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A FURTHER STUDY OF LIGHTNING STRIKES TO HELICOPTERS OVER THE NORTH SEA

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1 SUMMARY

This report presents research conducted at the UK Meteorological Office (UKMO) in fulfilment of Phase I of the UKMO development proposal 'Lightning Strikes to North Sea Helicopters'.[1]

The research involved the development and evaluation of two types of lightning forecast for use by North Sea helicopter operators. These were the Patton forecast for predicting triggered lightning and the NIMROD forecast for predicting natural lightning.

Patton and NIMROD forecasts were issued throughout the winter of 1998/99, with the forecasts being placed on the Internet for access by the helicopter operators. This successfully demonstrated the viability of the Internet for forecast dissemination.

Verification of the Patton forecasts failed to show that the forecasts accurately predicted areas of high lightning strike risk. However it could not be concluded that the forecasts were inaccurate because the data set used for verification was extremely small, consisting of just 3 new lightning strike events.

The Patton equation used for generating the Patton forecasts was refined from that derived in a previous study, by improving the derivation technique and incorporating additional data from 3 new strike events. The refinement was minor however, with the updated equation being very similar to the original version.

Verification of the NIMROD forecasts showed that they successfully identified areas of high lightning density. However the verification also showed that the probability of natural lightning interception by a helicopter is extremely low, such that the benefit of using NIMROD forecasts for North Sea flight planning would be limited.

2 INTRODUCTION

The objective of the project was to provide trial forecasts for identifying where helicopters are at risk from lightning strikes, and to verify the accuracy of these forecasts. There are two types of lightning strike; triggered lightning and the interception of naturally occurring lightning. Thus two types of forecast were required.

2.1 Patton forecasts

The Patton forecast method was derived in a previous UKMO study into the meteorological conditions associated with lightning strikes to helicopters operating over the North Sea [2]. In this study the UKMO developed an equation that with reasonable accuracy differentiated between the meteorological conditions for which strikes did and did not occur. This was called the Patton equation. The Patton equation had as independent variables data produced by the UKMO's Numerical Weather Prediction (NWP) model, while the dependent variable was termed the P-number. This was sensitive to the meteorological conditions that lead to triggered lightning strikes because the Patton equation was derived by investigating actual strikes to helicopters, the majority of which were probably triggered events. The study concluded that a forecast tool based on P-numbers could potentially provide valuable guidance to North Sea helicopter operators.

2.2 NIMROD forecasts

NIMROD is an operational UKMO forecasting system that provides short-range forecasts of the development and movement of rainfall and associated variables such as visibility and lightning [3]. The forecast method essentially extrapolates trends in observational data using variables output by the NWP model. In the case of lightning the observational components are the sferics recorded by the UKMO's lightning detection system. Sferics are low frequency radio signals emitted by lightning which can be used to determine the time and location of lightning strikes. The NIMROD lightning forecasts identify where helicopters are at risk of intercepting naturally occurring lightning because the vast majority of sferics are from naturally occurring strikes.

3 TRIAL PATTON FORECASTS

Trial Patton forecasts for the North Sea area were placed on the Internet in November 1998. They were updated throughout the following winter on a daily basis except for on a small number of occasions when UKMO computer failures rendered this impossible. The forecasts were password protected and only made available to the CAA and representatives of Bond Helicopters, Bristow Helicopters and British International Helicopters.

The forecasts were produced using the Patton equation described above. The equation did not incorporate the refinements discussed in section 5, as had been originally envisaged, because these developments were not complete until the concluding stages of the project.

The format for the presentation of the Patton forecasts was discussed at a meeting between the CAA, the UKMO and representatives of the helicopter operators. It was agreed that the UKMO should define the initial format, and that this should be modified during the trial period according to feedback from the helicopter operators. The UKMO therefore attempted to present the forecasts in a manner that would allow quick assessment of the forecasts in an operational situation. This initial format remained unchanged throughout the trial period.

The Internet site established by the UKMO is shown in Figure 1. From this website there was access to both Patton forecasts (under the heading 'Daily forecasts using the Patton algorithm') and NIMROD forecasts (under the heading 'Short period lightning forecasts').

As can be seen from Figure 1, Patton forecasts were issued for a range of times and altitudes. These forecasts were all calculated from the output of a NWP model run at midnight and were not updated throughout the day, allowing inspection by the helicopter operators just once per day prior to flight planning. The forecasts were uncontoured to maintain clarity and simply highlighted those regions in the North Sea where the P-number was greater than a danger threshold value of P-number = 0.5. An example of such a forecast is shown in Figure 2.

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CAA/Met Office Lightning Forecast Trial for North Sea Helicopter Operators.

Note: ***At this stage the models used for this trial have not been fully developed and as such should not be used in any way to predicate flight operations.***

Short period (Up to 3 hours) lightning forecasts.

Current Analysis	Forecast +30 mins	Forecast + 1 hour	Forecast + 1 hour 30 mins	Forecast + 2 hours	Forecast + 2 hours 30 mins	Forecast + 3 hours

Daily forecasts using the Patton Algorithm.

06:00 UTC	09:00 UTC	12:00 UTC	15:00 UTC	18:00 UTC	21:00 UTC
1000 FEET	1000 FEET	1000 FEET	1000 FEET	1000 FEET	1000 FEET
2000 FEET	2000 FEET	2000 FEET	2000 FEET	2000 FEET	2000 FEET
3000 FEET	3000 FEET	3000 FEET	3000 FEET	3000 FEET	3000 FEET
5000 FEET	5000 FEET	5000 FEET	5000 FEET	5000 FEET	5000 FEET

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Figure 1: The UKMO website that provided access to the NIMROD and Patton forecasts.

Forecast at 06:00 UTC 1000 Feet

[UP] | [NEXT]

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Figure 2: A Patton lightning forecast produced by the UKMO, as displayed on the Internet. Outlines of Scotland and southwest Norway are shown, and the North Sea oil rigs are represented by triangles. The green areas are where forecast P-numbers are greater than the threshold value of 0.5.

4 PATTON FORECAST VERIFICATION

Verification of the Patton forecasts can be performed in two ways. The first approach is to confirm that recent lightning strike events would have been successfully predicted by the forecasts, such that the helicopter was in a high risk area with P-number > 0.5. The second approach is to compare the Patton forecasts with the general occurrence of North Sea lightning. Results obtained for the two verification methods are presented here.

4.1 Verification against recent events

The details of four recent lightning strike events are given in Table 1. From this table it can be seen that for two of the events the forecast P-number was greater than 0.5, such that the helicopter was identified as being in a high risk area. For another event the forecast P-number may have been greater than 0.5, depending on the unknown altitude of the helicopter. For the remaining event the P-number was less than 0.5.

Table 1: Details of 4 recent lightning strike events. The location of the event on 24 Feb 1996 was identified through association with a sferic [2]. The altitude of the helicopter for the event on 12 Dec 1997 is unknown.

Date	Time	Longitude	Latitude	Altitude (ft)	P-number	Sferic detected
24 Feb 1996	14:30	0.1 W	59.9 N	3000	0.60	Yes
12 Dec 1997	12:50	7.5 W	59.8 N	1000? 2000? 3000?	0.45? 0.45? 0.68?	No
04 Feb 1998	17:00	0.1 E	60.6 N	2000	1.22	No
04 Mar 1998	09:23	1.8 E	56.6 N	2000	0.42	Yes

Estimates for the probability of achieving this success rate by chance alone are calculated in Table 2, considering just the three cases for which the helicopter altitude is known.

Table 2: Estimates for the probability of correctly forecasting by chance the 3 events for which helicopter altitude is known. See the text for details.

Altitude	Probability (P-number > 0.5)	Probability (2 or more successes)
1000 ft	0.18	0.086
5000 ft	0.40	0.352

The first column in the table is the probability of a forecast P-number being greater than 0.5, as calculated from the Patton forecasts issued during January – March 1999 using the formula:

$$\text{Probability (P-number} > 0.5) = \frac{\text{Number of P-numbers} > 0.5}{\text{Total number of P-numbers}} \qquad (1)$$

This probability is only available for altitudes of 1000 and 5000 ft because forecast details for the intermediate altitudes were not archived. However it can be safely

assumed that the probability increases with increasing altitude between the two levels.
The second column in the table is the probability of achieving the success rate by chance alone. Each probability is calculated from the corresponding probability in the first column, using binomial statistics. The calculations assume that all of the strikes occurred at the same altitude, being 1000 or 5000 ft as appropriate.

The results in Table 2 show that the probability of achieving the success rate by chance alone is between 8.6 and 35.2%, given that the strikes all occurred at altitudes of between 1000 and 5000 ft. It therefore cannot be concluded that Patton forecasts successfully identify areas of high lightning strike risk.

4.2 Verification against sferics

For each Patton forecast, sferics detected within a 3 hour period centred on the forecast time were retrieved from the UKMO database. Each of these sferics was then associated with a P-number, this being the P-number at the position in the forecast corresponding to the geographical location of the sferic. This association was performed for each of the altitudes for which forecasts were issued.

Probability density distributions for the sferic associated P-numbers are plotted in red in Figure 3, for altitudes of 1000 and 5000 ft. Only a small number of sferics were detected during the trial period and so there is random variation on the data.

Also plotted in Figure 3, for comparison purposes, are probability density distributions for all of the P-numbers contained in the Patton forecasts. These curves are plotted in blue and are smoother than those for the sferic associated P-numbers because of the large number of P-numbers contained in the forecasts during the trial period.

If there was no correlation between P-numbers and lightning then the probability density distributions for all P-numbers (in blue) and sferic associated P-numbers (in red) would be identical. This is because the P-number at the location of a sferic would not be significant in any way, but would simply be a random selection from all of the P-numbers contained in the forecast.

The main feature of Figure 3 is that the two peaks in each subfigure lie at the same P-number, rather than being translated with respect to each other as might be expected if there was a strong correlation between the P-numbers and natural lightning. This result is unsurprising given that P-numbers should be sensitive to the meteorological conditions that lead to a triggered lightning event, rather than those that lead to the natural occurrence of lightning.

However, Figure 3 also shows that the probability density distributions for the sferic associated P-numbers were actually different from those for all P-numbers, having a slightly lower peak and a more prominent tail extending to high P-numbers. This suggests that there was some small correlation between natural lightning and the high P-numbers.

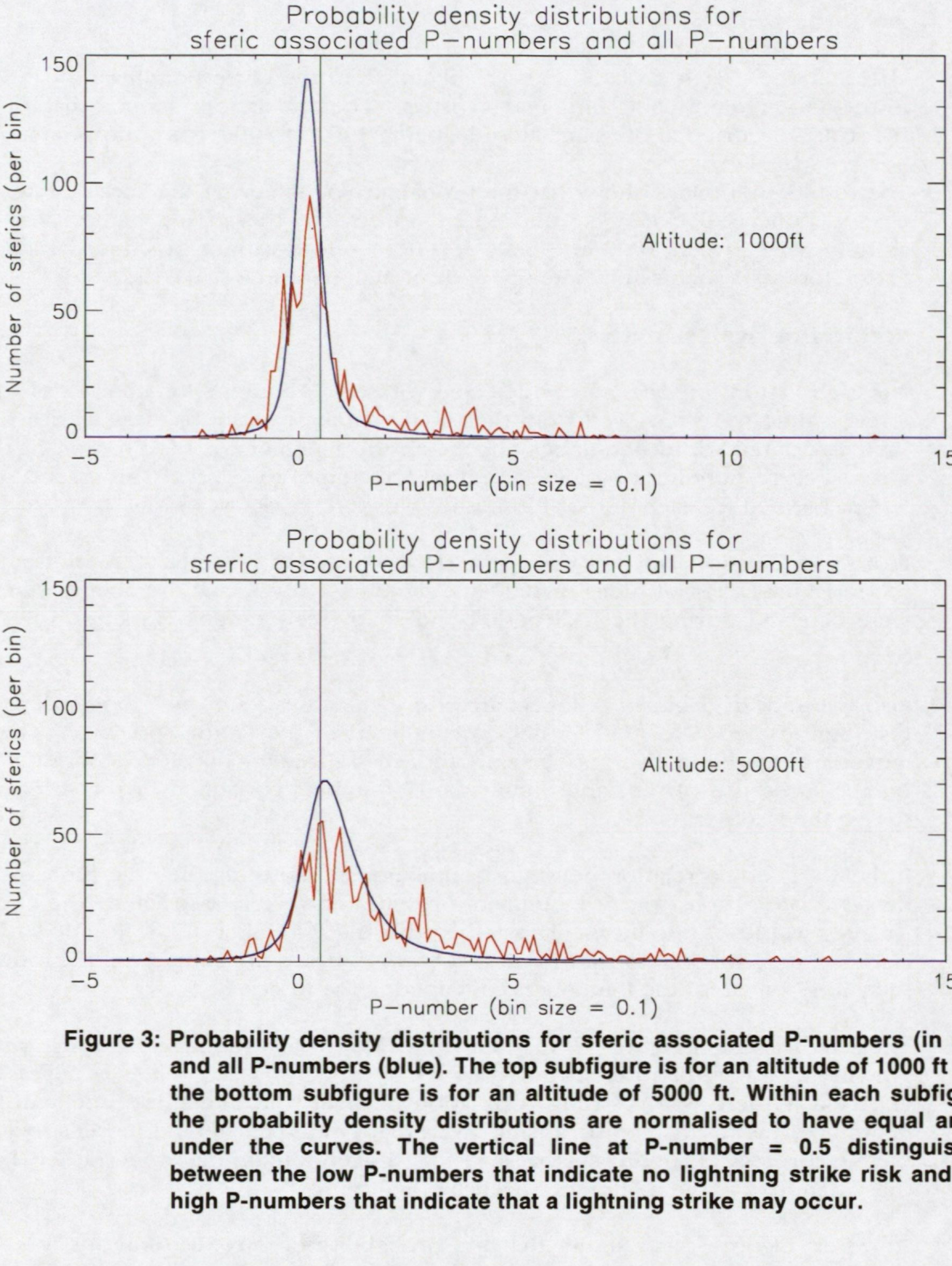


Figure 3: Probability density distributions for sferic associated P-numbers (in red) and all P-numbers (blue). The top subfigure is for an altitude of 1000 ft and the bottom subfigure is for an altitude of 5000 ft. Within each subfigure the probability density distributions are normalised to have equal areas under the curves. The vertical line at P-number = 0.5 distinguishes between the low P-numbers that indicate no lightning strike risk and the high P-numbers that indicate that a lightning strike may occur.

5 REFINEMENT OF THE PATTON EQUATION

The Patton equation was derived by comparing NWP model output for helicopter lightning strike events with the NWP model output for a carefully selected set of non-strike events [2]. The comparison was performed using stepwise regression analysis, which selects the most appropriate variables for use in the regression equation. The independent variables used in the analysis were all suspected of influencing whether or not a lightning strike would occur. The dependent

variable was the P-number, which was set to 1 for strike events and 0 for non-strike events.
The regression equation selected by the analysis was:

$$\text{P-number} = 19.1 - 2.61\,V - 0.0683\,T, \qquad (2)$$

where V is large scale vertical velocity in Pascals per second, such that negative values indicate upward movement of air. T is the temperature in Kelvin.

The Patton equation was good at distinguishing between the strike and non-strike cases. It correctly predicted 7 of the 11 strike cases and all 21 of the non-strike cases, as can be seen from Table 3.

Table 3: The forecasting accuracy of the linear regression equation that was derived from the original strike data set and the non-strike data set [2].

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

5.1 Inclusion of new events

The 3 events in Table 1 for which the helicopter altitude was known were added to the data set containing the previous strike and non-strike events. Regression analysis was re-applied and the variables selected as being significant were once again the vertical velocity and the temperature. The updated regression equation was:

$$\text{P-number} = 20.3 - 2.42\,V - 0.0726\,T. \qquad (3)$$

The corresponding contingency table is shown in Table 4. It can be seen that 9 of the 14 strike events are correctly predicted, as are all of the non-strike events. This result is not surprising given the similarity between the original and updated Patton equations and the P-numbers for the recent events as given in Table 1.

Table 4: The forecasting accuracy of the linear regression equation that was derived from the expanded strike data set and the non-strike data set.

		Forecast		
		Strike	No Strike	Total
Actual	Strike	9	5	14
	No Strike	0	21	21
	Total	9	26	35

5.2 Non-linear fitting

Only linear functions of the independent variables were considered in the regression analysis described above, even though the P-number could have had a non-linear dependence on some or all of the independent variables.

An example of non-linear dependence for the P-number is shown in Figure 4, for the simplified case of just one independent variable. This example has been artificially constructed such that helicopter lightning strikes occur only when the independent variable lies within a certain range of values. This dependence would not be well represented by a linear function.

It would be better represented by some non-linear function such as the top-hat curve shown in the figure.

The possibility of non-linear dependence for the P-number means that non-linear functions should have been used in the regression analysis. However there are an infinite number of non-linear functions and it is clearly impossible to consider all of them. A subset of these functions must be selected and there are three selection criteria that can be used.

1 The functions should have significantly fewer independent coefficients than there are data points, otherwise overfitting of the data could occur. Overfitted functions would closely follow the individual data points but might not represent the general trend in the data. An example of an overfitted function is shown in figure 5. The non-linear function in the figure passes through all of the data points but does not represent the general trend in the data. Conversely the linear function does not pass through any of the data points but it does represent the general trend.

   In the case of helicopter lightning strikes overfitted functions would probably be physically unrealistic and provide inaccurate forecasts.

   Unfortunately use of this selection method alone would not produce a subset of non-linear functions small enough for use in regression analysis.

2 The data can be inspected by eye prior to analysis, to identify trends in the data that might suggest the use of particular non-linear functions. However these trends will only be obvious if there are just one or two independent variables. This is unlikely to be the case for the helicopter lightning strikes and so this selection method is unsuitable for our purpose

3 There may be physical reasons to justify the use of particular non-linear functions. For helicopter lightning strikes, two variables for which non-linear functions may be appropriate are the temperature and the convective available potential energy (CAPE). (CAPE is described in reference [2].)

   (a) Helicopters may be particularly susceptible to being struck by lightning when they are flying close to the freezing level [4]. Thus it would be appropriate to use the absolute value of the temperature difference from freezing in the regression analysis.

   (b) The efficiency of charge separation in a cumulonimbus cloud may depend on the velocity of the updraft within the cloud. This velocity is proportional to the square root of CAPE and so it would be appropriate to use the square root of CAPE in the regression analysis.

Use of the above selection criteria therefore identifies 2 non-linear functions that could be sensibly used in the regression analysis for helicopter lightning strikes.

The regression analysis was repeated using these non-linear functions in addition to the linear functions used previously, but they were not identified as being significant for distinguishing between strike and non-strike events.

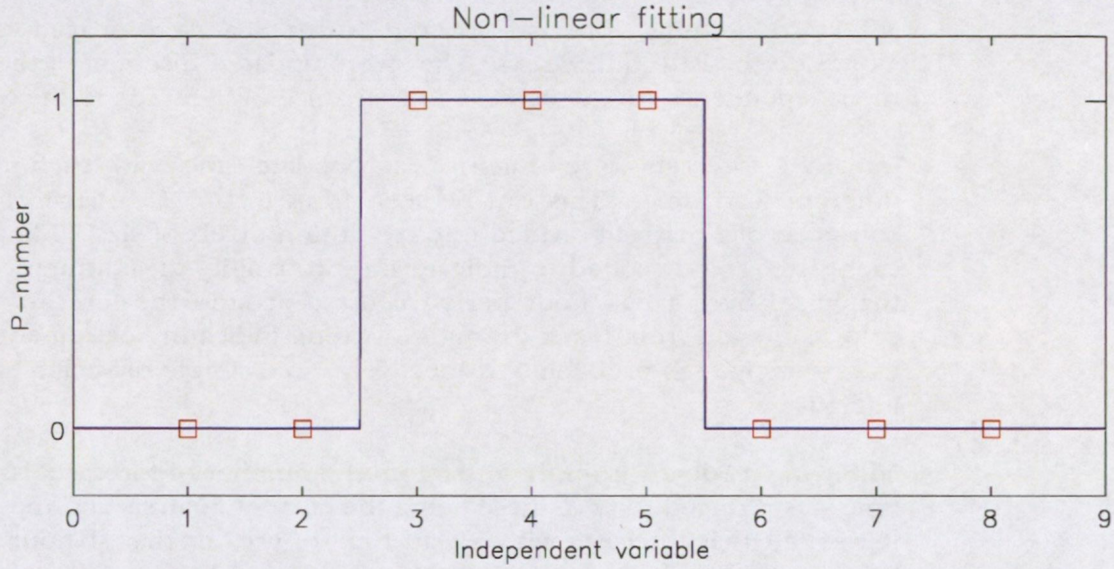


Figure 4: Helicopter strike and non-strike events plotted against an independent variable. This artificially constructed graph demonstrates non-linear dependence of the P-number on the independent variable.

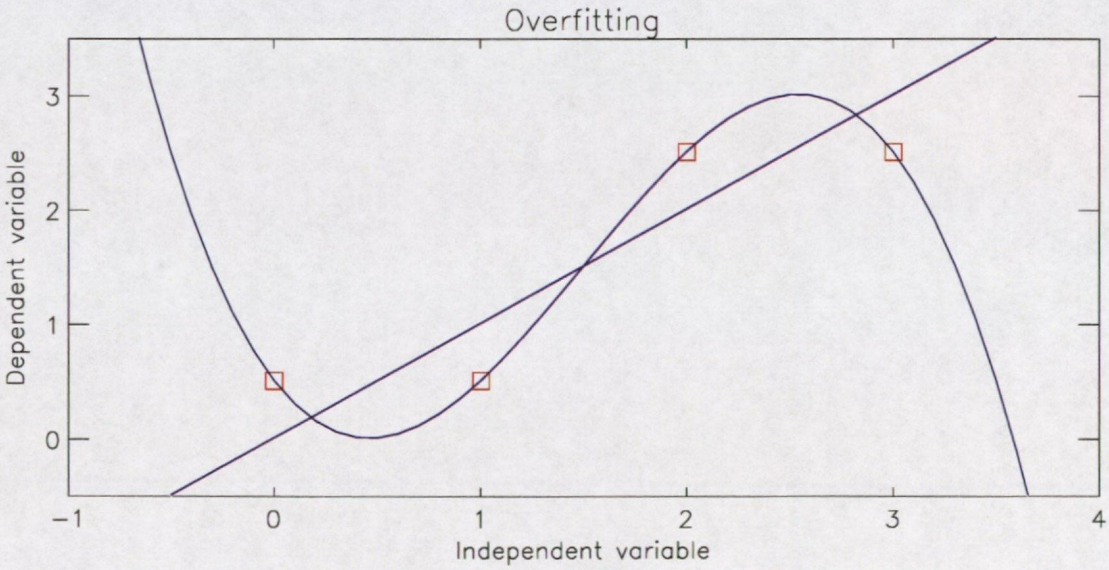


Figure 5: An illustration of overfitting. Although the curved line (with 4 independent coefficients) fits the 4 data points exactly, it does not follow the general trend in the data. The straight line (with 2 independent coefficients) is more representative of the general trend.

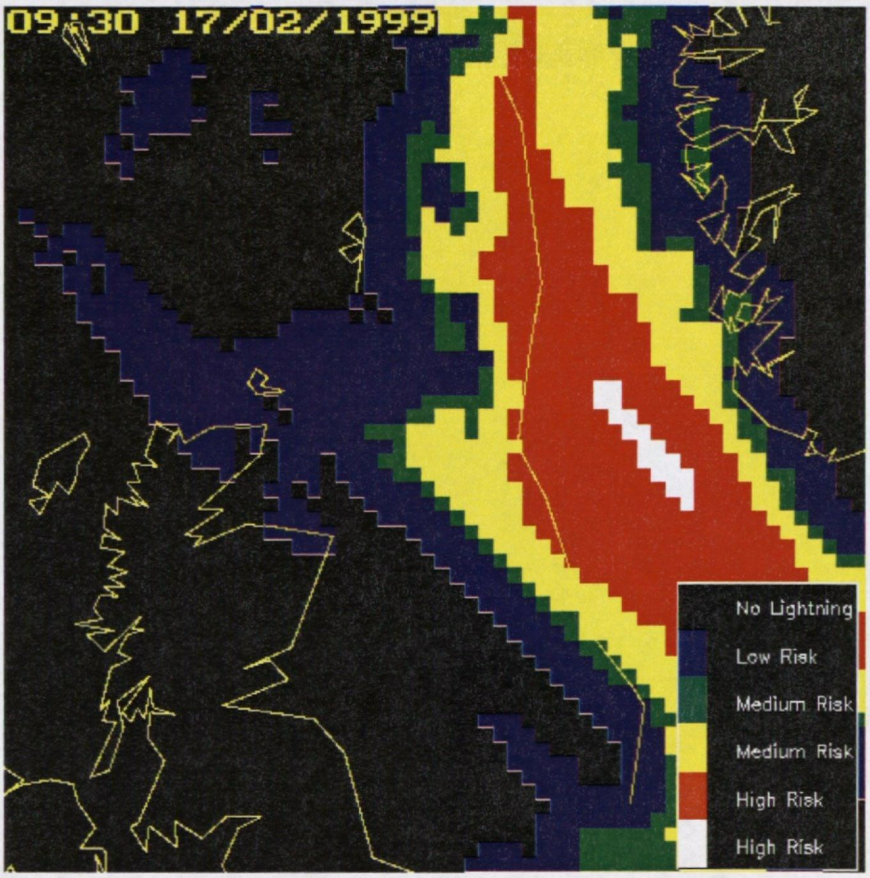
6 TRIAL NIMROD FORECASTS

NIMROD lightning forecasts for the North Sea were placed on the Internet alongside the Patton forecasts. They were updated throughout the day because of their dependence on the observed occurrence of lightning in the North Sea.

Initially 7 forecasts were issued at each update time, with each forecast having a different lead time. This can be seen from Figure 1. Each of these forecasts consisted of a map subdivided into resolution pixels of size 15 km by 15 km, with each pixel colour coded to indicate the probability of lightning occurring within that pixel over a half hour period centred around the forecast time. The pixel colours ranged from black through to white, indicating extremely low probability to extremely high probability respectively. An example of such a forecast is shown in Figure 6.

Following feedback from the operators the number of forecasts issued per update time was reduced to two, these being the current analysis and the 1 hour forecast. It was felt that forecasts with a lead time of greater than 1 hour were unhelpful because high risk areas propagated in an unrealistic manner as the lead time increased. The remaining forecasts were simplified to display only those regions where the lightning risk was originally classified as red or white, and these regions were displayed in red. An example of one of these updated NIMROD forecasts is shown in Figure 7.

Lightning forecast after 1 hour 30 minutes



[PREVIOUS] | [UP] | [NEXT]

Figure 6: A NIMROD lightning forecast produced by the UKMO, in the format first used for display on the Internet. Outlines of Scotland and southwest Norway are shown, and the North Sea oil rigs lie approximately along the line plotted down the centre of the figure. The colour of each pixel indicates the relative risk of lightning occurring in the pixel area.

Lightning forecast after 1 hour

[PREVIOUS] | [UP] | [NEXT]

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Figure 7: A NIMROD lightning forecast produced by the UKMO, in the updated format used for display on the Internet. The updated format has reduced colour resolution compared to the original format. The white areas were originally resolved into black, blue, green and yellow areas, while the red areas were originally resolved into red and white areas.

7 NIMROD FORECAST VERIFICATION

NIMROD lightning forecasts with a lead time of 1 hour were compared with the actual occurrence of lightning, for the period of November 1998 to mid May 1999. These forecasts were in their original format with full colour resolution.

Each sferic detected in the North Sea area during the study period was associated with a particular pixel of a particular NIMROD forecast, and hence a particular forecast risk level. The number of pixels of each risk level present in the forecasts during the study period are shown in the first row of Table 5. The number of pixels of each risk level that were associated with a lightning strike during this period are shown in the second row of Table 5. These data are also presented in a cumulative format in Table 6.

Table 5: The data used to compare NIMROD lightning forecast risk levels with the actual occurrence of lightning. See the text for a description of the data.

Risk level	Black	Blue	Green	Yellow	Red	White	Total
Number of pixels	8864771	952495	359031	334992	105070	4483	10620842
Number of sferics	56	93	57	101	50	0	357

Table 6: The data of Table 5 presented in a cumulative format

Cumulative risk level	= Black	≤ Blue	≤ Green	≤ Yellow	≤ Red	≤ White
Number of pixels	8864771	9817266	10176297	10511289	10616359	10620842
Number of sferics	56	149	206	307	357	357

The data presented in Tables 5 and 6 can be used to calculate various statistical results that are relevant to helicopter lightning interception.

Perhaps the simplest result is the frequency of lightning per unit area per unit time. This can be easily calculated by dividing the total number of sferics by the total number of forecast pixels, both of which are given in Table 5. Thus:

$$\text{Lightning frequency} \approx 3.4 \times 10^{-5} \text{ per half hour per pixel,} \qquad (4)$$

where a pixel is of size 15 km by 15 km as previously mentioned.

This result can be converted into the frequency of helicopter lightning interception by multiplying by a proportionality factor which depends on the interception dimensions of the helicopter. The interception dimensions may not necessarily equal the physical dimensions of a helicopter as the path of a lightning strike may be deviated towards a nearby helicopter. A generous interception area of 100 m x 100 m will therefore be assumed.

The frequency of helicopter lightning interception is thus approximately:

$$\text{Interception frequency} \approx 3.4 \times 10^{-5} \times \left[\frac{0.1}{15}\right]^2 = 1.5 \times 10^{-9} \text{ per half hour of flight time.} \qquad (5)$$

This frequency applies to helicopter operations where the flight planning process does not take into account the NIMROD lightning forecasts. If the NIMROD forecasts were taken into account then the interception frequency would be reduced, as follows.

Consider the results presented in Figure 8. They are the frequency of lightning per half hour per pixel, given a particular forecast risk level. The frequencies in the figure have been derived from the data in Table 5 and the error bars indicate the 95% confidence interval for the true frequencies. From the figure the frequency of lightning for a black risk level is 6.3×10^{-6} per half hour per pixel. Thus if the helicopter flew only in black risk areas then the frequency of lightning interception would be approximately 2.8×10^{-10} per half hour of flight time, which is smaller than the value obtained in equation 5 by a factor of 5.

Unfortunately it is probably impracticable for helicopters to fly only in black risk areas at all times. Results applicable to a more practicable flight planning scheme are thus presented in Figure 9. These results are the frequency of lightning per half hour per pixel for risk levels lower than a given value. They have been calculated from the cumulative data in Table 6.

As an example, Figure 9 shows that for yellow risk levels and below the frequency of lighting is approximately 2.9×10^{-5} per half hour per pixel. The frequency of lightning interception for a helicopter flying only in yellow risk levels or below at all times is thus on average over many flights on many days equal to 1.3×10^{-9} per half hour of flight time. This result assumes that the distribution of the risk levels encountered by the helicopter is the same as that for the risk levels in the top row of Table 5.

These results show that using NIMROD forecasts for helicopter flight planning could reduce the incidence of lightning interception by up to a factor of 5. Only minor route detours would usually be needed to avoid the highest risk areas, due to their relative scarcity. It can be seen from Figure 10 that a red risk level is forecast approximately 100 times less frequently than is a black risk level.

However the benefit of using NIMROD forecasts seem doubtful because the above results also show that the frequency of lightning interception must be extremely low anyway. It was estimated by the helicopter operators involved in the study that they log approximately 400 flight hours per day in the North Sea area. Using the results of equation 5, the frequency of lightning interception thus works out at around 0.0004 events per year. This may be a slight underestimate due to the shortness of the study and the underdetection of sferics, but it is unlikely to be inaccurate by more than a factor of 10. This suggests that the vast majority of helicopter lightning strikes must be triggered events, since there are on average about 2 per year.

It is worth noting that there have been rare occasions in the past when hundreds of sferics have been detected in a short period of time within a localised area, although no such occasion occurred during the study period. Flying in such extreme situations cannot be recommended because of the increased chance of lightning interception, and it is probably possible to visually identify these situations upon approach. It is thought that lightning interception may have caused at least one event previously investigated by UKMO, this being on 19 January 1995 and resulting in the ditching of the helicopter. Hundreds of sferics were detected around the vicinity and time of the event, which was a positive polarity cloud-to-ground strike [5].

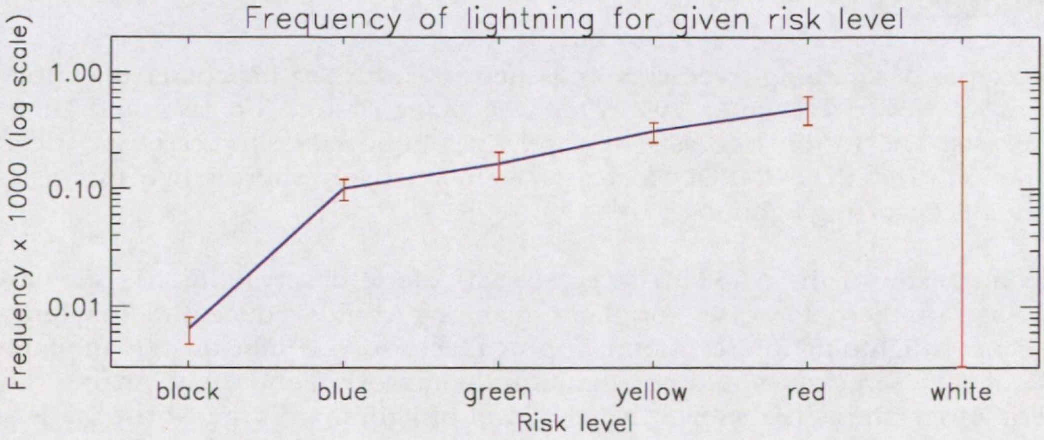

Figure 8: The frequency of lightning for given forecast risk level, with error bars in general indicating 95% confidence intervals. For the white risk level the error bar indicates the range of frequencies that give a > 5% chance of there being no lightning occurrences during the study period. This range has a minimum value of 0.

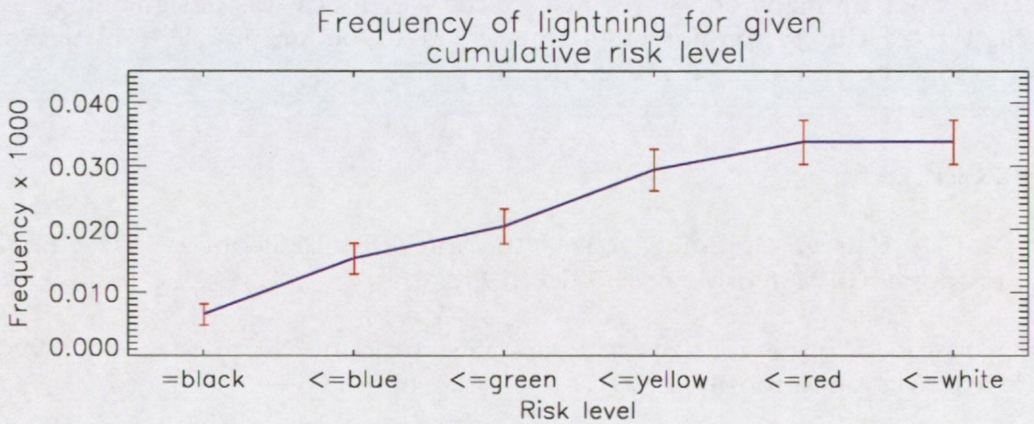

Figure 9: The frequency of lightning for given cumulative risk level, with error bars indicating 95% confidence intervals.

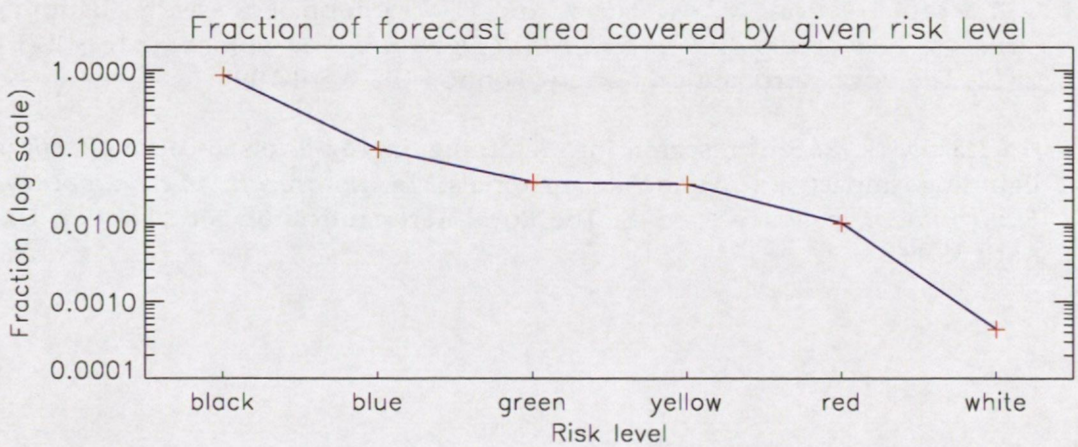

Figure 10: The fraction of NIMROD forecast area covered by each forecast risk level.

8 CONCLUSIONS

Two types of lightning forecast were issued to North Sea helicopter operators for a trial period over winter 1998/99, these being Patton forecasts and NIMROD forecasts. The Patton forecasts were relatively long range forecasts for triggered lightning, and the NIMROD forecasts were relatively short range forecasts for naturally occurring lightning.

A comparison of the NIMROD forecasts with sferic observations has shown that the use of these forecasts for flight planning could reduce the frequency of helicopter lightning interception by up to a factor of 5. Unfortunately though, the use of such forecasts would not significantly improve flight safety. Analysis of the sferic observations has shown that the level of lightning in the North Sea is such that intercepted lightning events probably form only a minority of North Sea helicopter strikes, with the vast majority being triggered events.

It has not been possible to verify the accuracy of the Patton forecasts, because only a small number of new strike events were available for verification purposes. However it became apparent during the trial that the forecasts were insufficiently specific, since on many occasions most of the North Sea was designated as being of high risk. The Patton forecasts thus seem to be unsuitable for use in an operational situation in their present form.

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