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Effects of Numbers, Sizes and Crystal Structures on Measurements of Ice Hydrometeors

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13. ABSTRACT (Maximum 200 words)

Simulated measurements of assumed ice hydrometeor environments generate number-size distributions similar to those from insitu measurements even to the point of reproducing several inconsistencies often found in actual data.

This report describes the computer fabrication of ice hydrometeors composed of single columns and combinations of columns with random spatial orientation and the simulated measuring of those particles by PMS 1-D instruments. Varying effects on distribution shapes are demonstrated by using different assumptions of particle numbers and sizes. Efforts were concentrated on exploring the problems of deficient number counts in the first or first few classes of precipitation probe data, non-compatible number concentrations from the cloud and precipitation probes, and the apparent existence of a few large particles that are not consistent with the rest of the distribution.

This investigation indicates that the numbers, sizes, crystalline structures, and spatial positioning of hydrometeors may be the cause of these effects.

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Effects of Numbers, Sizes and Crystal Structure on Measurements of Ice Hydrometeors

1. INTRODUCTION

Measuring numbers and sizes of ice crystals has always been a difficult and frustrating task. However, the accurate description of ice hydrometeor environments continues to be important in a number of investigations such as those concerned with electromagnetic attenuation and missile erosion.

The early days of ice crystal measurements involved long tedious hours of counting particle imprints on coated glass slides and film or on aluminum foil that had been exposed to ice crystal populations. The introduction of the PMS instruments[1] in the early 1970's greatly simplified the acquisition of hydrometeor data by providing the means to electronically count and size airborne particles. These measurements produce number versus size distributions that describe particular hydrometeor situations. Thus, the problems associated with ice crystal determinations has now shifted from one of data gathering to one of data interpretation.

(Received for publication 27 March 1990)

[1] Knollenberg, R.G. (1970) The optical array: an alternative to scattering or extinction for airborne particle size determination, *J. Appl. Meteorol* **1**: 86-103.

Typical measurements of precipitable ice hydrometeors by a PMS one-dimentional probe (1-D) show the largest number concentration at some small particle size with the numbers decreasing as the sizes of the hydrometeors increase. When the numbers are plotted versus size in a semi-logarithmic format, that decrease is found to be systematic and can be approximated by a straight line. Thus, number versus size distributions may be described by exponential functions. This phenomenon was also found in measurements of rain and was first reported by Marshall and Palmer[2] in 1948. The similarities in the shapes of measured number density distributions, both liquid and ice, gives rise to the possibility that all precipitable hydrometeors may naturally exist in exponential form.

There have been however, several recurring inconsistencies in ice crystal data from the 1-D precipitation probe that are difficult to explain, especially for smaller-sized hydrometeors. For instance, although the major portions of those type distributions may be described by exponential functions, the first or first few class sizes frequently show deficient number counts.[3] One possible explanation is that evaporation may be the cause of the lesser number of smaller particles.

Another problem is non-conforming number counts in the larger-sized classes of precipitation that generally indicate concentrations larger than that predicted by the exponential trend formed by the majority of points.

Recurring disturbances are also present in the measurements recorded by the cloud probe. Plots of those number densities display many varied shapes and often have values in their larger-sized classes that do not conform with those from the rest of the distribution and/or with those from the precipitation measurements. Also, in many cases, there are disparities in the normalized numbers (that is, numbers per millimeter bandwidth) in the overlapping size region of the cloud and precipitation instruments.

Figure 1 is a number density plot that shows examples of the inconsistencies mentioned above. The data were recorded on 15 February 1979 at an altitude of 5562 meters and temperature of −29.2°C. The predominant crystal type was identified as being columns.

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2 Marshall, J.S. and Palmer, W.M. (1948) The distribution of raindrops with size, *J. Meteorol* 5:165-166.

3 House, R.A., Hobbs, P.V., Herzegh, P.H., and Parsons, D.B. (1978) Airborne measurements of the size distributions of precipitation particles in frontal clouds, *Conf. on Cloud Physics and Atmospheric Electricity*, Jul 31-Aug 4, Issaquah, Wash.

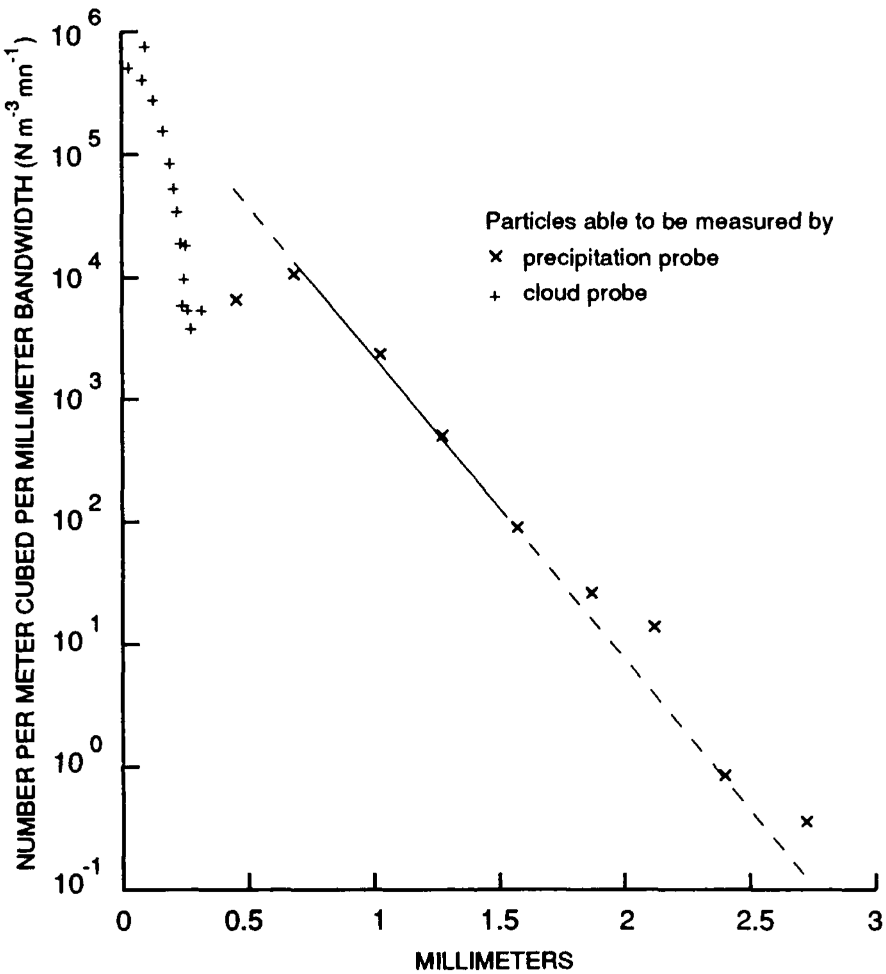

Figure 1. Processed PMS 1-D Data Taken on 15 Feb 1979 at an Altitude of 5562 Meters and Temperature of –29.2°C.

A study,[4] conducted in 1981, explored the measuring of various shapes of ice crystal forms by a PMS instrument. The data were simulated by specifying distributions of numbers and sizes and allowing each individual crystal to have a randomly-selected, spatial orientation. It was found that the measurements could be substantially different than those from the initial, actual distributions especially in cases of elongated crystalline structures.

The computer program used to fabricate single crystal measurements has since been expanded to allow the combining of individual crystals. The simulated data, in class sizes common to those of the PMS instruments, resulted in distributions similar in form to those

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[4] Berthel, R.O. (1981) *The Conversion of Aircraft Ice Crystal Measurements into Terms of Liquid Water Using Simulated Data*, AFGL-TR-81-0173, ADA106419.

from in-situ measurements. Different assumptions of crystal numbers and sizes were found to affect those distributions in varying degrees and could reproduce the inconsistencies cited above.

This report demonstrates the effects that numbers and sizes of both single and combinations of randomly oriented, cylindrical-columnar crystals may have on PMS 1-D measurements. It shows that measured number densities can vary because of crystal structure and concentration with the values, in some cases, having little resemblance to the sizes of the particles being sampled. This study is descriptive in nature only and does not delve into the conversion of ice hydrometeor measurements to equivalents of liquid water that are necessary for calculations of liquid-water contents. As such, it is just the first step in understanding the inherent complexities imbedded in measurements of irregular-shaped ice hydrometeors and for the subsequent interpretation of those measurements in the realistic definition of ice crystal environments.

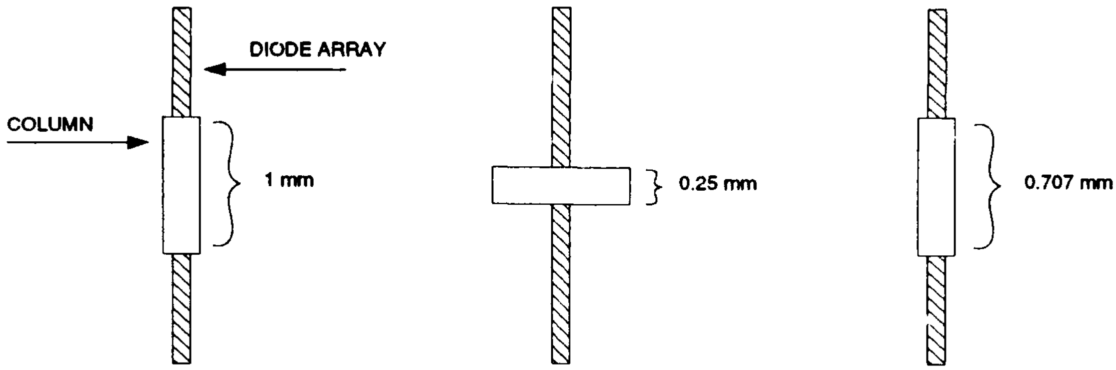
2. SIMULATED MEASUREMENTS

The data used in this investigation are composed of simulated measurements of columnar crystal forms of known numbers and sizes with PMS 1-D probes.

The 1-D instrument (simply stated) consists of a series of photodiodes illuminated by a laser. A hydrometeor passing through the sampling volume occludes one or more diodes thereby producing a measurement of one unspecified dimension that is referred to, in this report, as a shadow length or L_s. The output from the analyses of the 1-D data consists of the numbers of hydrometeors contained in 15 size classes with limits predetermined by instrument construction and calibration. In this investigation, the assumed measurements of the cloud probe spans the range from 0.01 to 0.31 mm in class widths of 0.02 mm. The precipitation probe covers 0.2 to 4.7 mm in class widths of 0.3 mm.

2.1 Single Crystals

The assumed ice crystals used in this study are solid columns with lengths (L) four times their diameters (D). If one were to look directly down upon such a falling column as diagrammed in Figure 2, the horizontal plane would be that of the page surface delineated by the x and y axes where the vertical plane is perpendicular to that surface, defined by the z axis. The diode array is assumed to be aligned with and below the paper's surface with the laser beam emanating from directly above. A column, with L=1 mm, passing through a 1-D instrument with its longitudinal axis aligned with the diode array in both the horizontal and vertical planes, as in Figure 2a, would result in a L_s measurement of the true length or 1 mm. If however, the column were rotated 90° in the horizontal plane as in Figure 2b, the L_s would be equal to D or 0.25 mm.



a. Column aligned with diode array in both horizontal and vertical.

b. Column of 1a rotated 90° in horizontal plane.

c. Column of 1a rotated 45° in vertical plane.

Figure 2. Diagrammatic Representation of the Measuring of a Column with a Diameter of 0.25 mm and Length of 1 mm in Three Particular Spatial Orientations.

The L_s is further affected by the crystal's orientation in the vertical plane as any degree of tilt of the column's longitudinal axis from that of the diode array in the z direction will result in a smaller shadow length as demonstrated in Figure 2c. The 1 mm column of Figure 2a, aligned with the diode array in the horizontal plane but now at an angle of 45° in the vertical, will give a L_s of 0.707 mm. Thus, a crystal's spatial orientation in both the horizontal and vertical planes has a direct effect on the measurement obtained with a 1-D type instrument.

This investigation assumes a hypothetical scenario where PMS probes are being flown through a known ice hydrometeor environment and are measuring a specific number of columns of defined sizes. Thus, the simulation of data begins with the specification of numbers and sizes of columnar crystals. Each column is then assigned a randomly selected angle to define the position of its longitudinal axis with respect to a probe's diode array. Ninety degrees of freedom are allowed in the horizontal plane and 45° in the vertical. Forty-five degrees of freedom in that plane are considered reasonable for environments of average wind-shear turbulence whereas 90° would represent severe conditions and tumbling crystals. The resulting L_s is then placed in the appropriate class-size category thereby mimicking the measuring of a crystal by a 1-D instrument.

Again, it must be emphasized that this investigation is intended to be descriptive only. No consideration has been given to instrument calibration, sampling times or aircraft speed. Therefore, the numbers cited in the simulated measurements will be in general terms (numbers per unit volume per probe bandwidth, $N\ V^{-1}\ bw^{-1}$).

Figure 3 shows the results of the fabricated measurements of 1000 single columns with L=1 mm in the class widths previously specified for the assumed 1-D probes and in a semi-logarithmic format common for number-density distribution plots. If each of these columns were precisely aligned with the 1-D's diode array, all of the 1000 measurements would have been contained in the third precipitation class (0.8 to 1.1 mm). Because of the crystal structure and random spatial position, just ~45 percent were recorded as being in that size range with the remainder being measured as smaller particles. Notice that some of the crystals were oriented in such a manner that the L_s values could also be measured by a cloud probe. The numbers and sizes shown in Figure 3, and in all the simulated measurements in this report, represent typical examples only, since random positioning will produce variations in separate simulations of identical crystals.

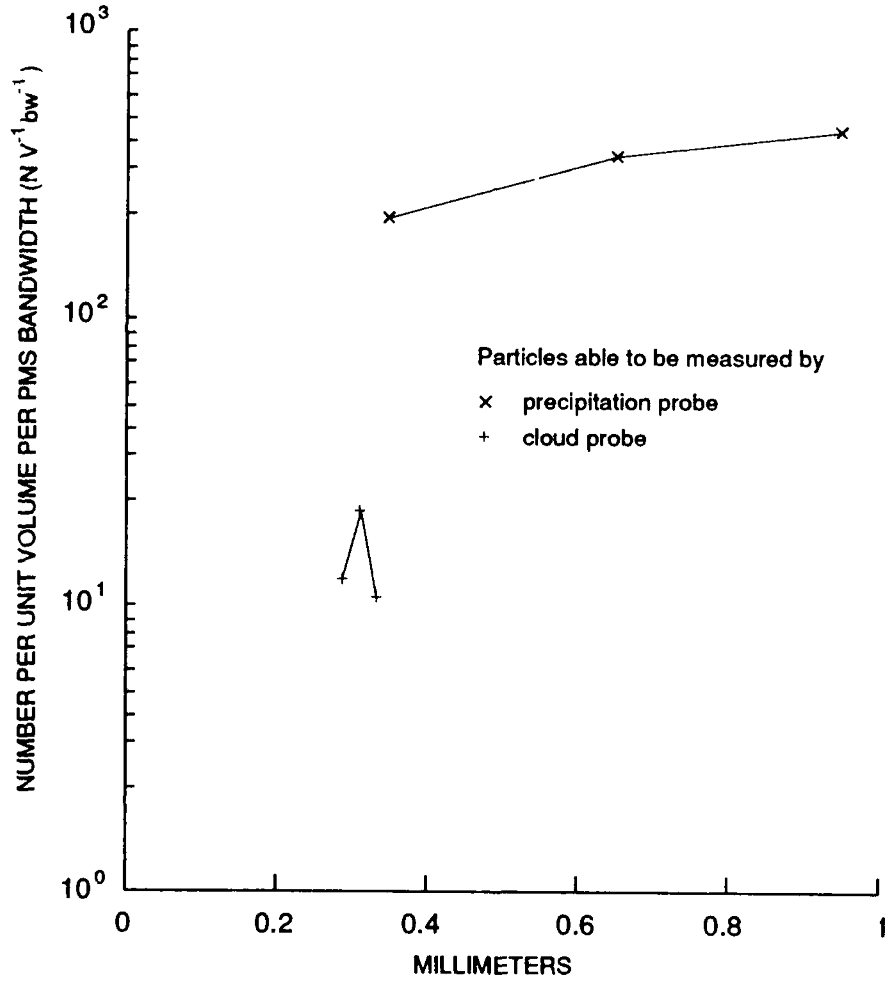


Figure 3. Simulated Measurements of 1000 Columns with Diameters of 0.25 mm and Lengths of 1 mm.

2.2 Combinations of Crystals

When the single columns described above are allowed to attach to one another in a random fashion, the resulting combinations display varying shapes from elongated chains to rosettes or tightly packed clusters. Figure 4 shows computer constructed combinations of 2, 3, 4, and 5 columns in several different configurations. Viewing these diagrams makes it easy to envision the myriad of measured sizes that may result from differences in crystal spatial orientation and position of attachment.

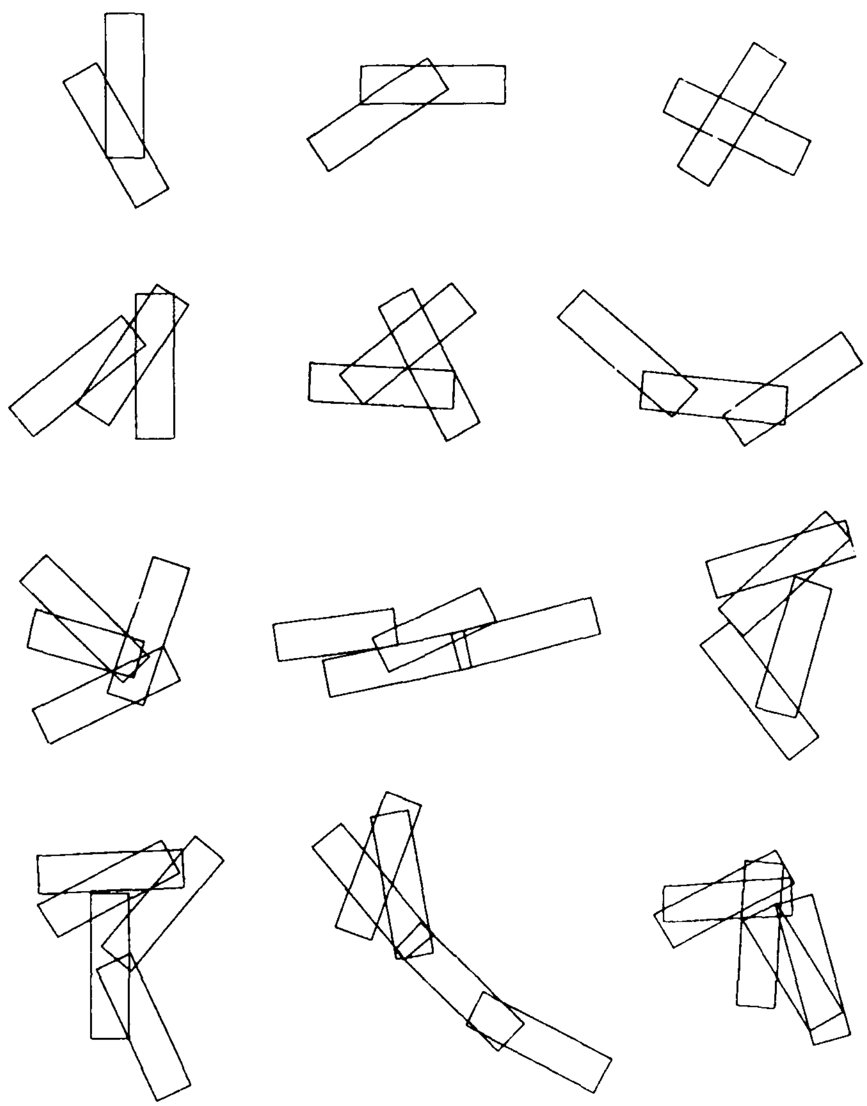


Figure 4. Computer Generated Examples of Combinations of 2, 3, 4, and 5 Columns.

Figure 5 shows the simulated measurements of 1000 of each of these combinations in the same semi-logarithmic plotting format as the single columns in Figure 3. The random selection of column positions and attachments tends to produce forms that approximate normal curves with both the peak number values and range of sizes increasing as the combinations become larger. Also, the numbers in the larger sized classes form general exponential shapes. There are no counts attributed to the cloud probe in these four cases although the possibility does exist for any one of these combinations to attain the necessary configuration and spatial orientation to fit into one of the last three classes of that assumed instrument.

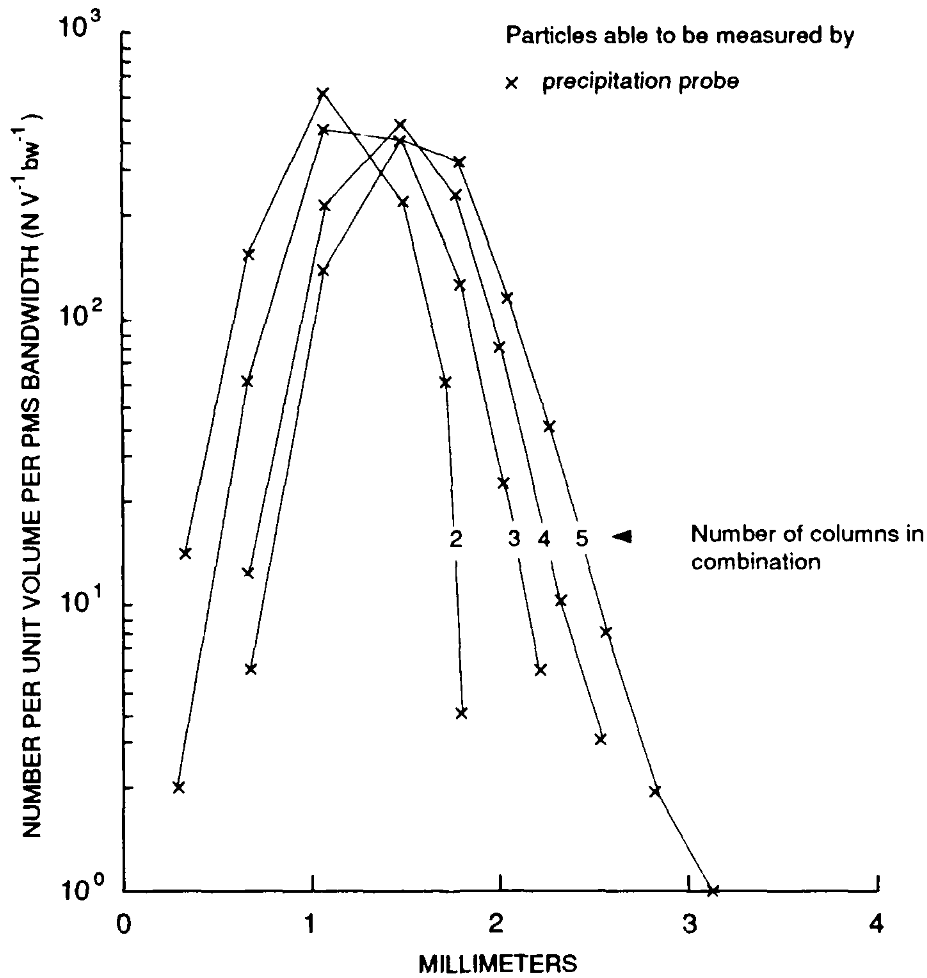


Figure 5. Simulated Measurements of 1000 of Each Combination of 2, 3, 4, and 5 Columns with 1 mm Lengths.

Five columns per combination are the maximum considered in this study as the mechanism of random adhesion used in this model tends to favor the stacking of crystals and produces "snowball" type structures from combinations consisting of larger numbers.

2.3 Mixtures of Single Columns and Combinations of Columns

Although measurements of small sized hydrometeors are sometimes conducted in environments consisting of all single columns or nearly identical combinations, it is more common to find singles coexisting with various combinations.

Specific populations of columns containing both single crystals and combinations may be defined by assigning numerical values to each hydrometeor category. This creates an assumed distribution that may be described mathematically where the concentration is a function of the number of columns making up a hydrometeor. However, it is desirable to describe the distribution in conventional terms of numbers versus sizes, except that the sizes of combinations cannot be specified because of uncertainties associated with the random attachment of crystals in the building of the hydrometeors. To overcome this ambiguity, the numbers of assumed hydrometeors are defined as exponential functions of their equivalent-melted diameters (D_e) or, in other words, the diameters of the spherical water drops resulting from the melting of the column or columns making up the hydrometeor. (The numbers and D_e sizes of the assumed particles subjected to simulated measurement will be designated by circles in all the following plots except in those cases where they are specified in the figure captions.)

When the numbers and sizes used in developing Figures 3 and 5 (1000 single columns and 1000 of each combination of 2, 3, 4, and 5 columns with L=1 mm) are assumed to exist as a mixture, the assumed distribution of hydrometeors forms an exponential slope (Λ) of zero. The simulated measurements of that mixture are shown plotted in Figure 6. The values in the precipitation classes display a general exponential shape for the latter portion of the distribution (as per the solid line in the figure) with the first four showing a deficiency in numbers with respect to the extrapolated exponential (dashed) line. The deviation from exponential shape is similar to but more pronounced than that normally observed in actual PMS measurements of ice crystals. The plot also shows a small number of counts in the latter three cloud probe classes similar to that of Figure 3.

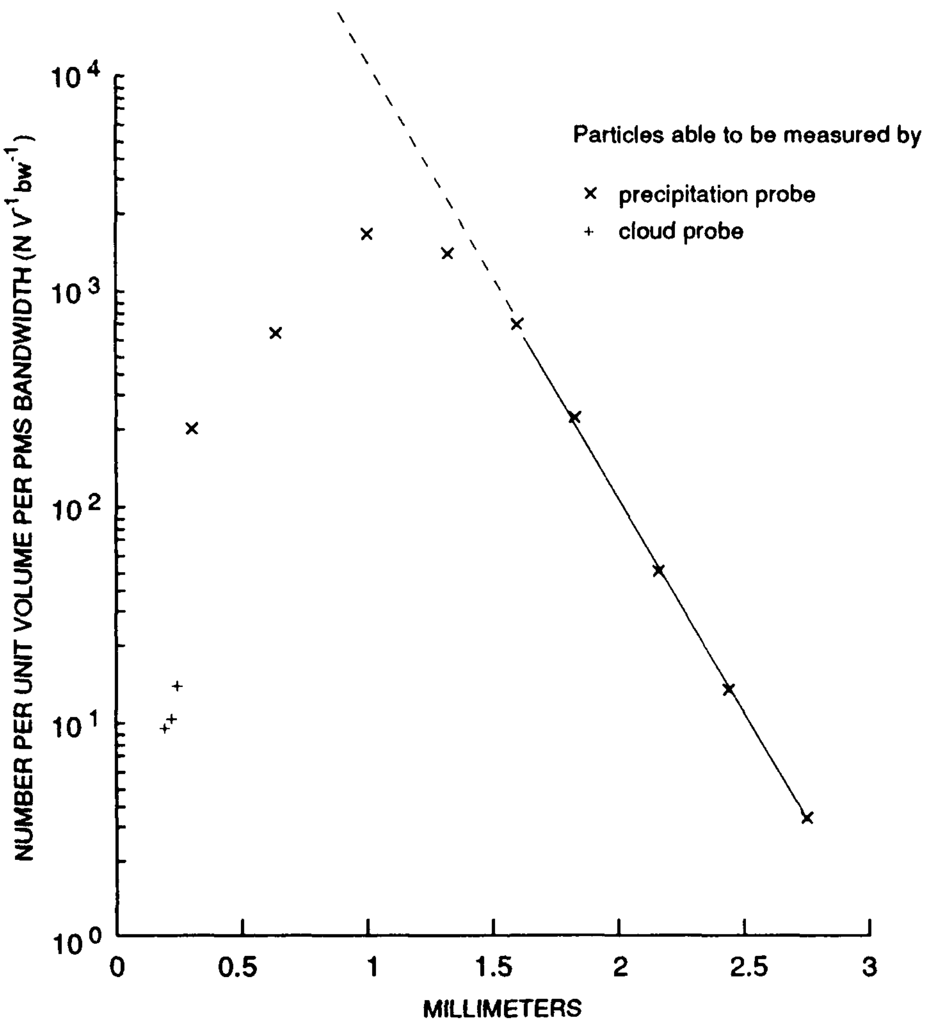


Figure 6. Simulated Measurements of an Assumed Distribution of 1000 Single and 1000 of Each Combination of 2, 3, 4, and 5 Columns with 1 mm Lengths.

3. EFFECTS OF CRYSTAL SIZE

When the L of the individual columns used in Figure 6 is changed to 0.5 mm and the same number of single and combinations of crystals are assumed to be measured, the plot of Figure 7 results. In this case, numbers are found in only five classes of precipitation with the last four being in exponential form. Although a difference still exists between the number in the first class and the extrapolated exponential line, the deficit is considerably less. The slope of the exponential line over the larger class sizes is also much steeper.

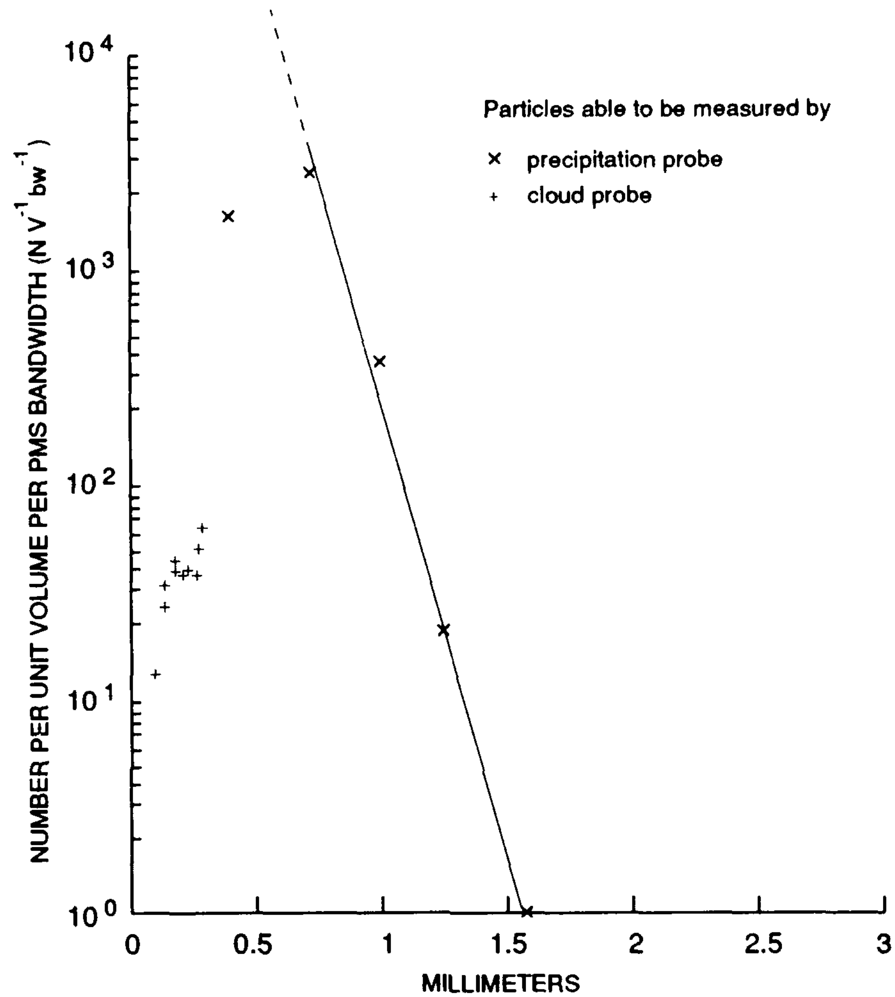


Figure 7. Simulated Measurements of an Assumed Distribution of 1000 Single and 1000 of Each Combination of 2, 3, 4, and 5 Columns with 0.5 mm Lengths.

Another outstanding feature is that the values associated with the cloud probe are considerably greater with counts in the latter 10 classes. The numbers c ntained in the first four of these classes (108) represent particles not included in the precipitation counts.

Simulated measurements from hydrometeors of columns with L's between 0.5 to 1 mm show that the numbers in the smaller-sized classes of the precipitation probe deviate further from the exponential lines as the columns become larger. Also, the slopes of the resulting distributions become more shallow with larger particle size.

4. EFFECTS OF RELATIVE-SIZE NUMBER CONCENTRATIONS

Variations in measurements caused by the relative numbers of different sized particles were explored using two scenarios. First, the number of assumed single columns was large with decending amounts as the crystals combined (negative exponential slope). Second, the number of singles was small with ascending amounts as the combinations grew larger (positive exponential slope).

Figure 8 shows the simulated 1-D measurements from an assumed hydrometeor distribution of single and combinations of 1 mm columns where numbers vs equivalent-melted diameters form a negative exponential slope of $-10\ mm^{-1}$. The last five classes follow a general exponential shape with the first two showing an abrupt, negative departure from the straight-line projection. The small number of counts in the last three classes of the cloud probe are again present as in Figure 6.

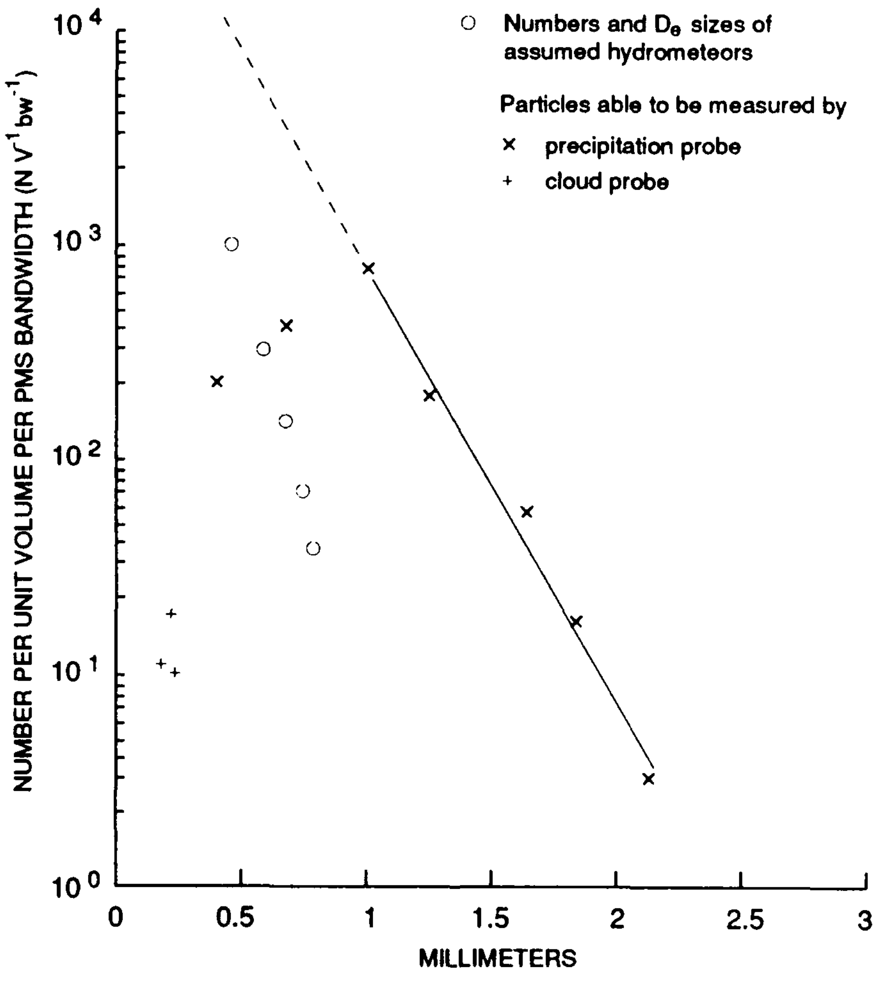


Figure 8. Simulated Measurements of an Assumed Distribution of Single and Combinations of 1 mm Columns Whose Numbers Versus Equivalent-Melted Diameters Form a $-10\ mm^{-1}$ Exponential Slope.

The plot of Figure 9 also exhibits an exponential trend in the latter four precipitation classes but over larger sizes. The initial assumed D_e distribution, in this case, was defined by a positive slope of 10 mm^{-1}. The first few classes however, display an exaggerated departure from the projected exponential line when compared to real data. Also, there are fewer counts in only two classes of the cloud instrument.

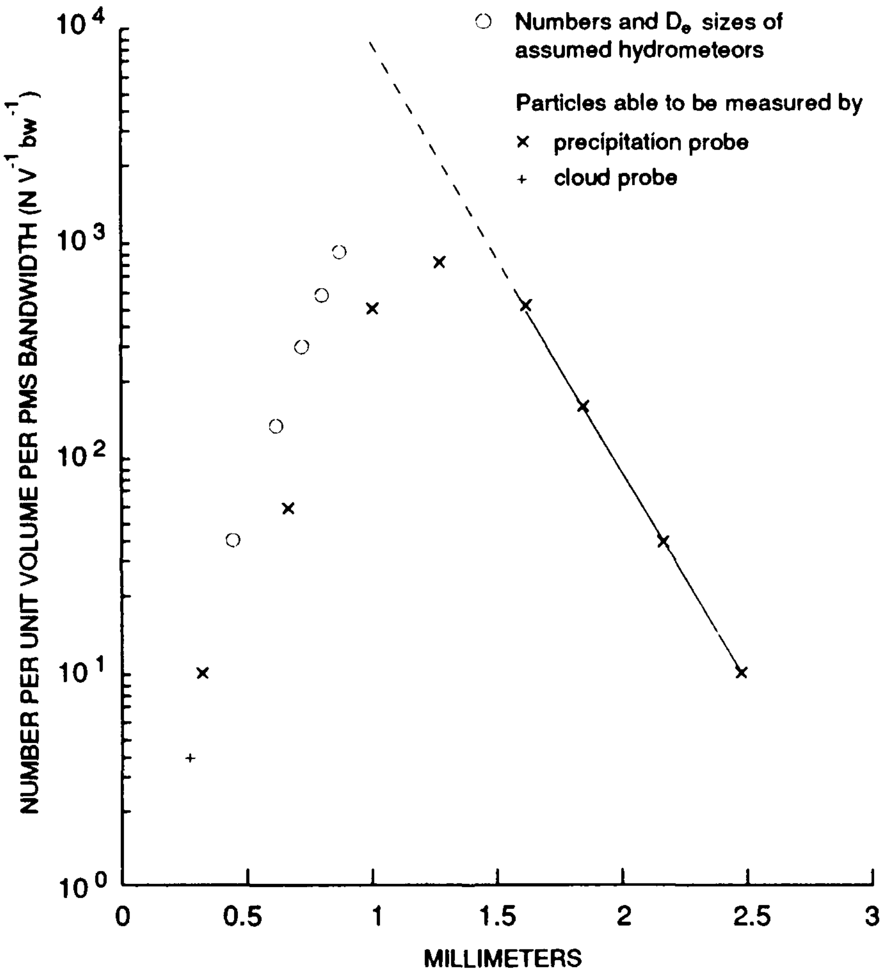


Figure 9. Simulated Measurements of an Assumed Distribution of Single and Combinations of 1 mm Columns Whose Numbers Versus Equivalent-Melted Diameters Form a 10 $^{-1}$ mm Exponential Slope.

It is interesting to note the similarities in the range of class sizes that form the exponential lines in the plot of Figure 6, which represents an initial distribution with zero slope, and Figure 9 with a slope of 10 mm^{-1}. The plot of Figure 8, with an initial slope of -10 mm^{-1}, forms a similar exponential but over a range of smaller sizes. It also shows more realistic numbers in the small classes.

Simulated measurement were also made on a relative-size, hydrometeor distribution of Λ=-10 mm^{-1} composed of columns with L=0.5 mm. The results are shown in Figure 10. When compared with Figure 7 where Λ=0 mm^{-1}, this plot shows the counts in the first precipitation class to be closer to the exponential projection. In fact, the counts in the first class of Figure 7 are smaller than that of the second, whereas the opposite is shown in Figure 10. The numbers in the latter three classes form an exponential nearly identical to the one in Figure 7 but over a smaller range of sizes. The cloud-sized counts are similar to Figure 7.

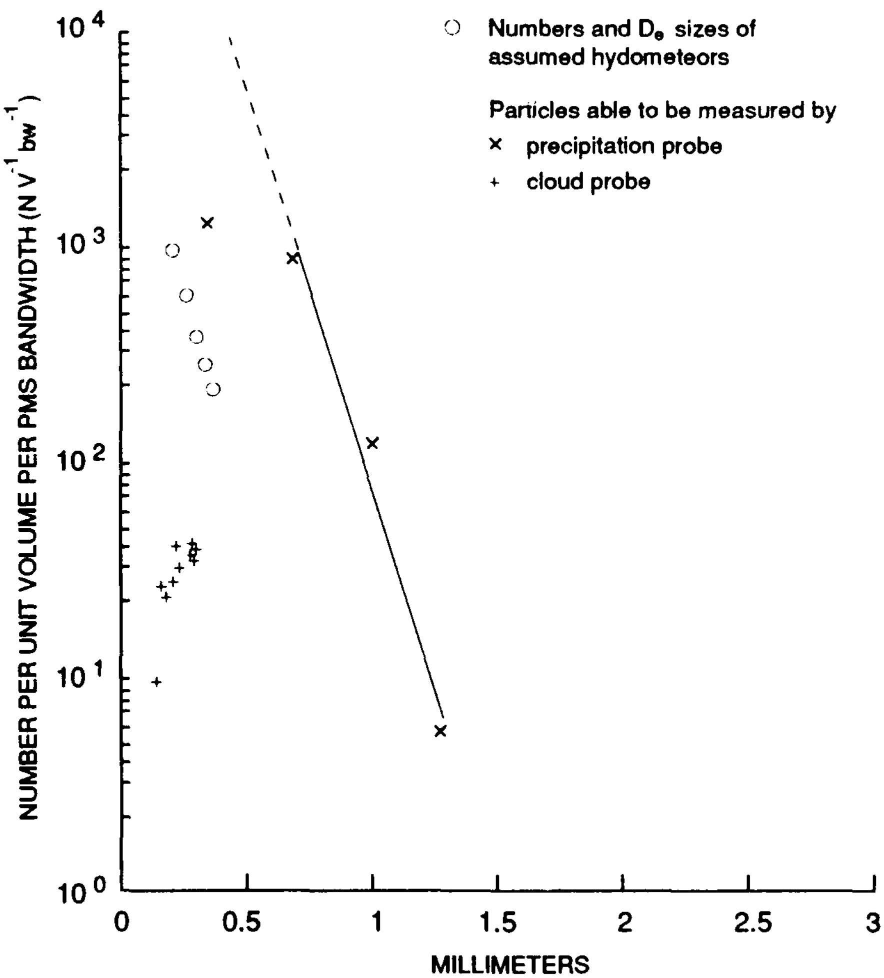


Figure 10. Simulated Measurements of an Assumed Distribution of Single and Combinations of 0.5 mm Columns Whose Number Versus Equivalent-Melted Diameters Form a -10 mm^{-1} Exponential Slope.

The distributions in Figures 6 through 10 indicate that the number deviations in the first and first few classes of the simulated precipitation data are dependent upon both the sizes and relative numbers of the small hydrometeors. The resulting slopes of the latter precipitation classes, on the other hand, seem only to be governed by larger hydrometeor sizes. Thus, any condition that affects the L_s sizes will cause a variance in slope. For example, adding combinations consisting of larger numbers of columns, hence larger hydrometeor sizes, will give lesser slopes while subtracting causes the opposite effect.

5. EFFECTS FROM A MIXTURE OF CRYSTAL SIZES

If a hydrometeor environment were composed of building blocks of different sized ice crystals, one would expect the measurements to display a mixture of the predominant characteristics of both the largest and smallest particles. Figure 11 shows the simulated measurements from a rough approximation of such a situation.

The initial distribution in this example was formulated from 0.5, 0.75, and 1 mm columns in singles and combinations as in the previous plots. The number versus D_e slope was assumed to be -10 mm^{-1} thus, the results of the simulated measurements may be compared to those plots that correspond to the largest (Figure 8) and smallest (Figure 10) column sizes.

In this case, the first precipitation class has slightly more counts than the second, very similar to Figure 10 but has a much smaller number discrepancy from the projected exponential line. This is because of the more shallow slope, approximately that of Figure 8. As expected, the number of particles with L_s sizes that could be measured with a cloud probe are similar to those of Figure 10.

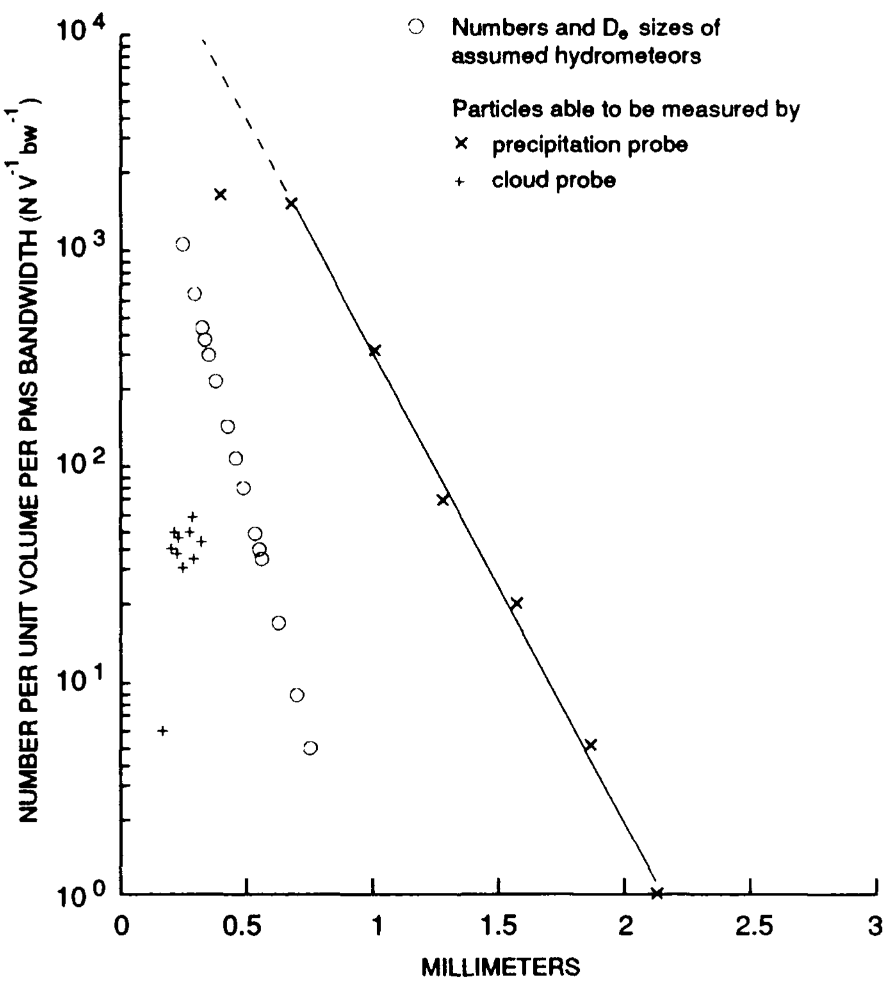


Figure 11. Simulated Measurements of an Assumed Distribution of Single and Combinations of Columns with 0.5, 0.75 and 1 mm Lengths Whose Number Versus Equivalent-Melted Diameters Form a $-10\ mm^{-1}$ Exponential Slope.

6. EFFECTS FROM SIMULTANEOUS HYDROMETEOR MEASUREMENTS

The inconsistencies normally present in the largest-sized measurements of the 1-D precipitation probe are apparently caused by a relatively small number of hydrometeors. Because the semi-logarithmic number versus size distribution plot has small counts in the larger-sized classes, the addition of one or two particles may cause a wide disparity from exponential shape. The random orientation of elongated ice hydrometeors may be an explanation, although this study indicates that a very low probability exists for the formation of such structures with the necessary spatial positioning. However, if it is possible for two hydrometeors to form a loose attachment and pass through the 1-D instrument simultaneously, then this phenomenon would be the anticipated result.

A simulation of this effect is shown in Figure 12. The X's in this plot are the simulated precipitation probe measurements from columns of L=0.7 mm with single crystals and combinations consistent with the previous plots. The initial D_e distribution has a slope of $-10\ mm^{-1}$. The line shows the exponential trend formed by the last four classes.

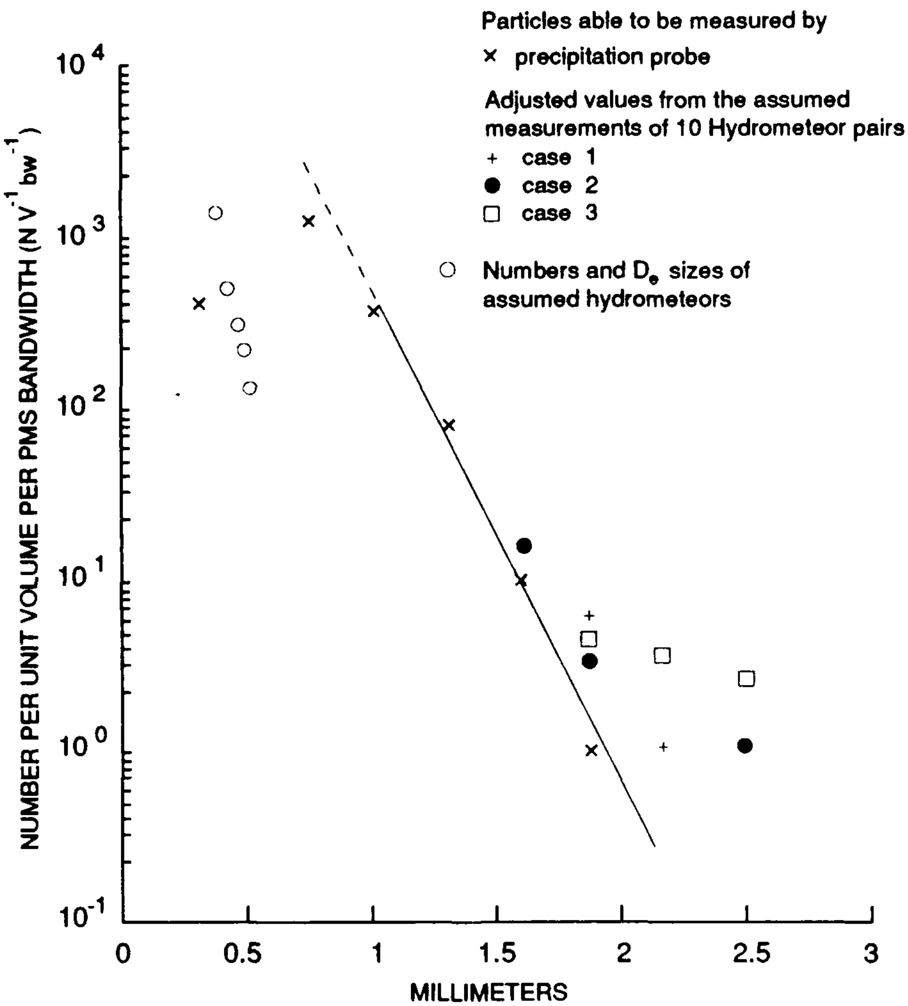


Figure 12. Simulations Showing the Possible Effects from Simultaneous Measurements of Hydrometeors.

Simultaneous measurements were simulated by randomly selecting 20 L_s values from this distribution, subtracting them from their classes and forming them into 10 pairs. The constituents of each pair were then assumed to be attached with new sizes equal to the sums of the individual L_s values. Classifying these combined particles thus produced an adjusted distribution with a net change in total number of just 10 hydrometeors or ~0.5 percent.

The results of three such adjustments displaying noticeable changes in the larger precipitation class sizes are plotted in Figure 12 and are designated by circles, squares and crosses. Distribution shapes similar to these, where the values of the larger precipitation classes deviate from the exponential, are not uncommon in PMS 1-D measurements (see Figure 1).

7. EFFECTS ON THE OVERLAPPING REGION OF THE CLOUD AND PRECIPITATION PROBES

The physical nature and random positioning of ice crystals may, as demonstrated for precipitable particulates in the preceding sections, affect the measurements from both the PMS cloud and precipitation probes. The severity of the effect is associated with hydrometeor shapes, and sizes of the particles and class widths of the measuring instrument. These phenomena may help to explain some of the inconsistencies observed in the overlapping size region of the cloud and precipitation instruments.

Figures 6-11 show that elongated particles, because of spatial positioning, may be placed in smaller class sizes than their lengths would indicate. Thus, a particular particle with a length normally associated with the precipitation probe may actually be recorded by the cloud instrument. Measurements from the cloud probe would also be affected in the same manner. In addition, although both probes would be exposed to the same hydrometeor environment during actual measurements, they would be sampling different particles of various shapes in different spatial positions. This adds another degree of uncertainty.

If measurements were made in an environment that contained ice spheres with sizes spanning both those of the cloud and precipitation probes, the measurements from the two probes, when "normalized" (divided by instrument bandwidth to give numbers per millimeter bandwidth), should form a smooth transition with number densities that accurately describe the hydrometeor population. If the ice spheres were changed to columns, the normalized values may be compatible but will not be true measurements of the hydrometeor numbers and sizes. Because of the uncertainties associated with measurements of different parcels of air with separate instruments and from random crystal attachment and spatial positioning, perfect compatibility should not be expected. This type situation would be found in generating cloud systems where ice crystals are being formed.

In non-generating cloud systems, smooth transitions in the measurements from the cloud and precipitation probes would be rare. The number density distributions from the cloud probe measurements may exhibit many varied shapes depending upon the individual populations of the cloud and unrelated precipitable hydrometeors.

An example of one possible effect is shown in Figure 13. In this scenario, the hydrometers producing the simulated measurements shown in Figure 10 are assumed to be falling through non-generating clouds. The X's are the normalized values from the precipitation probe. The normalized cloud probe values attributed to the assumed cloud hydrometeors are designated by the triangles. If the numbers of precipitable particles that were oriented such that they could be measured by a cloud probe were added to the assumed cloud hydrometeor values, the resulting normalized distribution would be that shown by the crosses. Distributions from in-situ measurements frequently show similar shapes (see Figure 1).

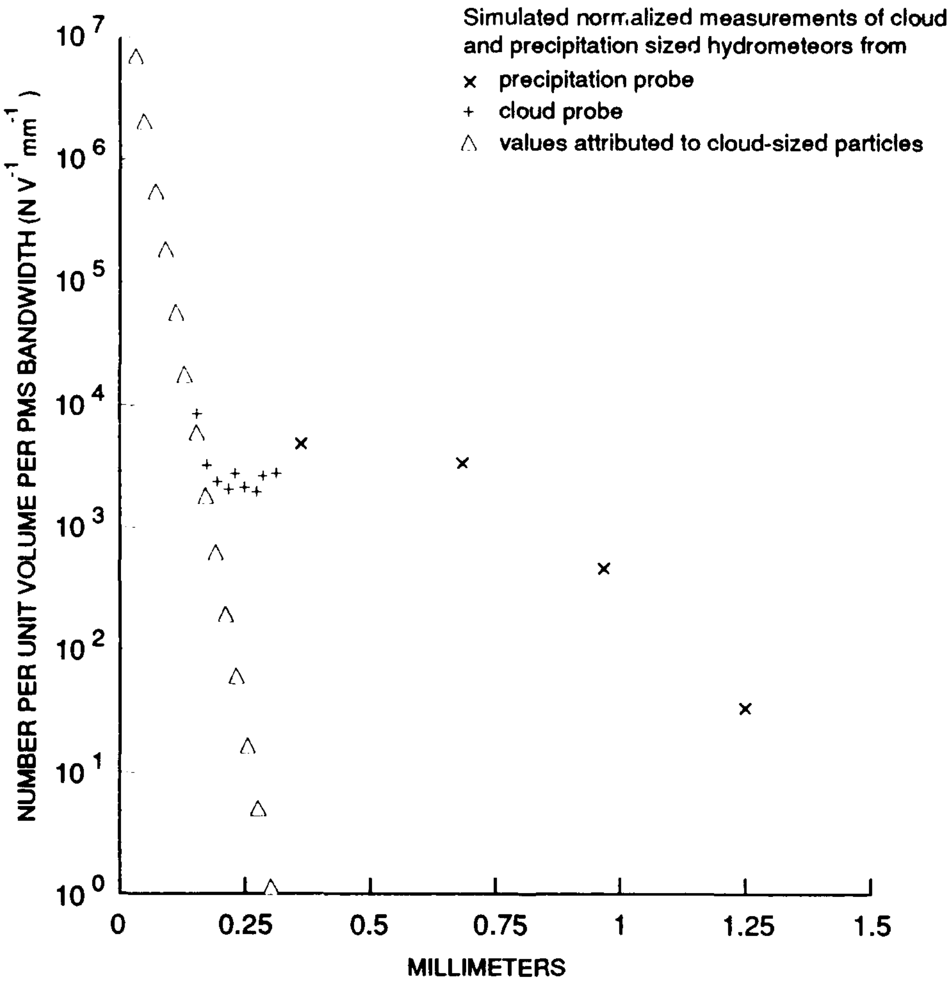


Figure 13. Simulated PMS 1-D Measurements of Assumed Cloud Hydrometeors in Concert with the Precipitable Particles Assumed in Figure 10. This hypothetical situation shows an example of incompatibility between cloud and precipitation probe data.

8. CONCLUSIONS

The investigation described in this report used simulated measurements of assumed ice crystal environments to explore several inconsistencies that are often present in PMS 1-D recordings. The results strongly indicate that the spatial orientation of irregular or elongated particles may be the cause as they can affect both number and size measurements.

Several interesting observations surfaced during the course of this study. For instance, the simulated data show that measuring and classifying randomly-oriented, irregular particulates can produce an apparent deficiency of numbers in the first or first few classes of the precipitation measurements. The magnitudes of those deficiencies are related to crystalline structure, particle sizes and numbers of those hydrometeors.

The major portions of the simulated precipitation measurements also form exponential shapes, as do actual data, where the slopes seem to depend on the numbers and sizes of the larger particles. The simulations of assumed ice distributions of identical sizes but with distinctly different number concentrations resulted in plots showing similar exponential slopes but over different size ranges. However, the assumption of more large hydrometeors than small produced a distribution shape that showed an exaggerated departure from the exponential line in the small-sized classes when compared to actual measurements. This would seem to indicate that natural hydrometeor populations contain larger amounts of smaller particles and may, in fact, form exponential distributions.

This study also showed that the number counts in the cloud probe can be adversely affected by the spatial orientation of ice crystals. Thus, numerous variations are possible in both the cloud and precipitation measurements depending upon the particular environment at the time of sampling. On the other hand, the inconsistent scattered number counts in the larger class sizes of the precipitation probe may be caused by the combining of hydrometeors or by the simultaneous measuring of more than one particle.

The columnar structure assumed in this investigation was chosen because it is often identified as the prevalent form in small ice crystal environments. The random combining of these type crystals also tend to form rosettes or combinations similar to those found in nature.[5]

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[5] Glass, M. and Varley, D.J. (1978) Observations of cirrus particle characteristics occurring with halos, *Conf. on Cloud Physics and Atmospheric Electricity*, Jul 31-Aug 4, Issaquah, Wash., AFGL-TR-78-0196, ADA059389.

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