Lightning Strikes to an Airplane in a Thunderstorm

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The analysis of radar echoes from lightning at the moments of strikes to the NASA Langley Research Center's F-106B instrumented airplane proves that the airplane itself triggers the lightning, rather than intercepting naturally occurring flashes. In 1982 the UHF band radar at the NASA Goddard Space Flight Center/Wallops Flight Facility was used to guide the F 106B through the upper regions of thunderstorms so that the airplane might be struck by lightning. The UHF band radar data was analyzed to determine the nature and characteristics of direct lightning strikes to the airplane, and the airborne data was used to document the environmental con ditions favorable for such strikes The echo characteristics of the strikes were similar to those of intracloud flashes, and indicated that most of the time the airplane was part of the lighting channel. The probability of a direct strike to the F-106B during storm penetrations (PDS) is defined here as the ratio of the number of direct strikes to the airplane to the total number of flashes occurring in the radar resolution volume containing the airplane Correlations between the PDS and the intensity of rain, the intensity of turbulence, the ambient temperature, and the lightning flash rate in the storms penetrated were obtained The correlations indicated that the highest risk for the F-106B to be struck by lightning during penetrations in the upper regions of thun derstorms occurred under the following conditions: 1) ambient temperatures of −40 C and colder; 2) negligible to light precipitation; 3) negligible to light turbulence; and 4) lightning flash rates of < 10 per minute

Introduction

CLOUDY weather conditions during airplane flights can be divided into two categories: nonelectrically active, nonstormy clouds which are considered to be "safe" (low probability of a lightning strike to a penetrating airplane), and electrically active storms which are considered to be "risky" (high probability of a lightning strike)

A large amount of data has been collected on lightning strikes to commercial and military airplanes flying in non stormy clouds The circumstantial evidence in this data, including synoptic conditions and radar observations, has strongly suggested that the nonstormy clouds in which the airplanes were struck had no previous lightning activity; therefore, the direct strikes were triggered by the airplane itself[1] Several reports[2 3 4,5] have shown that the most probable region for such strikes in nonstormy clouds is at or near the freezing level (0°C)

Data on strikes to airplanes in storms has been rather limited due to the understandable avoidance of stormy weather by commercial and military aviation, and the fact that there are few research programs equipped with aircraft which have been specially protected for storm penetrations

In this study, the following questions pertaining to light ning hazards in stormy clouds are addressed: 1) Does the airplane penetrating the storm trigger the lightning flash, or does it intercept a naturally occurring lightning channel? 2) What are the characteristics of the lightning strikes to the airplane as sensed by a radar? 3) What are the environmental conditions in the storm which lead to a direct lightning strike?

In this report, some results of the NASA Storm Hazards Program conducted in the summer of 1982 near Wallops Island, Virginia, are described. The emphasis is on radar echo parameters of direct strikes to the NASA Langley Research Center F 106B instrumented airplane, and on the conditions under which the airplane was struck as determined by the ground based UHF-band radar and the onboard in strumentation in the F-106B

Experimental Procedure

Instrumentation from the Atmospheric Sciences Research Facility at NASA Wallops Flight Facility, Wallops Island, Virginia, was used to provide guidance to the F 106B during storm penetrations The facility includes a UHF band radar with beamwidth of 2 6 deg and an S band radar (SPANDAR) with a beamwidth of 0 4 deg Both radars have "pencil" beam patterns and are capable of tracking airplanes The UHF band radar was used to obtain the range, azimuth, and elevation angle of echoes from ionized lightning channels An echo transient counter was designed to count the number of lightning echoes in a selectable range interval along the radar beam This device allowed the estimation of the lightning flash rate in real time This data and the storm's precipitation structure observed with the SPANDAR prior to and between storm penetrations were used to select the storm of interest and the desired altitude for the next penetration The course of the airplane was chosen on the basis of the conception that storm regions containing the greatest lightning activity were the ones in which the F-106B would most likely be struck.

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Therefore, the F 106B was sent into the upper centers of lightning flash density located usually above 10 km altitude as opposed to lower centers located usually lower than 8 km altitude [6] These locations were determined with the UHF band radar Flying through the upper center of lightning flash density presented less risk that the airplane would encounter hail

The method outlined above of guiding the F 106B with the SPANDAR and the UHF band radar has proven to be very successful During 44 penetrations made with this method in the summer of 1982, the F 106B was struck 49 times Previously during the 1981 season, without the use of the UHF band radar, out of 111 penetrations the F 106B was struck only 10 times [7] In each of the 49 confirmed direct lightning strikes to the F 106B, while it was being tracked by the UHF band radar, a lightning echo was recorded The radar detection of lightning echoes coincided well with visual observations of flashes by the flight crew

Results

Lightning Strikes Triggered by the Airplane

The development of echoes from lightning flashes that struck the airplane has been analyzed with a time resolution of 16 7 ms The size of the UHF band radar resolution volume determines the spatial accuracy of radar measurements. This truncated conical shaped volume has a depth along the radar beam equal to 150 m (a result of the transmitted pulse width of 1 μs), and a diameter equal to the beamwidth at a given range *R* (about 0 042 *R* for the radar used) Because the UHF band radar is "slaved" to the tracking radar, and thus has the airplane inside its antenna beam, any lightning flash that occurs within the radar resolution volume containing the airplane has an echo which coincides with that of the airplane

From the data obtained in 1982, every echo from a lightning strike to the F 106B started directly on top of the air plane echo and propagated outward Figure 1 shows a typical example of such echoes If the strike to the airplane had been caused by a naturally occurring flash, i e., by the airplane intercepting a flash, an observor would have seen 1) the echo appear in the radar beam at some distance from the airplane, 2) the progression of this echo toward the airplane, and 3) the lightning echo reaching the airplane's location at the instant of the strike However, none of the lightning flashes with this pattern of echo development (Fig 2), which is typical for the naturally occurring intracloud flash, ever struck the F 106B Thus, the UHF band radar data of direct strikes in stormy clouds strongly suggests that they were triggered by the air plane itself

The question remained as to whether there was a possibility that the radar would not detect the lightning channel as it approached the airplane Only when the lightning channel approaches the airplane perpendicularly to the radar beam is the progression of the lightning echo toward the airplane not observed. In this circumstance the length of the lightning echo would be no longer than 150 m There occurred only one instance of a lightning strike to the F 106B with an echo as narrow as 300 m That echo was also the shortest in duration (160 ms) In all other cases, echoes of strikes to the airplane had considerable radial extent Since the spatial orientation of naturally occurring lightning channels is independent of the azimuth angle of the tracking radar, the probability of a lightning channel approaching the airplane not being seen on the radar is considered small

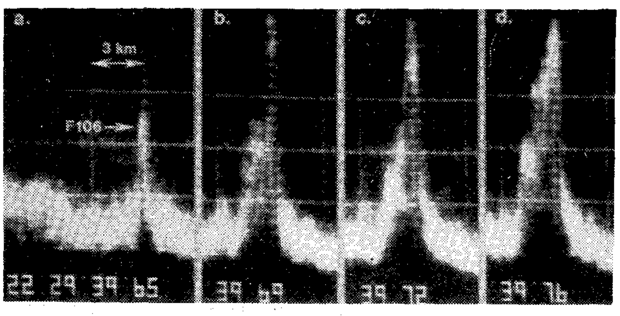


Fig 1 Radar echo development of a direct strike to the F 106B Photographs are made from a TV screen in sequence with time resolution of 30-40 ms Note the buildup of lighting echo above the airplane echo; this is typical of direct strikes

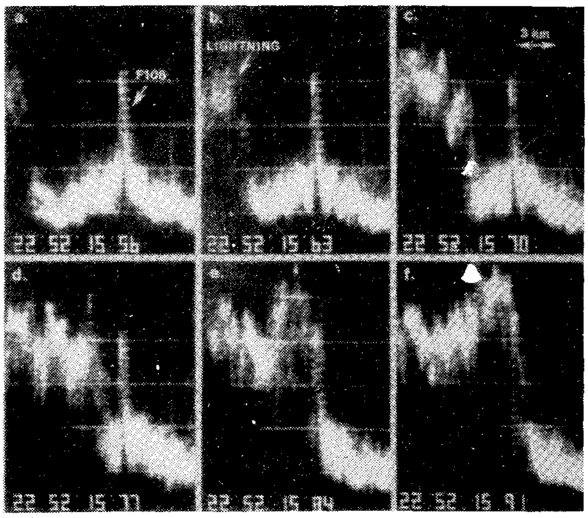
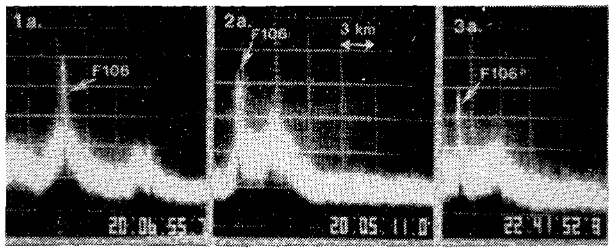
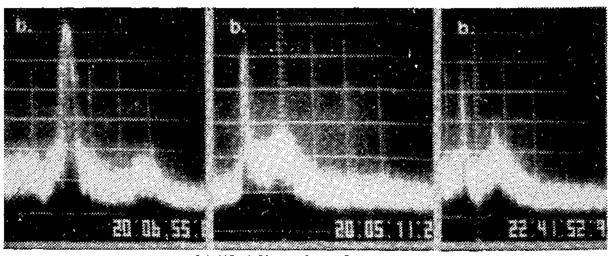


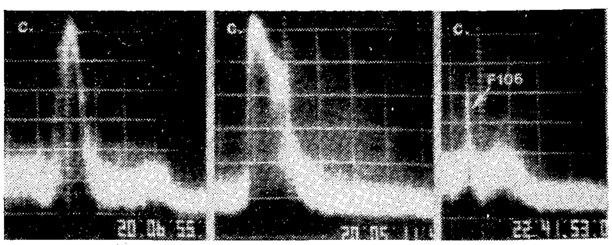
Fig 2 Radar echo development of a lightning flash propagated in space which passed near the F-106B without striking it The lightning echo appears at the left side of picture *a*, and propagates toward the right (pictures *b-f*), with an average radial velocity of 2 2 x 10^5 m/s^{-1}



a) Bidirectional type (most common)



b) Unidirectional type



c) Stationary type (rare, usually of very short lifetime).

Fig 3 Range development of echo from lightning strikes to the F 106B

Circumstantial evidence of the triggering of strikes by the airplane in nonstormy clouds[1], together with evidence ob tained from the UHF-band radar data in stormy clouds leads to the conclusion that strikes to the airplane in both stormy and nonstormy clouds are initiated by the airplane This agrees with the hypothesis of Kasemir[8], who also suggested that the triggered lightning is always preceded by a visually observable corona discharge This view is not supported by the F 106B flight crew's reports of visually observed direct strikes or by motion pictures of such strikes made with a 16-mm movie camera running at a speed of 14 frames per s (strikes always occurred abruptly and without visible corona discharge) However, additional observations aimed at corona measurements are needed

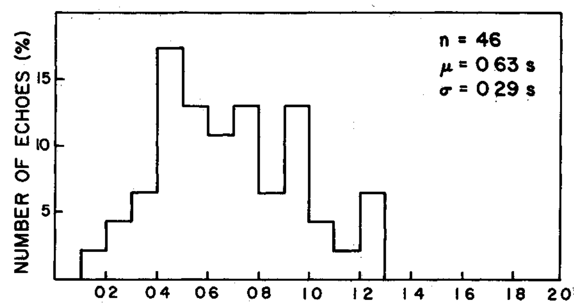
Echo Characteristics of Direct Strikes to the F 106B

At the moment of a direct strike, the radar echo represents a superimposition of two returns, one from the F 106B, and the other from the lightning channel (see Fig 1) The radar cross section (RCS) of echoes from the F 106B alone were always at least 20 dB less intense than those from lightning flashes at the moment of a strike, so that the F-106B's contribution to the RCS of a direct strike is insignificant The maximum RCS, echo duration, and range-time variation for each direct strike to the F 106B have been analyzed. The range-time variation of echoes has been characterized by their continuity in time, and by their development along the radar beam

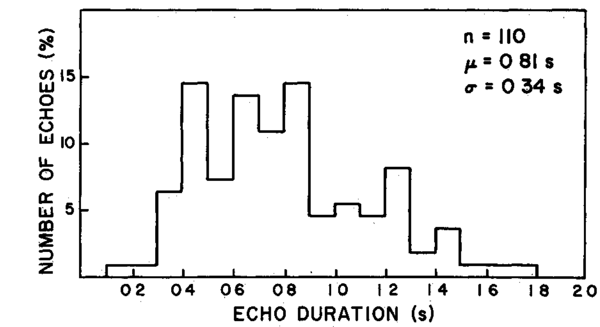
All direct strikes had a single echo Three different types of development were identified (see Fig 3): 1) bidirectional type, with simultaneous progression in both directions from the airplane, 2) unidirectional type, with movement in only one direction from the airplane, and 3) stationary type, with no movement Bidirectional echo development occurred in 79% of direct strikes

The similarities between direct strikes to the F 106B and naturally occurring flashes were also investigated Most of the nearby flashes are believed to have been intracloud (IC) due to the high altitudes at which they were observed There was no apparent difference found between the RCS of the naturally occurring IC flashes and those of direct strikes Also, the durations of both types of echoes, as shown in the histograms in Fig 4, were not significantly different, based on a statistical t-test of the means of the two populations of echo durations A difference was found, however, between the range development of direct strike echoes and IC flash echoes Frequently, the echo from an IC flash moved along the radar beam in a wavelike manner with the maximum RCS at the crest (Fig, 2) On the other hand, 85% of the direct strike echoes had their maximum RCS at the precise location of the F-106B, while the echo itself propagated uni and bi-directionally in range A lightning echo that begins and continues to have a maximum RCS at the airplane indicates that the airplane remains a part of the lightning channel during the entire flash A possible explanation for this might be that the highly conductive airplane body maintains the ionization during direct strikes The 630 ms average echo duration of direct strikes (Fig 4) and the fact that the maximum RCS coincided with the F 106B location during the flash development indicates the possible presence of con tinuous current flow to the airplane Observation of con tinuous current was reported in an earlier French study[9], based on measurements of the current on the airplane skin.

Lightning flash length was also estimated by the maximum extent of their echoes The lengths of direct strike echoes and those of IC flashes (Fig 5) were not statistically different Thus, based on the UHF band radar measurements the flashes encountered by the airplane penetrating upper regions of thunderstorms were not much different from naturally occurring IC flashes. This conclusion supports the hypothesis suggested by Clifford and Kasemir[1]

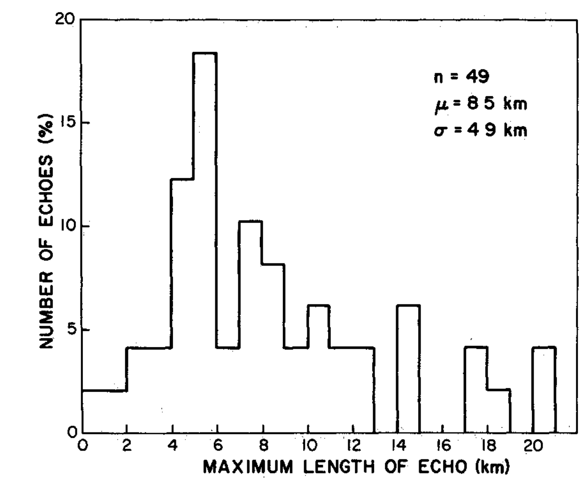


a) Direct lightning strikes to the F 106B measured at the airplane

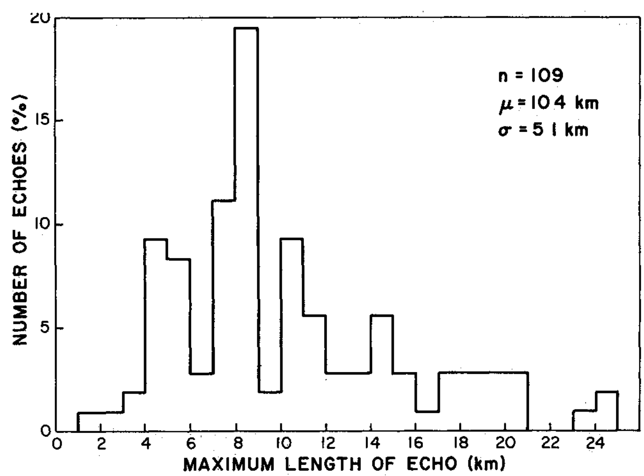


b) Naturally occurring lightning flashes at high altitudes (presumed to be mostly intracloud)

Fig 4 Histograms of radar echo duration



a) Direct lightning strikes to the F 106B



b) Naturally occurring lightning flashes in the vicinity of the F 106B (presumed to be mostly intracloud)

Fig 5 Histograms of radar echo lengths

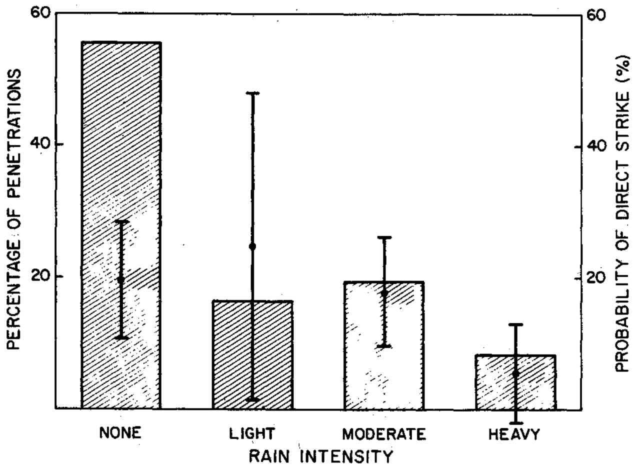


Fig 6 Rain intensity in penetrated storms and the probability of direct strike The total number of penetrations is 36 The shaded columns are the percentage of all penetrations made vs the level of rain intensity reported by the flight crew during penetration Dots are the average probability of direct strike Vertical bars are the 90% confidence intervals

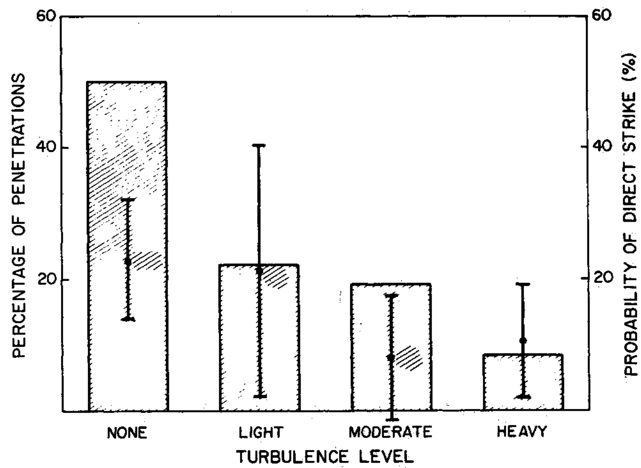


Fig. 7 Level of turbulence within the penetrated storm and the probability of direct strike The total number of penetrations is 36 The shaded columns are the percentage of all penetrations made vs the level of turbulence reported by the flight crew during penetration Dots are the average probability of direct strike Vertical bars are the 90% confidence intervals

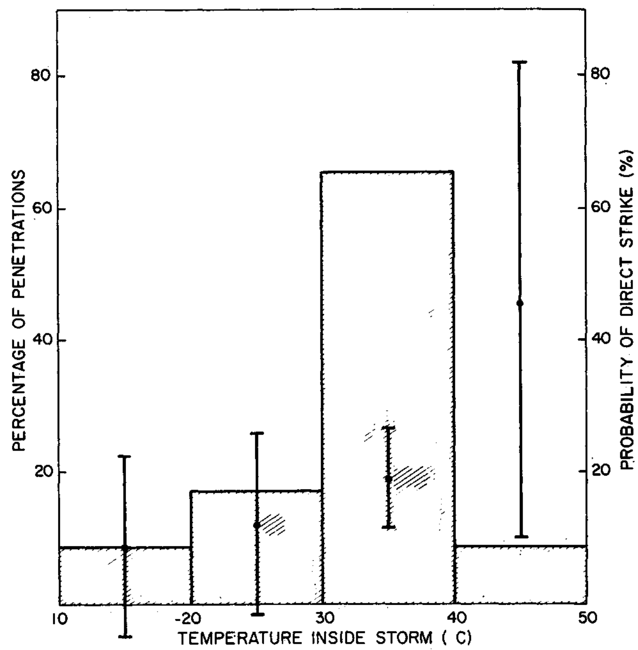


Fig 8 Temperature inside the penetrated storms and the probability of direct strike The total number of penetrations is 35 The shaded histogram is the percentage of all penetrations made vs the ambient temperature during the penetration Dots are the average probability of direct strike Vertical bars are the 90% confidence intervals.

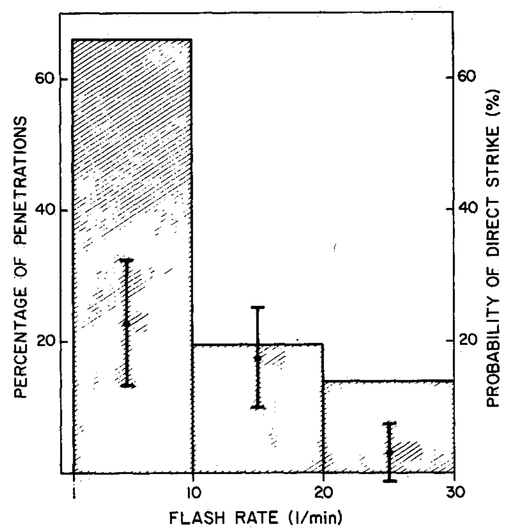


Fig 9 Lightning flash rate in penetrated storms and probablity of direct strike The total number of penetrations is 36 The shaded histogram is the percentage of all penetrations made vs the flash rate during the penetration Dots are the average probability of direct strike Vertical bars are the 90% confidence intervals.

Environmental Conditions Leading to Direct Strikes

In determining the conditions for direct strikes to the F 106B, environmental parameters such as precipitation, turbulence, ambient temperature, and lightning flash rate in penetrated storms, as well as the number of direct strikes during such penetrations, were considered In addition, the risk factor for a direct strike to the F-106B was determined This factor, called the probability of a direct strike (PDS) while penetrating a storm, is defined as the ratio of the number of strikes to the F 106B to the total number of lightning flashes in the radar resolution volume which contains the airplane The concept of PDS was first introduced by Fitzgerald[10] In his PDS, however, Fitzgerald used the total number of flashes in the whole storm as a parameter of lightning activity, as determined from electric field changes recorded on a second airplane which was flying above the storm As other recent studies[6,11] show, the lightning activity in some storms (including the types penetrated in this study) tends to have in its mature stage two centers of lightning flash density separated in altitude (the upper and the lower) It seems reasonable, therefore, to include in the PDS only those flashes which occur in the close vicinity of the airplane

Whenever possible, the beginning and the end of penetrations were identified as the moment the F 106B echo entered the precipitation reflectivity core (as indicated by the UHF band radar) and the moment it exited the core, respectively When this was not possible, the crew's visual observations were used to find these times In most cases penetration through a single storm cell lasted less than 1 5 min During two of the 38 penetrations, the UHF-band radar detected no lightning activity in the storm prior to penetration, and the direct strikes to the F 106B were the only lightning flashes which occurred In the remaining 36 cases, the UHF band radar indicated lightning activity prior to penetration Only these cases were considered for analysis.

Because of the small number of penetrations analyzed here, the results presented are not conclusive, but rather, are in dicative of trends in the relationship between the PDS and environmental parameters Figure 6 shows that the PDS is similar for storm regions containing negligible or light-to-moderate precipitation, but that it decreases considerably in heavy precipitation The PDS also tends to decrease with increasing turbulence, as seen in Fig 7 Although the flight crew's visual estimates of the relative precipitation and turbulence intensities may not be reliable, especially in distinguishing between light and moderate levels, the trend mentioned above is very noticeable when comparing the PDS in negligible to heavy intensities of precipitation and turbulence The histogram in Fig 8 shows that the PDS increases steadily with decreasing ambient temperature The greatest PDS lies within a range of ambient temperatures between -40° and 50°C The observations that the highest lightning strike rate occurs at the 40°C level agree with those by Fitzgeral,[9] and Fisher and Plumer [7]

The flash rates in the penetrated storms were also examined From the histogram in Fig 9, it may be seen that the average PDS in storms with a flash rate of >20 per min is very low, while the PDS in storms with a rate of <10 per min is much higher This discovery, which may at first seem paradoxical, is perhaps a manifestation of principal interrelationships between lightning initiation (natural and by the aircraft) and electrical forces which support the development of lightning in a thunderstorm No specific interpretation of this observation can be offered at the present time

Conclusion

The results of the 1982 Storm Hazards Program led to the following conclusions

1. The analysis of lightning echoes from direct strikes to the F 106B in thunderstorms strongly suggests that lightning strikes are triggered by the airplane

2 Direct lightning strikes to the airplane closely resemble intracloud flashes in their radar characteristics.

3 The greatest probability of a direct strike to an airplane of the F-106B type in the upper portions of a thunderstorm occurs in regions where the ambient temperature is 40°C or colder, where turbulence and precipitation intensities are negligible to light, and where the lightning flash rate is <10 flashes per min

Acknowledgments

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