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Study of cloud-to-ground lightning and precipitation and their seasonal and geographical characteristics over Taiwan

Y.-A. Liou, S.K. Kar *

Center for Space and Remote Sensing Research, National Central University, Chung-Li, Taiwan

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ABSTRACT

A long term (1998–2006) study of annual precipitation and cloud-to-ground (CG) lightning has been made at 31 stations over Taiwan. The CG-lightning data were collected by the ground-based Lightning Location System (LLS) built by Tai-Power Company of Taiwan while the precipitation data were collected from the Central Weather Bureau (CWB) of Taiwan. For the present study, a spatial scale of 0.1° latitude × 0.1° longitude ($\approx 10^2$ km^2) is selected to determine the flash density. CG-lightning and precipitation data are used to compute the values of "rain yield", defined as the mass of rain produced per CG-lightning flash in units of kg fl^{-1} over a given surface area. The rain yield is found to vary considerably with seasonal and climatic conditions, and geographical location. A positive linear correlation is observed between precipitation and lightning flash density with a highest correlation coefficient of 0.70 over inland stations. Out of the 31 stations, 13 stations are inland stations and these stations show higher rain yields clustering close to a mean of 0.7×10^{10} kg fl^{-1}, compared to the coastal stations which show a mean value 1.4×10^{10} kg fl^{-1}. When the stations are classified according to seasonal climate zones, the winter and winter-dominant rainfall stations show comparatively higher value of rain yield with an average of 2.8×10^{10} kg fl^{-1} than the summer and summer-dominant rainfall stations which exhibit a significantly lower value of rain yield of 2.1×10^{10} kg fl^{-1}. Inland stations exhibit a lower value of rain yield with a mean of 1.6×10^{9} kg fl^{-1} and 1.4×10^{10} kg fl^{-1} respectively during warm and cold seasons compared to the coastal stations. For each station, the average cold season rain yields are significantly higher than that of warm season values. These differences in rain yield values are attributed to local surface heating which indirectly controls such parameters as cloud base height and convectively available potential energy (CAPE) in the atmosphere. The variation of rain yield with geographical, seasonal, and climatic conditions, found in our observations, are in good agreement with studies found in the literature from other parts of the world.

1. Introduction

Close association between precipitation and lightning has been investigated since time immemorial. Before the use of lightning detection networks, sporadic research was conducted to study lightning and other associated meteorological events (Battan, 1965; Piepgrass et al., 1982). Battan (1965) computed visually the CG-lightning flashes and found the number of counts to be well correlated to the precipitation estimation from nearby thunderstorms. Later, with the deployment of lightning detection networks, many more sophisticated studies have been performed, especially in the United States. Because of a simple structure, nearly uniform spatial coverage and continuous observation, lightning location data has become advantageous for its use. Important applications of lightning and precipitation have been possible because of the extensive coverage of lightning detection network by the use of lightning data. Radar estimated rainfall has been found to be positively correlated to the intensity of lightning (Reap and MacGorman, 1989; Williams et al., 1992; Cheze and Sauvageot, 1997). Moore et al. (1962), Piepgrass et al. (1982), Jayaratne et al. (1995) and Jayaratne and Kuleshov (2006) have shown the intense falls of precipitation

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* Corresponding author. Tel.: +886 3 4227151; fax: +886 3 4254908.
E-mail address: sanjib_kar@hotmail.com (S.K. Kar).

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with the nearby CG-lightning. Studies conducted by various researchers (MacGorman and Rust, 1998; Uman, 1987; Latham, 1981; Marshall and Radhakant, 1978; Petersen and Rutledge, 1998; Carey and Rutledge, 2000; Kar and Ha, 2003) have shown lightning activity associated with convective systems to be a useful indicator of their rain yield. The higher correlation between CG-lightning and rainfall than that between total lightning and rainfall has been reported by Cheze and Sauvageot (1997). A research conducted by Petersen and Rutledge (1998) examined the relationship between the precipitation and lightning over large spatial and temporal scales for several different parts of the globe using total rain mass and CG flash density. Direct estimation of rainfall from CG-lightning observations has also been explored by various researchers (Piepgrass et al., 1982; Buechler et al., 1990). It has been shown that despite similar synoptic conditions, the actual lightning distribution varies day by day due to the random nature of thunderstorm occurrences (Finke, 1998). Moreover, Williams and Stanfill (2002) shed light, exploring new tests and older ideas, on the pronounced contrast in lightning between land and ocean. They showed that there is a critical island area required for exhibiting continental behavior in terms of lightning. It is worth mentioning in this context that the treatment of islands as thermal perturbations and as boundary layer aerosol perturbations leads to very different predictions for critical island area.

In recent years, the pronounced differences in the rain yield and electrical and dynamical properties of the tropical mesoscale cumulonimbus regimes embedded in the monsoonal convection during the monsoon season and the more vigorous but sparsely distributed thunderstorms of the premonsoon season have become the major concern of the atmospheric researchers (Rutledge et al., 1992; Williams et al., 1992; Jayaratne and Kuleshov, 2006; Petersen et al., 1996). Williams et al. (1992) indicated that the above-mentioned differences are very common in the tropical monsoonal storms and therefore an assessment of similar information from the region where land and warm waters are juxtaposed for monsoon development is highly needed. Taiwan is an ideal region of this kind. Taiwan lies about 120 km off the southeastern coast of China, across the Taiwan Strait, and has an area of 35,801 km^2. The island is 394 km long and 144 km wide and consists of steep mountains. The island is characterized by the contrast between the eastern two-thirds, consisting mostly of rugged mountains running in five ranges from the northern to the southern tip of the island, and the flat to gently rolling plains in the west. Taiwan's highest point is the Yu Shan at 3952 m, and there are five other peaks over 3500 m.

However, no attempt has been made so far to investigate the temporal and spatial analysis of precipitation and lightning over Taiwan. It should be emphasized that earlier studies related to precipitation and lightning have been carried out mostly in the United States and Europe, while the number of studies relating to other countries like Taiwan are limited. It is well known that the initiation mechanism and the characteristics of precipitation and lightning are greatly influenced by the local topography. Terrain influenced precipitation is often highly episodic in time and space. In Taiwan, lightning and thunderstorm events are very frequent and meteorologists have considered them as relevant for characterizing the meteorology of Taiwan. Therefore, a study of the precipitation and lightning activity is needed because of the complex topography of Taiwan. In the present analysis we have investigated the relationship between cloud-to-ground lightning and precipitation over Taiwan during the summer monsoon and winter seasons and estimated rain yields from precipitation and lightning data for each observing station. Finally the results have been compared with the findings available in the literature.

2. Data and methodology

Lightning data used in this study were collected from Tai-Power Company of Taiwan for the years 1998–2006 to determine the overall lightning patterns in Taiwan during the summer and winter seasons. For the present study lightning data over Taiwan were collected from Tai-Power Company of Taiwan. The Lightning Location System (LLS) was built in 1989. The system consists of one APA (Advanced Position Analyzer), and six Direction Finders (FD) installed at sites covering the entire area of Taiwan as shown in Fig. 1. Its sensors are the same as those used by the National Lightning Detection Network (NLDN) USA. All the sensors and Direction Finders are manufactured by Global Atmospherics, Inc. (GAI), Arizona, USA. The systems can detect only cloud-to-ground lightning events. Each Direction Finder detects cloud-to-ground lightning strikes and determines a direction toward a detected electromagnetic lightning discharge. The lightning events detected by sensors are transmitted to the Position Analyzer at Taipei to determine the polarity (positive versus negative), amplitude, latitude, longitude, date and time. The location of the lightning discharge is determined by triangulation of two or more lines of bearing. A Direction Finder automatically detects more than 90% of all cloud-to-ground lightning occurring within a maximum detectable distance of 200 km with 5 km accuracy. However, especially near the edges of the network the assumption of 90% uniform flash detection efficiency may not be realistic. However, no attempt was taken to correct the detection efficiency because previous studies (e.g. Naccarato et al., 2003 for a Lightning Position and Tracking System (LPATS); Orville, 1994 for the National Lightning Detection Network in the United States; Finke and Hauf, 1996 for a LPATS in Germany, and Pinto et al., 1999 for a LPATS in Brazil) reported an overall detection efficiency of 90% for several lightning detection networks. The details of the lightning network and its detection efficiency from past to present have been summarized by Cummins et al. (1998a,b) of GAI.

Quality controlled rain gauge data from the Central Weather Bureau (CWB) of Taiwan have been used to reckon the rain yield for the present investigation. Fig. 2 shows the location of 31 rain gauge stations over Taiwan whose rain gauge data have been considered. Monthly values of precipitation are computed by taking the sum of daily recorded precipitation data. A temporal scale of one month and a spatial scale of 0.1° latitude × 0.1° longitude (~8.3 km × 11.1 km ≈ 10^2 km^2) surrounding each rainfall observing station have been selected to find out the CG-lightning flash counts. After preparing the monthly rainfall and lightning data, monthly rain yields are computed by dividing the total monthly rain mass by the monthly total lightning flashes over each desired locations using Eq. (1).

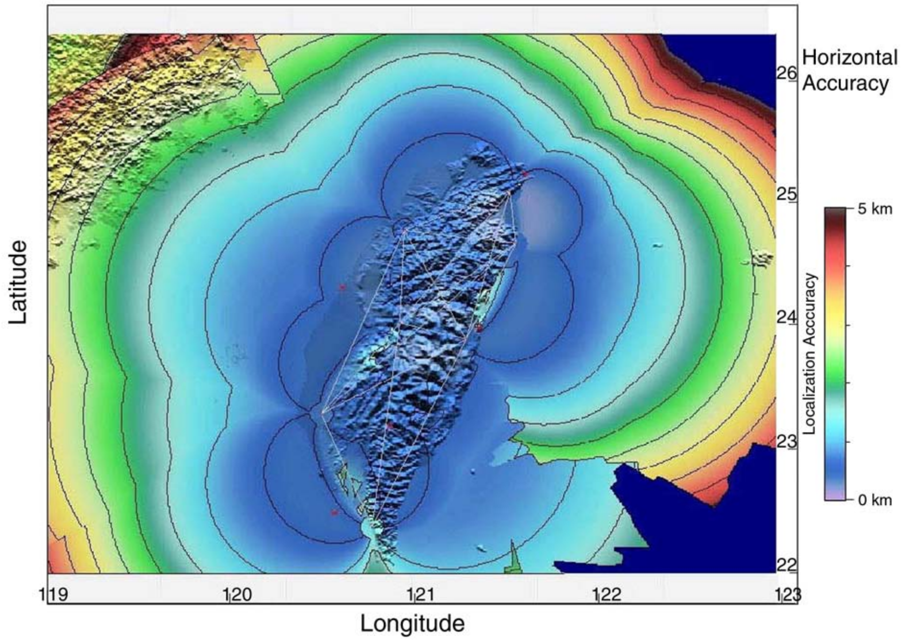

Fig. 1. Location of the sensors, coverage and accuracy of the lightning location system of Taiwan.

Seasonal rain yields are also computed following the same procedure but by taking the seasonal values of rainfall and lightning data.

$$\text{Rain yield} = \frac{\text{rainfall mass over a certain area}}{\text{number of CG flash counts over same area}} = Z_i = \frac{R(t, \delta x_i)}{N(t, \delta x_i)} \quad (1)$$

where Z_i stands for rainfall to lightning ratio at location i. $R(t, \delta x_i)$ and $N(t, \delta x_i)$ represent respectively the total rainfall mass and total number of lightning flash counts, each of which is associated with an area δx_i and a time t. δx_i and t are representative of our spatial and temporal scales and equal to 0.1° latitude × 0.1° longitude surrounding each rainfall observing station and one month respectively.

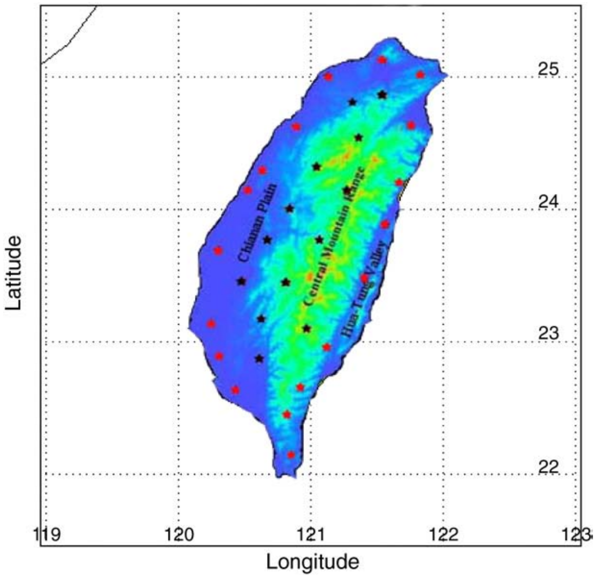

Fig. 2. Location of 23 rain gauge stations over Taiwan under study. Inland stations are marked by black stars while the costal stations are marked by red stars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Our spatial scale selection is almost the same as that of the rain gauge data which enables us to maintain the spatial variability associated with the orographic complexity of Taiwan. It is worth mentioning in this context that the rain yield values depend on various factors. Lang and Rutledge (2002) have shown that the rain yield can vary with different properties of the convection and pointed out that in the case of tropical cyclones or warm rain, substantial amounts of convective precipitation are found, but in these convective processes lightning are usually not observed. Taiwan is an island and most of our stations are either oceanic or coastal in nature. The convective system acts over Taiwan are mostly ocean generated convections. Ocean generated convections are usually characterized by high fractions of warm rain but very little or no lightning is found in these convective processes as suggested by Rutledge et al. (1992). "Low-echo entroid" (heights at or below −10 °C isotherm) precipitation system is another example of such events which produces little or no lightning. Moreover in mountainous terrain, orographic effects can inflate the precipitation without causing lightning. Hence, there was lot of possibility for our data to be contaminated by such events and because of the broad heterogeneity in spatial distribution of rainfall and lightning, our estimated rain yield values can only be considered close to the actual values, particularly for the long time scales.

3. CG-lightning activity and precipitation

In the present study we have carried out an extensive data analysis of precipitation and lightning over 31 stations spread almost uniformly over Taiwan (Fig. 2). Annual values of precipitation and CG flash density have been calculated for each station. It is to be noted that the lightning flash density, generally defined as the number of flashes of a particular type occurring on or over unit area in unit time, is used to describe lightning activity. We have used cloud-to-ground flashes to compute the CG-lightning flash densities in units of $\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$. We have not differentiated the polarity of ground flashes but the mean ratio of positive to negative ground flashes is found to be 0.03. A statistically significant linear relationship is found between the two aforesaid parameters. The values of rain yield for all the stations are computed taking the ratio of rainfall mass and number of CG-lightning flash count over a certain area in the units of $\mathrm{kg\,fl}^{-1}$.

3.1. Seasonal distribution

During the cold season (September–April), the precipitation over Taiwan is influenced basically by the northeasterly monsoon while during warm season (May–August), the same is influenced by southwesterly monsoon (Tao and Chen, 1987; Boyle and Chen, 1987; Chen et al., 1999). Hence, we have divided the annual data of rainfall and lightning into two parts, one for the cold season and the other for the warm season and then rain yields are computed for each season and for each station separately. Fig. 3 shows the spatial distribution of warm season rain yield over Taiwan. It is evident from Fig. 3 that the entire west coast and southwest coast exhibit the highest values of rain yield while an intermediate value is noticed over the entire east coast, north and northeast coasts. Calculations reveal that the mean rain yield observed in the west and southwest coast was $3.4\times10^{9}\,\mathrm{kg\,fl}^{-1}$ while that observed in the east and northeast coast was $2.6\times10^{9}\,\mathrm{kg\,fl}^{-1}$. The inland regions show the lowest value of rain yield with an average of $1.6\times10^{9}\,\mathrm{kg\,fl}^{-1}$ during this season.

In Fig. 4 we have shown the spatial distribution of cold season rain yield over Taiwan. During this season the highest value of rain yield is found over the entire east coast, north and the entire west coast and southwest coast. Calculations reveal that the mean rain yield in the cold season along the east, northeast and north coast was $2.8\times10^{10}\,\mathrm{kg\,fl}^{-1}$ while the value in the west and southwest coast was $2.1\times10^{10}\,\mathrm{kg\,fl}^{-1}$. Like the warm season the lowest value of rain yield occurred over inland regions with an average of $1.4\times10^{10}\,\mathrm{kg\,fl}^{-1}$. It is interesting to note that during the warm season the maximum value of rain yield occurred over the west and southwest coast but during the cold season the maximum rain yield is found over the north, northeast and east coasts. The average rain yield in all 31 stations is comparatively higher during the cold season than during the warm season. Moreover the mean rain yield along the east and northeast coast during the cold season is significantly larger than that along the west and southwest coast during the warm season. The difference in the means of cold and warm seasons is statistically significant at the confidence level of 95% as found in the statistical test.

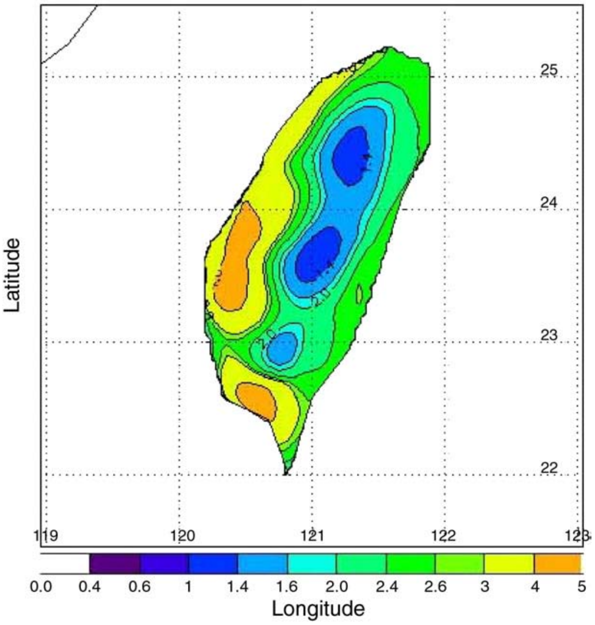

Fig. 3. Warm season spatial distribution of rain yield (units: $10^{9}\,\mathrm{kg\,fl}^{-1}$).

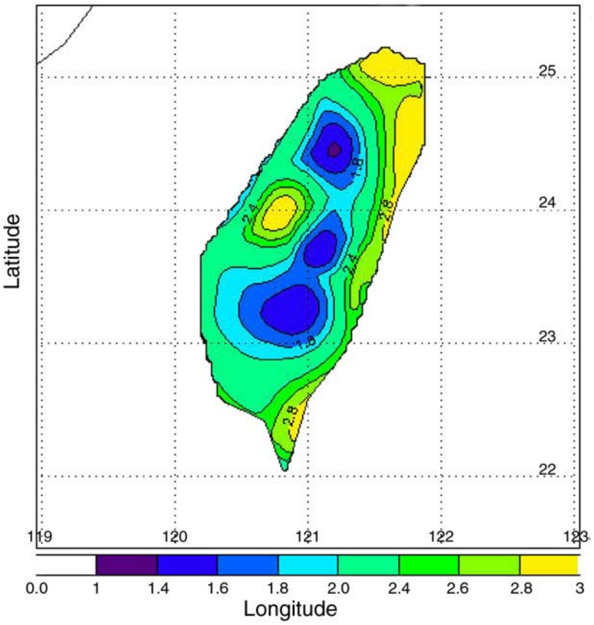

Fig. 4. Cold season spatial distribution of rain yield (units: $10^{10}\,\mathrm{kg\,fl}^{-1}$).

The values of rain yields for the cold season are plotted against that of warm season in Fig. 5. It is evident from Fig. 5 that the mean rain yield during the cold season for all the 31 stations is always higher than that of warm season by an order of magnitude. The average values of rain yield during the cold and warm seasons were found to be $2.1\times10^{10}\,\mathrm{kg\,fl}^{-1}$ and $2.53\times10^{9}\,\mathrm{kg\,fl}^{-1}$, respectively. The differences in the average rain yield values between cold and warm seasons are statistically significant at the 95% confidence level. These differences in rain yield values might be due to the fact that during the warm season the surface heating is more than that in the cold season. This excessive surface heating enhances the magnitude of convective available potential energy (CAPE) and its other characteristics in the atmosphere which in turn affects thunderstorm generation.

Moreover it has been found in previous studies that during the warm season excessive surface heating from the warm sea surface in northern South China Sea and southern Taiwan Strait along with moist air forms local convection and a low-

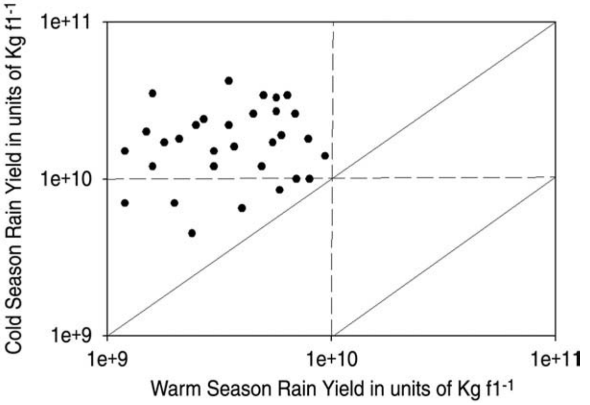

Fig. 5. Scatter plot of the average rain yields for the cold season versus that of warm season for each station. Each dot represents a station. The diagonal straight line represents equality of the two plotted parameters.

pressure system in the lower troposphere that moves frequently towards Taiwan under the prevailing southwesterly monsoon flow (Tao et al., 2000). This southwesterly monsoon flow is potentially unstable and enriched with abundant moisture, which brings warm, moist air from the south sea to Taiwan (Chen and Chen, 2003). With the progress of the summer season this south westerly monsoon flow becomes much warmer with more moisture content (Chen, 1993). This unstable, warm, moist air from the west coast then moves towards the land and meets the CMR, where orographic lifting is expected to take place. Besides orographic lifting, orographic blocking (Akaeda et al., 1995; Li et al., 1997; Yeh and Chen, 2002) and thermally driven circulations during the diurnal heating cycle (Chen and Li, 1995) are also expected to play an important role in producing a zone of higher lightning frequency along the western windward slopes and a zone of low lightning frequency along the eastern slope of the CMR.

On the other hand, during the cold season Taiwan is basically influenced by the northeasterly monsoon (Tao and Chen, 1987; Boyle and Chen, 1987; Chen et al., 1999). A rainfall maximum during the cold season is observed over most stations along the northern, northeastern and eastern coasts because of the presence of steep terrain as shown by Wang et al. (1984). Precipitation during the cold season is mainly related either to late-season typhoons (Chen and Wang, 2000) or transient disturbances embedded in the northeasterly monsoon flow during the passage of cold fronts (Chen, 2000; Lin and Chen, 2000). These precipitation systems are seldom associated with lightning and thus result in higher rain yield values during this season along the east, northeast and north coast stations compared to the warm season values and also compared to the west, southwest and west coast stations.

3.2. Geographical distribution

In Fig. 6 the variation of average annual precipitation with the average annual ground flash density have been displayed for east coast, west coast and inland stations. All the coastal stations show higher values of rain yield than the inland stations. It is interesting to note that besides getting a positive linear correlation between the two displayed parameters, the apparent clustering of stations of similar climatic conditions is also found. The correlation coefficients between the said two parameters for the east coast, west coast and inland stations are found to be 0.48, 0.65 and 0.70 respectively. Petersen and Rutledge (1998) have shown that the geographical climatic conditions control rain yield strongly. Hence, our results corroborate well the findings of Petersen and Rutledge (1998) for a range of stations within Taiwan for the first time. In Fig. 6, the two diagonal straight lines represent the constant rain yields value of 10^{9} kg fl^{-1} (lower line) and 10^{10} kg fl^{-1} (upper line). Close scrutiny of Fig. 6 reveals that most of the coastal stations lie close to the upper rain yield line, while all the inland stations lie closer to the lower line. Out of 31 stations under study, eleven stations showed rain yields greater than 1.0×10^{10} kg fl^{-1} and all are situated either on the east coast or west coast or in proximity to the coast. On the other hand, all thirteen inland stations, which are indicated by the square in Fig. 6, are found confined together just above the lower line. The thirteen inland stations show rain yields clustering close to a mean of 0.7×10^{10} kg fl^{-1}, while all the coastal stations show a mean value of 1.4×10^{10} kg fl^{-1}. This result is also in good agreement with other studies (Williams et al., 1992; Petersen and Rutledge, 1998; Kar and Ha, 2003), which indicated lower values of rain yield for the mid continental stations than that for the coastal stations. The difference in annual average rain yield values between coastal and inland stations is a factor of two. This difference is statistically significant at the confidence level of 95%. Among the coastal stations, the stations which are situated in the extreme northern part and east coast of Taiwan show the maximum value of rain yield. West coast stations show lower rain yield values compared to those of east coast stations.

It is interesting to note that the coastal locations in north, northeast, and east regions show relatively high value of rain yields as found from Fig. 6. These stations receive relatively higher rainfall during the cold season due to the northeasterly monsoon (Chen and Chen, 2003). Despite the high cold season rainfall, lightning activity during the cold season is relatively very low owing to the low surface temperatures and CAPE. As a result significant high rain yield values during the cold season are observed in these stations which finally control the annual average rain yield values of these coastal stations. On the other hand the coastal stations in west, southwest, and south receive most of their annual rainfall during the warm season months due to the southwesterly monsoon (Chen and Chen, 2003), when excessive surface temperatures and moisture transport from southeast sea give rise to higher CAPE and lightning activity (Williams and Renno, 1993). As a result, a lower value of rain yield is observed over west, southwest, and south coasts during warm seasons and lowers the average annual value of rain yields. Moreover, the air over inland stations is expected to be more polluted than maritime air and hence contains a higher cloud condensation nucleus (CCN) concentration. For such differences in boundary layer aerosol concentration the higher CCN concentrations over inland stations reduce the mean cloud droplet size which in turn decreases the process of coalescence and the droplet collision efficiency (Rogers and Yau, 1989). This enables the liquid water to reach the mixed-phase region of thunderclouds in a greater number to

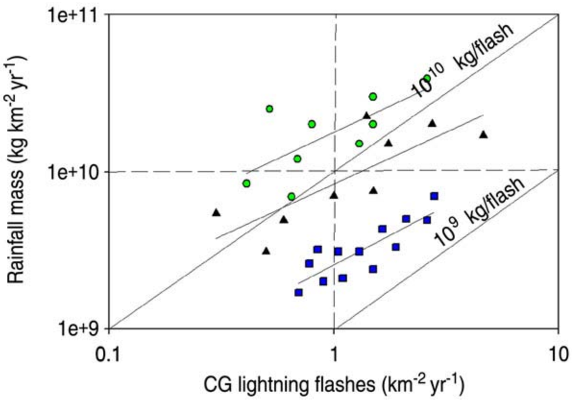

Fig. 6. The rain yield plot showing the annual rainfall mass versus CG-lightning flash density for all stations. Square dots represent the inland stations; circular dots represent the east coast stations while the triangular dots represent the west coast stations. Best fit lines for three different zones are displayed separately. Two diagonal straight lines represent constant rain yield of 10^9 kg fl^{-1}(lower line) and 10^{10} kg fl^{-1}(upper line).

participate in generating large graupel. The net effect of which is increased lightning activity, reduced rainfall and reduced rain yields at inland stations. But for the thermal and the aerosol hypothesis to be effective over an island like Taiwan, a minimum island area is required as indicated by Williams and Stanfill (2002). They showed that the critical island area for an island to act as a thermal perturbation is about 110 km^2 while a crude preliminary estimation of that for an island to act as an aerosol perturbation is about 20,000 km^2. The area of Taiwan under study is much greater than the critical area required for an island to act either as a thermal perturbation or aerosol perturbation.

3.3. Monthly variation of rain yield

In Fig. 7 we have plotted the monthly variation of rain yields for the east coast, west coast and inland stations. Completely different patterns of variation are observed between west coast and east coast stations. The highest fluctuation in monthly rain yield values is observed in east coast stations. A distinct phase change is noticed in rain yield values during the month of September between these two coastal stations. This phase change in rain yield values is very consistent with the earlier findings. Wang et al. (1984) showed that the two main rainy seasons in Taiwan are mei-yu, the early summer rainy season, and summer rainy season. Nevertheless, an autumn rainfall maximum during the annual cycle is observed over most of the stations along the northern and northeastern coasts because of the presence of steep terrain. Precipitation during late summer, early autumn and winter is mainly related either to late-season typhoons (Chen and Wang, 2000) or transient disturbances embedded in the northeasterly monsoon flow during the passage of cold fronts (Chen, 2000; Lin and Chen, 2000). Since these types of precipitation systems seldom carry lightning, the estimated rain yield during the cold season along the east, northeast and north coast is comparatively higher than in the warm season. These results also attest to the fact of the transition of the southwesterly monsoon to the northeasterly monsoon over Taiwan. Therefore as a result of such transition a distinct phase change in the variation of rain yield values occurred. A close scrutiny reveals that the overall pattern of the monthly variation of rain yield for the east coast stations is almost a mirror image of the rain yield variation of the west coast. Fig. 7 also reflects the fact that during warm season months, the west coast stations show highest value of rain yield while during cold season months, the east coast stations exhibit the highest value of rain yield. The inland stations always show the lowest values of rain yield except for a few months irrespective of the seasons. Higher monthly rain yield values are clearly visible during the cold season than during the warm season for all types of stations.

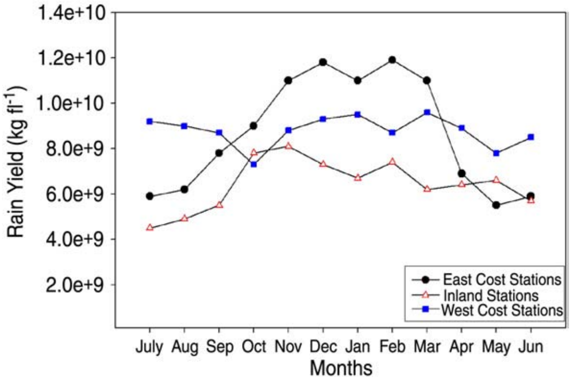

Fig. 7. Variation of monthly mean rain yield in units of kg fl^{-1}for the three different zones.

4. Summary and conclusions

Analysis of nine years precipitation and lightning data for 31 stations over Taiwan reflects a significant linear relationship between annual precipitation and CG flash density. Seasonal dependence of rain yield were studied by grouping the precipitation and lightning data into two categories namely cold season and warm season. Seasonal dependence of rain yield corroborates strongly the results found in other similar studies conducted over other parts of the world (Williams et al., 1992; Petersen and Rutledge, 1998).

It has also been found from the present analysis that all the east coast stations exhibited rain yields greater than 2.0×10^{10} kg fl^{-1}during both seasons while the west coast stations exhibited rain yields greater than 2.0×10^{10} kg fl^{-1} only during cold season. The thirteen inland stations showed an annual average rain yield of 0.78×10^{10} kg fl^{-1}, while all the coastal stations showed an annual average rain yield of 1.4×10^{10} kg fl^{-1}. The difference in annual average values of rain yield between land and coastal stations is statistically significant at the 95% confidence level. The lower value of rain yield during the warm season is mainly due to the comparatively higher number of lightning flash counts than in the cold season. During summer the land surface is basically hotter than sea. This additional surface heating directly affects convective available potential energy in the atmosphere thereby promoting atmospheric instability and stronger air motion that helps in thunderstorm generation. Moreover, typically the lightning activity over land is greater than over the oceans by an order of magnitude (Orville and Henderson, 1986). This accounts for the lowest value of rain yield over inland stations during both seasons and higher rain yield over costal stations than inland stations. On the other hand, northeasterly monsoon flow dominates over Taiwan during the cold season (Tao and Chen, 1987; Boyle and Chen, 1987; Chen et al., 1999). Late-season typhoons (Chen and Wang, 2000) or transient disturbances embedded in the northeasterly monsoon flow during the passage of cold fronts (Chen, 2000; Lin and Chen, 2000) cause major rainfall during this season. Such precipitation systems seldom carry lightning. Therefore the higher value of rain yield during the cold season is mainly due to the low lightning flash count. It is worth mentioning in this context that higher cloud base heights lead to larger updraft widths and reduced dilution by mixing (Williams and Stanfill, 2002). These two factors favor lightning production. Since the cloud base height over the inland region is generally two to three times greater than that over the coastal region and the lightning flash rate is increased with cloud base height as suggested by Williams et al. (2005), this factor might also be the cause of low rain yield value over the inland stations as found in our study.

Our results can also be interpreted from the perspective of differences in boundary layer aerosol concentration (Rosenfeld and Lensky, 1998). The air over inland stations is more polluted and hence contains more cloud condensation nuclei than maritime air. Rosenfeld and Lensky (1998) have shown that a very narrow or no coalescence zone, a deep mixed-phase zone and glaciation occur at higher levels for the clouds forming over polluted regions compared to relatively less polluted clouds. The higher CCN concentration over inland areas results in the reduction of the mean cloud droplet size, which in turn decreases the process of coalescence and the droplet collision efficiency (Rogers and Yau, 1989). Hence, more supercooled water is expected to exist at greater depths in clouds. The abundance of supercooled water may generate large graupel. The net effect is therefore an enhanced lightning activity, reduced rainfall and reduced rain yields at inland stations compared to maritime stations. Some doubts may arise on the use of aerosol hypothesis in the interpretation of our results and the separation of stations under study into continental and maritime for an island like Taiwan because of its area. Williams and Stanfill (2002) showed that there is a critical island area required for exhibiting continental behavior in terms of lightning. A cruder estimation leads to the critical island area of about 20,000 km^2 for an island to cause aerosol perturbation while an alternative and improved way to estimate a critical island size for aerosol perturbation showed that the critical island size is about 30,000 km^2 (Williams and Stanfill, 2002). So it is obvious that the treatment of islands as boundary layer aerosol perturbations leads to very different predictions for the critical island area depending on the way of estimation. The area of Taiwan (35,801 km^2) is much greater than the critical area required for an island to cause aerosol perturbation irrespective of the way of estimation. Moreover because of typical orographical features, the weather of Taiwan is deeply influenced by the South China sea breeze on one side and the East China sea breeze on the other of this island along with the Philippine sea breeze. The intruding sea breezes either from the southwest coast or northeast coast get obstructed by the north–south oriented high mountain across Taiwan and are unable to replace the island's polluted boundary layer with clean maritime air within half a day (Chen and Wang, 2000). The clear difference in rain yield between the inland and coastal stations as found in Fig. 6 also attests to the fact that our choice of stations into two different categories is appropriate. These factors resolve the doubts of using the aerosol hypothesis in the interpretation of our results and the separation of stations into continental and maritime for an island like Taiwan.

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