STATISTICS OF LIGHTNING STRIKES TO AIRCRAFT IN WINTER
AROUND KOMATSU AIRBASE, JAPAN

Koichiro Michimoto

Department of Geoscience, National Defense Academy
Hashirimizu, Yokosuka, Kanagawa 239, Japan

Abstract. Statistics of lightning strikes to aircraft were compiled for 255 attacks over the 30 years from 1961 to 1990 in the peripheral area of Komatsu Airbase, Japan. The statistics reveal that most attacks (196) occurred in winter months, from December to February. Furthermore, almost all of the attacks in early to late winter (from November to March) occurred at low altitudes (below 3000 meters) in cloud and liquid and/or solid precipitation. We investigated the relationship between the temporal variations of transmittance near the ground surface and surface electric field when radar echoes passed over our observational sites. It was confirmed that when radar echoes associated with thunderclouds and similar strong convective clouds passed over observational sites, the transmittance reduced quickly and the electric field reached strong negative and positive values in turn. These results imply that lightning strikes occur when aircrafts invade the region of intense electric field at low altitudes created by negative and positive space charges which are accumulated by liquid and/or solid precipitation particles. And we suggest that, when aircrafts penetrate such convective clouds, many lightning strikes to aircraft occur as triggered lightning discharges.

1. Introduction

It is well known that lightning discharges from winter thunderclouds to aircraft and ground have frequently occurred around Komatsu Airbase. Many studies on lightning strikes to aircraft have been carried out in the United States. For example, Mazur et al. (1984; 1986) reported that: 1) lightning strikes to aircraft are caused by aircrafts invading thunderstorms, 2) lightning strikes seem to occur when aircrafts invade dissipating thunderstorms rather than developing or mature ones, and 3) air temperature surrounding the attacked aircrafts is widely dispersed, from 0 to -40°C . Another statistic shows that more than 50 percent of strikes occurred during flight rather than during landings and takeoffs (Lee and Beckwith, 1983). Investigating the air temperature surrounding attacked aircrafts in Japan, Murooka (1986) reported that the air temperature ranges from -10 to $+10^{\circ}\text{C}$ for all seasons and for all of Japan.

On the other hand, in winter over the Hokuriku coastal area including Komatsu Airbase, an interesting statistical correlation is found between the lightning activity associated with the life cycle of radar echoes in winter convective cloud systems and the altitude of the -10°C level over Komatsu Airbase (Michimoto, 1989).

The present article statistically analyzes lightning strikes to aircraft over Komatsu Airbase, mainly in winter, including several case studies and reports the result of analysis for winter by separating it into early and late months (November, December and March, hereinafter referred to as ELM) and midwinter months (January and February, hereinafter referred to as MM).

Fig. 1. Map of the Hokuriku district including Komatsu Airbase and Wajima Aerological Weather Station, including the sferics direction finder antenna sites at Komatsu, Shishiku and Kariyasu.

2. Analytical method and observational results

The statistical analysis was carried out using captain reports from aircrafts landing at or taking off from Komatsu Airbase. Air temperatures at a given time and altitude were derived by linear interpolation from the observed data at Wajima Aerological Station 120 km north-northeast from the Airbase. Statistical aerological data at Wajima were retrieved from the statistics of Rika-nenpyo (1991).

Figure 1 presents a map of the Hokuriku district including Komatsu Airbase and Wajima city. Instrumentations that were used for our observations are as follows:

(1) Weather radar

We used a 3-cm wavelength conventional radar with a transmittance power of 40 kW and an observational range of 60 km. The horizontal and vertical resolution of the stepped PPI echo was about 0.5 km at a distance of 25 km from the radar site. Stepped PPI data were recorded on magnetic tape every 180 seconds at Komatsu Airbase. On the basis of radar echo data obtained by the stepped PPI technique, CAPPI (Constant Altitude Plan Position Indicator) images were delineated from the surface (0 km) to an altitude of 7 km at 0.5-km intervals for winter cloud systems.

(2) Fieldmill

We also used one of the fieldmills composing the network of 27 fieldmills at Komatsu Airbase for surface electric field measurement. The

grounded rotor of the fieldmill had four open sectors and turned at 2000 rpm. Its dynamic range was -40 to $+40$ kV/m, with a minimum resolution of 200 V/m. These fieldmills were positioned at intervals of about 10 km. Data measured at each fieldmill were picked up discretely every 90 seconds and transmitted to the control center in Komatsu Airbase, where they were recorded on magnetic tape. In a previous paper, Michimoto (1990) indicated that, by comparing this discrete data of the fieldmill with analog data measured by point discharge currents, the continuous variation of surface electric fields could be represented fairly well by the plots of the 90-second interval discrete data. Data measured by the fieldmill at Komatsu Airbase were continuously recorded on a chart.

(3) Local sferics direction-finder system

100.5 MHz frequency sferics were received by three antennas of the sferics direction-finder system and recorded on magnetic disk within a radius of about 100 km. The position of individual lightning flashes was determined on the plane map as the intersection of the three direction lines. The three antennas were located at Komatsu, Shishiku and Kariyasu. These locations are shown in Fig. 1.

(4) Air temperature data

Upper air temperatures at a given altitude and time were interpolated from the JMA (Japan Meteorological Agency) routine rawinsonde observations at 0900 and 2100 JST at Wajima Aerological Observatory (Fig. 1), 120 km north-northeast from Komatsu Airbase, while surface weather data were represented by those of Komatsu Airbase.

(5) Transmissometer

A transmissometer was used to measure visibility. This instrument consists of a fixed light projector and a receiver. Light projected at a fixed intensity reaches the receiver either as projected or decreased in intensity in proportion to the amount of visibility-restricting particles in the air between the two points. The receiver translates the light it receives into visibility readings in terms of hundreds of meters. These readings are recorded continuously on a moving chart and are used by meteorological observers for advising pilots of flying conditions. Runway visual range (RVR) measured by transmissometer was used to compare the reduction of surface visibility and the temporal variation of surface electric field.

3. Analytical results

The histogram shown in Fig. 2(a) indicates the distribution of 255 lightning strikes to military or commercial aircrafts around Komatsu Airbase from January of 1961 to December of 1990. It was found that the frequency of lightning strikes is greatest in winter, and in particular in December and January. Winter months (December, January and February) accounted for 77 percent of the total number of such strikes.

Curves in Fig. 2(b) show relative humidity values at 900, 850, 800, 700 and 500 mb obtained from 2100 JST Wajima's routine rawinsonde observations. These statistical results were retrieved from Rika-nenpyou (1991), which contains aerological data for Wajima from 1961 to 1990.

Relative humidity values at 900, 850, 800 and 700 mb, which correspond with the altitude from 1 to 3 km, are very high in the winter season (December through February).

Figure 3 shows that almost all cases occurred below the altitude of 3 km, and that over 50 percent occurred below 1 km, which is the altitude range for aircraft landing and takeoff. As was shown in the table in Fig. 3, over 70 percent of the attacks occurred during take off or landing.

Fig. 2(a). Monthly distribution of the number of lightning strikes to aircraft around Komatsu Airbase from January 1961 to December 1990.

Fig. 2(b). Monthly distribution of relative humidity at 2100 JST at 900, 850, 800, 700 and 500 mb at Wajima obtained by using data from 1961 to 1990 in Rika-nenpyo (1991).

Table 1. Position of lightning strikes in relation to cloud

IN CLOUD	93
BELOW CLOUD	11
BETWEEN CLOUD	1
TOTAL	105

Table 2. Precipitation types during lightning strikes

SNOW SHOWER	37
GRAUPEL	12
RAIN & SNOW	24
RAIN SHOWER	21
NONE	11
TOTAL	105

Fig. 3. Histogram of the number of lightning strikes to aircraft classified by altitudes. At the right side of this figure, there is a classification of flight situations when aircrafts were attacked by lightning strikes.

This result suggests that lightning strikes in winter frequently happen when aircrafts invade cumulonimbus clouds with a very low cloud top altitude over the Sea of Japan and the Hokuriku coastal area.

Of the total 236 cases, tables 1 and 2 show the position of lightning strikes in relation to clouds and the precipitation types for the 105 cases occurring from November to March. These tables were prepared from the captain reports, which completely elucidated the relation with clouds and the precipitation types. Almost all cases were in cloud, and over 90 percent were in solid and/or liquid precipitation.

Fig. 4. Reliable 55 positions of lightning strikes obtained from captain reports. At the top of this figure, there is a table showing the case breakdown in terms of distance from the Airbase for each 10 km interval when aircraft were attacked by lightning strikes.

Fig. 5. Annual variation in the monthly mean temperatures of surface at Komatsu Airbase and of 850, 700, 500 mb at Wajima Aerological Weather Station. (after Komatsu Air Weather Service squadron, 1988)

Fig. 6. The number of lightning strikes in relation to air temperature and altitudes of -10°C level in November, December and March. Open circles indicate the number of times of occurrence.

Fig. 7. Same as Fig. 6, but for January and February. The altitude of 1.8 km can be used to divide the distribution into two groups, G1 and G2. Black circles indicate the number of times of occurrence.

Figure 4 indicates that the 55 attacked positions of comparatively high reliability which are able to be plotted on the chart are distributed within a 30 km radius of Komatsu Airbase. The table in Fig. 4 shows the number of strikes for each 10 km interval. Almost all cases occurred within a 50 km radius of Komatsu Airbase. This implies that it is more reasonable for the statistics to utilize the surface temperature at nearby Komatsu Airbase than that at Wajima. However, we must use the upper air data at Wajima for strike altitudes above 850 mb.

Figure 5 covers the 26 years from January of 1962 to December of 1987, and indicates the trend of 10-day mean temperatures from surface to 500 mb in winter based on JAM routine rawinsonde data (Komatsu Air Weather Service squadron, 1988). Two broken lines divide the winter months into two groups: early and late winter months (November, December and March (ELM)) and midwinter months (January and February (MM)).

Figures 6 and 7 show the statistical distribution for a total of 236 cases: 118 in ELM and 118 in MM. The ordinate of Figs. 6 and 7 indicates the altitude of -10°C at the time of the lightning strikes, and the abscissa, the air temperature at the altitude of the lightning strikes. Both were interpolated from the upper air data at Wajima and the surface data at Komatsu Airbase. In ELM, the -10°C level at the time of lightning strikes ranges fairly evenly from 1 to 3 km. By contrast, in MM, the corresponding level may be divided into two groups, G1 and G2, with reference to the altitude of 1.8 km. Almost all lightning strikes occur when the altitude of -10°C descends below 1.8 km.

Based upon the result that almost all strikes occurred below the altitude of 3 km, we investigated the relationship between radar echoes and temporal variations of surface electric field. An example on 29 January 1991 is presented here.

Figure 8 indicates a CAPPI image at the altitude of 0.5 km obtained at 1142 JST on 29 January 1991 by the weather radar at Komatsu Airbase. Several band shaped echoes were located in the Sea of Japan area, which is northwest from Komatsu Airbase. Echoes moved from northwest to southeast at a velocity of about 30 km/hr. We forecasted from this radar observational result that within about 1 hour, three band shaped echoes would cover and pass over Komatsu Airbase. Actually, at 1216 JST, a lightning strike, which may have been triggered by the takeoff of a commercial aircraft, occurred at 5 km west from Komatsu Airbase. This strike occurred in the second band shaped echo in Fig. 8.

Figure 9 presents an enlarged map of the northeast runway end area of Komatsu Airbase. Radar, fieldmill (FM) and transmissometer (TX and RX indicate projector and receiver, respectively) were located within an approximately 500 meter radius of Komatsu weather observational station (SITE).

Figure 10 indicates the relationship between temporal variations of surface electric field and transmittance (basically equal to Runway Visual Range: RVR) obtained from the FM site and RVR (TX, RX) site in Fig. 9. It can be seen that there is a good correspondence between strong negative and positive electric fields (over 15 to 20 kV/m) and decreased transmittance (less than 80 percent). Furthermore, the duration of both of the aforementioned elements corresponds with the period of radar echo coverage of and passage over Komatsu Airbase (see Fig. 8). The 5 km west strike at 1216 JST is indicated by an arrow. The electric field at the FM site maintained a strong positive value (over 15 kV/m) for about 20 minutes after the lightning strike.

Fig. 8. CAPPI image at 0.5 km obtained at 1142 JST on 29 January 1991 by the 3 cm wavelength weather radar. Echo motion is indicated by an arrow. The radar reflectivity pattern is shown by the contours of 16, 22, 28, 34 and 40 dBZ (starting from the outermost). A band shaped radar echo, which was located 20 km northwest of Komatsu Airbase, approached the Airbase, and a lightning strike to aircraft occurred at 1216 JST in this echo.

Fig. 9. Enlarged map of northeast area of Komatsu Airbase. RVR's TX and RX indicate the transmissometer projector and receiver, respectively. SITE indicates weather observational station of the Komatsu Air Weather Service squadron. FM indicates a fieldmill station of the network of 27 fieldmills. All instruments are located within an approximately 500 meter radius.

4. Discussion

Figure 11, which also appeared in a previous paper by this author (Michimoto, 1989), indicates the relationship among three elements: the radar echo top temperature, the altitude of -10°C , and presence or absence of lightning discharges from those echoes of winter thunderclouds. We found that, if the radar echo top does not exceed the -20°C level (broken line in Fig. 11), no lightning activity occurs from such convective clouds. Furthermore, when the radar echo top exceeds the -20°C level and the altitude of -10°C is above 1.8 km, relatively intense lightning activity occurs. But if the altitude of -10°C is below 1.8 km, there is no or only very weak lightning activity, which is locally called "IPPATSU-RAI" (hereinafter referred to as IPR), (Michimoto, 1989).

Fig. 10. The relationship between temporal variations of surface electric field and transmittance obtained by a fieldmill and a RVR (Runway Visual Range) measuring instrument. A lightning strike to aircraft at 1216 JST is indicated by an arrow.

From the simulations of thunderstorms, Takahashi (1984) pointed out that when the altitude of -10°C descends below 1.8 km, the electrical activity of winter thunderstorms becomes very weak. Furthermore, Takahashi (1987) indicated, referring to his simulation of lightning origins, that lightning discharges occur when the cloud top ascends near the -30°C level in the developing stage of thunderclouds and gradually descends near the -10°C level in mature and dissipating stages, and that the lightning activity near the -10°C level is more intense than that near the -30°C level. But when the -10°C level descends near the cloud base or the ground surface, only very weak lightning activity occurs as mentioned above. Therefore, it can be inferred that lightning strikes may occur when aircrafts invade the cloud top area with an intense electric field in the developing or early mature stage of thunderclouds, and when aircrafts invade the lower layer near the -10°C level with a more intense electric field in the late mature or dissipating stage.

As was shown in Fig. 7, the altitude of the -10°C level can be divided into G1 and G2 with reference to the 1.8 km line, and almost all lightning strikes are found in G2. For the winter thunderclouds in the Hokuriku district, the 1.8-km line is a very interesting factor. In short, intense lightning activities are observed as convective events in a cold front with an upper cold layer northwesterly and lower warm layer southwesterly, but they gradually cease as one proceeds to the layers behind the front due to weakening convective instability. Thus, the altitude of 1.8 km appears during the period of transit from G1 to G2. Takahashi's model (1984) suggests that lightning strikes in G2 are triggered by aircrafts as opposed to being natural lightning discharges (see Fig. 7). The fact that lightning strikes occur more frequently in the dissipating stage than in the developing or mature stage, as pointed out by Mazur et al. (1984; 1986), supports this suggestion.

Fig. 11. Lightning activities divided by the height of -10°C in winter around Komatsu Airbase. Temperature at the top of echoes is indicated on abscissa. When the altitude of -10°C is below 1.8 km (dashed-and-dotted line), convective clouds without lightning discharges (open circles) or with only very weak lightning discharges (black triangles) are found. Convective clouds with lightning discharges (crosses) and convective clouds without lightning discharges (black circles) are found when the echo top temperature is below -20°C (dashed line). (after Michimoto, 1989)

Figures 12(a) and 12(b) present schematic charts of ELM and MM storm examples on 27 December 1988 and on 24 January 1990, respectively, as well as surface data from Komatsu and upper air data from Wajima. In the ELM example, since the -10°C level was near 2.0 km and the sea surface air temperature near the strike was estimated at about 5°C , relatively intense lightning activity occurred in this thundercloud. On the other hand, in the MM example, when the -10°C level was near 1.0 km and the ground surface temperature near the strike was about 0°C , development and dissipation of radar echoes were observed continuously. The 20-to-30 dBZ echoes descended gradually as the storm approached the coast line. At 1630 JST, two minutes before the strike, the echo penetrated inland and graupel particles were observed at the head of the takeoff runway. At 1632 JST, the strike occurred at an altitude of 100 m near the cloud base within graupel particles.

Fig. 12. Upper air temperature and wind velocity profiles at Wajima on 27 December 1988, an early winter day (a) and on 24 January 1990, a midwinter day (b).

These observations together with Tables 1 and 2 show that almost all lightning strikes take place in liquid and/or solid precipitation. Furthermore, as shown in Figs. 8 and 10, strong negative and positive electric fields (over 15 to 20 kV/m) and decreased transmittance (less than 80 percent), which basically may be equated with radar echo coverage and passage, are in very good correspondence. As was mentioned in the former section, a strike occurred in the second band shaped echo and then the surface electric field was continuous strong positive value. Many cases of the correspondence between strong surface electric fields and passage of radar echoes over fieldmill sites have been reported by the same author (Michimoto, 1990 and Michimoto, 1993).

It may therefore be inferred that there is a correspondence between the duration of strong electric fields and radar echoes which cover and pass over a fieldmill site. This suggests a relation between lightning strikes and liquid and/or solid particles, which govern both the distribution of negative and positive charges and the intense negative and positive electric fields in thunderclouds. Tomine et al. (1987) investigated surface electric fields when lightning strikes to aircraft occurred in the Hokuriku district by the same fieldmills network. They reported that, when the electric field exceeded 10 kV/m, the frequency of lightning strikes may increase.

Fitzgerald and Byers (1958) reported that, in large congestus clouds, negative space charges are magnified 10 to 100 times by the generation of solid precipitation. For example, in the preceding MM case, the lightning strike occurred when the aircraft invaded falling graupel particles just after takeoff. It can be inferred that there are many thunderclouds whose electric field is not intense enough to cause natural lightning discharges but has the potential for discharge when triggered by aircrafts in the Hokuriku coastal area in winter.

Table 3 shows statistics on lightning discharges for the total of 847 days (excluding the days of maintenance of the VHF sferics direction-finding system) from January 1983 to March 1990 in the four winter months of December, January, February and March detected from the direction-finding system installed at Komatsu Airbase and its vicinity and several weather observatory sites of JMA, where visual observation of flash-thunder from thunderclouds is routinely carried out.

Table 3. Statistics of lightning strikes to aircrafts and of natural lightning discharge

Statistical period January to March and December of 1983 to 1989 January to March of 1990	847 Days
Number of days with lightning discharge detected by VHF sferics direction finding system	291 Days
Number of days with aircraft lightning strikes	100 Days
Number of days with both aircraft lightning strikes and natural lightning discharge detected by VHF sferics direction finding system	92 Days
Number of days with only aircraft lightning strikes detected by VHF sferics direction finding system	8 Days

Lightning strikes to aircrafts took place in 100 out of the total of 291 days in which lightning discharges were detected. Since lightning discharges and strikes to aircrafts overlap in 92 days, only strikes to aircrafts occurred in the remaining 8 days. In the region around Komatsu Airbase in winter time, lightning discharges occurred once every three days on the average. One third of the lightning discharges struck aircrafts, and about 10 percent were aircraft strikes alone. This suggests that, in midwinter, even if no natural lightning discharges occur, aircrafts invading thunderclouds could possibly be struck by triggered lightning.

5. Conclusions

Previous studies have focused on only air temperature at the altitude of the strike. The present statistics reveal that the air temperature profiles as well as the life cycle stages of thunderclouds are important factors in lightning strikes to aircraft in the Hokuriku coastal area in winter. The conclusions are as follows:

- 1) During midwinter months (MM), lightning strikes to aircraft may be divided into two groups with reference to the altitude of 1.8 km for the -10°C level. Since almost all strikes occur below 1.8 km, it is inferred that strikes are triggered by aircrafts invading the region of intense electric field.
- 2) During early and late winter months (ELM), the -10°C levels at lightning strikes are widely and uniformly dispersed between 1 and 3 km. This result suggests that, first, intense lightning activity is generated by a cold front, and then, when cold air advects to lower parts, the rate of convective instability is low and precipitation particles in thunderclouds or convective clouds may activate the relation between lightning strikes and liquid and/or solid particles, which govern the distribution of negative and positive charges and generate intense negative and positive electric fields.
- 3) The correspondence between radar echoes covering and passing over the fieldmill and the appearance of strong electric fields is confirmed by many observational results. This implies that strong negative and positive electric fields may be generated by precipitation particles associated with radar echoes in low altitude below thunderclouds or convective clouds.
- 4) It can be inferred that, in midwinter, even if no natural lightning discharges occur, aircrafts invading thunderclouds or convective clouds can trigger lightning strikes ("IPR") to them.

There is a need for further research of winter thunderclouds and convective clouds in order to avoid lightning hazards in winter time.

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