Characteristic Differences of Rainfall and Cloud-to-Ground Lightning Activity over South Korea during the Summer Monsoon Season

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ABSTRACT

In this paper the characteristic variations of cloud-to-ground (CG) lightning and total precipitation during the Korean summer monsoon (June–August) season have been extensively analyzed for different climate regimes. The data used in this study consist of the monthly CG lightning flash count as detected by the lightning detection network installed at the Korean Meteorological Administration (KMA) and the monthly precipitation data from 23 meteorological observatories spread over the Korean peninsula for a period of 10 yr from 1988 to 1997. Temporal and spatial scales of 1 month and 10^2 km^2, respectively, were considered to determine the seasonal values of rain yield or rain volume per CG flash (defined as the ratio of total precipitation to CG flash count over a common area). Seasonal values of rain yield have been compared with that of monthly values separately. The results of variation of the rain yield during the different months constituting the monsoon season are also presented. Results show that the variation of rain yield for the monsoon season closely resembles that of July indicating that July, rather than the other two monsoon months, dominates the overall monsoon pattern. The maximum values of rain yield are observed in the east coast of the Korean peninsula, particularly in the region east of Tae-back Mountain, with a mean value of 3 \times 10^5 m^3 fl^{-1} while the minimum value is seen in the west of Tae-back Mountain, with an average value of 8 \times 10^4 m^3 fl^{-1}. The method for separating convective rain designed on broad heterogeneity similar to the Petersen and Rutledge method shows on average 82% of the total rainfall is convective in nature at the west coast stations, 53% is convective at the middle of the peninsula, and 46% is convective at the east coast stations. Maximum convective rain occurred at Kanghwa in the northwest, while the minimum was seen at Ulsan in the southeast. The correlation coefficient between the total precipitation and CG lightning during the summer monsoon season is 0.54, which is not very high since in most cases total precipitation persists longer than CG lightning. This may be due to the occasional development of mesoscale convective systems (MCSs), which produce light stratiform precipitation during their dissipation stage or might have been contaminated by the upslope precipitation or by nonlightning producing frontal precipitation. This low correlation coefficient could also be due to the episodic presence of warm rain convection or a “low-echo centroid” precipitation system.

1. Introduction

Lightning and convective precipitation are two related phenomena of thunderstorms. The development of lightning detection systems for mapping cloud-to-ground (CG) lightning flashes has opened the door for a wide variety of operational and research applications. Using lightning detection systems the cloud-to-ground lightning flashes are counted easily, but there is no direct way to measure the convective precipitation. Rain gauge networks cannot differentiate the “stratiform” and “convective” precipitation. Convective precipitation is the precipitation that falls from cumuliform clouds possessing a vertical motion scale (\sim 1–10 m s^{-1}) that equals or exceeds the terminal fall speed of snow (\sim 1 m s^{-1}) while stratiform precipitation is defined as the precipitation that originates from nimbostratus clouds possessing a vertical velocity scale (\sim 0.1–1 m s^{-1}) that is small compared to the terminal fall speed of snow and ice crystal (Houze 1993). Because of the close association of lightning and convective rainfall, it is necessary to establish a relationship between convective precipitation and lightning flash count so that convective precipitation can readily be estimated. Moreover, as suggested by Zipser (1994) and Petersen and Rutledge (1998), their spatial distribution would be a useful quantitative indicator of different rainfall regimes.

The process of cloud electrification has been documented by various researchers through inductive (Brooks and Saunders 1994) and noninductive (Saunders et al. 1991; Reynolds et al. 1957) charging mechanisms. Initiation of lightning production is supposed to be associated with the development of a robust ice phase without depending on the charging mechanism (Carey and Rutledge 1996; Chauzy et al. 1985). Plenty

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of observations suggest the presence of precipitation-size ice in lightning-producing clouds (Petersen et al. 1996; Williams et al. 1989). Particularly in summer, a large percentage of convective precipitation is produced in midlatitude continental areas by ice-based process (Young 1993). Hence, a positive correlation could be expected between lightning and convective precipitation.

The connection between lightning and rainfall has been documented by various researchers for many years (MacGorman and Rust 1998; Shackford 1960; Marshall and Radhakant 1978; Bhattacharya et al. 1996). Techniques for estimating rainfall directly from cloud-to-ground lightning observations have been explored by several researchers (Piepgrass et al. 1982; Buechler et al. 1990). Zipser (1994) introduced an index that is defined as the ratio of monthly rainfall to number of thunderstorms days to study the rainfall and thunderstorm relation for the West African region. Earlier workers (Battan 1965; Maier et al. 1978; Piepgrass et al. 1982) calculated the rain yield using the rainfall and lightning activity over cloud scales or mesoscales based on single or multiple thunderstorm case studies. Recently Petersen and Rutledge (1998) used the total rain mass and CG flash density to examine the relationship over large spatial and temporal scales for several different parts of the globe. In this present study we have followed the method of Petersen and Rutledge (1998) to find out the rain yield.

Very few studies are found in the literature (Lim and Lee 2002) of convective lightning in time and space over Korea. It is well known that topography has a great influence on the initiation and on the characteristics of convective precipitation and lightning. Convective rainfall, especially when influenced by terrain, is often highly episodic in time and space. Therefore, because of the complex topography of the Korean peninsula, a study of the rainfall and lightning activity is needed. In this paper we present the results of the analysis of lightning activity and associated monsoon rainfall over Korea. This information will be useful in understanding the role of lightning in the monsoon rainbow over Korea.

The Korean Meteorological Administration (KMA) has been using a lightning detection network since 1988. The network is an excellent reference for determining the location of deep convective activity in South Korea. In our investigation, only the cloud-to-ground lightning data for the years 1988–97 are used to determine the overall lightning patterns in South Korea during the monsoon seasons as the lightning detection network of KMA can detect only CG flash. Hence we had no way to know how much intracloud lightning occurred in the storm or over the 3-month period during the 10 yr. However, the connection between precipitation on the surface and CG lightning has been reported many times (Williams et al. 1989; Carey and Rutledge 1996; Petersen et al. 1996; Sheridan et al. 1997; Petersen and Rutledge 1998; Tapia et al. 1998). For example, Cheze and Sauvageot (1997) found that the correlation between CG lightning and rainfall is higher than that between total lightning and rainfall. The convective activity within the Korean peninsula starts increasing from June, attains its maximum value during July, and then starts decreasing through the August months. This trend is followed from 1988 to 1997. Therefore, we restricted our analysis to only the monsoon months. The seasonal, diurnal, and spatial variability of CG lightning will be presented and compared to precipitation information.

2. Data and methodology

The lightning data used in this study were collected from a lightning detection network installed by the Korean Meteorological Administration. The network consists of Advanced Position Analyzer, Model 280 (APA), Advanced Display System (ADS), Network Display System (NDS), Integrated Storm Information System (ISIS), and Advanced Lightning Direction Finder (ALDF, model 141), made by Lightning Location and Protection Inc., which is currently known as Vaisala-GAI, Tucson, Arizona. Each magnetic 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 to determine the polarity (positive vs negative), amplitude, latitude, longitude, date, and time. A direction finder automatically detects nearly 80%–90% of all cloud-to-ground lightning occurring within a nominal detectable distance of 400 km with less than 4-km accuracy. However, especially near the edges of the network the assumption of 80% uniform flash detection efficiency may not be realistic. However, no attempt was taken to correct for detection efficiency. The publications by Cummins et al. (1998a,b) of GAI, summarize the detection efficiency of the lightning network from its past to its present form.

In finding out the total (both negative and positive) CG lightning flash counts, we considered a temporal scale of 1 month and a spatial scale of 0.1° latitude × 0.1° longitude surrounding each rainfall observing station. Moreover, for the sake of simplicity we assumed that the precipitation is uniformly distributed within each block. This assumption is reasonably good just for monthly mean and small area associated with each block. The contouring algorithm uses the triangulate method. The temporal and spatial scales that we have considered are considerably different from those used by Petersen and Rutledge (1998) but the same as Soriano et al. (2001), which considered the relationship between convective precipitation and lightning to find out the rain yield. A temporal and spatial resolution of 1 month and ~10⁵ km² were used by Petersen and Rutledge to calculate the convective rain yield. Monthly CG lightning flash counts were calculated over each desired location and for the months of interest. Our selection of small spatial scale is approximately the same as the rain
gauge data and helps us to preserve the spatial variability associated with the complex orography of the Korean peninsula. We have obtained the precipitation data using the quality controlled rain gauge data from KMA. Precipitation data is recorded daily and we have summed the daily values to obtain the monthly rainfall data. Here, we have considered the rain gauge data provided by 23 observing stations throughout the Korean peninsula as shown in Fig. 1. When the monthly rainfall and lightning data were prepared, monthly and seasonal area average rain yields were computed by taking the ratio of total monthly rain mass to the monthly total lightning flashes over each desired locations using Eq. (1):

\[
\text{rain yield} = \frac{\text{rainfall over a certain area}}{\text{number of lightning flash counts over same area}}
\]

\[
(RLR)_i = X_i = \frac{R(t, \Delta x_i)}{N(t, \Delta x_i)} \ldots \quad (1)
\]

where \((RLR)_i\) is the rainfall to lightning ratio, that is, rain yield at the location \(i\); \(R(t, \Delta x_i)\) is the total rainfall associated with the area \(\Delta x_i\) over a time period \(t\); and \(N(t, \Delta x_i)\) is the total number of lightning flash counts associated with the area \(\Delta x_i\) over a time period \(t\).

Here, \(\Delta x_i\) is small area associated with 0.1° latitude \(\times 0.1°\) longitude surrounding each rainfall observing station and \(t = 1\) month.

Since we were interested in total rainfall and lightning activity, we have included all rain yield values, even those that were exceptionally high compared to the surrounding areas or previous months. Such large values occur when the precipitation persists longer than lightning activity and indicate that the total precipitation included the precipitation from nonlightning storms such as that associated with a frontal passage.

Although we were interested in the percentage occurrence of convective precipitation, we followed the method adopted by Petersen and Rutledge (1998) to ensure that our rainfall data represent only convective precipitation. In this case, we have imposed the following addition restriction to calculate the convective rain yield:

\[
(RLR)_i = X_i = \begin{cases} 
\text{nonconvective}, & \text{if } X_i \geq 3(X_{\text{surrounding stations of ith station}}) \quad \text{and} \quad X_i \geq 3(X_i\text{previous months}) \\
\text{convective}, & \text{otherwise.}
\end{cases}
\]

To filter out all the nonconvective precipitation we examined the rain yield values for a given month and for a particular station. If the rain yields for a particular month and station were extraordinarily large (threelfold or more) compared to the surrounding stations or previous months, we examined the daily variations of lightning and rainfall to find out the nature of abrupt increase in rain yield. Such large values may indicate that convective precipitation was inflated. These values were removed to maintain a consistency among the dataset. It is worth mentioning that the convective rainfall may occur even in the absence of lightning and convective rain yield can vary with different properties of convection. As, for example, when convective rainfall is entirely or mostly characterized as warm rain (i.e., growth of mm-sized particles is exclusively or even primarily governed by collision-coalescence), lightning is usually not observed. The fraction of warm convective rain in a given precipitation system modulates the frequency of lightning and hence the amount of convective rain yield. These events were eliminated from the sample. Another example of such an event is the tropical cyclone, which can and does influence the long-term climatology of a particular location and also contains significant fractions of convective rain that also happens not to be associated with lightning (Lang and Rutledge 2002). Moreover, undoubtedly our data is contaminated by the “low-echo entroid” (heights at or below \(-10°C\) isotherm) precipitation system, which produces little or no lightning. Most of our stations are oceanic and coastal in nature. Since oceanic convection and often monsoon convection over land (Rutledge et al. 1992) is usually characterized by high fractions of warm rain and also little or no lightning and because of the broad heterogeneity in spatial distribution of rainfall and lightning, our convective rain yield values cannot be treated as a unique amount of precipitation associated with an individual CG flash, rather it indicates only a general relationship between convective precipitation and CG lightning.

3. Lightning density and rain yield

a. Seasonal mean

The monthly variations in lightning activity in different latitude belts across the Korean peninsula are shown in Fig. 2. For the interbelt comparison of lightning activity, we have not used the earlier grid (0.1° latitude \(\times 0.1°\) longitude) scale rather the total number of lightning flash counts was taken over each latitude belt over a count area of 1° latitude \(\times 3°\) longitude to cover the whole peninsula. For the first (34°–35°N) and last latitude belts (38°–39°N), the longitudinal range extends from 126° to 129°E and 125.5° to 128.5°E, respectively, while for the three middle latitude belts the
longitudinal range extends from 126.5° to 129.5°E. From the figure it is evident that there is a distinct phase shift and amplitude variation in different latitude belts. In all the latitude belts there are two maxima and two minima of amplitude in each year. The amplitude of first maximum occurred in the month of May for all the latitude belts except for the first latitude belt (34°–35°N) for which no prominent maxima is seen. The amplitude of second maximum is seen in the month of July for all the latitude belts except for the first latitude belt (34°–
35°N) for which the second maximum occurred in the month of August. The amplitude is gradually increasing for the first three belts (34°–35°N, 35°–36°N, 36°–37°N), but in the fourth belt the amplitude decreased slightly compared to the third belt. In the fifth belt the amplitude is seen to increase again and the maximum amplitude is in this belt compared to the other belts. An oscillation of amplitude is seen over the five latitude belts in the Korean peninsula and most of the lightning activity is seen to occur in the months of July and August. In June, there are relatively smaller occurrences in lightning flash counts compared to July and August. This small number is mainly due to Monsoon rain, which starts late June. Before late June, there is drought period shortly (Kang et al. 1999).

The spatial distribution of lightning flash counts over a gridded area of 0.1° latitude by 0.1° longitude for the 3-month period [June–July–August (JJA)] over Korean peninsula is shown in Fig. 3. The maximum lightning activity region is seen in two different parts of Korea: one in the northern part, which increases northwestward, and the other in the midwest coast of Korea. The western coast of the Korean peninsula is the intrusion pathway of moist air with Asian monsoon flow. Results of Kang et al. (1999) suggest that the excessive surface heating from warm sea surface temperature in the western Pacific during summer monsoon season along with the mist air forms the local convection and a low pressure system in the lower troposphere, which is supposed to be responsible for this high value of lightning activity on the west coast. This convection grows until the circulation system has a large-scale wave to transport the access energy poleward. Minimum values occurred at the east coast areas. It should be noted that the lightning activity is higher over the west coast than over the east and south coasts.

To describe the lightning or rainfall distribution one needs to know the physical features of the Korean peninsula. Over 70% of the land in Korea is covered by mountain. Covering the entire east coast there is a large mountain range (Tae-back) spreading parallel to the entire east coast from north to south (Fig. 1). Other major ranges are almost parallel to each other and oriented northeast to southwest. These mountains and the low-level wind pattern have a great influence on the spatial variability of lightning over the Korean peninsula and adjacent coastal areas. Two main circulation types are expected to play an important role in determining the spatial pattern of lightning distribution over South Korea. The sea breeze from the Yellow Sea on the west coast that moves toward land is aided by low-level wind, while the sea breeze from the East Sea on the east coast remains stationary after being obstructed by Tae-back Mountain. This causes the coastal gradient of lightning frequency on the eastern side of the peninsula and a zone of high lightning frequency along the west coast (Shin and Lee 1989). The highest lightning activity in the northern and middle west coast may also be due to the presence of moist convection in the western and southwestern part of Korea during this season. Availability of moisture, location of the subtropical ridge axis, transitory troughs in westerlies, and low-level moisture surges from the west and southwest of Korea can affect thunderstorm occurrences, which in turn will affect the lightning production (Park et al. 1989).

Figure 4 shows the spatial distribution of the observed rainfall amount on the same spatial and timescales as in Fig. 3. Rainfall mass increases toward seas and attains their maximum values on the coasts. Minimum values are seen over the lower middle part. The northwest and southwest coast shows the maximum value while the northeast and southeast coast shows slightly lower value than the maximum.

Seasonal values of rain yield have been plotted in Fig. 5. Northeast coast and southeast coast follows a similar trend of variation for rain yield. Rain yield is gradually increasing toward the coastal area in the northeast while it shows a remarkable low value on the entire west and south coasts despite the fact that lightning activity is higher in the north and middle west coast. These results are physically consistent. Oceanic cumulonimbus are generally associated with low lightning activity (Williams et al. 1992; Rutledge et al. 1992; Petersen et al. 1996) and high amounts of precipitation (Zipser 1994; Rickenbach and Rutledge 1998), since oceanic convection and often monsoon convection over land is usually characterized by high fraction of warm rain and also little or no lightning. Heavy convective rain in the inner-eyewall of tropical cyclones is similar.
These convective systems can be deep (i.e., echo tops to troposphere at 18–20 km) but most of the echo mass is located at temperatures warmer than −10°C and not associated with mixed phase precipitation processes (i.e., graupel, ice crystal, supercooled water), which are believed to be crucial for electrification and lightning production. Therefore, the rain yield is expected to increase or decrease as the climate regime changes. The highest value of rain yield in the northeast may partly be caused by the rain yields that have been inflated by upslope precipitation because of the presence of mountains in this region oriented in a north–south direction.

The values of seasonal mean rain yields over the Korean Peninsula are clustered near $10^5$ m$^3$ fl$^{-1}$. Our result is in good agreement with the results of Petersen and Rutledge (1998), who reported a value of rain yield $10^8$ kg fl$^{-1}$ for the continental United States, $10^9$ kg fl$^{-1}$ for the island ocean rainfall regime, and $10^{10}$ kg fl$^{-1}$ for the tropical ocean rainfall regime. The seasonal mean rain yield in the eastern part of the Tae-back Mountain range is $3 \times 10^5$ m$^3$ fl$^{-1}$ and that for the western part of the Tae-back range is $8 \times 10^4$ m$^3$ fl$^{-1}$. For the humid United States Petersen and Rutledge (1998) suggested a value of $1.3 \times 10^8$ kg fl$^{-1}$ for the humid southeast and $2.5 \times 10^8$ kg fl$^{-1}$ for the north, while for the arid United States a value of $5.7 \times 10^7$ kg fl$^{-1}$ and $1.1 \times 10^8$ kg fl$^{-1}$ was assigned for the arid southwest and midcontinent, respectively. The value of seasonal rain yield within the west of Tae-back Mountain on the Korean Peninsula varies between $2 \times 10^4$ m$^3$ fl$^{-1}$ and $18 \times 10^4$ m$^3$ fl$^{-1}$, while for the east coast region—that is, the region east of Tae-back Mountain—it ranges from $0.7 \times 10^5$ m$^3$ fl$^{-1}$ to $11 \times 10^5$ m$^3$ fl$^{-1}$.

b. Intraseasonal variation

In order to investigate the monthly variations of rain yield, we have calculated the rain yield for each of the three months and plotted separately. The mean monthly lightning flash count for the month of June is shown in Fig. 6a. The values of rainfall and rain yield for the month of June are plotted in Figs. 6b and 6c, respectively. Rain yield shows a maximum value on the southeast coast, moderate value on the northeast coast, and a considerable low value in the entire west coast and middle of Korea. Minimum value is seen over a very small region on the middle east coast. The high rain yield values on the southeast coast are mainly due to the low lightning flash counts. One possible explanation of this low lightning count may be that in this region a mixture of rainfall processes is operative that is responsible for this low lightning flash count and hence higher rain yield values. The inland flow of bai-u rain from Japan and the mei-yu front of China forms the mixed precipitation processes in this region after being obstructed by So-back Mountain. These mixed precipitation processes include significant amounts of warm-rain convection with low lightning production (Tanaka 1992). The fraction of this warm rain might be responsible for the high value of rain yield in this region. The higher value of rain yield in the northeast coast might be due to the inflated rainfall in that region influenced
by stratiform rainfall associated with the cold Okhotsk high. The average value of rain yield for the month of June in the region east of Tae-back Mountain on the Korean peninsula is $8.2 \times 10^5$ m$^3$ fl$^{-1}$, while that for the western region of Tae-back Mountain is $1.6 \times 10^5$ m$^3$ fl$^{-1}$, respectively.

Most of the lightning activity occurs in the month of July over Korea as evident from Fig. 2, and the spatial distribution of the flash counts for July are shown in Fig. 7a. It is seen from the figure that the lightning activity is maximum in the northwest part, while a moderate value is maintained at the middle and west coast. The maximum lightning activity in the northwest is mainly due to the abundant moist air associated with the westerly and southwesterly flows in the lower part of the air causing highly unstable parcels and the development of mesoscale convective systems (MCSs), which is caused by the perturbation of such unstable
Fig. 7. (a) Spatial distribution of lightning flash density \((10^{-2} \text{ fl km}^{-1} \text{ month}^{-1})\) in Jul over the Korean peninsula. (b) Spatial distribution of observed rainfall \((\text{mm month}^{-1})\) over a gridded area of 0.1° × 0.1° for Jul over the Korean peninsula during 1988–97. (c) Total rainfall to lightning ratio \((\text{units } 10^5 \text{ m}^3 \text{ fl}^{-1})\) over a gridded area of 0.1° × 0.1° for Jul and for 23 Korean rainfall stations during 1988–97.

parcels in this region (Sun and Lee 2002). It is well known that lightning is frequently observed in association with the stratiform portion of continental MCSs (Rutledge and MacGorman 1988; Williams 1989). Hence, these two factors favor the development of strong lightning in this region. Minimum value is seen in the entire east coast along Tae-back Mountain because of the coastal gradient of lightning frequency on the eastern side of the peninsula due to the high-elevation of the mountain. We have shown the rainfall and rain yield values for the month of July in Figs. 7b and 7c, respectively. Most of Fig. 7b shows a very low value of rain yield through the month of July except for the northeast and southeast of the Korean peninsula. Figure 7c shows slightly higher values of rain yield increasing toward the coast and follows the same trend of variation. Low rain yield values over most of the area are due to the higher convective fraction in July. The monthly av-
average value of rain yield for July is $6 \times 10^4$ m$^3$ fl$^{-1}$ for the western part of Tae-back Mountain and $1.5 \times 10^5$ m$^3$ fl$^{-1}$ for the eastern part of the mountain. A close scrutiny between the seasonal variation of rain yield and that of July shows that the variations of rain yield in the monsoon season closely resemble that of July indicating that July dominates the overall monsoon pattern. As expected from the above discussion the pattern of spatial distribution of lightning flash count, shown in Fig. 7a, for the month of July is also very similar to that of seasonal variation compared to the other two months. So the characteristic variation of lightning distribution and rain yield for the month of July is very interesting from the climatological point of view in finding out the effect of lightning on Korean monsoon.

The spatial distribution of lightning flash count, rainfall, and rain yield for the month of August has been plotted in Figs. 8a, 8b, and 8c, respectively. Lightning
activity is seen to decrease on the northwest, middle west, and southwest coasts and maintains a more or less uniform lightning distribution. Maximum value of rain yield is seen over a wide region to the north and east, while a moderate value is found in the south. Minimum value is observed over the entire west coast. It is interesting to note that in June the rain yield was maximum in the south and southeast and was moderate on the northeast coast, but for August the maximum and minimum values have changed their position. So, there is a distinct phase change in the rain yield values. The overall pattern for August is almost a mirror image of that in June. A similar argument is true if we compare the lightning distributions from June and August. The average value of rain yield for the month of August is $1.1 \times 10^5$ m$^3$ ft$^{-1}$ and $2.4 \times 10^4$ m$^3$ ft$^{-1}$ for the west and east of Tae-back Mountain, respectively.

It is worth mentioning that the values of rain yields over the entire west coast and the middle of the Korean peninsula are always lower than that over the east coast when monthly mean rain yields are considered. A close scrutiny of Figs. 6c, 7c, and 8c indicates that the monthly rain yields are higher in June and August than in July for both the regions. The passage of bai-u rain in early June and other frontal systems in late August over the Korean Peninsula is supposed to be responsible for this higher value of rain yield computed for June and August relative to July, which might have been contaminated by the nonconvective frontal precipitation. The high value of rain yield might also be due to the warm rain associated with bai-u rain. During convective rainfall characterized entirely or mostly as warm rain, lightning is usually not observed. The fraction of this warm convective rain in a given precipitation system might modulate the amount of lightning frequency and hence the rain yield.

4. Estimation of convective rain

Out of the 23 stations, we have calculated the convective rain yield for 10 stations to examine the percentage of convective rain over the total rain in each station. These 10 stations were purposely chosen to show the characteristic variation and percentage contribution of convective rain over the total rain for the monsoon season. Six of them are situated on the east coast and west coast (three on each coast), the other three are situated in the middle, and the last one is an island near the Korean peninsula. Total rain yield, convective rain yield, and percentage of convective rain during the summer monsoon season over all 10 stations are shown in Table 1. The stations that are situated deep inland are associated with relatively smaller values of rain yield compared to coastal stations. Rain yield values are larger for the stations, which are oceanic/coastal in nature. It is evident from Table 1 that the average percentage contribution of convective rain is maximum in west coast stations, moderate in middle stations, and minimum in the east coast stations. The maximum contribution of convective rain occurred at Kanghwa in the northwest, while the minimum occurred at Ulsan in the southwest. Since manual analyses were done to discriminate convective and nonconvective rain yield, selection of $Z \geq 3$ particularly for the coastal stations, undoubtedly ignored some of the events like tropical cyclones, warm rain convection, or low-echo entroid precipitation systems, which produce significant fraction of convective rainfall but associated with little or

<table>
<thead>
<tr>
<th>Stations</th>
<th>Total rain yield (units $10^5$ m$^3$ ft$^{-1}$)</th>
<th>Convective rain yield (units $10^3$ m$^3$ ft$^{-1}$)</th>
<th>Percentage of convective precipitation</th>
<th>Average percentage</th>
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<tr>
<td>West Coast</td>
<td></td>
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<tr>
<td>Kanghwa</td>
<td>0.41</td>
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<td>0.55</td>
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<td>Sanchong</td>
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<td>0.51</td>
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<td>0.10</td>
<td>12</td>
<td>12</td>
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</table>
no lightning. Hence, the convective rain yield values listed in Table 1 do not imply that the amount of rain mass is associated with an individual lightning flash, rather it represents only a general relationship between convective precipitation and CG lightning. The minimum value occurred at Cheju, but since it is an Island, slightly off the main peninsula, we are not considering it as minimum for the main Korean peninsula.

5. Conclusions

In this work, the relationship between CG lightning and total precipitation during the Korean summer monsoon season is analyzed extensively using 10 years of lightning and precipitation data from 1988 to 1997. A temporal scale of 1 month and a spatial scale of $0.1^\circ \times 0.1^\circ$ longitude surrounding each rainfall observing station has been considered to find out the rain yield.

Rain yield, which is defined as the ratio of rain mass to CG lightning over a common area, has been used to quantify the relationship between CG lightning and surface precipitation. Total precipitation and CG lightning have a similar pattern of variation. The variation of rain yield in the monsoon season closely resembles that of July, which indicates that July dominates the monsoon pattern. The values of rain yield cluster around $\sim 10^3$ m$^3$ fl$^{-1}$, which is in good agreement with the values reported by Petersen and Rutledge (1998) for the continental United States but the values are different for different climate regimes. The maximum values of rain yield are observed on the east coast of the Korean peninsula, particularly in the region east of Tae-back Mountain, with a mean value of $3 \times 10^3$ m$^3$ fl$^{-1}$ while the minimum value is seen in the region west of Tae-back Mountain, with an average value of $8 \times 10^4$ m$^3$ fl$^{-1}$.

Maximum convective precipitation occurred at Kanghwa in the northwest of Korea, while the minimum value of convective precipitation is seen at Ulsan in the southeast. The average percentage of convective rain for the east coast, west coast, and the middle of the Korean peninsula is 46%, 82%, and 53%, respectively. Correlation coefficient between the total precipitation and CG lightning during the summer monsoon season is 0.54, which is not very high. This is not an unexpected result since we have considered the total rainfall. In most of the cases total precipitation lingered longer than lightning. This may be due to the occasional development of mesoscale convective systems, which produce light stratiform precipitation during their dissipation stage or might have been contaminated by the upslope precipitation or by nonlightning producing frontal precipitation. Warm rain convection (i.e., growth of mm-sized particles is exclusively or even primarily governed by collision-coalescence) or low-echo centroid (heights at or below $-10^\circ$C isotherm) precipitation systems, which produce little to no lightning, could also be another factor responsible for this low correlation coefficient.

These results suggest that the discrimination of non-lightning-producing precipitation can give higher correlation coefficient and thus the convective rain yield could be a more precise and useful quantitative tool to indicate different climate regimes and estimate changes in the precipitation regime.

It is worth mentioning that the rain yield is not a measure of unique amount of rain mass associated with an individual lightning flash. In our calculation of summer monsoon convective rain yield on the Korean peninsula we assumed that the majority of the rainfall is associated with deep convection. Since the rainfall data used in our calculation are undoubtedly contaminated by the cloud system precipitation with little or no CG lightning flash (e.g., precipitation produced by meso-scale convective system stratiform region) or by upslope precipitation, the values of rain yield simply indicate a general relationship between cloud-to-ground lightning and precipitation over the South Korean peninsula during the said time period.

It has been proved that the CG lightning has a wide potential application in describing the rainfall statistics over a certain region because of its relatively straightforward way of mapping. Using the available VLF techniques or spaceborne sensors the lightning detection network can have a widespread coverage particularly over the remote tropical ocean where accurate rainfall estimates are difficult for climate-based studies (Bhattacharya et al. 1997). However, rain estimation by satellite can provide us the required coverage over the remote tropical oceans. Hence, the use of lightning detection and location networks and space-borne sensors now seems timely, especially to provide coverage in the Tropics.

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