COVER SHEET

Jayaratne, R and Kuleshov, E (2006) Geographical and seasonal characteristics of the relationship between lightning ground flash density and rainfall within the continent of Australia. *Atmospheric Research* **79(1):pp. 1-14.**

Geographical and seasonal characteristics of the relationship between lightning ground flash density and rainfall within the continent of Australia

E.R. Jayaratne [a] and Y. Kuleshov[b, *]

[a] International Laboratory for Air Quality and Health, Queensland University of Technology, GPO Box 2434, Brisbane, QLD 4001, Australia
[b] National Climate Centre, Australian Bureau of Meteorology, GPO Box 1289K, Melbourne, Victoria 3001, Australia

* Corresponding Author:

Dr. Yuriy Kuleshov
National Climate Centre
Australian Bureau of Meteorology
GPO Box 1289K
Melbourne Victoria 3001
Australia

Email: y.kuleshov@bom.gov.au

Telephone: (+613) 9669 4896

FAX: (+613) 9669 4760

Abstract

Ground-based observations of annual rainfall and lightning incidence collected over periods ranging from 9 to 22 years at 23 stations around the continent of Australia were used to compute values of 'rain yield', defined as the mass of rain produced per lightning ground flash (units: kg fl^{-1}) over a given area of ground. The rain yield was found to vary considerably with geographical location, season and climatic conditions. Of the 23 stations, five were mid-continental, and these showed a mean rain yield of 2.64 x 10^{8} kg fl^{-1} in contrast to the coastal and near-coastal stations that showed a corresponding mean value of 9.91 x 10^{8} kg fl^{-1}. The difference was statistically significant at the confidence level of 95%. When the stations were classified according to seasonal climate zones, the winter and winter-dominant rainfall stations showed a rain yield of 1.28 x 10^{9} kg fl^{-1} while the summer and summer-dominant rainfall stations showed a significantly lower value of 5.44 x 10^{8} kg fl^{-1}. Again the difference was statistically significant at the 95% confidence level. Every one of the 23 stations showed mean winter rain yields that were significantly higher than the summer values. These differences are attributed to surface heating which controls such parameters as cloud base height and convective available potential energy in the atmosphere. In terms of the behaviour of the rain yield with geographical, seasonal and climatic conditions, the Australian observations are in good agreement with studies in other parts of the world.

Keywords

Lightning; Rainfall; Ground flash; Rain yield

1. Introduction

The close association between rain and lightning has been recognized since time immemorial. The Roman philosopher Lucretius observed the correlation in 58 BC and concluded that thunder caused rainfall. Robert Hooke noted a relationship between gushes of rain at the ground and overhead lightning in 1664. More recently, Lord Kelvin and Faraday both made references to the phenomenon and hypothesized that falling rain may cause lightning. However, systematic scientific studies were not carried out until the latter half of the last century. Battan (1965) and Piepgrass et al. (1982) related number counts of cloud to ground (CG) lightning from nearby thunderstorms to rain gauge readings and found them to be well correlated. Many studies have found the intensity of lightning to be positively correlated to rainfall estimated from radar measurements (Kinzer, 1974; Reap and MacGorman, 1989; Williams et al.., 1992; Cheze and Sauvageot, 1997). Intense falls of rain associated with nearby CG lightning have been documented by Shackford (1960), Moore et al. (1962), Piepgrass et al. (1982) and Jayaratne et al. (1995).

2. Rain Yields

Although there is a high positive correlation between rainfall and lightning, the ratio of rain mass to CG lightning flash count over a common area, with units of kilograms of rain per flash, quantitatively defined as the “rain yield”, varies considerable with location. In general, heavy rain associated with monsoon or oceanic convection show rain yields of the order of $10^9 – 10^{10}$ kg fl^{-1}, while continental convective thunderstorms show much smaller values of $10^7 – 10^8$ kg fl^{-1} (Williams et al., 1992; Petersen and Rutledge, 1998). Zipser (1994) found that the number of thunder days associated with heavy rain in tropical monsoon and oceanic storm regions was significantly lower than that in continental rainfall regimes. Observing the results of several studies at various geographical locations, Petersen and Rutledge (1998) concluded that the rain yield varied by a factor of 10 or more at any given location and by a factor of up to 10^3 between different locations and rainfall regimes. At the lower end, values of around 5×10^7 kg fl^{-1} were found in the arid south-western United States. A wide section of the mid-continental United States showed remarkably stable values clustered near 10^8 kg fl^{-1}, as did a landlocked station in Botswana within the African subcontinent. In tropical locations, the rain yields increased systematically from a continental value of 4×10^8 kg fl^{-1} to a maritime value of 10^{10} kg fl^{-1} in the western Pacific Ocean. Williams et al. (1992) identified two distinct rainfall regimes in Darwin in continental northern Australia. Rain yields for tropical continental break period thunderstorms and tropical oceanic thunderstorms differed by almost an order of magnitude, being 3×10^8 kg fl^{-1} and 2×10^9 kg fl^{-1} respectively. Similarly, rain yields for break and monsoon period convection that occurred offshore over Melville and Bathurst Islands near Darwin showed values of 8×10^8 kg fl^{-1} and 8×10^9 kg fl^{-1} respectively.

Williams et al. (1992) attributed the contrasting lightning activity in the two types of rainfall regimes to differences in convective available potential energy (CAPE). Many studies have demonstrated a strong increase in lightning activity with CAPE (Williams et al., 1992; Petersen et al., 1996). This is not surprising as CAPE bears a strong relationship to the potential wet bulb temperature, T_w, - a parameter that increases with temperature and humidity – both of which lead to an increase in lightning activity (Williams and Renno, 1993). Williams et al. (1992) showed that a 1ºC change in T_w resulted in a change in CAPE of about 1 kJ kg^{-1}. The mean daily maximum surface T_w in Darwin during the 1988-89 wet season dropped by about 2ºC from the break periods to the monsoon periods. Highly active lightning storms occurred during the break periods while relatively little lightning was observed in the monsoonal storms. The mean values of CAPE during the two periods were 2000 J kg^{-1} and 800 J kg^{-1} respectively. The corresponding lightning flash rates observed over an area of 40,000 km^2 were about 1000 and 100 per day respectively.

Continental land surface is systematically hotter than the sea. This gives rise to greater CAPE, atmospheric instability and stronger air motions that are vital for deep convection and thunderstorm formation. Although the total rainfall is about the same, lightning activity over land is an order of magnitude greater than over the oceans (Orville and Henderson, 1986). Thus, maritime stations, in general, have a higher rain yield than continental stations.

An alternative hypothesis for the land-ocean contrast in lightning is based on differences in boundary layer aerosol concentrations (Rosenfeld and Lensky, 1998). Continental air is more polluted than ocean air and contains more cloud condensation nuclei. Typical concentrations range from 100-200 cm^{-3} over the oceans to values greater than 1000 cm^{-3} over land. The resultant larger numbers of smaller cloud droplets at continental locations give rise to a dominance of diffusional droplet growth and suppressed coalescence. This leads to a reduction in rainfall and allows liquid water to ascend to the higher mixed phase region of thunderclouds where strong electrification takes place. The net result is increased lightning activity, reduced rainfall and reduced rain yields at continental stations when compared to maritime stations.

A further possible explanation for the contrast in lightning and rainfall characteristics between land and ocean thunderstorms is based on cloud base height (Williams and Stanfill, 2002). They argue that higher cloud base heights provide larger updraught widths and reduced dilution by mixing – two factors that promote lightning activity. It has been shown that lightning flash rate increases with cloud base height (Williams et al, 2004). Typically, cloud base heights over the maritime and continental locations are about 500 m and 3000 m respectively and the associated lightning flash rates between these two locations differed by an order of magnitude.

3. Lightning Detection

The Australian Bureau of Meteorology (ABM) maintains a network of about 40 lightning sensors scattered widely around Australia. The sensor used is the CIGRE-500 (CIGRE - International Conference on Large Electric Systems, 500Hz ground-flash counter). These counters are specifically designed to detect negative ground flashes and have been used extensively to provide estimates of ground flash density (Barham, 1965; Prentice, 1972). The antenna used is a vertical aluminium tube of dimensions and electrical characteristics conforming to CIGRE standards. The number of flashes is registered on a mechanical counter that increments once for every flash detected. Multiple strokes within a flash are eliminated by a one second dead time interval introduced by the circuitry after every first-stroke. The best estimate of the effective horizontal range of the counter in Australia is 30 km (Prentice and Mackerras, 1969) corresponding to a detection area of 2827 km^2.

4. Climatology

The continent of Australia contains a diverse range of climatic zones. The tropical northern and eastern coastal rim is generally humid and experiences heavy rainfall in the summer. The continental interior is largely arid and the southern regions are mostly temperate. The average rainfall in Australia is 450 mm. Around 80% of the landmass has a median rainfall less than 600 mm per year with 50% less than 300 mm. Large areal pockets within South and West Australia have less than 150 mm. The vast interior of the continent has a median annual rainfall of less than 200 mm. This region is not normally exposed to moist air masses for extended periods and rainfall is irregular. However, in favourable synoptic situations, which occur infrequently over extensive parts of the region, up to 400 mm of rain may fall within a few days and cause widespread flooding. The region with the highest annual rainfall is the east coast of Queensland near Cairns, with some stations recording over 3000 mm per year.

Owing to its low relief, compared to other continents, Australia causes little obstruction to the atmospheric systems that control the climate. However, as outlined earlier, the rainfall pattern is strongly seasonal in character, with a winter rainfall regime in the south and a summer regime in the north. During the southern hemisphere winter (May-October), huge anticyclonic high pressure systems transit from west to east across the continent and may remain almost stationary over the interior for several days. Northern Australia is thus influenced by mild, dry south-east winds, while southern Australia experiences cool, moist westerly winds. During the winter, frontal systems passing from the west to the east over the southern ocean have a controlling influence on the climate of southern Australia, causing rainy periods. In the summer months (November-April), the anticyclones move in a more southerly track along the coast, directing easterly winds over the continent and providing fine, hot weather in southern Australia. During this season, northern Australia is heavily influenced by the intertropical convergence zone. The associated intrusion of warm moist air gives rise to hot and humid conditions. Heavy rain may be prevalent for two to three weeks at a time due to tropical depressions caused by monsoonal low-pressure troughs. Thus, in contrast to the wet summer/ dry winter typical of Darwin and Brisbane, Adelaide and Perth show the wet winter/dry summer pattern whereas Sydney, Melbourne, Canberra and Hobart show a relatively uniform pattern of rainfall throughout the year.

A rainday is defined as a 24-hour period, usually from 9 am to 9 am the next day, when more than 0.2 mm of rain is recorded. The frequency of raindays does not necessarily correlate well with the annual rainfall. For example, the frequency exceeds 150 per year in parts of the north Queensland coast where the annual rainfall is over 2000 mm, as well as in much of southern Victoria and in the extreme south-west of Western Australia where it is not more than about 600 mm. Over most of the continent the frequency is less than 50 raindays per year. In the high rainfall areas of northern Australia, the number of raindays is about 80 per year, but much heavier falls occur in this region than in southern regions.

5. Methods

Although most of the lightning sensors at the ABM stations have been operating for 10-20 years, not all of them have provided complete data sets; there being some significantly long gaps in the records at many sites, mainly due to instrument and battery failure. Of the 40 stations, 23 were selected for their reliability and availability of lightning and rainfall data over sufficiently long periods of observation and to represent a wide geographical distribution across the continent. These sites are shown on the map in Fig 1. Table 1 lists the stations, arranged according to state. Station identification numbers are given in column 1. Columns 3, 4 and 5 show the latitude and longitude of each site and the number of years over which reliable data were available for use in this study.

A method of deriving lightning ground flash density from CIGRE-500 counter registrations has been described by Kuleshov and Jayaratne (2004). This method takes into account the detection efficiency of the instrument and makes further corrections to eliminate a small number of falsely-counted intracloud flashes and to include the small fraction of ground flashes (4%-6%) that carry a net positive charge and are not counted by the instrument. Therefore, the ground flash density reported in this paper is the total number of ground flashes (negative and positive) per square kilometre per year.

The annual rainfall data were obtained from the ABM National Climate Centre archive. Readings were averaged over the number of years of data availability shown in column 5 of Table 1.

6. Results and Discussion

6.1. Lightning Incidence

Column 6 of Table 1 shows the mean annual ground flash density, N_g in units of km^{-2} yr^{-1} for each of the 23 stations. Note that the two coastal west Australian towns of Geraldton and Moora show the lowest lightning incidence (0.25 and 0.29 respectively), much lower than the dry mid-continental locations such as Tennant Creek (1.80) and Kalgoorlie (0.94). The two north coast stations of Darwin and Kununurra have the highest lightning ground flash densities (7.15 and 7.14 respectively), well above all the other stations. It is interesting that Centre Island, which is also a north coast station but lies within the Gulf of Carpentaria, has an N_g value of only 2.27 which is three times less than for Darwin and Kununurra. To confirm the veracity of this difference, we derived values of the total flash density, N_t (ground flash + intracloud flash) from worldwide satellite remote sensing data gathered by NASA instruments for lightning detection – Optical Transient Detector (OTD) and Lightning Imaging Sensor (LIS) for these three localities. The N_t values for Kununurra, Darwin and Centre Island were 26.14, 22.87 and 8.14 fl km^{-2} yr^{-1} respectively. Thus, the total lightning activity as derived from the satellite data for Darwin and Kununurra is also three times higher than for Centre Island, which confirms our findings.

Column 7 of the table gives the mean annual rainfall in mm. Column 8 gives the rain yield calculated in kg of rain per flash (kg fl^{-1}).

6.2. Rain Yield – Geographical Distribution

In Fig 2, we plot the mean annual rainfall of the stations against the mean annual ground flash density. There is a positive linear correlation of $r = 0.43$ ($P = 0.04$) between the two parameters (best line not shown). However, what is more important is the apparent clustering of stations of similar climatic conditions. The two straight lines show the constant rain yields of 10^8 kg fl^{-1} (lower line) and 10^9 kg fl^{-1} (upper line). Williams et al. (1992) showed that the rain yield from Darwin break period storms was below the lower line, while for the monsoonal periods at the same location the value was above the upper line. These values were computed over two lightning seasons. Note that our overall value for Darwin (station 9), computed using 21 years of data, lies almost exactly in-between the two lines. Petersen and Rutledge (1998) showed that most of the arid mid-continental stations lay close to or below the lower line while the maritime and tropical oceanic stations showed values above the upper line. These results covered a wide range of locations around the world. In agreement, as we shall show next, our results for Australia indicate a similar trend.

In Fig 2, most of the coastal stations lie close to the upper rain yield line, while almost all of the arid continental stations lie closer to the lower line. For example, the six stations with the highest rain yields (above the upper line) are all situated on the coast or in proximity to the coast (1, 4, 5, 15, 20 and 21). At the other end of the scale, all five dry inland stations (shown as triangles) are found clustered together near the lower line (2, 3, 10, 13 and 17). Two coastal stations with relatively low rain yields are Kununurra (8) and Port Hedland (6). Both these stations are situated along the dry north-west coast. Although coastal fringes are comparatively moist, this is less evident along the north west coast where continental effects are marked. Kununurra, in fact, shows the lowest rain yield of all the stations investigated. The station with the highest rain yield is Nowra (20), which is a temperate station on the east coast.

Another interesting feature that emerges from the figure is the relatively high rain yields in the low lightning coastal locations in Western Australia (1, 4, 5 and 7), South Australia (12) and Victoria (21, 22 and 23). These are the locations that receive winter rain. Despite the high winter rainfall, lightning activity during this time is low owing to the low surface temperatures and CAPE. The coastal stations in New South Wales and Queensland (14, 15, 16, 17, 18, 19 and 20) receive most of its annual rainfall during the summer months when high surface temperatures give rise to higher CAPE and lightning activity.

6.3. Rain Yield – Seasonal Distribution

In order to investigate a seasonal difference, we separated the rainfall and lightning data for each station into two seasons – arbitrarily defined as winter half of the year (Apr-Sep) and summer half of the year (Oct-Mar) and calculated the corresponding rain yields. In Fig 3 we plot the winter-half rain yield versus the summer-half rain yield. Each point represents a station. The straight line shows equality. As expected, every one of the 23 stations showed a winter-half rain yield greater than the summer-half yield. At many stations, especially in the tropics, the winter-half values were over an order of magnitude greater than the summer-half values. The mean winter-half and summer-half values were 2.46×10^9 kg fl^{-1} and 4.53×10^8 kg fl^{-1} respectively. A Students t-test analysis showed that the winter-half mean value was significantly greater than the summer-half mean at a confidence level of 99%. This difference was also obvious in the monthly variation. In Fig 4, we show the mean monthly rain yields for three of the stations. Note the sharp increase in rain yield in the winter months over the summer months. This pattern was observed at all stations, with the differences being most marked at tropical stations and less obvious at stations along the southern coast.

6.4. Seasonal Rainfall Zone Classification

In attempting to look for trends in relation to climatic conditions, it was necessary to identify the various climatic zones in Australia. We used the classification proposed by the ABM based on Gaffney (1971) and grouped the stations into six seasonal rainfall zones as shown in the map in Fig 1. The zones are listed in Table 2, together with the stations in each zone and the corresponding zonal station mean annual rainfalls, ground flash densities and rain yields. These values are shown graphically in Fig 5. The error bars show the corresponding standard deviations of the station readings about the zonal mean. Although there is considerable scatter, some features stand out. The annual rainfall in the two summer rainfall zones, S and SD, were significantly higher than in the two winter rainfall zones, W and WD. However, the converse was true for the rain yield, with the W and WD values being significantly higher than those for S and SD. The mean rain yields for groups S and SD was 5.44 x 10^8 kg fl^{-1} and for groups W and WD it was 1.28 x 10^9 kg fl^{-1} – a difference of over a factor of two. Statistical analyses showed that the winter zone rain yields were significantly higher than both the summer zone and arid zone values at a confidence level of 95%. The rainfall and rain yield in the arid zone, A, was significantly lower than in all other zones. As expected, the ground flash densities were highest in the two seasonal rainfall zones S and SD. The large error bar for the SD group is owing to the relatively high lightning activity (greater than 7 fl km^{-2} yr^{-1}) at Darwin and Kununurra. In this seasonal rainfall group, these two stations which are situated on the northern coastline have much higher lightning activity than the other stations.

6.5. Geographical Zone Classification

Next, we used a purely geographical classification and grouped the stations into two zones – coastal (near or on the coastline) and inland (mid-continental; at least 500 km from the nearest coast). Then we grouped the coastal stations into four according to their locations on the N, S, E and W coastlines of the continent. Table 3 lists the five zones, with the stations in each zone and the station mean rain yields in each zone. Fig 6 is a graphical representation of the rain yields in the five zones. In good agreement with other studies (Williams et al., 1992; Petersen and Rutledge, 1998), the mean rain yield for the mid-continental stations (2.64 x 10^8 kg fl^{-1}) was lower than the corresponding overall mean value of the coastal stations (9.91 x 10^8 kg fl^{-1}). A statistical analysis showed that the difference was significant at the confidence level of 95%. The mean rain yield values for stations along the E, S and W coasts were significantly higher than the values on the N coast and the inland. The relatively low station mean rain yield computed for the N coast is strongly influenced by Kununurra (8) that, as explained before, lies in a peak lightning area with an annual rainfall of only 705 mm.

In agreement with previous studies, the present results in Australia show increased rain yields at coastal stations over inland stations and during the winter over the summer seasons. These observations are broadly explicable in terms of the differences in surface heating between the two seasons and between the geographical locations. Greater surface heating is related to higher cloud base height and greater CAPE, both of which have been linked with higher lightning activity (Williams et al, 2004; Williams and Renno, 1993). Moreover, the air over inland stations contain higher aerosol and cloud condensation nuclei concentrations than coastal stations and, by the explanation given in the introduction, may exhibit higher lightning activity, lower rainfall and lower rain yields.

7. Summary and Conclusions

Analysis of rainfall and lightning data from 23 stations widely scattered around the continent of Australia showed a statistically significant linear relationship between annual rainfall and ground flash density. These two parameters were used to estimate rain yields for all the stations as mass of rain per lightning ground flash (units: kg fl^{-1}).

In agreement with previous studies in Darwin and other parts of the world, the Australian stations confirmed that the rain yield was strongly controlled by seasonal climatic conditions at the various locations. Six stations showed rain yields greater than 1.0×10^9

kg fl^{-1}. All six of these stations were situated on the coast or very near the coast. The five mid-continental stations gave rain yields clustered close together with a mean of 2.64 x 10^8 kg fl^{-1}, while all the coastal stations showed a mean value of 9.91 x 10^8 kg fl^{-1} – a difference of a factor of over three. A Students t-test showed that the difference was statistically significant at the confidence level of 95%.

When the data were separated into two halves, April-September (winter-half) and October-March (summer-half), every one of the 23 stations showed a higher mean rain yield during the winter-half over the summer-half. Mean monthly rain yields were computed and these showed a sharp increase of rain yields in the winter months over the summer months, with the differences being more marked in the tropics and least along the southern coast. These observations may be explained in terms of seasonal heating. Surface heating directly affects convective available potential energy in the atmosphere – the driving force for thunderstorm generation.

Classification of the stations into the six major seasonal rainfall zones defined by the ABM showed that the mean rain yield in the winter and winter-dominant rainfall zones, along the south west and southern coast, was 1.28 x 10^9 kg fl^{-1}, while the value in the summer and summer-dominant rainfall zones, along the north and east coast, was significantly lower at 5.44 x 10^8 kg fl^{-1}. The rain yield in the mid-continental arid zone showed the lowest value of 2.84 x 10^8 kg fl^{-1}. The differences in the mean of the winter and winter-dominant rainfall group and each of the other two groups (summer/summer dominant rainfall and arid) were statistically significant at the 95% confidence level.

Acknowledgements

The lightning flash counter registration data were provided by the Observations and Engineering Branch, Australian Bureau of Meteorology. Satellite data were taken from the v1.0 LIS/OTD gridded climatology provided by the Global Hydrology Resource Center, NASA, USA. Graham de Hoedt, National Climate Centre, Australian Bureau of Meteorology prepared a map of major seasonal rainfall zones of Australia (http://www.bom.gov.au/climate/environ/other/aus_seas_zones.shtml).

References

Barham, R.A. 1965. A transistorised lightning flash counter. Electron. Lett. 1, 173.

Battan, L.J. 1965. Some factors governing precipitation and lightning from convective clouds. J. Atmos. Sci. 22, 79-84.

Cheze, J.L., Sauvageot, H. 1997. Area average rainfall and lightning activity. J. Geophys. Res. 102, 1707-1715.

Gaffney, D.O. 1971. Seasonal rainfall zones in Australia. Bureau of Meteorology. Working papers. No. 141, 9 p.

Jayaratne, E.R., Ramachandran, V., Devan, K.R.S. 1995. Observations of lightning flash rates and rain gushes in Gaborone, Botswana. J. Atmos. Terr. Phys. 57 (4), 325-331.

Kinzer, G. 1974. Cloud-to-ground lightning versus radar reflectivity in Oklahoma thunderstorms. J. Atmos. Sci. 31, 787-799.

Kuleshov, Y., Jayaratne, E.R. 2004. Estimates of lightning ground flash density in Australia and its relationship to thunder-days. Austral. Meteor. Mag. 53, 189-196.

Moore, C.B., Vonnegut, B., Machado, J.A., Survilas, H.J. 1962. Radar observations of rain gushes following overhead lightning strokes. J. Geophys. Res. 67, 207-220.

Orville, R.E., Henderson, R.W. 1986. Global distributions of midnight lightning: September 1977 to August 1978. Mon. Weather Rev. 114, 2640-2653.

Piepgrass, M.V., Krider, E.P., Moore, C.B. 1982. Lightning and surface rainfall during Florida thunderstorms. J. Geophys. Res. 87, 11193-11201.

Petersen, W.A., Rutledge, S.A. 1998. On the relationship between cloud to ground lightning and convective rainfall. J. Geophys. Res. 103, 14025-14040.

Petersen, W.A., Rutledge, S.A., Orville, R.E. 1996. Cloud to ground lightning observations from TOGA COARE: selected results and lightning location algorithms. Mon. Wea. Rev. 124, 602-620.

Prentice, S.A. 1972. CIGRE lightning flash counter. Electra 22, 149-171.

Prentice, S.A., Mackerras, D. 1969. Recording range of a lightning flash counter. Proc. Inst. Elect. Eng. London 116, 294-302.

Reap, R.M., MacGorman, D.R. 1989. Cloud-to-ground lightning: climatological characteristics and relationships to model fields, radar observations, and severe local storms. Mon. Wea. Rev. 117, 518-535.

Rosenfeld, D., Lensky, I.M. 1998. Satellite-based insights into precipitation formation processes in continental and maritime convective clouds. Bull. Amer. Meteorol. Soc. 79, 2457-2476.

Shackford, C.R. 1960. Radar indications of a precipitation-lightning relationship in New England thunderstorms. J. Meteor. 17, 15-19.

Williams, E.R., Renno, N. 1993. An analysis of the conditional instability of the tropical atmosphere. Mon. Wea. Rev. 121, 21-36.

Williams, E.R., Stanfill, S. 2002. The physical origin of the land-ocean contrast in lightning activity. C.R. Physique. 3, 1277-1292.

Williams, E.R., Mushtak, V., Rosenfeld, D., Goodman, S., Boccippio, D. 2004. Thermodynamic conditions favourable to superlative thunderstorm updraft, mixed phase microphysics and lightning flash rate. Atmos. Res. (In Press).

Williams, E.R., Rutledge, S.A., Geotis, S.G., Renno, N., Rasmussen, E., Rickenbach, T. 1992. A radar and electrical study of tropical “hot towers”. J. Atmos. Sci. 49, 1386-1395.

Zipser, E.J. 1994. Deep cumulonimbus cloud systems in the tropics with and without lightning. Mon. Wea. Rev. 122, 1837-1851.

Figure Captions

1. Map of Australia showing the six major seasonal rainfall zones and the locations of the 23 stations used in the analysis. Refer to Table 1 for the station identification numbers. The stations are listed according to rainfall zone in Table 2.

2. The Rain Yield plot showing the annual rainfall versus the ground flash density for the 23 stations. Station identification numbers refer to column 1 of Table 1. The five inland stations (Table 3) are shown as triangles. All other stations, shown as squares, are coastal or near-coastal. The two solid straight lines represent constant rain yields of 10^8 kg fl^{-1} (lower line) and 10^9 kg fl^{-1} (upper line).

3. Rain yields for the winter-half of the year plotted against the rain yield for the summer-half of the year. Each point represents a station. The solid straight line represents equality of the two plotted parameters. All stations have a higher rain yield in the winter half over the summer-half.

4. Mean monthly rain yields for the three stations Coffs Harbour, Kalgoorlie and Melbourne.

5. Graphical representation of the mean values of (a) rainfall (b) ground flash density and (c) rain yield in the six major seasonal rainfall zones listed in Table 2.

6. Graphical representation of the mean rain yield in the five geographical zones listed in Table 3.

Tables

Table 1: List of stations used in the study with associated details and data. See the map in Fig 1 for the geographical locations of the stations on the continent.

Station ID	Location	Latitude (deg S)	Long (deg E)	Years of data	Ng (km^{-2} yr^{-1})	Rainfall (mm yr^{-1})	Yield (kg flash^{-1})
1	Geraldton WA	28.8	114.7	22	0.25	432.1	1.76E+09
2	Kalgoorlie WA	30.8	121.5	22	0.94	291.5	3.10E+08
3	Meekatharra WA	26.6	118.5	20	1.14	275.7	2.41E+08
4	Moora WA	30.6	116.0	17	0.29	463.0	1.59E+09
5	Perth WA	31.9	116.0	21	0.41	744.7	1.81E+09
6	Port Hedland WA	20.4	118.6	22	0.96	319.2	3.33E+08
7	Three Springs WA	29.5	115.8	16	0.40	384.7	9.52E+08
8	Kununurra WA	15.8	128.7	9	7.14	705.3	9.87E+07
9	Darwin NT	12.3	131.0	21	7.15	1801.8	2.52E+08
10	Tennant Creek NT	19.6	134.2	20	1.80	453.7	2.53E+08
11	Center Is NT	15.7	136.8	9	2.27	923.7	4.07E+08
12	Ceduna SA	32.1	133.7	19	0.35	273.4	7.90E+08
13	Mt Isa QLD	20.6	139.5	19	2.73	440.2	1.61E+08
14	Brisbane QLD	27.5	153.0	15	1.74	1118.6	6.42E+08
15	Townsville QLD	19.1	146.5	13	0.83	1108.9	1.34E+09
16	Bowraville NSW	30.7	152.8	12	2.47	1159.0	4.70E+08
17	Cobar NSW	31.5	145.8	18	1.16	410.0	3.55E+08
18	Coffs Harbour NSW	30.3	153.1	20	1.85	1663.5	9.00E+08
19	Lismore NSW	28.8	152.3	17	1.96	1223.8	6.26E+08
20	Nowra NSW	35.0	150.5	14	0.44	1118.0	2.54E+09
21	Ballarat VIC	37.5	143.8	21	0.40	662.5	1.67E+09
22	Melbourne VIC	37.7	144.8	21	0.81	518.9	6.37E+08
23	Whitlands VIC	36.9	146.3	20	1.41	1407.5	1.00E+09

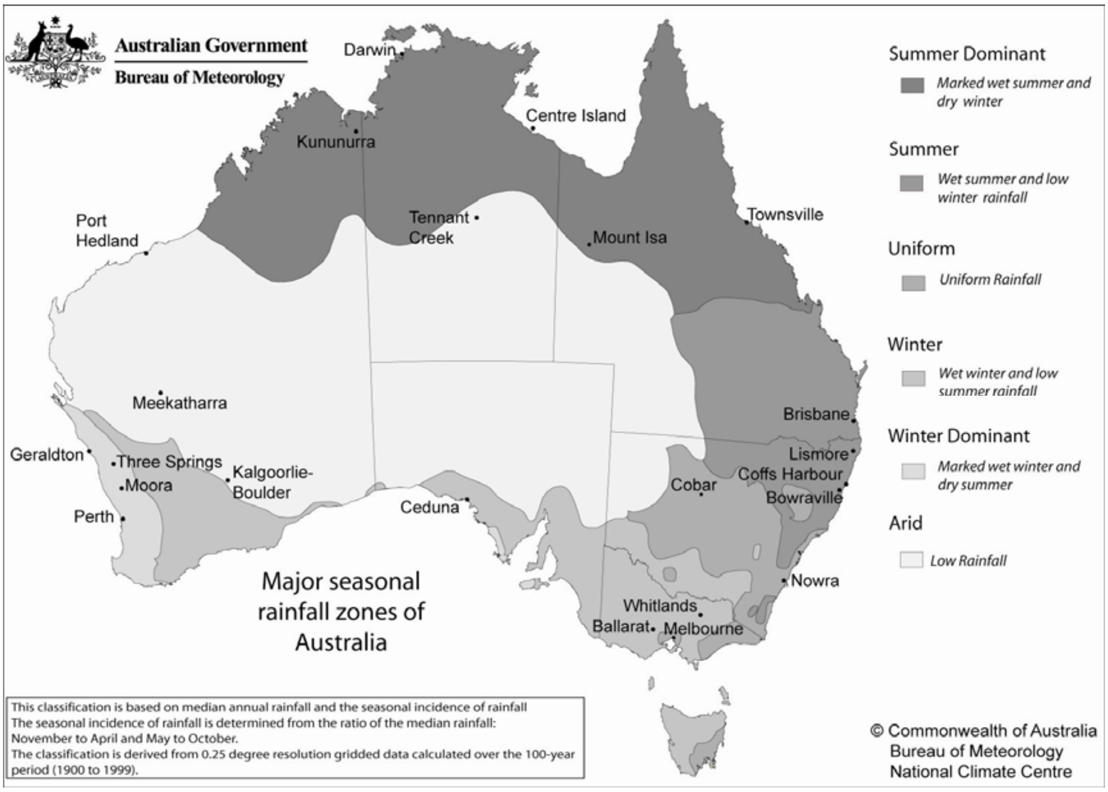
Table 2: The stations classified according to the six major seasonal rainfall zones

Zone	**Notation**	**Stations**	**Mean Rainfall ($\times 10^8$ kg km^{-2} yr^{-1})**	**Mean Ground Flash Density, N_g (fl km^{-2} yr^{-1})**	**Mean Rain Yield ($\times 10^8$ kg fl^{-1})**
Summer	S	14, 16, 18, 19	12.9	2.00	6.59
Summer Dominant	SD	8, 9, 11, 13, 15	9.96	4.02	4.52
Uniform	U	17, 20	7.64	0.80	14.5
Winter	W	12, 21, 22, 23	7.16	0.74	10.3
Winter Dominant	WD	1, 4, 5, 7	5.06	0.34	15.3
Arid	A	2, 3, 6, 10	3.35	1.21	2.84

Table 3: The stations classified according to geographical location. Also shown in the last row is the overall mean for all coastal stations.

Zone	**Notation**	**Stations**	**Mean Rain Yield ($\times 10^8$ kg fl^{-1})**
Inland	I	2, 3, 10, 13, 17	2.64
Northern Coastal	NC	8, 9, 11	2.52
Eastern Coastal	EC	14, 15, 16, 18, 19, 20	10.9
Southern Coastal	SC	12, 21, 22, 23	10.3
Western Coastal	WC	1, 4, 5, 6, 7	12.9
All Coastal			9.91

Fig 1



This classification is based on median annual rainfall and the seasonal incidence of rainfall
The seasonal incidence of rainfall is determined from the ratio of the median rainfall: November to April and May to October.
The classification is derived from 0.25 degree resolution gridded data calculated over the 100-year period (1900 to 1999).

Fig 2

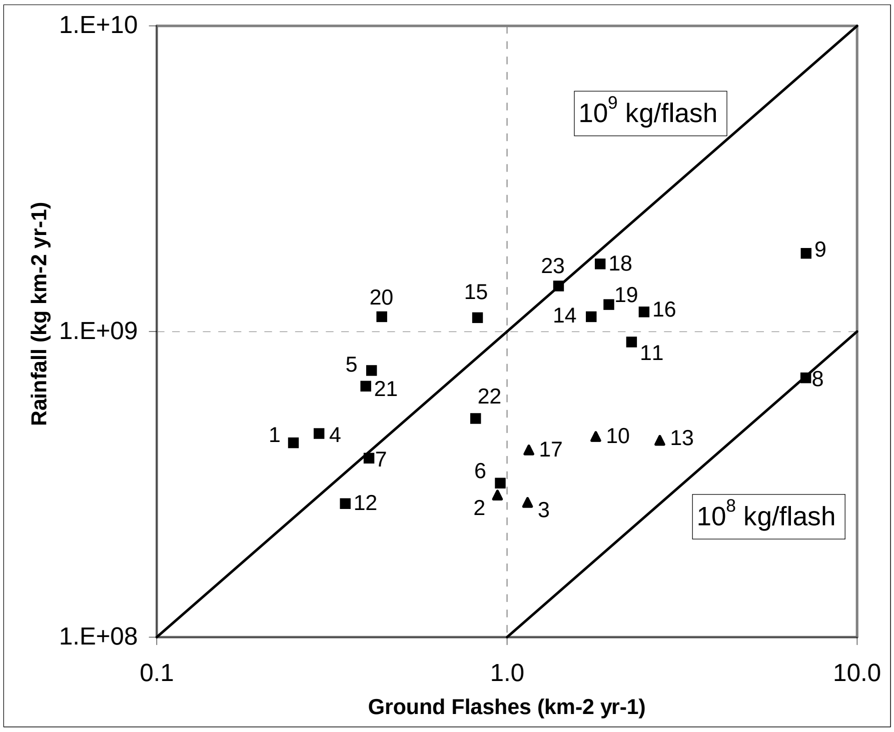

1.E+10
1.E+09
1.E+08
0.1
1.0
10.0
Ground Flashes (km-2 yr-1)
Rainfall (kg km-2 yr-1)
10^9 kg/flash
10^8 kg/flash
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23

Fig 3

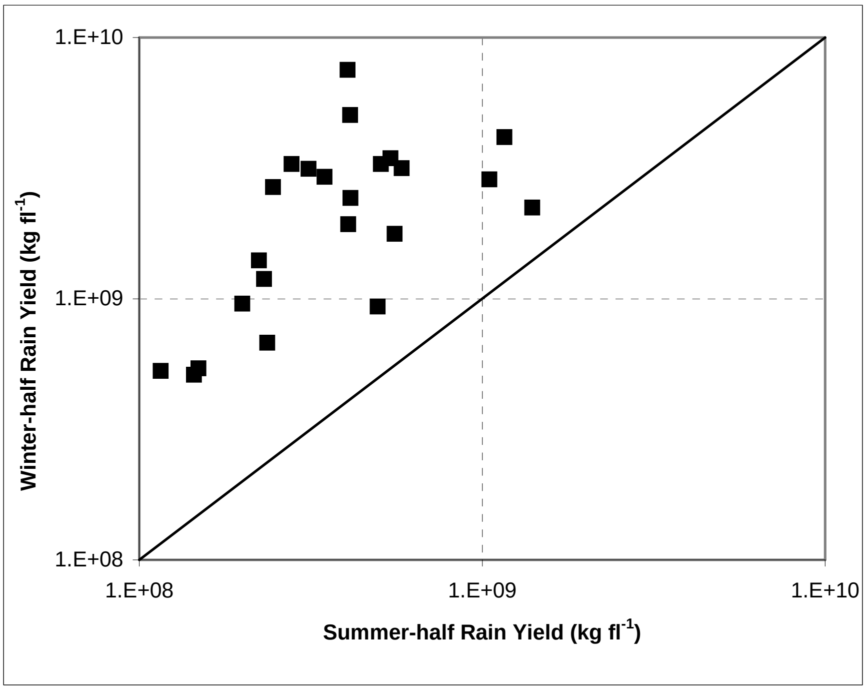

1.E+10
1.E+09
1.E+08
1.E+08
1.E+09
1.E+10
Winter-half Rain Yield (kg fl^{-1})
Summer-half Rain Yield (kg fl^{-1})

Fig 4

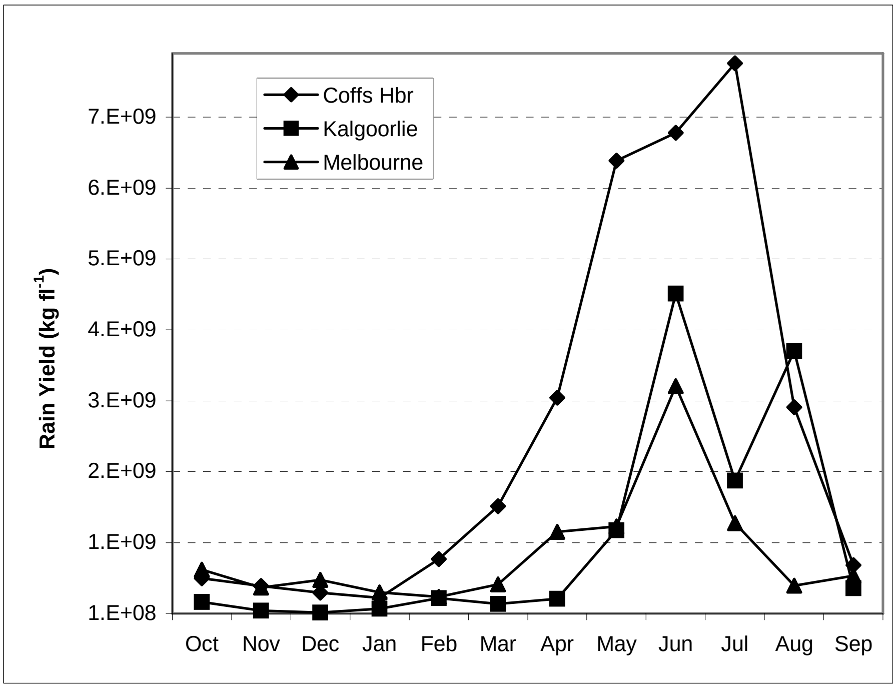

Coffs Hbr
Kalgoorlie
Melbourne
Rain Yield (kg fl^{-1})
7.E+09
6.E+09
5.E+09
4.E+09
3.E+09
2.E+09
1.E+09
1.E+08
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep

Fig 5

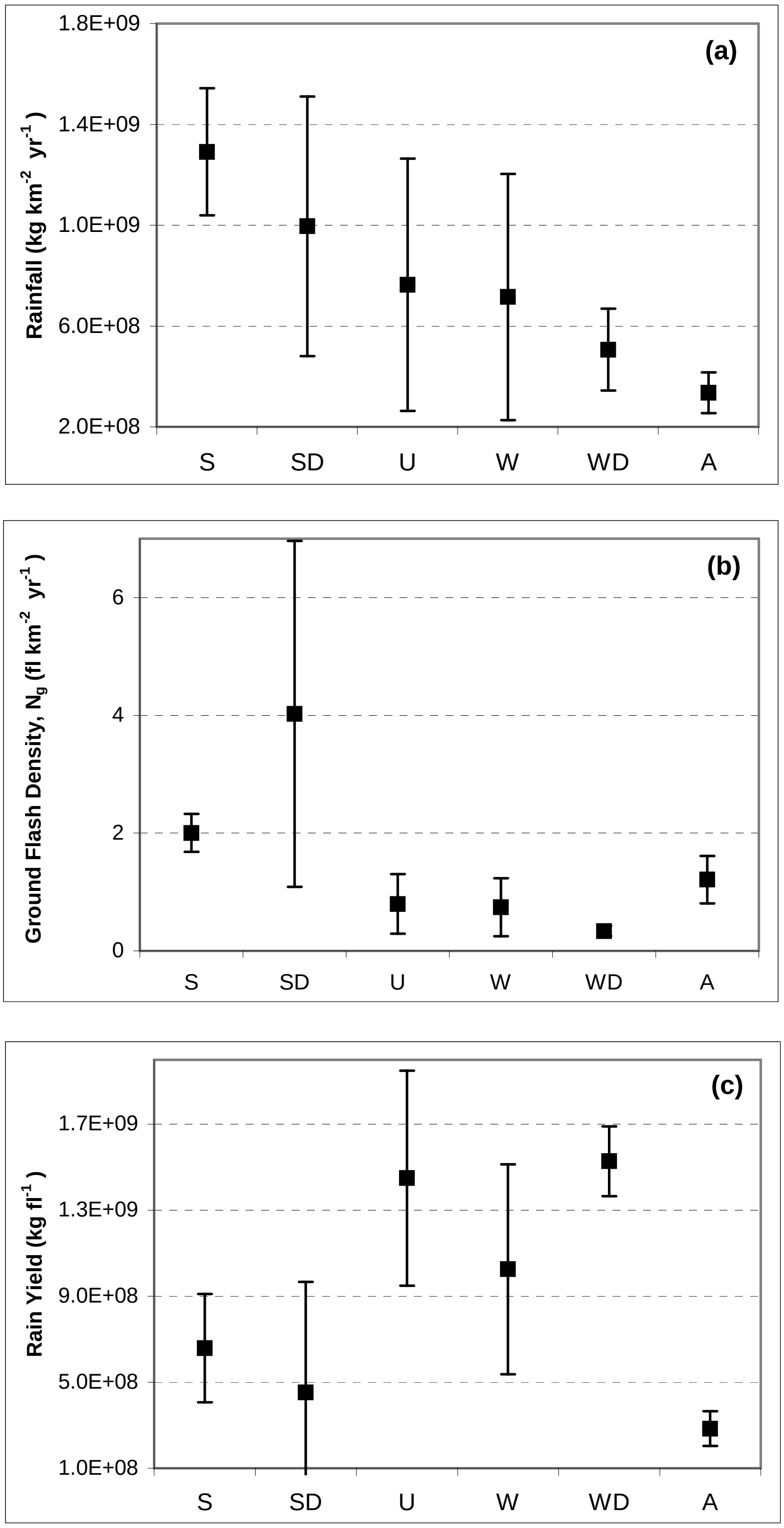

(a)
Rainfall (kg km^{-2} yr^{-1})
1.8E+09
1.4E+09
1.0E+09
6.0E+08
2.0E+08
S
SD
U
W
WD
A
(b)
Ground Flash Density, N_g (fl km^{-2} yr^{-1})
6
4
2
0
S
SD
U
W
WD
A
(c)
Rain Yield (kg fl^{-1})
1.7E+09
1.3E+09
9.0E+08
5.0E+08
1.0E+08
S
SD
U
W
WD
A

Fig 6