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# ASSESSMENT OF LIGHTNING THREAT TO NORTH SEA HELICOPTERS: FINAL REPORT

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# ASSESSMENT OF LIGHTNING THREAT TO NORTH SEA HELICOPTERS: FINAL REPORT

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## Foreword

Following the accident to an Aerospatiale AS332L Super Puma in January 1995, which resulted from a lightning strike to the carbon composite tail rotor blades, it was suggested that the lightning strike threat in the North Sea is more severe than might be expected in most other parts of the world. A precise understanding of this threat level was required in order to ensure that the protection afforded by the current design requirements is adequate under all operating conditions likely to be incurred by UK registered aircraft.

AEA Technology was awarded a contract to investigate the lightning threat to helicopters operating in the North Sea. EA Technology and the Met. Office also participated in the study. They were also tasked with assessing whether the meteorological conditions prevailing at the time of the strike were significant to the probability of a strike occurring.

Assessments were made of the variation in Strike Polarity Distribution for the North Sea and the meteorological conditions determined for strikes to helicopters as reported by the Mandatory Occurrence Reporting system.

This report has been prepared by AEA Technology and a further report CAA Paper 99008 on the study has been prepared by the Meteorological Office.

# Contents

# 1 INTRODUCTION

Recent strikes to helicopters in the North Sea suggest that the lightning threat to aircraft in this region is higher than presently accepted certification levels. The aim of this project was to assess whether existing lightning strike data in this region support this supposition and whether there is anything unusual about the meteorological conditions in the North Sea area that would give rise to these enhanced threat levels.

The contract is based on the proposal issued to CAA (See report [A] in Section 8), in which detailed objectives were defined. This report describes the outcome of the various work packages. Section 2 describes the background to the study in more detail. Sections 3 and 4 report results from the lightning strike data study and meteorological study respectively. Section 5 reviews some pertinent literature and makes some speculations on the reasons for the predominance of winter incidents and Section 6 summarises the main results from the study.

Several reports were issued during the course of the project. Important results were provided through subcontracts to EA Technology and the Met. Office. Results from these reports are discussed and they are referred to as [A], [B], etc. to distinguish them from references noted as [Reference 1], [Reference 2], etc. The references and reports are listed in Sections 7 and 8 respectively.

# 2 GENERAL BACKGROUND TO THE PROJECT

On 19 January 1995 an Aerospatiale AS332L Super Puma was struck by lightning near an oil platform in the North Sea, resulting in the helicopter ditching into the sea. Results of the subsequent investigation by the Air Accidents Investigation Branch were published in September 1997 [Reference 1]. Some damage and mass loss was sustained by one of the tail rotor blades; the ensuing severe vibration resulted in cyclic overstressing of the gearbox attachments, ultimately resulting in complete detachment of the tail rotor gearbox assembly. It transpired that the blades had been certificated to an earlier lightning test standard and consequently were not proven to withstand the effects of a severe lightning strike as specified in more recent standards. Nevertheless, to recreate in simulated lightning tests the same damage on the blade that occurred in the incident, more severe energy levels than the standard severe threat were required.

As well as this catastrophic incident, other strikes to helicopters have occurred, resulting in costly repair and maintenance. Therefore the helicopter operators and the CAA are very concerned about the possibility of strikes in the North Sea. Their concerns include:

- Are the existing Lightning Certification Levels adequate, in particular for helicopters operating in the North Sea?
- What are the electrical and meteorological conditions during North Sea storms?
- Are there tools that could be used to avoid regions where the helicopters might be struck?

As noted in the introduction, this project approaches these questions respectively by reviewing available lightning strike data in the UK area and by looking at the prevailing meteorological conditions at the times of recent strikes. The operators have also investigated the possibility of using electric field data/lightning activity data in real time for the avoidance of strikes but this is outside the scope of the present study. In the following subsections of Section 2 background material to the incidents in the North Sea, the lightning threat and conditions for aircraft strikes are given.

## 2.1 Helicopter Incidents in the North Sea

Early surveys in the United Kingdom suggested that helicopters were unlikely to be struck by lightning. No strikes had been recorded over 168,000 flying hours. A more recent study undertaken by the Culham Lightning Club using data received from some operators gave 1 strike every 7000 flying hours ($1.4 \times 10^{-4}$/hour). The null strike rate of the earlier study is presumed to be due to the flight envelope of the aircraft involved; not all helicopters can operate in IFR conditions. Recent anecdotal evidence from operators suggested that the Super Puma was particularly susceptible to being struck.

A more recent database compilation at the CAA has some 46 events from 1978 to 1996; these and other data give strike rates as shown in Figure 1 and Table 1. The mean rate over all helicopter strikes is one every 45,000 hours; the highest rate is for the BV234 (Chinook) at one every 6000 hours; the Super Puma has one every 27,000 hours. Given that the average rate for fixed wing aircraft in Europe is about one incident every 2100 flying hours and assuming that all the strikes (even those not requiring any maintenance) have been included in the sample, then the strike rate to helicopters in the North Sea is actually very modest. The perceived susceptibility of the Super Puma is thus probably related to the consequences of the strike rather than to its actual frequency.

**Table 1 Lightning Strike Rate Per Hour by Aircraft Type**

| Aircraft | Hours | Strikes | Rate Per Hour |
|---|---|---|---|
| BV 234 | 35,338 | 6 | 1.7E-04 |
| AS332 | 574,096 | 21 | 3.7E-05 |
| Chinook (mil) | | | 3.2E-05 |
| S61N | 723,563 | 17 | 2.3E-05 |
| AS330 (mil) | | | 1.0E-05 |
| Sea King (mil) | | | 6.4E-06 |
| Bell 212 | 158,898 | 1 | 6.3E-06 |

The strikes were often in light turbulence and icing in or around cloud, with an Outside Air Temperature (OAT) around 0°C, and in light precipitation. Cumulonimbus clouds were usually present in the general area. The cloud base in general for these strikes was quite low.

These other data are presented in Figures 2 to 4, showing recorded OAT, altitude and month of strike. Figure 4 is very dramatic showing that all strikes occur in the winter months from October to April when the number of storm days is much lower than in the summer months; this suggests that the helicopters may be triggering the lightning strikes. The OAT varies from -4°C to +3°C; the altitude of strike is at or below the cruising altitude of 5000ft. This is quite different to the situation for fixed wing aircraft, as can be seen from Figure 5 [Reference 2] which shows a survey of altitude of strikes to transport aircraft. However, this may not be as significant as first appears as the flight envelope for helicopters precludes them from flying high. Nevertheless it would appear that the strikes occur near the cloud base around the 0°C line. The implications of this are discussed further in Section 2.3.

## 2.2 Lightning Threat Levels

Natural lightning strikes can occur both inside cloud formations and from cloud to ground; whilst most strikes are inside the cloud most statistical knowledge relates to cloud to ground strikes and these have more severe energy content than intracloud strikes.

Records of civil airliner strikes accrued by reporting schemes in the USA and Europe during the 60's and 70's showed that many strikes to aircraft occur in cloud. It is believed that most of these aircraft strikes are initiated by the presence of the aircraft itself in the cloud electric field. Instrumented aircraft have been flown into clouds during NASA and French research programmes in the 1970's. Above 7km the strikes are exclusively intracloud. Below 7km, 25% of the aircraft initiated strikes can develop into cloud to ground strikes. A limited number of aircraft initiated strikes of any type were recorded and the maximum current value was 54kA.

However some strikes to aircraft also occur below the cloud and these can involve cloud to ground strikes. Statistics on natural cloud to ground strikes have been used to formulate the severe strike threat. The data sets used are those of Cianos and Pierce [Reference 3] for negative strikes and Berger et al [Reference 4] for positive strikes taken from instrumented towers. The Cianos and Pierce data are mean values from several different sources.

The strike rate to ground depends on local topographic and meteorological conditions. In the UK the rate is up to several cloud-ground strikes per square km/annum (isokeraunic rate). It has also been assumed that most of these are negative polarity cloud to ground strikes whose parameter probability levels are shown in Table 2. It has been assumed that globally about 10% of all strikes to ground are positive strikes; although rarer, they can have more severe parameters (see Table 3).

**Table 2 Relationship between Parameters and Probability for Negative Flashes**

| Parameter | Units | Probability of Exceeding Parameter Value | | |
|---|---|---|---|---|
| | | 20% | 10% | 2% |
| Peak Current | kA | 50 | 100 | 200 |
| Maximum di/dt | kA/μs | 70 | 80 | >100 |
| Impulse Charge | C | 5 | 9 | 22 |
| Total Charge | C | 50 | 80 | 200 |
| Action Integral | $10^6 A^2 s$ | 0.08 | 0.19 | 0.7 |
| Duration | ms | 300 | 500 | 800 |

**Table 3 Relationship between Parameters and Probability for Positive Flashes**

| Parameter | Units | Probability of Exceeding Parameter Value | | | |
|---|---|---|---|---|---|
| | | 38% | 18% | 11% | 8% |
| Peak Current | kA | 40 | 100 | 140 | 200 |
| Maximum di/dt | kA/μs | 4 | 10 | 15 | 20 |
| Impulse Charge | C | 24 | 60 | 100 | 120 |
| Total Charge | C | 100 | 200 | 300 | 350 |
| Action Integral | $10^6A^2s$ | 0.9 | 3.5 | 7 | 11 |
| Duration | ms | 120 | 250 | 350 | 420 |
| Front Time | μs | 30 | 70 | 111 | 120 |

Direct effects damage is caused by Joule heating and arc root damage which are primarily dependent on the action integral and total charge transfer parameters respectively. In the aerospace community weighted averages of the two sets of levels taking into account their relative frequency have resulted in the present test standard of 200kA with $2 \times 10^6A^2s$ and 200C for action integral and charge transfer respectively.

The cumulative frequency of occurrence of strikes against energy level follows a log-normal distribution which results in a straight line when plotted on probability-log paper. The data used for the tables are shown in this form in Figure 6 extracted from Reference 2. It can be seen that for an action integral of $2 \times 10^6A^2s$ (J/Ω) the probabilities of exceeding this value are .5% and 30% for negative and positive strikes respectively. Hence, assuming 10% of strikes are positive:-

1000 strikes comprise 900 negative; of these .5% exceed $2 \times 10^6A^2s$ i.e., 4.5 strikes
and 100 positive; of these 30% exceed $2 \times 10^6A^2s$ i.e., 30 strikes
Therefore total number of strikes with action integral exceeding $2 \times 10^6A^2s$ = 34.5
**= 3.45%**

Because positive strikes are more severe in terms of the Direct Effects they have more weight in determining the percentage figure. If positive strikes were disregarded the percentages for 200C and $2 \times 10^6A^2s$ would be 2% and .5% respectively (see Table 2 and Figure 6). It is sometimes loosely stated that the present threat is at the 2% level. The actual % level depends on the weighting given to the positive strike content. The 2% level is only precisely true for the charge transfer for negative strikes.

If positive strikes are more frequent, say 40% of all events, then the percentages exceeding 200C and $2 \times 10^6A^2s$ would be 8.4% and 15% respectively.

Assuming 10% of strikes are positive, the above analysis shows that the present standard would cover about 96.5% (100% – 3.45%) of cloud to ground strikes for the action integral parameter.

Other world data occasionally show high percentage positive content. For example, in the USA, Florida has the highest incidence of storms but shows less than 3% positives, whereas the Pacific North West region shows over 25% positives [Reference 5].

The key to assessing the threat for the North Sea would seem to be the determination of the relative occurrence of positive and negative strikes and the threat levels associated with the different polarities of strikes in that region.

A method of determining strike magnitudes and polarities is to measure the associated magnetic field, which is proportional to current, remotely from the strike. This has the advantages of accumulating high statistics and avoiding the influence of the tower in instrumented measurements. However, the interpretation of the measurements is more difficult – the calculation of the current depends on a model and makes several assumptions. Nevertheless a recent French study [Reference 6] claims a self consistent data set, which is not inconsistent with Berger's tower data for negative strikes, and hence claims that its high statistics data for positive strikes are valid. It concludes that there are many positive cloud to ground strikes exceeding 200kA (see Figure 7). Positive strikes are generally of much longer time duration than negative strikes and consequently for the same peak current have much bigger action integrals; hence the French study would suggest many positive strikes exceeding $2 \times 10^6 A^2 s$ action integral.

EA Technology Limited have installed a similar mapping system for cloud-ground strikes based on a three orthogonal element detection system at six outstations in the UK. Results from this system are presented in Section 3.

The EA Technology study has been restricted to assessing the polarity of the strikes since there is some uncertainty in the EA Technology algorithm used for the determination of peak current amplitude; it assumes a particular spectral content for the lightning impulse. It is believed that the algorithm used may overestimate the peak current amplitude of positive strokes.

## 2.3 Conditions for Lightning Strikes to Aircraft

The altitude of the helicopter strikes noted in Figure 3 and Section 2.1 compared to the histogram for fixed wing aircraft in Figure 5 shows that whereas fixed wing aircraft are more often struck at moderate altitudes at about 12,000 ft in cloud, the fixed ceiling of helicopter flight operations means that they are struck at relatively low altitudes, possibly below the cloud base. At the moderate altitudes within the cloud where fixed wing aircraft are often struck, the charge structure in summer clouds is optimum for creating a large ambient electric field at the aircraft. This tends to result in corona discharges from the aircraft extremities which can develop into a triggered lightning strike. Generally below the cloud, the ambient field is insufficient to cause triggered lightning and strikes at these lower altitudes could result from the interception of a naturally occurring cloud to ground lightning strike. As noted in Section 2.2 these types of lightning strike are much less frequent but are believed to be more severe than the intracloud variety. Also it is believed that the energy in the cloud to ground strike is higher the nearer to ground the strike intercepts the aircraft.

Data on fixed wing aircraft (see histograms for USA/Europe in Figure 5) show only 1 in 20 strikes below cloud and below 5000ft. Assuming a similar strike rate to helicopters whose flight profile restrict their altitude to similar levels implies the strike rate will be 1/20 of one incident every 2100 flying hours (average fixed wing) or one every 42000 flying hours. This predicted rate is not dissimilar to the observed rate for helicopters in the North Sea. Hence the strike rate is not at all anomalous compared to other aircraft. Moreover, fixed wing civil aircraft spend much less time at these low altitudes during climb and descent.

Another feature noted in Section 2.1 was the fact that the OAT is clustered around the 0°C value (Figure 2). This is generally the case for both civil and military aircraft strikes. For example a recent Japanese survey [Reference 7] has strike rates higher in the winter months too but a significant number in summer. Over 25% of the aircraft strikes were at an altitude of less than 1km during climb or descent, and inside the cloud, particularly in winter. Some 86% of events are within OAT's of ±10°C (see Figure 8a). A survey of UK military incidents [Reference 8] also has 80% within ±10°C (Figure 8b). This is sometimes taken as indicating that aircraft more easily trigger lightning in the presence of wet ice. Indeed Reference 9 the FAA Aircraft Lightning Protection Handbook quotes pilots anecdotal evidence on avoidance of lightning strikes: 'climb or descend through the freezing level as quickly as possible'.

A specific study of the electric field values necessary to trigger a strike on a Super Puma has been undertaken in the FULMEN programme [Reference 10]. Figure 9 shows the typical charge distribution within a typical summer storm cloud used for the calculation. Figure 10 shows the resultant electric field contours. Supplementary calculations showed that the value of ambient electric field value required for the Super Puma to initiate a triggered lightning strike was about 150kV/m. Such fields are encountered only above 4km or 12000ft, well above the cruise altitude of the helicopters. Hence for typical summer clouds the helicopter will not be able to trigger a lightning strike, it will have to intercept a naturally occurring strike. For winter storms the freezing level is much lower and charge separation and accumulation can occur at lower altitudes, possibly allowing triggering. This is certainly the case for Japanese winter storms where the negative charge centre is at about 3km; 3 times lower than in summer. It is alleged that the charge centres in winter are at the same temperature levels as in the summer months, being -10°C for the negative charge centres [Reference 11].

To conclude:

- All recorded strikes to helicopters in the North Sea occur in the winter months when the natural lightning activity is expected to be lowest, implying that the helicopter triggers the strike. This is confirmed by the results of the actual cloud to ground strike rates in winter and summer described in Section 3.

- Typical charge distributions for summer storm clouds will not result in triggered lightning for moderate sized helicopters flying below 5000ft., which taken with the previous point implies that the winter thunderclouds are quite different in terms of the height of the charge centres. Such differences would be expected to show up in the Meteorological study [F]. No obvious feature was found in the winter storms other than lower temperature (see Section 4). The freezing level is probably quite important for charge generation and separation, as the presence of ice crystals and graupel will be necessary. Because of the lower temperature these can occur at lower altitudes in winter and thus should create the charged regions at a lower altitude. The triggering process may also be most efficient at about 0°C ±10°C.

- The actual frequency of strikes per flying hour is not dissimilar to average rates for fixed wing aircraft flying at similar altitudes in Europe, and therefore the helicopters flying in the North Sea cannot be considered to be particularly prone to being struck by lightning. Civil aircraft with much less restricted flight profiles and which fly higher into the cloud are struck 20 times more frequently when their entire flight profile is considered. This is because they enter the charged regions of the cloud and trigger the strike. In fact, given that helicopters spend more time than civil aircraft at these lower altitudes, we might expect a higher strike rate at these altitudes for helicopters. However, the larger fixed wing aircraft would be more likely to trigger strikes.

## 3 RESULTS OF THE LIGHTNING STRIKE INCIDENCE AND POLARITY STUDY

This study was subcontracted to EA Technology, and was broken down into five tasks.

These were:

**Task 1** Produce a report defining the level of internal consistency of the EA Technology polarity data.

**Task 2** Analyse strike data to produce data sets representing the polarity information required.

**Task 3** Produce area plots of mean polarity of strikes from 1989 to present day.

**Task 4** Produce 3d area plots of strike density and mean polarity of strikes from 1989 to present day.

**Task 5** Investigate lightning strike occurrence on the days when specific incidents occurred.

### 3.1 Consistency of Data

Task 1 assesses the consistency of the EA polarity data. A particular criterion for assigning polarity is used and leads to consistent results between the majority of outstations. This is documented in Report [B] (see Section 8).

The positive polarity percentage is defined as $p = \frac{n_+}{n_+ + n_-} \times 100$, where $n_+$ is the number of positive and $n_-$ is the number of negative strikes. Only events with unambiguous polarity assignments are used in the calculation.

The data analysed in Report [B] from April 1993 to July 1994 had 91.7% of unambiguous assignments.

### 3.2 Polarity Maps

The remaining tasks (2–4) in the polarity study are the collation and analysis of strike data for producing the maps and data for individual incidents; these comprise 2D area maps and 3D maps of mean polarity for all strikes from the year 1989 to June 1997 for both winter (October-April inclusive) and summer (May-September inclusive) periods. Areas selected are the British Isles and surrounding sea and the western Norwegian seaboard. The data are published in the EA Technology report [C]. Tabular data are also available; the positive polarity percentage is assigned to 50km × 50km square patches over the areas of interest. The percentage ambiguous events, the standard deviation and range of polarities with 95% and 90% confidence levels are also tabulated for each patch.

### 3.2.1 *British Isles Maps*

The British Isles area extends from Eastings –200km to 650km and Northings –100km to 1250km. The co-ordinates are the UK Ordnance Survey National Grid frame of reference. In general there are more strikes in the south of the British Isles than the north giving larger errors in the northern area patches than the southern ones. There are also generally many more strikes in the summer than winter.

A binomial probability distribution has been assumed for the events giving a standard deviation in the percentage values of $\sqrt{(Nnp)}\,/\,N$, where N is the total number of events in the patch, p is the positive polarity percentage and n is the percentage negatives. A rough idea of polarities and associated distribution of standard deviations in the 50 × 50km patches can be obtained from the following table which gives summer and winter values for three particular areas:

**Positive Polarity Percentage**

| Location | Winter % | Summer % |
|---|---|---|
| South East (London; 500E, 150N) | 62 ± 2 | 42 ± 1 |
| North Sea (Nr. Aberdeen; 500E, 800N) | 62 ± 7 | 32 ± 1 |
| North West (Hebrides; 100E, 900N) | 77 ± 3 | 65 ± 6 |

There are more strikes in the summer but there are still significant numbers of strikes in the winter allowing reasonably significant statistics for polarity estimates.

There would appear to be significantly greater than 10% positive content in the North Sea especially in winter, indicating that while there are fewer strikes in winter they are more likely to be positive. As positives on average tend to have a higher amplitude than negatives, the winter strikes are thus more likely to have a higher amplitude.

More detail on the variation of the strike rate and polarity values are illustrated in the subsequent figures.

Figures 11 and 12 show variations along the patches running south to north at Easting 500km. The ordinate is the number of the patch starting at the –100km Northing. This goes through London and north into the North Sea. From Figure 11 it may be seen that there are roughly 10× higher strike rates in summer than winter. The average strike rate is about $1/km^2/year$, which is consistent with data in BSI publication [Reference 12] which gives a maximum of $.7/km^2/year$ in East Anglia and $.6/km^2/year$ in the south east. The strike rate falls off very rapidly to the north. Tabulated results give the rates in the north of Scotland as $\approx .01/km^2/year$; this is lower than Reference 12 which gives $< .1/km^2/year$. In central Scotland it is $.13/km^2/year$ compared to the Reference 12 value of $.2/km^2/year$.

Figure 12 shows the fraction of positive strikes, giving a comparison between summer and winter polarities. It is noted that there are roughly 30–40% positives in summer along the whole south-north band, increasing to 50–60% in winter.

Figures 13 to 14 show similar figures for an east-west line at Northing 1050 (between Shetlands and Orkney). The number of strikes is very low $\approx .01/km^2/year$, but more frequent in the west in winter, with percentage positive polarity rising to 70–80%.

More information on the distribution of confidence levels and ambiguous events in patches was presented in the Progress Report No 1 [E]; this is not reiterated here. It should be noted however that this further detail showed that the polarity differences between summer and winter were statistically significant for all patches and that the number of ambiguous events was variable but only of the order of 10% over most of the geographic range studied.

### 3.2.2 *Norwegian Sea*

This area covers Eastings 634km to 884km and Northings 798km to 1348km. It corresponds to longitude 2½° to 6° and latitude 57° to 62° and covers the western coast of Norway from Egersund to Ålesund.

Similar figures and data to the British Isles map are tabulated in Report [C]. In Progress Report [E] the data were compiled in figures similar to Figures 11–14 discussed in Section 3.2.1.

The analysis showed that as in and around the British Isles, there are many more strikes in summer than winter and there are less strikes in the north. The strike rate in the south of the Norwegian area studied is averaged over summer and winter at about .15 strikes/$km^2$/year which is similar to the rate in the North Sea off Aberdeen (but see discussion below).

The positive polarity percentage is 30–40% in the summer and 40–50% in the winter in the south but increases both in winter and summer towards the north part of the mainland included in the area; values of up to 87 ± 6% are reached in summer.

Reference 13 reports a similar study with a tracking system in Norway. This was undertaken since, despite lower lightning strike rates compared with elsewhere, electric utilities had higher rates of transformer failures due to those lightning strikes. This was thought to be due to a large number of positive strikes. Strikes were recorded over a 10 year period (1981–1990) and the average polarity over winter and summer in the south west of Norway was 40%; positives rose to a maximum value of 92 ± 4% in the north west near the coast.

The results of the EA and Norwegian study were very similar. Plots were presented in the AEAT report [E], showing the EA percentage for positive polarity strikes as possibly higher by about 10%. However, Reference 13 also indicates strike rates in the North of .4/$km^2$/year, which is up to 10 times the rate recorded by EA. The EA system gathers data at a much larger distance than the Norwegian system and might lead to attenuation of the signal giving events below the EA system detection threshold. Because positives are generally believed on average to have higher current and higher low frequency content than negatives (the EA system detects signal strength at 1kHz), remotely stationed sensors might preferentially select positives and give a higher measured positive percentage. However, given that the sensitivity of the EA detection system is 3kA at 1000km, this would only occur if there were large numbers of very small cloud to ground strikes.

### 3.3 Implications of the Incidence and Polarity Study

First of all it is worth noting that there are 10 times more cloud to ground strikes in summer than winter and yet no incidents at all have been reported in the summer months. This is highly suggestive that the helicopters are triggering the strikes as discussed earlier in Section 2.3. Otherwise if the helicopters were intercepting natural strikes we would expect on average more strikes to be sustained in summer.

With respect to the threat level, the conclusions depend on the EA data not being biased in any way with respect to either polarity. This requires very careful consideration, given the surprisingly high proportion of summer positive strikes in the British Isles. For example, the efficiency for detection of positives and negatives could be different, and moreover the values could change from summer to winter. It was thought that cloud bases are lower in winter and the length of the cloud to ground lightning channel could be smaller, hence leading on average to smaller signals. The Met Office study reported in Section 4 shows that the cloud bases are similar in summer and winter.

It can be shown that the true percentage polarity is related to the measured polarities as follows:

$$P_+ = \frac{1}{1 + \frac{p_- e_+}{p_+ e_-}}$$

where $P_+$ is the true percentage positive polarity, $p_+$, $p_-$ the measured percentage positive and negative polarities and $e_+$, $e_-$ the detection efficiency for positives and negatives respectively.

For example, if the true rate for positives is 10% rather than our large 40% summer value then the efficiency for detecting positives would have to be six times the negative detection efficiency. It is believed that the efficiency for detecting positives and negatives does not show such a large difference and hence the rate for positive strikes will be greater than 10%.

Disregarding for the moment such unknown systematic errors in detection efficiency we can make the following observations:

While in general there are many less strikes in the winter months than summer, there is statistically a higher percentage of positive strikes in the winter.

The largest positive percentages were registered in the north west region of the British Isles in winter and the north west of mainland Norway (winter and summer) at 80–90%.

The polarity values determined for Norway show a similar trend with latitude with other data in the open literature, though generally higher, possibly due to remote location of the sensors.

The large numbers of positives in winter are also consistent with data from Denmark [Reference 14], which show a large proportion of positive winter strikes. The north western extremity of the Danish data is adjacent to the south eastern extremity of the EA Norwegian sea data. Strike rate is similar but the Danish study only showed about 20% positive polarity in winter, suggesting the EA data is biased towards higher values at remote locations.

French data [Reference 15] also show large positive percentages in winter but less than 10% in summer. Of the positives recorded in winter it is claimed about 20% exceed 200kA.

The EA data suggest a much higher positive content in the British Isles in general, and in the winter months in particular, than assumed hitherto. If aircraft are involved in cloud-ground strikes, then values higher than certification levels are more likely to be sustained in winter than in summer. This of course assumes that the energy content distribution of the cloud to ground strikes is the same as that used hitherto for the definition of the lightning threat as described in section 2.2. A high proportion of low energy positive strikes would invalidate this supposition.

Because the measured percentage of positives is much larger than assumed hitherto and its impact controversial, it is recommended that correlation of the EA data with other area data is made. If northern France is in range, this would be an area for investigation and cross-correlation to see if the percentage positives decrease with latitude. Reference 6 noted above would appear to have some coverage of the south of the British Isles and English Channel. So far no information has been obtained from France.

However, taking the results at face value, the mean value for the North Sea during the winter months is about 60%. Using the scheme noted in Section 2.2, this would imply 18% of all incidents involving cloud to ground strikes in winter would be likely to have more energetic strikes than the certification level. It would be interesting to compare this figure with energy levels deduced from in-flight data; unfortunately this is difficult. Whilst world wide it is beyond doubt that occasionally aircraft sustain strikes above certification levels, the incidence of such strikes as a percentage of all strikes is not generally known. If we assume that 10% of the strikes to helicopters in the North Sea are triggered cloud to ground strikes, the polarity data would imply that 1.8% of these strikes would exceed certification levels. If every strike involved is a cloud to ground strike then 18% would exceed certification levels. Data made available in the FULMEN programme from Eurocopter, and also presented to the CAA/DGAC, has a sample of data that shows 4 out of 81 events (5%) to helicopters exceeding certification levels. This 5% figure would correspond to 28% of strikes involving a cloud to ground strike. This number is consistent with the percentage for cloud to ground strikes deduced from a study of individual events in Section 3.4 and 4.4.

Hence, despite some reservations about the high percentage values given by the EA Technology data, when viewed in the context of other data including:

- The unexpectedly high percentage outages of Danish and Norwegian electrical installations corresponding to high percentage positives in winter.

- Evidence of some helicopter incidents exceeding certification levels,

it would appear that the data do indicate that severe positive cloud to ground strikes to helicopters exceeding existing certification levels will occasionally occur. The Working Group of EUROCAE, WG31 has been requested by the CAA to review the data in due course. The results of the study should be forwarded to this committee.

To summarise:

- The natural cloud to ground strike rate is 10 times higher in summer than in winter implying that the strikes that occur only in winter are triggered by the helicopter.

- The percentage positives is about 40% in summer and even higher at 60% in winter for the UK.

- If the positive lightning strikes are on average more severe than negative strikes as most world wide data suggest, cloud to ground strikes in the UK in general and in the UK winter in particular will exceed the severe threat certification level 15% and 18% of the time respectively compared to only about .5% for the tropics.

## 3.4 Study of Individual Events

The spreadsheets of individual strikes to helicopters provided by the CAA were forwarded to both EA Technology and The Met Office for correlation with recorded strike logging data. EA have strike data covering events from 1988 onwards, giving a total of 26 events over a period for which we have time or position data or usually both. It should be noted that all the strikes occurred in the winter period as dramatically shown by Figure 4. The resolution of the EA Technology system for cloud to ground strikes in the British Isles is, according to report [D], about 2km although it varies depending on remoteness of the strike. The sensitivity is 3kA at 1000km. The EA Technology report [D] issued in October 1998 gives a breakdown of individual events as follows:

| | |
|---|---|
| Events with cloud-ground strike identified (within 10 mins and 75 km) | 4 (+1) |
| (The one event in brackets was the 20/11/96 event; it was weak and possibly an intracloud strike, see [D] and Section 4.4. It has not been counted as a cloud-ground strike in this analysis.) | |
| Events with cloud-ground strike identified (within 10mins but no position data, i.e., possibly cloud-ground strike coincident with event) | 4 |
| Events with cloud-ground strike identified (within 75km but no time data, i.e., possibly cloud-ground strike coincident with event) | 3 |
| Events with cloud-ground strikes in the vicinity but no time/position correlation with event | 9 |
| No cloud-ground strikes in immediate vicinity | 5 |

Hence, depending on whether or not the events with a time or position coincidence, but no position or time data respectively, are treated as a correlated strike, the CAA data sample implies that a percentage of 15 ± 7% or 42 ± 10% of helicopter incidents involve a cloud-ground strike. This is of the same order or higher as the generally assumed percentage of cloud to ground strikes to transport aircraft. Of course there are few data on the percentage as it is only such studies as the present one that would provide such data. A coincidence registered of course does not necessarily prove that the cloud to ground strike is associated with the helicopter strike; it could have been an intracloud strike occurring in the same time and position window as the cloud to ground strike.

For the incident where polarity data were available no unique feature was apparent; on days where several strikes were recorded there were roughly equal numbers of positives and negatives.

It was assumed that the remainder not having a correlated cloud-ground strike are intracloud strikes. For some of the events we have Met Office sferics data; the correlation is discussed further in Section 4.4. Some events had no correlation with either sferics or EA data, and are possibly weak strikes. Some events could have been missed by EA or the Met Office if the detection efficiency is much less than 100% for the weaker strikes.

Where an incident can be correlated with a registered cloud to ground strike, there is no obvious further correlation with the general meteorological conditions from the database.

# 4 METEOROLOGICAL STUDY

## 4.1 Introduction

This study was subcontracted to The Met Office and was completed in March 1998 and a report submitted to AEA Technology in May 1998 [F]. The report 'Lightning Strikes to Helicopters Operating over the North Sea' is very comprehensive and details the meteorological conditions associated with an incident where the data are available. Only the main findings of the report are summarised here as well as a detailed study of lightning strike data for each event. The study can roughly be divided into two approaches:

- Good meteorological data were available for 11 incidents from the CAA database from 30/10/92. Each event was studied to see if any similarities between the conditions for these strikes could be discerned and also any differences between the meteorological conditions for these events and for the general conditions in summer. At the outset it was believed that some meteorological conditions might favour a preponderance of positive strikes, for example windshear displacement of upper positive charged regions. Moreover it was hoped, given the dramatic difference in incident occurrence between winter and summer, that some features of storms in winter would be evident. In the event no particular feature was identified. The data assembled are described in Section 4.2 and general features of the data are discussed in Section 4.3. An analysis of correlation between damage and lightning strikes detected by EA Technology and The Met Office is given in Section 4.4.

- For the winter months data describing the meteorological conditions when no strikes to helicopters were registered, even though thunderclouds and lightning were present, were assembled (the 'null' data set) and compared statistically with the conditions when strikes to helicopters occurred (the 'strike' data set) to see if a quantitative algorithm of some parameters could be devised giving a simple forecasting tool. An algorithm giving a statistically significant success rate in predicting strikes was developed. These results are summarised in Section 4.5 and of course described in more detail in The Met. Office report [F].

## 4.2 Data Assembled

For each event a large amount of data was potentially available. This comprised:

1. Synoptic charts giving an overall view of the large scale situation.

2. Radiosonde data from weather balloons launched from a variety of locations at 12 or 6 hourly intervals giving a grid of temperature, humidity and wind speed variables.

3. Satellite data giving also, like the synoptic charts, a good overview of the development of the conditions on the day of the incident.

To supplement the radiosonde data there was the Met Office Limited Area Model which provided data on wind velocity, temperature, humidity, vertical velocity, rain rates, cloud base and tops and water and ice content of the clouds in a grid of 45km horizontal resolution.

Also to complement the EA lightning strike data for each incident, there were Met Office sferics reports which give data on lightning strike location. As for the EA Technology system, the sferics are electromagnetic signals radiated by the lightning strike. The Met Office system uses an arrival time difference for reconstructing the position. In principle it is more efficient in detecting cloud to ground strikes than intracloud strikes. However intracloud events are not rejected and it is likely that some of the strikes detected in the North Sea will be intracloud events. It does not measure the polarity of the strikes.

## 4.3 General Observations

- Despite some pilots reporting no lightning activity in the vicinity before their incident, convective activity and cumulonimbus clouds were without exception present, implying that natural lightning strikes in the region could be expected. Precipitation was also always present, for all eleven occurrences, though the model data does not always give a consistent picture at the region of the incident. In seven cases where model data were available, four had cloud ice and one water. Five showed the helicopter near regions of high convective rain rate.

- In 10 of the 11 cases a frontal system was present either soon before or at the time of the incident.

- 6 of the 11 cases showed that the helicopter was near the region where ascending and descending air meet.

- Data from observers and from analysis of both the observational (dew point) and model data showed that there was no significant variation in cloud base from summer to winter and that it was at a fairly low level when clouds were present (1000 to 3000ft).

- 7 of the 11 events had a sferics record corresponding to the incident. In 2 of these cases the sferic record was the only one of the day implying that it was probably triggered by the helicopter.

- For 9 of the 11 events there were less than 50 sferics recorded in the day compared to an average of 500 when lightning normally occurs in winter, implying that the natural lightning strike rate is low even compared to average winter storm days.

- No one consistent pattern of helicopter position relative to cloud base and freezing level was found. In 8 of the 11 cases the helicopter was below the cloud base. In 7 of the 11 cases the entire cloud was below freezing. The disposition of the helicopter with respect to the cloud was deduced from the tephigram analysis (a standard meteorological tool, see Section 4.5). This did not always agree with the pilots observation. A summary of the various scenarios, for the eleven incidents studied, is shown in Figure 15.

### 4.4 Study of Individual Events

Table 4 shows the events where Met Office sferics data are available from Report [F]. Also compiled in the same table are EA Technology data and an indication from the original CAA spreadsheets of the nature of the helicopter damage. Unfortunately this is subjective as some operators have referred to damage as being 'light' even if the rotors and gearbox had been replaced!

According to the sferic data there are helicopter strikes corresponding to the only strike in the vicinity that day, probably triggered by the helicopter and also strikes possibly triggered by the helicopter during an existing natural strike situation (i.e., several cloud-ground strikes registered in the vicinity that day). Where there is a good correlation with both the sferic and the EA data and severe damage has been recorded, this has occurred in a day when many sferics have been recorded. This might possibly indicate that these strikes correspond to strong cloud to ground events. The strikes not detected by EA could be weak or triggered intracloud strikes. Both of the two severe strikes registered show a good correlation with EA strike location. One of these is the G-TIGK incident and this is a positive cloud to ground strike.

In the following we assume that helicopter incidents that have only a correlated sferic correspond to intracloud strikes. Hence selecting those events with good matches with the EA Technology data as well as a sferic as corresponding to cloud to ground strikes we have 3 out of 7 cloud to ground events or 43 ± 18% of strikes. Including the events that have poor match, as well as those that have good match, we have 5 out of 9 cloud to ground strikes or 55 ± 16% of strikes. The criterion of selection of 'good' match is fairly coarse. For the EA data a separation less than or equal to the EA detection system resolution is required. For the sferic data a good match requires the strike to be within 10 nautical miles and 8 minutes of the incident. Imposing such a selection for the events would only result in 2 out of 7 or 28± 17% of strikes. Hence, despite the uncertainty in the percentage of cloud to ground strikes, it is nevertheless a significant percentage.

The limited statistics give large errors on the percentage value so it is difficult to make a definitive statement. Moreover, for the event of 29/2/96 when EA Technology recorded no lightning activity, severe damage to a helicopter was experienced. (This event does not appear in the table below because there was no time or position data for the incident.) Also for the event of 26/11/96, whilst a good match was obtained, according to EA it was only a weak strike and would normally have been rejected. It was only found because an incident had occurred and the criterion for detection was relaxed. It could therefore have been an intracloud strike.

**Table 4**

| | Sferic Data Met Office | | | | EA Technology Data | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | Time Difference (min) | Separation (km) | No. of Strikes | Good Match | Time Difference (min) | Separation (km) | No. of cloud/ ground Strikes | Good Match | Polarity | Damage to Helicopter |
| 30/10/92 | ⁕ | ⁕ | 27 | No | 19 | 430 | 2 | No | Positive | U/K |
| 15/01/93 | -5 | 13 | 167 | **Yes** | -8 | 22 | 1 | **Yes** | ? | **Severe** |
| 18/02/93 | -3 | 57 | 11 | Poor | 107 | 96 | 1 | No | Positive | U/K |
| 20/02/93 | -6 | 9 | 42 | **Yes** | 25 | 145 | 3 | No | Positive | U/K |
| 03/10/94 | 13 | 229 | 3 | No | -27 | 992 | 4 | No | Positive | U/K |
| 19/01/95 | -5 | 11 | 307 | **Yes** | 2 | 1 | 8 | **Yes** | Positive | **Severe** |
| 21/02/95 | -5 | 27 | 15 | **Yes** | -4 | 63 | 1 | Poor | Negative | Moderate |
| 01/03/95 | -2 | 17 | 49 | **Yes** | 10 | 562 | 4 | No | Negative | Light |
| 08/12/95 | -4 | 35 | 34 | Poor | -2 | 73 | 3 | Poor | Positive | Light |
| 08/02/96 | -8 | 24 | 1 | **Yes** | ⁕ | ⁕ | ⁕ | No | ⁕ | Light |
| 26/11/96 | -3 | 10 | 1 | **Yes** | 0 | 21 | 1 | **Yes** | Positive | Light |

⁕For the event of 30/10/92 no sferic data were recorded within 400 km and for the event of 8/2/96 no EA Technology data were recorded within 400 km of the incident.

## 4.5 Quantitative Regression Analysis

The regression analysis is described in more detail in the comprehensive Met Office report [F].

From meteorological data accrued, a tephigram could be constructed which allows the Convective Available Potential Energy (CAPE) to be evaluated. The tephigram is a standard meteorological tool for displaying and interpreting ambient and dew point temperature data obtained from a radiosonde ascent. It was thought that the CAPE might be related to the vigour of any charge separation process. The convective vertical velocity within the cloud system is proportional to the square root of CAPE. This is not the same as the large scale vertical velocity described in the next paragrpah. CAPE divided by the cloud depth is an indication of the acceleration within the cloud. Comparisons of values of either of these parameters between the null and strike data sets did not show any significant differences, i.e., the values cannot be used to predict lightning strikes to helicopters.

The Met. Office Limited Area Model was also used to compare null and strike data sets. The best results were achieved using 2 parameters only, when the summer data from Hemsby were excluded, the temperature at the helicopter altitude and the vertical velocity. For the purposes of the regression analysis the null and strike events were assigned values of 0 and 1 respectively. The best fit was obtained using the equation $p = 19.1 - 0.0683 \times T -2.61 \times VV$, where T is the absolute temperature at the helicopter altitude and VV the vertical velocity. An arbitrary cut off value of .5 was used to decide strike or no strike. It is important to note that the vertical velocity is the large scale vertical velocity averaged over 50km and not the local vertical velocity discussed in some speculations in the next section. The equation derived correctly predicted 28 out of 32 strike/no strike cases. The associated contingency table for the regression result and one that would be obtained using a random allocation are shown in Tables 5 and 6 respectively. The contingency tables show that the statistical model performs much better than a random distribution.

Reference [F] states that the probability of obtaining the same result by chance is less than 1%. The basis for this success can be seen simply in a scatter plot of vertical velocity against temperature (Figure 16). The strike data set tends to have lower temperatures and larger values of negative updraft (air ascending) than the null data set; hence a line drawn diagonally through the plot with a negative gradient has only points from the strike data set below it.

**Table 5 Contingency table for forecasts calculated using the regression equation (for Hemsby null cases excluded)**

| | Forecast | | | |
|---|---|---|---|---|
| Actual | | Strike | No Strike | Total |
| | Strike | 7 | 4 | 11 |
| | No Strike | 0 | 21 | 21 |
| | Total | 7 | 25 | 32 |

**Table 6 Contingency table that would be expected for random forecasts (for Hemsby null cases excluded)**

| | Forecast | | | |
|---|---|---|---|---|
| Actual | | Strike | No Strike | Total |
| | Strike | 4 | 7 | 11 |
| | No Strike | 7 | 14 | 21 |
| | Total | 11 | 21 | 32 |

The Met. Office report [F] recommends that a feasibility study should be carried out to test the utility of the model in an operational situation. Such a study should examine the impact of a forecast of 'regions of increased risk' on helicopter operations in the North Sea. The report [F] recommends that the feasibility study should investigate the need for forecasts at different levels through the atmosphere and at different time resolutions. For example, forecasts could be required at three hourly intervals or a general forecast could be issued at the start of each day. Also to be considered is the requirement for 'grading' the areas of increased risk. It is imperative that helicopter operators are involved in such a feasibility study.

# 5 SOME SPECULATIONS ON THE METEOROLOGICAL CONDITIONS FOR THE NORTH SEA HELICOPTER STRIKES

## 5.1 Characteristics of Winter Storms

Reference 11 describes features of winter storms in Japan. Much significance is given to the following differences between winter and summer storms.

(1) The –10°C contour is at a much lower altitude in winter than summer. The contour is believed to be where significant charge separation can occur during graupel/ice crystal collisions. (Graupel is a type of soft hail.) Obviously for significant frictional charging solid particles are necessary.

(2) The depth of the troposphere is lower in winter and leads to smaller convective cells.

In Reference 11, the following important factors are noted:

(3) Vertical updraft is important and this is constrained at low altitudes to low values by the large amount of air above. A condition for lightning activity is significant updraft at the –10°C contour.

(4) The tripolar structure of clouds is generally believed to be due to sign reversal in the charge transfer process at the –10°C contour. This leads to positively charged graupel in the lower part of the cloud, a large negative section (graupel) at about the –10°C contour and positive snow crystals in the higher altitudes.

The effect of points (1), (3) and (4) is that in winter, because of the small updrafts in the lower part of the clouds, the graupel drops quickly leaving an essentially positive monopolar structure in the dissipating phase. This leads to a large proportion of positive strikes which tend on average to be more severe.

If the –10°C region is below the 1.4km level, the small vertical updrafts mean that significant charging processes do not occur and little natural lightning takes place.

For all eleven events studied, assuming an adiabatic lapse rate of 2°C/300m and extrapolating from the OAT data, the –10°C contour is at a fairly uniform altitude, between 1.8 and 2.4km and generally at about 2km altitude (see Figure 17). In summer this contour would be nearer 6km.

The high proportion of positives, and the relative severity of Japanese winter storms, has long been recognised. In fact the increased hazard to flight safety has led to special procedures being introduced for flight under winter storm conditions in Japan [References 16 and 17] as long ago as 1968!

Unfortunately, it has not been possible to obtain copies of the airline Operations Manual. Only an incomplete copy of Pierce's paper was obtained, though this does cite the Operations Manual. From the incomplete Pierce paper it is deduced that a feature of the Japan winter storms relative to aircraft is that the natural strike rate is low; aircraft tend to trigger the strike and hence reliance on available techniques dependent on the detection of naturally occurring strikes are relatively ineffective. However it should be pointed out that the two strikes causing severe damage noted in Section 4.4 occurred when there were many recorded natural strikes on that day. One of these was the G-TIGK incident which also corresponded to a positive cloud to ground strike.

These differences between winter and summer storms are also noted in Reference 18. Key factors are the lower strike rates (<1 strike per minute during the active phase lasting only 10 minutes), low updraft velocity (few m/s) and low liquid water content ($<.2 g/m^3$).

Similar observations are also noted in Denmark, Reference 14. Here, though, an additional feature claimed was displacement of upper positive charge by windshear.

No obvious feature of winter storms in the North Sea has been evident from the meteorological study except, of course, that the temperature is a lot lower probably leading to quite different charge structure within the cloud and in particular the possibility of significant icing and charge separation in the lower part of the cloud. Despite lack of knowledge of the electrical structure of the winter clouds some similarities with the Japanese situation are apparent – relatively low strike rates and a higher proportion of positive discharges.

It has been reported that natural lightning requires the presence of wet ice crystals for initiation and that in winter storms when the cloud is entirely frozen, natural lightning strikes will be inhibited and the presence of an aircraft is required to trigger the strike.

Also, as discussed in Section 2.3, the fact that aircraft incidents are clustered around the OAT temperature of 0°C implies that triggering is also more likely to occur in the presence of wet ice. Reference 19 reports on a research radar system that can distinguish wet ice from dry ice and rain using an LDR (Linear Depolarisation Return) as opposed to the standard reflectivity. A comparison was made of standard radar return (Z), differential reflectivity (ZDR) and the linear depolarisation ratio (LDR) for a cloud in which a lightning strike to an aircraft occurred. The strike occurred as the aircraft was passing through the region where wet graupel was inferred to be present. This region shows up in the LDR plot but on the Z plot the Z was about 40dBZ. It is claimed that 50dBZ is usually required to indicate a lightning hazard on a weather radar.

If such radar information were available it could be used to identify regions which the helicopter should avoid where there would be an enhanced risk of a triggered lightning strike.

### 5.2 Speculation on the North Sea Strikes

An hypothesis can be made as follows.

During summer there are more storms and natural lightning strikes. Despite the fact that the cloud bases are similar to those in winter, the level of the -10°C contour will be well above the normal cruise altitude of the helicopters. In this situation the helicopter will not trigger a lightning strike as the charge centres are remote from the helicopter. It would have to be in a strong active thunderstorm to have any chance of being struck, and in this case it would have to be near a naturally downward propagating leader. Given the low strike rate/unit area/year this is unlikely.

In winter the helicopter is at a similar height relative to the cloud base. However the lower temperature compared to summer might result in charge centres being closer to an aircraft and it could therefore trigger a strike. Existing aircraft data suggest that the temperature level of 0±10°C is where most triggered strikes occur. The presence of wet ice is believed to be optimum for the triggering process. If the electrification is similar to the Japanese storm systems, the strike could occur in either the mature active phase, when natural strikes are also occurring, or in the dissipating stage when natural strikes are more unlikely. In the mature phase, the strike could be either positive or negative. In the dissipating stage the triggered cloud to ground strike would tend to be positive and consequently of possible higher amplitude. Unfortunately there are no data available on the electrical characteristics of North Sea storms.

Another feature noted in the Met Office study was the generally low numbers of strikes on incident days. This is puzzling. However, paradoxically it is possible that the aircraft is more likely to trigger a strike where the natural lightning activity is small. If the natural activity is high then strikes are occurring anyway which discharge the cloud. The presence or not of the aircraft has little effect. This was reported in Reference 20: the F106 tended to trigger strikes more often in regions of the cloud where no natural activity was occurring. Moreover, as noted in Section 5.1, dry ice clouds produce little natural lightning activity. Also if there is an existing storm the crew might have avoided the region showing on the weather radar.

## 6 SUMMARY AND CONCLUSIONS

1. The recorded helicopter strikes since 1978, without exception, occur in the winter months of October to April inclusive. However, the strike rate per flying hour is modest and not dissimilar from rates for civil aircraft at similar altitudes, though civil aircraft spend much less time at these low altitudes.

2. The EA Technology data confirm that there are many more strikes in summer than winter by an order of magnitude, implying that the strikes are in some way triggered by the helicopter.

3. There are about 15-40% incidents involving cloud to ground strikes, although the statistics available preclude giving an accurate number. Two cloud to ground strikes detected by EA Technology showing a good correlation with the incident resulted in severe damage to the helicopter. One of these was the G-TIGK incident which involved a positive cloud to ground strike. These strikes occurred in an area where natural lightning strikes were occurring on that day. A real time indicator of lightning detected activity might have warned of these dangers.

4. The EA Technology data indicate that there is a higher proportion of positive cloud to ground strikes in the UK in general, and in winter in particular, compared to world-wide averages. Other data in the public domain also indicate an increased proportion of positive severe strikes in northern latitudes, and a higher proportion of positive strikes in winter. Hence North Sea helicopter strikes might be more likely to involve positive cloud-ground strikes at low altitude, than transport aircraft world-wide. Therefore on average we would expect greater energy levels to be sustained by helicopters than transport aircraft during a lightning strike.

5. Some strikes not showing any EA Technology detected cloud to ground strikes do have a correlated sferic, possibly corresponding to an intracloud strike. These have occurred either in situations of moderate or low lightning activity.

6. The qualitative Met Office study showed little difference between winter and summer storms. The CAPE is higher in summer leading to larger clouds. Surprisingly the cloud base altitude is similar. For winter storms the temperature is much lower.

7. The Met Office study also showed no single common factor for each recorded strike, for example in the disposition of the helicopter relative to cloud base, or in freezing levels.

8. There are some similarities with reported strike incidents in Japanese winter storms in that the natural strike rate is low and that the aircraft probably triggers the strike. In the Japanese storms the strikes also occur at low altitude and with an OAT near O°C.

9. The Met Office regression analysis on strike and null data sets for winter show a definite correlation between the strikes and the parameters for temperature and large scale vertical velocity. This is not inconsistent with expectations for different charge scenarios than those for summer with increased large scale vertical velocity and the lower -10°C contour as described in the Japanese studies. They recommend that a feasibility study on the utility of such a model to an operational situation should be carried out.

10. Most strikes occur with an outside air temperature of 0±4°C. This is similar to other lightning surveys which indicate most events occur at OAT's around 0°C, possibly due to triggering being aided by the presence of wet ice. Some workers claim polarisation radar can help to identify regions of wet ice which probably correspond to dangerous regions for triggering lightning.

## 7 REFERENCES

See also Section 8 for a list of reports issued during the course of this research programme which are referred to in the text.

[1] Air Accidents Investigation Branch. 'Report on the accident to Aerospatiale AS332L Super Puma, G-TIGK, in North Sea 6nm south-west of Brae Alpha Oil Production Platform on 19 January 1995'. Aircraft Accident Report 2/97, September 1997.

[2] 'Atmospheric Electricity Hazards Threat Environment Definition'. Air Force Wright Aeronautical Laboratories, Dayton Ohio, March 1994

[3] Cianos and Pierce. 'A ground lightning environment for engineering usage.' SRIR Report 1972.

[4] Kröninger. 'Further analysis of Berger's San Salvatore lightning current data.' NEERI CSIR Special Report, Elek53, 1974.

[5] Orville. 'Cloud to ground lightning flash characteristics in the contiguous United States: 1989-1991.' Journal of Geophysical Research, Vol. 99, No. D5, May 1994.

[6] Le Boulch et al. 'Observation of very large amplitude lightning flashes in France.'

[7] Goto, Murooka. 'Statistics of lightning interaction with aircraft in Japan.' 1988 International Aerospace and Ground Conference on Lightning and Static Electricity, Oklahoma City, April 1988.

[8] Odam. 'Highlights of RAE lightning strike investigations.' 1988 International Aerospace and Ground Conference on Lightning and Static Electricity, Oklahoma City, April 1988.

[9] FAA aircraft lightning protection handbook. September 1988.

[10] 'Discharge initiation phase: Definition of a typical atmospheric configuration, determination of airframe polarisability, experimental determination of the attachment points.' FULMEN report D3.1a, September 1997.

[11] Kitagawa et al. 'Meteorological and electrical aspects of winter thunderclouds'. J Geophysical Research, Vol. 99, D5, 20 May 1994.

[12] British Standards Institution. 'British standard code of practice for protection of structures against lightning'. BS 6651: 1985.

[13] Rolfseng et al. 'Lightning protection of distribution transformers in Norway'. 21st International Conference on Lightning Protection, September 1992.

[14] 'Lightning registration systems'. Publication No. 9505. Electrical Power Engineering Department, Technical University of Denmark.

[15] 'The Meteorage thunderstorm monitoring system'. 20th International Conference on Lightning Protection, Paper 6.13P, September 1990.

[16] Pierce. 'Winter thunderstorms in Japan – A hazard to aviation'. Nav. Res. Review, June 1976.

[17] 'Winter flight operations manual for Toyama, Fukui and Komatsu airports'. All Nippon Airways, 1968.

[18] Williams, comment on a paper, end of special issue journal, J.Geophysical Research, Vol. 100, D1 January 20 1995.

[19] Frost, Illingworth, Caylor. 'Aircraft and polarisation radar measurements of a triggered lightning event.' 1989 International Conference on Lightning and Static Electricity, Bath. September 1989.

[20] Mazur, Fisher, Gerlach. 'Lightning strikes to a NASA airplane penetrating thunderstorms at low altitudes'. A1AA 24th Aerospace Sciences Meeting, Reno, Nevada, January 1986.

## 8 REPORTS ISSUED DURING THE STUDY

[A] 'Proposal to CAA to Assess the Lightning Threat', Issue 2 June 1997.

EA Technology Reports:

[B] Report 4271: 'Internal Consistency of EA Technology Polarity Information'. Pauline Sinclair, Mike Lees (EA Technology), August 1997.

[C] Report 4345: 'Assessment of the Polarity of Lightning Strikes', Mike Lees (EA Technology), October 1997.

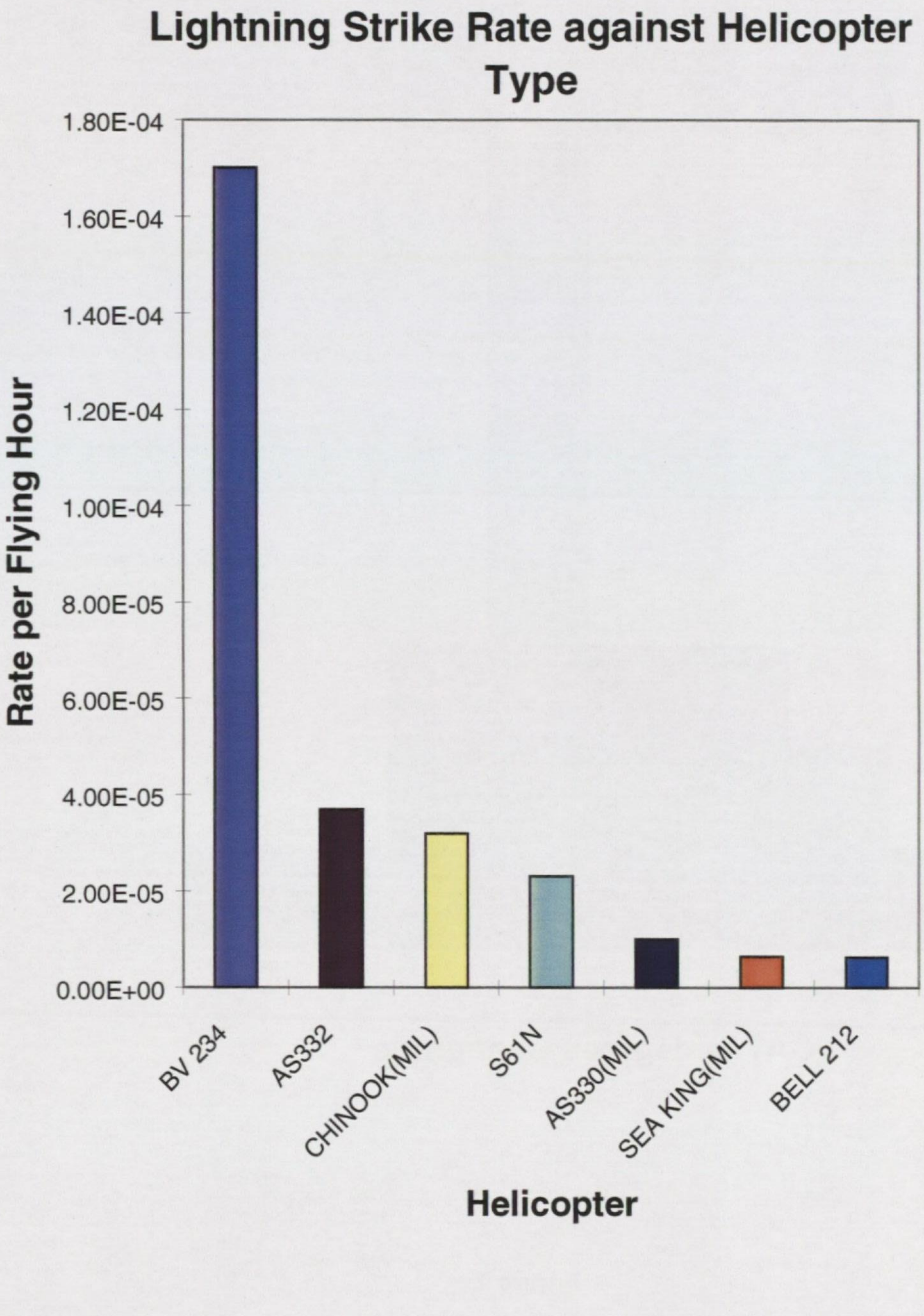
[D] Report 4363: 'Lightning Activity'. Don Eaton (EA Technology), September 1997; reissued as Report 4600, Issue 2 October 1998.

AEA Technology Report:

[E] Report AEAT-2387: 'Assessment of Lightning Threat to North Sea Helicopters; Progress Report No. 1'. C J Hardwick, October 1997

Met Office Report:

[F] CAA Paper 99008 'Lightning Strikes to Helicopters over the North Sea'.



Lightning Strike Rate against Helicopter Type
Rate per Flying Hour
1.80E-04
1.60E-04
1.40E-04
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
BV 234
AS332
CHINOOK(MIL)
S61N
AS330(MIL)
SEA KING(MIL)
BELL 212
Helicopter


**Figure 1**

## Frequency Distribution of Outside Air Temperature OAT (as measured on the helicopter) for North Sea Strikes

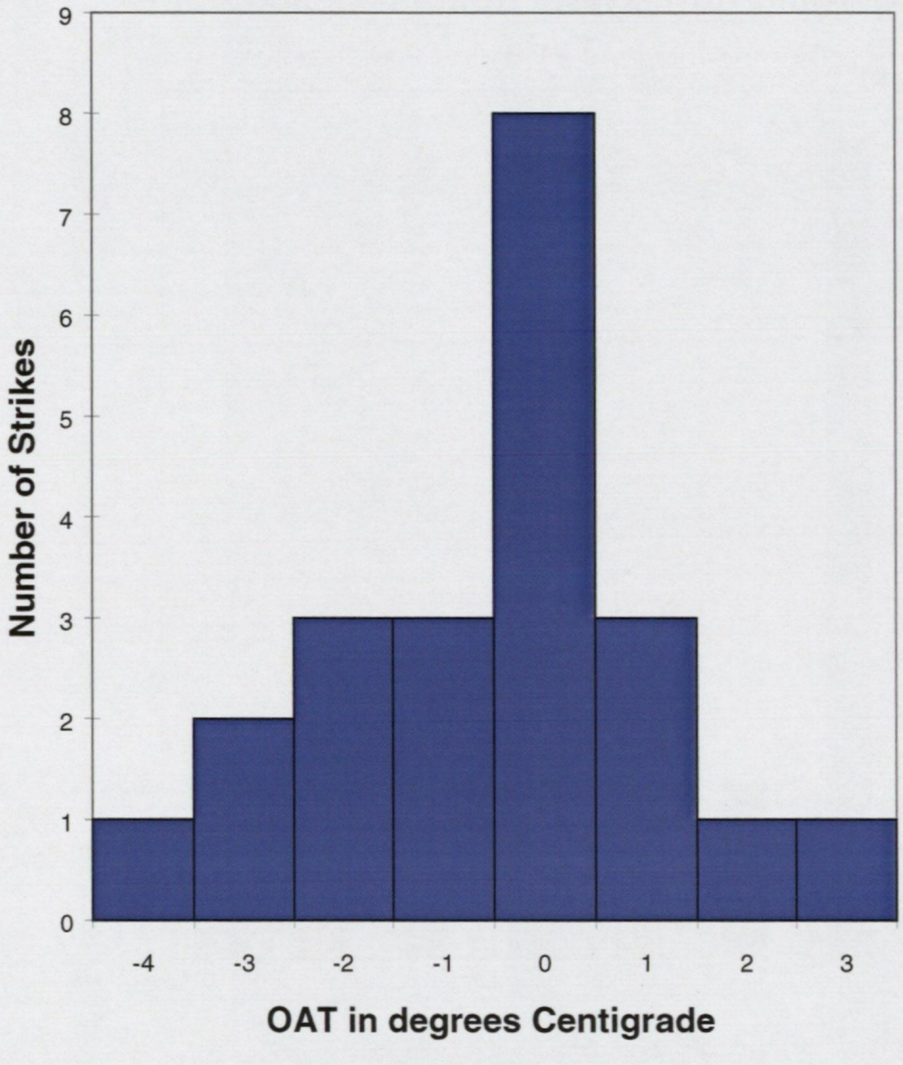



Figure 2

## Frequency Distribution of Altitude (as measured on the helicopter) of Helicopter for North Sea Strikes

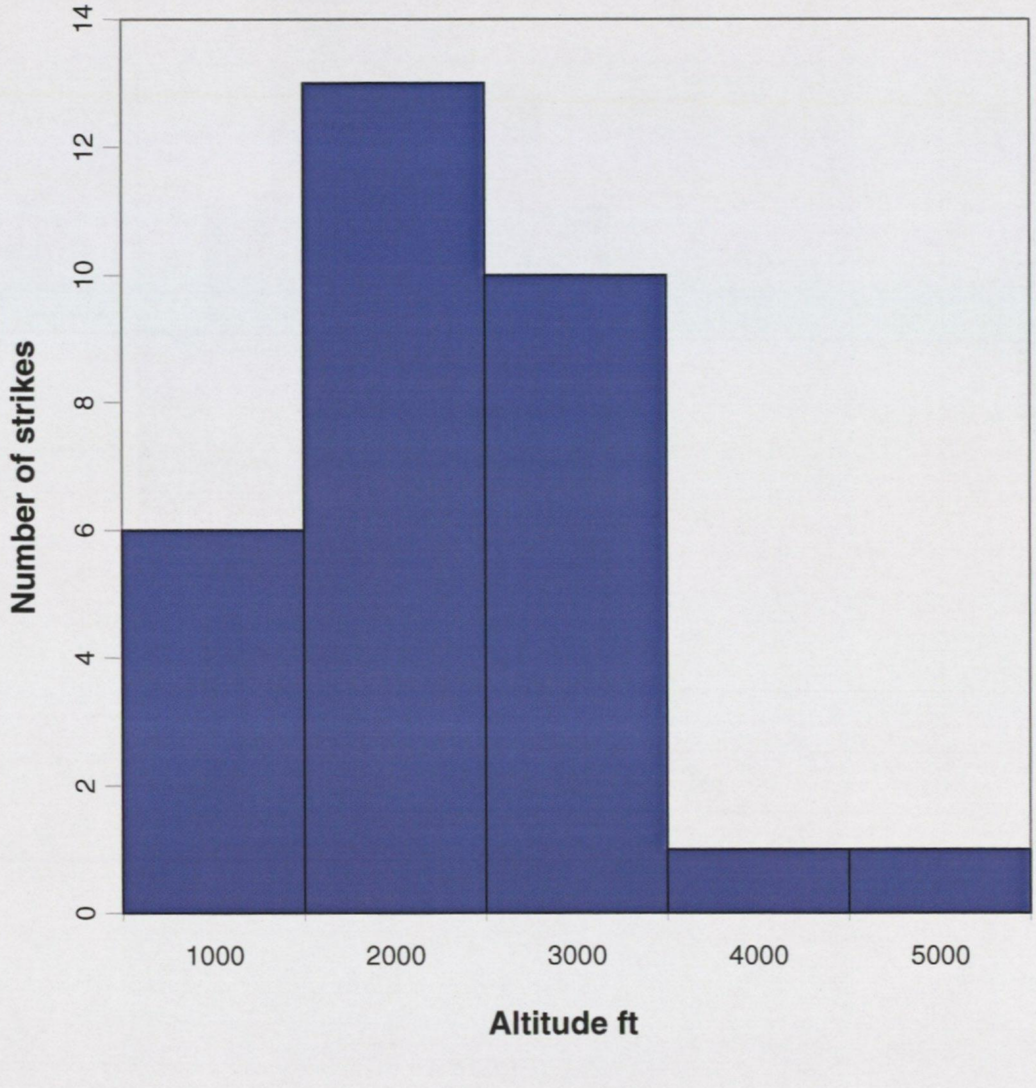



Figure 3

## Frequency Distribution of Helicopter Lightning Strikes against Month

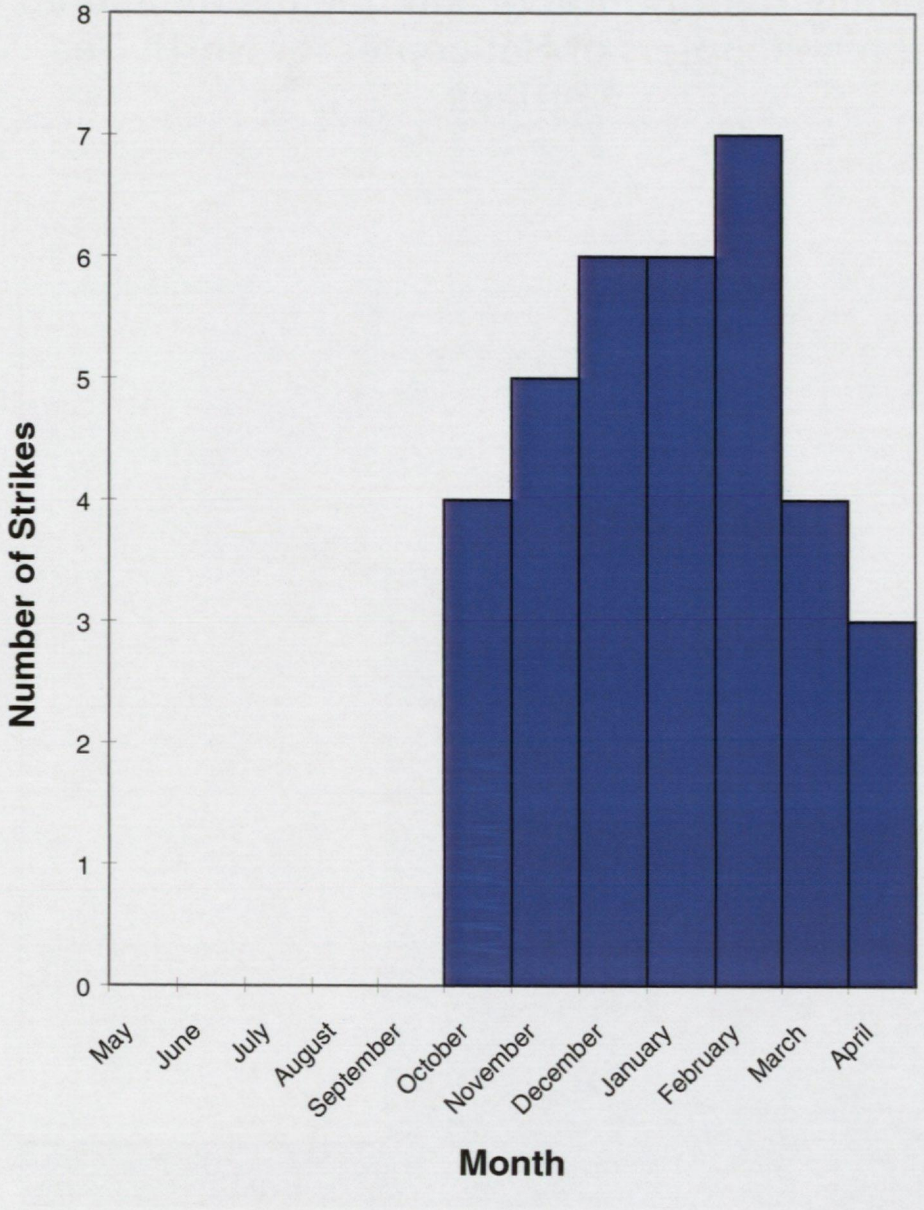



Figure 4

## Transport Aircraft Strike Histogram

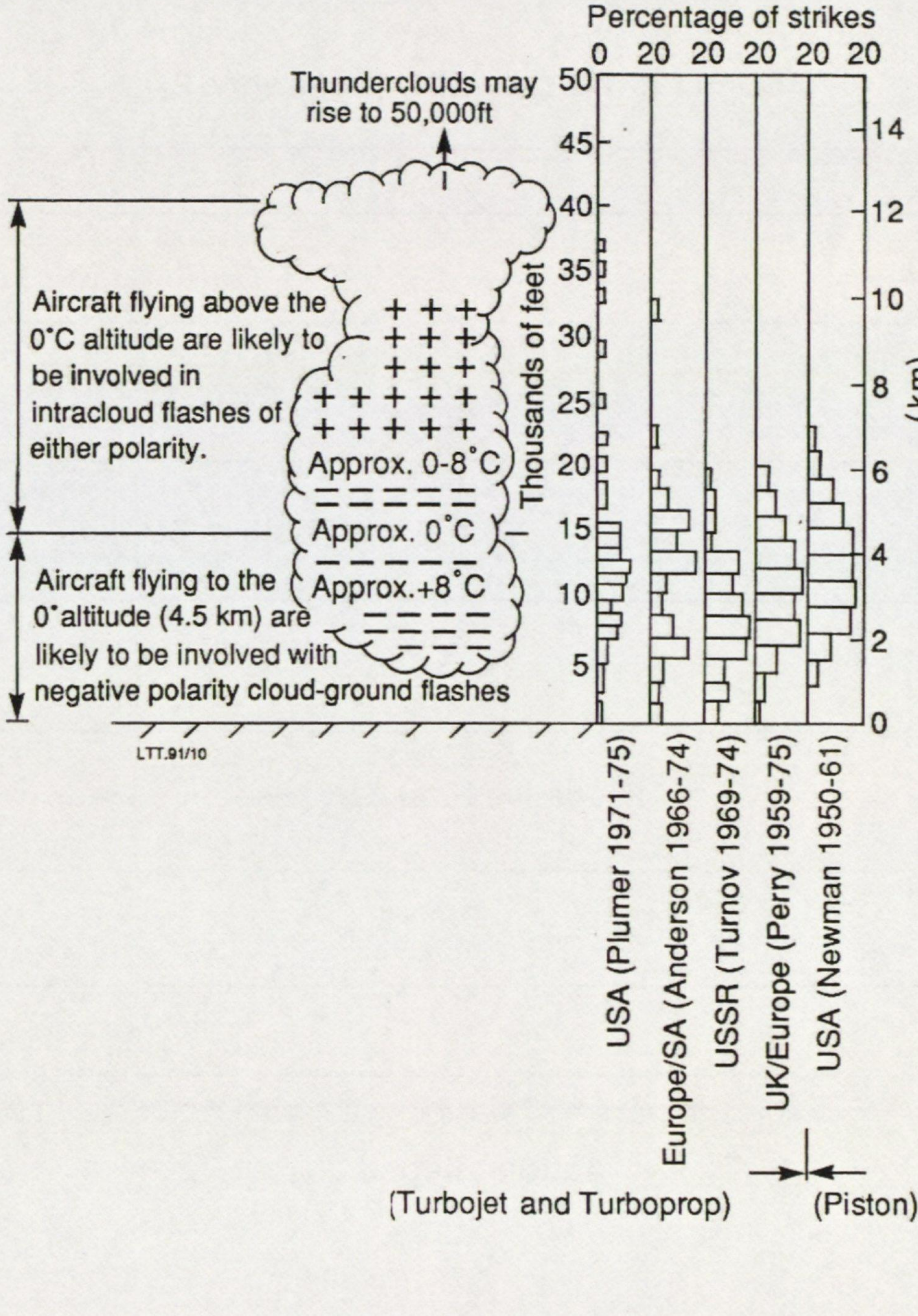



**Figure 5**

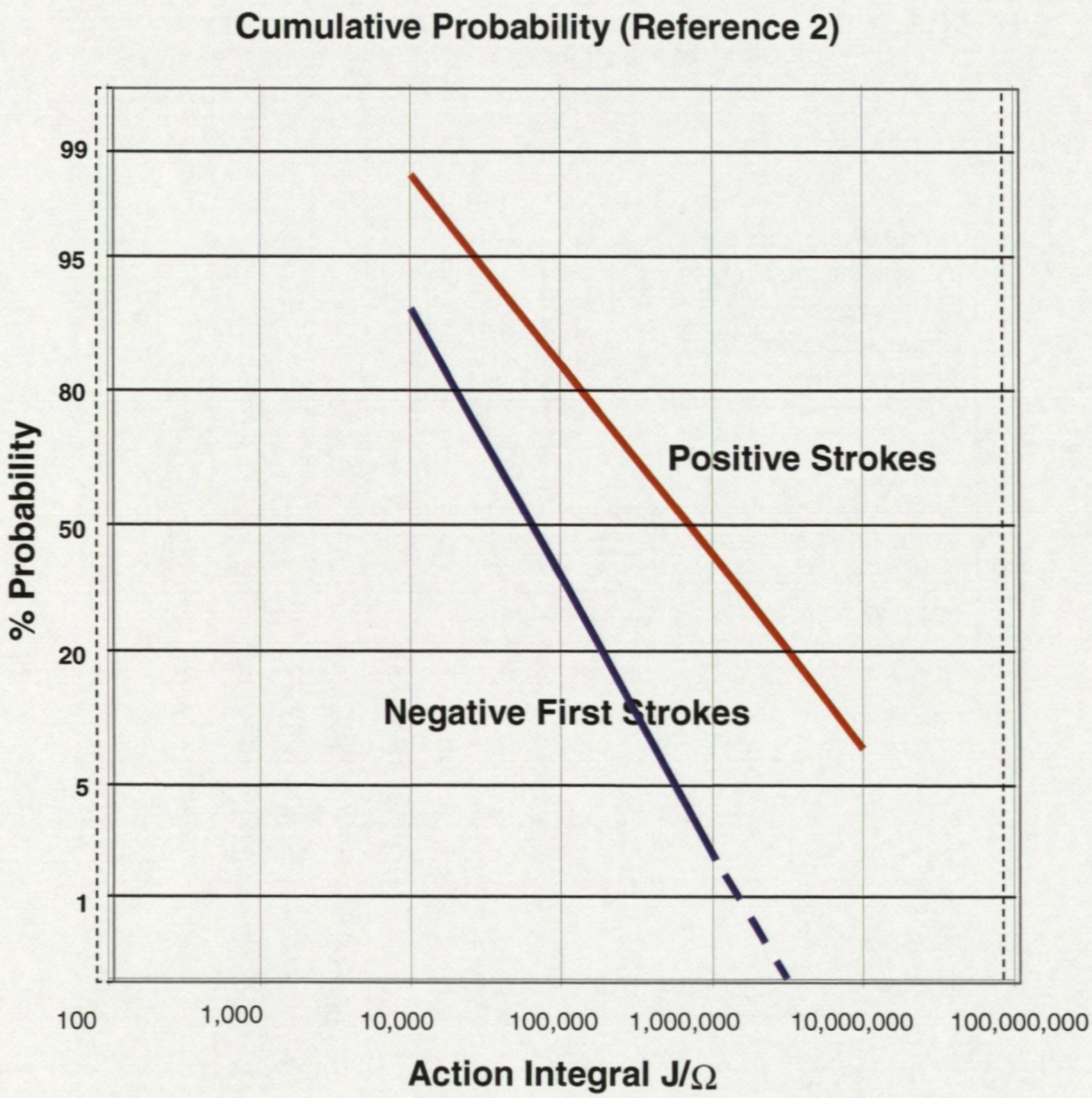

Cumulative Probability (Reference 2)
99
95
80
50
20
5
1
% Probability
Positive Strokes
Negative First Strokes
100
1,000
10,000
100,000
1,000,000
10,000,000
100,000,000
Action Integral J/Ω

Figure 6

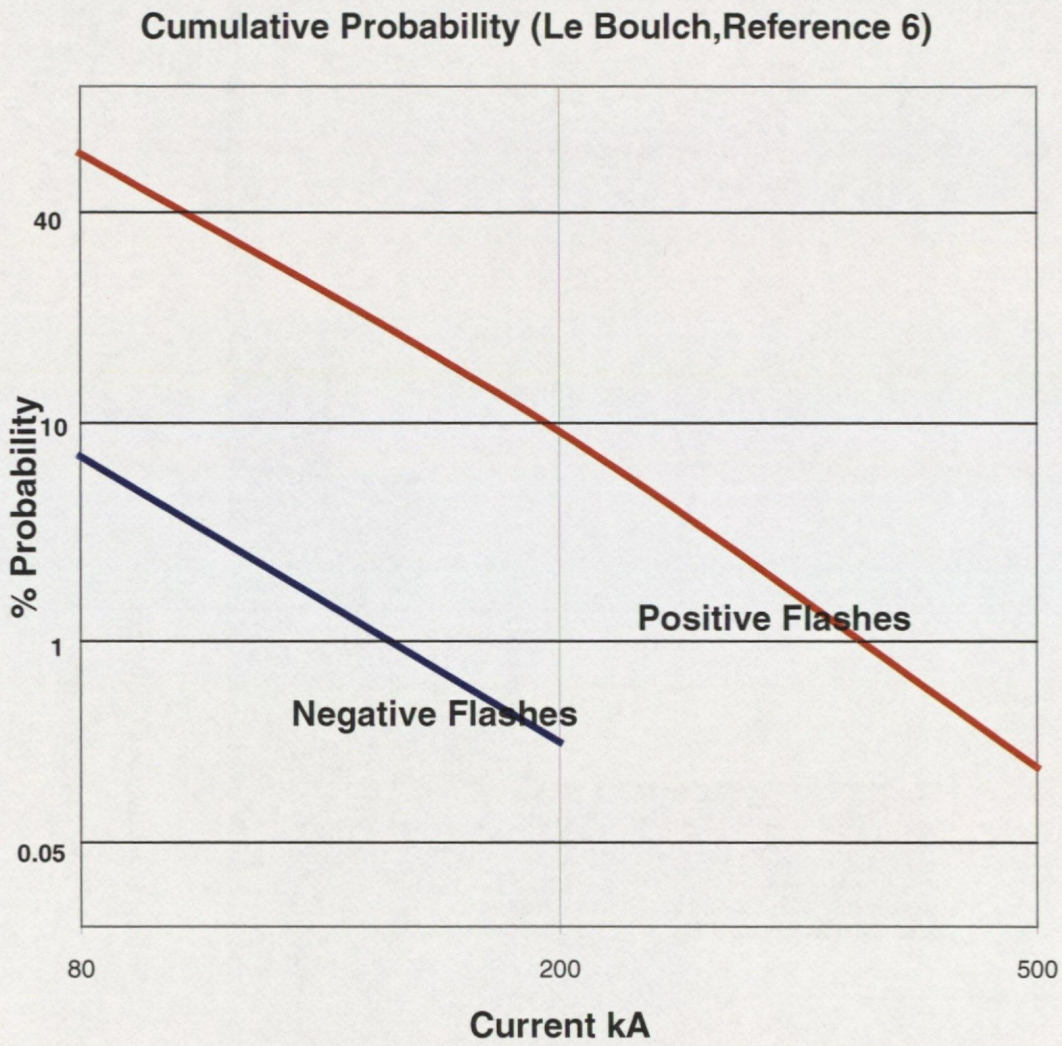

Cumulative Probability (Le Boulch,Reference 6)
% Probability
40
10
1
0.05
Positive Flashes
Negative Flashes
80
200
500
Current kA

Figure 7

## OAT for Fixed Wing events from Reference 7

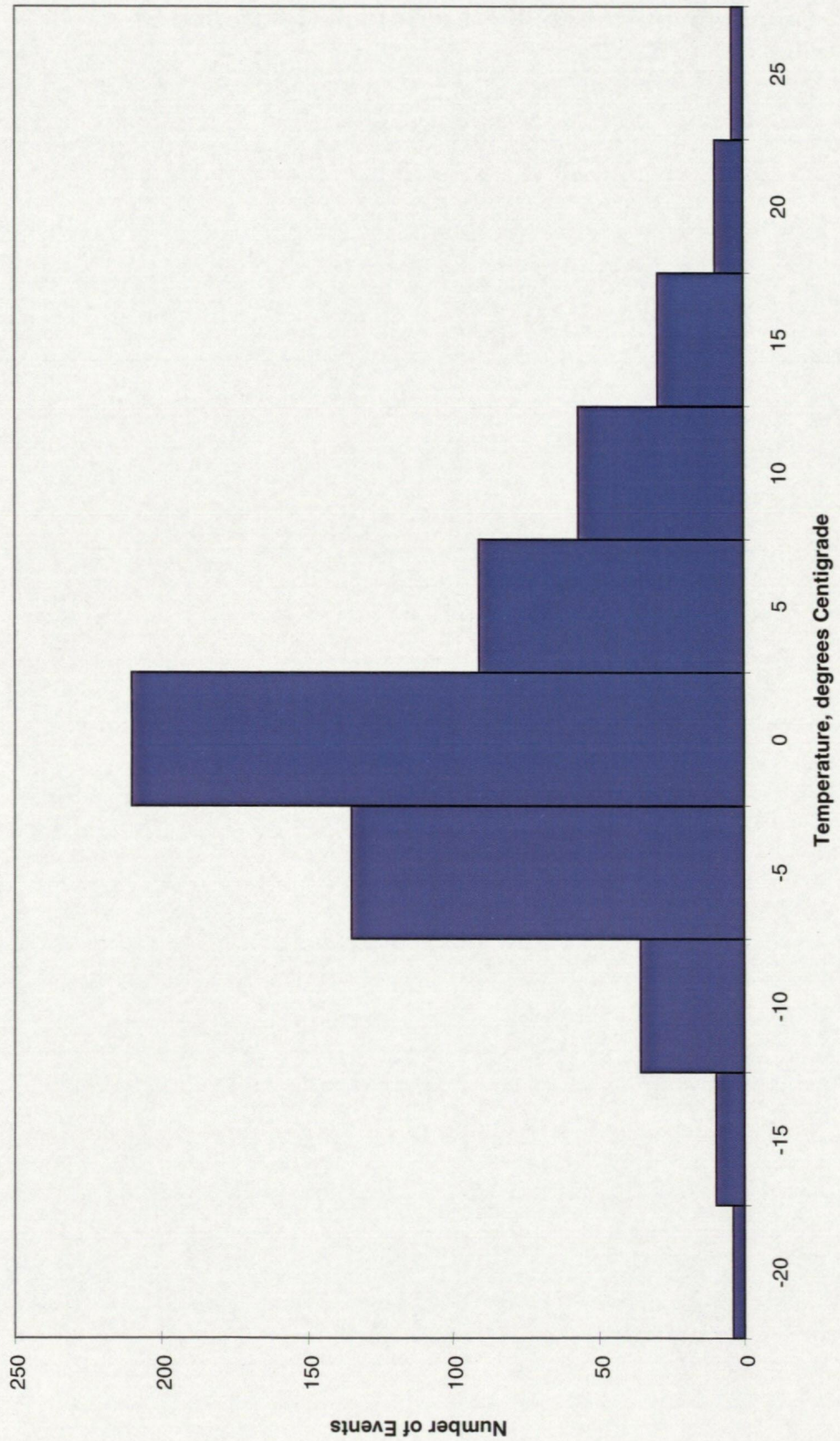



Figure 8a

## OAT for Fixed Wing events from Reference 8

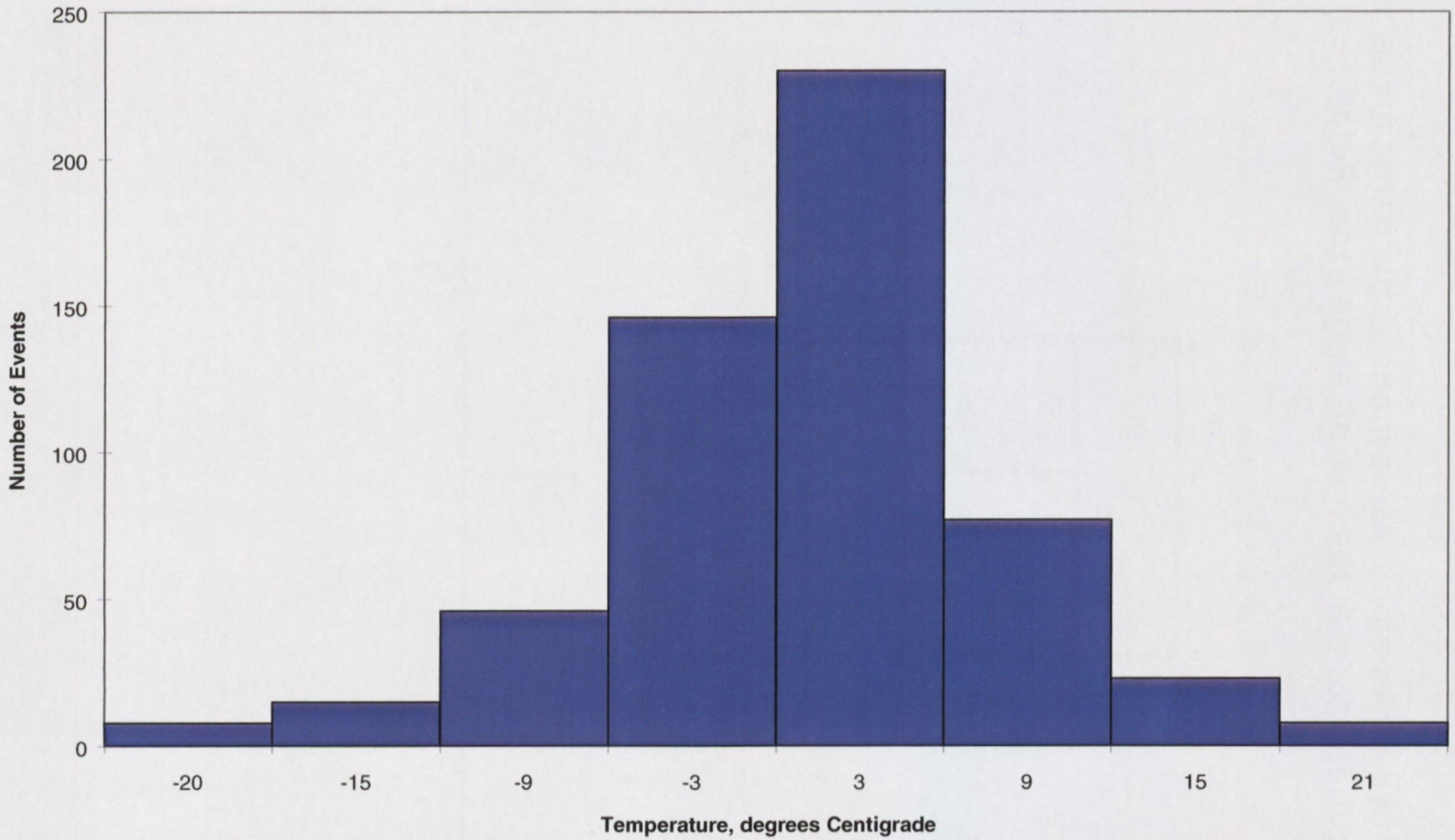



Figure 8b

## A two dimensional axissymmetrical charge model of a thunderstorm at the mature stage (from Reference 10)

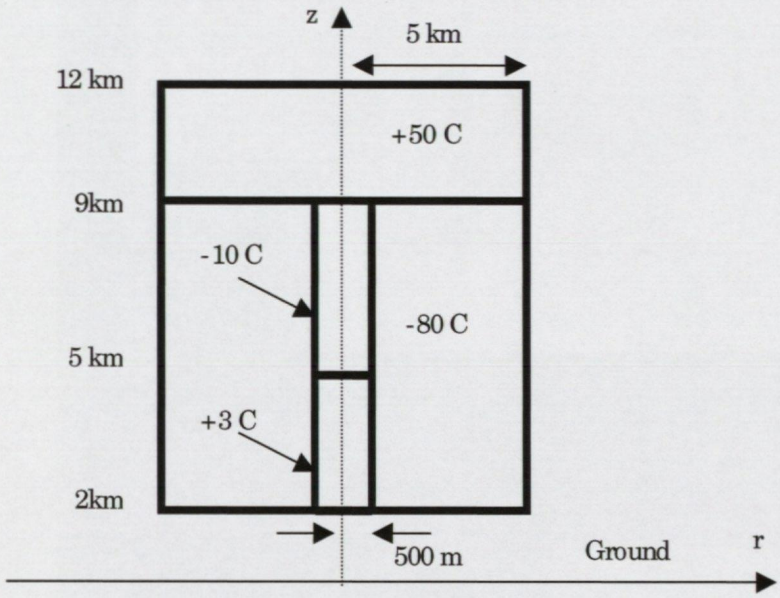



**Figure 9**

## Normalised E-field distribution in a vertical cross section of the thundercloud (from Reference 10)

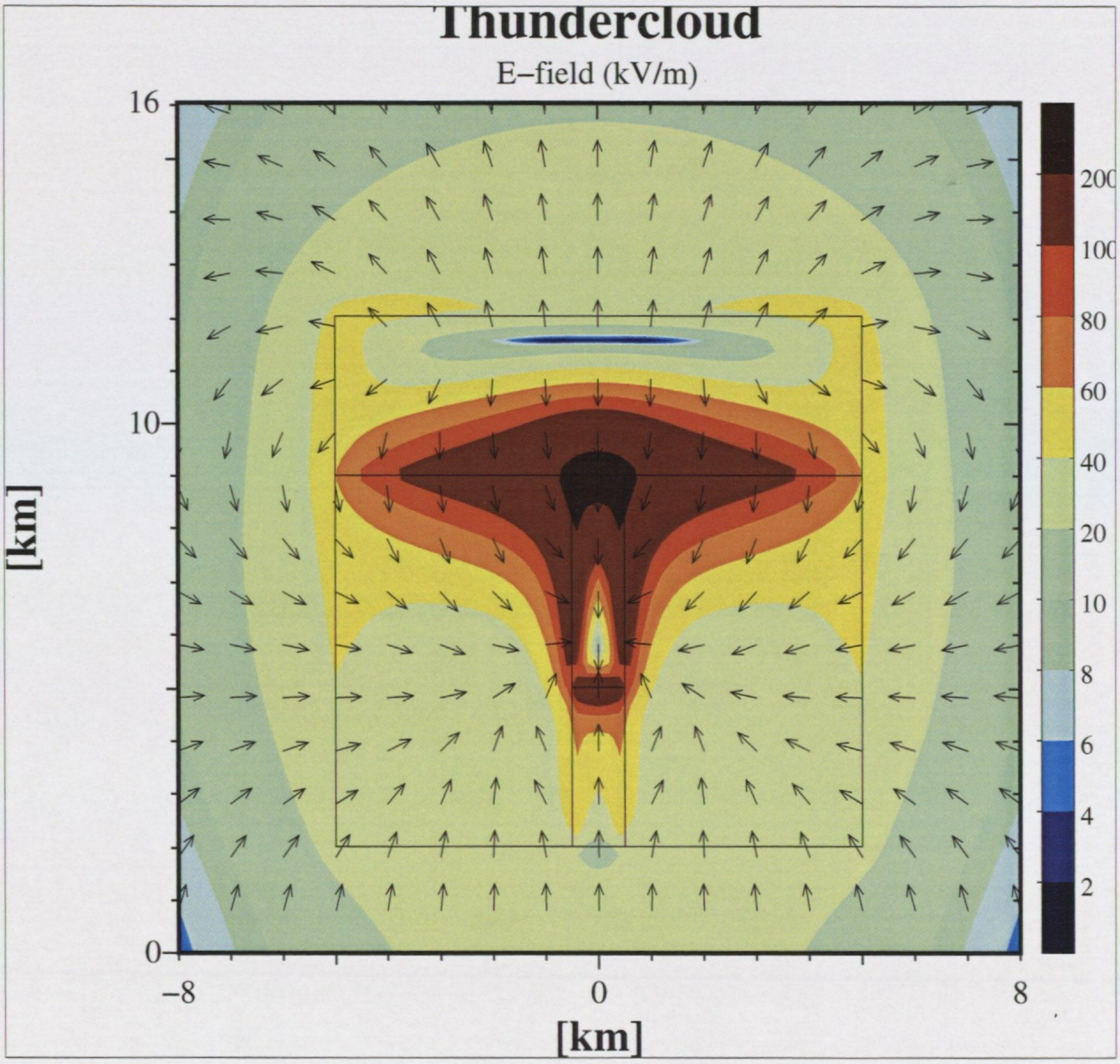



Figure 10

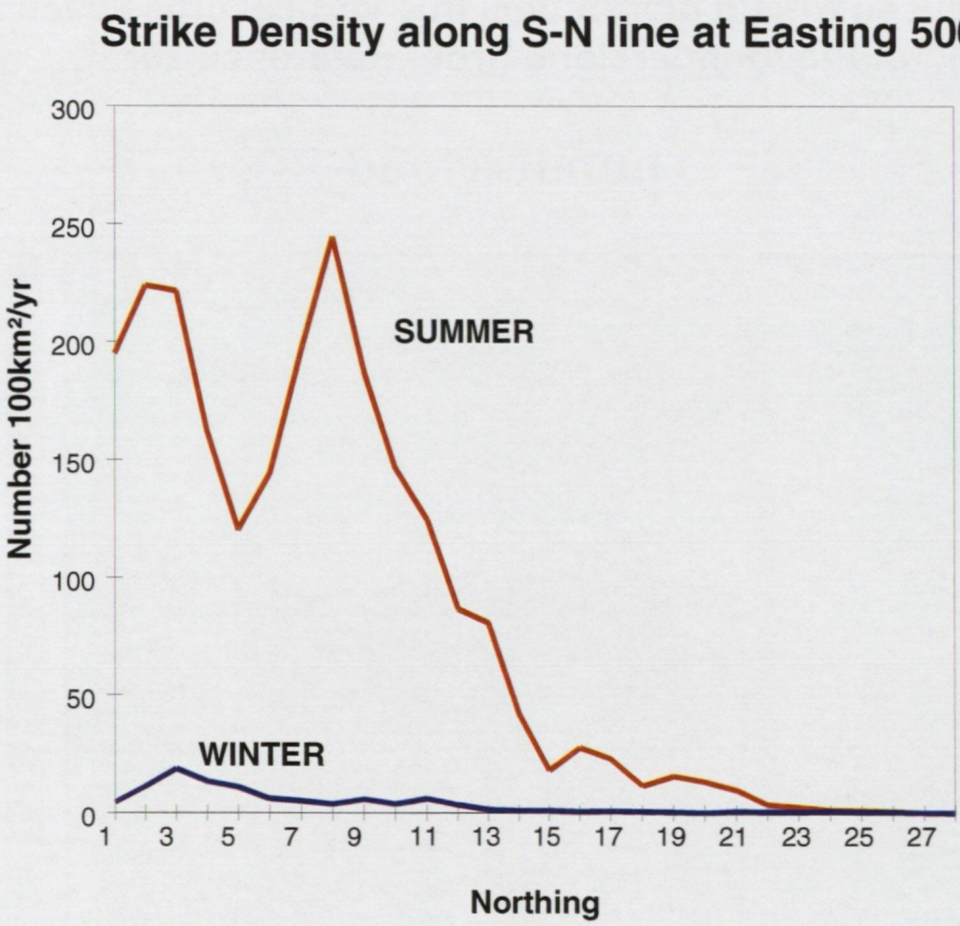



Figure 11

E A Technology data – Cloud to Ground Strikes

## Fraction of Strikes of Positive Polarity along S-N Line at Easting 500

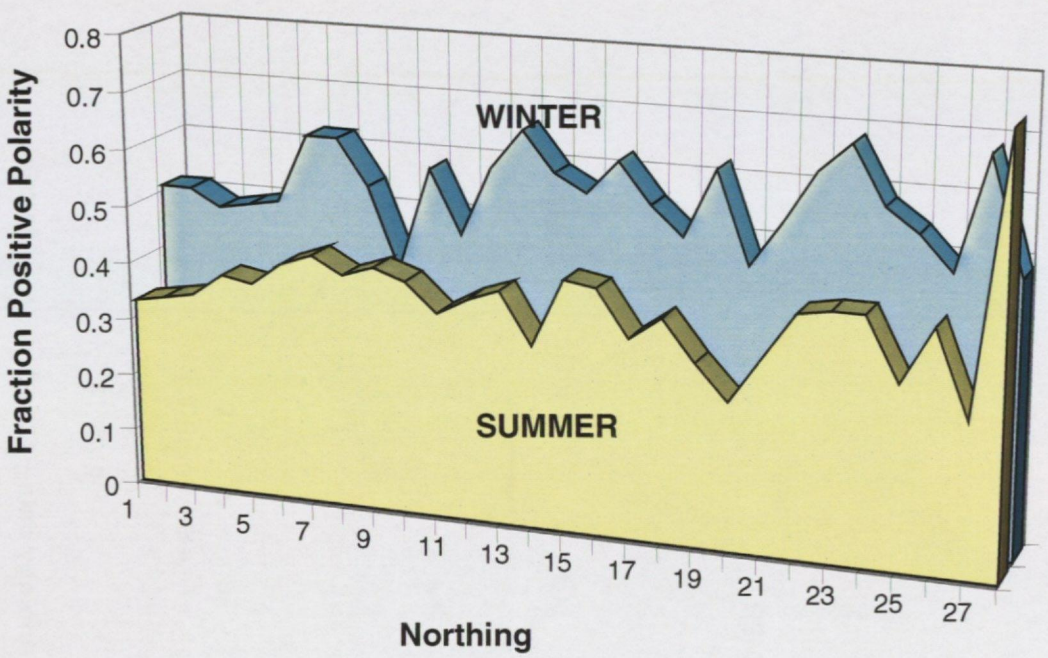



**Figure 12**

**E A Technology data – Cloud to Ground Strikes**

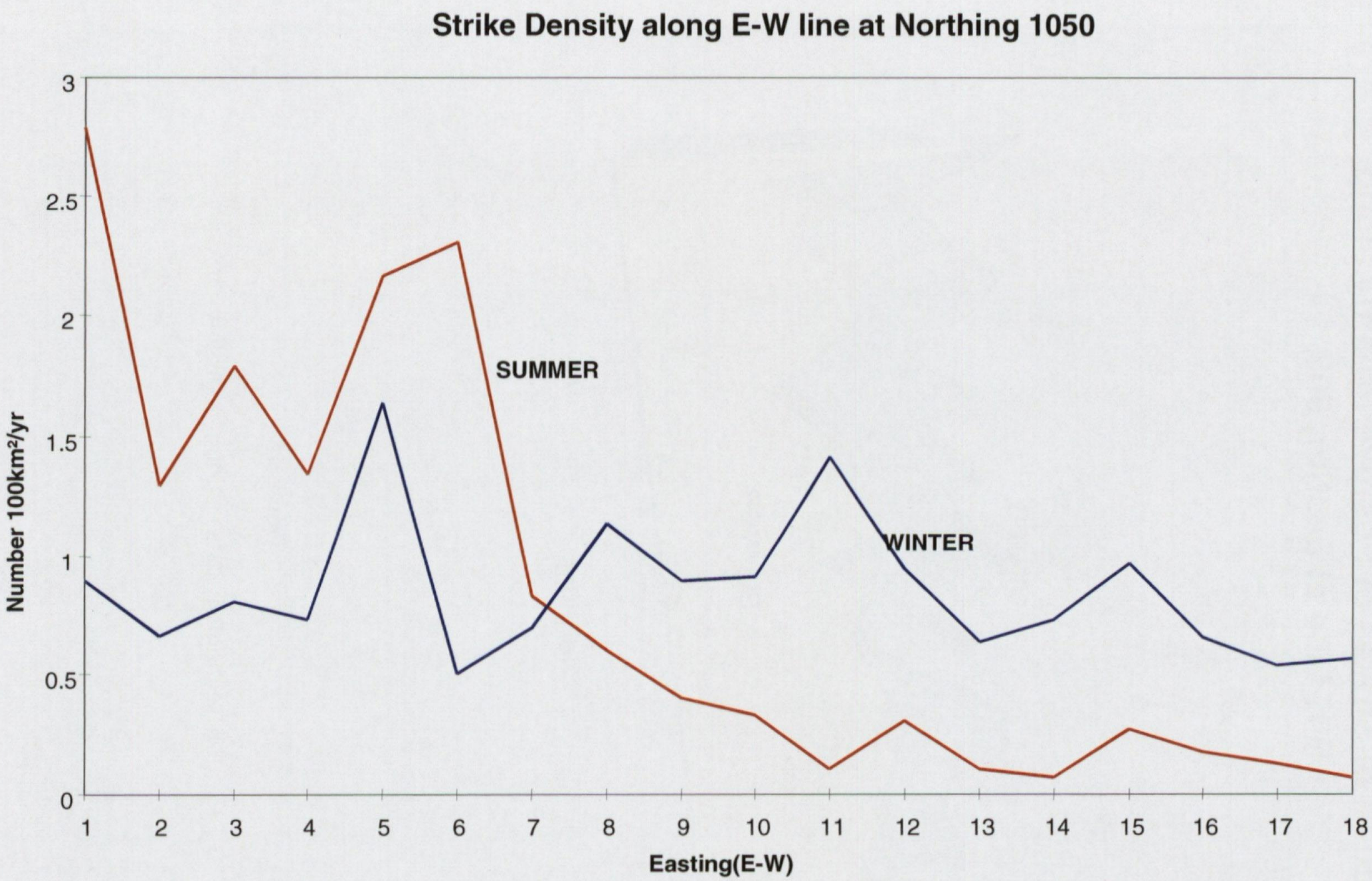



Figure 13

E A Technology data – Cloud to Ground Strikes

## Fraction of Strikes of Positive Polarity along E-W line at Northing 1050

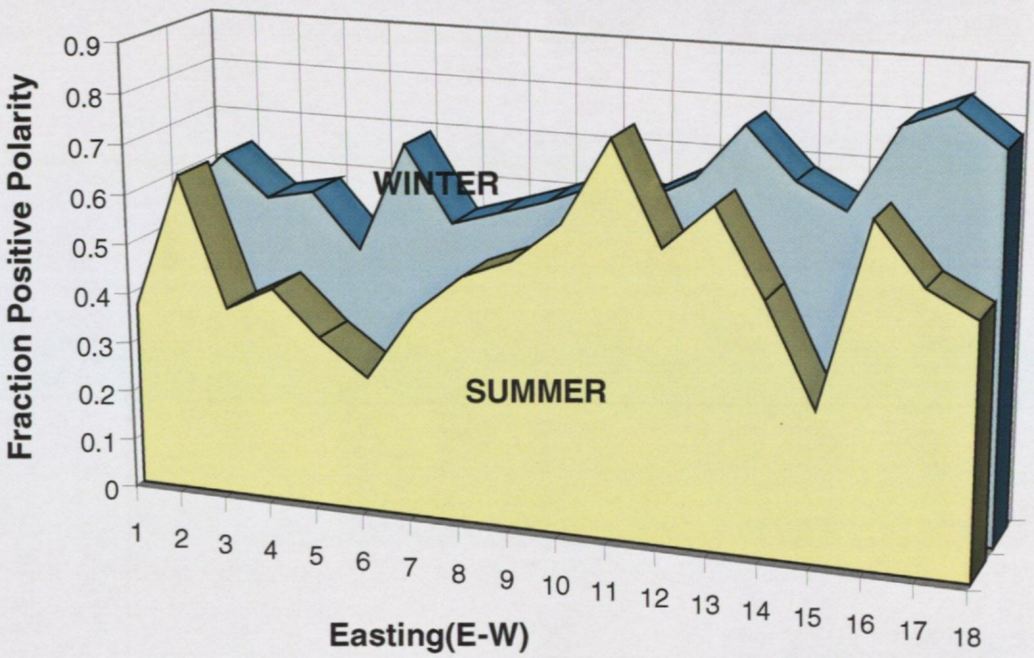



**Figure 14**

**E A Technology data – Cloud to Ground Strikes**

**Distribution of relative positions of convective cloud base, freezing level and helicopter height. CAPE values for the respective incidents are also shown**

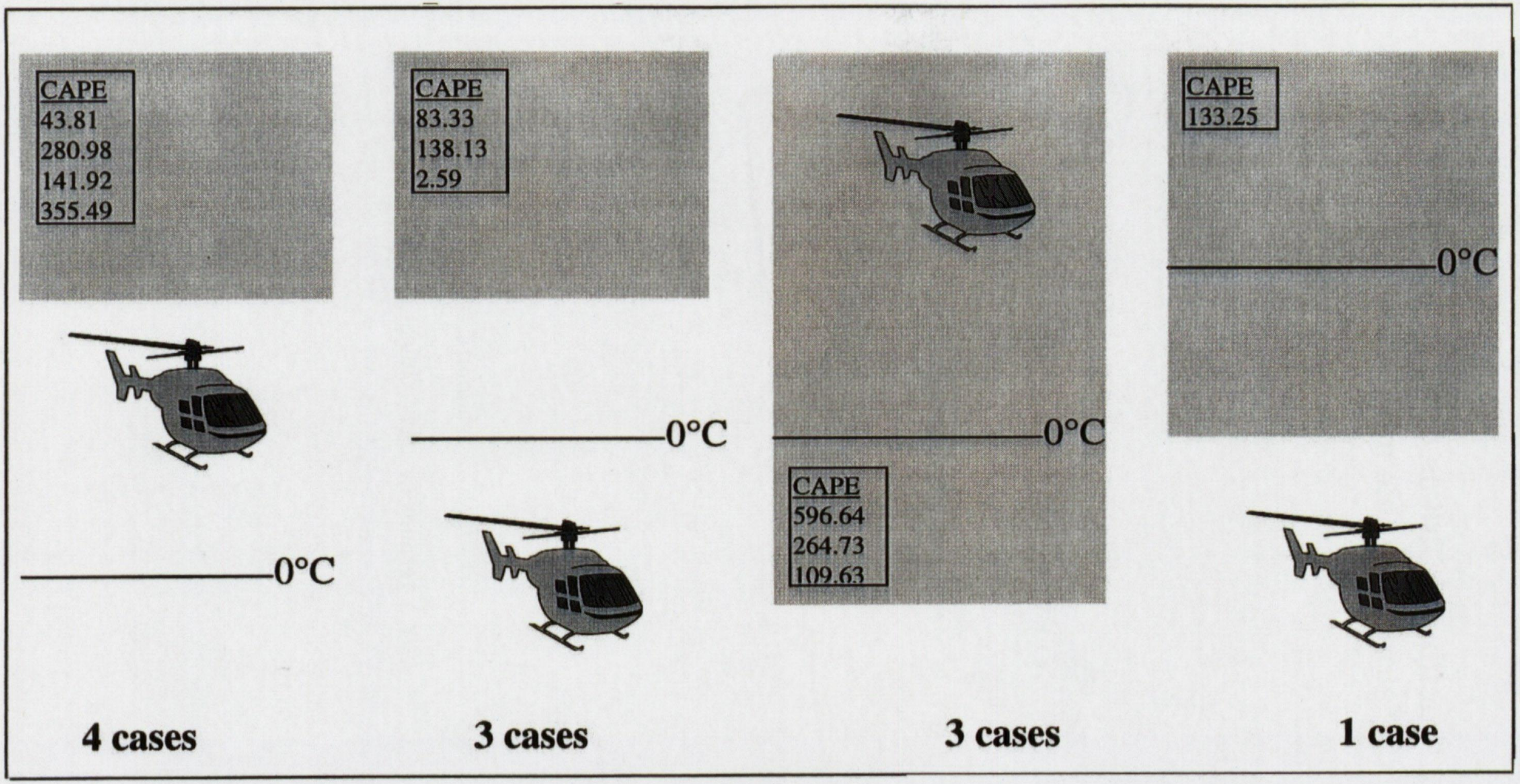



Figure 15

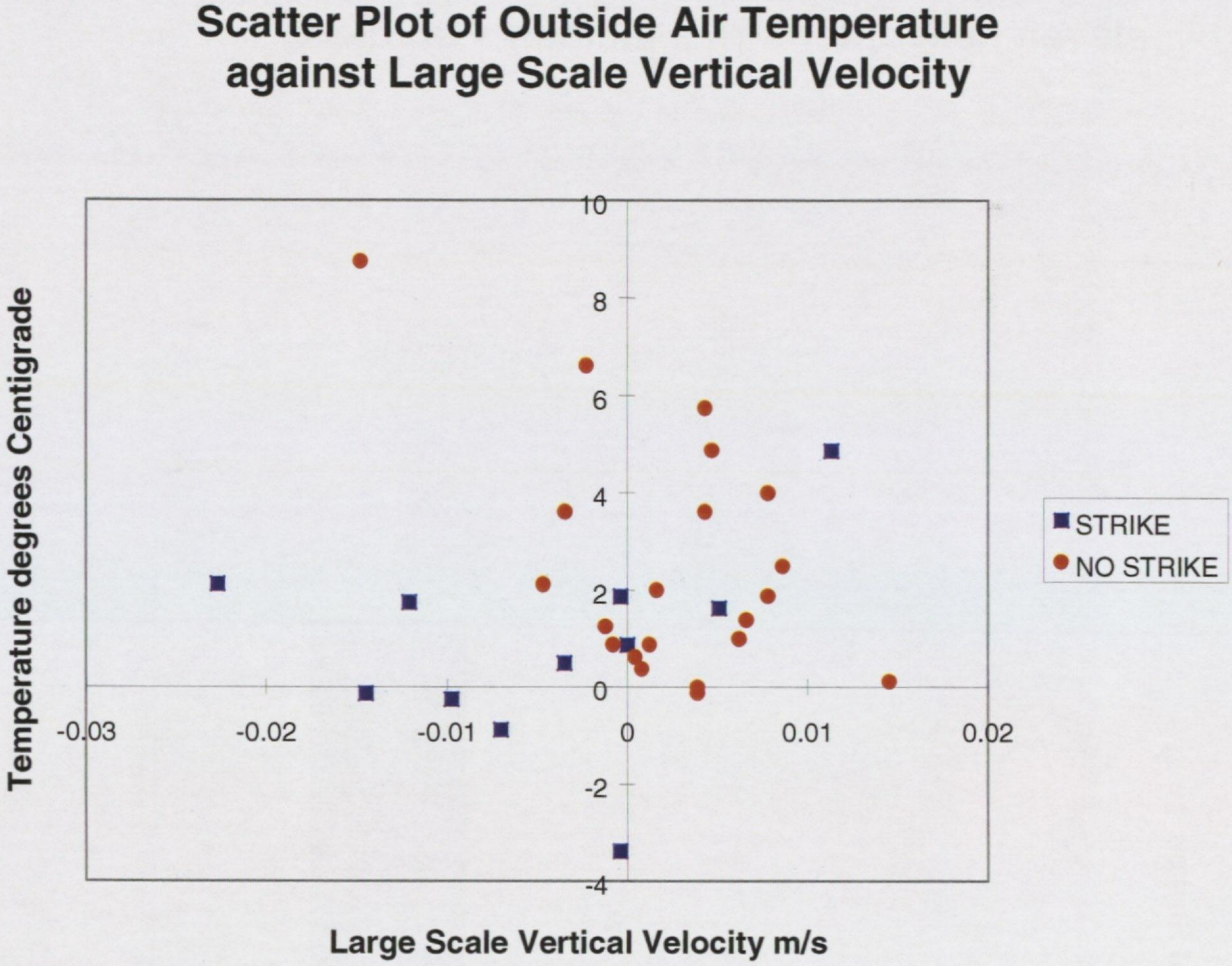

Scatter Plot of Outside Air Temperature against Large Scale Vertical Velocity
Temperature degrees Centigrade
Large Scale Vertical Velocity m/s
10
8
6
4
2
0
-2
-4
-0.03
-0.02
-0.01
0
0.01
0.02
STRIKE
NO STRIKE

Figure 16

## Height of–10 degree Centigrade Temperature for the eleven helicopter strike incidents studied.

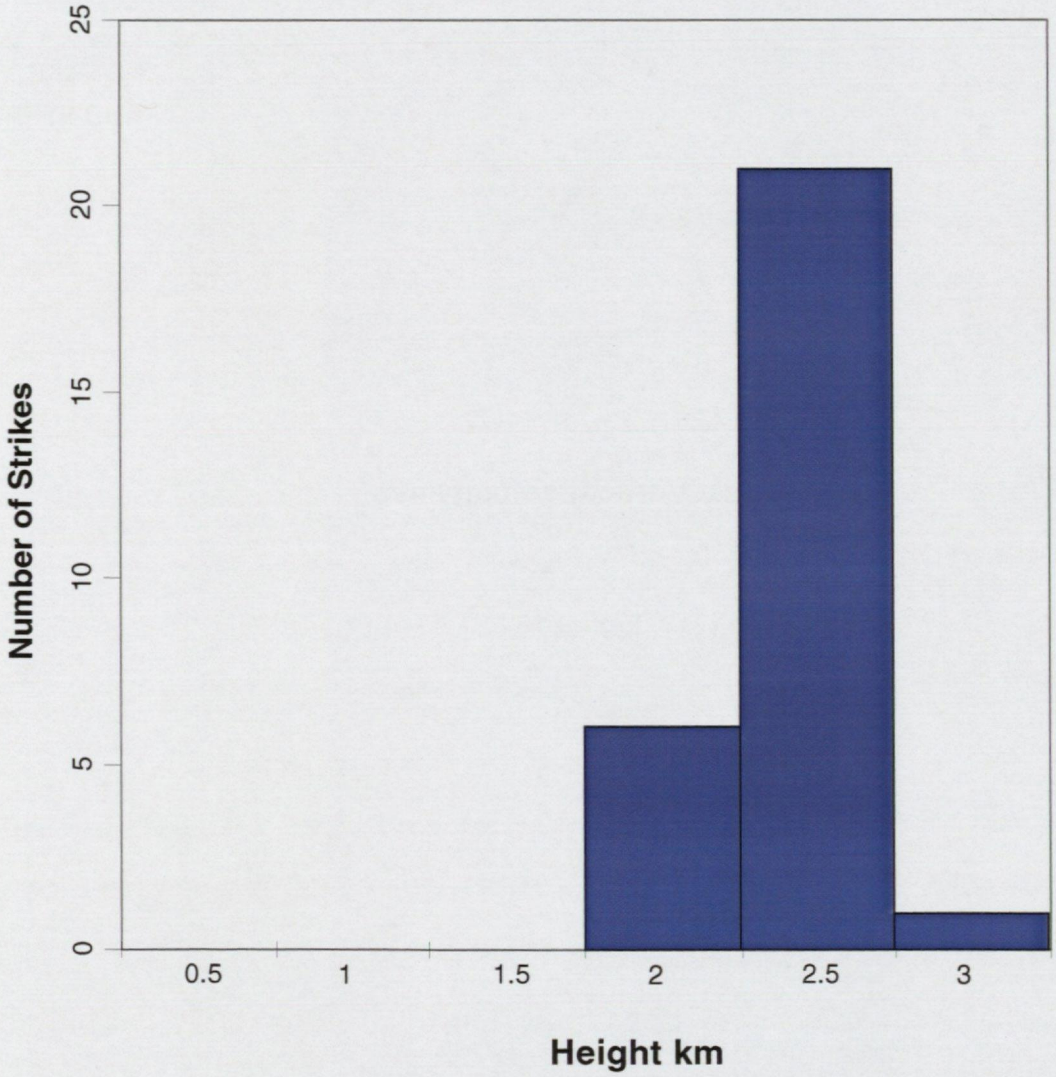



Figure 17

**dbZ returns for conventional and LDR radars at the time of an aircraft triggered event (from Reference 20)**

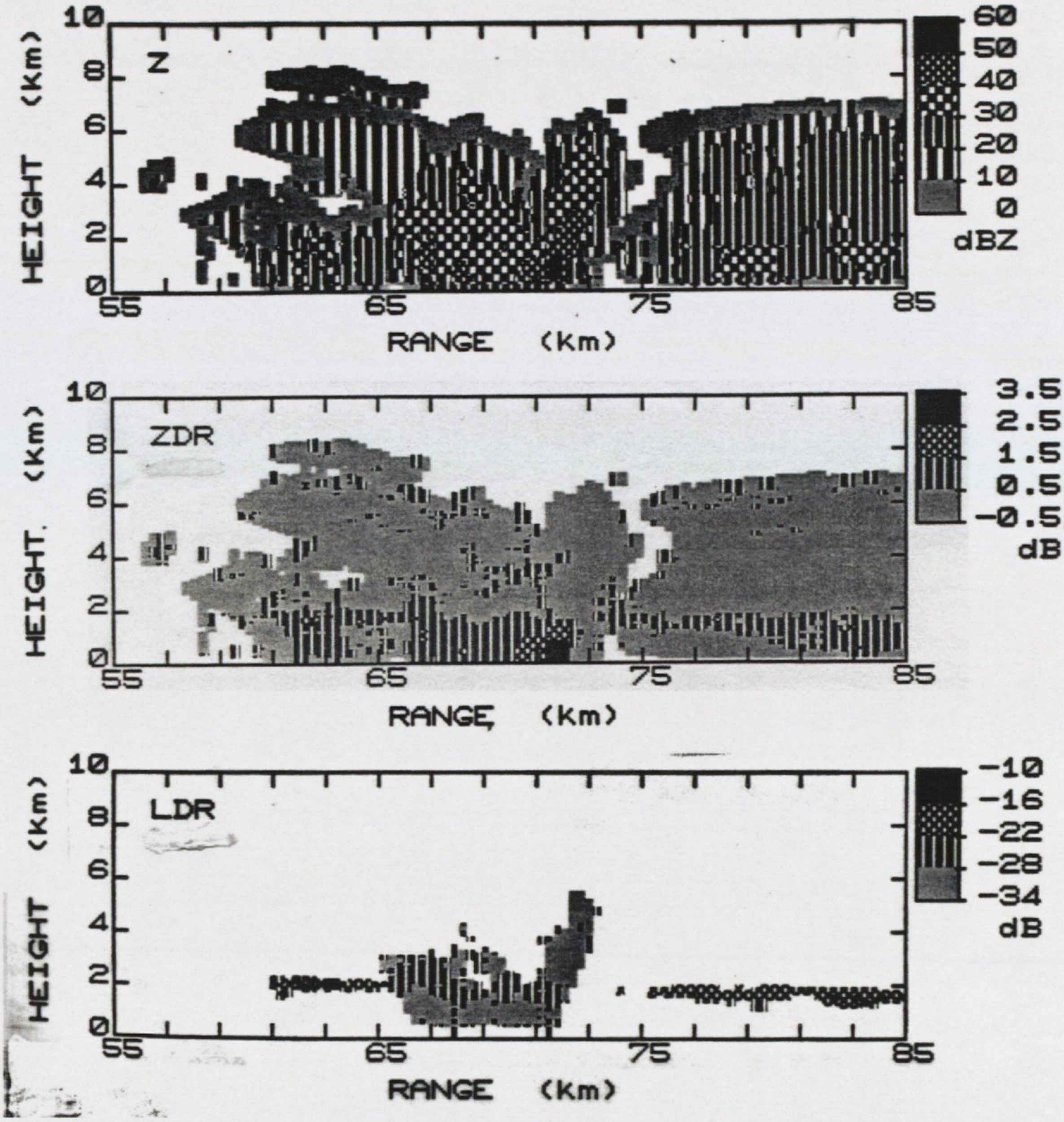



Figure 18