Australian Meteorological and Oceanographic Journal 63 (2013) 487–495

Lightning flash density 1995–2010 in Brisbane, Australia

David Mackerras[1]
Previously with the Department of Electrical Engineering, University of Queensland, St. Lucia

(Manuscript received May 2013; revised October 2013)

Observations of nearby lightning have been made in Brisbane, Australia (27.3ºS, 153.0ºE) from 1995 to 2010 using CGR3 and CGR4 lightning sensors and a 500 Hz CIGRE lightning flash counter, with the objective of measuring long-term lightning flash densities and their diurnal and annual variations. The observations with the CGR4 sensor covered a circular area around the sensor of about 400 km^2. The 16-year average flash densities based on direct measurements were: ground flash density = 2.29 km^{-2} yr^{-1}, cloud flash density = 2.81 km^{-2} yr^{-1} and total flash density = 5.1 km^{-2} yr^{-1} and average of 16 annual measurements of the cloud flash-to-ground flash ratio (denoted Z) = 1.56. The most probable long-term ratio of positive to all ground flashes is about 0.04 based on the period 2006 to 2010 when the more reliable measurements were made. The range of values was about 0.02 to 0.17 with a 16-year average of about 0.06. The average annual variation of total flash density shows that about 35 per cent of all lightning occurs from January to June and about 65 per cent from July to December. The diurnal variation of total flash density has the expected peak between 1700 and 1800 hours when 16 per cent of all lightning occurs and a secondary peak between 2000 and 2100 hours when 13 per cent of all lightning occurs. The inter-annual variation in total flash density is large with about a 9:1 range from 1.4 to 12.2 km^{-2} yr^{-1}. The average annual thunder day level was 25 with a range from 14 to 31 per year, about a 2:1 range. There is a weak correlation between annual flash densities and thunder days, but attempting to predict a flash density from the thunder day level is subject to large uncertainty. It was found that, averaged over the 16-year study period, 50 per cent of all local lightning occurs on about two days per year.

Introduction

Lightning discharges are broadly classified as negative ground flashes, positive ground flashes and cloud flashes. These types of lightning produce nearby electric and magnetic field effects that have been used as the basis for the design of sensors to detect and count the events. The wide distribution of values of charge and current in lightning discharges prevents the design of a simple sensor with a cut-off in response at a specified distance from the sensor. The effective range of the types of sensor used in this study can be thought of as the distance from the sensor such that the events counted beyond the effective range are equal to the events within the effective range that are not counted. Three types of sensor, the CIGRE 500 Hz, the CGR3 and the CGR4 were used to provide lightning occurrence information in the vicinity of Brisbane, Australia between 1995 and 2010.

The lightning observations were carried out at the author's home located at the eastern edge of the Brisbane suburb of Taringa, about 4 km south of the CBD, in the period 1995 to 2011. From January 1995 to January 2004 a CGR3 lightning sensor was used and from January 2004 to June 2011 a CGR4 sensor was used. Methods have been developed to design the CGR4 sensor for specified effective ranges and to check by observation the effective ranges for negative ground flashes (NGF) positive ground flashes (PGF) and for cloud flashes (CF). This information is required to be able to convert annual counts to flash densities, usually expressed in km^{-2} yr^{-1}.

Equipment

Each of the three sensors requires a vertical aerial to detect the changes of electric field and electromagnetic radiation caused by nearby lightning. The vertical-aerial form of the CIGRE 500 Hz Sensor (Barham and Mackerras 1972,

Corresponding author address: C/– Paul Hettrick, Bureau of Meteorology, p.hettrick@bom.gov.au.
[1]Deceased: date of death 21 February 2014.

Prentice et al. 1975, Anderson et al. 1979) has been in use in Australia and overseas for several decades. The network of this type of sensor operated in Australia by the Bureau of Meteorology (Kuleshov 2004, Kuleshov and Jayaratne 2004) has provided Australia-wide information on ground and total flash densities. The effective ranges of this sensor were estimated by Prentice and Mackerras (1969) to be 30 km for ground flashes and 20 km for cloud flashes; this estimate was later reduced to 18 km, (Kuleshov et al. 2006).

The CGR3 sensor was able to detect negative ground flashes, positive ground flashes and cloud flashes with effective ranges 14, 16 and 12 km respectively (Baral and Mackerras 1992, 1993). This sensor was used from 1995 to 2004. The CGR4 Sensor (Mackerras et al. 2009) was used from about 2004 on. The effective range is currently set at about 11.3 km for all types of lightning, giving an effective area of about 400 km^2, so a flash density in km^{-2} yr^{-1} is obtained by dividing an annual count by 400.

The aerial originally recommended for the vertical-aerial version of the CIGRE 500 Hz sensor is a 38 mm diameter aluminium tube 3.3 m long with its base at a height of 1.75 m above ground (Anderson et al. 1979). The electrical characteristics of this aerial were shown by Prentice et al. (1975) to be as follows: capacitance to ground, C_{ae} = 57 pF, effective height, h_a = 2.4 m and $C_{ae}\, h_a$ = 140 pFm. The value of $C_{ae}\, h_a$ controls the relation between the electric field change and the voltage change on the aerial; it is needed to establish a relationship between electric field changes and the corresponding voltage changes in the sensor circuitry.

An equivalent form of vertical aerial consists of a PVC pipe, nominally 50 mm outside diameter, 3.33 m long, base 1.75 m above ground, with four equi-spaced strands of insulated wire, outside diameter 5 mm, stranded conductor 3 mm overall diameter, spiralled around the tube from base to top. This has equivalent electrical characteristics to those noted above. A third form of vertical aerial, mainly intended for use at Bureau automatic weather station (AWS) sites, consists of a 3.15 m length of 50 mm diameter aluminium tube contained inside a nominally 50 mm PVC pipe about 5 m long with its base at ground level. At sites on level ground clear of nearby obstructions, such as Bureau AWS sites, the lower end of the aluminium tube is located 1.62 m above ground (Mackerras et al. 2009).

These types of aerial have been used in this investigation. They have been positioned vertically beside the house referred to in the Introduction with their heights above ground adjustable. Methods were developed to calibrate one aerial against a similar aerial at a clear site at the University of Queensland about 2 km to the east, and to inter-compare aerials at the house so that all aerials had the electrical characteristics noted above.

Data recording and processing

Daily logs were kept of the lightning sensor counts and supplementary observations such as days when thunder was heard and lightning seen or photographed. For part of the period of study, an event recorder was used to record time-stamped lightning sensor operations, thunder heard, and lightning seen signals. The ground flash density (GFD), cloud flash density (CFD) and total flash density (TFD) were calculated by dividing counts by the appropriate effective area (π times the effective range squared), using the appropriate effective ranges for the sensor. The uncertainty in the resulting flash densities and the ratios between them reported here is about ± 30 per cent, mainly because of uncertainty concerning the electrical constants of the aerials used. For sensors at AWS sites, the uncertainty would be about ± 20 per cent.

Results and discussion on individual observations

Summary of 16 years of observations

Table 1(a) gives a summary of the six-month, annual and long-term average flash densities and thunder day observations for the period of study. Some notable outcomes are as follows. The 16-year average annual flash densities were: GFD = 2.29 km^{-2} yr^{-1}, CFD = 2.81 km^{-2} yr^{-1}, TFD = 5.1 km^{-2} yr^{-1}, and average of 16 annual measurements of the cloud flash-to-ground flash ratio, Z = 1.56. The ratio of the mean six-month TFD January–June to the annual TFD is about 0.35, and the ratio of the mean six-month TFD July–December to the annual TFD is about 0.65. The 16-year average of the CFD/GFD ratio = 1.23.

The most probable long-term ratio of positive to all ground flashes was about 0.04 based on the period 2006 to 2010 when the more reliable measurements were made. The range of values from 1995 to 2010 is about 0.02 to 0.17 with a 16-year average of about 0.06. Some suggestions that the true value of this ratio is higher than the ones noted in Table 1(a) are discussed by Kuleshov et al. (2011). The large inter-annual variability of all the flash densities is notable, for example, the total flash density for the year 2000 was 1.4 km^{-2} yr^{-1}, compared with 12.2 km^{-2} yr^{-1} in 2004, a ratio of about 9:1.

Adjustment for failure to count some cloud flashes during very active storms

During very active storms the electric field changes caused by nearby negative ground flashes and coincident cloud flashes sometimes overlap. The design of the sensor is such that the resulting combined field change can only be assigned to a single event, and usually, the event will be classified as a negative ground flash and the cloud flash will fail to be counted. An approximate adjustment to the cloud flash count can be made by estimating the number of missed cloud flashes in each very active storm in which the NGF count, G, exceeded 100. The time required by the sensor to make an assignment is T_g = 1.35 s, and if a cloud flash occurs during this time it will be missed. The mean interval between NGF events is G/T_s , where T_s is the storm duration, here

Table 1. (a) Summary of six-month and annual lightning flash densities.

Year	January to June Per km² per 6 months			July to December Per km² per 6 months			Annual km⁻² yr⁻¹			Ratios		T-day
	NGF	PGF	CF	NGF	PGF	CF	GF	CF	TF	PGF/GF	CF/GF	Per yr
1995	0.922	0.040	1.795	3.342	0.090	4.903	4.394	6.698	11.092	0.029	1.524	26
1996	0.793	0.015	1.556	0.775	0.096	2.637	1.678	4.193	5.871	0.066	2.499	25
1997	0.898	0.012	1.306	2.139	0.091	2.425	3.140	3.731	6.871	0.033	1.188	20
1998	0.497	0.027	1.054	2.543	0.072	3.417	3.140	4.472	7.612	0.032	1.424	28
1999	0.400	0.021	0.710	0.148	0.041	0.604	0.609	1.313	1.923	0.102	2.155	23
2000	0.018	0.004	0.135	0.236	0.047	0.964	0.304	1.099	1.403	0.167	3.610	14
2001	0.492	0.015	1.556	0.593	0.071	1.903	1.171	3.459	4.630	0.073	2.955	31
2002	0.229	0.025	0.942	1.395	0.072	2.423	1.721	3.364	5.085	0.056	1.955	25
2003	0.226	0.027	0.405	0.484	0.070	1.295	0.807	1.700	2.507	0.120	2.107	26
2004	5.822	0.026	3.331	0.879	0.102	2.089	6.829	5.420	12.249	0.019	0.794	31
2005	0.387	0.033	0.559	2.040	0.091	2.881	2.550	3.440	5.989	0.048	1.349	27
2006	1.113	0.041	1.291	0.672	0.023	0.500	1.848	1.791	3.639	0.034	0.969	26
2007	0.167	0.025	0.234	1.137	0.037	0.561	1.366	0.795	2.161	0.046	0.528	27
2008	0.272	0.008	0.127	3.405	0.080	1.000	3.764	1.127	4.891	0.023	0.299	29
2009	0.115	0.003	0.232	1.356	0.082	1.334	1.556	1.566	3.121	0.055	1.006	24
2010	0.122	0.015	0.199	1.501	0.050	0.586	1.688	0.785	2.473	0.038	0.465	18
Mean	0.779	0.021	0.965	1.415	0.070	1.845	2.285	2.810	5.095	0.059	1.555	25.3

taken as typically 2400 s (40 minutes). Hence the fraction of time when overlap occurs, which is also the probability that a cloud flash will be missed (assuming that the timings of cloud and ground flashes are independent), is:

$$F = T_g / (T_s / G) = G\, T_g / T_s . \qquad \ldots(1)$$

If C is the total number of cloud flashes occurring, C_r is the number recorded, and C_m is the number missed, then $C = C_m + C_r$, and

$$F = C_m / C = (C - C_r) / C = 1 - C_r / C. \qquad \ldots(2)$$

Solving Eqn 2 for C:

$$C = C_r / (1 - F), \qquad \ldots(3)$$

and

$$C_m = C - C_r. \qquad \ldots(4)$$

Applying these equations to 47 storms in the 16-year period with over 100 NGF counts, the number of missed cloud flash counts was estimated and converted to an equivalent flash density using the appropriate effective range. This missed cloud flash density was added to the originally calculated flash density and to the original total flash density to give the adjusted values in Table 1(b). This has increased the mean annual cloud flash density by 19 per cent from 2.81 to 3.34 km⁻² yr⁻¹, the mean of 16 annual CFD/GFD values by ten per cent from 1.56 to 1.72, and the mean 16-year total flash density by ten per cent from 5.10 to 5.62 km⁻² yr⁻¹.

Table 1. (b) Adjustment of flash densities and ratio for missed cloud flashes.

Year	Adjusted for cloud flashes missed			
	CFD Missed km⁻² yr⁻¹	Adjusted. CFD km⁻² yr⁻¹	Adjusted CFD/ GFD	Adjusted TFD km⁻² yr⁻¹
1995	0.842	7.540	1.716	11.934
1996	0.380	4.574	2.726	6.251
1997	1.247	4.978	1.585	8.118
1998	1.006	5.478	1.745	8.617
1999	0.029	1.342	2.202	1.951
2000	0.029	1.127	3.705	1.432
2001	0.139	3.599	3.074	4.769
2002	0.276	3.641	2.115	5.362
2003	0.024	1.724	2.137	2.531
2004	3.325	8.745	1.280	15.574
2005	0.572	4.012	1.573	6.561
2006	0.214	2.006	1.085	3.854
2007	0.015	0.810	0.593	2.176
2008	0.060	1.187	0.315	4.951
2009	0.073	1.638	1.053	3.194
2010	0.188	0.973	0.576	2.660
Mean	0.526	3.336	1.718	5.621

Fig. 1. Time series 1995–2010 of the monthly total flash density in Brisbane.

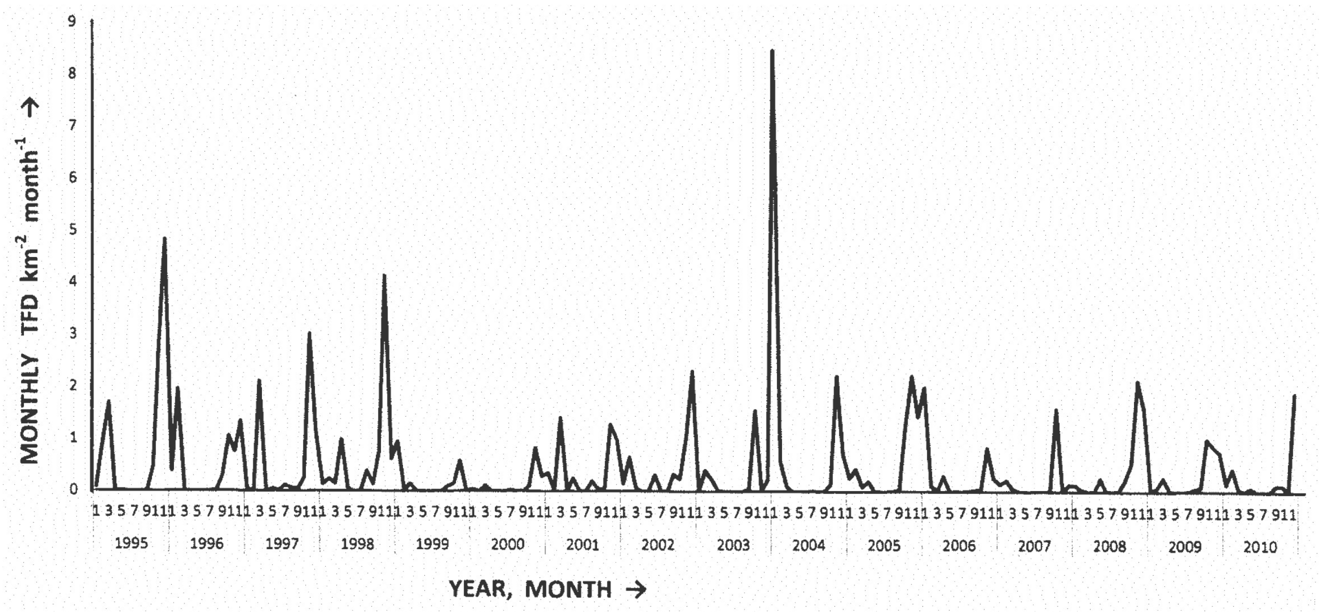


Fig. 2. Annual variation of (A) average monthly total flash density and (B) average monthly ground flash density based on 15-year averages.

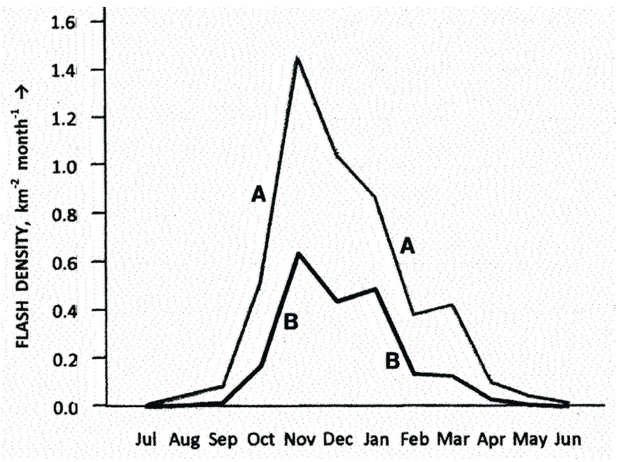


Figure 1 shows the monthly total flash density as a time series from 1995 to 2010. Notable features of this series are the low flash density values in the winter months and the relatively high values in the spring and early summer months. The extremely high value in January 2004 resulted from a series of particularly active thunderstorms in the last few days of January. The large inter-annual variability should also be noted.

Figure 2 shows the variation of average monthly total flash density and ground flash density from July to June, indicated by the monthly TFD and GFD values, based on fifteen year averages. Notable features here are the relatively low winter values from May to August and the relatively high values in the spring and early summer. As noted in Table 1(a), about 35 per cent of annual lightning occurs between January and June and about 65 per cent between July and December. This curve is similar to the seasonal distribution curve given by Kuleshov (2004) for Darwin.

Table 2. Comparison of thunder days estimated from CGR3 and CGR4 sensors with observed thunder days.

Period	*Sensor*	*Test condition*	*TFC≥1*	*TFC≥2*	*TFC≥3*	*TFC≥4*	*TFC≥5*
1995–2003	CGR3	T-day estimate	201	185	184	173	170
		Actual T-days		187			
2004–2009	CGR4	T-day estimate	133	123	117	112	105
		Actual T-days	131				

The diurnal distribution shown in Fig. 3 has been based on hourly counts of total flashes for the 11 years 1999 to 2006 and 2008 to 2010 inclusive. The year 2007 data were incomplete because of recording equipment failure. Notable features of the diurnal distribution are the relatively low values from 0200 to 1100 hours and the increase to a peak in the late afternoon where 16 per cent of the daily lightning occurs between 1600 and 1700 hours. Figure 3 shows that there exists a secondary peak between 2000 and 2100 hours where 13.3 per cent of the daily total occurs. This secondary peak is barely suggested by a slight kink in the diurnal variation curve used by Mackerras et al. (1998). The second local peak may indicate a different mechanism operating in the evening than that usually used to explain the late afternoon peak in terms of solar heating of land promoting instability.

To test the hypothesis that days per year with non-zero CGR4 total flash counts might be used as a substitute for annual thunder days, an investigation was carried out with

Fig. 3. The diurnal variation of total lightning plotted as the percentage of all lightning in each hour increment versus time of day (local Eastern Standard Time).

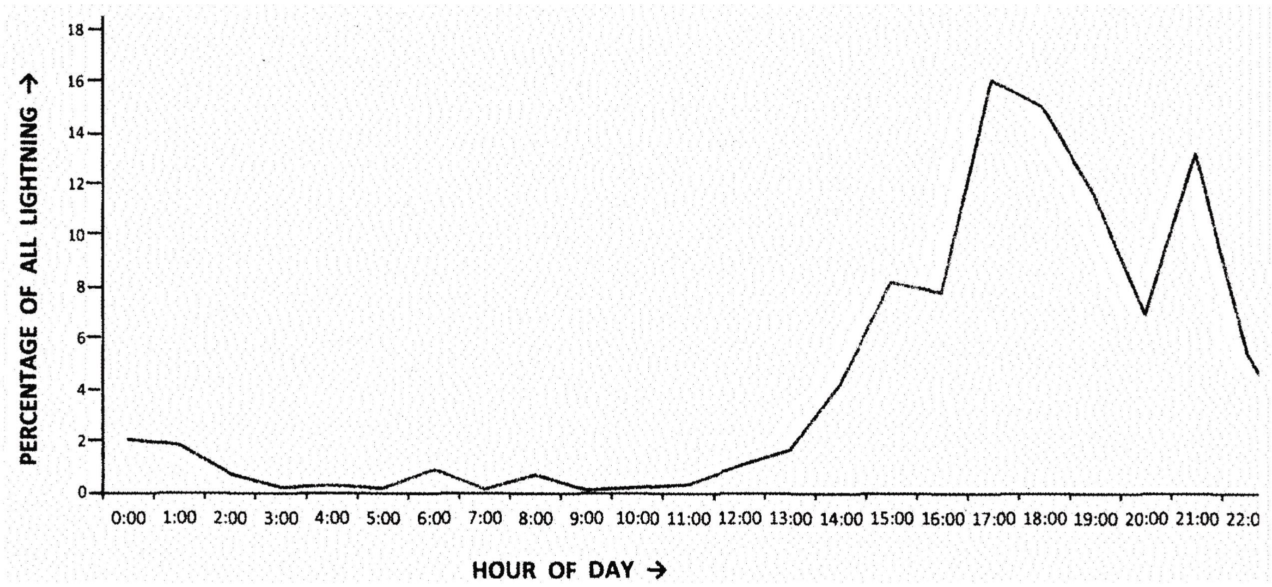
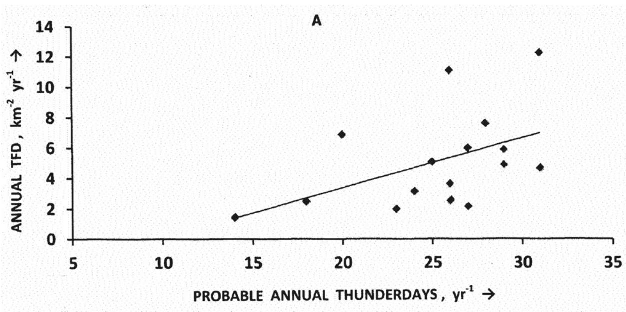
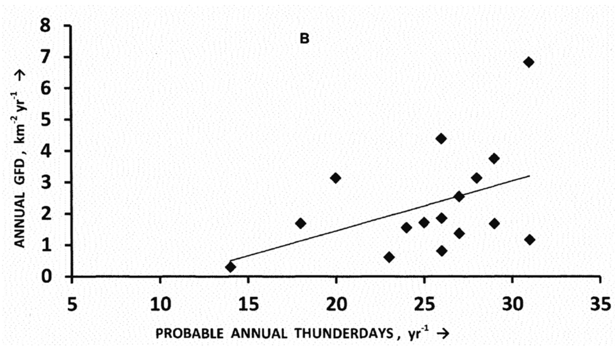


Fig. 4. Annual flash density plotted against probable annual thunder days; (a) total flash density, (b) ground flash density, with best fit lines shown.





results summarised in Table 2. The test conditions tried out were: a thunder day could be inferred if, on a particular day, the total flash count, TFC, was $\geq x$, with x set successively at 1, 2, 3, 4 or 5. The number of thunder days actually observed was found and the best match with the number of inferred thunder days was determined. For the CGR3 sensor the best match was found by using TFC ≥ 2, and for the CGR4 by using TFC ≥ 1. For this investigation a subset of the records was used, including only days on which both an observer was available to hear thunder and sensors were operating correctly. So, to maintain continuity with the long period of existing thunder day records (Kuleshov et al. 2002), annual thunder days could be taken as equal to the number of days per year when TFC ≥ 1 in the CGR4 record.

In Fig. 4 the annual thunder days were obtained from direct observations and by the use of the rules noted above on days when no aural observations were made. There are weak correlations between annual TFD (Fig. 4(a)) and annual thunder days (R^2 = 0.233) and between annual GFD (Fig. 4(b)) and annual thunder days (R^2 = 0.196). Weak correlations are only to be expected as annual TFD has about a 9:1 range whereas annual thunder days has about a 2:1 range during the period of this study.

For Fig. 4(a) the best fit line was

$$y = 0.329x - 3.211, (R^2 = 0.233). \quad ...(5)$$

For Fig. 4(b) the best fit line was

$$y = 0.159x - 1.724, (R^2 = 0.196). \quad ...(6)$$

Kuleshov and Jayaratne (2004) have presented four different equations for calculating the ground flash density, N_g, from the annual thunder day level, T_d, using an equation of the form, $N_g = \boldsymbol{a}\, T_d^{\,b}$ where $\boldsymbol{a}$ and $\boldsymbol{b}$ are constants. The data provided in Table 1(a) show that with an annual T_d of 25.3 the recorded value of N_g is 2.29 km^{-2} yr^{-1}. The method identified as the CIGRE method uses an equation of the form

$$N_g = 0.04\, T_d^{\,1.25}\ km^{-2}\ yr^{-1} \quad ...(7)$$

This CIGRE formula is due to Anderson et al. (1984). For the T_d value of 25.3 from Table 1(a), the CIGRE formula gives N_g = 2.27 km^{-2} yr^{-1} in very good agreement with the present result. The other three equations give results between 32 per cent and 60 per cent lower than the N_g value found in this study.

Fig. 5. Distribution of daily total flash density (TFD) values plotted against fraction of days per year; (a) daily TFD values, (b) cumulative total of daily TFD values plotted as a percentage of the annual total TFD.

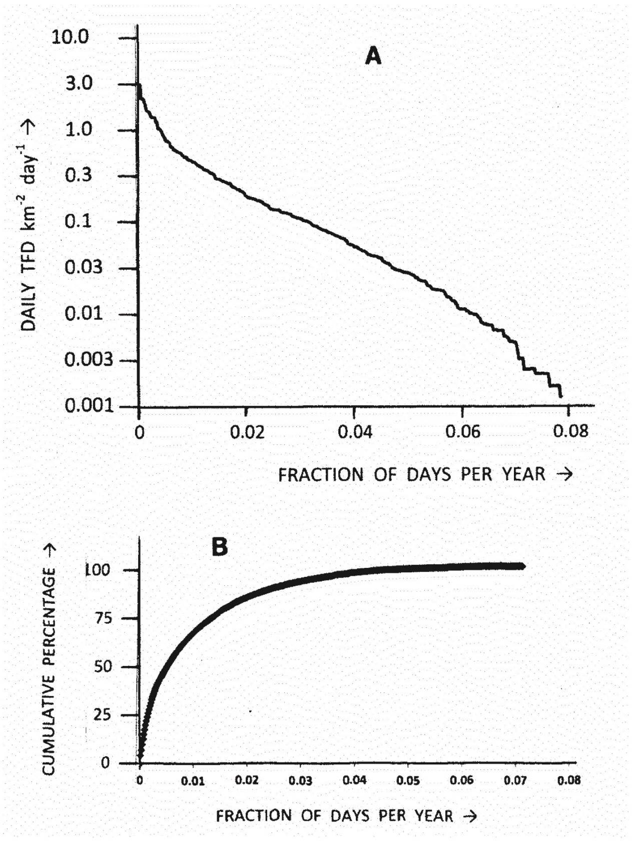


Fig. 6. Response of sensor CGR4 to storm on 16 November 2008 between 1500 and 1800. The left hand scale shows counts per five minutes of (g) ground flashes and (c) cloud flashes. The right hand scale shows minimum distance to thunderstorm cell (d) from the radar record.

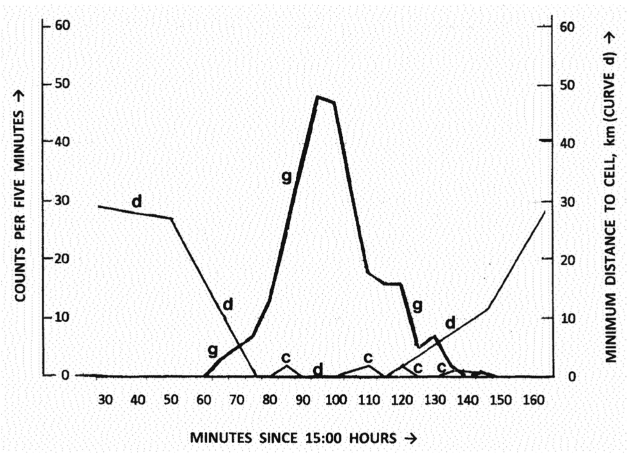
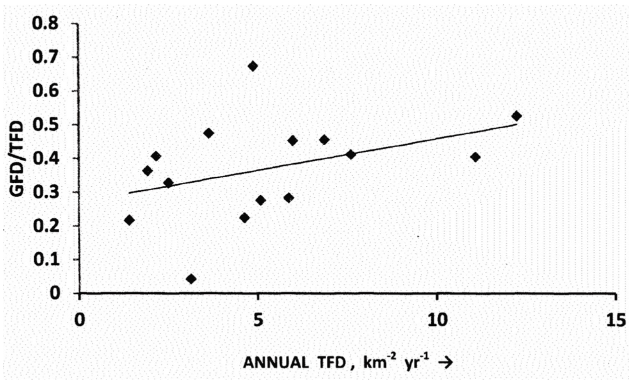


Fig. 7. The relationship between the ratio of the annual ground flash density to total flash density (GFD/TFD) and the annual total flash density (TFD); the best fit line is shown.



Comparison between responses of CGR4 and CIGRE 500 Hz sensors

This comparison was based on four years of records in 2005, 2006, 2008 and 2010 when both annual CIGRE 500 Hz counts and annual values of TFD from the CGR4 sensor were available. Using the equations given by Prentice and Mackerras (1969) for converting CIGRE 500 Hz counts to flash density, with effective ranges R_g = 30 km for GF and R_c = 18 km for CF, and a selected value of *Z*, gives annual total flash density and ground flash density estimates. The equations are as follows.

$$N_g = K\,Y_g / (\pi R_g^2), \qquad ...(8)$$

where $Yg = [\,1 + Z\,(Rc / Rg\,)2\,]\text{-}1,$ ...(9)

and $Nt = Ng\,(1 + Z).$ ...(10)

From Table 1(a), for the selected four years, the mean flash densities were as follows.

Mean GFD = 2.462 km^{-2} yr^{-1}, mean TFD = 4.248 km^{-2} yr^{-1}, mean CFD = 1.786 km^{-2} yr^{-1} and the ratio mean CFD / mean GFD = 0.725 (the overall mean *Z* for the four years). The average of four yearly values of *Z* was 0.771.

Table 3 give a comparison of the values of TFD and GFD calculated from the CIGRE 500 Hz sensor results and the values recorded by the CGR4 sensor. It shows that good agreement within about five per cent between the two methods is obtained when several years of records are used, and when the assumed value for *Z* is close to the value obtained from the CGR4 record.

Daily TFD values were obtained from CGR3 and CGR4 lightning sensors on 419 days in the 16-year period of this study. The available daily TFD values were calculated from the daily NGF, PGF and CF counts using the appropriate effective ranges. A list of all daily TFD values was sorted in descending order of values and plotted in Fig. 5(a) against the fraction of days in the total period of study (5844 days), from the largest daily TFD (2.9 km^{-2} d^{-1}) at abscissa value 1/5844 to the smallest daily TFD (0.0013 km^{-2} d^{-1}) at abscissa value 419/5844 (= 0.0717). Figure 5(b) shows the cumulative

Table 3. Comparison of calculated 4-year average TFD and GFD from CGR4 and CIGRE 500 Hz sensors based on years 2005, 2006, 2008 and 2010.

	Reference value from CGR4			
	Total flash density, TFD, N_t = 4.248 km^{-2} yr^{-1}		*Ground flash density, GFD, N_g = 2.462 km^{-2} yr^{-1}*	
Assumed value of Z	*Calculated TFD from CIGRE 500 Hz*	*Compared with CGR4*	*Calculated GFD from CIGRE 500 Hz*	*Compared with CGR4*
3.0	6.168	45% high	1.542	37% low
2.0	5.592	31% high	1.864	24% low
1.6	5.293	25% high	2.036	17% low
0.771	4.447	5% high	2.512	2% high
0.725	4.389	3% high	2.544	3% high

total of daily TFD values plotted against the same abscissa values as in Fig. 5(a), that is, the curve is the integral of the curve in Fig. 5(a). It shows, for example, that 50 per cent of all lightning within the area covered by the sensors occurred on 0.55 per cent of days, equivalent to about two days per year.

Observations of individual storms

The storm on 16 November 2008 was a particularly active one. The five-minute subtotals of CGR4 events were used to plot the temporal variation of recorded lightning activity in Fig. 6. The minimum distance to the cell from the observation point was obtained from the Bureau radar website (Brisbane area, Mt. Stapylton radar) and is shown on the figure as curve ***d***. For the purpose of this measurement the edge of the area displayed in red on the radar image was used as the boundary of the active lightning-producing part of the storm. The five-minute numbers of counts of ground flashes, GF (=NGF + PGF) marked ***g***, and cloud flashes, CF, marked ***c*** are shown on Fig. 6. An interesting feature is that the relatively rapid increases in counting rate as the storm approaches mainly affect the GF curve, whereas the rate for CF only increases slightly. Thus one tends to have relatively high GF counts in the few very active storms each year, whereas in the storms with moderate lightning activity one tends to have higher CF counts than GF counts. Thus the few very active storms each year contribute disproportionately to the ground flash annual total, and hence lead to relatively low estimates of the annual *Z* values.

Relationship between the annual GFD/TFD ratio and TFD

Figure 7 shows the annual GFD/TFD ratio plotted against annual TFD, indicating that the years with relatively low total flash occurrence tend to have a low ratio of ground flashes to total flashes whereas the years with higher total flash occurrence tend to have a higher ratio of ground flashes to total flashes. However, the correlation is weak (R^2 = 0.159). This appears to be a consequence of the observation that years with high TFD usually have some very active storms dominated by high GF rates of occurrence, while years with low TFD tend to have mainly storms with low flash rates and low GF occurrence rates.

The best fit line for Fig. 7 was

$$y = 0.018x + 0.27, (R^2 = 0.159). \qquad ...(11)$$

Sensor response to visually observed or photographed lightning

Visual and photographic observations of lightning flashes to ground and the corresponding response of the CGR4 and CIGRE 500Hz sensors were made during three storms between November 2008 and May 2011. The direct visual observations were made mainly in a northwest to north direction from the Taringa house. Photography was carried out using a Canon EOS 1000 D SLR camera used in manual mode with the shutter remotely triggered by a signal from the CGR4 sensor. This signal was derived from internal voltages in the CGR4 representing positive and negative excursions of the electric field, causing the shutter to be triggered when the electric field change exceeded 200 V/m in either direction. The duration of the exposure was adjustable from about 0.1 s for use in dull daylight to about 0.9 s used at night. The camera could be used in two ways: (1) pointing in a north-northwest direction, or (2) mounted in a weather-proof enclosure at an elevated position where the camera was pointed downwards at a spherical mirror so that a 360 degree view horizontally, and from the horizon to 60 degrees in elevation was obtained.

It was found that the response of the CGR4 sensor to a total of 27 GF either visually observed or photographed or both was 21 NGF, 1 PGF, 1 CF, 2 TFIR (total flash intermediate range), and 2 DF (distant flash). The distances of 17 events for which a clear thunder signal could be obtained was between 2–11 km. The response of 1 PGF out of 22 GF agrees with the estimate of PGF being about four per cent of GF. The one CF is to be expected as the estimated error rate for signalling CF in response to a GF is about ten per cent (Mackerras et al. 2009). The CIGRE 500 Hz sensor responded to 26 out of the 27 observed ground flashes. The TFIR register indicated events beyond the range for NGF, PGF and CF but with overall field change over 280 V/m. This register was used during field tests to indicate the presence of lightning up to about 16 km away. The DF register indicated the presence of lightning up to about 100 km, based only on a burst of radio-frequency radiation (Mackerras et al. 2009).

General discussion

Possible reasons why the cloud flash density could have been underestimated

Firstly, the estimated effective range for cloud flashes was based on observed flashes which tend to be those with larger charges and field changes, thus giving a biased sample and hence an effective range estimate larger than the correct value. A smaller effective range would have resulted in a larger cloud flash density for a given CF count.

Secondly, during periods of high lightning rates of occurrence, overlapping ground flash and cloud flash field changes usually result in only a ground flash being signalled. Thus cloud flash numbers tended to be underestimated. Table 1(b) shows values of flash densities adjusted for missed cloud flashes, but it is possible that the number of missed cloud flashes has been underestimated.

Long-term trends in lightning activity

Mackerras (1977) reported a study covering the ten-year period July 1959 to June 1969 using visual observations and CIGRE 500 Hz lightning sensors, with the following results averaged over the period: total flash density, N_t = 5 km^{-2} yr^{-1}, ground flash density, N_g = 1.2 km^{-2} yr^{-1}, and cloud flash-to-ground flash ratio, Z = 3.2.

During a portion of the above period, 1964 to 1968, Prentice and Mackerras (1969) reported: Nt = 6 km^{-2} yr^{-1}, N_g = 1.2 km^{-2} yr^{-1}, and Z = 4, based on CIGRE 500 Hz sensors.

As part of a worldwide study using CGR3 sensors covering observations between 1987 and 1991, Mackerras and Darveniza (1994) reported for a four year period in Brisbane: N_t = 4.5 km-2 yr-1, N_g = 1.3 km^{-2} yr^{-1}, and Z = 2.5.

A summary of the 16-year study 1995–2010 reported here, based on CGR3 and CGR4 sensors is: N_t = 5.1[5.6] km^{-2} yr^{-1}, Ng = 2.29 km^{-2} yr^{-1}, and Z = 1.56 [1.72].

Values adjusted for missed cloud flashes are shown in brackets [].

A comparison of these total flash density values shows that there has been no significant change in total lightning activity over the period for which observations are available. However, estimates of Z have declined since the 1960s accompanied by a rise in the ground flash density estimates. It is probable that earlier estimates of Z were affected by the difficulty in interpreting visual observations when a large fraction of flashes were unidentifiable, particularly during very active storms. In addition, there was a preconception based on estimates by Pierce (1970) that tropical and subtropical values of Z were six to nine, and estimates by Prentice and Mackerras (1977) that tropical values of Z were about six. Correspondingly, the earlier estimates of $N_g \approx$1.2 km^{-2} yr^{-1} were too low and the current estimate $N_g \approx$ 2.3 km^{-2} yr^{-1} is more realistic.

Acknowledgments

The support of the Australian Bureau of Meteorology in the process of developing the CGR4 sensor, in particular by Dr. Yuriy Kuleshov, Dr. Paul Hettrick and Mrs Nicole Farnsworth is gratefully acknowledged. The consulting company Lightning and Transient Protection and its Director, Em. Prof. Mat Darveniza, provided the basis for the design and testing of the sensor. Mr. Robert Greenfield assisted in the design and construction of the hardware and documentation of the sensor. The earlier work in developing the CGR3 sensor and distributing it to several sites was supported by University of Queensland and other research grants. Mr. Damien Green ably assisted in the processing and analysis of the data recorded during the period of this study.

References

Anderson, R.B., A. J. Eriksson, H. Kroninger, D. V. Meal and M. A. Smith. 1984. Lightning and Thunderstorm parameters, IEEE Int. Conf. Lightning and Power systems, London, UK.

Anderson, R. B., H. R. van Niekerk, S. A. Prentice and D. Mackerras. 1979. Improved lightning flash counters, *Electra*, *66*, 85–98.

Baral, K. N. and D. Mackerras. 1992. The cloud flash-to-ground flash ratio and other lightning occurrence characteristics in Kathmandu thunderstorms, *J. Geophys. Res.*, *97*, 931–938.

Baral, K. N. and D. Mackerras 1993. Positive cloud-to-ground lightning discharges in Kathmandu thunderstorms, *J. Geophys. Res.*, *98*, 10,331–40.

Barham, R. A. and D. Mackerras. 1972. Vertical-aerial CIGRE-type lightning flash counter, *Electron. Lett.*, *8*, 480–82.

Kuleshov, Y. 2004. Seasonal and latitudinal variations of lightning ground flash activity in Australia, *Aust. Meteorol. Mag. 53*, 189–96.

Kuleshov, Y., G. de Hoedt, W. Wright and A. Brewster. 2002. Thunderstorm distribution and frequency in Australia, *Aust. Meteorol. Mag. 51*, 145–54.

Kuleshov, Y., P. Hettrick, D. Mackerras, M. Darveniza, R. Jayaratne and K. Zhang. 2011. On occurrences and distribution of negative and positive polarity cloud-to-ground lightning flashes in Australia, XIV International Conference on Atmospheric Electricity, August 08–12, 2011, Rio de Janeiro, Brazil.

Kuleshov, Y. and E. R. Jayaratne. 2004. Estimates of lightning ground flash density in Australia and its relationship to thunder-days, *Aust. Meteorol. Mag. 53*, 189–96.

Kuleshov, Y., D. Mackerras and M. Darveniza. 2006. Spatial distribution and frequency of lightning activity and lightning flash density maps for Australia, *J. Geophys. Res., 111*, D19105, 1–14, doi:10.1029/2005JD006982.

Mackerras, D. 1977. Lightning occurrence in a subtropical area in *Electrical Processes in Atmospheres*, edited by H. Dolezalek and R. Reiter, Steinkopff, Darmstadt, 497–502.

Mackerras, D. and M. Darveniza. 1994. Latitudinal variation of lightning occurrence characteristics, *J. Geophys. Res., 99,* 10813–21.

Mackerras, D., M. Darveniza and P. Hettrick. 2009. The CGR4 lightning sensor, *Aust. Met. Oceanogr. J., 58.* 263–73.

Mackerras, D., M. Darveniza, R. E. Orville, E. R. Williams and S. J.Goodman. 1998. Global lightning: Total, cloud, and ground flash estimates, *J. Geophys. Res., 103,* 19791–809.

Pierce, E. T. 1970. Latitudinal variation of lightning parameters. . *J. Appl. Meteorol., 9*, 194–5.

Prentice, S. A. and D. Mackerras. 1969. Recording range of a lightning flash counter, *Proc. Inst. Elec. Eng., 116,* 294–302.

Prentice, S. A., and D. Mackerras. 1977. The ratio of cloud to cloud-ground lightning flashes in thunderstorms, *J. Appl. Meteorol., 16,* 545–50.

Prentice, S. A., D. Mackerras and R. P. Tolmie. 1975. Development and field testing of a vertical-aerial lightning-flash counter, *Proc. I. E. E.*, London, 122, 487–91.