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The relation between raindrop size distribution, rate of rainfall and the electrical charge carried down by rain in the tropics*

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(*Received 20 February 1959*)

ABSTRACT. Best (1953) has shown from an analysis of data from *Geophys. Mem.*, No. 84 (Simpson 1949) that consideration of the drop size distribution in rain leads to the non-linearity of the relation between rain current (total charge brought down by rain per sq. cm per second) and rate of rainfall. The purpose of the present paper is to show the same conclusions as reached by Best but with some slight modifications. It is shown that a knowledge of rain current is also necessary to find out the variation in drop size distribution between two rain measurements, especially when both the liquid water content and intensity of rainfall are same in both cases. Further the origin of rain, whether from freezing or non-freezing clouds, can be clearly brought out from a knowledge of the electric charge carried by rain. The difference in the electricity carried by precipitation *with and without point discharge* has been shown.

1. Introduction

It has been pointed out by the author in an earlier paper (1959) that numerous workers (Marshall and Palmer 1948, Spilhaus 1948, Laws and Parsons 1943, Best 1950) have developed empirical relations to represent drop size distributions in relation to intensity of rainfall. These no doubt show the general nature of the distribution of drops with intensity of rainfall, but the individual characteristics of any particular type of precipitation observed have not completely been brought about. The distribution observed at the ground is an equilibrium distribution attained by the rain after getting modified in the intervening space between the level of origin of precipitation and the ground. The size distribution of raindrops at the level of origin depends on the precipitation mechanism and other physical factors such as water content of the cloud, updraught, and thickness of cloud etc. Mason and Ramanadham (1954) have theoretically examined the observed variations in the distribution at the ground due to three main causes—(*a*) The growth of raindrops by accretion with cloud droplets, (*b*) Coalescence between raindrops of different sizes and (*c*) Differential rates of evaporation of raindrops of different sizes, when falling between cloud base and ground.

An examination of these factors has been made by Rigby and Marshall (1951) on the assumption that the drop size distribution at the level of origin is the same as that observed at the ground level, who concluded that these factors cannot be of major importance in determining the drop size spectrum.

Blanchard (1953) in a detailed study of raindrop size distribution in Hawaiian rains has found considerable change in the drop size distribution of rain as it falls from cloud to ground due to wind shear, gravity separation, evaporation and drop collision. The evaporation problem was eliminated and the others minimised by sampling all the orographic rain at *cloud base* or *within cloud* itself. He has used the liquid water content W as a measure of drop distribution. The differences in drop size distribution, liquid water content, median volume diameter and

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*This paper forms a part of the thesis supplicated by the author for his Ph. D. degree to the Universty of Madras in January 1959 radar reflectivity of rains from freezing and non-freezing clouds have been clearly brought about. For a given intensity in an orographic rain, the median volume diameter is about half that found in thunderstorm and frontal type rains.

Best (1953) has shown from an analysis of data from *Geophys. Mem.* No. 84 (Simpson 1949) that consideration of the drop size distribution in rain leads to the non-linearity of the relation between rain current and rate of rainfall. The purpose of the present paper is to show the same conclusions reached by Best, but with some slight modifications. It is not always convenient to compare two sets of rain measurements by comparing their drop size distribution. In the present paper it is shown that a knowledge of the rain current, *i.e.*, the total charge brought down by rain per sq. cm per second, is also necessary to find out the variation in drop size distribution between two rain measurements, especially *when both the liquid water content and intensity of rainfall* are same in both cases. Further the origin of rain whether from freezing or non-freezing clouds can be clearly brought about from a knowledge of the electric charge carried by rain. These are explained below from a study of the records taken at Poona.

2. Relation between rate of rainfall, rain current and drop size distrbution

Drop size distribution—It has been shown by Best (1950) that the size distribution of raindrops can be described by

$$F=1-\exp\left[-(x/a)^n\right] \qquad (1)$$

when F=fraction of liquid water in the air comprised by drops with diameter less than x; a and n being constants. The parameter

$$a=A\times R'^p$$

where $A=1\cdot30$, R' =rate of rainfall in mm/hr, and $p=0\cdot232$ and, therefore, varies with the rate of rainfall. No relation has been found between n and the rate of rainfall.

If W=the liquid water concentration on the air in cubic millimetres per cubic metre, the volume of water comprised by drops with diameter between x and $x+dx$ is

$$=W\times\left(\frac{\partial F}{\partial x}\right).\,dx$$

The number of drops with diameter between x and $x+dx$ is

$$=\frac{6W(\partial F/\partial x)dx}{\pi x^3}$$

$$=\frac{6Wnx^{n-4}\exp\left[-(x/a)^n\right]dx}{\pi a^n} \qquad (2)$$

Rate of rainfall—If R'=rate of rainfall in mm|hr and V=terminal velocity of a drop of diameter x (mm) in m/sec, we have

R'=No. of drops × volume × terminal velocity per hour

$$=\frac{1}{6}\pi\,\Sigma\,N x^3 V$$

$$\text{or, } R' = \frac{6Wn}{\pi a^n}\int_0^\infty x^{n-4}\ \exp\left[-(x/a)^n\right]dx \times \tfrac{1}{6}\,\pi x^3 \times V \times 3600 \times 10^3 \times 10^{-9}$$

$$= 36 \times 10^{-4}\ \frac{Wn}{a^n}\int_0^\infty x^{n-1}\ \exp\left[-(x/a)^n\right]V\ dx \ \text{ mm/hr.} \tag{3}$$

Rain current—Rain current i=total quantity of electricity falling per sq. cm/sec. If each drop carries a charge $K.\ x^2$ e.s.u., we have $K = -3X/400$ [for, the maximum theoretical charge for a drop radius $\left(\frac{x \text{ cm}}{20}\right)$ is $-3\,X\,(\text{radius})^2$ as per Whipple and Chalmer's theory (1944)] $= -\frac{3X.x^2}{400}$ where X = electric field in e.s.u. We have from equation (2) the total number of drops per metre (10^6 c.c.) of air between x and $(x+dx)$

$$= \frac{6W\ n\ x^{n-4}\exp\left[-(x/a)^n\right]dx \text{ drops}}{\pi\ a^n}$$

∴ The total charge per sq. cm per second, *i.e.*, rain current

$$i = \int_0^\infty \frac{W\ n\ x^{n-4}\ \exp\left[-(x/a)^n\right]dx}{\pi\ a^n} \times \frac{100 \times V}{10^6} \times Kx^2$$

$$\textit{i.e.},\ i = \frac{6W\ n\ K}{\pi a^n} \times \frac{100}{10^6}\int_0^\infty x^{n-4}\ x^2 \exp\left[-(x/a)^n\right] V dx \ \text{ e.s.u. cm}^{-2}\ \text{sec}^{-1} \tag{4}$$

$$\text{From equation (3), } \int_0^\infty x^{n-1}\exp\left[-(x/a)^n\right]Vdx = \frac{R'}{36 \times 10^{-4} \times \frac{Wn}{a^n}} \tag{5}$$

$$\text{From equation (4), } \int_0^\infty x^{n-2}\ \exp\left[-(x/a)^n\right] Vdx = \frac{i}{6 \times 10^{-4} \times \frac{WnK}{\pi a^n}} \tag{6}$$

$$\textit{i. e.,}\ \frac{\int_0^\infty x^{n-2}\ \exp\left[-(x/a)^n\right] Vdx}{\int_0^\infty x^{n-1}\ \exp\left[-(x/a)^n\right] Vdx} = \frac{i \times \pi a^n}{6 \times 10^{-4} WnK} \times \frac{36 \times 10^{-4} \times Wn}{R' \times a^n}$$

$$= \frac{i \times 6\pi}{KR'} \tag{7}$$

If $H(p, n) = \int_{0}^{\infty} x^{p} \exp[-(x/a)^{n}]\, V dx$,

we can write equation (7) as

$$i = R' \frac{K}{6\pi} \cdot \frac{H(n-2, n)}{H(n-1, n)} \qquad (8)$$

Best (1953) has proved by logarithmic methods that

$$\frac{H(n-2, n)}{H(n-1, n)} = B a^{t} \qquad (9)$$

where B and t depend upon the value of n.

Combining equations (8) and (9), we have

$$i = R' \frac{K}{6\pi} B a^{t} \qquad (10)$$

Using Best's equation:

$$W = 67 (R')^{0 \cdot 846} \qquad (11)$$

we can show $R' = 36 \times 10^{-4} A\, W\, n\, a^{s-n}$ (12)

where A and s depend upon the value of p and n. Substituting from equation (11) we have:

$$(R')^{0.154} = 0 \cdot 241\, A\, n\, a^{s-n} \qquad (13)$$

$$\therefore \left(\frac{6\pi i}{R'KB} \right)^{\frac{1}{t}} = \left[\frac{(R')^{0.154}}{0 \cdot 241 A n} \right]^{\frac{1}{s-n}}$$

If $n = 2$, Best (1953) has calculated the values as follows

$B = 1 \cdot 111$, $t = -0 \cdot 87$,

$A = 1 \cdot 875$, $s = 2 \cdot 53$

$$\frac{6\pi i}{1 \cdot 111 \times K} = R'^{3/4} \,.\, (0 \cdot 9)^{1 \cdot 6}$$

$$\frac{17}{K} \times i = R'^{3/4} \,.\, (0 \cdot 84)$$

$$\begin{aligned} i &= K . R'^{3/4} \,.\, (0 \cdot 05) \\ &= C . R'^{3/4}, \text{ where } C = 0 \cdot 05K \\ &= C (R')^{0.75} \end{aligned} \qquad (14)$$

$$\text{or} \quad 10^{4} \frac{C}{K} = 500 \text{ (approx.)}$$

$$K = \frac{-3\,(X)}{400}$$

where X = electric field in e.s.u.

$$i \text{ (calculated)} = \frac{-0 \cdot 05 \times 3(X) \times R'^{3/4}}{400} \qquad (15)$$

$$= -37 \cdot 5 \times (X) R'^{3/4} \times 10^{-5} \text{ e.s.u./sq. cm/sec.}$$

$$\text{or approximately} = -40 (X) R'^{3/4} \times 10^{-5} \text{ e.s.u./sq. cm./sec.}$$

3. Comparison with actual observations

Tables 1(a) and 1(b) give the summary of observations of the electricity carried by precipitation with and without point discharge current I. In Fig. 1, the data for a typical thunderstorm on 27-28 September 1955 have been used to plot log i/I against log R'. Using the method of least squares, two lines of best fit, as was done by Best for Simpson's data have been computed. The equations for these two lines are—

$$i/I = 12 \cdot 84 \times 10^{-8} \times (R')^{0.7} \qquad (16)$$

$$i/I = 2 \cdot 59 \times 10^{-8} \times (R')^{1.31} \qquad (17)$$

It has already been found by Sivaramakrishnan (1959) by purely empirical methods that

$$i/I = 9 \cdot 732 \times (R')^{0.7} \times 10^{-8} \qquad (18)$$

Equation (14) indicates that i varies as $(R')^{r}$ where r has a value of $0 \cdot 75$, which differs little from equation (16).

4. Discussion

Best was not interested in calculating the absolute value of i, the rain current, but only with the variation of i as R' varies. But here we want to show that for the same liquid water content and same rate of rainfall in two sets of rain measurements the rain currents in the two sets are found to be different, probably due to the difference in the *drop size* distribution in the two cases.

Fig. 2 shows portions of records of potential gradient, point discharge current, rain charge

TABLE 1(a)

Summary of observations of electricity carried by precipitation when point discharge occurs

R' (rate of rainfall in mm hr^{-1}) a (average radius of raindrop in mm given in brackets)	i e.s.u.		q e.s.u.		I e.s.u.		P V/cm		i/I	Q e.s.u.		Q/I	Q/a^2
	+	−	+	−	+	−	+	−		+	−		
	$\times 10^{-5}$				$\times 10^{3}$				$\times 10^{-8}$	10^{-3}		$\times 10^{-6}$	
2 (0·416)	11·35 (6)	7·57 (9)	1·73 (6)	1·96 (9)	0·641 (11)	0·632 (4)	6·4 (9)	5·0 (6)	12·69 (15)	0·53 (6)	0·44 (9)	0·90 (15)	0·31
3 (0·461)	12·50 (22)	9·40 (9)	1·64 (22)	1·04 (9)	0·399 (8)	0·916 (27)	5·5 (10)	10·3 (21)	18·79 (31)	0·67 (19)	0·44 (7)	0·96 (26)	0·31
4 (0·495)	35·25 (14)	14·51 (23)	3·43 (14)	1·21 (23)	0·211 (12)	0·601 (27)	5·7 (13)	8·5 (23)	62·10 (35)	0·45 (14)	0·31 (30)	2·3 (34)	0·18
5 (0·527)	14·48 (12)	12·53 (9)	1·02 (12)	0·94 (9)	0·737 (13)	0·508 (11)	9·9 (15)	10·8 (10)	32·21 (17)	0·52 (11)	0·56 (8)	1·5 (19)	0·19
6 (0·548)	24·17 (7)	17·04 (8)	1·46 (7)	0·98 (8)	0·522 (13)	1·254 (7)	8·4 (8)	9·8 (9)	58·84 (13)	0·97 (7)	0·52 (6)	1·97 (13)	0·32
7·5 (0·580)	32·9 (7)	22·9 (14)	1·05 (7)	0·88 (14)	0·443 (3)	0·868 (22)	5·3 (8)	6·8 (17)	68·61 (20)	1·15 (2)	0·71 (19)	1·38 (21)	0·34
10 (0·623)	33·49 (24)	24·17 (14)	1·19 (24)	0·86 (14)	0·510 (6)	1·026 (35)	6·0 (5)	5·5 (33)	55·68 (36)	1·32 (26)	1·04 (9)	1·6 (36)	0·34
15 (0·689)	38·60 (40)	23·23 (28)	0·94 (40)	0·54 (28)	0·575 (8)	0·974 (62)	3·7 (14)	6·8 (52)	77·06 (66)	1·41 (38)	0·70 (26)	1·94 (64)	0·29
30 (0·820)	51·70 (21)	25·25 (6)	0·60 (21)	0·30 (6)	0·479 (5)	0·652 (25)	3·5 (3)	4·7 (25)	99·31 (24)	1·28 (18)	0·60 (5)	2·50 (23)	0·19
45 (0·907)	62·77 (7)	29·37 (4)	0·54 (7)	0·23 (4)	0·266 (3)	0·599 (8)	3·3 (3)	4·1 (8)	169·41 (11)	1·49 (8)	0·75 (2)	2·8 (10)	0·18
60 (0·975)	108·1 (9)	.. (0)	0·63 (9)	.. (0)	0·266 (1)	0·449 (8)	3·3 (6)	2·8 (3)	564·23 (8)	2·47 (9)	..	3·1 (5)	0·26
75 (1·031)	95·16 (5)	56·40 (1)	0·50 (5)	0·26 (1)	0·266 (1)	0·505 (5)	3·3 (4)	1·3 (1)	353·8 (6)	2·67 (6)	..	3·6 (4)	0·25
90 (1·079)	25·85 (2)	.. (0)	0·10 (2)	.. (0)	0·266 (2)	.. (0)	4·6 (1)	.. (0)	97·2 (2)	0·4 (1)	..	1·4 (1)	0·34
Total No. of observation	(176)	(125)	(176)	(125)	(86)	(241)	(99)	(208)	(284)	(151)	(127)	(270)	
Mean of all observations	38·52	18·9	1·22	0·86	0·487	0·832	5·93	6·97	83·88	1·2	0·5	2·02	0·27

Figures in brackets indicate the number of cases

i = Rain current in e.s.u. /cm^2/sec

q = Charge per c.c.

I = Point discharge current in e.s.u./sec

P = Potential gradient in V/cm

Q = Charge per single drop (charge per c.c. × mean mass of raindrop)

TABLE 1(b)

Summary of observations of electricity carried by precipitation when point discharge does not occur

(Mean value of P.D. = –4 V/cm)

R' (rate of rainfall in mm hr^{-1}) a (average radius of raindrop in mm given in brackets)	i (e.s.u.) $\times 10^{-5}$ +	i (calculated) $= -0\cdot194\times10^{-5} \times (P-1)\,R'$ +	q (e.s.u./cm^3) +	P (V/cm) —	Q (e.s.u.) $\times 10^{-3}$ +
5 (0·527)	7·6 (21)	5·9 (21)	0·67 (21)	3·00 (21)	0·5 (21)
10 (0·623)	8·3 (21)	7·3 (21)	0·38 (21)	2·75 (21)	0·4 (21)
15 (0·689)	14·4 (99)	16·0 (99)	0·50 (99)	4·50 (99)	0·7 (99)
30 (0·820)	31·5 (26)	28·1 (26)	0·37 (26)	3·70 (26)	0·7 (26)
45 (0·907)	53·7 (26)	44·3 (26)	0·42 (26)	4·70 (26)	1·1 (26)
60 (0·975)	59·3 (21)	57·1 (21)	0·40 (21)	4·00 (21)	1·1 (21)
75 (1·031)	118·1 (15)	170·3 (15)	0·50 (15)	5·20 (15)	2·2 (15)
90 (1·079)	200·2 (5)	109·3 (5)	0·78 (5)	5·30 (5)	4·0 (5)
105 (1·121)	115·9 (3)	103·9 (3)	0·39 (3)	4·1 (3)	2·3 (3)
Total No. of observations	237	237	237	237	237
Mean of all observations (without point discharge)	67·7	60·2	·49	4·14	1·4

Figures in bracket indicate number of cases

i = Rain current in e.s.u./cm^2/sec q = Charge per c.c. P = Potential gradient in V/cm

Q = Charge per single drop (charge per c.c. × mean mass of raindrop)

TABLE 2

	Period (Hrs)	Rain current $i \times 10^{-5}$ e.s.u./sq.cm/sec —calculated using Eq. (15) +	Rain current $i \times 10^{-5}$ e.s.u./sq.cm/sec —observed +	q (e.s.u./cm^3) +	Q $\times 10^{-3}$ (e.s.u.) +	P (V/cm) —	R' (rate of rainfall) (mm/hr)	W (liquid water content) (mm^{3}m^3)
27 Sep 1955	2259-2300	13·9	79·9	1·87	2·6	—13·7	15	839·9
	2325-2326	6·6	65·8	1·54	2·1	—6·5	15	839·9
	2326-2327	8·6	150·4	3·52	4·8	—8·5	15	839·9
	2329-2330	5·99	105·4	2·42	3·3	—5·9	15	839·9

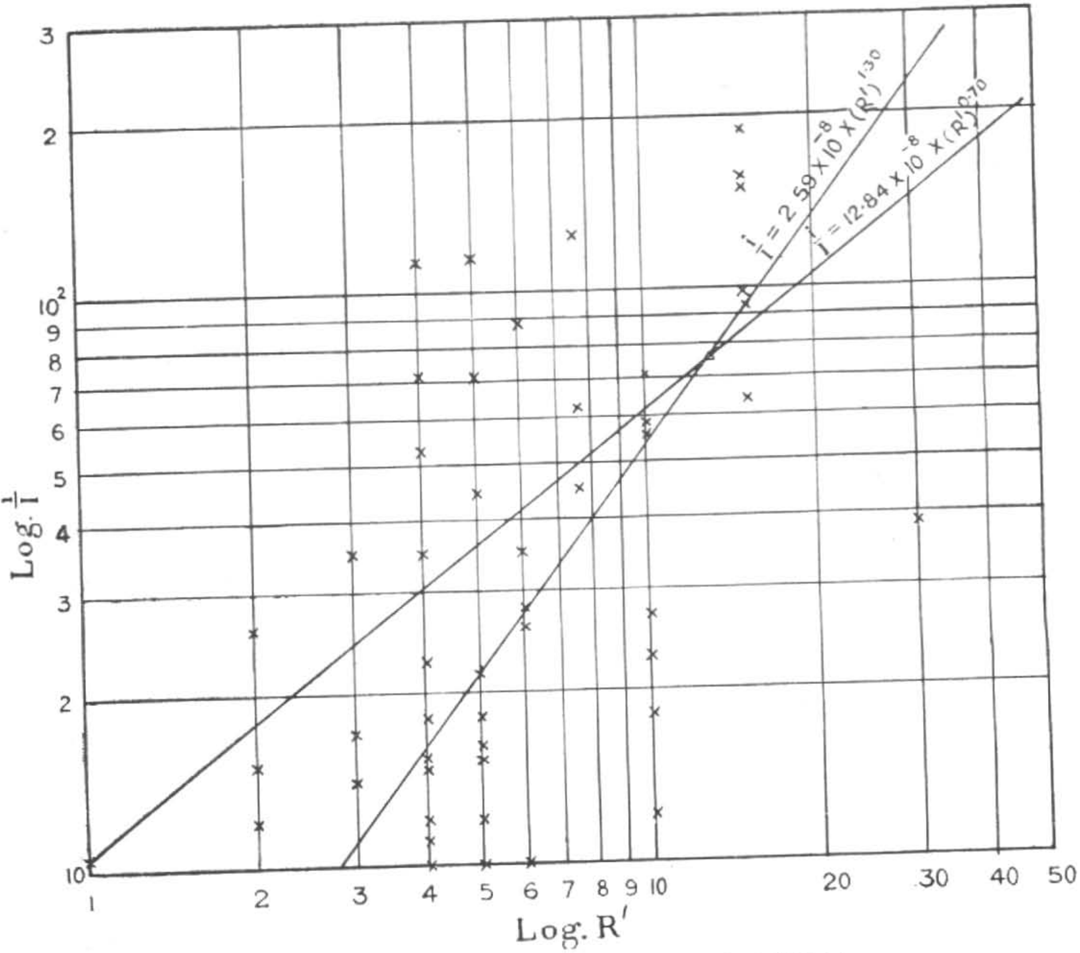


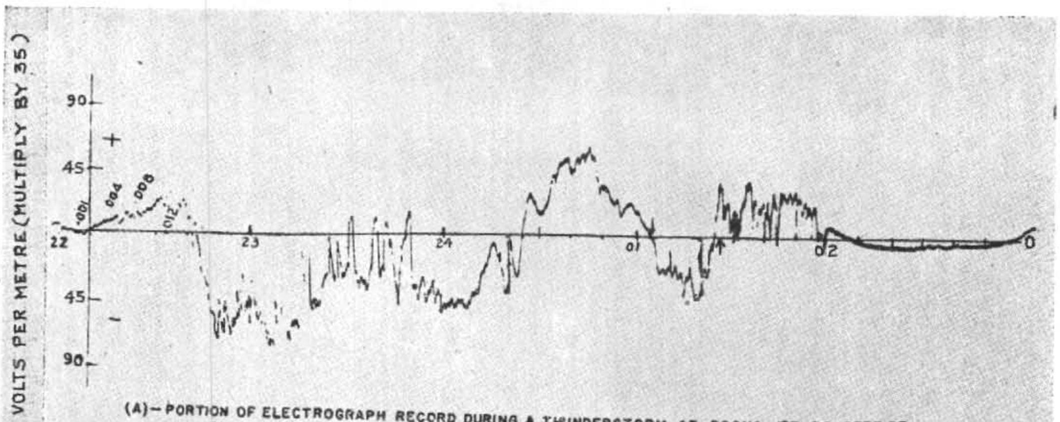
Fig. 1. Relation between rain current (i) and rate of rainfall (R')

and rainfall during a severe thunderstorm on 27-28 September 1955 at Poona. The following interesting points are clearly brought about by the above records—

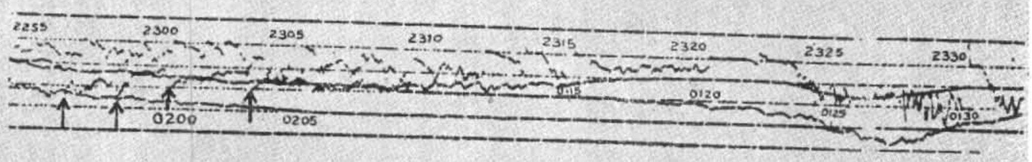
(1) The intensity of rainfall and liquid water content at 2259-2300, 2325-2326, 2326-2327 and 2329-2330 hrs are same but the rain currents i for the above periods are not the same. The respective values of i, potential gradient P, charge per c.c. average charge per drop Q are given in Table 2.

It is clear from Table 2 that consideration of rain current also is necessary for the measurement of drop size distribution. But the calculated and observed values of i are not same but widely different. It has already been observed at Poona by the author (1959) that the observed values of electric charge of rain-drops are found to be more than six times the theoretical maximum charge—$3X$. $(\text{radius})^2$ found by Whipple and Chalmers (1944). The real cause for this difference between calculated and observed i is not clear from the present series of measurements.

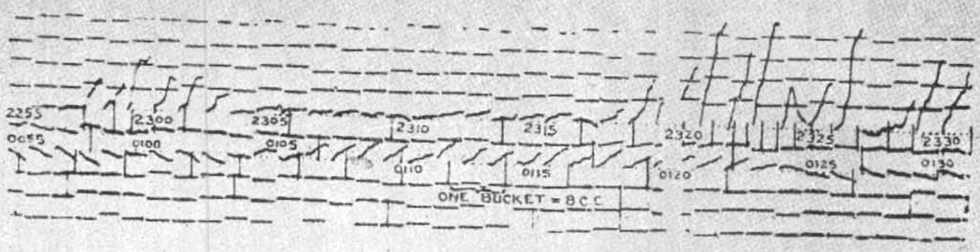
(2) The time lag between field change and onset of rain on 27 September 1955 is about 15 minutes and therefore as per Workman



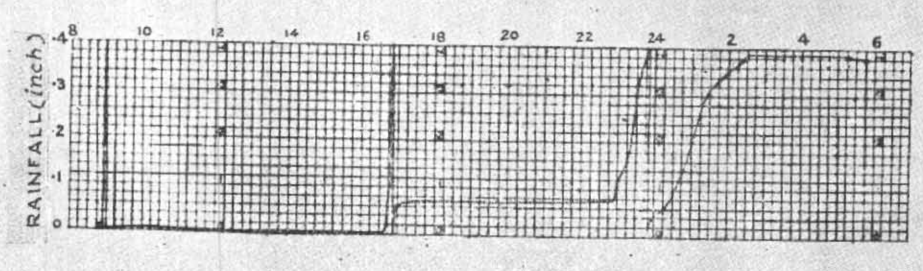
(A)— PORTION OF ELECTROGRAPH RECORD DURING A THUNDERSTORM AT POONA 27-28 SEPT 55



(B)— PORTION OF THE POINT DISCHARGE RECORD CORRESPONDING TO (A) SCALE ↕=1 MICROAMPERE ↑ POSITIVE



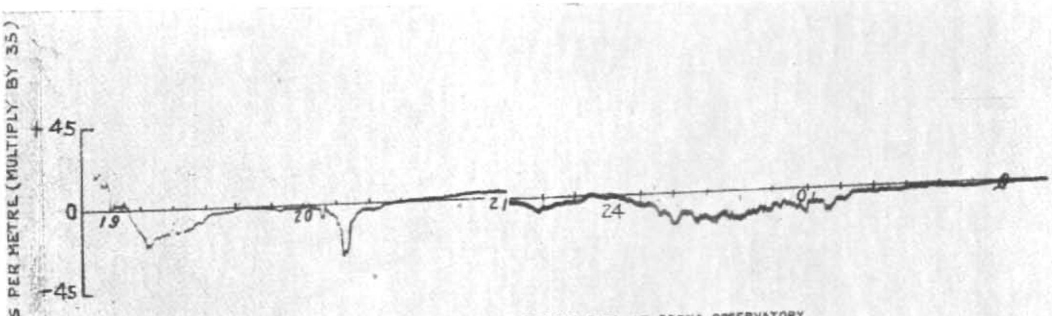
(C)— PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO (A) AND (B) ↑ POSITIVE



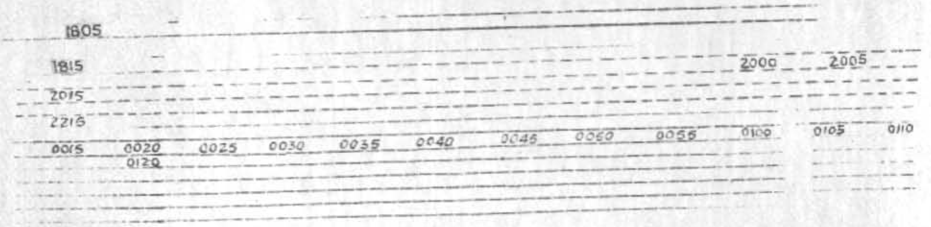
(D)— NATURAL SYPHON RAINGAUGE RECORD CORRESPONDING TO (C)

Fig. 2. Portions of potential gradient, point discharge current, rain electrograph and natural syphon raingauge records during a thunderstorm on 27—28 September 1955 showing simultaneous change in the sign of rain charge and field (mirror image effect) at 0105 and 0123 IST and not wih the point discharge current at those times

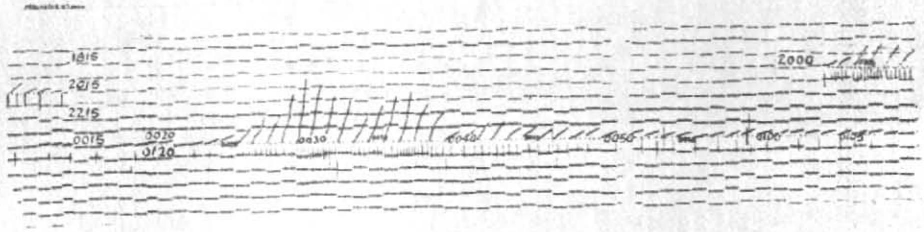
The records show lightning impulses at 2356, 2358, 2400 and 0004 hrs, but rain drops during these periods are found to have no electrical charge



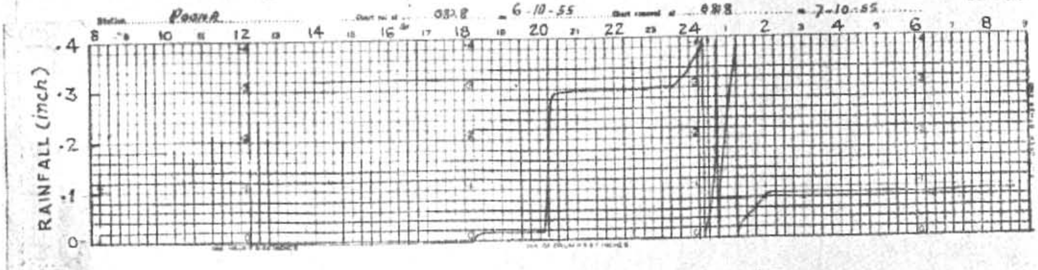
A — PORTION OF ELECTROGRAPH RECORD DURING CONTINUOUS RAIN AT POONA OBSERVATORY



B — PORTION OF THE POINT DISCHARGE RECORD CORRESPONDING TO FIG A — SCALE ↕ = 1 MICROAMPERE ↑ POSITIVE



C — PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO FIG 'A' 'B'



D — NATURAL SYPHON RAINGAUGE RECORD CORRESPONDING TO FIG 'C'

Fig. 3. Portions of potential gradient, point discharge current, rain electrograph and natural syphon raingauge records during continuous rain on 6-7 October 1955 showing positive charge only on raindrops with low *negative* potential gradient and *without point discharge*

and Reynolds (1949) the height of fall of raindrops, assuming a terminal velocity of $4\cdot6$ metres for a rate of rainfall of 10 mm/hr is $15\times60\times4\cdot6=$*4140 metres*. The average drop size of raindrop for a rate of rainfall of 10 mm/hr is $1\cdot880$ mm.

From 2303 to 2315 hrs the raindrops are found to have little charge. The rate of rainfall during the period is about 4 mm/hr and assuming a terminal velocity of $3\cdot9$ m sec^{-1}, the distance of fall of raindrops may be taken as $14\times60\times3\cdot9=$ *3276 m* and so the origin of these raindrops is below the freezing level (freezing level as per radiosonde ascent taken at 2000 hrs on 27 September 1955 is 4900 m a.s.l.). It is, therefore, probable that these raindrops are not electrically charged, because their origin is below the freezing level.

(3) Again between 2326-2327 hrs the raindrops are highly charged and in the next minute, *i.e.*, between 2327 to 2328 hrs the raindrops are not charged though the rate of rainfall is practically same in both these cases. These are probably due to the production of raindrops due to Langmuir's (1948) 'chain reaction process' which postulates the existence of updrafts and cloud thickness exceeding a critical value. Raindrops are presumed to grow to a point where turbulance or drop collision causes breaking into two or more smaller drops which in turn repeat the same process. If the origin of these drops is below the freezing level, it is probable that the drops do not have any electrical charge.

(4) A perusal of Fig. 2 shows that from 2357 to 0030 hrs the rain drops are found to have no electrical charge as the origin of these drops appear to be below freezing level due to the rate of rainfall being below 2 mm hr^{-1} and terminal velocity about $3\cdot2$ m sec^{-1}. It is surprising to see however from the point discharge record that lightning impulses are seen at 2356, 2358, 2400 and 0004 hrs though the raindrops during these periods are found to have no electrical charge.

(5) Again from 0055 to 0122 hrs the rate of rainfall is nearly 5 mm hr^{-1} and the rain current also is practically same, but the sign of the rain current changes at 0105 hrs from negative to positive synchronous with the field change in the opposite direction, *i.e.*, from positive to negative in accordance with the mirror image effect (Simpson 1949, Sivaramakrishnan 1957). These clearly show that rain currents of two rain measurements depend upon the field also.

(6) It is seen from Table 1 and Fig. 3 that rain always carries *positive electricity* when point discharge *does not occur*. The charge per c.c. of rain q is independent of the rate of rainfall in this case, whereas during point discharge the charge on rain q is proportional to (a) the rate of rainfall R' for constant point discharge, (b) the point discharge current I for constant rainfall. The sign of the charge on rain may be postive or negative depending upon the the sign of the potential gradient. They are opposite in sign, showing the mirror image effect of Simpson (1949).

(7) During point discharge, the rain current (Eq. 16) is proportional to the square of the potential gradient [for $I=a(P^2-M^2)$, where $a=$constant, $M=$minimum field for onset of point discharge and $P=$ potential gradient in V/cm]. Whereas without point discharge, the current is proporational to the *displacement* of the potential gradient *from the fine weather field* [for $i=-0\cdot194(P-1)R'\times10^{-5}$ e.s.u., 1 volt/cm being the normal fine weather field at Poona].

(8) The rain current is proportional to $R'^{3/4}$ (approx.) *during point discharge* but proportional *to R' without point discharge.*

(9) The charge per drop Q is proportional to the square of the radius of drop [$Q/a^2=$ constant$=\cdot27$] during point discharge.

The above factors have to be borne in mind in deducing the relation between rain current, the rate of rainfall and the drop size distribution in rains.

5. Acknowledgement

I am thankful to Shri S. P. Venkiteshwaran, Director (Instruments), Meteorological Office, Poona, for giving me necessary facilities for this investigation.

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