Statistical Relationships of Precipitation Rate and Wind Gust Intensity to Lightning Activity in Japan

Syugo HAYASHI

Meteorological Research Institute, 1-1 Nagamine, Tsukuba 305-0052, Japan.
E-mail: shayashi@mri-jma.go.jp

Abstract. This study examined the relationships of precipitation rate and wind gust intensity to lightning activity in Japan by using data recorded at ~1,000 automatic weather stations and a lightning detection network at 10 minute intervals for three years from June 2009 to May 2012. The relationships were evaluated by correlation analyses in 11 climatologically distinct areas of Japan. To investigate the frequency of simultaneous occurrences of precipitation, gusts, and lightning activity, observations were subjectively divided into four categories, based on their distributions in a plot of precipitation and gust data versus lightning activity.

There were weak positive correlations between cloud-to-ground (CG) lightning activity and precipitation rate in summer, except in northern Japan, but no significant correlations between CG lightning activity and precipitation rate in winter. High precipitation rate was associated with 5%–40% of occurrences of high lightning activity, suggesting that lightning activity has only limited application as an indicator of high precipitation rate in summer. There were no significant correlations of lightning activity with wind gusts in summer or winter in any of the 11 areas. Only 0%–11% of occurrences of high lightning activity were accompanied by strong gusts in winter, indicating that lightning activity is not a useful indicator of strong wind gusts in winter.

Key words: lightning activity, wind gust, precipitation intensity

1. Introduction

Previous studies have identified a relationship between lightning activity and severe weather conditions (e.g., MacGorman and Rust, 1998). Most of these studies were of short duration, over small regions, and most were based on observation data of coarse resolution in time and space. Sheridan et al. (1997) statistically examined the relationship between cloud-to-ground (CG) lightning and surface daily area-averaged precipitation in six regions of the south-central United States (each based on data from about 10 stations within areas on the order of 10,000 km²) over five consecutive summers. They reported linear correlations between the number of CG lightning events and average precipitation in each of these regions. Lang and Rutledge (2002) investigated the relationship between convective storm kinematics, precipitation, and lightning for 11 thunderstorms (six from the mid-latitudes, five from the tropics) and showed that the storms that produced
predominantly positive cloud-to-ground (CG+) lightning in their lifetime were characterized by much larger volumes of updraft and greater amounts of precipitation than those that produced little CG lightning. Soula and Chauzy (2001) found a consistent positive correlation between rain and lightning for four storms in the Paris area. They also reported that CG+ lightning is associated with higher rainwater volumes than negative CG lightning. Many studies have investigated the relationship between lightning activity and wind gusts, especially for strong winds associated with tornadoes. Perez et al. (1997) analyzed CG lightning patterns in 42 violent tornado-producing (F4 and F5) supercells and found a local peak in CG rate in 74% of them. However, they stated that the occurrence of a peak CG rate is of little value for predicting tornado genesis. In a study of 264 tornadic thunderstorms, Knapp (1994) found no monotonic increases in CG lightning before tornado touchdown. However, Knapp (1994) found that a polarity change of CG lightning was a useful predictor of tornado touchdown. In a study of tropical cyclone tornados, McCaul et al. (2004) reported that CG lightning rates were highest in the strongest of the tornadic storms, even though the lightning rates were only weak to moderate. Further quantitative and statistical studies based on more observation data and higher temporal resolution are required to better understand the relationship between lightning activity and severe weather, particularly heavy precipitation and strong wind gusts.

The purpose of this study was to apply a statistical approach to data recorded over three years (2009-2012) at the Japanese lightning detection network and at ~1,000 automatic weather stations to clarify the relationships of lightning activity with precipitation rate and wind gust intensity in Japan.

2. Data source and analysis method

The meteorological data used in this study cover the three-year period from June 2009 to May 2012.

All lightning data were observed by the Lightning Detection Network (LIDEN), which was installed in March 2000 and is operated by the Japan Meteorological Agency (JMA; JMA, 2001). The network includes 30 detecting sensors (Fig. 1); network coverage was modified slightly in March 2009 (Ishii et al., 2014). The LIDEN system observes CG lightning with time, location, polarity, and estimated electric current, and Cloud-to-Cloud (intra-cloud, IC) lightning with time and location.

Surface precipitation and maximum wind gust data were collected by JMA's Automated Meteorological Data Acquisition System (AMeDAS). In 2009, JMA began to use AMeDAS data to report maximum wind velocity (912 stations) recorded at 3-second intervals over 10 minute (wind gust intensity, GUST10) and accumulated precipitation (1,265 stations) over 10-minute intervals (PREC10).

Lightning activity was defined as the number of lightning events during 10-minute intervals (LA10) within a "specific radius" (explained below) from each AMeDAS station. Three types of LA10 data were recorded: LA10 of CG events (LA10CG), LA10 of positive CG events (LA10CG+), and LA10 of total lightning events (LA10TT; the sum of CG and IC events).

The specific radius was defined as the radial distance from AMeDAS stations at
which the strongest correlations of LACG10 with PREC10 and GUST10 were achieved for the entire wind and precipitation dataset (2.0 × 10^8 data for PREC10, 1.4 × 10^8 data for GUST10). The strongest correlation between LA10CG and PREC10 was clearly for a radius of 6 km (Fig. 2). Because there was no clear peak for the correlation between LA10CG and GUST10, the 6 km radius was also used for the GUST10 analyses.

Correlations of GUST10 and PREC10 with each of the three types of LA10 data were calculated for the entire observation periods for 11 climatologically distinct areas (Fig. 1; S-1 to S-11) defined by JMA (2008). The numbers of AMeDAS precipitation and wind gust stations in each of these climatological areas are also indicated in Fig. 1.

In this study, the approach used by Sheridan et al. (1997) was applied to all data for the three-year study period to evaluate the usefulness in Japan of LA10CG as an indicator for PREC10 and GUST10. Sheridan et al. (1997) showed that plots of precipitation data and gust data versus number of lightning events provided distinct clusters of data points, which they divided subjectively into four categories.

In this study, the following four categories were defined for the relationship of PREC10 to LA10CG (Fig. 3). Category a) HIGH: included all observations for 10-minute intervals during summer (June-August) for which PREC10 was ≥ 10 mm and LA10CG ≥ 10 with in a 6 km radius of an AMeDAS station. For winter
(December–February), a lower LA10CG threshold of one per 10 minute interval was used, because the lightning activity is lower in winter than in summer (Ishii et al. 2014). Category b) HIGH PRECIPITATION: for PREC10 ≥ 10 mm and LA10CG < 10 (summer) or 1 (winter). Category c) HIGH LIGHTNING: for PREC10 < 10 mm and LA10CG ≥ 10 (summer) or 1 (winter). Category d) LOW: for PREC10 < 10 mm and LA10CG < 10 (summer) or 1 (winter). A similar classification system was used for the relationship of GUST10 to LA10CG, with lower threshold for STRONG GUST set at 20 m s⁻¹ for all climatological areas and seasons. The reliability of LA10CG as an indicator for PREC10 and GUST10 was determined by considering probability of detection (POD), false alarm rate (FAR) and threat score (TS) derived from the above categories a to d as follows.

POD = a / [a + c] (a value of 100% indicates perfect detection)
FAR = b / [a + b] (a value of 0% indicates no false alarms)
TS = a / [a + b + c] (a value of 100% indicates a perfect score)

3. Results

3.1. Relationship between precipitation rate and lightning activity

Correlations between PREC10 and the three categories of lightning activity for each climatological area in summer and winter (Table 1) show that in summer, correlation coefficients between PREC10 and LA10CG ranged from 0.12 in area S-2 to 0.21 in area S-7. The correlations for areas S-1, S-2, and S-3 were weaker, because northern Japan is a region of lower lightning activity (Ishii et al. 2014). Weak positive correlations between PREC10 and LA10CG were also found in the other climatological areas. The correlation between PREC10 and LA10CG for summer was the strongest correlation returned of all those calculated (all areas and both seasons). For summer data, there was no significant difference between the correlations for LA10CG+ and LA10TT. For winter data, all correlations were weaker than those for summer data. There were very weak positive correlations ranging from 0.01 in area S-2 and S-3 to 0.12 in area S-9. Correlations between PREC10 and both LA10CG+ and LA10TT were also weak.
above correlation analyses do not clarify the relationship between lightning activity and precipitation rate.

Table 2 lists the total number of observations in each of the four categories defined in Figure 3 for each climatological area and, the results of the reliability analyses (POD, FAR, TS).

In summer, occurrences of high precipitation rate (PREC10 \( \geq \) 10mm; category a + b) represent about 0.01% of total observations. In southern and eastern Japan (areas S-7, S-8, and S-9), more than 1,900 occurrences of high precipitation rate were observed. The greatest number of occurrences of LA10CG \( \geq \) 10 (category

| Area | S-1 | S-2 | S-3 | S-4 | S-5 | S-6 | S-7 | S-8 | S-9 | S-10 | S-11 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| S-1  | 0.14| 0.05| 0.13| 0.02| 0.01| 0.00|
| S-2  | 0.12| 0.06| 0.08| 0.01| 0.01| 0.01|
| S-3  | 0.16| 0.04| 0.08| 0.01| 0.01| 0.01|
| S-4  | 0.18| 0.12| 0.13| 0.04| 0.03| 0.04|
| S-5  | 0.20| 0.10| 0.10| 0.08| 0.07| 0.06|
| S-6  | 0.18| 0.12| 0.11| 0.06| 0.04| 0.04|
| S-7  | 0.21| 0.15| 0.15| 0.07| 0.05| 0.08|
| S-8  | 0.18| 0.11| 0.07| 0.07| 0.04| 0.04|
| S-9  | 0.16| 0.09| 0.09| 0.12| 0.04| 0.09|
| S-10 | 0.18| 0.10| 0.08| 0.02| 0.01| 0.01|
| S-11 | 0.18| 0.08| 0.13| 0.07| 0.04| 0.03|

Table 2. Number of precipitation observations in each category defined in Fig. 3 and calculated values of POD, FAR, and TS.

| Area | S-1 | S-2 | S-3 | S-4 | S-5 | S-6 | S-7 | S-8 | S-9 | S-10 | S-11 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| a) HIGH | 16% | 40% | 5% | 31% | 17% | 16% | 16% | 23% | 32% | 15% | 23% |
| b) HIGH RAIN RATE | 96% | 96% | 99% | 91% | 89% | 90% | 83% | 94% | 97% | 94% | 98% |
| c) HIGH LIGHTNING | 3% | 4% | 1% | 7% | 7% | 6% | 9% | 5% | 3% | 4% | 2% |

Winter (December-January-February)

| Area | S-1 | S-2 | S-3 | S-4 | S-5 | S-6 | S-7 | S-8 | S-9 | S-10 | S-11 |
|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| a) HIGH | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| b) HIGH RAIN RATE | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| c) HIGH LIGHTNING | 31 | 13 | 1 | 490 | 181 | 181 | 449 | 727 | 350 | 85 | 58 |
| d) LOW | 3.9x10^6 | 2.6x10^6 | 1.9x10^6 | 3.5x10^6 | 4.2x10^6 | 4.6x10^6 | 4.6x10^6 | 9.3x10^6 | 7.5x10^6 | 5.4x10^6 | 4.4x10^6 | 1.1x10^6 |
| POD [a/(a+c)] | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| FAR [b/(a+b)] | 89% | 82% | 60% | 84% | 100% | 99% |
| TS [a/(a+b+c)] | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
a + c: 2,080 cases) were recorded in area S-7, and 16% of them were accompanied by PREC10 \(\geq 10\) mm. POD for high precipitation rates in summer ranged from 5% in area S-3 to 40% in area S-2; these results may reflect the activity of convective clouds. However, FAR for high precipitation rates ranged from 83% to 99% (false alarm dominant). Moreover, TS for high precipitation rates was very low, from 1% to 9%. These results indicate that high lightning activity in summer is sometimes accompanied by high precipitation rates, so summer lightning activity may be a useful indicator of high precipitation rate in summer.

In winter, the frequency of occurrences of high precipitation rates for all climatological areas was markedly lower than in the summer. High precipitation rates were up to about 0.001% of total observations. POD for occurrences of high precipitation rate ranged from 0% to 5%. The largest occurrences of LA10CG \(\geq 1\) (category a + c) was observed in area S-6, but no corresponding high precipitation rate was observed. FAR for high precipitation rate ranged from 60% to 100%, but the number of category a + b events was too small for meaningful statistical analysis. Consequently, a statistically significant relationship between winter lightning activity and precipitation rate was not identified.

### 3.2. Relationship between wind gust and lightning activity

Correlations between GUST10 and the three categories of lightning activity (Table 3) show no significant correlations in either season in any of the climatological areas. The correlations in area S-6 were slightly stronger than elsewhere, but the highest correlation coefficient was 0.03 only.

Table 4 lists the total number of observations in each of the four categories defined in Figure 3 for each climatological area and the results of the reliability analyses (POD, FAR, TS).

In summer, about 3,000 occurrences of strong GUST10 (category a + b), representing 0.04% to 0.08% of total observations, were observed in each of three areas (S-7, S-8, and S-9) in southern and eastern Japan. These may reflect strong winds associated with typhoon activity. Although the greatest number of high LA10CG (category a + c) occurrences were in area S-7, only 14 of these were associated with strong GUST10. The other climatological areas showed the same tendency. Thus, the simultaneous occurrence of high LA10CG with strong GUST10 (category a) was rare. Hence, no significant relationship was evident between high LA10CG and strong GUST10 in summer.

In winter, more than 10,000 occurrences of strong GUST10 (\(-0.4%\) of all observations) were observed in each of climatological area S-1, S-2, S-4, S-6 and S-7. Strong GUST10 occurrences were five more frequent in winter, mostly because of winter monsoon activity over the Sea of Japan. The frequency of simultaneous occurrences of strong GUST10 and high LA10CG (category a) was very much lower than the frequency of simultaneous occurrences of strong GUST10 and low LA10CG (category b), so FAR for strong GUST10 was almost 100%. POD for strong GUST10 ranged from 3% to 11%. These results indicate that the occurrence of lightning may be a slightly useful indicator for strong gust in winter, especially in climatological areas S-5 and S-7. Note, however, that the number of strong gust occurrences without CG lightning (category b) was extremely
high compared to the number of occurrences of strong gusts with CG lightning (category a). In practice, it would be very difficult to use observations of high lightning activity as an indicator for strong wind gusts.

4. Concluding remarks

This study investigated the statistical relationships of lightning activity with surface precipitation rate and wind gust intensity by examining Japanese meteorological data from about 1,000 surface observation stations in consecutive 10 minute intervals over period of three years. The principal conclusions are as follows:

Table 3. Correlation coefficients for summer and winter maximum wind gust in 10 minute intervals (PREC10) versus lightning activity (LA10CG, LA10CG+, and LA10TT) in the same 10 minute intervals.

| Area | Summer (June-July-August) | Winter (December-January-February) |
|------|--------------------------|-----------------------------------|
|      | CG | CC+ | Total | CG | CC+ | Total |
| S-1  | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| S-2  | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| S-3  | 0.01 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 |
| S-4  | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| S-5  | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| S-6  | 0.03 | 0.02 | 0.02 | 0.03 | 0.02 | 0.02 |
| S-7  | 0.02 | 0.02 | 0.02 | 0.01 | 0.01 | 0.00 |
| S-8  | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| S-9  | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| S-10 | 0.02 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| S-11 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Table 4. Number of wind gust observations in each category defined in Fig. 3 and calculated values of POD, FAR, and TS.

### Summer (June-July-August)

| Category | S-1 | S-2 | S-3 | S-4 | S-5 | S-6 | S-7 | S-8 | S-9 | S-10 | S-11 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| a) HIGH  | 7   | 0   | 0   | 1   | 1   | 6   | 14  | 8   | 2   | 0    |      |
| b) STRONG GUST | 745 | 955 | 467 | 750 | 596 | 404 | 2858 | 3722 | 2977 | 934 | 9156 |
| c) HIGH LIGHTNING | 29 | 8 | 12 | 83 | 125 | 286 | 1425 | 443 | 132 | 177 | 21 |
| d) LOW   | 3.1x10^6 | 2.0x10^6 | 1.5x10^6 | 2.6x10^6 | 3.1x10^6 | 3.2x10^6 | 6.6x10^6 | 5.4x10^6 | 3.7x10^6 | 3.2x10^6 | 0.9x10^6 |
| POD [a/(a+c)] | 19% | 0% | 0% | 1% | 1% | 2% | 2% | 0% | 1% | 0% |
| FAR [b/(a+b)] | 99% | 100% | 100% | 100% | 100% | 99% | 100% | 100% | 100% | 100% |
| TS [a/(a+b+c)] | 1% | 0% | 0% | 0% | 0% | 1% | 0% | 0% | 0% | 0% |

### Winter (December-January-February)

| Category | S-1 | S-2 | S-3 | S-4 | S-5 | S-6 | S-7 | S-8 | S-9 | S-10 | S-11 |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|------|
| a) HIGH  | 2   | 0   | 0   | 16  | 10  | 53  | 39  | 20  | 14  | 4    | 0    |
| b) STRONG GUST | 15642 | 11973 | 4383 | 11092 | 5842 | 10686 | 20365 | 4551 | 5475 | 1345 | 794 |
| c) HIGH LIGHTNING | 18 | 10 | 1 | 311 | 112 | 1340 | 331 | 552 | 241 | 65 | 48 |
| d) LOW   | 3.1x10^6 | 2.0x10^6 | 1.6x10^6 | 2.5x10^6 | 3.1x10^6 | 3.2x10^6 | 6.4x10^6 | 5.3x10^6 | 3.6x10^6 | 3.1x10^6 | 0.9x10^6 |
| POD [a/(a+c)] | 0% | 0% | 0% | 5% | 8% | 4% | 11% | 3% | 5% | 6% | 0% |
| FAR [b/(a+b)] | 90% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| TS [a/(a+b+c)] | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
Weak positive correlations were found between CG lightning activity and precipitation rate in summer, except for areas of the northern Japan. All correlations between CG lightning activity and precipitation rate in winter were weaker than those in summer. These positive correlations may be related to the activity of convective clouds, because both lightning activity and precipitation rate are positively correlated with updraft intensity (Lang and Rutledge, 2002). The positive correlations in summer are consistent with a previous study by Sheridan et al. (1997), although the strengths of the correlations in this study are considerably lower than those of the earlier studies (e.g., Sheridan et al., 1997; Soula and Chauzy, 2001; Lang and Rutledge, 2002). These differences may be a consequence of the large volume and finer temporal resolution of the observation data used in this study, and that no specific weather condition was applied for correlation analyses in this study.

Correlations of CG lightning with precipitation rate and wind gust intensity were higher than those for positive CG lightning and total lightning, for which the correlation strengths were almost identical. Although previous studies have reported that positive CG lightning activity is a good indicator of both high precipitation rate and strong wind gusts (e.g., Soula and Chauzy, 2001; Lang and Rutledge, 2002; Carey et al., 2003), this is not supported by the results of this study. Schultz et al. (2011) reported that total lightning activity is a better indicator of severe weather than CG lightning activity. Again, this is not supported by the results of this study. These inconsistencies may reflect the current level of understanding of differences in lightning discharge processes under different meteorological conditions (e.g., mechanism of electrification and polarity of lightning). These are topics to be addressed in future research.

In this study, high lightning activity was in some cases accompanied by high precipitation, predominantly in summer, so lightning activity as an indicator of heavy precipitation may have some application in summer. To improve the accuracy of this indicator, however, a better understandings is needed of the meteorological circumstances that promote simultaneous occurrences of high lightning activity and heavy precipitation.

No significant correlations were established between lightning activity and wind gusts, so lightning activity is of little practical value as an indicator of strong wind gusts. This study was purely statistical analysis that did not consider the causes of the relationships established. Further multiscale analyses (cloud-microphysics scale to synoptic-scale) of meteorological parameters are needed to clarify the meteorological and electrical causes of these relationships. Future analyses of these relationships, focused on specific meteorological condition (e.g., tornado, typhoon, winter monsoon), may provide stronger correlations than those reported here.

Acknowledgement. The author thanks JMA observatory department for providing AMeDAS and lightning data sets. The author thanks to Dr. Fumiaki Fujibe at Tokyo Metropolitan University, Dr. Masahide Nishihashi at the National Institute for Environmental Studies and Mr. Kyosuke Ishii at the Japan Meteorological Agency for their kind support and valuable guidance. This work was supported by the Japan Society for the Promotion of Science KAKENHI Grant Number 25350514.
References

Carey, L. D., S. A. Rutledge and W. A. Petersen, 2003: The relationship between severe storm reports and cloud-to-ground lightning polarity in the contiguous United States from 1989 to 1998. *Mon. Wea. Rev.*, 131, 1211-1228.

Ishii, K., S. Hayashi, and F. Fujibe, 2014: Statistical analysis of temporal and spatial distribution of cloud-to-ground lightning in Japan from 2002 to 2008. *J. Atmospheric Electricity*, 34, 79-86.

JMA, 2001: Introduction of LIDEN. *Kisho*, 45, 17426-17429 (in Japanese).

JMA, 2008. Global warming projection Vol. 7: Climate change projection around Japan for the A1B and B1 SRES scenarios, 59 pp. (in Japanese) [English version is available online at http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp7/index-e.html]

Knapp, D. I., 1994: Using Cloud-to-Ground Lightning Data to Identify Tornadic Thunderstorm Signature and Nowcast Severe Weather. *National Weather Digest*, 19, 35-42.

Lang, T. J., and S. A. Rutledge, 2002: Relationships between convective storm kinematics, precipitation, and lightning. *Mon. Wea. Rev.*, 130, 2492-2506.

MacGorman, D. R., and W. D. Rust, 1998: The Electrical Nature of Storms. Oxford Univ. Press, 422 pp.

McCaul, E. W., D. E. Buechler, S. J. Goodman, and M. Cammarata, 2004: Doppler radar and lightning network observations of a severe outbreak of tropical cyclone tornadoes. *Mon. Wea. Rev.*, 132, 1747-1763.

Perez, A. H., L. J. Wicker, and R. E. Orville, 1997: Characteristics of cloud-to-ground lightning associated with violent tornadoes. *Wea. Forecasting*, 12, 428-437.

Schultz, C. J., W. A. Petersen, and L. D. Carey, 2011: Lightning and severe weather: a comparison between total and cloud-to-ground lightning trends. *Wea. Forecasting*, 26, 744-755.

Soula, S., and S. Chauzy, 2001: Some aspects of the correlation between lightning and rain activities in thunderstorms. *Atmos. Res.*, 56, 355-373.

(Received August 14, 2015; revised January 13, 2016; accepted January 13, 2016)