in Appendix
A in connection with the calibration experiments. However, the
raindrop recorder replaces the plastic container.

**Splashing from the Observer's Body**

In order to operate the ASB raindrop recorder, the observer
must sit near it. As a result, the risk of splashing from the ob-
server's head and body arises. Determining the quantity of this type
of splashing required the designing and performing of a series of
experiments.

Water sprayed from a hose atop a 50-foot tower fell onto the
observer and recorder, thus simulating rainfall. The recorder and
observer assumed a position centered in the cone of spray. Part one
of the experiment to determine how much water splashed off the ob-
server required him to operate the recorder for one minute in a
normal position, marking the paper every 15 seconds. For the
second minute the observer crouched beside the recorder low enough
so that no splashes could possibly ricochet off his body. He continued
to mark the paper every 15 seconds, and alternated in this manner
for six minutes.

The analyzed results of this test show no oscillation pattern in
the frequency of occurrence in any of the drop sizes.
Figure 8. Drops 4.3 millimeters in diameter striking paper. Note no splashing.
Figure 9. Five drops 4.3 millimeters in diameter striking one on top another. Note the large amount of splashing.
Table 1. Splashing from observer's body.*

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*Number of drops striking recorder when observer assumes normal operating position (up), and when observer assumes the crouched position (down).

Part two of the experiment consisted of shielding the recorder from direct hits of the spray and recording only splashing from the observer. Again the observer alternated at one-minute intervals between the normal and crouched positions.

An analysis of the results again shows no splashing from the observer.
Table 2. Splashing from observer's body with recorder shielded from direct hits.*

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<tr>
<th>Position of observer</th>
<th>up</th>
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<th>up</th>
<th>down</th>
<th>up</th>
<th>down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of Drop</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
<td>10</td>
<td>7</td>
<td>0</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>0.3</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*Amount of splashing from observer with recorder shielded from any direct hits. Observer varies from normal operating position (up) to crouched position (down).

Both tests indicate that no appreciable splashing occurred from the head and shoulders of the observer.

Splashing from the Observer's Hand

The observer makes time marks with a felt-tip pen on the moving record of the ASB raindrop recorder. Splashing may occur from the observer's hand when he makes these marks. An experiment performed to determine whether appreciable splashing occurred required that both observer and recorder again be located in the center of a cone of spray from a 50-foot tower. The observer crouched beside the recorder so that no splashing would occur from his body. For one minute the observer made time marks every 15 seconds; for the next minute he made no time marks. Again he alternated thusly for six minutes.

Analyzed results of these data show no appreciable splashing
from the observer's hand.

Table 3. Splashing from observer's hand.*

<table>
<thead>
<tr>
<th>Size of Drop</th>
<th>Time Marks on Paper</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>with</td>
<td>without</td>
<td>with</td>
<td>without</td>
<td>with</td>
<td>without</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>103</td>
<td>113</td>
<td>82</td>
<td>101</td>
<td>98</td>
<td>85</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>8</td>
<td>14</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>7</td>
<td>7</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>3</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>0.7</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td></td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>25</td>
<td>4</td>
<td>1</td>
<td>12</td>
<td>15</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>0.9</td>
<td>16</td>
<td>16</td>
<td>13</td>
<td>15</td>
<td>18</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>20</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>1.1</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>1.2</td>
<td>1</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>7</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1.4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Number of drops striking record when observer makes time marks (with), and when he makes no marks (without).

Splashing from the Recorder

Splashing from the recorder can cause serious problems in a drop-size distribution. Nevertheless, few investigators have bothered to examine this splashing effect. To reduce splashing on the Hanford Raindrop Recorder, Engelmann (1962) spread towelling around the window. He states that this towelling, even when wet,
eliminated nearly all splashing.

Placement of one-half-inch thick sponge around the window of the ASB raindrop recorder helped reduce splashing. Testing the effectiveness of this sponge required another series of experiments.

Water drops 4.3 millimeters and 2.2 millimeters in diameter (see Appendix A) released 30 feet above the recorder struck the sponge at varying distances from the paper. These distances ranged from one-half inch to six inches from the paper. Table 4 expresses the average number of splashes from a 2.2 millimeter and a 4.3 millimeter drop striking within one inch, one to three inches, three to five inches, and five to seven inches of the paper.

<table>
<thead>
<tr>
<th>Distance from Paper</th>
<th>Splash Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.2 mm diameter drops</td>
</tr>
<tr>
<td></td>
<td>.2</td>
</tr>
<tr>
<td>1 inch</td>
<td>18</td>
</tr>
<tr>
<td>2 inches</td>
<td>7</td>
</tr>
<tr>
<td>4 inches</td>
<td>0</td>
</tr>
<tr>
<td>6 inches</td>
<td>0</td>
</tr>
</tbody>
</table>

*Number of splashes from drops striking sponge at various distances from paper.

Figure 10 presents the amount of splashing of different sizes that will occur when any given number of drops 2.2 or 4.3 millimeters in diameter appear on the record. Construction of these lines
Figure 10. Number of splashes produced by various numbers of drops 4.3 millimeters and 2.2 millimeters in diameter.
requires that one determine the areas of the intervals from the edge of the window to a distance of one inch, one to three inches, three to five inches, and five to seven inches around the perimeter of the window. If a known number of drops strike the paper, determination of the drop density (number of drops of a certain size per unit area) occurs easily. This drop density remains constant over the top surface of the recorder. Knowing the areas of each interval and the drop density, one can easily calculate the number of drops of a certain size striking in each interval. The sum of the splashes from each interval equals the total number of splashes striking the paper.

On the basis of Figure 10, it would appear that splashing occurring from the sponge-covered recorder was negligible in nearly all cases examined in this study. Consideration of an extreme case reveals 13 as the maximum number of drops 2.2 millimeters in diameter. A study of Figure 10 indicates that 90 splashes of 0.2 millimeters occurred and that 15 splashes of 0.3 millimeters occurred. Reviewing the data for this case shows that 3316 drops of 0.2 millimeters and 1333 drops of 0.3 millimeters appear on the record. Therefore, splashing from the sponge for 2.2 millimeter drops accounts for about 2.7 percent of the 0.2 millimeter drops and about 1.1 percent of the 0.3 millimeter drops. No drops collected appeared as large as 4.3 millimeters. In nearly all cases, drops large enough to cause substantial splashing occurred in numbers too
small to affect the data.

**Width of the Sampling Paper**

As mentioned earlier, the filter paper consists of a three-inch wide, 150-foot long roll. Narrowsness of the record may have caused errors by not sampling a representative volume of air.

The volume sampled in this study using three-inch wide paper (assuming drops 1.0 millimeters in diameter) equals approximately 2.4 meter$^3$/minute.

In this regard, Mueller and Sims (1966, p. 1) state:

The results of the drop size sample study indicate that volumes of about 50 m$^3$ are necessary to estimate rainfall rate and radar reflectivity to 10 percent accuracy with 95 percent confidence. One-cubic-meter samples are sufficiently large that rainfall rate-radar reflectivity relationships can be reliably determined. The sample size variances contribute about 10 percent of the logarithmic scatter around the regression line.

Engelmann (1962) appeared satisfied with the volume sampled using six-inch wide paper. In this study, therefore, tests were conducted to determine whether significant differences occur between three-inch wide paper and six-inch wide paper.

Table 5 presents the results of two strips of three-inch paper exposed side by side. No significant variation appears in the distribution (Figures 11-13). Apparently no significant difference occurs between six-inch and three-inch wide filter paper.
Table 5. Comparison between three-inch and six-inch wide paper.

<table>
<thead>
<tr>
<th>Drop Diameter</th>
<th>1st 3-inch</th>
<th>2nd 3-inch</th>
<th>6-inch</th>
<th>6-inch/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>.2</td>
<td>90</td>
<td>85</td>
<td>175</td>
<td>87</td>
</tr>
<tr>
<td>.3</td>
<td>70</td>
<td>70</td>
<td>140</td>
<td>70</td>
</tr>
<tr>
<td>.4</td>
<td>63</td>
<td>63</td>
<td>126</td>
<td>63</td>
</tr>
<tr>
<td>.5</td>
<td>63</td>
<td>60</td>
<td>123</td>
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</tr>
<tr>
<td>.6</td>
<td>37</td>
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<td>71</td>
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<tr>
<td>.7</td>
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<tr>
<td>.8</td>
<td>26</td>
<td>29</td>
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<td>27</td>
</tr>
<tr>
<td>.9</td>
<td>15</td>
<td>24</td>
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</tr>
<tr>
<td>1.0</td>
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</tr>
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<tr>
<td>1.3</td>
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<td>1.4</td>
<td>9</td>
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<td>8</td>
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<td>1.5</td>
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<td>4</td>
<td>9</td>
<td>5</td>
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<tr>
<td>1.6</td>
<td>5</td>
<td>2</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>1.7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1.8</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2.0</td>
<td>1</td>
<td></td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Figure 11. Drop-size distribution for 6 inch wide strip of paper.
Figure 12. Drop size distribution for three inch wide strip of paper.
Figure 13. Drop size distribution for three inch wide strip of paper.
THE AN/TPS-10D WEATHER RADAR

A portion of the data used in this study came from the weather radar station operated by the Atmospheric Science Branch at Oregon State University. The radar station stands on 2,200-foot McCulloch Peak, located 5.6 miles northwest of Corvallis, Oregon, on the eastern edge of the Coast Range.

AN/TPS-10D Weather Radar

The AN/TPS-10D weather radar transmits a maximum power of 250 kilowatts at a wave length of 3.2 centimeters. It may operate on either short or long pulse. Short pulse produces a 0.5 microsecond pulse length repeated at the rate of 465.5 pulses per second. Long pulse yields 2.0 microsecond pulse length. The "orange peel" antenna has a vertical beam-width of 0.755° and a horizontal beam-width of 2.05°. The antenna can scan automatically from -2.0 to +23.0 degrees at a rate of 0.5 cycles per second or 1.0 cycles per second (Mendenhall and McFadden, 1966).

Automatic Step Gain Control

The step gain control provides a means for automatically setting the gain of the IF amplifier of the radar receiver to a predetermined value. With each successive step the gain increases,
causing the area covered by the echo on the scope to either remain the same or to increase. The gain changes with each sweep of the antenna (Mendenhall and McFadden, 1966).

Photographic Presentation of the Data

This study utilizes the data obtained from a 16-millimeter film record of the Range-Height Indicator (RHI) scope of the AN/TPS-10D radar. A Bell and Howell Model 240 16-millimeter movie camera took the photographs (Mendenhall and McFadden, 1966).
DATA COLLECTION

Collection of the desired data for this study necessitated movement of the recorder at will. Also, communication between the radar station and the recorder's operator seemed desirable.

The size of the recorder allowed easy transportation in a standard automobile. Communications between McCulloch Peak and the observing automobile occurred via citizen-band (CB) radio, or by telephone.

Generally the procedure went as follows. The radar operator on McCulloch Peak examined the radar and determined the location of showers. He then decided the approximate direction and speed of a likely shower and turned to a detailed map of the area on which azimuth and range markers appear. From these he could ascertain the approximate path that the rain shower would take; he could also determine a good location for collecting raindrop samples and the simplest route for the observer to take. By approximating the speed of the shower, the operator tried to allow time for the observer to reach this location and set up the recorder before the shower reached him. After making all these calculations, he called the observer on the CB radio and relayed this information to him. This method worked well, and a number of continuous records of drop-size distributions resulted from showers which passed over the observer.
DATA ANALYSIS

Drop-Size Data Analysis

Analysis of the data consisted of an extremely tedious procedure which required over 300 hours to complete.

An equation obtained in an earlier section relating drop size to spot size provided the necessary information for construction of a template which directly determines drop diameter from the spot diameter. A circle appears on the template for every 0.1 millimeter diameter, ranging from 0.2 millimeters to 3.1 millimeters. The worker placed the template over a raindrop spot and moved it until he found a circle corresponding in size to the spot. On the template a number appears which states the drop diameter for that particular spot. Every drop on the record required this type of measurement. A four-power magnifying glass aided in matching circles with spots.

Data reduction consisted of a wearisome and time-consuming procedure. The tedious nature of this work makes data analysis one of the major disadvantages of the "filter-paper" method of collecting drop-size distributions.

Analysis of Radar Data

Sixteen-millimeter film recorded the necessary data from the RHI scope of the AN/TPS-10D radar. The analyst projected this
Figure 14. Template used in analyzing the raindrop data.
film onto a sheet of paper, and for each step of the step-gain he drew a contour line around the echo. By changing paper he repeated this process for each sequence of steps. The resulting series of iso-echo contour lines permitted detailed examination of the radar echo.

Examination of the echo "above" the raindrop recorder demanded a knowledge of the winds aloft. Salem, Oregon's rawinsonde provided these data. A simple calculation yields the component of the wind blowing parallel to the direction of the radar beam. Then, by determining the time for the mean-size raindrop to fall to ground level, and by knowing the wind velocity, calculations of the horizontal distance drops at a certain height travel before they strike the ground became possible. A line drawn through the precipitation echo shows the location of those drops which will eventually strike the recorder. The echo along this line represents the echo "above" the recorder.
SYNOPTIC SITUATION

6 May 1966

The synoptic pattern for 6 May 1966 showed at the 500 millibar level an intense low centered approximately 50 miles off the coast of Oregon with south to southeasterly winds blowing across central western Oregon. At lower levels, the wind decreased in speed and backed to the southwest. At the surface a low center in southeastern Washington extended as a trough down along the eastern border of Oregon; a cold front lay in this trough. Another cold front, which ran north-south along the 135th meridian, extended from a low located in the Gulf of Alaska. At 0400PST the freezing level existed at 7800 feet, falling during the day until at 1000PST it stood at about 6000 feet, where it still remained at 1600PST. The air moving over Oregon at 0400PST appeared quite moist at the surface but remained dry up to about 750 millibars, where it became moist again. By 1000PST it became fairly moist at all levels up to 600 millibars, and by 1600PST it seemed fairly moist at all levels except around 750 millibars. The Showalter stability index (as defined by Petterssen, 1956) for 0400PST equaled 10°C; for 1000PST, it equaled 2°C; and for 1600PST it equaled 15°C. Generally, when the index occurs below 3°C showers become possible (Petterssen, 1956).
15 May 1966

The synoptic pattern for 15 May 1966 indicated a large low pressure area in the Gulf of Alaska at the 500 millibar level. Circulation around this low caused west winds aloft over Oregon which backed with decreasing altitude until at ground level they blew from the south-southwest. At the surface a frontal system extended from a low in the Gulf of Alaska and ran parallel to the coast. Because the front occurred perpendicular to the winds aloft, it moved fairly fast and passed through western Oregon around 1200PST.

The Salem sounding indicated very moist conditions in western Oregon after 0800PST. For 1000PST the Showalter stability index equaled 9°C; for 1600PST it equaled 2°C; and for 1900PST it equaled 9°C. The freezing level changed from 6000 feet at 0400PST to 4200 feet at 1000PST, to 4800 feet at 1600PST, and to approximately 4400 feet at 1900PST.

31 May 1966

On 31 May 1966 an intense low pressure at the 500 millibar level existed on the central Washington coast, causing south-southwest winds aloft over the Corvallis area. The wind veered with decreasing height until at the surface it blew from the west. In northeastern Washington a small low existed at the surface, and a large
high pressure area lay in the central eastern Pacific.

The sounding at Salem showed generally moist air at all levels up to 700 millibars at 0400PST. As the day progressed, general drying occurred at all levels. The freezing level for the entire day lay between 3000 and 4000 feet. The Showalter stability index for 0400PST equaled 9°C, and at 1600PST it equaled 5°C.
RESULTS

Sampling Rate

One might profitably examine how often raindrop samples must be gathered in order to obtain an accurate description of the drop-size spectra in a shower. Serious errors may arise by collecting, say, only one or two one-minute samples from a shower. Figure 15 demonstrates a possible cause for such errors. Suppose, for example, one wants to discover the mean drop size which fell on a given area as a shower passed overhead. Determination of the mean from only one one-minute sample may lead to a false conclusion due to the selection of a minute with a particularly high or low value of the mean.

Figure 15 shows how the graph of the change in mean drop diameter per minute of data would appear if data collection took place at five- and ten-minute intervals. Such a sampling procedure seems analogous to describing the topography of a lake bottom by taking only a few soundings. Most of the minor fluctuations and some of the major ones do not appear; however, the mean diameter throughout the entire shower equals 0.46 millimeters for observations at ten-minute intervals and 0.43 millimeters for observations at five-minute intervals. The mean diameter for observations at one-minute
Figure 15. Change in mean drop diameter per minute with respect to time.
intervals equals 0.42 millimeters. These values indicate that sampling at ten-minute intervals produces approximately a ten percent error and that sampling at five-minute intervals produces approximately a two percent error in the mean drop diameter.

Therefore, if one requires only a parameter such as mean drop diameter for the entire shower, it does not appear necessary to sample continuously. Approximately ten samples collected in the shower appear sufficient to calculate this value quite accurately. However, if one needs to obtain those fluctuations which occur throughout a shower, then continuous data must be gathered.

Change in Drop-Size Spectra with Time

The continuous record of a drop-size distribution allows examination of changes in various aspects of raindrop spectra with respect to time. Eventually, studies of such changes may prove useful in describing precipitation mechanisms.

This part of the study investigates five rainshowers, all of which occurred in the eastern hills of the Coast Range. In each case the recorder collected data from the time the shower began until the shower ended. A summary of these data appears in Appendix F.

Figures 16-20 present the change in total number of drops 0.2 millimeters in diameter and smaller per minute with respect to change in time. No systematic variation in the number of small
Figure 16. Change in the number of drops 0.2 mm in diameter and smaller per minute with respect to time. Case No. 1.
Figure 17. Change in the number of drops 0.2 mm in diameter and smaller per minute with respect to time. Case No. 2.
Figure 18. Change in the number of drops 0.2 mm in diameter and smaller per minute with respect to time. Case No. 3.
Figure 19. Change in the number of drops 0.2 mm in diameter and smaller per minute with respect to time. Case No. 4.
Figure 20. Change in the number of drops 0.2 mm in diameter and smaller per minute with respect to time. Case No. 5.
drops occurs.

Figures 21-25 give perhaps a more meaningful representation of the change in small drops with time. They show the ratio of the total number of drops 0.2 millimeters in diameter and smaller per minute to the total number of drops per minute versus time. Again, no consistent change in the ratio with time seems evident. Upon closer examination, however, one feature appears common to all five graphs: the ratio always increases at the end of the shower. Mason and Andrews (1960) also noted this phenomenon in showers that did not extend above the freezing level. All five showers in this study extended above the freezing level, ranging from 800 feet to 8500 feet above. No relationship exists between the distance the shower extends above the freezing level and the increase in the percentage of small drops.

A tendency occurs in some showers toward a general increase in the percentage of small drops (cases 1, 2, and 4), while in other showers a tendency toward a decrease in the percentage of small drops (cases 3 and 5) prevails. No feasible explanation for this phenomenon lies in the data.

Figures 26-30 indicate the change in size of the largest drop collected in a one-minute period with respect to time. Case 5 shows the variation with respect to time in the largest size drop that may be expected in a shower; the diameter increases with time until the
Figure 21. Change in the ratio of the number of 0.2 mm and smaller drops per minute to the total number of drops per minute with respect to time. Case No. 1.
Figure 22. Change in the ratio of the number of 0.2 mm and smaller drops per minute to the total number of drops per minute with respect to time. Case No. 2.
Figure 23. Change in the ratio of the number of 0.2 mm and smaller drops per minute to the total number of drops per minute with respect to time. Case No. 3.
Figure 24. Change in the ratio of the number of 0.2 mm and smaller drops to the total number of drops per minute with respect to time. Case No. 4.
Figure 25. Change in the ratio of the number of 0.2 mm and smaller drops per minute to the total number of drops with respect to time. Case No. 5.
Figure 26. Change in the size of the largest drop per minute with respect to time. Case No. 1.
Figure 27. Change in the size of the largest drop per minute with respect to time. Case No. 2.
Figure 28. Change in the size of the largest drop per minute with respect to time. Case No. 4.
Figure 29. Change in the size of the largest drop per minute with respect to time. Case No. 3.
Figure 30. Change in the size of the largest drop per minute with respect to time. Case No. 5.
middle of the shower and decreases from then until the end of the shower. However, the other four cases do not display this same type of variation, indicating that no systematic change in the maximum drop diameter with time exists among these five showers.

Figures 31-40 show the change in rainfall rate, $R$, with time and the change in reflectivity, $Z$, with time. Appendix C describes the relationships used to calculate $Z$ and $R$. These relationships appear as:

$$Z = \sum_{j=0.2}^{C,D} \frac{6}{A V^j} (\text{mm}^6 \text{mm}^{-3})$$

and

$$R = \sum_{j=0.2}^{\pi D^3 C} \frac{6A_j}{6A_w} (\text{mm min}^{-1})$$

where time equals one minute.

Changes in $R$ and $Z$ with time appear in Figures 31-40, and again no consistent variation occurs in either with time. However, the maximum $Z$ and the maximum $R$ always occur somewhere near the middle of the shower, never during the beginning or end. The peaks and troughs of $Z$ and $R$ occur at approximately the same time, but those of $Z$ generally seem more pronounced than those of $R$. Considering the method used to calculate $Z$ and $R$, this result appears reasonable.
Figure 31. Change in rainfall intensity with respect to time. Case No. 1.
Figure 32. Change in rainfall intensity with respect to time. Case No. 2.
Figure 33. Change in rainfall intensity with respect to time. Case No. 3.
Figure 34. Change in rainfall intensity with respect to time. Case No. 4.
Figure 35. Change in rainfall intensity with respect to time. Case No. 5.
Figure 36. Change in reflectivity with respect to time. Case No. 1.
Figure 37. Change in reflectivity with respect to time. Case No. 2.
Figure 38. Change in reflectivity with respect to time. Case No. 3.
Figure 39. Change in reflectivity with respect to time. Case No. 4.
Figure 40. Change in reflectivity with respect to time. Case No. 5.
Figures 41-45 examine the change in the mean drop diameter, calculated for each minute of data, with respect to time. Appendix C describes the calculation of this quantity. No significant relationship among the five different cases is immediately evident, but upon closer examination the variance alters somewhat from case to case. In addition, the average of all the mean drop diameters differs in each case.

A further investigation of this point necessitates the construction of four more graphs (Figures 46-49). These graphs have the average mean drop diameter for each of the five cases plotted on the horizontal axes and the mean echo top, the average number of maximum intensity areas, mean average gradient of echo intensity, and mean average echo intensity plotted on the vertical axes. Appendix B describes the method used in calculating these quantities.

Figure 46 demonstrates a tendency toward a relationship between the average mean drop diameter and the mean echo top. None of the other graphs shows any similar correlation.

Also, as mentioned earlier, the variance of the mean drop diameter differs from case to case for the five showers under inspection. Figures 50-51 present the variance of the mean drop diameter on the horizontal axes and mean echo top and average mean echo intensity on the vertical axes. From these data one can see a definite tendency toward a relationship between the mean echo top and the
Figure 41. Change in the mean drop diameter with respect to time. Case No. 1.
Figure 42. Change in the mean drop diameter with respect to time. Case No. 2.
Figure 43. Change in the mean drop diameter with respect to time. Case No. 3.
Figure 44. Change in the mean drop diameter with respect to time. Case No. 4.
Figure 45. Change in the mean drop diameter with respect to time. Case No. 5.
Figure 46. Height of mean echo top versus mean drop diameter for five complete showers.
Figure 47. Average number of maximum intensity areas versus average mean drop diameter for five complete showers.
Figure 48. Average gradient of echo intensity versus average mean drop diameter for five complete showers.
Figure 49. Average echo intensity versus the average mean drop diameter for five complete showers.
Figure 50. Height of the mean echo top versus the variance of the mean drop diameter for the five complete showers.
Figure 51. Average echo intensity versus variance of the drop diameter for five complete showers.
variance of the mean drop diameter.

Another inspection of Figures 26-30 reveals that the variance and mean of the maximum drop diameters recorded for each minute and averaged over the entire shower vary from case to case for each of the five showers. Pursuing this idea required the construction of Figures 52-53. They present the mean echo top on the vertical axes and the mean maximum drop diameter collected per minute and the variance of the maximum drop diameter on the horizontal axes. The correlation among these quantities appears ill-defined. Four of the points in Figure 52 form a straight line, but the fifth point falls considerably off the line. This point (from Case 3) apparently has no unique qualities.

Delving into the possibility of a relationship between mean average drop size and mean echo top and between variance of the mean drop size and the echo top, this investigation examined the contingency of a correlation relating one of the constants $a$ or $b$ in the $Z$-$R$ relationship

$$Z = bR^a$$

where

$Z =$ reflectivity

$R =$ rainfall intensity

to a parameter obtained from the radar data. Development of the $Z$-$R$ relationships appears in Appendix D.
Figure S2. The height of the mean echo top versus the mean maximum drop diameter for five complete showers.
Figure 53. Height of mean echo top versus the variance of the mean maximum drop diameters for five complete showers.
For case 1, \[ Z = 260 R^{1.31} \]
For case 2, \[ Z = 92 R^{1.61} \]
For case 3, \[ Z = 465 R^{1.76} \]
For case 4, \[ Z = 195 R^{1.60} \]
For case 5, \[ Z = 285 R^{1.30} \]

Figures 54-65 present the constants \( a \) and \( b \) plotted against the height of the maximum echo, the average number of maximum intensities areas, the mean average gradient of the echo, the variance of the mean drop size, the average mean drop size, and the height of the mean echo. The calculation of the parameters obtained from the radar appears in Appendix B. These graphs do not indicate a relationship of either \( a \) or \( b \) with any of the parameters examined.

**Drop-Size Parameters Compared to Radar Echo Parameters**

This section compares three drop-size parameters with three radar echo parameters. The drop-size parameters include the mean drop diameter, the range of the drop sizes, and the parameter derived from the equation

\[
(D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_{5})
\]

where

\[ D_{\text{max}} = \text{maximum drop diameter} \]
Figure 54. Height of echo maximum versus the constant $a$ from $Z = bR^a$. 
Figure 55. Height of maximum echo versus the constant $b$ from $Z = bR^a$. 
Figure 56. Average number of maximum intensity areas versus the constant $a$ from $Z = bR^a$ for five complete showers.
Figure 57. Average number of intensity maxima versus the constant $b$ from
$Z = bR^a$ for the five complete showers.
Figure 58. Mean average gradient of echo intensity versus the constant $a$ from $Z = bR^a$ for five complete showers.
Figure 59. Mean average gradient of the echo intensity versus the constant $b$ from $Z = bR^a$ for five complete showers.
Figure 60. Variance of the drop size versus the constant $a$ from $Z = bR^a$ for five complete showers.
Figure 61. Variance of the mean drop diameter versus the constant $b$ from $Z = bR^a$ for five complete showers.
Figure 62. Average mean drop diameter versus the constant $a$ from $Z = bR^a$ for five complete showers.
Figure 63. Average mean drop diameter versus the constant $b$ from $Z = bR^a$ for five complete showers.
Figure 64. Height of mean echo top versus the constant $a$ from $Z = b R^a$ for five complete showers.
Figure 65. Height of mean echo top versus the constant $b$ from $Z = bR^2$
for five complete showers.
\[ D_{\text{min}} = \text{minimum drop diameter} \]
\[ D_{1000} = \text{diameter for the largest drop that occurs 1000 times} \]
\[ D_{500} = \text{diameter of the largest drop that occurs 500 times} \]
\[ D_5 = \text{diameter of the largest drop that occurs five times.} \]

This last parameter attempts to characterize the entire distribution through the use of one number. These three parameters occur from one-minute averages of the drop-size record. A description of the parameters obtained from the radar (height of echo top, mean echo intensity, and mean gradient of intensity) appears in Appendix B.

The data employed in this section came from the five complete showers described in the previous section plus data from four more showers. These data, however, do not extend throughout each entire shower as in the previous five cases. In two of the cases, data collection commenced after the shower began and continued until the shower ended. In the other two cases, data began after the shower started and finished before the shower did.

Figures 66-68 show the average mean drop diameter for each shower plotted on the horizontal axes and the average maximum echo height, average mean echo gradient, and average mean echo intensity for each shower plotted on the vertical axes. The reason for the
Figure 66. Height of mean echo top versus the average mean drop diameter for nine showers.
Figure 67. Average mean echo gradient versus average mean drop diameter for seven showers.
Figure 68. Average mean echo intensity versus average mean drop diameter for seven showers.
differing number of points on these graphs appears shortly. Figure 68 graphs all nine points and includes the curve fitted to Figure 46; however, two points fall notably below the curve. The data which compose these points (cases 8 and 9) come from the center of the showers—in other words, data collection began after the shower had and ended before the shower concluded. To check the possibility that the portion of the shower which produced the observed data affects the relation between the average mean drop diameter and the height of the mean echo top, data were purposely extracted solely from the center portion of the five complete showers (cases 1 through 5) in order to determine whether they would lie below that collected from a possible shower. If this possibility exists then these five points should lie on a new curve below the original curve and also in line with the points under examination. Figure 69 shows the nine points plotted in Figure 67 plus the five points extracted as described above. Generally speaking, these points lie below the original curve but still do not fall on a curve with the two points under examination.

Additional study of these two cases reveals that the lateral edge of the shower passed over the observation point in both cases. In the seven other cases, however, the center third of the shower passed over the observation point. It appears that a correlation between radar echo parameters and drop-size parameters would be difficult to make near the edge of a shower and therefore these two
Figure 69. Height of mean echo top versus average mean drop diameter for nine showers plus the center portion of five complete showers.
cases were not included in the remainder of the analysis. A possible reason for the difficulty arises because the radar will indicate the actual height of the edge of the shower, but the drop-size data may be altered by wind sorting.

Figures 70-72 present the mean of the parameter

$$(D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_{5})$$

for each case plotted on the horizontal axes and the mean height of the echo top, the average mean echo intensity, and the average mean gradient of intensity for each shower plotted on the vertical axes. A tendency appears for a relationship between

$$(D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_{5})$$

and the average mean echo intensity. A poorly defined relationship also occurs between this drop-size parameter and the average mean gradient of intensity.

Figures 73-75 present the mean range for each shower plotted on the horizontal axes, and the average mean echo intensity, average mean echo gradient, and the height of the mean echo top for each case plotted on the vertical axes. A tendency arises in Figure 73 for a relationship between mean range and average mean echo intensity.
Average Mean Gradient of Intensity (watts/1000 ft) versus $\frac{(D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_s)}{D_{50} + D_{10} + D_s}$.

Figure 70. Mean gradient of intensity versus $\frac{(D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_s)}{D_{50} + D_{10} + D_s}$. 
Figure 71. Mean height of the echo top versus the mean of
\( (D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_{5}) \)
Figure 72. Average mean echo intensity versus the mean of 
\[ \text{Mean of } (D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_{5}) \]
Figure 73. Average mean echo intensity versus mean range of drop sizes for seven showers.
Seventh point located at 79-1.79

Figure 74. Average mean echo gradient versus mean range of drop sizes for seven showers.
Figure 75. Mean echo height versus mean range of drop sizes for seven showers.
Examination of the Drop-Size Parameters with Respect to Days and Location

This section examines the effects which different synoptic conditions and different locations impose on mean drop diameters and the range of drop sizes. Table 6 summarizes the data for the mean diameter and for the range of diameters. Application of Student's $t$-test using the hypothesis that $\mu_n = \mu_m$ ($\mu$ equals the population mean of the parameter being tested) for the differences between two means yields

$$
t = \frac{\bar{X}_n - \bar{X}_m}{\sigma \sqrt{\frac{1}{N_n} + \frac{1}{N_m}}}
$$

where

$$
\sigma = \sqrt{\frac{N_n S_n^2 + N_m S_m^2}{N_n + N_m - 2}}
$$

$N_n$ = number of observations in $n$

$\bar{X}_n$ = sample mean of $n$

$S_n^2$ = variance of $n$

The subscripts $n$ and $m$ indicate the two means under examination.

Table 7 presents the calculated values of $t$. 
Table 6. Data used in Student's t-test.

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Diameter (μ)</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 15 May</td>
<td>2</td>
<td>.45</td>
<td>15</td>
<td>0.0058</td>
<td>0</td>
</tr>
<tr>
<td>2) 15 May</td>
<td>4</td>
<td>.38</td>
<td>29</td>
<td>0.0103</td>
<td>0</td>
</tr>
<tr>
<td>3) 31 May</td>
<td>2</td>
<td>.45</td>
<td>18</td>
<td>0.0099</td>
<td>0</td>
</tr>
<tr>
<td>4) 31 May</td>
<td>4</td>
<td>.40</td>
<td>10</td>
<td>0.0157</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Range of Diameter

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Diameter (μ)</th>
<th>Variance</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) 15 May</td>
<td>2</td>
<td>1.78</td>
<td>15</td>
<td>0.28</td>
<td>0</td>
</tr>
<tr>
<td>2) 15 May</td>
<td>4</td>
<td>1.13</td>
<td>29</td>
<td>0.35</td>
<td>0</td>
</tr>
<tr>
<td>3) 31 May</td>
<td>2</td>
<td>1.83</td>
<td>18</td>
<td>0.19</td>
<td>-.40</td>
</tr>
<tr>
<td>4) 31 May</td>
<td>4</td>
<td>0.80</td>
<td>10</td>
<td>0.46</td>
<td>.74</td>
</tr>
</tbody>
</table>

1 See Appendix E for explanation of locations.

2 The mean diameter equals the average derived from all data collected at each location on each date.

3 Pearson's first coefficient of skewness given by

\[
\text{skewness} = \frac{\text{mean} - \text{mode}}{\text{standard deviation}}
\]

For a normal curve Pearson's first coefficient of skewness equals 0.

4 Moment coefficient of kurtosis given by

\[
a_4 = \frac{M_4}{S^4}
\]

where \( S^4 = \text{standard deviation to the fourth power} \)

\[
M_4 = \frac{\Sigma(X - \bar{X})^4}{N}
\]

\( X = \text{the observation value} \)
\( \bar{X} = \text{the mean value} \)
\( N = \text{the number of observations} \).

For a normal curve the moment coefficient of kurtosis equals 3.
Table 7. Hypothesis and conclusion from Student's t-test.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>t</th>
<th>$t_{.975}$ to $t_{.975^{*}}$</th>
<th>Conclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_1 = \mu_2$</td>
<td>2.34</td>
<td>-2.13--2.13</td>
<td>reject</td>
</tr>
<tr>
<td>$\mu_1 = \mu_3$</td>
<td>---</td>
<td>---</td>
<td>accept</td>
</tr>
<tr>
<td>$\mu_1 = \mu_4$</td>
<td>2.25</td>
<td>-2.23--2.23</td>
<td>reject</td>
</tr>
<tr>
<td>$\mu_2 = \mu_3$</td>
<td>2.34</td>
<td>-2.10--2.10</td>
<td>reject</td>
</tr>
<tr>
<td>$\mu_2 = \mu_4$</td>
<td>---</td>
<td>---</td>
<td>accept</td>
</tr>
<tr>
<td>$\mu_3 = \mu_4$</td>
<td>2.25</td>
<td>-2.23--2.23</td>
<td>reject</td>
</tr>
<tr>
<td>$\mu_1 = \mu_2$</td>
<td>3.60</td>
<td>-2.13--2.13</td>
<td>reject</td>
</tr>
<tr>
<td>$\mu_1 = \mu_3$</td>
<td>---</td>
<td>---</td>
<td>accept</td>
</tr>
<tr>
<td>$\mu_1 = \mu_4$</td>
<td>6.30</td>
<td>-2.23--2.23</td>
<td>reject</td>
</tr>
<tr>
<td>$\mu_2 = \mu_3$</td>
<td>4.70</td>
<td>-2.10--2.10</td>
<td>reject</td>
</tr>
<tr>
<td>$\mu_2 = \mu_4$</td>
<td>1.57</td>
<td>-2.23--2.23</td>
<td>accept</td>
</tr>
<tr>
<td>$\mu_3 = \mu_4$</td>
<td>---</td>
<td>---</td>
<td>reject</td>
</tr>
</tbody>
</table>

At the 95 percent confidence level utilization of Student's t-test produces the following results for the mean drop diameters:

\[
\mu_1 \neq \mu_2 \quad \mu_2 \neq \mu_3
\]

\[
\mu_1 = \mu_3 \quad \mu_2 = \mu_4
\]

\[
\mu_1 \neq \mu_4 \quad \mu_3 \neq \mu_4
\]

Student's t-test employed at the 95 percent confidence level gives the following results for mean ranges of the drop diameters:
These equations reveal that the mean diameter and the range of the diameters of drops collected at location 2 (see Appendix E) on 15 May equal the mean diameter and the range of drop diameters collected at location 2 on 31 May. In addition, the mean and range of drop diameters collected at location 4 on 15 May equal those collected at location 4 on 31 May. This means, therefore, that under two different synoptic situations (see section 9) the mean drop diameters appear identical for the same location.

However, a significant difference arises between the mean and the range of drops collected at location 2 and the mean and the range of drops collected at location 4 for both dates. The larger mean and range occurred at location 2. Since location 2 lies in the eastern hills of the Coast Range, the air above it may be more turbulent than that over location 4, in the level valley. A drop held in the air by turbulence has more time to grow through coalescence. It would seem reasonable to assume, therefore, that turbulence keeps drops in the air longer at location 2 than at location 4, thereby giving them more time to grow.

\[
\begin{align*}
\mu_1' &= \mu_2' \\
\mu_1' &= \mu_3' \\
\mu_1' &\neq \mu_4'
\end{align*}
\]
Comparison of Each Minute of Drop-Size Data with Each Minute of Radar Data

Another interesting relationship may appear between each minute of drop-size data and each minute of radar data. In this instance, however, a major problem occurs. One must remember that a one-minute average of the drop-size data gathered at the ground was viewed sometime earlier by the radar. The researcher must therefore account for a certain time lag in comparing the radar data with the drop-size data. This time lag occurs as a function of (1) the diameter of the drops and (2) the height at which drop formation takes place, assuming no vertical air motion.

Attempting to determine the time lag from these two factors presents more difficulties. First, in specifying the drop diameter a question arises in deciding just which diameter to choose from the wide range of drop sizes. In addition, the diameter of the drop changes continuously as it falls. Secondly, the impossibility of determining the exact height at which drop formation occurs precludes any adequate definition of this factor.

Assume, however, that one may select the mean drop diameter as the proper drop diameter and the point half-way between the echo top and the ground as the height of rain formation. Assume further a fairly realistic situation with an echo height of 4,000 meters and a mean drop diameter of 0.4 millimeters. Figure 76 shows that it
Figure 76. Time required for various size drops to fall any distance.
will take 21 minutes for a mean-size drop to fall from the middle of the echo to the ground. In other words, the time lag equals 21 minutes, and the researcher must therefore compare the drop-size data to the radar echo as it appeared 21 minutes earlier. Unless the wind happens to blow parallel to the line between the radar and the observer, the radar probably will not be viewing that part of the cloud which releases those drops which strike the recorder. These problems may be one of the reasons for the poor relationship between the computed Z-R equations and the observed reflectivity.

Because of the many difficulties in general, and the large time lag in particular, this study did not attempt a comparison of drop-size data with each minute of radar data. By taking the mean of the parameter throughout the entire passage of the shower, however, elimination of several of these problems results. This appears particularly true for showers which approach a steady-state condition.
CONCLUSIONS

The limited number of cases examined in this study prevents drawing any definite conclusions. However, the cases considered indicate the following tendencies:

1. If one requires only a parameter such as mean drop diameter for an entire shower, it does not appear necessary to sample continuously. Approximately ten samples collected in the shower prove sufficient to calculate this value accurately. However, the need to obtain minor fluctuations which occur throughout a shower requires continuous gathering of data.

2. For the five showers investigated no systematic change occurs in the number of drops 0.2 millimeters and smaller per minute throughout each shower. The ratio of the total number of drops 0.2 millimeters in diameter and smaller per minute to the total number of drops per minute plotted against time yields one feature in common for all five cases examined: the ratio always increases at the end of the shower. A study of the change in the maximum drop diameter per minute with time reveals no systematic variation. Furthermore, no consistent change occurs with time for the reflectivity, Z, and the rainfall intensity, R. An examination of the mean drop diameter for each minute of data displays a tendency toward a relationship between the average mean drop diameter and the mean echo top and between
the variance of the mean drop diameter and the mean echo top. No correlation appears between either the mean maximum drop diameter and the mean echo top or between the variance of the maximum drop diameter and the mean echo top. The constants in the $Z-R$ relationship exhibit no relationship with the height of the maximum echo, the average number of maximum intensity areas, the mean average gradient of the echo, the variance of the mean drop size, the average mean drop size, or with the height of the mean echo top.

3. In seven rainshowers examined, a tendency occurs for a relationship between the average mean drop diameter and the height of the mean echo top. The average mean drop diameter displays no correlation with either the average mean echo gradient or the average mean echo intensity. A tendency appears for a relationship between

$$ (D_{\text{max}} - D_{\text{min}})(D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_{5}) $$

and the average mean echo intensity. In addition, a poorly defined relationship arises between this parameter and the average mean gradient of intensity. The mean range of the drop diameters manifests a tendency toward a correlation with the average mean echo intensity. No relationship occurs between the mean range and either the average mean echo gradient or the height of the mean echo top.

4. Under two different synoptic situations the mean drop diameter and the range of the drop diameters appear equal at the same
locations. However, a significant difference arises between the mean and range of the diameters collected in the hills and those collected in the valley.

5. The attempt to compare each minute of drop-size data with each minute of radar data presents a great many problems, chief among them being the determination of the length of time it takes for a drop to fall from a cloud.
RECOMMENDATION FOR FURTHER RESEARCH

This author feels that two main results appeared from this study:

(1) development of an accurate and easy to use raindrop recorder,
and (2) introduction of several possible relationships derived from
data collected with this recorder. Further study with the ASB re-
corder should include the following:

1. Further examination of the relationship between average
mean drop diameter and the mean height of the echo top.

2. Additional study of the relationship between variance of the
mean drop diameter and the mean height of the echo top.

3. Investigation of the relationship between average mean echo
intensity and mean range of drop sizes.

4. Further study of the relationship between average mean
echo intensity and the mean of the parameter

\[ (D_{\text{max}} - D_{\text{min}}) \left( D_{1000} + D_{500} + D_{100} + D_{50} + D_{10} + D_5 \right) \]

5. Additional investigation of the differences in average mean
drop diameters and average range of the diameters at different loca-
tions and under different synoptic conditions.

If the tendencies for the relationships examined in this study
receive confirmation in new evidence, a significant step forward in
the "characterization of precipitation by radar" will have resulted.


APPENDIX A

CALIBRATION OF THE ASB RAINDROP RECORDER

Any raindrop recorder which utilizes the "filter-paper" technique requires the observer to derive a relationship relating drop diameter to spot diameter. A relationship derived experimentally has proven successful.

Experimental Procedure for Large Drops

A number 27 hypodermic needle and a 50 milliliter burette produce drops of a size useful for this experiment. Gunn and Kinzer (1949) show that drops in this size range must fall about 30 feet before they reach terminal velocity. Therefore, the calibration procedure for large drops requires the use of a stair well.

A plastic container four inches in diameter and four inches high collects the falling drops. Splashing appears reduced by placing a circular sponge about one-half inch thick in the bottom of the container. In addition, a tight-fitting cover eliminates most of the evaporation from the container.

Use an analytical balance to weigh the container and the full hypodermic needle. Clamp the full needle in place with a burette holder. The container, with its lid removed, occupies a
Drop from burette

Drop from No. 27 needle

Drops sprayed from needle

Figure 77. Spots made by different size drops.
predetermined spot 30 feet below the needle. Placing the needle in a vertical position causes the plunger, by its weight alone, to force drops out the needle at a frequency of about one per second. The collection of about 200 drops appears sufficient. Replacing the container's lid, reweighing the container plus the 200 drops collected and reweighing the needle, permit determination of the volume, and therefore the diameter, of the drops. Use this same procedure for the burette with the exception that, rather than weighing the burette before and after, measure the volume of water directly.

Because the container sits for several minutes with the lid off while the drops fall into it, evaporation may occur. By saturating the sponge in the container with water and placing the container on the analytical balance, rate of evaporation may be calculated. Observations of the change in weight from minute to minute provide data for the construction of a graph of weight versus time. Recording the length of time the lid remains off the container allows the application of a correction factor to the raw data. This identical procedure, conducted with the lid on the container, produced no change in weight. Therefore, when the lid remains on the container, no appreciable evaporation occurs.

Results

This experiment determines two parameters: (1) the size of
drops produced by a number 27 needle and a burette, and (2) the amount of evaporation which occurs from drops of these sizes in a fall of 30 feet.

A number 27 needle yields a drop 2.2 millimeters in diameter, which in turn makes a spot nine millimeters in diameter on the ozalid paper. In a fall of 30 feet a 2.2 millimeter drop decreases by not more than four percent through evaporation. Five trials of 200 drops per trial produced these results.

The burette produces a drop 4.3 millimeters in diameter which causes a spot 24 millimeters in diameter to appear on the filter paper. A drop 4.3 millimeters in diameter decreases in size by no more than one percent through evaporation in a fall of 30 feet. Six trials of 200 drops per trial yielded these results. Throughout all these measurements the relative humidity remained between 70 and 75 percent.

**Experimental Procedure for Small Drops**

Production of drops smaller than two millimeters requires spraying water from a number 27 needle held in a horizontal position. Applying a constant pressure to the plunger produces the spray. Drops produced by this method need fall only about three meters in order to reach terminal velocity (Gunn and Kinzer, 1949).

In order to measure the size of drops sprayed from the needle,
a container sits in line with four circular pieces of filter paper all cut to the same diameter as the container. Two pieces of paper occupy positions on either side of the container. Position the needle in line with the papers and container, and about ten feet away from them.

The container in this part of the experiment did not have a tight-fitting cover. Observations of changes in weight with changes in time, with the lid both on and off, allowed the construction of evaporation curves similar to the curve previously described.

Water sprayed from the needle falls both in the container and on the surrounding papers. Interpolations from the number of drops on the papers yield the number of drops striking the container. Ascertaining changes in the container's weight (plus the correction factor due to evaporation) and the number of drops permits computation of the volume, and therefore the diameters, of the drops.

Results

The experiment described above produced drops 0.56 millimeters and 0.64 millimeters in diameter. These drops make spots 1.5 millimeters and 2.0 millimeters in diameter respectively.
APPENDIX B

CALCULATION OF PARAMETERS FROM RADAR DATA

A description of the analysis of radar data from the 16 millimeter film appears in section 8. These analyzed data resulted in the determination of five parameters: (1) the height of the echo top, (2) the height of the maximum intensity, (3) the number of maximum intensity areas, (4) the average gradient of the echo intensity, and (5) the average echo intensity.

The Height of the Echo Top

Determination of the height of the echo top comes directly from the analyzed data with the gain setting at a maximum. Estimation of height occurs to the nearest 500 feet.

Height of the Maximum Intensity

The analyzed data also directly indicate the height of the maximum intensity. The height of the lowest part of the maximum intensity area equals the height of the maximum intensity. If two or more areas of high intensity appear, and if these different areas have equal intensities, then the lowest one equals the level of maximum intensity.
Calculating the number of maximum intensity areas requires the construction of a graph for each sequence of steps in the step-gain control. The analyzed film yielded the necessary data for the graph of height versus intensity. For this construction, take the echo intensity at each 1000 feet and enter it on the graph. This results in a vertical zig-zag line from which the number of maximum intensity areas appears readily.

Average Echo Intensity

The graph previously described also presents the average echo intensity. Summed and divided by the total number of levels, the intensity at each 1000-foot level equals the average echo intensity.

Average Gradient of Echo Intensity

Establishing the average gradient of echo intensity entails the construction of another graph for each sequence of steps in the step-gain control. This graph plots height on the vertical axis and gradient of intensity on the horizontal axis. Calculation of the gradient of intensity from the analyzed film requires determining the change in intensity for each 1000 feet; this value equals the gradient of intensity in the 1000-foot interval. Plotted on the graph for each 1000
feet this value presents a graph of gradient of intensity with respect to the height. Summing the gradients for each 1000 feet and then dividing by the number of intervals results in the average gradient for the entire echo. A graph of this type also reveals immediately the areas of maximum gradients.
APPENDIX C

CALCULATION OF PARAMETERS FROM DROP-SIZE DATA

This study uses the calculation of reflectivity, Z, rainfall rate, R, the mean diameter, and the range of the diameters for each minute of data. One can easily calculate the range from

\[ \text{Range} = D_{\text{max}} - D_{\text{min}} \]

where

\[ D_{\text{max}} = \text{maximum drop diameter} \]
\[ D_{\text{min}} = \text{minimum drop diameter} \]

The mean drop diameter equals

\[ \sum_{j=0.02} C_j D_j/N \]

where \( C_j \) equals the number of raindrops having diameter \( D_j \) and \( N \) equals the total number of drops.

A simple computation of \( Z \) and \( R \) from the drop-size data results from a consideration of the following theory.

The fall velocity of raindrops varies with the size of the raindrop, and one must take this into account when determining the number of drops having diameters \( D_i \) per unit volume. A raindrop with a terminal velocity \( v_i \) falls a distance \( d \)
\[ d = v_i t \]
during time \( t \).

If only one drop falls on a given horizontal area \( A_w \) in time \( t \), the volume enclosing that one drop equals

\[ V = A_w d = A_w v_i t \]

If \( N_i \) number of drops strike the area \( A_w \) during time \( t \), the number of drops per volume appears as

\[ \frac{N_i}{V} = \frac{N_i}{A_w v_i t} \]

Since the reflectivity, \( Z \), equals the sixth power of the diameter of all raindrops in a unit volume, one can approximate this value by employing the numbers \( C_j \) of raindrop spots having diameters \( D_j \) for each 0.1 millimeter interval for drops 0.2 millimeters in diameter to the largest. In addition, one must use the window area \( A_w' \), the terminal velocity \( v_i \) of the raindrops having diameters \( D_j \), and the time between marks on the filter paper \( t \).

\[ Z = \sum_{j=0.2}^{C_j D_j^6} \left( \frac{A_w D_j}{v_i} \right) \]  

(1)

Raindrop spots on the filter paper also make possible the calculation of rainfall intensity, \( R \). This value equals the volume of rain falling on a given area per unit time.
\[ R = \frac{\text{Volume of Rain}}{A_w t} \]

Assuming a spherically shaped raindrop, the volume of a raindrop with diameter \( D_i \) equals

\[ \text{Volume of Rain} = \frac{\pi D_i^3}{6} \]

Approximation of the rainfall intensity results from using the numbers \( C_j \) of raindrop spots having diameters \( D_j \), the window area, and the length of time between marks on the filter paper.

\[ R = \sum_{j=0.2} \frac{\pi D_j^3 C_j}{6A_w t} \quad (2) \]

Relationships (1) and (2) as well as the relationships for determining mean and range convert readily to a computer program. This program, written in Fortran IV language and run on Oregon State University's CDC 3300, produced the values of \( Z \), \( R \), mean diameter, and range of diameters required for this study.
APPENDIX D

CALCULATION OF Z-R RELATIONSHIPS

This study entailed computing the Z-R relationship for the five complete cases examined (Cases 1 through 5). The Z-R relationship appears in the form

\[ Z = bR^a \]  \hspace{1cm} (1)

where

- \( Z \) = reflectivity
- \( R \) = rainfall rate
- \( a, b \) = constants which depend on the slope and position of the Z-R curve.

The method of calculation described in Appendix C yielded values of \( Z \) and \( R \) for each minute of data. When plotted on log-log paper, these values fall in a straight line. By determining the slope of this line, \( a \) may be calculated.

\[ a = \frac{\log Z_2 - \log Z_1}{\log R_2 - \log R_1} \]

In examining relationship (1), it appears that

\[ \log Z = a \log R + b \]
If $\log R$ equals 0, then

$$b = \log Z$$

The $\log R$ equals 0 when $R$ equals 1; therefore, $b$ may be read directly off the graph at the intersection of $R$ equals 1 and the $Z$-$R$ curve.

Figures 78-82 present the $Z$-$R$ graphs for the five rainshowers having continuous data collection and show the $Z$-$R$ relationships for each case.
Figure 78. Z-R relationship for Case 1. \( Z = 260 \times R^{1.31} \).
Figure 79. Z-R relationship for Case 2. $Z = 92 R^{1.16}$. 
Figure 80. Z-R relationship for Case 3. $Z = 465 R^{1.76}$. 

$Z = \text{(mm}^6 \text{mm}^{-3})$
Figure 81. Z-R relationship for Case 4. $Z = 195 \ R^{1.60}$. 

$Z = \text{mm mm}^{-3}$

$R = \text{mm hr}^{-1}$
Figure 82. Z-R relationship for Case 5, \( Z = 285 R^{1.30} \).
APPENDIX E. TOPOGRAPHIC MAP OF THE CORVALLIS AREA SHOWING THE LOCATIONS OF THE OBSERVATION POINTS

Locations of Observation Points

1. Philomath
2. Wren
3. Pedee
4. Corvallis
5. Albany

1000
2000
3000
4000
5000
6000
7000
8000
9000
10000

Statute Miles
APPENDIX F

SUMMARY OF IMPORTANT DATA

Table 8. Data used in Figures 52-62.

<table>
<thead>
<tr>
<th>Case</th>
<th>No. of Max. Intensity Areas</th>
<th>Variance of Mean Diameter ($\times 10^{-4}$mm$^2$)</th>
<th>Mean Max. Diameter (mm)</th>
<th>Variance of Max. Drop Diameter ($\times 10^{-2}$mm$^2$)</th>
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<td>234</td>
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<td>1.7</td>
<td>30</td>
<td>1.16</td>
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<td>109</td>
<td>1.57</td>
<td>36.0</td>
</tr>
<tr>
<td>Case</td>
<td>Location*</td>
<td>Date</td>
<td>Time PST</td>
<td>Average mean drop diameter (mm)</td>
</tr>
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<td>-----------</td>
<td>-----------</td>
<td>----------</td>
<td>---------------------------------</td>
</tr>
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<td>0.51</td>
</tr>
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*See Appendix E.