

Seasonal and latitudinal variations of lightning ground flash activity in Australia

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The seasonal and latitudinal variations of lightning ground flash activity in Australia have been analysed using lightning flash counter data. A number of parameters to describe lightning activity such as lightning-days, ground flash occurrence and ground flash frequency have been derived using counter registrations and compared for eighteen localities across Australia. Lightning activity is the highest in the northern part of the country and it has a clear defined seasonality with sharp increases of lightning-days, ground flash occurrence and ground flash frequency during the wet season months. Lightning activity generally decreases towards the south and seasonal distributions of lightning parameters are more uniform in higher latitudes, but lightning mainly stays a summer phenomenon over Australia. A reduction in lightning ground flash density by a factor of about ten for a 30° change in latitude has been found.

Introduction

Lightning, one of the most powerful forces in nature, once was mysterious, magical and feared as the great weapon of the Gods. Ancient Greeks feared lightning as it was believed to be hurled by Zeus, the king of the Gods. For the Vikings, lightning was produced by Thor as his hammer struck an anvil while riding his chariot across the sky. American Indians believed that lightning was caused by bright flashing feathers of a mystical bird, and thunder was created by its flapping wings. From ancient times lightning and thunder were associated with each other even if the explanations for these natural phenomena were far from reality. Scientific study of lightning began with the works of Franklin, Lomonosov and Tesla, and today scientists explain lightning as 'any and all of the various forms

of visible electrical discharge produced by thunderstorms. Thunder is the sound emitted by rapidly expanding gases along the channel of a lightning discharge' (Glossary of Meteorology 1959).

During thunderstorms partial separation of electrical charges within the thundercloud usually results in regions with net negative charge mainly in the lower parts of the thundercloud, and regions with net positive charge mainly in the upper part (MacGorman et al. 1981; Williams 1985). Lightning is an electrical discharge between differently charged regions within the cloud (cloud flash, also referred to in literature as intracloud flash) or between a charged region, nearly always the lower negatively charged region, and earth (cloud-to-ground lightning flash, or simply ground flash). Direct and nearby cloud-to-ground lightning strikes can be hazardous to persons, structures and installations. Lightning can start bushfires, which cause damage to the natural environment, property and life loss. There have been 650 registered fatalities

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in Australia in the period 1803-1992 caused by lightning strikes (Coates 1996). Given the potential hazards associated with lightning, knowledge about lightning ground flash activity is of great importance.

To obtain instrumental records of lightning incidence, lightning flash counters (LFCs) have been installed at meteorological sites worldwide. For several decades, the Australian Bureau of Meteorology used CIGRE-500 counters, which have been utilised for registration of ground flashes (Barham 1965; Prentice 1972). Recently, remote-sensing data gathered by satellite instruments such as the Optical Transient Detector (OTD) and the Lightning Imaging Sensor (LIS) became available. Compared with LFCs, satellite data provide better spatial coverage of lightning which is a phenomenon that, by its nature, is highly variable and localised. Remote sensing data present an opportunity to determine the average global flash rate (Christian et al. 2003). However, there may be considerable uncertainty in utilising the global flash data from OTD and LIS for some applications such as estimating the number of ground flashes. Estimates of ground flash activity derived from the long-term LFC records would greatly assist with resolving uncertainties of the remote sensing data. Consequently, lightning flash counter records have been analysed in this study in order to derive a number of parameters of lightning activity for selected sites and to estimate their variability around the country.

Latitudinal variation of lightning activity

Moist convection is systematically deeper and more frequent in the tropics than in higher latitudes. It has been shown that lightning activity is higher in the tropics: approximately two thirds of global lightning flashes occur in the latitude interval $\pm 23^\circ$ (Williams 1992). An early attempt to utilise LFC data for describing latitudinal variation of lightning ground flash activity in Australia and establishing relationships between lightning ground flash density, N_g , and thunder-days was made by Mackerras (1978). It was found that regions with higher thunder-day levels tend to have more flashes per thunder-day than regions with low thunder-day level. However, due to limitations of the method used for derivation of N_g it resulted in underestimation of ground flash activity. This study was followed by several other studies on latitudinal variation of lightning activity using different methods. Orville and Spencer (1979) reported satellite-based optical observations of total lightning flash density at local dusk and midnight over a lati-

tude range 60°N to 60°S and demonstrated a reduction in flash frequency by a factor of ten for a 40° increase in latitude in the southern hemisphere. Results of another satellite-based observations using radio-frequency detection of lightning indicated a similar rate of change of total flash density – a reduction in lightning flash rate by a factor of about ten for a change in latitude from 20°S to 60°S (Kotaki et al. 1981). Mackerras and Darveniza (1994) analysed latitudinal variation in lightning activity using data from ground-based lightning flash counters recorded at fourteen sites in eleven countries covering latitudes from 60°N to 27°S , and concluded that total flash density falls by a factor of 10 for 30° increase in latitude. Considering the differences in the methods used, the agreement among these estimates of the rate of change of total flash density with latitude is reasonably good. The above-mentioned conclusions were drawn for latitudinal variation of total lightning flashes, which comprise of all types of lightning discharge (i.e. the ground flashes and the intracloud flashes). The current study investigates variation of lightning ground flashes for the range of latitudes over Australia and compares our findings with the results of earlier studies.

Seasonal variation of lightning activity

Mackerras and Darveniza (1994) analysed lightning activity using data from ground-based lightning flash counters and derived the annual variation of total flash density for seven sites around the world. Mackerras et al. (1998) analysed annual variation of total flash density using the Defense Meteorological Satellite Program data and plotted the annual variation curves for the northern hemisphere, for an equatorial strip, and for the southern hemisphere. There is general agreement between the two sources of information, with the peaks in lightning activity occurring in spring and summer months in the respective hemispheres. The seasonal variation of lightning ground flash activity for Brisbane was derived by Mackerras (1978) using LFC data and it was shown that ground flash density is highest in the months September through April. It was suggested that this is typical of the seasonal variation of lightning activity over Australia. However, Mackerras (1978) indicated that there are sites in the southern parts of Australia where the difference between summer and winter lightning activity is less well marked. Recent study of thunderstorm distribution and frequency in Australia demonstrated that, in contrast with most other parts of Australia, the monthly distributions of thunder-days

in Perth (Western Australia) and Strahan (western Tasmania) indicated a winter maximum in thunderstorm frequency (Kuleshov et al. 2002). One of the objectives of this study is to analyse seasonal variation of ground flashes and to compare it with seasonal variation of thunderstorm frequency.

Instruments and methods of recording of thunderstorms and lightning

Recording of thunderstorms

Traditionally, thunderstorm occurrence at a particular location is expressed in terms of thunder-days. A thunder-day, T_d , is defined as ‘an observational day (any 24-hour period selected as the basis for climatological or hydrological observations) during which thunder is heard at the station. Precipitation need not occur’ (Glossary of Meteorology 1959). The 24-hour period selected at the Bureau of Meteorology for the phenomenon registration is midnight to midnight (local standard time). The requirement that thunder should actually be heard limits the area covered by each observing point to a circle with a radius of some 20 km (World Meteorological Organization 1953). Clearly, this method of phenomenon registration is subject to human error, and it was noticed that thunderstorm events are often under-reported at certain Bureau stations, especially those staffed with cooperative observers. On the other hand, the Bureau’s climate sites provide reliable long-term thunder-day records which proved to be a useful source of information about thunderstorm occurrences around the country. However, for many scientific and practical purposes it is important to know the actual lightning incidence rather than a fact of occurrence of a thunderstorm. The number of thunder-days does not always reflect occurrence of lightning appropriately. That is, a tropical thunderstorm with hundreds of lightning flashes and a high-latitude thunderstorm with very few claps of thunder will both be recorded as one thunder-day.

Lightning flash counter network

The installation of lightning flash counters allowed the Bureau to obtain instrumental records of regional lightning activity. The LFC used is the CIGRE-500 counter (Barham 1965; Prentice 1972). Prentice and Mackerras (1969) evaluated an effective range of the counter detection for ground flashes as 30 km. By the definition of the effective range, the total number of flashes that occur outside this range and are counted is equal to the total number of flashes that occur within this range and are not counted. Thus, the assumption that all flashes within the effective radius are

counted and all flashes outside the effective range are missed gives a numerically correct value in working out the ground flash density. CIGRE-500 lightning counters were designed primarily to measure lightning strikes to ground. However, many intracloud flashes are also counted by the instrument. Kuleshov and Jayaratne (2004) calculated the detection efficiency of the CIGRE-500 counter to ground flashes as 0.68. This is the fraction of counter registrations that are ground flashes.

The Australian network of lightning flash counters was designed to provide estimates of regional lightning activity and counters were placed mainly in densely populated areas along the coast, and very few are inland. After the quality control procedure, LFC registration data from eighteen sites were selected for this study. Table 1 gives the location, latitude and longitude of each site and the corresponding number of years over which lightning flash count data were available (columns 1 to 4, respectively).

Variability of thunderstorms and lightning: results and discussion

Seasonal variations of lightning days and ground flash activity

Thunderstorms are most frequent over the northern half of Australia, and generally decrease southward, with lowest frequencies in southeast Tasmania (Kuleshov et al. 2002). The northern half of Australia is very favourable for thunderstorms in the wet season months (October – April), and especially in the far north, thunderstorms are frequent and often associated with heavy rainfall and intense lightning. High boundary-layer moisture levels and lower surface pressure during the wet season in the northern half of Australia favour thunderstorm development. The peak frequency of thunderstorms is in the vicinity of Darwin (Fig. 1, black bars), with over 90 thunder-days annually on average. Comparison with plotted lightning-days, L_d , i.e. number of days with lightning as detected by a lightning flash counter (Fig. 1, grey bars) shows that monthly mean number of lightning-days is always higher than that of thunder-days.

Darwin has a clear lightning season which corresponds to the wet season months October through April (99.7 per cent of annual flashes) with a peak in lightning activity in November, December and January (62 per cent of annual flashes) when the monthly mean of lightning ground flashes, N , is over 3500 (Fig. 2). There is very low lightning activity during the dry season months May through September (0.3 per cent of annual flashes) with hardly any lightning during the months June to August. Seasonal dis-

Table 1. Details of the 18 stations including a number of the relevant parameters of lightning activity. The annual flashes refer to the mean number of ground flashes per year of observation. The annual flashes, as well as annual thunder-days T_d and annual lightning-days L_d have been computed for the respective periods of observation at each station. The daily flashes refer to the mean number of ground flashes per lightning-day.

1 <i>Location</i>	2 <i>Lat. (°S)</i>	3 <i>Long. (°E)</i>	4 <i>Years of data</i>	5 <i>Annual T_d</i>	6 <i>Annual L_d</i>	7 <i>Annual flashes</i>	8 <i>Daily flashes</i>
Albany	34.9	117.8	20	15	31	603	19
Geraldton	28.8	114.7	21	11	24	691	29
Kalgoorlie	30.8	121.5	22	21	38	2520	66
Meekatharra	26.6	118.5	19	22	41	3214	78
Moora	30.6	116.0	16	7	13	826	64
Perth	31.9	116.0	21	15	26	1125	43
Port Hedland	20.4	118.6	22	23	48	2531	53
Kununurra ¹	15.8	128.7	10		113	19 156	170
Darwin	12.3	131.0	20	97	157	19 347	123
Tennant Creek	19.6	134.2	20	34	61	4909	80
Ceduna	32.1	133.7	18	14	38	922	24
Mt Isa	20.6	139.5	19	37	54	7514	139
St Lucia	27.5	153.0	15	25	39	4714	121
Townsville	19.1	146.5	12	19	53	2343	44
Cobar	31.5	145.8	18	27	48	3111	65
Coffs Harbour	30.3	153.1	20	36	66	5102	77
Lismore	28.8	152.3	16	26	44	5247	119
Melbourne	37.7	144.8	21	13	57	2268	40

1. Average annual number of thunder-days for Kununurra is not included (data were not reliable).

Fig. 1 Seasonal distributions of monthly mean thunder-days and lightning-days in Darwin.

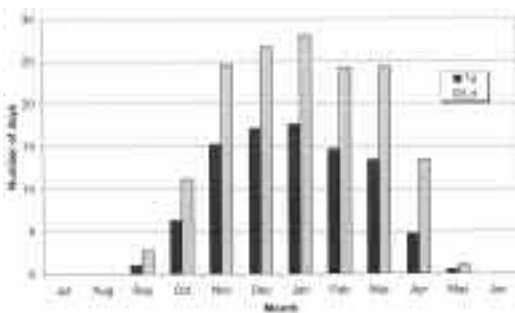
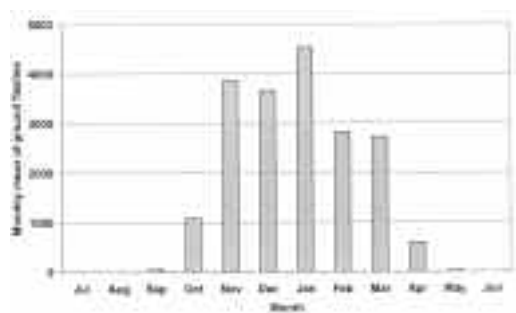


Fig. 2 Seasonal distribution of monthly mean lightning ground flashes in Darwin.

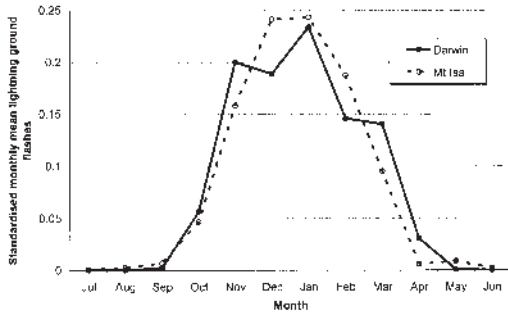


tributions of lightning-days and ground flashes for tropical sites (Darwin and Kununurra) demonstrate a build-up of the number of thunderstorms and the number of lightning strikes in September - October, high lightning activity during the months from November to March, and its decline in April - May.

Lightning flash counter data from Mt Isa, Tennant Creek and Port Hedland (all sites are located around 20°S) confirm results of earlier studies

that lightning activity decreases with increase in latitude. For example, values of monthly mean lightning ground flashes during the months November to March for Mt Isa are about two to four times less than those in Darwin. However, comparison of seasonal distributions of standardised monthly mean lightning ground flashes for Darwin and Mt Isa (Fig. 3) demonstrates that lightning seasonality stays clearly defined.

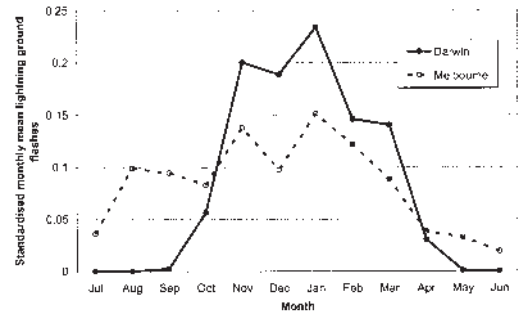
Fig. 3 Seasonal distributions of monthly mean lightning ground flashes in Darwin and Mt Isa, expressed as a fraction of the annual mean.



Thunderstorms generally decrease southward and are less frequent in Victoria, the southern parts of Western Australia and South Australia, and Tasmania, with less than ten thunder-days a year in some areas. The seasonal distributions of lightning parameters are more uniform in higher latitudes (see for example, comparison of seasonal distributions of standardised monthly mean lightning ground flashes for Darwin and Melbourne in Fig. 4). These results are in agreement with early findings of Mackerras (1978), Mackerras and Darveniza (1994), and Mackerras et al. (1998). However, at some sites in the southern part of Australia the peaks of lightning-days and ground flashes do not coincide.

Analysing seasonal distributions of thunderstorms at different localities, Kuleshov et al. (2002) found that in contrast with most other parts of Australia, a thunder-day histogram for Perth indicates a winter maximum in thunderstorm frequency. It was concluded that this reflects the prevalence of active frontal systems at this time, which produce a winter rainfall maximum along the southwest coast, whereas the summer months are generally hot and dry. The distribution of lightning-days in Perth shows that about 56 per cent of days with lightning occurrences were registered during months May to October with maximum of about four lightning-days in June, and about 44 per cent from November to April (Fig. 5). However, the distribution of monthly mean values of ground flashes demonstrates more lightning in warmer months (61 per cent of lightning ground flashes occur in November – April and 39 per cent in May - October) with a maximum of 179 ground flashes in January (Fig. 6). Thus, it was concluded that in Perth, thunderstorms occur more frequently in winter months but lightning activity is higher in summer month storms.

Fig. 4 Seasonal distributions of monthly mean lightning ground flashes in Darwin and Melbourne, expressed as a fraction of the annual mean.



Comparing seasonal distributions for T_d and L_d one can find that they are similar, however, monthly mean number of lightning-days is always higher than that of thunder-days. A linear relationship between average annual number of lightning-days and average annual number of thunder-days for the studied localities was found (correlation coefficient is 0.95). This most likely indicates that the range of detection of electric discharges by counters (30 km) generally exceeds the range of detection of sound waves by observers (20 km).

Lightning frequency

Mackerras (1978) indicated that regions with higher thunder-day levels tend to have more flashes per thunder-day than regions with low thunder-day level. In this study, lightning ground flash frequency, N_d , described in terms of the number of lightning ground flashes per lightning-day, was analysed (Table 1, column 8). A comparison shows that the annual average values of N_d are actually higher in Kununurra ($N_d = 170$) and Mt Isa ($N_d = 139$) which have lower number of lightning-days (113 and 54 days per year, respectively) than in Darwin ($N_d = 123$) which has the highest recorded value for L_d (157). These findings are not surprising: Christian et al. (2003), analysing world frequency and distribution of lightning as observed from space by the OTD, noticed that lightning flash density maxima do not necessarily coincide with the absolute thunder-day maxima. Thus, they observed values of total flash density of about 23 fl km⁻² yr⁻¹ at Entebbe ($T_d=206$) and Kampala ($T_d=242$), Uganda, while the planet's 'lightning hot spot', Kamembe, Rwanda, has 83 fl km⁻² yr⁻¹ and 221 thunder-days recorded.

Fig. 5 Seasonal distributions of monthly mean thunder days and lightning days in Perth.

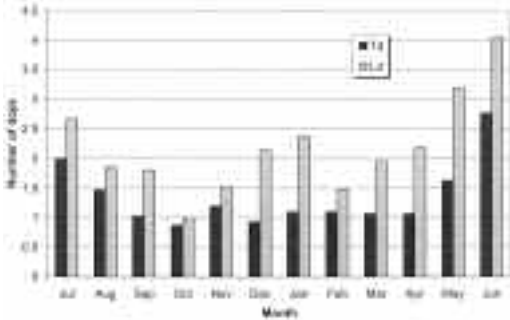
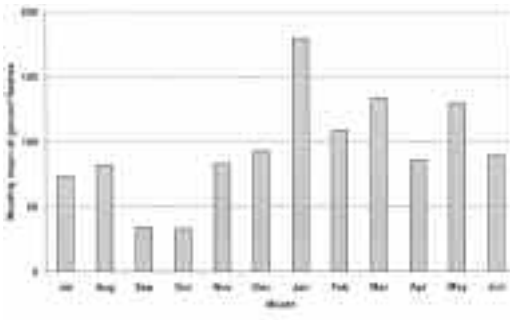


Fig. 6 Seasonal distribution of monthly mean lightning ground flashes in Perth.



Latitudinal variation of lightning parameters

It has been demonstrated above that lightning ground flash density and frequency in the tropics in Australia are higher than in the southern parts, and it is pertinent to examine possible meteorological determinants for such latitudinal variation in lightning activity. It has been shown in several studies (Rutledge et al. 1992; Williams et al. 1992; Petersen and Rutledge 1996) that lightning activity increases with increases in convective available potential energy (CAPE) and wet-bulb temperature. We examined dependence of ground flash density, N_g , on monthly mean daily maximum wet-bulb temperature, $T_{w, \max}$, for four Australian localities from different climatic regimes. It has been shown that tropical stations with a monsoon regime have clearly defined lightning seasons corresponding to the wet season months. High sensitivity of ground flash density to changes in $T_{w, \max}$

during the wet season was found in the tropics, with an increase in N_g values of about an order of magnitude for an increase in $T_{w, \max}$ of less than two degrees (Fig. 7, Darwin). In general, the boundary layer moisture supply deteriorates away from the coast, and comparing lightning activity in Darwin (12.3°S) and Mt Isa (20.6°S) one can see the marked drop in ground flash density, as well as its sensitivity to changes in $T_{w, \max}$. Mt Isa is located in northwest Queensland and lies approximately 350 km south of the Gulf of Carpentaria. The climate of the city is tropical continental with a marked wet season in the summer months. The annual mean rainfall recorded over the studied period was 455 mm, with about 75 per cent of it occurring from December to March. Being so far inland the average humidity is quite low throughout the year, with 3 pm humidity ranging from 30 to 40 per cent in summer. The decline in ground flashes is even more evident in Port Hedland (20.4°S). Port Hedland has a dry climate characterised by high temperatures and low and variable rainfall. The main broadscale influences are the subtropical ridge well to the south and the monsoon which delivers moist air from the warm tropical waters to the north. The annual mean rainfall for the studied period was 314 mm, about 70 per cent of which occurred from January to March in association with thunderstorms and tropical lows or cyclones. The relative humidity is generally uniform from month to month, averaging about 30 to 40 per cent at 3 pm for much of the year although values were approximately 10 per cent more in the wettest months. Compared with Darwin, a decrease in the sensitivity of ground flash density to $T_{w, \max}$ changes for Mt Isa and Port Hedland was observed, with an increase in N_g values of about half an order of magnitude for an increase in $T_{w, \max}$ of about 5 degrees (Fig. 7). In contrast to the sites in the northern half of the country, the sensitivity of the relationship between N_g and $T_{w, \max}$ for Melbourne (37.7°S) was weak. Melbourne's climate is temperate and variable, with moderate rainfall received in most months. Thunderstorms are more frequent during late spring and summer, when there is adequate surface heating to provide energy for convection, but thunderstorms also occur in cooler months in association with cold frontal systems. The explanation for the latitudinal decrease in sensitivity of the relationship between N_g , and CAPE and $T_{w, \max}$ is not straightforward. It is suggested that CAPE remains a main driving force for development of thunderstorms for the tropics and mid-latitudes, however in temperate climates CAPE is strongly affected by the cold dry air aloft and only weakly influenced by the wet-bulb temperature of the boundary layer, compared with the tropics (Williams

Fig. 7 Estimates of annual mean lightning ground flash density, N_g , plotted against monthly mean daily maximum wet-bulb temperature, $T_{w, \max}$, for Darwin, Mt Isa, Port Hedland (wet season months only) and Melbourne (all months).

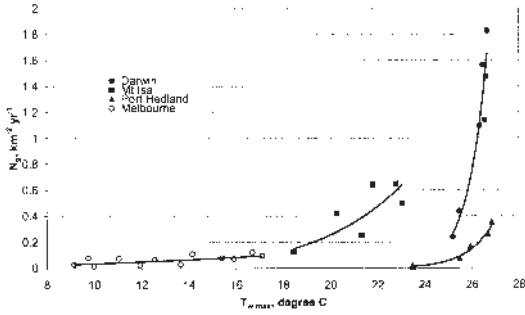


Fig. 8 Estimates of annual mean lightning ground flash density, N_g , plotted against latitude.

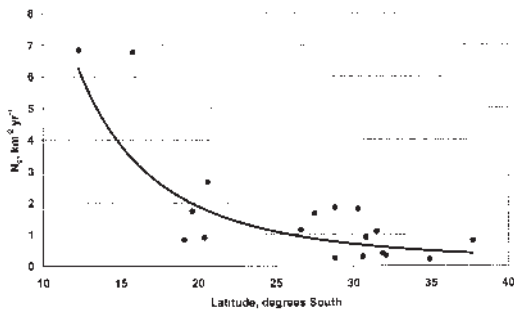
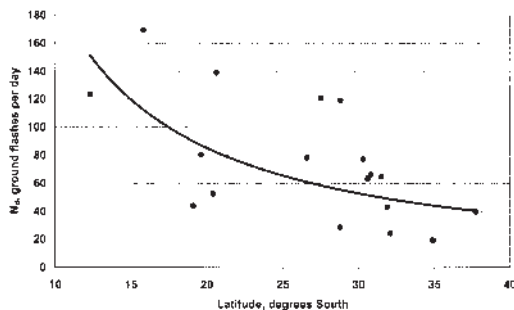


Fig. 9 Estimates of annual mean lightning frequency, N_d , plotted against latitude.



and Renno 1991). A strongly non-linear relationship between lightning incidence and CAPE (and wet bulb temperature) has been demonstrated. However, more studies on understanding the microphysics of charge separation within thunderclouds are required for a better understanding of this relationship.

To compare our results on variations in lightning activity with the results of previous studies, we plotted the N_g values against latitude (Fig. 8). The results demonstrate a reduction in lightning ground flash density by a factor of about ten for a change in latitude from 10°S to 40°S. This reduction rate is similar to the reduction rate in lightning total flash density (an order of magnitude per 30 degrees latitude) found in early studies (Orville and Spencer 1979; Kotaki et al. 1981; Mackerras and Darveniza 1994). Latitudinal variation of lightning frequency (number of ground flashes per lightning day), N_d , has also been analysed. As demonstrated above, the highest number of days with lightning does not automatically imply the highest lightning ground flash frequency at a particular locality. Nevertheless, values of estimates of lightning ground flashes frequency, plotted against latitude, for eighteen Australian sites (Fig. 9) show a decrease with increase in latitude. A rate of reduction in the number of lightning ground flashes per day for an increase in latitude from 10°S to 40°S by a factor of about three was found, which was smaller than that for ground flash density.

Summary and concluding remarks

The seasonal and latitudinal variations of lightning ground flashes in Australia have been analysed in this paper using lightning flash counter data. A number of parameters to describe lightning activity such as lightning-days, ground flash occurrence and lightning ground flash frequency was derived using counter registrations, and compared for eighteen localities across Australia. In general, lightning activity is highest in the northern part of the country and decreases towards the south, which is similar to thunder-days distribution in Australia. Lightning activity in the northern half of Australia has a clearly defined seasonality with a sharp increase in lightning-days, ground flash occurrence and ground flash frequency during the wet season months. A plausible explanation for this behaviour is the sensitive dependence of lightning parameters on convective available potential energy, which is the driving force for thunderstorm development. Seasonal distributions of lightning parameters in higher latitudes are more uniform: thunderstorms and lightning are more frequent in warmer months, but they also occur in cooler months in association with cold frontal systems.

A thunder-day or a lightning-day is a convenient descriptive parameter of seasonality of the phenomenon, but it does not describe lightning activity in terms of actual lightning incidence. Ground flash occurrence (e.g. average annual and average monthly numbers of ground flashes) and lightning frequency (i.e. the number of lightning ground flashes per lightning-day) are more appropriate parameters for this purpose. A reduction in lightning ground flash density by a factor of about ten for a change in latitude from 10°S to 40°S was found. This rate of reduction is similar to results of earlier studies of the rate of reduction in total lightning flash density. Latitudinal variation of lightning ground flash frequency also demonstrated a reduction in the number of ground flashes per lightning day with increase in latitude, however the rate of reduction was smaller than that for ground flash density (a factor of about three for a change in latitude from 10°S to 40°S).

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