The Ratio of Cloud to Cloud-Ground Lightning Flashes in Thunderstorms

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ABSTRACT

Observations of the ratio of cloud to cloud-ground lightning flashes in thunderstorms have been reviewed, and used to obtain empirical relationships between this ratio (z), latitude (λ) and annual thunderdays (T). The 29 observations, covering a latitude range 69°N to 37°S, gave a mean value of z of 3.35. The empirical relationship proposed between z and λ is

$$z(\lambda)=4.16+2.16\cos 3\lambda,\quad 0\leqslant\lambda\leqslant 60^\circ.$$

From 26 pairs of values of z and T, covering the range 5 to 81 thunderdays per year, the proposed relationship is

$$\begin{aligned} z(T)&=1.0+0.063T, && 10\leqslant T\leqslant 84\\ z&=6.3, && T>84. \end{aligned}$$

Information on z for high latitudes is sparse. It is probable that z lies between 1 and 2 for $\lambda>60^\circ$ and $T<10$.

The existence of a relationship between z and T is attributed to the fact that both are related to latitude. The relationship between z and λ probably depends on the variation of freezing level height with latitude, and a possible relationship between z and freezing level height is examined.

Where both λ and T are known, the proposed estimate of z for λ up to 60° and T up to 84 is

$$z(\lambda,T)=(4.16+2.16\cos 3\lambda)[0.6+0.4T/(72-0.98\lambda)].$$

1. Introduction

The literature on the ratio z of cloud to cloud-ground lightning flashes has been reviewed, and the data obtained are summarized in Table 1. The term "cloud flash" includes all flashes which do not terminate at the earth's surface, *viz.*, intra-cloud, inter-cloud and cloud to air. The term "cloud-ground" flash (or simply ground flash used henceforth) applies to flashes between cloud and earth, and includes composite flashes with at least part of the discharge between cloud and ground. Most data on the ratio of cloud flashes to ground flashes have been obtained incidently to general studies of thunderstorms either visually, or by analysis of electric field changes, or from automatic counting devices triggered by lightning flashes. Specific studies of the ratio have been made as part of research programs on lightning-caused forest fires, using visual and field change observations. The very large differences in the ratio between thunderstorms in one locality and the variation in the ratio during the progress of a single thunderstorm add to the difficulty of obtaining representative values.

It is assumed that, at any locality, a long-term mean value of z exists, which may be expressed as $\overline{N_c/N_g}$ where N_c and N_g are the densities, in flashes per unit area and time, for cloud and ground flashes respectively. Any reported value of the ratio contributes toward estimating the long-term mean, subject to various errors discussed below.

2. Estimates of ratio from visual observations

Experience with observations at a lightning observatory in Brisbane, Australia, is probably not very different from that elsewhere. A relatively large number ($\sim$80%) of flashes cannot be classified with confidence. Visibility problems may be caused by daylight, precipitation and obstructions. Ground flashes can be identified with least uncertainty. Inter-cloud flashes can be classified with confidence when the mainly horizontal discharge channels are visible. Intra-cloud flashes are the commonest type of flash, but are the least easy to identify with certainty. Some are sufficiently high to be classified, but distant intra-cloud flashes often cannot be distinguished from distant ground flashes obscured behind precipitation. As the probability of identifying a ground flash is greater than that of identifying a cloud flash, an estimate of z based purely on the numbers of identified flashes is likely to be less than true value.

On the other hand, if an observer classifies as cloud flashes all events in which a channel to ground is not visible, z will be overestimated. Thus visual estimates of z can err in either direction, and this partly accounts for the scatter in values shown in Table 1.

TABLE 1. Ratio of cloud flashes to cloud-ground flashes.

								Observations			Annual Thunderdays T		
Item	Location of observations	Country	Height above sea level (m)	Latitude λ	Longitude	Source	Method (1)	Period	Number of flashes	Number of storms	During period of observations	Long-period average (2)	Ratio z C to C-G flashes
1	Singapore	Singapore	11	2°N	104°E	Wang (1963)	FC	1950–51	1 340	37	—	171	5.0**
2	Zaria	Nigeria	—	11°N	8°E	Perry*		—		—	—	81	7.0
3	Bangalore	India	900	13°N	78°E	Aiya and Sonde (1963)	FC+LFC +V	1962–63	—	—	—	46	9.0
4	Salisbury	Rhodesia	1500	18°S	31°E	Anderson**	FC	1962–63	1 083	—	—	65	2.2
5	Near Salisbury	Rhodesia	1300	19°S	30°E	Anderson and Jenner (1954)	LFC	1953–54	—	72	—	65	5.5
6	Brisbane	Australia	8	27°S	153°E	Prentice and Mackerras (1969)	V+LFC	1959–69	10 000	—	—	30	3.5
7	Somerset East	S. Africa	740	33°S	26°E	Schonland and Craib (1927)	FC	1926	798	18	—	—	5.0***
8	Somerset East	S. Africa	740	33°S	26°E	Schonland (1928)	V	1926–27	2 625	—	—	—	9.5***
9	Beppu	Japan	—	33°N	131°E	Tamura (1940)	FC	1938	2 487	—	—	25	3.4
10	Kyoto	Japan	43	35°N	135°E	Tamura (1940)	FC	1933	4 034	—	—	30	2.1
11	New Mexico	U.S.A.	—	~35°N	—	Fuquay (1962b)	V	1961	—	13	—	47	1.6
12	Maebashi	Japan	—	36°N	139°E	Takeuti (1965)	FC	1963	—	13	—	30	2.0
13	Gunma Ken	Japan	113	37°N	139°E	Ishikawa (1960)	FC	—	1 265	—	—	30	3.0
14	Auckland	New Zealand	25	37°S	174°E	Kreielsheimer and Lodge-Osborn (1971)	FC	1966–69	577	—	—	15	2.7
15	Washington–Oregon	U.S.A.	—	43°N	123°W	Morris (1934)	V	1925–31	4 800	—	25	25	1.6
16	Tessin	Switzerland	—	46°N	9°E	Muller-Hillebrand (1963)	FC	1960–61	4 761	24	47	—	3.3
17	Missoula†	U.S.A.	2000–2500	47°N	116°W	Barrows (1962)	V+FC	1958–59	—	—	—	30	3.0
18	Missoula†	U.S.A.	2000–2500	47°N	116°W	Fuquay (1962a)	FC	Pre 1962	—	—	—	30	1.5
19	Missoula†	U.S.A.	2000–2500	47°N	116°W	Fuquay (1962b)	FC	1960–61	5 300	—	—	30	1.65
20	Missoula†	U.S.A.	2000–2500	47°N	116°W	Fuquay and Baughman (1969)	FC	1965–67	13 850	—	—	30	3.8
21	Rostov	U.S.S.R.	77	47°N	40°E	Semjenov (1967)	V	1964–65	1 729	—	23	25	2.7
22	Kiev	U.S.S.R.	179	50°N	30°E	Semjenov (1967)	V	1964–65	694	—	22	30	5.8
23	Cambridge	U.K.	85	52°N	0	Pierce (1955)	FC	—	—	—	—	14	1.6
24	Cambridge	U.K.	85	52°N	0	Wormell (1939)	FC	Pre 1939	500	—	—	14	1.7
25	L. Baikal	U.S.S.R.	1000	54°N	108°E	Filippov *et al.* (1972)	V	1968	4 066	91	—	20	2.0
26	Moscow	U.S.S.R.	156	56°N	38°E	Semjenov (1967)	V	1964–65	441	—	17	28	2.4
27	Leningrad	U.S.S.R.	4	60°N	30°E	Semjenov (1967)	V+FC	1959–64	573	—	23	16	1.8
28	Uppsala	Sweden	15	60°N	18°E	Muller-Hillebrand (1963)	FC	1960–61	319	4	—	11	1.9
29	Murmansk	U.S.S.R.	46	69°N	33°E	Semjenov (1967)	V	1964–65	140	—	7	5	0.9

(1) V = visual; FC = field change; LFC = lightning flash counter.
(2) Long-period averages for annual thunderdays obtained from World Meteorological Organization (1956).
† Stations in vicinity of Missoula.

* Private communication (1973).
** Private communication (1971).
*** Omitted from computer data for z vs T regression analysis.

3. Estimates of ratio by indirect methods

The method based on examination of field changes requires identification of a characteristic feature in recordings of the electromagnetic field change produced by lightning which will distinguish cloud flashes from ground flashes. Some workers have associated the sign of the field change with the identity of the discharge, based on a model in which a vertical discharge path applies to both ground and intra-cloud flashes. A ground flash is assumed to produce a positive field change at all distances and a cloud flash to produce a positive field change within the reversal distance and a negative field change beyond it.

Observations of electric field changes, e.g., Mackerras (1968), show that ground flashes transfer charge mainly by impulsive discharge processes whereas cloud flashes do so mainly by non-impulsive processes, although there are exceptions. Thus the field change of a ground flash usually exhibits relatively large positive-going steps, while cloud flash field changes usually do not.

A biased estimate of z may result from use of an electric field change measuring system with too short a time constant, causing rapid changes to be emphasized unduly, thus leading to erroneous attribution of cloud flash field changes to ground flashes. However, it is not possible to assess whether any systematic bias exists in estimates of z from field change observations.

Kreielsheimer and Lodge-Osborn (1971) found that, at frequencies of the order of 10 MHz or more, "gaps" in the noise radiation from lightning follow a different distribution law, depending on whether the radiation emanates from a cloud or a ground flash. The authors found that a counter based on this characteristic showed good selectivity to ground flashes.

An instrument to discriminate between cloud and ground flashes was designed by Gane and Schonland (1948); Anderson and Jenner (1954) gave extensive data for southern Rhodesia using this device.

4. Relation between z and λ

The 29 pairs of values of z and λ in Table 1 were plotted in Fig. 1. The scatter in the values of z for a given λ are partly attributable to errors of the type noted above, but may also indicate genuine differences between z for different localities at about the same latitude. Further errors may be related to the short duration of some of the observations, but these errors are almost certainly random.

Making the assumption that there is no systematic bias in the observations and that all are of equal statistical weight, the observations were subdivided into four groups, and the means for each obtained:

$\lambda = 2°\text{–}19°$, mean $z = 5.7$

$\lambda = 27°\text{–}37°$, mean $z = 3.6$

$\lambda = 43°\text{–}50°$, mean $z = 2.9$

$\lambda = 52°\text{–}69°$, mean $z = 1.8$.

Fig. 1 indicates that $dz/d\lambda$ is small for $\lambda = 50°\text{–}60°$; further, there is no evidence for a rapid increase in z as λ approaches zero. It is unlikely that there are rapid changes in the structure and dynamics of thunderclouds over the range $\lambda = 0°\text{–}10°$. In view of the above considerations, the empirical function selected to relate z to λ was required to have $dz/d\lambda = 0$ at $\lambda = 0°$ and $60°$. The selected function was $z(\lambda) = A + B\cos 3\lambda$, and fitting this function by the least-squares method gave $A = 4.1609$ and $B = 2.1605$. The square of the coefficient of correlation was 0.36. Although other functions with two adjustable constants can be found giving a better statistical fit, they do not satisfy the additional conditions stated above.

The proposed empirical relation is

$$z(\lambda) = 4.16 + 2.16\cos 3\lambda. \tag{1}$$

Pierce (1965) gave a relationship between the proportion p of ground flashes and latitude λ (deg):

$$p = 0.1 + 0.25\sin\lambda, \tag{2}$$

where

$$p = N_g/(N_c + N_g) = (1+z)^{-1}.$$

With further data, Pierce (1970) modified the relationship to

$$p = 0.1[1 + (\lambda/30)^2], \tag{3}$$

noting that this is a better fit of the data and that the scatter of points scarcely justifies a more elaborate relationship. In discussing this relationship, Pierce (1970) adopted the usual model of a charged thundercloud with a net positive charge at a height H, and a number of negative charge centers at a mean height h, and noted that the smaller $(H-h)$ is relative to h the

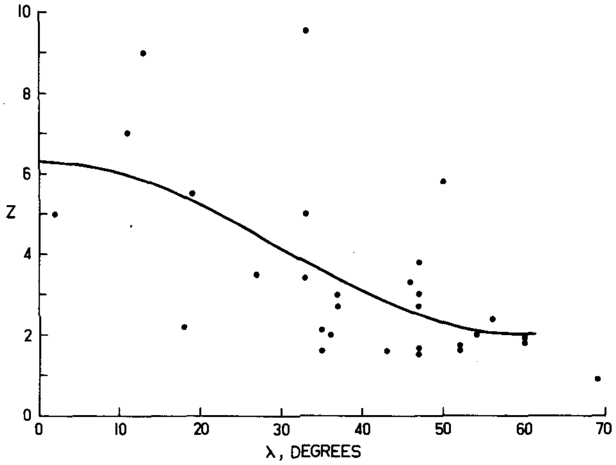

FIG. 1. Relation between observed values of the ratio z of cloud flashes to ground flashes and latitude λ. The 29 data points from Table 1 and the proposed empirical relation are shown.

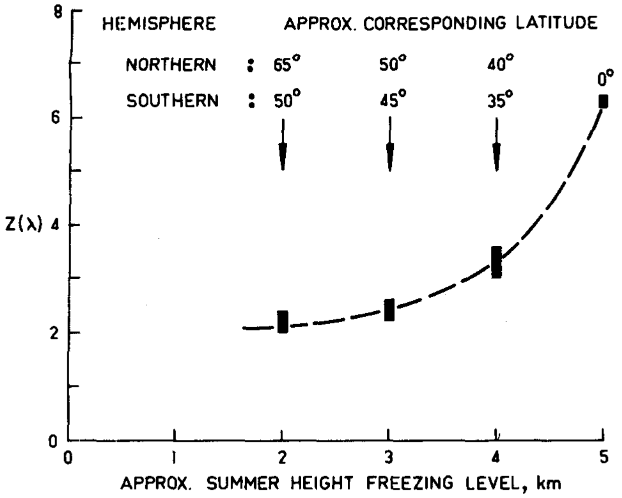

FIG. 2. Relation between the empirically estimated ratio $z(\lambda)$ of cloud flashes to ground flashes, and the height of the freezing level in summer, with latitude as parameter. Freezing level heights were obtained from NAVAIR 50-1C-54, *U. S. Navy Marine Climate Atlas of the World*. Numbers above the curve indicate, for each hemisphere, the approximate latitude at which the given freezing levels occur over continents. Vertical bars on the curve indicate the corresponding range of $z(\lambda)$ values.

greater is the probability of a cloud flash rather than a ground flash. The implication here is that $H-h$ is not dependent on λ, whereas h is, so thundercloud intrinsic structure is independent of λ and only the elevation of the structure depends on λ.

The implied relation between z and h was investigated by plotting in Fig. 2 pairs of values of z and h_F, the approximate mean height of the freezing level in summer over continents, with λ as parameter. Assuming that the negative charge zone is disposed at about freezing level, this shows that the ratio varies from $z\approx 2$ at $h\approx 2$ km to $z\approx 6$ at $h\approx 5$ km.

The strength of the charging source supplying the lower positive charge zone in thunderclouds may be related to h or λ or both; as this zone has an important influence on the initiation of ground flashes, the explanation of the z–λ relation may also have to take this factor into account.

5. Relation between z and T

Annual thunderdays were available for 26 of the 29 items in Table 1, either as values supplied by the author or as long-term means, for T in the range 5 to 81. The Singapore value ($T=171$) was far removed from the remainder, and was therefore omitted in this analysis. Linear regression analysis gave the best fit line as $z(T)=A+BT$ with $A=1.0113$ and $B=0.0627$. The square of the coefficient of correlation was 0.35. The proposed empirical relation is

$$z(T)=1.0+0.063T \qquad (4)$$

for $10\leqslant T\leqslant 84$.

Although information for higher T is scarce, it is clear that $T>84$ normally exists only for low λ, so to be consistent with (1), $z\approx 6.3$ for $T>84$. The data points and (4) are shown in Fig. 3.

Although more complicated functions with two adjustable constants can be fitted with better correlation, the proposed function is considered to be all the data justify, and is consistent with (1) at low λ. The relationship between z and T obviously exists because T, in general, increases with λ, after averaging regional

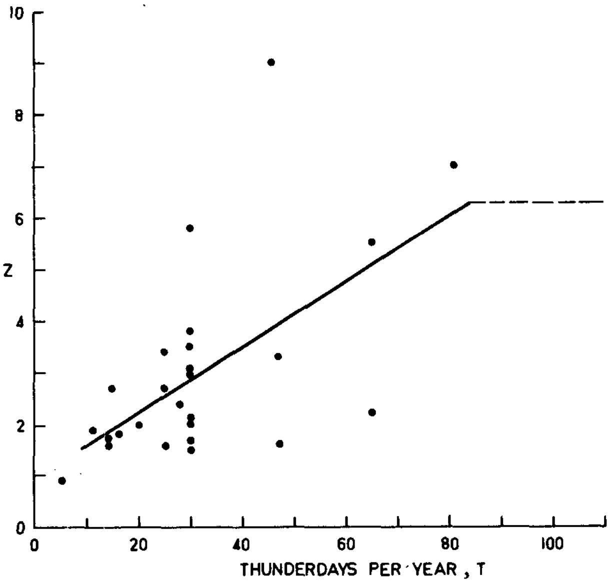

FIG. 3. Relation between observed values of the ratio z of cloud flashes to ground flashes and thunderdays per year T. The 26 data points from Table 1 and the proposed empirical relation are shown.

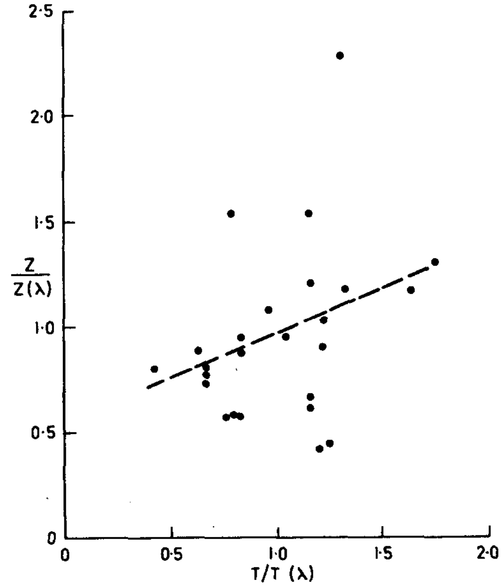

FIG. 4. Values of $z/z(\lambda)$ plotted against $T/T(\lambda)$.

fluctuations in T at fixed latitude. From the Table 1 data, (omitting items 1, 7, 8, 18, 19, 20 and 24), the linear regression line of T on λ (deg) is

$$T(\lambda)\approx 72-0.98\lambda, \quad \lambda\leqslant 60^\circ. \qquad (5)$$

Maxwell *et al.* (1970), in studies of VLF atmospheric noise obtained the empirical relationship

$$p=0.05+(\sin\lambda+0.05)/(N_{\mathrm{TD}}+3)^{\frac{1}{2}}, \qquad (6)$$

where $p=(1+z)^{-1}$ and N_{TD} is the number of thunder-days per month, as an approximate fit for data from 11 stations between $\lambda=0$ and 60°.

The implication of (6) is that, for constant λ, z increases with N_{TD}; thus the meteorological factors which increase N_{TD} also increase z, probably through increasing h_F and h. To test whether Table 1 contains evidence for this tendency, the values of z and T were divided by $z(\lambda)$ and $T(\lambda)$, respectively, from (1) and (5). Fig. 4 shows $z/z(\lambda)$ plotted against $T/T(\lambda)$ for $\lambda\leqslant 60^\circ$ and $T<84$. Items 1, 7, 8 and 29 in Table 1 were omitted in Fig. 4. A weak relationship is apparent, and the regression line of $z/z(\lambda)$ on $T/T(\lambda)$ has slope ≈ 0.4. Where T is known as well as λ, the following estimate of z is therefore proposed:

$$z(\lambda,T)=(4.16+2.16\cos 3\lambda)[0.6+0.4T/(72-0.98\lambda)], \quad T\leqslant 84,\ \lambda\leqslant 60^\circ. \qquad (7)$$

This equation gives a better estimate of the observed z than (1) for 16 of the 25 items in Table 1 for which $\lambda\leqslant 60^\circ$ and $T\leqslant 84$. For 15 of the items, the discrepancy between the observed z and $z(\lambda,T)$ is less than 30%. The mean of $|z(\lambda,T)-z|$ for the 25 items was 0.92. This indicates the order of accuracy of any estimate of z based on (7).

6. Applications

Interpretation of the annual registrations of lightning flash counters (Prentice, 1972) requires an estimate of z to enable registrations to be converted to flash densities (N_c and N_g). For localities where T is known, Eqs. (1), (4) and (7) each provide estimates of z.

The empirical relationships will assist in checking the validity of any dynamic thundercloud model. Specifically, any model which is capable of simulating a succession of discharges, and has h as one of its parameters, should predict a relation between z and h of the type indicated in Fig. 2.

In weather modification studies, observations of z may provide one measure of the influence of the modification method on the thundercloud. It would be necessary to have a reliable automatic lightning detector of known performance from whose registrations z could be obtained. Preliminary work in this direction has been reported by Mackerras and Gillett (1975).

In order to improve knowledge of z on a worldwide basis, there is need for a program of observations in representative regions over an adequate period and the development of appropriate procedures to ensure that results are comparable.

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