Numerical **Weather Prediction**

Forecasting Research
Technical Report No. 253

Lightning strikes to helicopters over the North Sea

by

R Patton

September 1998

The Met.Office

Excelling *in weather services*

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Abstract.

A preliminary study to investigate lightning strikes to helicopters operating over the North Sea showed that on a significant number of the events the pilots reported no previous lightning activity to be present. This led to the hypothesis that the helicopter triggered the lightning strike as a result of its presence at that point in space and time. Fourteen incidents dating back to 1992 have been studied. The analysis of the synoptic data (synoptic charts and satellite pictures) showed that in all cases being studied, cumulonimbus (Cb) clouds were in the vicinity. This information is not strictly in contradiction to the previous study in that the Cbs may not have started producing lightning until the helicopter flew into it.
A null data set was generated from dates, times and locations when similar Cb clouds were present alongside helicopters and a lightning strike did not occur. The Met. Office NWP model data from both strike and null data sets were used in a statistical regression analysis. The resulting statistical model equation uses temperature and vertical velocity as key predictors of a lightning strike to helicopters operating in this region such that the probability of the results being random were less that 1 in 100.

Lightning strikes to helicopters over the North Sea

1. Introduction

A preliminary study to investigate lightning strikes to helicopters operating over the North Sea showed that on a significant number of the events the pilots reported no previous lightning activity to be present. This led to the hypothesis that the helicopter triggered the lightning strike as a result of its presence at that point in space and time. This study set out to investigate the meteorological conditions surrounding the lightning strikes. Eleven incidents dating back to 1992, have been studied. Data have been extracted from Met. Office archives for the dates and times of the incidents. The analysis of the data (synoptic charts and satellite pictures) showed that in all eleven cases being studied, cumulonimbus (Cb) clouds were in the vicinity. This information is not strictly in contradiction to the previous study in that the Cbs may not have started producing lightning until the helicopter flew into it. It is true to say, however, that large, charged regions will have developed within these Cbs.
A null data set was generated from dates, times and locations when similar Cb clouds were present alongside helicopters and a lightning strike did not occur. The meteorological data from this null data set were then compared with the meteorological data from the eleven strike incidents that are being studied in depth. Many parameters were studied individually and a couple of them are detailed here. The only really useful results obtained came from a logistic regression analysis which combined the various parameters to produce a statistical equation which predicts the likelihood of a lightning strike.
Please note that this technical report is a scaled down version of the report submitted to AEA Technology plc, the customer for this work. A copy of the full report is available on loan from Neil Halsey.

2. Data

Synoptic charts, radiosonde data, sferics data, satellite data and model data were extracted for the 11 incidents to be studied. These data are referred to throughout this report as the 'strike data set'. It became apparent that the original plan to obtain data for incidents occurring from 1988 was over optimistic due to changes in the way that satellite, radiosonde and model data are produced and archived. Many of the changes took place during 1992 and so it was decided that data were to be obtained for all events from 30/10/92 inclusive for which there is an accurate time and location (in longitude and latitude). The annex shows the data from the dates studied that were unobtainable.
In addition to this, radiosonde data and model data were extracted to form a 'null data set'. The null data set was generated from days on which either thunderstorms or deep convective cloud was seen by ground observing stations in the Shetlands and along the eastern coast of the UK. For the analysis to be valid the following assumptions are made.

1. The data set of lightning strikes to helicopters must be complete.
2. Helicopter flights must have taken place on the days selected for the null data set.

The CAA (Civil Aviation Authority) provided confirmation of the above assumptions. In some of the analyses described the null data set and the strike data set are compared. Note that the null data set contains 21 dates from the Lerwick area and three dates from the Hemsby area. It should also be noted that the three dates from the Hemsby area are in the summer months.

3. Qualitative data analysis

The synoptic charts and the satellite data provide a large-scale appreciation of the meteorological situation. Each incident was studied in qualitative terms in order to find any similarities in the general synoptic situation. Contour plots of meteorological parameters from the Limited Area Model (LAM) also gave an insight to the large-scale situation.

Convective activity is reported in land observations plotted on the synoptic charts and confirmed by satellite imagery in all eleven cases. In five of the eleven cases the lightning strike to the helicopter follows the passage of a cold front 3–7 hours previously. In four of the cases a trough has been identified and is either overhead the incident location at the time of the incident or has passed overhead in the previous 6 hours. In one case there was the recent passage of an occluded front, in the final case no fronts were in the vicinity.

Precipitation was reported in all of the cases studied. In two cases the precipitation was all frozen (snow or hail), in three cases it was non-frozen (rain) and in six of the eleven cases both frozen and non-frozen precipitation was observed in the vicinity.

The winds varied in strength and direction and no correlation is found between the cases.

Three patterns are identified from an inspection of the NWP model output:

- In 5 of the 7 cases for which convective rain rates are available, we see that the helicopter was on the edge of cells of high convective rain rate.
- In 6 of the 11 cases the helicopter was very close to the 0 Pa s^{-1} contour. That is to say that the helicopter was close to the point at which ascending and descending air meet.
- In 3 of the 11 cases the vertical structure of the humidity showed a 'sandwich' of dry air between two layers of moist air. In the other cases, no pattern in the humidity cross-section was noted.

The implications of these three patterns are discussed in section 5, *Conclusions and discussion.*

4. Quantitative Data Analysis

4.1 Cloud base and dewpoint depression

Given the fact that all the incidents took place in the months October to March, it was thought that there might be some correlation between the convective cloud base and the months of the year. It was hoped that the observations of cloud base made hourly from Lerwick and Hemsby would prove that the convective cloud base was lower in the winter than in the summer. Unfortunately, for Lerwick no variation in the convective cloud base exists. There is a slight variation for Hemsby with a summer peak being visible.

The lack of variation in cloud base on a month-to-month basis was not expected. Given that the cloud base recorded by a human observer could be subjective the dew-point temperature was extracted for 1997. It was expected that the dew-point depression (and therefore the convective cloud base) would be higher in the summer months. Whilst the dew-point depression does change from month to month there is no trend to support the theory that convective cloud base is lower in the winter than in the summer.

It must be remembered that only data from 1997 were used in the analysis and that 30 years of data may be more representative.

4.2 Tephigram Analysis

A tephigram analysis of the convective cloud base, the freezing level and the height of the helicopter was done for both the null and strike data sets.

It was found that there was no difference in cloud base between the two data sets. When the strike data set is compared with the Hemsby cases included in the null data set it is noted that the freezing level is lower and the cloud depth shallower in the strike data set. With the Hemsby cases removed however, the freezing level in the null data set becomes lower than the strike data set. The cloud depth is still shallower in the strike data set but by a smaller margin. In effect, removing the Hemsby data makes the null data set more similar to the strike data set.

A significance test shows that both with and without the Hemsby cases included in the null data set there is no significant difference in the means between the strike and null data sets. If the results from the strike incidents are considered in isolation we see that there are six possible arrangements of convective cloud base, freezing level and helicopter height in the vertical plane. Only four of them are represented by the incidents being studied. Figure 1 shows a scale plot of the three parameters for each of the incidents with incident number plotted along the x-axis and height in hPa along the y-axis. It is worth noting that in 7 of the 11 incidents studied the entire cloud was below freezing and in 8 of the 11 cases the helicopter was below the base of the cloud. In the remaining 3 incidents the helicopter was 20–40 hPa (600–1200 ft) above the base of the cloud.

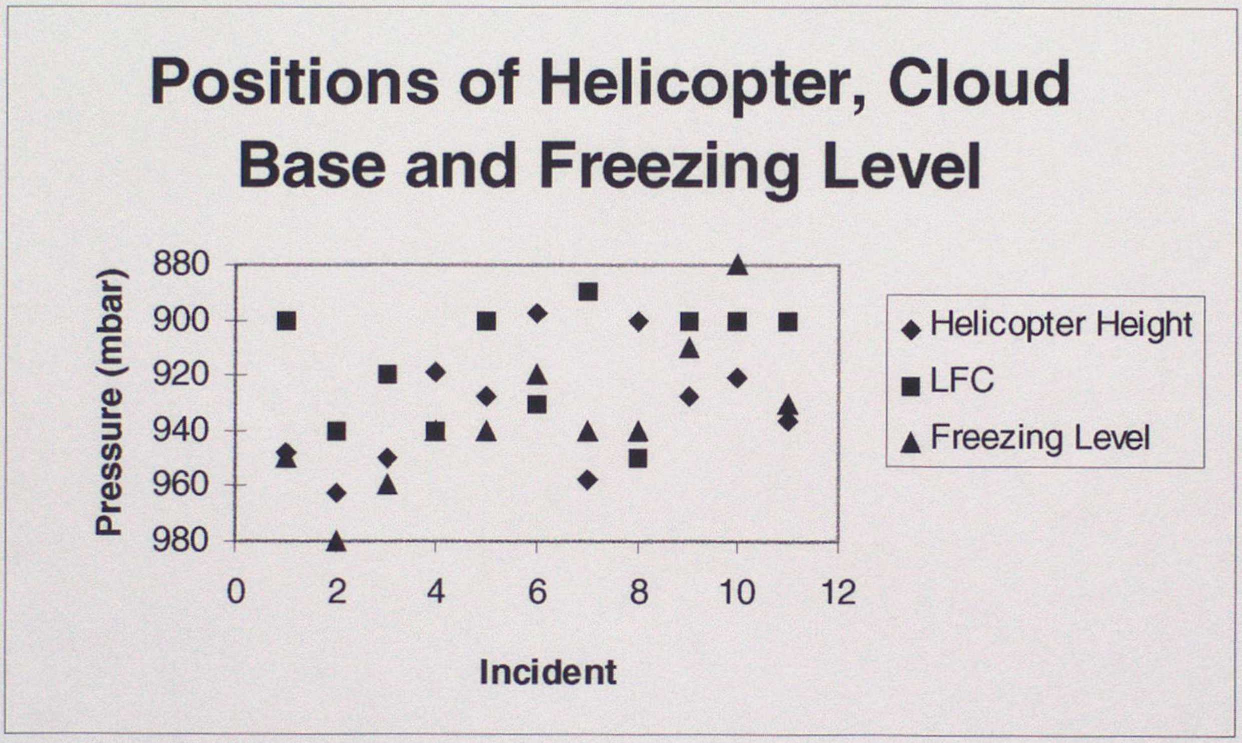

Figure 1. Relative positions of convective cloud base, freezing level and helicopter height.

The CAPE was also calculated for both data sets. The mean CAPE is lower in the strike data set than in the null data set when the Hemsby cases are included. When the Hemsby cases are removed the CAPE is still lower in the strike data set than the null data set but by a smaller margin. A significance test shows that both with and without the Hemsby cases included in the null data set there is no significant difference in the mean between the strike and null data sets. Following the inconclusive nature of the convective cloud base, freezing level and CAPE results it was thought that there may be some relationship between the CAPE and the cloud depth for the different data sets. The vertical velocity is proportional to the square root of the CAPE so if the CAPE is divided by the cloud depth, the resultant parameter is an indicator of the acceleration within the cloud.

Again, it is found that there is no significant difference in the values of this parameter between the strike and null data sets. A significance test shows that both with and without the Hemsby cases included in the null data set there is no significant difference in the mean between the strike and null data sets.

4.3 Sferics data

Data were extracted from the Met. Office archive for the 11 incidents that are being studied. Table 1 below gives details of the time, latitude and longitude of the incident, the time, latitude and longitude of the nearest sferic recorded and the total number of sferics that were recorded within 400 km of the incident on the entire day in question. The 7 sferics marked with an asterisk in Table 1 are considered to be a good spatial and temporal match to the incident since they are within 10 n mile and 8 minutes of the incident. It is considered that the accuracy of the incident report may not be much better than this. No good sferic match was found for the remaining 4 of the incidents.

Date	Incident latitude	Incident longitude	Incident time	Latitude of nearest sferic	Longitude of nearest sferic	Sferic time	Total no. of sferics	
26/11/96	53.85	1.42 E	14.56	53.90	1.50 E	14.53	1	*
08/02/96	60.68	1.25 E	10.30	60.75	1.45 E	10.22	1	*
08/12/95	60.33	0.33 E	10.48	60.62	0.20 W	10.44	34	
01/03/95	60.00	1.00 W	09.07	60.02	0.85 W	09.05	49	*
21/02/95	59.33	1.00 E	09.18	59.47	1.20 E	09.13	15	*
19/01/95	58.47	0.85 E	12.34	58.47	0.95 E	12.29	307	*
03/10/94	60.30	0.32 E	13.50	59.35	2.15 E	14.03	3	
20/02/93	60.08	1.05 W	11.25	60.00	1.05 W	11.19	42	*
18/02/93	60.17	1.20 E	17.06	60.67	1.10 E	17.03	11	
15/01/93	57.08	0.60 W	16.00	56.97	0.55 W	15.55	167	*
30/10/92	60.97	1.42 E	10.04				27	

Table 1. Temporal and spatial match between incident and observed sferics. Sferics marked with an asterisk indicate a good match (within 10 n mile and 8 minutes).

It can be seen from Table 1 that there is a great deal of variability in the total number of sferics, with a minimum of one sferic on the two 1996 incidents and a maximum of 307 on the January 1995 incident. A closer inspection of the time sequence of the 307 sferics showed that the location and time of the incident could have been predicted as being of high risk as a large number of sferics were observed in the area shortly before the incident took place. Time sequences for the other incidents showed that a similar prediction could not have been made. It is believed that the two cases in 1996 were triggered by the helicopter since only one sferic was recorded on each day and these reports were a good match in both time and location to the incident concerned. Data were also extracted for an incident on 26 February 1996 for which the only location given from the pilot report was '35 n mile east of ?'. On that date, only one sferic was reported at the exact time of the incident 35 n mile east of Sumburgh. Despite this finding, this incident has not been included in the other data analyses.

4.4 Regression analysis

The technical name for the regression analysis applied to the data is logistic regression analysis. In simple linear regressions both 'cause' and 'effect' data types are continuous (for example temperature versus rainfall). In this lightning scenario, the 'cause' data are continuous (e.g. temperature, relative humidity) but the 'effect' data are not continuous but discrete or categorical. The two categories involved here are 'lightning strike' or 'no lightning strike'. The data that have been extracted for the strike data set fall into the 'lightning strike' category. As described earlier, a null data set has been generated, containing meteorological data for the 'no lightning strike' category so that the parameters extracted can be compared.

The parameters taken from the model output for the strike data set are valid for the nearest grid point (in the horizontal and the vertical) to the incident. Rain rates and the cloud water and cloud ice content are not available for incidents in 1992 and 1993, however. Also worthy of note is that vertical velocity and relative humidity from the model are not available on all model levels during these years.

The parameters taken from the model output for the null data set were taken at 59° N, 1° E for the Lerwick-centred dates and at 53.85° N, 1.42° E for the Hemsby-centred dates. The Lerwick position was chosen from an inspection of the distribution of the strike incidents. The Hemsby position was chosen as the location of the one helicopter strike that occurred in that area.

A vertical profile of temperature and relative humidity was also taken. These two parameters were input to the CAPE calculating routine to obtain CAPE values from cloud base up to cloud top, cloud base up to the –10 °C isotherm and from cloud base up to the –15 °C isotherm. These two extra values of CAPE were added because Kitagawa and Michimoto (1994) say that the vertical velocity at the –10 °C isotherm has implications for the electrical structure of the cloud (CAPE is proportional to the vertical velocity).

The complete list of parameters compared in the regression analysis is given below.

- Data type (0 for null data set, 1 for strike data set in the Lerwick area, 2 for the strike data set in the Hemsby area)
- Temperature
- Temperature (average of four points surrounding the strike incident)
- Relative humidity (average of four points surrounding the strike incident)
- Vertical velocity
- Vertical velocity (maximum of four points surrounding the strike incident)
- Convective rain rate
- Convective rain rate (maximum of four points surrounding the strike incident)
- Convective cloud depth
- Cloud ice content
- Cloud water content
- Freezing level
- Total positive CAPE
- Positive CAPE up to –10 °C isotherm
- Positive CAPE up to –15 °C isotherm
- Logical parameter indicating whether base of cloud is higher than the freezing level (0 if yes, 1 if no)

The correlations were calculated initially to highlight those parameters that were highly correlated (over 90%) with each other. CAPE to the –10 °C Isotherm and CAPE to the –15 °C isotherm were highly correlated with the CAPE up to cloud top so both of these parameters were rejected at this stage. The freezing level was highly correlated with the temperature so the freezing level was also rejected.

The regression analysis, which gave the best model fit to the data, was then done twice. The first regression included the Hemsby data and the second regression did not. Three tables are presented for each analysis:

- a model summary which gives the overall level of fit with the regression;
- a coefficients table giving the coefficients for each of the parameters used in the regression;
- a contingency table which gives a comparison of the forecast and actual data types (strike or null),

It should be noted in these results that the vertical velocity output by the model is the *large-scale* vertical velocity and that negative values indicate upward movement of air. A large negative vertical velocity indicates that there is large-scale ascent and therefore instability. Instability gives rise to convective cloud. It is *not* the same as the convective-scale vertical velocity, which would be considered to be correct in a thunderstorm cell. The convective vertical velocity is proportional to the square root of the CAPE.

In the first regression which included the Hemsby cases, we asked the statistical model to predict either zero, one or two representing null case at Lerwick, strike case and null case at Hemsby, respectively. In the second regression, the model had to predict either one or zero representing null case at Lerwick and strike case, respectively. A stepwise technique was used to select the most appropriate variables.

It can be seen that when the Hemsby cases are included, convective rain rate, total positive CAPE, temperature and vertical velocity are chosen. When the Hemsby cases are excluded, temperature and vertical velocity are chosen. This affects the number of cases for which there is a forecast outcome. For example, the convective rain rate is not available for the four oldest strike cases. Therefore, the statistical model that has been derived cannot forecast whether or not a strike would have occurred without this information. This is reflected in the totals in the contingency tables.

It is thought that total positive CAPE and the convective rain rate were chosen in this analysis in order for the model to distinguish between the Hemsby null cases and the Lerwick null cases: these parameters being distinguishing factors between the two. The temperature is almost certainly included because of the proximity of the helicopters to the freezing level. Vertical velocity is almost certainly included because of the instability of the atmosphere in the regions under consideration in each case.

When comparing the summaries of the two statistical models in Tables 2 and 5 we see that a much better adjusted R square is given with the Hemsby cases included than when they are excluded. This implies that the model including the Hemsby cases is better. The most important aspect of the comparison though concerns the contingency tables, which are given in Tables 4 and 7. With the Hemsby cases excluded, the statistical model predicted 7 out of the 11 strike cases and all of the null cases correctly. The performance of the model, which included the Hemsby cases, was much worse. Only 3 out of 7 strike cases were predicted correctly and 21 out of 24 null cases were predicted correctly. Tables 3 and 6 show the coefficients that are used in the statistical model equations.

The equation for the Hemsby cases being included is:

$$\textbf{strike/no strike} = -8.6547 - 4489.6802 \times \text{CRR} + 0.0304 \times \text{CAPE} + 0.331 \times \text{T} - 3.9006 \times \text{VV}$$

The equation for the Hemsby cases being excluded is:

$$\textbf{strike/no strike} = 19.1068 - 0.0683 \times \text{T} - 2.605 \times \text{VV}.$$

where CRR = convective rain rate, T = temperature and VV = vertical velocity.

4.4.1 Hemsby Cases Included

R[1]	R square[2]	Adjusted R square[3]	Std. Error of the estimate
0.7153	0.5117	0.4365	0.5044

Table 2. Model summary for Hemsby cases included in the regression analysis. Predictors used are a constant, vertical velocity, temperature, convective rain rate and total positive CAPE.

	Unstandardised coefficients		t[4]	Significance[5]
	B	Std. Error		
(Constant)	–8.6547	7.4169	–1.1669	0.2538
Convective rain rate	–4489.6802	1933.7182	–2.3218	0.0283
Total positive CAPE	0.0304	0.0088	3.4401	0.0020
Temperature	0.0331	0.0270	1.2265	0.2310
Vertical velocity	–3.9006	1.5704	–2.4838	0.0198

Table 3. Model coefficients for Hemsby cases included in the regression analysis.

	Forecast			
Actual		Strike	Null	Total
	Strike	3	4	7
	Null	3	21	24
	Total	6	25	31

Table 4. Contingency table for Hemsby cases included in the regression analysis.

4.4.2 Hemsby cases excluded

R	R square	Adjusted R square	Std. Error of the estimate
0.5504	0.3029	0.2548	0.4166

Table 5. Model summary for Hemsby cases excluded from the regression analysis. Predictors used are a constant, vertical velocity, temperature.

	Unstandardised coefficients		t	Significance
	B	Std. Error		
(Constant)	19.1068	8.5760	2.2279	0.0338
Temperature	–0.0683	0.0312	–2.1884	0.0368
Vertical Velocity	–2.6050	0.9257	–2.8142	0.0087

Table 6. Model coefficients for Hemsby cases excluded in the regression analysis.

[1] R is the correlation coefficient between the predicted answers and the actual answers. Takes values between -1 and +1.

[2] R square is the square of R and is therefore an increasing function taking values between 0 and 1.

[3] R square is adjusted such that it takes into account the number of cases included and the number of variables and is intended to represent the whole population rather than this small sample.

[4] t indicates the level of importance of the variable relative to the other variables used in the model. The higher the absolute value, the higher the level of importance.

[5] Significance indicates the percentage probability that the variable concerned is irrelevant. The lower the number, the more significant the variable.

	Forecast			
Actual		Strike	Null	Total
	Strike	7	4	11
	Null	0	21	21
	Total	7	25	32

Table 7. Contingency table for Hemsby cases excluded in the regression analysis

4.4.3 Summary of regression analysis

The regression has produced 2 statistical models which uses only two or four parameters to predict strike and null cases with a statistically significant degree of skill. This is borne out by the Tables 8 and 9 given below which show the expected frequencies for the contingency tables given a *random* distribution. As can be seen the statistical model performs much better than a random distribution.

Hemsby cases included

	Forecast			
Actual		Strike	Null	Total
	Strike	2	5	7
	Null	5	19	24
	Total	7	24	31

Hemsby cases excluded

	Forecast			
Actual		Strike	Null	Total
	Strike	4	7	11
	Null	7	14	21
	Total	11	21	32

Tables 8 and 9. Contingency tables for Hemsby cases included (left) and excluded (right) in the regression analysis if guesswork was applied.

The contingency tables show the model with Hemsby cases excluded to be better. Subsequent discussion on the statistical model will be concerned with this 2-parameter model only. A χ^2 test of the statistical model from the 'Hemsby excluded' regression analysis shows that the probability of obtaining the same results by guesswork are considerably less than 1%.

Figure 2 shows the values that the statistical model predicted for the strike and null cases. The cut-off of 0.5 is clearly shown. Three of the four strike incidents that were predicted as null cases are seen to be well below the cut-off. If the cut off had been moved to 0.4 (for example) there would have been 8 out of 11 strike cases predicted correctly and 27 out of 32 null cases correctly.

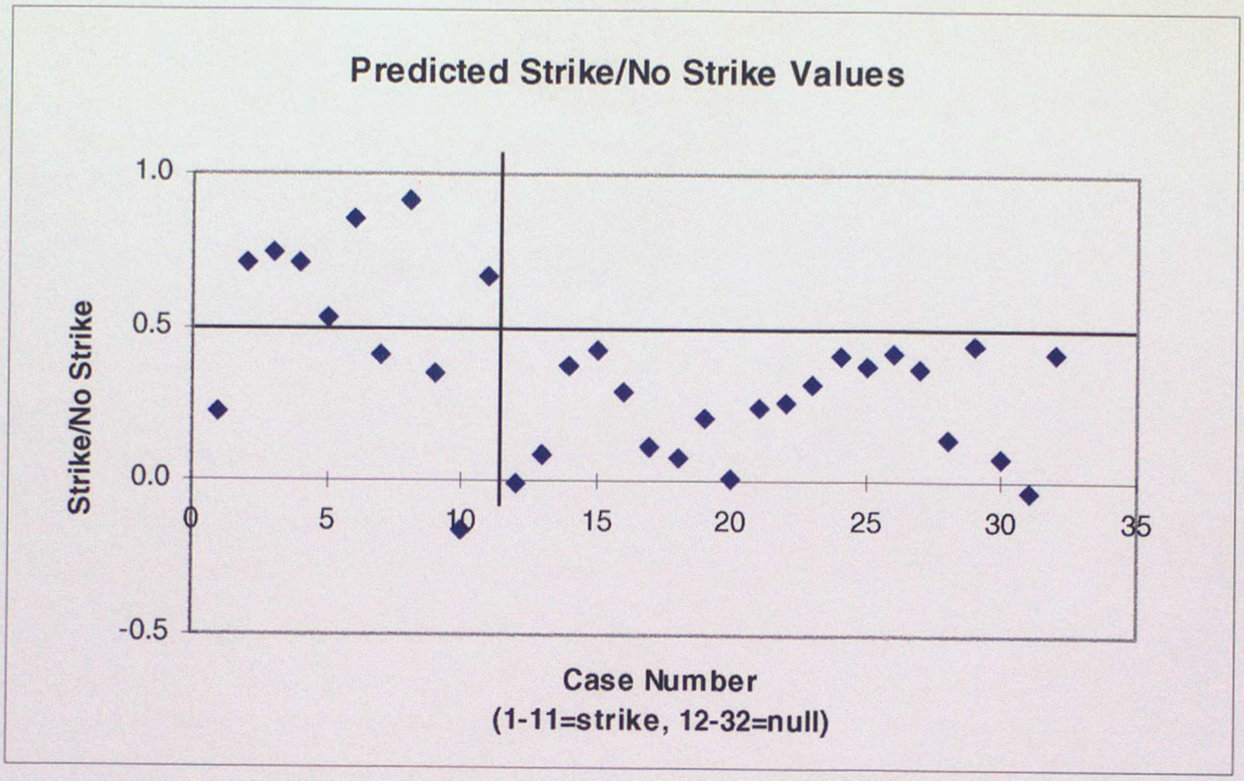

Figure 2. Predicted values of strike/no strike from the statistical model.

It should be noted that this regression has had only a very limited amount of data to analyse. With a much larger data set the results may well have been quite different. For example, the total positive CAPE was calculated using only 9 values of temperature and relative humidity. If this calculation was done in real time with all 31 values from the model, quite different values for total positive CAPE could have been obtained. This in turn would have had an effect on the parameters chosen for the model.

5. Conclusions and discussion

1. Convective activity is observed from the ground and confirmed by satellite imagery in all the incidents studied.
2. A front or a trough is either present or has been present in the preceding 3–7 hours in 10 out of the 11 cases studied.
3. Precipitation is observed by trained meteorological observers in all cases.
4. In 7 of the 11 cases sferics reports were found to coincide with the time and location of the incident. In 2 of these 7 cases, the sferics report was the only one recorded on the day in question implying the helicopter triggered the lightning strike. In 9 of the 11 cases the number of strikes per day was less than 50.
5. The height of the cloud base as recorded by a human observer does not vary from month to month. The height of the cloud base therefore can not explain the absence of summer strikes. This result is verified by an analysis of the dew-point depression which is a more objective indicator.
6. The mean height of cloud base, height of freezing level and cloud depth obtained from the tephigram analyses for the strike data set are not significantly different to those values obtained for the null data set.
7. According to the tephigram analysis the helicopter was below the base of any convective cloud in 8 out of the 11 cases. In 7 out of the 11 cases the entire cloud was below the freezing level.

8. There is no difference between the strike and null data sets for values of the ratio of CAPE to cloud depth.
9. A statistical model using temperature and vertical velocity as variables was derived which predicted 28 out of 32 strike/no strike incidents correctly.

General meteorology

Kitagawa and Michimoto (1994) describe meteorological aspects of winter thunderstorms which form over the Sea of Japan. Typically dry polar air masses are advected over the warm sea current which can cause intense tropospheric instability which in turn leads to thunderstorms. Strong vertical wind shear is reported and the vertical extent is said to be half that observed in the summer storms. The storm duration is shorter in the winter than in the summer and single flash storms are common in winter.

Price and Penner (1997) comment that the lightning frequency varies according to cloud height. They cite different relationships for continental areas and marine areas. These are given below:

Lightning frequency for continental thunderstorms: $F_c = 3.44 \times 10^{-5} H^{4.92}$

Lightning frequency for marine thunderstorms: $F_m = 6.40 \times 10^{-4} H^{1.73}$

where H = convective cloud-top height in kilometres.

As can be seen, the lightning frequency over the sea is proportional to the square (approx.) of the convective cloud-top height whereas land thunderstorms have lightning frequencies which are proportional to the fifth (approx.) power of the convective cloud-top height. They say that marine thunderstorms have very weak updraft intensities which result in very low lightning frequencies.

These two effects, the winter nature of the North Sea incidents studied here and the fact that all the incidents occurred over the sea would mean that we should expect low lightning frequencies in the storms found there. With the exception of the incidents on 19/1/95 and 15/1/93 all lightning rates were below 50 per day in the strike data set. Climatology suggests that on days when sferics are reported during the winter, the mean number of sferics over the northern North Sea is of the order of 500. The days studied in this report therefore, have a lower than average daily lightning frequency for days on which sferics were detected.

Influence of precipitation

Rudolph *et al.* (1986) describe lightning strikes to an instrumented aircraft and report that the majority of strikes were encountered in regions of zero or negligible precipitation. They observed two maxima of lightning sources at 6 km and 12 km altitude. Both of these altitudes are much higher than the altitudes applicable to the North Sea incidents (1–2 km). However, the paper considers particles to be an important factor in the model that they derived. The particles may increase the propagation speed of the lightning channel or even initiate a lightning strike. Note that particles and precipitation have different meanings.

Gardiner and Hallett (1985) state categorically that the charging of their aircraft only occurred in the presence of ice but calculate that the charge gained on the aircraft was a result of the ice impacting the aircraft rather than the transfer of charge already carried by the ice particle. Both vapour grown ice crystals and graupel charged the aircraft. Lightning strikes to the aircraft did not appear to be correlated with an increase in either the aircraft charge or the electric field in the vicinity of the aircraft. They concluded that the aircraft was simply in the path of naturally occurring lightning strikes. This conclusion is in doubt however as they were only measuring the electric field in the vertical plane.

Sheridan *et al.* (1997) present a linear relationship between total cloud-to-ground lightning strikes and the mean precipitation over a region. They report a great variation from region to region and from month to month. They do not examine the relationship on the scale of isolated storms.

The influence of precipitation seems to be a little confused which may be due in part to the definitions of cloud particles and precipitation. Rudolph *et al.* (1996) remain clear of precipitation yet Gardiner *et al.* (1995) are sure that the aircraft charging is due to ice crystals and graupel, the former being of cloud particle size and the latter being a precipitation-sized particle. Having said that the aircraft charging itself did not seem to play a part in the initiation of a lightning strike to the aircraft.

The results presented in this study show that precipitation was observed from the ground on all cases. Of the seven incidents which have valid model values for cloud ice and cloud water, four have cloud ice and one has cloud water at the incident location. Five of the seven incidents show that the helicopter is on the edge of regions of high convective rain rate.

Vertical velocity

Sheridan *et al.* (1997) give the relationship between CAPE and vertical velocity that is described earlier in this report and state categorically that a higher vertical velocity results in more efficient charge separation and therefore greater lightning activity. Volland (1995) goes on to explain that the maximum vertical velocity provides an upper limit to the size of the ice (graupel and hail) particles that grow by riming in the mixed-phase region[6] of the atmosphere. They say that the updraft speed of most interest is actually below the cloud top. This means that the vertical velocity used should not be derived from the total CAPE calculated to the cloud top but should be that which is calculated to a lower altitude and consequently a higher temperature. This is the reason we used CAPE values up to the –10 °C and –15 °C isotherms in the regression analysis.

Clearly the vertical velocity inside a thunderstorm cell is of great importance in any study of lightning. However, the vertical velocity that was chosen by the regression analysis from the many model parameters that were input, represents the large-scale vertical velocity which is averaged over 50 km. It is not the vertical velocity discussed in these papers which is on the scale of only a few kilometres. In 6 of the 11 cases studied, the model data contour plots showed the helicopter to be very close to the 0 Pa s^{-1} contour which means that the helicopter is close to the point where ascending air and descending air meet. Without going into too much detail, the air that is following directly behind a front tends to be descending for approximately 30–60 km before the air starts to ascend. There is an increase in the risk of organised convection at the changeover from descent to ascent. This is a large-scale feature which is predicted well by the numerical model.

Electrical structure

As hinted above, it is the electrical structure of the thundercloud which is affected by the vertical velocity. Kitagawa and Michimoto (1994) say that the winter storms over the Sea of Japan have updraught velocities that are so low that the familiar dipole structure of thunderclouds (positive at the top, negative in the middle to lower parts of the cloud) lasts only a matter of minutes. They say that the positive monopole structure dominates for the remainder of the life-cycle once the negatively charged larger particles have been rained out. The tripolar structure which has an additional smaller positively charged region at the base of the cloud, depends on the altitude of the –10 °C isotherm according to Kitagawa and Michimoto (1994). If this temperature level is lower than 1.4 km then the tripole structure is not observed. They also say that the vertical velocity at this temperature must be greater than 2 m s^{-1} for the tripolar charge distribution to occur. Feynman *et al.* (1977) say that the lower positively charged region occurs at a lower altitude than the 0 °C isotherm (i.e. at a higher

[6] The mixed phase region in a thunderstorm is typically between 0°C and -40°C and contains both frozen and liquid water.

temperature). In contradiction to Feynman *et al.*(1977) Williams *et al.* (1994) say that the lower positive charge originates within the mixed-phase region between the main negative charge region and the 0 °C isotherm. Weber *et al.* (1993) simply report that the positively charged region at low levels contributes to the occurrence of cloud-to-ground lightning. Bullock and Jones discuss the presence of areas of positive charge at 4.9 km. Again this is much higher than the operating height of the helicopters which were struck by lightning over the North Sea. They report that their aircraft was struck by lightning once on entering such a charge region and once on leaving it. They report that at that time, the aircraft was in a large electric field gradient. This is compounded by Bicknell and Shelton (1985) who say that the largest ambient fields are on the periphery of a negative or positive space-charge volume. Unfortunately this study does not present data on the electrical structure of the atmosphere at the times and locations of the North Sea incidents since none is available. It is worthy of note that in 7 of the 11 cases the tephigram analyses indicated that the entire cloud was below the freezing level. If Williams *et al.* (1994) were to be correct then a tripolar structure would have been present in these seven cases. It is likely that the geographical location of these different studies will affect the patterns they observe in the electrical structure and therefore not all of them may be appropriate to the geography of the North Sea. Further examination of this aspect is not within the scope of this study.

Humidity

Small (1995), Hewston (1996a) and Hewston (1996b) all present hypotheses on the meteorological conditions surrounding the presence of charged regions in the atmosphere. In particular they consider the approach of a warm front which slides vertically above colder air. Middle-level altostratus cloud and embedded cumulus cloud associated with this front can become positively charged. Dry air that is forced down by the approaching front is rained into from these positively charged clouds. The rain evaporates on meeting the dryer layer, leaving a pocket of charged air behind. In three of the 11 incidents studied the model indicated a 'sandwich' of dryer air exists between two layers of moister air which could support this hypothesis. Further study of this aspect was beyond the scope of this study because of the lack of accurate observations in the North Sea to support the model data.

6. Summary

Many theories have been examined in this study yet no single element has been found capable of identifying why helicopters should be struck by lightning on one day and not on another during which cumulonimbus clouds were observed. Any patterns that have been detected and commented on can only remain as conjecture in the context of forecasting lightning strikes to helicopters over the North Sea.

The story is not all bad news. It has been found that the combination of vertical velocity and temperature in a statistically derived equation predicted 28 out of 32 strike/no strike cases correctly. This combination is clearly the way forward in the development of any forecast tool which has the advantage of using automated model data. Consequently, the forecasts would be both timely and cost effective.

In all the data analyses conducted the issue of the very small data set always has to be considered. As time progresses, the data set can only grow and therefore the ability to forecast the likelihood of a lightning strike can only improve.

7. Further work

The results have proved encouraging enough to start negotiations on a follow up contract with the CAA. At the time of writing this report the proposal for the development work is well under way. It's contents are outlined below.

In the run up to Winter 1998-1999 the strike/no strike equation and presentation of the output will be refined according to the user requirement that will be obtained from the helicopter operators. An example of the type of plot which could be produced is given in Figure 3.

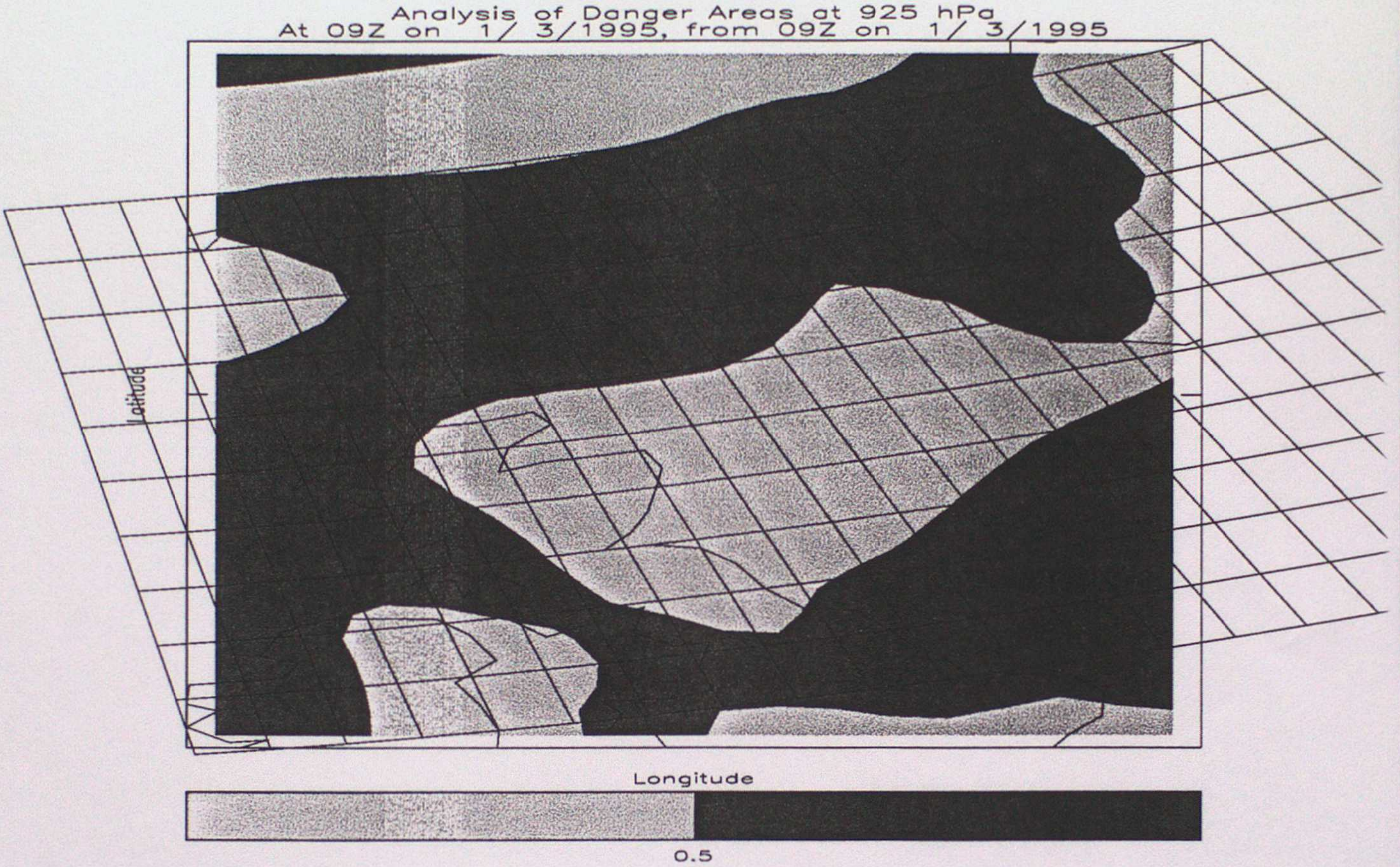

Figure 3. Sample plot of areas of increased risk which would form part of the feasibility study.

The operators will trial output of this nature during winter 1988-1999 and provide feedback as to how it could be improved. Once the trial is complete the forecasts from the trial will be verified as part of a feasibility study to determine the benefits of developing a full forecast tool for winter 1999-2000.

It is hoped that additional data from a flight trial and additional incidents will be included in the refinement of the predictive equation at a later stage in time for winter 1999-2000.

8. Acronyms

ATD Arrival Time Difference
CAA Civil Aviation Authority
CAPE Convective Available Potential Energy
LAM Limited Area Model
MCS Mesoscale Convective System
NOAA National Oceanic and Atmospheric Administration
NWP Numerical Weather Prediction
SIAG Satellite Image Applications Group
UTC Universal Time Clock

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Annex : Missing data		Time	Synoptic charts	Satellite Images			Model data	Radiosonde ascents
				I/R	VIS	WV		
31	30-Oct-92	10:04	✓	✓	✓	✓	all parameters at 1000 and 925 hPa	✓
32	15-Jan-93	16:00	✓	✓	✓	✓	rain rates, cloud water & cloud ice at all levels	✓
33	18-Feb-93	17:06	✓	✓	✓	✓	vertical velocity at 950, 400 and 300 hPa	✓
34	20-Feb-93	11:25	✓	✓	✓	✓	relative humidity at 250 hPa	✓
36	03-Oct-94	13:50	✓	✓	✓	✓	✓	✓
37	19-Jan-95	12:34	✓	✓	✓	✓	✓	✓
38	21-Feb-95	09:18	✓	✓	✓	✓	✓	✓
39	01-Mar-95	09:07	✓	0900	0900	✓	✓	✓
40	08-Dec-95	10:48	✓	✓	✓	✓	✓	✓
42	08-Feb-96	10:30	✓	✓	✓	✓	✓	✓
43	24-Feb-96	14:30	✓	✓	✓	✓	✓	✓
46	26-Nov-96	14.56	✓	1200	1200 1500	✓	✓	✓