作物の雹害被害率からみた雹の粒度分布の特徴

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On the Characteristics of Hail Size Distribution Related to Crop Damage

Hiroshi SEINO

(Kyushu National Agricultural Experiment Station, 496 Izumi, Chikugo-shi, Fukuoka 833, Japan)

Abstract

The total kinetic energy of a hailfall derived from hailpad is known to be closely related to the degree of crop damage. The hail size distribution (space concentration distribution) is also considered as one of the factors related to crop damage. Hailpad data, however, contain no information on the time of hail. Therefore, the hail size distribution can not be calculated directly from hailpad. In this paper an attempt was made to estimate hailfall duration from hailpad data in the damaged area of approximately 4 km width and 8 km length suffered by the northern Kanto hailstorm on 9 June 1975. The degree of crop damage had been classified into 5 groups. The hailpad data were classified according to the degrees of crop damage and averaged over each class. The number frequency distribution obtained from hailpad was converted to hail size distribution with the estimated hailfall duration. The characteristics seen in the size distributions were described in relation to crop damage. Furthermore, the size distributions were fitted by the equations of Marshall and Palmer (1948) and Shiotsuki (1975). From the relations of the parameters in these equations to crop damage, it was found that the mean diameter was closely related to crop damage. Thus, as the mean diameter can be derived directly from hailpad, the hailpad observation system is suggested to be useful for the objective assessment of crop-hail damage.

1. Introduction

Hailfall parameters such as number, maximum diameter, mass, momentum and kinetic energy of hailstones derived from hailpad have been correlated with crop damage. Changnon (1971) concluded that frequency of hailstones with diameter over 6.4 mm and the energy imparted by the total hailfall were closely related to crop damage. Strong (1974) also correlated kinetic energy of hailstones with crop damage. Omoto and Seino (1978) described that the degrees of crop injuries were relatively well correlated with impact energy (kinetic energy), mass and number of hailstones with diameter over 6.4 mm.

The hail size distribution is defined by the number of hailstones per unit volume of air in a size range from D to $D+\Delta D$, and is also considered as one of the factors related to crop damage. There are few literatures on hail size distribution. Douglas (1964), and Federer and Waldvogel (1975) reported mean hail size distributions in Canada and Switzerland, respectively. However, these hail size distributions were not used to correlate with crop damage. In order to measure hail size distribution, time-resolved measuring apparatus is required. On the other hand, there are much data of hailpad in hailfall observation networks through the world. When properly calibrated, hailpad provides an estimate of the hail size frequency distribution at a point, integrated over the duration of the hailfall. With certain assumptions, the mass, vertical velocity, momentum and energy of impact can be derived. A distinct problem in the study of individual storms is that there is no information on the time of begining or end of hail. This problem has been partially overcome by installing hailpads near weighing-bucket recording raingages (Changnon, 1966). In the case that hail falls with intense rain, the time and duration can be approximately estimated with the help of radar and/or raingages near the hailpad (Seino *et al.*, 1978).

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Hailfall duration is one of the significant informations to hail research. In addition, if hailfall duration is observed or estimated in some way or other, size frequency distribution obtained from hailpad is converted to space concentration distribution (hail size distribution). In this paper an attempt is made to estimate time dependent parameters such as hailfall rate, radar reflectivity factor, kinetic energy flux, and duration of hail by using hailpad data. Furthermore, hail size distributions classified according to the degrees of crop damage are calculated from the data with the duration, and the characteristics seen in the distributions are studied in relation to the degree of crop damage.

2. Method and Data

2.1 A method to estimate hailfall duration

Hailpad data contain the sum total of number and size of hailstones during a hailfall. The hailfall parameters of hailfall rate R (mm hr^{-1}), radar reflectivity factor Z (mm^6 m^{-3}), liquid water content W (g m^{-3}), and kinetic energy flux $\dot{E}$ (J m^{-2} sec^{-1}) are calculated by the following equations (*e.g.*, Waldvogel *et al.*, 1978a):

$$R=\{3.6\times10^{-3}\pi/(6St)\}\sum_{i=1}^{n}(N_iD_i^3), \quad (1)$$

$$Z=\{1/(St)\}\sum_{i=1}^{n}(N_iD_i^6/V_i), \quad (2)$$

$$W=\{10^{-3}\rho\pi/(6St)\}\sum_{i=1}^{n}(N_iD_i^3/V_i), \quad (3)$$

$$\text{and } \dot{E}=\{\rho\pi/(12\times10^6St)\}\sum_{i=1}^{n}(N_iD_i^3V_i^2), \quad (4)$$

where it was assumed that the hailstones were hard, smooth spheres of known homogeneous density falling through undisturbed air of known density and viscosity. N_i is the number of hailstones of diameter D_i (mm), S the sampling area of hailpad (m^2), t the duration of a hailfall (sec), ρ the density of water, and V_i the terminal velocity of hailstone given by

$$V_i=v_o\sqrt{D_i}\ ,$$

where v_o is a constant. Because hailpad data contain no information on the time of hail, the hailfall parameters of Eqs. (1)-(4) can not be calculated directly from hailpad data. However, the ratios of pairs of these hailfall parameters can be calculated from hailpad data, because the term of time is eliminated. The ratios of R/W, Z/W, P/E and $Z/\dot{E}$ were made in connection with the W-R and W-Z relations used in radar meteorology and the $\dot{E}$-Z relation described by Waldvogel *et al.* (1978a). P and E are total precipitation amount and total kinetic energy of a hailfall, respectively, which are calculated directly from a hailpad. Using Eqs. (1)-(4), the ratios are written as follows:

$$R/W=3.6\,v_o\sum_{i=1}^{n}(N_iD_i^3)/\sum_{i=1}^{n}(N_iD_i^{2.5})=K_1, \quad (5)$$

$$Z/W=\{6\times10^3/(\rho\pi)\}\sum_{i=1}^{n}(N_iD_i^{5.5})/\sum_{i=1}^{n}(N_iD_i^{2.5})=K_2, \quad (6)$$

$$P/E=R/(3.6\times10^3\dot{E})=(2/v_o)\sum_{i=1}^{n}(N_iD_i^3)/\sum_{i=1}^{n}(N_iD_i^4)=K_3, \quad (7)$$

$$\text{and } Z/\dot{E}=\{12\times10^6/(\rho\pi v_o^3)\}\sum_{i=1}^{n}(N_iD_i^{5.5})/\sum_{i=1}^{n}(N_iD_i^4)=K_4. \quad (8)$$

In case where reliable relations are given among those hailfall parameters, it is possible to estimate R, Z, W, and $\dot{E}$ indirectly from hailpad data. It is known in radar meteorology that W, R and $\dot{E}$ are related to Z by the following equations:

$$W=AZ^{\alpha}, \quad (9)$$

$$R=BZ^{\beta}, \quad (10)$$

$$\text{and } \dot{E}=CZ^{\gamma}, \quad (11)$$

where A, B, C, α, β and γ are constants. Therefore, the ratios are solved by using the hail parameter relationships of Eqs. (9)-(11) as follows:

$$Z_1=\{(A/B)K_1\}^{1/(\beta-\alpha)}, \quad (12)$$

$$Z_2=(AK_2)^{1/(1-\alpha)}, \quad (13)$$

$$Z_3=\{(3.6\times10^3C/B)K_3\}^{1/(\beta-\gamma)}, \quad (14)$$

$$\text{and } Z_4=(CK_4)^{1/(1-\gamma)}. \quad (15)$$

If Eqs. (9)-(11) are suitable for the hailfall to which the method is applied, it is expected that the values from Z_1 to Z_4 result in almost same values. The other parameters are determined by use of the following equations for Z:

$$\dot{E}=Z/K_4,$$

$$W=Z/K_2,$$

$$R=ZK_1/K_2,$$

$$\text{and } t=E/\dot{E} \text{ or } P/R.$$

The duration of a hailfall can be determined with the above equation. A few literatures was reported on the hail parameter relationships. Douglas (1964) and Stormy Weather Group (1971) reported almost same *W-R* relations in Canada. Recently Waldvogel *et al.* (1978a) reported the following relations:

$$W = 2.32 \times 10^{-5}\ Z^{0.706},$$

$$R = 6.53 \times 10^{-4}\ Z^{0.747},$$

$$\text{and}\quad \dot{E} = 5.0 \times 10^{-6}\ Z^{0.840}.$$

They made an attempt to estimate kinetic energy E from Z *via.* $\dot{E}$-Z relation (Waldvogel *et al.*, 1978b). Since the hail parameter relationships were not specified for the present study, the relations reported by Waldvogel *et al.* (1978a) were used.

2.2 Estimate of hail size distribution

With the terminal velocity and hailfall duration estimated in the previous section, the number frequency distribution is converted to hail size distribution. The number of hailstones per unit volume of air is expressed as N_D, and hail size distribution is defined as the distribution of N_D with size. The hailfall duration estimated in the previous section is not the values at a point but the average value over the damaged area. Therefore, it is impossible to calculate hail size distribution at a point. Then the number frequency distributions were classified according to the degree of crop damage and averaged over each class. Moreover, the hailfall durations in the area of each degree of crop damage were assumed to be equal to the average duration. The degree of crop damage had been classified into 5 groups, that is, 0-30, 30-50, 50-70, 70-90 and 90-100%. In order to study the characteristics of the average hail size distributions classified according to the degrees, the distributions were fitted by the equations of Marshall and Palmer (1948), and Shiotsuki (1975). The equations are written as

$$N_D = N_O \exp(-\Lambda D) \quad \text{(Marshall and Palmer)},$$

$$\text{and}\quad N_D = \{6\times10^3 WD^{-3}/(\rho\pi\sigma\sqrt{2\pi})\} \times \exp\{-(D-\bar{D})^2/(2\sigma^2)\} \quad \text{(Shiotsuki)},$$

where N_O and Λ are the intercept ($\text{mm}^{-1}\ \text{m}^{-3}$) and the slope ($\text{mm}^{-1}$) of N_D distribution, and $\bar{D}$ and σ are the mean diameter (mm) and the standard deviation (mm). $\bar{D}$ and σ are given by

$$\bar{D} = \int_0^\infty N_D D^4\,\mathrm{d}D \Big/ \int_0^\infty N_D D^3\,\mathrm{d}D,$$

$$\text{and}\quad \sigma^2 = \left(\int_0^\infty N_D D^5\,\mathrm{d}D \Big/ \int_0^\infty N_D D^3\,\mathrm{d}D\right) - \bar{D}^2.$$

2.3 Data

The 34 hailpad data of the 9 June 1975 hailstorm in the northern Kanto district were analysed in this paper. The analysed hailfall area was approximately 4 km width and 8 km length in and arround Nitta Town, Gunma Prefecture. The results of radar observation and hailfall distribution of the hailstorms which contained the hailstorm analysed in this paper were described by Omoto *et al.* (1976). The relation of hailfall characteristics of the hailstorm to crop-hail damage was discussed by Omoto and Seino (1978) with the use of the time-independent parameters such as kinetic energy and mass of hailstones. The data used in this paper were taken by National Research Center for Disaster Prevention.

3. Results and Discussion

3.1 Hailfall parameters

Fig. 1 shows the values of $\dot{E}$ and t estimated at each observation point. The figure shows that the hailfall parameters estimated by four equations (12)-(15) are different each other. This means that some of the hail parameter relationships used were not suitable for the hailstorm of the present study.

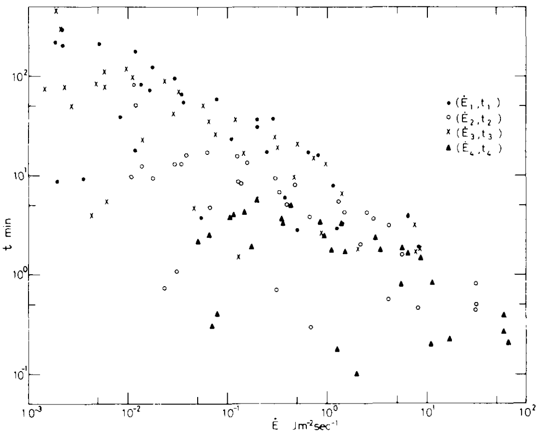

Fig. 1. Estimated $\dot{E}$ and t in units of $\text{J m}^{-2}\ \text{sec}^{-1}$ and min., respectively. Suffixes 1, 2, 3 and 4 indicate that they were estimated by using R/W ratio with R-Z and W-Z relations, Z/W with W-Z, P/E with R-Z and $\dot{E}$-Z, and $Z/\dot{E}$ with $\dot{E}$-Z, respectively.

Then, in order to determine the most reasonable set of hailfall parameters, the t values were examined with other informations on hailfall duration. Omoto *et al.* (1976) described that the record of raingages located in the hailfall area showed short rainfall duration, and the duration could not be determined because in the week recording paper used in this area we could not read the scale shorter than 15 min. Furthermore, they described that the hail had fallen with intense rain. Omoto and Seino (1978), on the basis of field survey, described that the hailfall duration was very short, *i.e.*, even in the severely damaged area it was less than 5 min. The result of radar observation reported by them showed that the hailstorm echo covered the hailfall area for about 15 min. According to those informations, the values of t_1 and t_3 are obviously overestimated. Though the values of t_2 are not impractical, they are somewhat overestimated. The values of t_4 agree well with the above informations. Therefore, the hailfall parameters estimated by $Z/\dot{E}$ ratio and $\dot{E}$-Z relation were decided to be the most reasonable for the hailfall of the present study. The result, thus, means that the W-Z and R-Z relations were not suitable for the hailfall, and the $\dot{E}$-Z relation of the northern Kanto hailstorm on 9 June 1975 was similar to those observed in Swiss hailstorms by Waldvogel *et al.* (1978a).

Because the hailfall parameters were not observed in the northern Kanto case, it is impossible to discuss in detail on the error contained in the estimated hailfall parameters. Then, instead, with the data of raindrops obtained from ten convective rainfalls in the northern Kanto district, it was made to estimate the error. The result is shown in Table 1. The estimated values of t for ten convective rainfalls were compared with the observed ones. The rain parameter relationships between W and Z, R and Z, and $\dot{E}$ and Z were decided for the ten cases. In some cases, the error due to the method becomes at least more than 100%. However, the average values of the ten cases agree well with each other. The error of the average values of t_3 is 10%, the smallest of them. The result shows that, although the hailfall parameters estimated at each observation point contain noticeable error, the method can give a reasonably accurate estimate of the average values of hailfall parameters for the hailfall area. The average values of the hailfall parameters in the damaged area were estimated as R=84 mm hr^{-1}, Z=8.4×10^6 mm^6 m^{-3}, W=1.7 g m^{-3}, $\dot{E}$=2.4 J m^{-2} sec^{-1}, and t=126 sec.

3.2 Hail size distribution in relation to crop damage

Fig. 2 shows the average hail size distributions

Table 1. The rainfall durations (min) of ten rainfalls observed and estimated by using R/W ratio with R-Z and W-Z relations (t_1), Z/W with W-Z (t_2), P/E with R-Z and $\dot{E}$-Z (t_3), and $Z/\dot{E}$ with $\dot{E}$-Z (t_4). The percentage deviations from the observed t values are given in parentheses.

Case	t obs.	t_1 estimated	t_2 estimated	t_3 estimated	t_4 estimated
A	12	3.0 (−75)	9.0 (−25)	8.8 (−27)	12.0 (0)
B	7	4.1 (−41)	7.0 (0)	6.3 (−10)	8.5 (21)
C	14	5.2 (−63)	5.1 (−64)	6.0 (−57)	4.7 (−66)
D	33	14.3 (−57)	14.2 (−57)	17.2 (−48)	13.0 (−61)
E	6	22.8 (280)	15.4 (157)	22.5 (275)	9.3 (55)
F	13	16.3 (25)	19.4 (49)	14.1 (8)	23.7 (82)
G	19	34.8 (83)	26.4 (39)	21.0 (11)	27.4 (44)
H	18	14.8 (−18)	11.7 (−35)	10.4 (−42)	11.8 (−34)
I	22	39.1 (78)	32.5 (48)	41.7 (90)	27.6 (25)
J	40	80.9 (102)	65.3 (63)	55.5 (39)	67.0 (68)
Mean	18.4	23.5 (28)	20.6 (12)	20.3 (10)	20.5 (11)

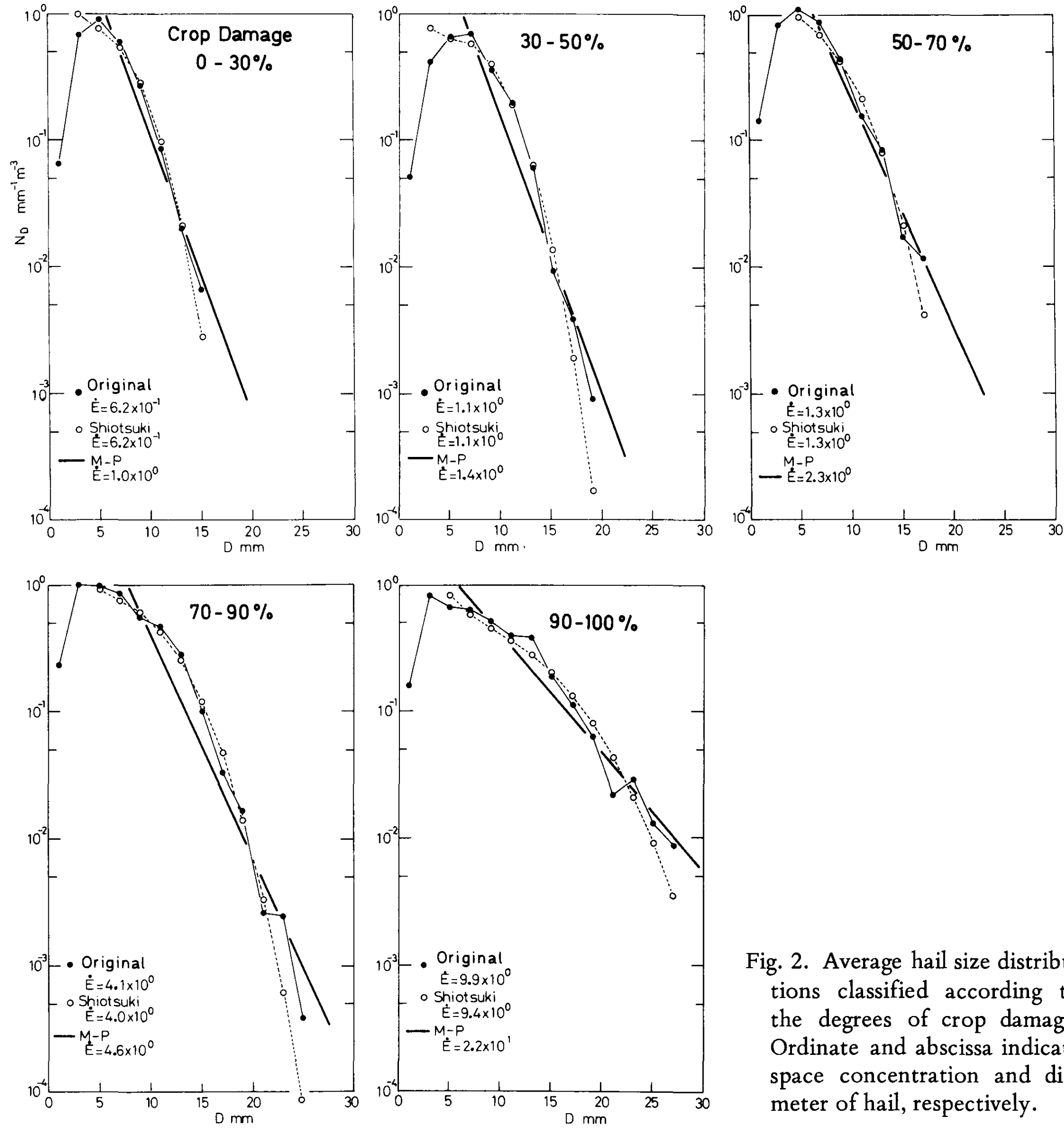

Fig. 2. Average hail size distributions classified according to the degrees of crop damage. Ordinate and abscissa indicate space concentration and diameter of hail, respectively.

classified according to the degrees of crop damage. The distributions fitted by the equations of Marshall and Palmer (1948), and Shiotsuki (1975) are also shown in the figure. The original distributions show that the N_D values become large with the increment of degree of crop damage. The rate of increase of N_D values is larger in the range of crop damage over 70% than in damage below 70%. For instance, the approximate values of N_D at D=15 mm are 0.1 mm^{-1} m^{-3} in the former cases and 0.01 mm^{-1} m^{-3} in the latter cases, respectively. Maximum diameter is not proportional to the degree of crop damage. This agrees with the relation between the distributions of crop damage and maximum diameter described by Omoto and Seino (1978). However, there is noticeable difference between maximum diameters in the ranges of crop damage over 70% and below 70%. Namely, they are less than 19 mm in the range of crop damage below 70%, while they are more than 25 mm in the range over 70%. The size distributions are approximated better by Shiotsuki's equation than the exponential distribution. When N_D equation is known, kinetic energy flux $\dot{E}$ is given by

$$\dot{E}=\{\rho\pi/(12\times10^6)\}\int_0^\infty N_D D^3 V^2\, dD.$$

By substituting the equation of Marshall and Palmer or Shiotsuki, $\dot{E}$ is written as follows:

$$\dot{E}=\rho\pi v_o^3\Gamma(5.5)N_O/(12\times10^6\Lambda^{5.5})$$

(Marshall and Palmer),

where $\Gamma(x)=\int_0^\infty t^{x-1}\exp(-t)\,dx \quad (x>0)$, and

$$\dot{E}=\{v_o^3/(2\times10^3)\}W\bar{D}^{1.5}(1+0.375k^2)\ \text{(Shiotsuki)},$$

where $k=\sigma/\bar{D}$.

E values calculated with each equation are also shown in Fig. 2. They show that the values calculated from Shiotsuki's equation are near to the original. The average size distribution in the damaged area was expressed by using the exponential distribution as follows:

$$N_D = 6.9\exp(-0.340\,D).$$

It is similar to $N_D=3.1\exp(-0.309\,D)$ reported by Douglas (1964) and to $N_D=12\exp(-0.42\,D)$ by Federer and Waldvogel (1975).

The parameters of N_O, Λ, $\bar{D}$, σ, W and k were correlated to crop damage, in order to study the characteristics of hail size distribution related to crop damage in detail. The results are shown in Fig. 3. N_O and Λ in the exponential distribution decrease with the increase of the degree of crop damage. They are extreamely smaller in the range of crop damage of more than 90% than of less than 90%. This means that the slope of size distribution corresponding to crop damage of more than 90% is more gentle and the N_D values

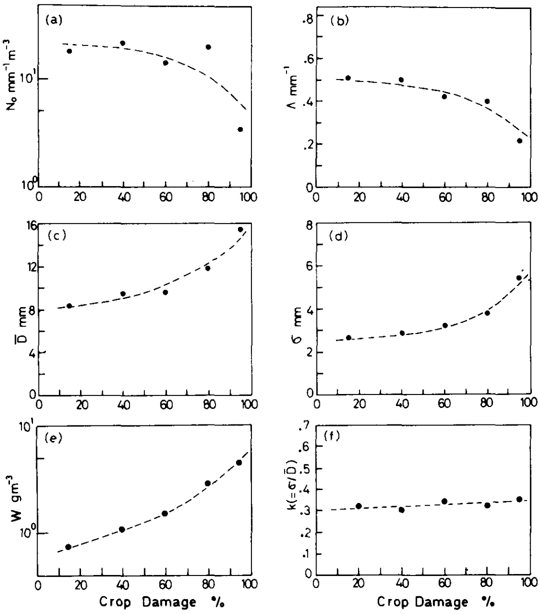

Fig. 3. Relations of N_O, Λ, $\bar{D}$, σ, W and k to crop damage. The degrees of crop damage are represented by the medium values of the corresponding range. Broken lines are drawn with the eye and show the general tendency of the plots.

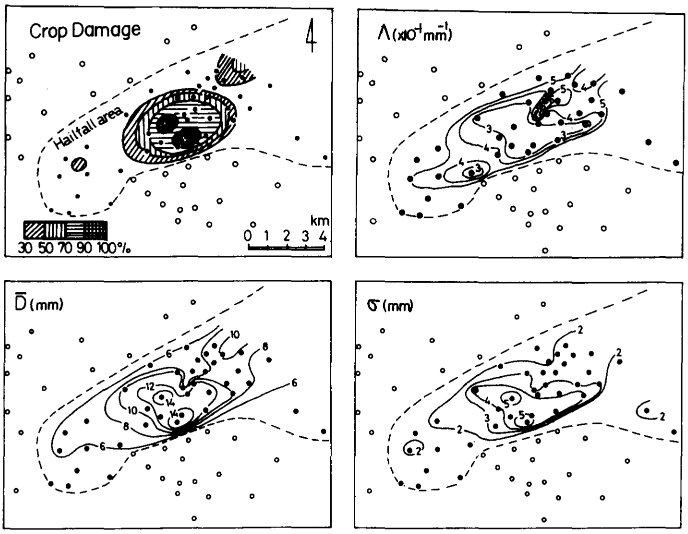

Fig. 4. Distributions of crop damage after Omoto and Seino (1978), Λ, $\bar{D}$, and σ. Broken line shows the boundary of hailfall area. Black circles indicate hail-recorded sites.

in medium size range or more become larger than in the range of less than 90%. W, $\bar{D}$ and σ in Shiotsuki's equation increase with crop damage. This also shows the same tendency of size distribution as mentioned above. Furthermore, it means that size distribution becomes wide and liquid water content per unit volume of air becomes large, as the degree of crop damage increases. The coefficient k $(=\sigma/\bar{D})$ is almost constant (about 0.3). This implies that the shapes of size distributions corresponding to any degree of crop damage are almost similar, that is, the N_D values in medium size range are larger than the corresponding exponential distribution. It is expected that the difference among the hail size distributions may come out as the difference among kinetic energy fluxes as shown in Fig. 2.

The parameters of N_O , and W estimated at each hailpad site contain uncertainty, because they are functions of time. Therefore, the distributions of Λ, $\bar{D}$ and σ at hailpad sites in the hailfall area were compared with the one of crop damage reported by Omoto and Seino (1978). The result is shown in Fig. 4. There are four maximum regions of crop damage. The distribution of $\bar{D}$ agree well with the crop damage distribution. The maximum of crop damage in western part of the hailfall area was not obtained in the $\bar{D}$ distribution, because there was no hailpad site. However, it is expected that there may be a maximum, from the isopleth of 6 mm which extends to western part of the area. The other maxima agree well with the crop damage distribution. Omoto and Seino (1978) concluded that the distribution of E in the same hailfall area of this case agreed well with the crop damage distribution. The $\bar{D}$ distribution was very similar to the one of E.

4. Conclusions

In order to study the relation between hail size distribution and crop damage from hailpad data which essentially lack time resolution, an attempt was made to estimate hailfall duration in the severely damaged area of approximately 4 km width and 8 km length. With the duration, the average hail size distributions classified according to the degrees of crop damage were estimated, and the characteristics seen in the distributions were studied in relation to crop damage. The results can be drawn as follows:

1) Although hailpad data contain no information on the time of hail, the average hailfall duration in the damaged area could be estimated.

2) The N_D values of hailstones increased with the increment of degree of crop damage. Especially, in the range of damage of more than 70%, the rate of increase of N_D values became large.

3) Maximum diameter in each distribution was not proportional to the degree of crop damage. However, there was noticeable difference of diameter between in the range of crop damage of more than 70% and less than 70%.

4) The size distributions could be approximated well by the equation proposed by Shiotsuki (1975). The hailfall parameters such as kinetic energy flux and hailfall rate calculated by that equation were near to the original ones.

5) The relations between crop damage and the paremeters in the equations of Marshall and Palmer (1948), and Shiotsuki (1975) showed the same result as described in 2).

6) The distribution of $\bar{D}$, the mean diameter of spectrum in the equation of Shiotsuki (1975), agreed well with that of crop damage.

Changnon (1971), and Omoto and Seino (1978) described that the number of hailstones with diameter over 6.4 mm and the kinetic energy imparted by the total hailfall were closely related to crop damage. The relation between hail size distribution and crop damage showed that the mean diameter of size distribution was closely related to crop damage. Thus, as $\bar{D}$ can be derived at least from hailpad data, the hailpad observation system is suggested to be more useful for the objective assessment of crop-hail damage.

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* in Japanese with English summary

作物の雹害被害率からみた雹の粒度分布の特徴

清　野　　豁

（九州農業試験場，福岡県筑後市和泉496）

要　　約

簡単な降雹記録計（Hailpad：HP）から求められる雹粒の運動エネルギーが作物の被害率と密接に関係することがこれまで報告されている。雹粒の粒度分布（空間密度分布）も運動エネルギーと同様に，被害率に関係づけられる要因の一つであると考えられる。しかしHPは時間の情報を含まないので，時間の関数である空間密度分布を直接計算することはできない。本文では1975年6月9日の群馬県新田町付近の降雹による幅約4 km，長さ約8 kmの被害域のHPデータ（小元・清野，1978）を用いて，この領域の平均的な降雹継続時間の推定を試みた。さらにこの継続時間を用いてHPデータから得られる粒径頻度分布を空間密度分布に変換し，被害率と関連づけてその特徴を調べた。粒度分布の計算に際して，5段階に分類された各被害領域の降雹継続時間は推定された平均降雹継続時間に等しいと仮定し，各観測点のHPデータを被害別に分類し平均化した。推定された各粒度分布にMarshall and Palmer（1948）とShiotsuki（1975）の粒度分布式をあてはめ，これらの式中のパラメータと被害率の関係を調べた。結果は次のように要約される。

1）本来時間の情報を含まないHPデータから，被害域内の平均的な降雹継続時間を推定することができた。

2）雹粒の空間密度は被害率の増大に伴い増加した。とくに被害率70％以上になるとその増加度合が大きくなった。この傾向は二つの粒度分布式中のパラメータと被害率の関係からもよく説明された。

3）各粒度分布の最大直径は被害率に必ずしも比例しないが，被害率70％以上とそれ以下の各被害率別粒度分布の最大直径間には明らかな差が見られた。

4）各粒度分布はShiotsuki（1975）の式により良く近似された。とくにその式を用いて計算される運動エネルギーフラックス等の降雹パラメータは原分布から計算される値に非常に近いものであった。

5）二つの粒度分布式中のパラメータのうち，Shiotsuki（1975）の粒度分布式における，各観測点毎に求められた粒度分布の平均直径$\bar{D}$の分布は作物の被害率の分布と良く一致した。

上記の結果から被害率に密接に関係するパラメータとして新しく$\bar{D}$が加えられた。$\bar{D}$はHPデータから直接求められるパラメータであるので，HPの有用性はさらに高まると考えられる。