NOTES AND CORRESPONDENCE

On Determinations of Maximum Hailstone Sizes from Hailpad Observations

PAUL L. SMITH

Institute of Atmospheric Sciences, South Dakota School of Mines and Technology, Rapid City, South Dakota

ALBERT WALDVOGEL

Laboratorium für Atmosphärenphysik, ETH-Hönggerberg, Zürich, Switzerland

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ABSTRACT

Reports of hailstones larger than those indicated by hailpad observations being found on the ground around the hailpad sites raise questions about the validity of maximum-size determinations. Data from the Grossversuch IV hailpad network demonstrate this characteristic behavior. An analysis of the hailstone sampling process shows this to be an expected consequence, which interferes with reliable determinations of maximum hailstone sizes.

1. Introduction

The maximum size of the hailstones in any particular hailfall is of scientific and practical interest (see, for example, Admirat et al. 1980; Morgan 1982b). The maximum size gives clues to the hail formation and growth processes, and the degree of hail damage is related to the maximum size. Hailpad observations can provide estimates of the maximum sizes, but such estimates are subject to a considerable amount of sampling variability. Substantial variations in the characteristics of hailfalls over distances of only a few hundred meters have been noted (e.g., Morgan and Towery 1975; Strong and Lozowski 1977).

It is sometimes reported that larger hailstones were found lying about the ground around a hailpad, casting doubt on the validity of maximum sizes estimated from the pad data. Changnon (1971) found differences between reports from cooperative observers and presumably more systematic hailpad observations. Cheng et al. (1985) also noted such behavior in comparisons between volunteer observer and hailstone catcher data. Morgan (1982a), on the basis of statistical sampling considerations, suggested that observer reports of maximum hailstone sizes might well be more reliable than values inferred from hailpad observations. The purpose of this note is to clarify this situation and present some relevant quantitative relationships.

2. Some sampling aspects of the hailpad measurement process

Measuring hail with hailpads or related devices involves sampling from one or more populations. It is not always clear just what population is of interest. For example, if several hailpads in a network are hit, one must decide whether to regard the data as multiple samples from a single population, or to regard each pad as representing a sample from a different population. The available information on small-scale variability of hail (e.g., Morgan and Towery 1975) suggests the latter to be preferable for most purposes. Thus, for the present discussion, we consider the population to be all of the hailstones that fall over an area of the order of a few square kilometers for the entire duration of the hail occurrence. (In Grossversuch IV, the hailpad network grid size was 3.8 km^2.)

We assume that only one hailpad is present within this area, so that a single sample is available from the population of interest. Variations over smaller spatial scales may be of concern for some purposes, and time variations within a hailfall may also be important (e.g., Pell 1971). In those cases, the populations being sampled would have to be redefined accordingly. Such considerations will not affect the essence of what follows here.

3. Examples of maximum hailstone size observations

The differences between maximum hailstone sizes estimated from hailpad observations and those found in samples picked up from the ground around the hail-

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Corresponding author address: Dr. Paul L. Smith, Institute of Atmospheric Sciences, SDSM&T, 501 East St. Joseph St., Rapid City, SD 57701-3995.

pads can be illustrated by some data gathered during the hail suppression experiment Grossversuch IV (Federer et al. 1986). Figure 1 shows the setup of the hailpad network; it consisted of two parts, operated by French and Italian research crews. A total of more than 300 hailpads were used; one hailpad has a sampling surface of 0.1 m^2 and represents an area of almost 4 km^2. Details of the network, the calibration, and the evaluation of the hailpads can be found in Vento (1976) and Mezeix and Chassany (1983). The observers were farmers living near a hailpad station, or people driving hailchase vehicles (Waldvogel et al. 1978).

Table 1 shows the comparison between maximum hailstone diameters measured by hailpads and determined from hailstones found by observers close by the corresponding hailpads. The exact distance between the hailpad and the collection point is not known, but it can be assumed to be of the order of 10 m or less. A total of 55 comparisons could be made. In 30 cases, the observers collected some hailstones (as indicated in the right-hand column of Table 1) and put them in a freezer for further crystallographic and embryo type analyses. The number of collected hailstones varied considerably; Table 1 shows a maximum sample of 369, whereas the smallest number collected was one hailstone only. It is clear that the observers collected the largest hailstones preferentially. In all 30 cases, however, the maximum diameter was measured in the laboratory later. In the other 25 comparisons shown in Table 1, only the diameter of the largest hailstone was measured and no collection was taken at all. For those cases, a dash appears in the column where the number of hailstones collected should be given. The accuracy of the measurements in these cases is less certain, and the reliability of these estimates of maximum hailstone diameters will be compared to the values measured from the collected samples in the following.

A first look at Table 1 shows that the observers usually find larger hailstones than the hailpads. There are only eight cases (15%) with a contrary result, and half of those involve differences no greater than 1 mm. Most such cases had small hailstones ($\approx$1.5 cm or less); in one case only, the maximum diameter (hailpad) was 2.35 cm. There are two possible explanations for this unusual behavior, apart from random sampling variability: the observer may have been somewhat late ar-

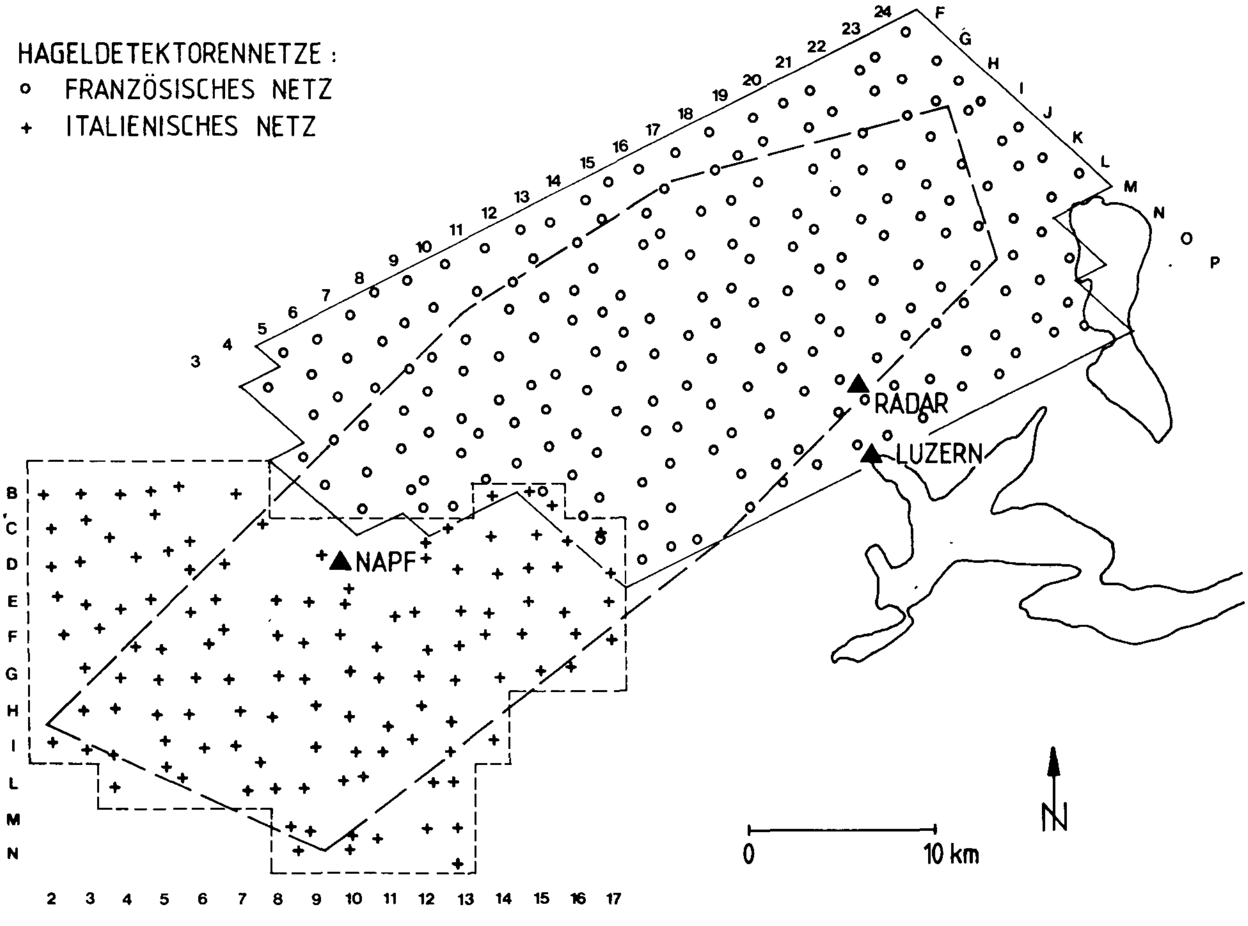

FIG. 1. The hailpad network used in Grossversuch IV.

TABLE 1. Comparison of maximum hailstone diameters, measured by a hailpad and determined by observers near the hailpad site. The identification of the hailpad and the number of hailstones sampled and collected, respectively, are also given.

	Hailpad			Observer	
Date	Identification	$D_{\max}$ (cm)	Hailstones (Sampled)	$D_{\max}$ (cm)	Hailstones (Collected)
27/6/75	CH40	1.8	118	2.3	49
11/7/75	FO09	1.85	1146	2.4	25
19/5/76	FO09	2.4	252	4.0	5
	FN11	4.0	24	4.8	21
	FN13	2.35	49	1.7	25
	FM13	2.1	649	2.5	50
	FK15	1.4	196	2.0	56
	FP12	1.05	81	3.9	3
	FL10	0.9	11	2.9	10
6/8/77	IM11	3.36	158	4.9	71
3/6/78	IH10	1.5	35	2.0	45
14/7/78	IG13	2.07	299	2.7	15
	IF14	1.12	232	1.7	109
6/8/78	FI08	1.3	14	2.0	2
	FG04	1.55	172	1.5	2
	FH06	1.5	58	1.6	2
	FH05	1.65	32	2.3	52
	FI12	1.6	80	1.7	83
	FI10	1.8	15	2.8	100
30/5/79	IC12	1.04	65	1.1	—
	IE10	1.3	84	1.6	—
	IF10	0.0	0	1.35	—
	IH06	1.26	131	1.0	—
	II06	1.28	51	2.1	—
	IL06	1.86	35	1.85	—
10/6/79	IE13	0.91	87	1.0	—
	IF13	1.37	631	1.4	—
	IG13	1.27	292	1.2	—
	IF12	1.4	861	1.5	—
12/6/79	IB04	1.56	184	1.7	369
	IB05	1.49	166	1.7	309
	IC03	2.08	28	2.85	31
	IC04	1.38	100	2.9	89
	IC05	0.79	1	1.8	1
	ID02	2.38	83	2.7	275
	ID03	1.97	143	3.0	70
	ID04	1.27	15	1.8	107
	ID05	0.92	7	1.35	78
	IE02	1.86	109	2.5	116
	II04	1.25	271	1.1	—
14/6/79	IF04	0.88	111	0.7	—
	IF05	0.9	308	0.8	—
7/8/79	FO14	1.3	286	1.7	184
15/7/82	K11	2.85	95	3.6	—
	L11	2.6	216	3.9	—
	K13	1.81	608	3.3	—
	M11	2.3	8	3.6	—
	H17	2.43	252	2.9	—
16/7/82	N11	0.85	47	4.9	—
	M14	2.55	18	3.5	—
	N15	1.76	136	2.6	—
	L15	0.0	0	3.1	—
	O13	2.55	182	3.3	—
	O12	4.53	162	5.5	—
	O10	2.56	15	3.2	—

riving at the hailpad site and therefore the hailstones on the ground could have partially melted, or the maximum diameter on the hailpad may have been due to two hailstones hitting the pad close by. The majority of the comparisons, however, show a clear picture: observers find larger hailstones than one would expect from the hailpad data alone.

Figure 2 provides a scatter plot of the corresponding hailpad and observer estimates of maximum hailstone sizes; the tendency mentioned above can be clearly seen. As noted, there are two groups of "observer" maximum hailstone diameters: group 1 (30 cases) was measured from collected samples, whereas group 2 (25 cases) includes reports of less certain quality. Separate regression lines were computed for the two groups but, as indicated in Fig. 2, the difference was slight (e.g., the slopes were 0.51 for group 1 and 0.48 for group 2). This was confirmed by testing the two slopes for any possible statistically significant difference; no difference at all was found (P-value larger than 0.50). This interesting result indicates a high degree of reliability for the (at first glance) scientifically weaker "reported values" of maximum hailstone diameter.

The two groups were therefore pooled to obtain an overall regression equation. The relationship is highly significant, with a correlation coefficient of 0.67 for the 55 points. It can be expressed mathematically by considering the regression between maximum hailstone diameters obtained from hailpads (D_{mp}) and observers (D_{mo}):

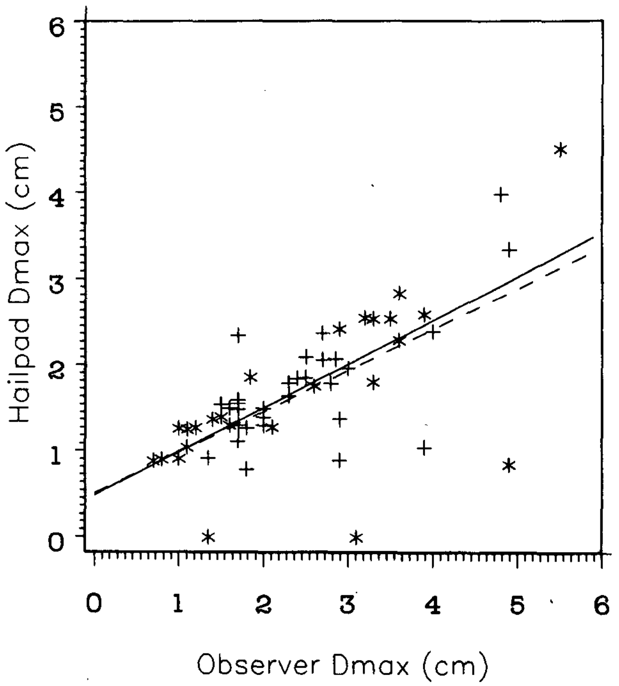

FIG. 2. Scatter diagram comparing maximum hailstone diameters obtained from hailpad measurements and from hailstones found by observers near the hailpads. Solid regression line and + symbols are for D_{mo} values measured from collected hailstones; dashed regression line and * symbols are for D_{mo} values reported by observers.

$$D_{mp} = 0.506 + 0.493 D_{mo}. \qquad (1)$$

The diameters D_{mp} and D_{mo} are expressed in centimeters. According to (1), the estimates would be about equal for maximum diameters around 1 cm, while there would be an underestimate of the maximum hailstone diameter of up to 50% for large hailstones when only hailpad data are used. The following sections provide an explanation for this behavior.

4. Relationship between maximum observed hailstone size and sampling volume

Differences like those illustrated in Section 3 are often broadly attributed to sampling differences, but the sampling differences can be explained more specifically in the following way. We shall represent the size distribution of hailstones graphically using the "inverse cumulative number concentration" $N_L(D)$ (Smith 1982), which is related to the number concentration per unit size interval, $n(D)$, by

$$N_L(D) = \int_D^\infty n(D)dD. \qquad (2)$$

Thus, $N_L(D)$ represents the number concentration (m^{-3}) of hailstones with sizes larger than or equal to D. The underlying size distribution for the population of hailstones can be taken to be of the Marshall–Palmer exponential form $n(D) = n_0 e^{-\Lambda D}$, at least as a working hypothesis (e.g., Federer and Waldvogel 1978; Cheng and English 1983). Then $N_L(D)$ will also be an exponential function with the same slope parameter Λ but with intercept $N_L(0) = n_0/\Lambda$. Figure 3 represents the function $N_L(D)$ schematically.

Now consider the sampling process where a hailpad is used. Dents of a particular size in the pad represent the hailstones of size D contained in a sampling volume given by

$$V_{\text{pad}} = A_{\text{pad}} v_t(D) t_h. \qquad (3)$$

Here A_{pad} represents the area of the pad, which is typically 0.1 m^2, $v_t(D)$ represents the fall speed of hailstones of diameter D, and t_h represents the duration of the hailfall at the pad site. In plotting an observed hailstone size distribution on the coordinates of Fig. 3, the lowest concentration that can be depicted corresponds to the one largest hailstone in the sample and is $1/V_{\text{pad}}$. Entering this value on the ordinate, we see that the expected maximum size is $\hat{D}_{mp}$. Because sampling hailstones with hailpads is a discrete process, random sampling variations will usually cause the maximum size actually observed to differ somewhat from this expected value.

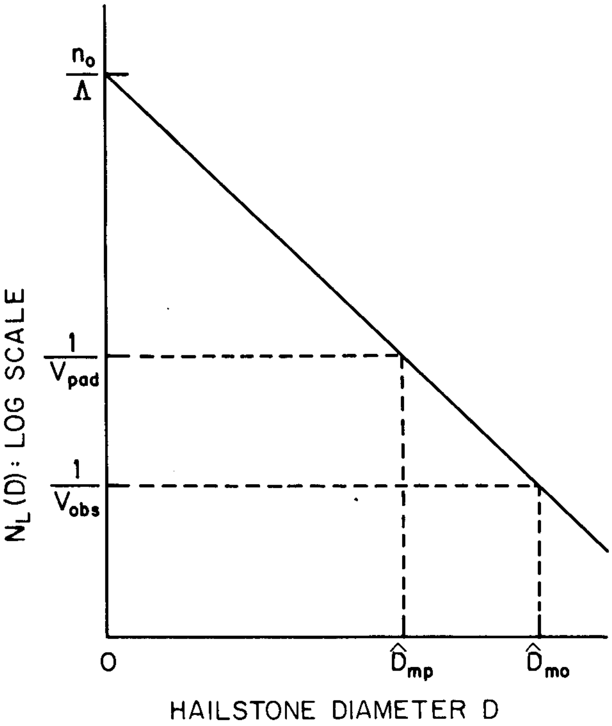

FIG. 3. Schematic illustration of the "inverse cumulative number concentration" $N_L(D)$ for an exponential particle size distribution.

Next consider an observer, who examines some area A_{obs} on the ground around the pad and notes the maximum hailstone size D_{mo}. The area involved here is typically of the order of 10–100 m^2 and the sampling volume analogous to (3) is

$$V_{\text{obs}} = A_{\text{obs}} v_t(D) t_h. \qquad (4)$$

This volume may be 100 to 1000 times as large as that for the hailpad data. Again, the minimum observed concentration that can be depicted on Fig. 3 is related to the sampling volume by $1/V_{\text{obs}}$. When we enter this concentration on the ordinate, we find a corresponding maximum expected size $\hat{D}_{mo}$ which is larger than $\hat{D}_{mp}$. The random sampling variations would also cause the actual maximum size found in a particular case to differ somewhat from this expected value.

Very small-scale variations in the hailstone size distribution, and the possibility of partial melting before the observer can record D_{mo}, could also influence the results. The important conclusion, however, is this: One should *expect* the largest hailstone found by an observer under these circumstances to be larger than the largest hailstone indicated by the hailpad. Moreover, by a similar argument one would expect the largest hailstone in the population being sampled to be even larger.

5. An estimate of the expected difference

The expected difference between D_{mo} and D_{mp} can be estimated if the hailstone size distribution is exponential and the slope parameter Λ of the distribution

$$D_{mp} = 0.506 + 0.493D_{mo}. \tag{1}$$

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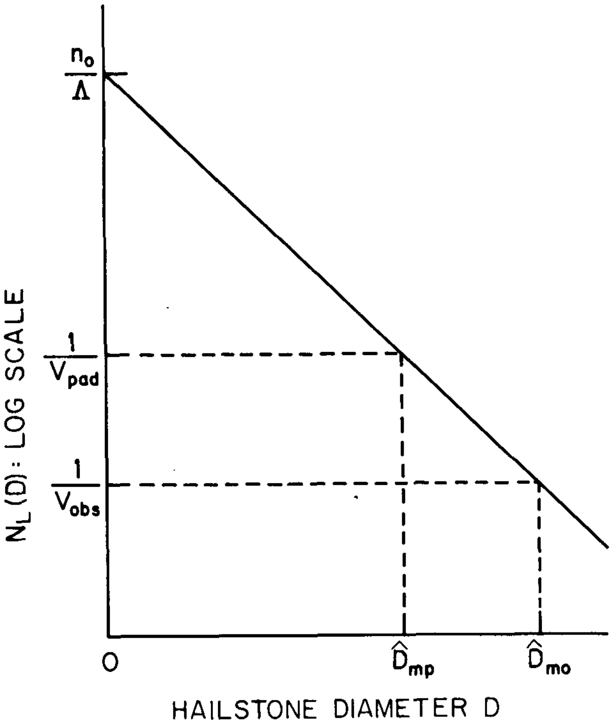

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5. An estimate of the expected difference

The expected difference between D_{mo} and D_{mp} can be estimated if the hailstone size distribution is exponential and the slope parameter Λ of the distribution and the respective sampling areas are known. We have from Fig. 3 (omitting the expected-value carets)

$$N_L(D_{mp}) = 1/V_{\text{pad}} = (n_0/\Lambda)\exp(-\Lambda D_{mp})$$
$$N_L(D_{mo}) = 1/V_{\text{obs}} = (n_0/\Lambda)\exp(-\Lambda D_{mo}). \qquad (5)$$

Dividing these two equations,

$$\frac{V_{\text{obs}}}{V_{\text{pad}}} = e^{\Lambda(D_{mo}-D_{mp})}. \qquad (6)$$

The difference between the sampling volumes is due almost entirely to the difference between the sampling areas; the difference between $v_t(D_{mo})$ and $v_t(D_{mp})$ is of little consequence. Therefore,

$$\frac{V_{\text{obs}}}{V_{\text{pad}}} \approx \frac{A_{\text{obs}}}{A_{\text{pad}}} \qquad (7)$$

and

$$\ln\left(\frac{A_{\text{obs}}}{A_{\text{pad}}}\right) \approx \Lambda(D_{mo} - D_{mp}) \qquad (8)$$

from which

$$D_{mo} - D_{mp} \approx \frac{1}{\Lambda}\ln\left(\frac{A_{\text{obs}}}{A_{\text{pad}}}\right). \qquad (9)$$

The ratio of the sampling areas is typically of the order of 10^2–10^3. Federer and Waldvogel (1978) indicate that the average value of Λ for hailstone samples collected in Switzerland is about 5 cm^{-1}. Cheng et al. (1985) show a similar average value for hailstone size distributions from Alberta. Consequently, the difference between the maximum hailstone size estimates would be expected to be about

$$D_{mo} - D_{mp} \approx 0.9 \text{ to } 1.4 \text{ cm}. \qquad (10)$$

Thus, the expected difference would be of the order of a centimeter. Larger differences can occur because of random sampling variations or differences in the form or parameters of the size distribution. Smaller differences can occur for the same reasons as well as the effects of partial melting of the hailstones measured by observers.

Figure 4 (which reproduces the data from Fig. 2) indicates quite a bit of variation in the difference ($D_{mo} - D_{mp}$). The dashed line in the figure corresponds to a difference of 1.0 cm; the median difference is 0.6 cm and the mean is 0.7 cm. The agreement between the rough estimate in (10) and the observed values is only fair, and values of A_{obs} toward the lower end of the range assumed (or even smaller) may be appropriate for most of these observations. In any case, the differences can readily be accounted for by this or the other factors discussed above.

Observations have shown a relatively narrow range of values for the product $\Lambda D_{\max}$ (e.g., Ulbrich and Atlas 1982; Cheng et al. 1985). Thus there appears to be some tendency for larger observed maximum sizes to be associated with smaller values of Λ. According to (9), that would lead to greater differences when larger hailstones are observed—a tendency apparent in Fig. 4 and reflected by the regression relationship (1). Thus the overall qualitative agreement is adequate to substantiate the validity of this basic explanation.

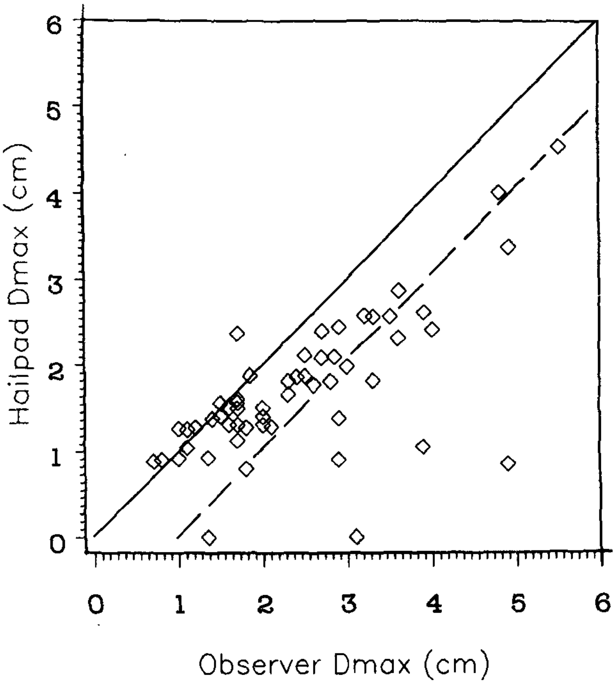

FIG. 4. Scatter diagram comparing maximum hailstone diameters obtained from hailpad measurements and from hailstones found by observers near the hailpads. The solid line shows the 1:1 relationship, while the dashed line indicates a difference ($D_{mo} - D_{mp}$) of 1 cm.

One should not attempt to extrapolate this analysis too far, or interpret the results too literally. If a large value (say, the hailpad network grid area of about 4 km^2) is inserted for A_{obs}, then (9) may indicate an expected D_{mo} several centimeters larger than D_{mp}. We do not intend to imply that such a large hailstone *must* be present in the population; the proper inference is only that one should expect hailstones larger than D_{mp} in the population. The actual value of a maximum size (i.e., truncation point) for the distribution is therefore not established by the hailpad data.

6. Discussion

The main conclusion of this work is that one should expect the largest hailstone in a hailfall to be larger than that indicated from hailpad observations. We would therefore argue (as was done in Smith 1982, for raindrop size distributions) that one cannot establish a reliable maximum hailstone size, or truncation point for the size distribution, from hailpad observations or from any other observations involving a limited sampling area or volume. Thus, the significance of experimentally determined maximum hailstone sizes is questionable, in spite of the importance attached to such values by Ulbrich (1977), Cheng et al. (1985), and other workers. If a serious need for maximum size data exists, then methodology similar to that used for extrapolating available rainfall observations to estimate probable maximum precipitation (e.g., Riedel and Schreiner 1980) is probably required.

An exponential size distribution was assumed in Section 5 to obtain a quantitative estimate of the difference $(D_{mo} - D_{mp})$, but the function $N_L(D)$ necessarily decreases monotonically with increasing size. Therefore the qualitative conclusion does not depend upon the specific form of the size distribution. For any given form, the methodology used in Section 5 could be employed to estimate the difference. However, the result would still depend upon the sampling areas associated with the measurement techniques. The process would also be subject to considerable uncertainty due to the random sampling variability and the effects of melting.

In some cases, the maximum sizes indicated by hailpad data and those found by observers are essentially the same. That could occur occasionally as a result of the random aspects of the sampling process, but also seems to occur when there is a substantial amount of hail, of relatively small maximum size (no more than about 1.5 cm). In such cases, partial melting of the hailstones on the ground, before the observers make note of the sizes, can be especially important. Also, the hailstone size distributions in these cases sometimes appear to deviate substantially from the exponential form, which would invalidate the quantitative arguments in Section 5.

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