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Investigation and prediction of helicopter-triggered lightning over the North Sea

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ABSTRACT: Helicopter-triggered lightning is a phenomenon which affects operations over the North Sea during the winter. It is thought that the presence of the helicopter triggers the majority of lightning strikes, since there is generally little or no natural lightning activity in the area in question prior to or following the strike, and strike rates are much higher than would be expected if due purely to chance. However, there has been little progress to date in the ability to predict triggered lightning strike occurrence with NWP data. Previous attempts have resulted in forecasts which are insufficiently discriminating (i.e. high false alarm rate) to be of practical use.

In this study, previous work on triggered lightning is reviewed and case studies are examined in order to identify common meteorological conditions for helicopter-triggered lightning strikes. Using forecast data from the Met Office Unified Model, an algorithm for triggered lightning risk was produced based on outside air temperature and precipitation rate. Evaluation against past helicopter strike cases has demonstrated that the new algorithm successfully forecasts lightning risk on 80% of occasions when triggered lightning occurred. In addition, the algorithm correctly forecast 8/9 natural lightning strikes which were observed in the operating area during winter 2010–2011. The areas of risk highlighted are usually small, which should allow helicopter operators to plan flights around high risk regions. The information in this study can also be used to inform helicopter operators of the likely conditions in which triggered lightning strikes occur.

KEY WORDS Unified Model; microphysics; thunderstorm electrification; convective clouds; cold air outbreak; aviation

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1. Introduction

Helicopter-triggered lightning is a phenomenon which has been observed during winter over the North Sea, between October and April. There have been a number of instances recorded by the UK Civil Aviation Authority (hereafter CAA) where helicopters are either struck by lightning, or a lightning flash occurs very close to the aircraft. In these situations there is often very little or no warning of the triggered lightning strike and very little natural lightning activity is observed in the area. For this reason, and because the helicopter strike rate is much higher than would otherwise be expected, it is believed that the presence of the helicopter actually triggers the strike, rather than the helicopter simply being unfortunate enough to find itself between the cloud and the ground in the path of a natural strike.

Lightning strikes present a significant safety risk to helicopters operating in the North Sea region. Although the aircraft have some protection against lightning strikes, the lightning environment in the North Sea region has been demonstrated to present a risk five times higher than that assumed during the design and certification process (Hardwick, 1999). There have been two recent instances of air accidents that have resulted from triggered lightning strikes. In January 1995, a triggered lightning strike to a helicopter caused a loss of control, which then resulted in the helicopter ditching and later sinking (AAIB, 1997). In a separate incident, a fatal accident involving a helicopter has been attributed in part to a rotor blade which had previously been struck by lightning. In this case, despite safety checks on the rotor blade, the damage remained undetected (AAIB, 2005). In addition to the safety risk, once an aircraft has been struck it often needs to be taken out of service and, in some cases, the transmission and rotor blades have to be replaced. This comes with a large financial cost, plus the inconvenience and loss of revenue while the aircraft is out of service.

Despite these concerns, helicopter-triggered lightning is not documented widely in the literature. Hardwick (1999) showed that the strike rate *per* flying hour for helicopters in the North Sea is similar to that seen for fixed wing aircraft flying at similar altitudes. Hardwick also observed that most winter time lightning strikes were of positive polarity, therefore being stronger and more damaging. Lande (1999) highlighted the following common atmospheric conditions for triggered lightning strikes to helicopters in the North Sea:

- Outside Air Temperature (OAT) at flight level near freezing level: $0 \pm 2\,^{\circ}$C;
- frozen precipitation in the form of snow, snow grains, hail and/or ice crystals;
- altitude: 1000–3000 ft (305–914 m);
- winter: October to April;
- in-cloud or immediately below clouds, and,
- within 5 nautical miles (NM; roughly 9.3 km) of a cumulonimbus (Cb) cloud.

The recorded temperature observations of Lande (1999) are in close agreement with those of Hardwick (1999), who suggests that most helicopter-triggered lightning strikes occur at or very close to $0\,^{\circ}$C, as shown in Table 1.

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Table 1. Frequency distribution of North Sea helicopter triggered lightning strikes as a function of outside air temperature.

Outside air temperature (°C)	Number of strikes
3	1
2	1
1	3
0	8
−1	3
−2	3
−3	2
−4	1

Based on figure 2 of Hardwick (1999).

Hardwick (1999) supports the findings of Lande (1999) of altitude, seasonality and location with respect to cloud. In addition, Patton (1999) supports the conditions of cumulonimbus cloud, which were present in all the cases analysed. Patton (1999) also notes that in 6 out of 11 cases mixed phase precipitation was observed in the vicinity, with only frozen precipitation observed for 2 cases and only rain observed for 3 cases. This may also indicate why the condition on flight level OAT is so restrictive, since mixed phase precipitation only occurs for a narrow range of temperatures around 0 °C (273 K).

It is interesting to note that all documented strikes to helicopters occur in the winter, when thunderstorm and natural lightning activity are at their lowest, which indicates that helicopters may be triggering strikes. The −10 °C temperature level is often used as a proxy for the height of the charge layers in a thunderstorm (Kitagawa and Michimoto, 1994; Ely and Orville, 2005). During the winter the −10 °C temperature level is lower and it is possible that the helicopters are close enough to the charge centres in the cloud to trigger a lightning strike (Hardwick, 1999). Secondly, it is likely that the altitude condition results from the height range of the 0 °C isotherm in the winter combined with the altitude of the normal flight paths over the North Sea (Hardwick, 1999). Third, the condition for the presence of a Cb within a 5 NM (9.3 km) radius indicates that helicopter-triggered lightning strikes require significant convective activity in the immediate vicinity. This is consistent with the findings of Patton (1999) who noted that Cb clouds were present in satellite images in the vicinity of the triggered strike for all cases. Additionally Patton (1999) observed that, 10 out of 11 triggered strikes analysed took place in the presence of frontal activity whilst 5 out of 7 triggered strikes occurred on the edge of a region with high convective rain rates indicative of a convective cell.

Lande (1999) states that most helicopter-triggered lightning strikes occur in conditions that are not typical for natural lightning (i.e. no forecast or observed Cb or thunderstorm activity or indications on the weather radar). This statement directly contradicts the results of Patton (1999) who observed Cb clouds in the vicinity of the triggered strike in all 11 cases analysed. Lande (1999) highlights that in some documented cases triggered lightning strikes occur during light snow fall from stratocumulus (Sc) cloud. Of the 68 cases presented in the Lande (1999) data set only 28 cases contain information about cloud type, with Sc cloud being noted in 6 of these cases (21%), suggesting that lightning events in these conditions are fairly rare. Alternatively, it is possible that pilots may struggle to identify winter thunderstorm activity, especially when it is embedded in layer cloud, resulting in inaccurate classification of events. Considerable research has been conducted into winter thunderstorms over the Sea of Japan which are likely to be similar to those that occur in the North Sea since, in both cases, advection of dry polar air masses over a warmer sea surface leads to potential instability. Winter thunderstorms in the Sea of Japan are characterized by a small vertical extent, short duration and low flash rates, with most storms only exhibiting a few lightning flashes over their whole duration (Kitagawa and Michimoto, 1994). If winter North Sea thunderstorms exhibit the same characteristics then they will be hard to identify in-flight, particularly if they are embedded in layer cloud. Strong evidence for helicopter-triggered lightning comes from the seasonal distribution of helicopter triggered strikes relative to all lightning strikes. All helicopter-triggered strikes occurred in the winter despite the fact that there is an order of magnitude more natural lightning strikes in summer than in winter (Hardwick, 1999).

Despite the risks posed by helicopter-triggered lightning, the chances of a lightning strike are still pretty rare, with only one or two strikes *per* winter season, despite there being typically 100 flights *per* day leaving Aberdeen for oil and gas fields to the north and east of Scotland. Therefore, one of the challenges in this study, as with previous ones (e.g. Lande, 1999; Hardwick, 1999 or Patton, 1999) is working with a very limited data set. It should be mentioned that helicopter pilots will not fly in to any region which they perceive as having a risk as a triggered lightning strike (e.g. Cb clouds). This partially accounts for the low strike rate and also makes the phenomenon challenging to verify. As a triggered lightning strike requires the presence of a helicopter there may be occasions when the atmospheric conditions are sufficient to trigger a strike, yet no strike occurs simply because the helicopters actively avoid the regions of risk. This can be contrasted with purely natural phenomena (e.g. a tornado), which will occur whenever the atmospheric conditions allow the formation of such a feature.

1.1. Previous forecast methods

Patton (1999) performed a linear regression of 11 helicopter-triggered lightning strike cases and 21 null cases which gave the following outcome:

$$R = 19.1 - 0.0683T - 2.61w, \qquad (1)$$

where T is the temperature in Kelvin and w is the pressure vertical velocity in Pa s^{-1}. Note that, due to the resolution of the NWP model used by Patton (1999), the vertical velocity here relates to the large-scale vertical motion of the air such as that seen in a frontal system rather than the small-scale vertical updrafts seen in individual convective clouds. Patton (1999) set the threshold for a triggered lightning strike of $R > 0.5$. Based on this threshold Equation (1) correctly forecast 7/11 triggered strike cases and 21/21 null cases. However, it was noted that on many occasions during the trial period (winter 1998–1999) the resultant of Equation (1) highlighted the whole of the North Sea region as a high risk area, indicating that Equation (1) was insufficiently discriminating to be suitable for operational use. Furthermore, the equation indicates that the chances of a triggered strike becomes more likely at lower temperatures; this is not consistent with Table 1, which shows that temperatures for the North Sea events are centred around 273 K with the majority of strikes happening at a temperature of 273 K. The use of vertical velocity in Equation (1) is also questionable; a temperature of 273 K and a vertical velocity of 0.1 Pa s^{-1} (roughly equivalent to a 1 m s^{-1} updraught typical of a storm) would produce a risk of 0.193, when in fact these conditions would potentially be ideal for a natural strike.

Since the publication of the papers by Hardwick (1999) and Patton (1999), the science behind NWP has evolved due to advances in computing and improved NWP modelling. Hardwick (1999) makes reference to using the Met Office limited area model with a horizontal resolution of 45 km. The present resolution of the UK model used in this study is 4 km. A 1.5 km version of the UK model is also running operationally, although it does not presently cover the whole of the North Sea operating region. It is intended that the 1.5 km model will replace the UK 4 km model in due course. The increased resolution means that synoptic and meso-scale features are much better resolved by the model. These advances in NWP indicate that it is worthwhile investigating whether a new triggered lightning forecast algorithm might perform well enough to be of use to helicopter operators. This paper is therefore focused on the development of a new triggered lightning forecast algorithm. The synoptic conditions which are common to helicopter-triggered lightning strikes are examined, before developing an hypothesis of how strikes occur and developing a new algorithm to predict these strikes. This is then tested on past strike cases and a null data set to assess the performance of the algorithm.

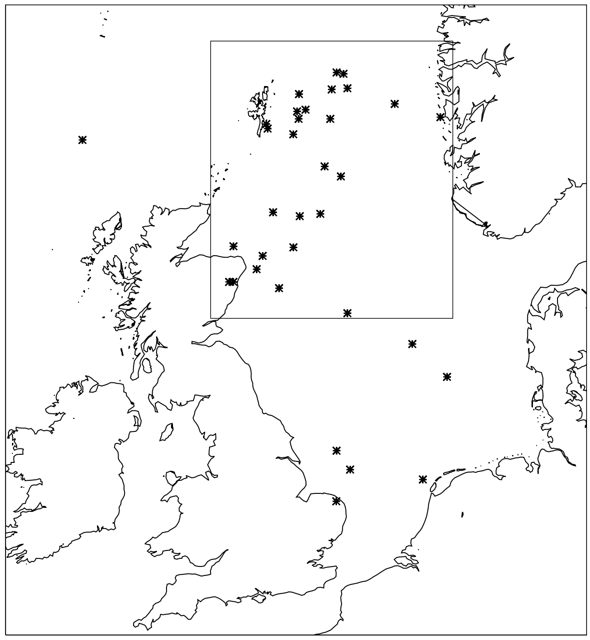

Figure 1. The location of the 34 helicopter triggered lightning strikes where accurate position information has been obtained. All the triggered strikes discussed by Patton (1999) are included. The box over the northern North Sea, between Scotland and Norway shows the domain of the null data set, as referred to in Section 4.

2. Helicopter triggered lightning strike data set

2.1. Triggered lightning strike locations and times

A dataset of helicopter lightning strike cases was provided by the CAA, from their mandatory occurrence reporting (MOR) system. This was supplemented with additional data from the helicopter operators (Bond, Bristow and CHC), and from previous data from Hardwick (1999) and Patton (1999). Table 2 shows the distribution of these helicopter-triggered strikes by month over the winter. There is a clear peak in the number of triggered strikes in February. It is to be noted that 20 out of the 36 strikes occur in the period from 15 January until 15 March, with only one third of triggered strikes occurring in the first 3 months of the winter (October to December), while the remaining two thirds occur from January to March. The large number of triggered lightning strikes between January and March is probably because the melting level of precipitation, thought to be crucial to the triggered lightning strikes, is closest to the flight levels of 2000 and 3000 ft (610 and 914 m respectively) where helicopters typically operate. This also corresponds to when the sea surface temperatures in the North Sea are climatologically at their coldest, following the HadISST data set (Rayner *et al*., 2003).

The locations of 34 of the 36 events (for which there are accurate position data) are plotted in Figure 1. There is a clear cluster of triggered strikes from Aberdeen airport to the East Shetland Basin, with a few other triggered strikes observed in the southern North Sea, some of which have originated from CHC Danish operations and from Norwich airport to the Sole Pit and Viking areas of the North Sea. The cluster of strikes between Aberdeen and the East Shetland Basin corresponds directly to common helicopter flight paths in this region. Although triggered strikes are able to occur at any given latitude in the North Sea during any month of the winter, the majority of strikes do appear to occur close to 60 °N, which suggests a possible link to polar low development.

Table 2. Helicopter triggered lightning strike cases *per* month, from 1991 to 2010.

October	6
November	4
December	3
January	5
February	13
March	5

2.2. Model rerun data set

Two sets of model data have been used for the analysis. The first data set is a rerun of the model with the up-to-date physics used as of March 2011 in the Met Office Unified Model (hereafter referred to as MetUM). In this process, the global model was run from the best analysis of the atmospheric conditions on the date in question. This model runs with a horizontal grid spacing of 25 km. The global model provides boundary conditions to a 12 km model which, in turn, provides boundary conditions for a 4 km model. These are intended to represent the capabilities of the Met Office's current operational suite, although the rerun models have a slightly different grid to cover the entire North Sea operating area. The advantage of using this method is that model performance is analysed using up-to-date physics: previous versions of the operational model, especially those from some years ago, do not represent small-scale features as well as current models do. The disadvantage of this method is that the model does not run with data assimilation. Data assimilation is the process by which a model's atmospheric analysis is merged with observational data to create the best estimate of the current state of the atmosphere from which to run the model forward in time. When running without data assimilation the location and timing of some features is less likely to be accurate. However, it is anticipated that these errors

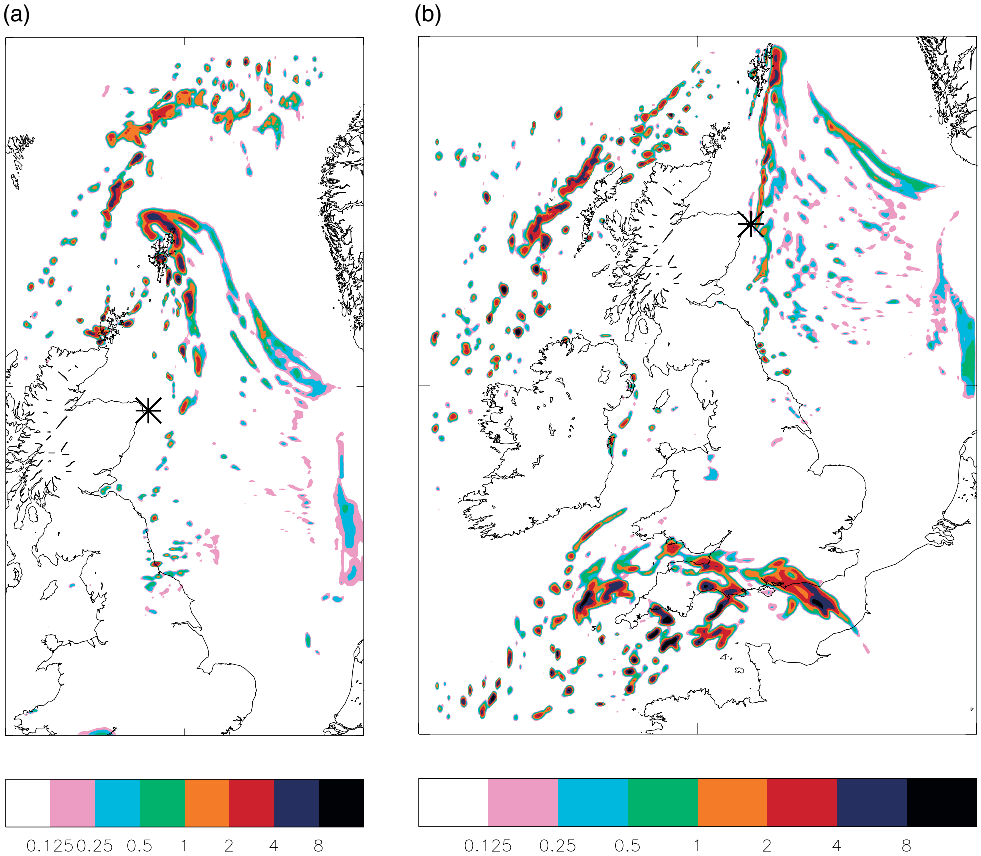

Figure 2. Precipitation forecasts for (a) the rerun model and (b) the operational model 0800 UTC on 18 February 2010, showing rainfall rate in mm h^{-1}. The location of the triggered lightning strike (which occurred at 0755 UTC) is marked with the black star in each plot. This figure is available in colour online at wileyonlinelibrary.com/journal/met

will be minimized by selecting a model run that starts a few hours before the triggered strike time. It was possible to analyse reruns of model data back for 10 triggered lightning strikes between 2002 and 2010. For cases prior to 2002 appropriate data for initializing the model was not available. Figure 2 shows an example rainfall rate chart produced by the rerun model, and also defines the model boundaries. The time has been taken to coincide with the helicopter triggered lightning strike at 57.44 °N, 1.39 °W on 18 February 2010. This figure shows the domain that has been used for the rerun model. It is also worth noting that the rerun model forecast heavy showers in approximately the correct region.

2.3. Operational model data set

The second data set consists of operational UK4 model data for the eight triggered lightning strike cases between 2006 and 2010. In each case, the model data were available at 1 h resolution, therefore the closest hour to the helicopter strike time was used (e.g. 0900 UTC for a strike at 0835). The UK4 model runs four times each day starting at 0300, 0900, 1500 and 2100 UTC. In each case, the model run used was the one that started closest, yet prior to the helicopter strike time. For example, to analyse a triggered lightning strike event at 0700 UTC, the UK4 model run that started at 0300 UTC would be used.

The UK4 model data are available from 2006 to present and have been used to examine eight of the triggered lightning strikes between 2006 and 2010. The advantage of using the operational model is that it includes data assimilation, so the location of heavy showers and rainfall is likely to be more accurate than in the rerun model. The main disadvantage of this method is that model performance will generally reduce the further back in time the helicopter-triggered lightning strike is from the present day.

Comparison of the two plots in Figure 2 reveals differences in rainfall location and intensity between the two models. This is because of the effect of data assimilation in the operational model (which is not in the rerun model), and the effect of improved physics in the rerun model (which were not available at the time the operational model was run). It is not possible to know exactly which model would be most like the present-day model. It is likely to be a combination of the two models, probably with the rainfall location of the operational model, but with the rainfall intensity accuracy of the rerun model. Therefore, it is important to examine both models in this analysis.

2.4. Arrival Time Different Network (ATDnet)

Location and time of lightning strikes can be determined from using the Met Office very low frequency (VLF) Arrival Time Difference Network (ATDnet), as documented in Lee (1986), with recent modifications described in Gaffard *et al.* (2008). Each lightning strike emits a short pulse of VLF energy (alternatively known as lightning-induced radio atmospherics or more commonly, ‘sferics’). Such pulses have typical frequencies of approximately 10 kHz and are capable of travelling over

Table 3. Synoptic conditions for helicopter triggered lightning strikes since October 2003.

Date	Time (UTC)	General features	Frontal or other features	Sferics within 50 km?
22 October 2003	1208	Low over Norfolk, Light W-NW winds	Trough in North Sea near strike location	Yes, many
21 January 2005	1540	Strong N-NW winds	Behind cold front located over France at 12Z	Yes
25 November 2005	1200	Low N. North Sea. Very strong airflow	Occluded front near strike	Yes, many
28 February 2006	0840	Low N. North Sea, strong N airflow, cold.	Trough over E. Shetland basin behind cold front over North France	One nearby
3 March 2006	1503	Low N. North Sea, calm	Troughs present	No
6 February 2007	1700E	Low N. North Sea	Troughs present; Cold front over N. France	One
19 March 2007	1545	Lows Norway and N. Italy with very strong N airflow near strike	Occlusion near strike and decaying front over Spain	One
31 January 2008	0740	Very deep low near Faroe Islands; Westerly Gales	Strong cold front bright radar echoes (high reflectivity values)	Yes
22 February 2008	1330	Strong Westerly Gales	Troughs behind cold front	One
22 October 2008	1047	Breezy W to NW winds	Troughs present behind cold front over France	One
22 March 2009	1041	Low iceland	Mixed troughs/cold fronts	Yes
1 February 2010	1210	Low North Sea; calm	Occluded front	No
18 February 2010	0755	Low Norway; calm	Occluded front near strike	Yes
22 November 2010	0830	Calm easterly flow	Strong occlusion tracking south	No

A letter E after the strike time on 6 February 2007 notes that the time of strike was estimated from time of a few sferics close to the reported strike location.

thousands of kilometres. The present network consists of 11 stations in Europe (Gaffard *et al*., 2008). By using a triangulation method with three or more stations it is possible to predict the location and time of the strike by examining the arrival time difference between the stations. ATDnet is able to detect most lightning strikes that occur below the cloud base: however, not every strike that occurs within cloud can be detected, as these strikes generally have too low a current to be detectable by ATDnet.

3. Synoptic analysis of helicopter triggered lightning strike conditions

In order to understand the conditions common to triggered lightning strikes, synoptic conditions were examined using a similar approach to Patton (1999). It was possible to analyse the conditions for triggered lightning strikes from October 2003 onwards, covering 14 strikes in total. These are detailed in Table 3. Synoptic analysis charts are available for 0000, 0600, 1200 and 1800 UTC and the nearest charts in time to each helicopter strike were examined. Radar data images were also available for subjective analysis of the triggered lightning strike events for this period. However, the weather radar network does not cover the whole of the North Sea area and only four strikes since 2003 occurred within the UK radar network coverage. However, in some cases radar images can be used to examine the intensity of features that pass over the UK before heading to the North Sea.

Examining the synoptic conditions for triggered lightning strikes, summarized in Table 3, the following observations can be made about the conditions when triggered lightning strikes occurred.

- Cold airflow: in all 14 cases, the airflow over the North Sea where the helicopter strikes occurred was cold (meaning the air had originated from polar latitudes to the north, northwest or northeast). In some cases, for example 6 February 2007, a cold front had recently passed over the UK and the North Sea region. In other cases, such as 22 November 2010, no feature had passed recently over the UK, but the airflow remained cold. A cold front passed over the North Sea during 20 November 2010, and the airflow remained cold for a number of days after this, despite the wind being calm. There is no obvious link between the strength of the wind and the presence of a triggered lightning strike.
- Features: in almost every case, the helicopter strike location was on or nearby a cold or occluded front, or trough line. One notable exception is 28 February 2006, where the nearest feature was a trough over the East Shetland Basin, approximately 150 km away. However, in this case, the airflow was a strong northerly and showers were observed on the UK radar network.
- Sferics: The presence of sferics varied from case to case. In some cases there were no sferics observed near the triggered lightning strike during the day. In other cases, there was a number of sferics observed during the day, some in the region of the triggered strike prior to the helicopter flying through that region. The presence of sferics may depend on the ability of ATDnet to detect triggered lightning strikes, since ATDnet is unable to detect all in-cloud strikes that occur. In all cases,

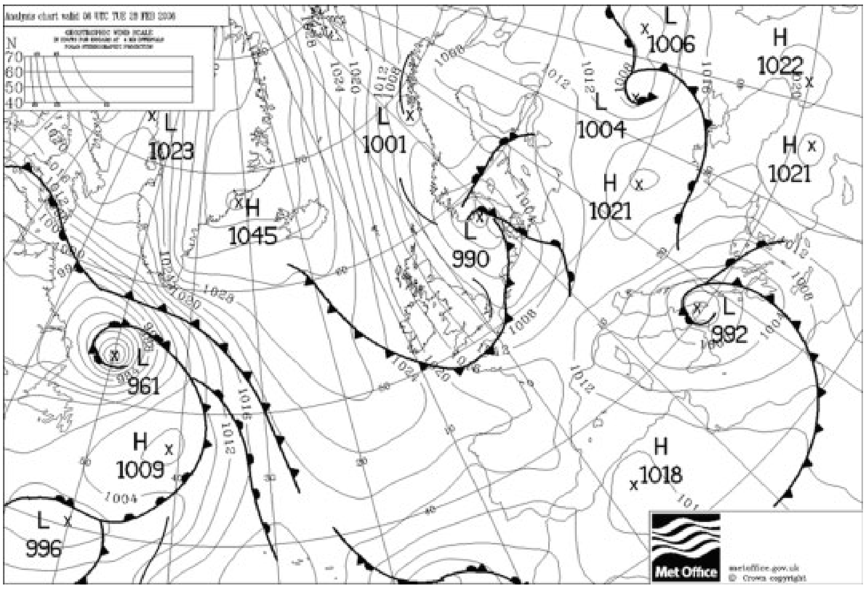

Figure 3. 0600 UTC analysis for the triggered lightning strike of 28 February 2006. The strike occurred at 0840 UTC close to Aberdeen airport.

the number of sferics was much lower than that which would be seen for a typical summertime thunderstorm.

In the majority of cases, it appears that helicopter-triggered lightning strikes have occurred in cold air convective outbreaks or in cold air situations. This is in agreement with the case of fixed-wing aircraft-triggered lightning described by Kobayashi *et al*. (2007). A typical North-Sea cold air outbreak is described in Section 3.1.

3.1. Description of a cold air outbreak

Cold air outbreaks are common over the North Sea in winter. They occur when a cold airflow flows over relatively warm sea: the temperature difference between the sea and the air above is often 6 °C or more. This strong temperature gradient leads to strong heating of the air above and often convection extending to 4 km or more in height. The case of 28 February 2006 was a good example of such an outbreak. Figure 3 shows the 0600 UTC analysis for the North Atlantic region. A triggered lightning strike occurred at 0840 UTC close to Aberdeen airport. A cold front had recently passed over the UK, bringing strong northerly winds behind it, leading to heating of the air by the relatively warm North Sea.

Figure 4 shows the corresponding radar image from 10 min before the triggered strike. Although the pilot report specifically mentioned that there was no precipitation or icing on the aircraft, the helicopter was clearly flying in the vicinity of some deep convection. The red echoes on the radar represent precipitation rates of at least 4 mm h^{-1}, or roughly 30 dBZ in radar reflectivity.

Examining the radar images subjectively for the four cases where the triggered strike occurred in the region covered by the UK weather radar network, it was found that the strikes occurred very close to a rainfall rate of 4 mm h^{-1} or greater, with no more than 15 km between the strike location and the rain echo. The presence of many small, yet high-rainfall, echoes suggests that Cb or deep cumulus clouds are present close to the triggered strike location. Clouds which extend up to 4 km or higher and produce intense precipitation are capable of being charged. So, based on the synoptic charts and radar images, it is possible to suggest a few hypotheses as to how a triggered lightning strike may occur.

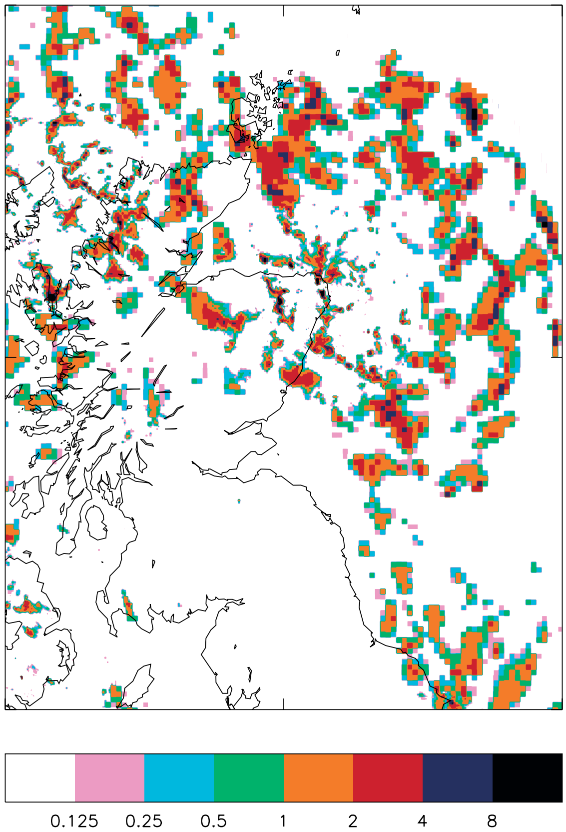

Figure 4. 0830 radar image for the triggered lightning strike of 28 February 2006. The rain rates are given in units of mm h^{-1}. This figure is available in colour online at wileyonlinelibrary.com/journal/met

3.2. Hypotheses of how triggered lightning strikes occur

It is well known that helicopters generally acquire a negative charge due to frictional contact with the air (e.g. Born *et al*.,

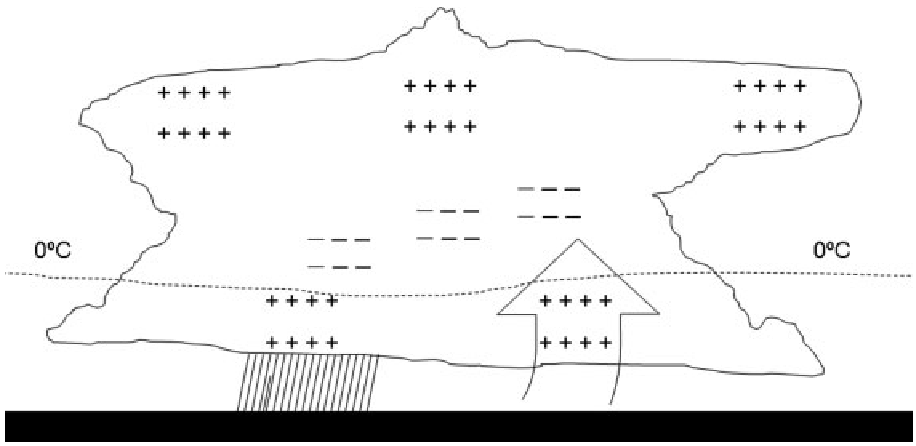

Figure 5. Schematic of the basic charge structure in the convective region of a North Sea wintertime convective thunderstorm cell. The dashed line marks the height of the freezing level and the arrow shows the main updraught. Adapted for North Sea thunderstorms from Stolzenburg *et al.* (1998).

1972). A rapidly rotating rotor blade will also acquire a negative charge for the same reason. The charge it acquires will be much greater due to the rapid angular velocity of the blades and it will be unlikely that the charge will dissipate until the helicopter lands. The most likely triggered lightning strike mechanism is a negatively-charged helicopter encountering a region of positively charged cloud, resulting in a positive strike. The strike polarity noted in Hardwick (1999) is positive for seven out of nine case studies where the polarity of the helicopter triggered strike is known even though, globally, 90% of cloud-to-ground strikes are negative. The following three possible mechanisms for triggered lightning strikes are proposed.

1. Although most of the cloud base generally tends to be negatively charged (e.g. Rakov and Ulman, 2003), small cores of positive charge do appear close to the base of the clouds, often in the vicinity of the updraught and close to the 0 °C isotherm (e.g. Cooray, 2003; Rakov and Ulman, 2003). Broc *et al.* (2005) have shown with a cloud electrification model that there is a strong positive charge below 1500 m in North Sea winter time thunderstorms. Figure 5 shows the typical structure of a convective thunderstorm in the North Sea. It should be noted that positive and negative charges are present close to the freezing level, and that both are present in the vicinity of the precipitation. It is likely that a negatively-charged helicopter flying into or in the vicinity of a positively charged region would trigger a strike, if the potential difference is large enough.
2. In winter time, the tropopause tends to be lower and, behind a strong cold front, stratospheric intrusions can occur bringing the tropopause even lower (e.g. Browning and Reynolds, 1994). Any resulting deep convection can start to form anvil clouds much lower than their summer counterparts, with cloud tops observed as low as 4 km. Thunderstorm anvils tend to be positively charged (e.g. Cooray, 2003), thus a helicopter flying underneath such an anvil may trigger a strike. This may be the explanation behind the triggered lightning strike of 28 February 2006, where no precipitation was observed by the pilot.
3. Finally, to account for the few negative triggered lightning strikes, it is possible that an aircraft could trigger a strike by travelling between positively and negatively charged regions, or that it might trigger a negative cloud-to-cloud strike in between the two regions.

Although there are many deep convective events in the winter, there have only been 36 triggered lightning strike events recorded over a 20 year period in the North Sea, equating to 1 or 2 strike events *per* year. On any given operating day, there are around 100 flights in total. Therefore, a triggered lightning strike is a rare occurrence. Given that there are likely to be several flights through the field of showers or frontal surfaces on the triggered lightning strike days, it is possible that triggered lightning strikes do not occur due to the skill of the helicopter crews in avoiding Cb clouds and the rarity of positively charged regions of the cloud.

Although some pilot reports mention triggered strikes occurring in areas of Sc (e.g. the report of 28 February 2006 says the helicopter was flying in broken Sc), little other evidence has been found to suggest that triggered lightning strikes result from Sc clouds. Furthermore, Sc is unlikely to have the 3–4 km depth necessary for electrification (Mason, 1953). It is more likely that deep cumulus and cumulonimbus clouds are embedded within the Sc. These would be difficult for a pilot to detect, unless they are flying above the Sc cloud.

In conclusion, it is probably best for helicopters to avoid areas of the North Sea which are likely to be in the vicinity of charged clouds. Although there have been attempts to model in-cloud electric fields and natural lightning strikes (e.g. Rawlins, 1982; Barthe and Pinty, 2007), it has only been possible to model small areas (30 × 30 km) and the methods used would be too computationally expensive for a numerical weather prediction model. Furthermore, the accuracy to which these models capture the small areas of positive charge near the base of a thunderstorm is unknown. Any algorithm must use other means to determine the location of charged clouds.

4. Algorithm design and description

In designing an algorithm using 4 km Met Office Unified model data, the following considerations were made.

- The algorithm should be able to pick out the areas where a triggered strike has previously occurred.
- The algorithm should be sufficiently discriminating to minimize disruption to flight operations. One of the problems with Equation (1) was that it often indicated high risk over a large geographical area which, if acted on by the helicopter

operators, would lead to a shut-down of helicopter operations throughout most of the North Sea several times during each winter, a situation which is clearly untenable for the operators.

- Discussions with the helicopter operators indicated that it was preferable to fly around areas of risk, rather than to climb or descend. This is because to descend could require flying dangerously close to the sea surface and to fly much higher would mean that they would be likely to encounter icing and other air traffic. Flying around the danger area would have additional benefits as there are other phenomena (e.g. strong turbulence) which are associated with cumulonimbus clouds that may be encountered at higher altitudes.

In view of the fact that helicopter strikes typically occur close to precipitation rates of 4 mm h^{-1} or more, it was decided to use this value as the first condition for the new algorithm.

Hardwick (1999) highlighted that triggered lightning strikes tend to occur around the melting layer, with outside air temperatures for the majority of strikes being close to 0 °C. In Section 1, it was suggested that this should form the basis for the algorithm, along with some measure of convective activity which can identify the location of thunderstorm cells. In designing the algorithm, the total precipitation rate has been used as the prediction of convective activity together with the initial assumption that the outside air temperature must be within the range 0 ± 5 °C. In analysing triggered strike data, the average model temperature between 2000 and 3000 ft (610–914 m) was examined. It was found that in all triggered strikes, the average model temperature lies in the range between 267 and 272 °K (−6 to −1 °C). The difference between this range and that given in Section 1 is probably due to the averaging encompassing temperature data which was at a higher altitude than the triggered lightning strike (and therefore colder) for the majority of strikes.

In Section 1, it was also suggested that mixed-phase precipitation is required for a triggered lightning strike to occur. Typical values for the saturated adiabatic lapse rate are around 5 K km^{-1}. As 2000 ft is approximately 610 m, surface temperatures can be at −1.5 °C, and the temperature at the 2000 ft (610 m) flight level will be typically about −4.5 °C (within the range to trigger the algorithm). However, the height of the freezing level (0 °C) will be below the surface. Therefore, in addition to temperature and precipitation, the height of the freezing level in the model for the most recent eight triggered strikes was examined and, in all cases, the model freezing level was above 1000 ft (305 m) and below 4500 ft (1372 m). In most cases the freezing level height was close to 2000 ft (610 m). To try and represent the criteria for mixed phase precipitation, the algorithm has been set to only include grid points where the freezing level height is between 1000 and 4500 ft (305 and 1372 m). This means that the algorithm should only indicate triggered lightning strike probability during winter events and will not identify summer thunderstorms.

To summarize, an individual model cell is to be considered at risk of a triggered lightning strike if the following three conditions are met:

1. average model temperature between 2000 and 3000 ft (610 and 914 m) is between −6 and −1 °C;
2. total surface precipitation rate is 4 mm h^{-1} or greater, and,
3. height of the freezing level is between 1000 and 4500 ft (305 and 1372 m).

In order to 'stabilize' the overall output, an individual cell is only considered at risk if more than 10 cells within a 56 × 56 km grid box, centred on the cell in question, meet these criteria. This 'smoothing' scheme was derived empirically from historical data of triggered lightning strikes by selecting the number of cells that gave good hit rates, but low false alarms.

To examine the performance of the algorithm for a null data set, historical data for the 2010–2011 winter were used. These were generated by taking the 1200 UTC model forecast (from a start time of 0900 UTC) and selecting a region of interest. The region of interest was the North Sea area from Aberdeen to the west coast of Norway, covering the East Shetland Basin. Examining the triggered lightning strike locations from Figure 1, it was found that a box from latitude 56.5 °N to 61.5 °N and from 3.0 °W to 5.5 °E enclosed an area that contained 27 out of 34 strikes. This is shown as the box in Figure 1.

The performance of the algorithm was analysed for every available day between 1 November 2010 and 31 March 2011. Due to archiving problems, 143 out of a possible 151 days were available. It should also be noted that data from 22 November 2010 were not included in the null data set. This is because a triggered lightning strike occurred near Denmark at 0830 UTC. Even though this was out of the null domain, it was considered sufficiently close enough to allow the atmospheric conditions to be similar in the strike and null regions. To prevent any bias towards the analysis, this case was removed from the null data set.

5. Results

5.1. Ability of the operational model to forecast helicopter triggered lightning strike events

The operational model was analysed for eight helicopter strike cases from 2006 to 2010. Operational model data were not available for strikes occurring before 2006. In addition, the strikes on 6 February 2007 and 22 October 2008 were outside the UK4 domain and could not be used. The strike time on 6 February 2007 was estimated from the time of sferics around the reported strike location. As there was no accurate time information on this strike with which to verify the model, it was not considered as part of this analysis.

Out of the eight strike events, in six cases the model highlighted strike conditions for the model grid point nearest to the strike and, indeed, for a number of points around the strike location. In two triggered lightning strike cases (28 February 2006 and 18 February 2010) the model did not forecast a strike risk. In both of these cases this was because the model did not have a high enough rain rate in the area close to the triggered lightning strikes. In both cases, the helicopter strikes were very close to Aberdeen airport. The model precipitation and radar image for the 18 February 2010 strike case is shown in Figure 6. The model has the showers in the correct place, but the showers have rain rates of 1–2 mm h^{-1} and not the 4 mm h^{-1} threshold which would trigger the algorithm. The radar precipitation has areas of precipitation rate greater than 4 mm h^{-1} in the area close to the strike. This underestimation of precipitation rate seems to be a fairly rare occurrence as far as the UK4 model is concerned, but should be noted.

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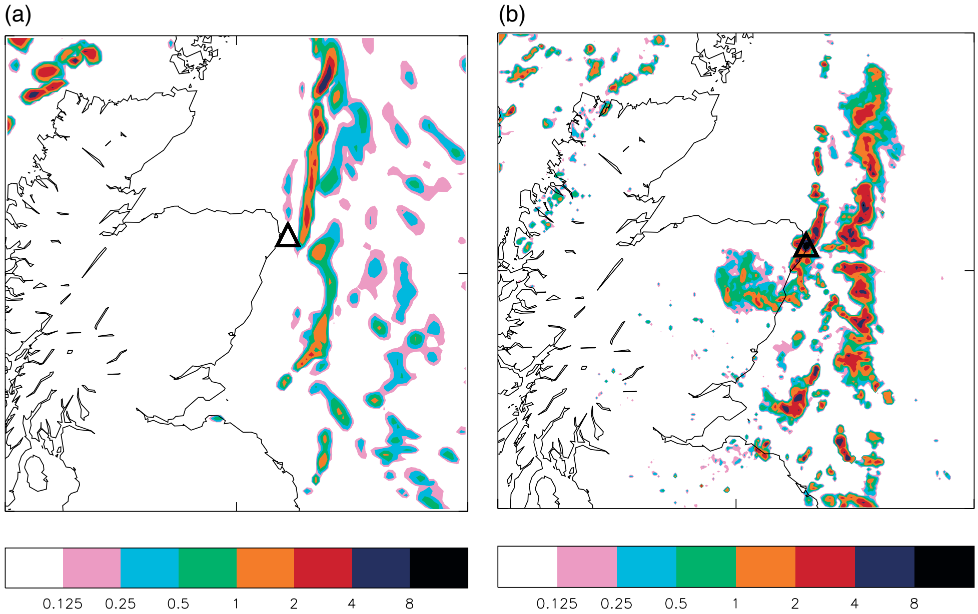

Figure 6. (a) UK4 operational model precipitation rate in mm h^{-1} for 0800 UTC on 18 February 2010. (b) The rainfall rate in mm h^{-1} derived from the UK radar network. The location of the helicopter triggered lightning strike is in the centre of the triangle on each plot. This figure is available in colour online at wileyonlinelibrary.com/journal/met

5.2. Skill scores for operational model forecasts of triggered lightning strikes

A contingency table was constructed with the null data set (143 cases) and the operational strike data (8 cases). A hit was deemed to occur when the model correctly forecast a triggered strike, a false alarm when the model forecast a triggered strike which did not occur, a miss when a triggered strike occurred which was not forecast and a correct rejection when the model did not forecast a triggered strike and one did not occur. Following methods described in Doswell *et al.* (1990) and Wilks (2006) skill scores can be used to define the performance of the algorithm. In the present study the hit rate, false alarm ratio and probability of false detection are used. The hit rate (HR) is defined as:

$$HR = \frac{H}{H + M}, \quad (2)$$

where H is the number of hits and M is the number of misses. Similarly, the false alarm ratio (FAR) is defined as:

$$FAR = \frac{FA}{H + FA}, \quad (3)$$

where FA is the number of false alarms. Finally, the probability of false detection (POFD; sometimes known as false alarm rate) is defined as:

$$POFD = \frac{FA}{FA + CR}, \quad (4)$$

where CR is the number of correct rejections.

In order to understand how restrictive the algorithm is likely to be, the results were examined using different thresholds for the area of the domain highlighted as being at risk of a triggered lightning strike. A single 4 × 4 km grid box that is at-risk is only a problem if the helicopter needs to fly through that region, but a large risk area is more likely to pose a problem. One of the complaints made by the helicopter operators was that the Patton (1999) algorithm over-forecast the size of the area at risk, often blocking out the entire operating region for a whole day. In order to assess the performance of the new algorithm the area of the domain that was highlighted as at risk was examined. Table 4 shows the results for different thresholds of areas at risk. The hit rate is generally high, but the false alarm ratio is also high.

Figure 7 shows the percentage area that was highlighted to be at risk for the whole of the null data set. The largest area identified as being at risk during the whole of winter 2010/2011 was close to 15% of the domain, and on only 7 days did the algorithm forecast more than 10% of the domain to be at risk. So, although the algorithm highlights risk areas in 34% of the cases, in only 6% of the cases did it highlight a large area (above 10%) of the domain to be at-risk.

5.3. Ability of the rerun model to forecast helicopter-triggered lightning strike events

The rerun model data were analysed in the same way as the operational model data. However, the results are slightly

Table 4. Contingency table for different threshold areas highlighted as being at risk for the operational model.

Threshold	Hits	False alarms	Misses	Correct rejections	H.R.	F.A.R.	P.O.F.D.
Above 1 point	6	47	2	95	0.750	0.887	0.331
Above 1% of domain	6	38	2	104	0.750	0.864	0.268
Above 5% of domain	6	14	2	128	0.750	0.700	0.099
Above 10% of domain	5	6	3	136	0.625	0.545	0.042

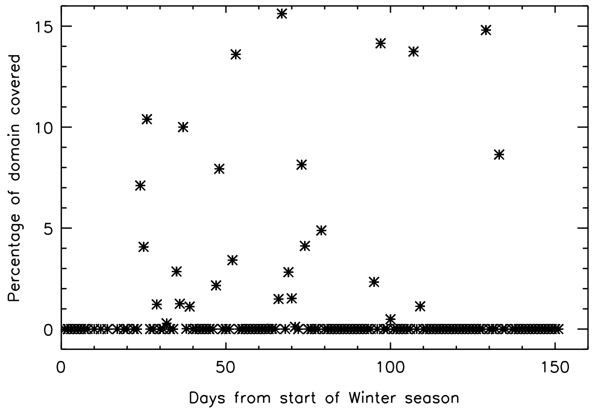

Figure 7. The percentage of the null domain shown in Figure 1 that was highlighted to be at risk of a triggered lightning strike by the algorithm, plotted against the number of days since the start of the wintertime null data set. Day 0 corresponds to 1 November 2010 and day 151 is 31 March 2011. Days where the data were not available have no value indicated.

different due to the lack of data assimilation in the rerun model. This means that while most features are represented, the position error in the location of fronts and showers is greater than in the operational model. However, the rerun model contains the latest physics package, which contains several improvements to the model physics over the operational model data which was used to analyse past strikes.

An example forecast from the rerun model is shown in Figure 8. In the triggered strike of 19 March 2007, the model does not capture the strike location precisely, but there is a risk area close by. In the case of 18 February 2010, the increased intensity of the precipitation for the rerun case (as shown in Figure 2) meant that the model highlighted some areas of risk. However, the lack of data assimilation in the rerun model means that there is a large distance between the location of the triggered strike (in observed heavy showers) and the actual warning area. This error in the location of precipitation should not be as large in the operational model.

The distance from each triggered lightning strike to the nearest highlighted risk region has been determined and the results are shown in Table 5. It can be seen that the majority

Table 5. Distances from the helicopter triggered lightning strikes to the nearest highlighted danger area in the rerun cases.

Date	Distance from triggered strike to forecast area (km)
22 October 2003	DNF
25 November 2005	35
6 February 2007	24
19 March 2007	25
31 January 2008	10
22 October 2008	DNF
22 March 2009	46
1 February 2010	32
18 February 2010	125
21 November 2010	52

DNF stands for cases where the model did not forecast a strike within 150 km of the reported strike.

of the strikes are within 50 km of the location of heavy precipitation in the forecasts. In two cases, the models did not forecast a triggered strike anywhere within 150 km of the reported strike location. However, with the majority of the triggered strikes forecasts being close to the reported echoes, it would appear that the rerun model (i.e. updated physics) has a slightly better chance of detecting the risk of a triggered lightning strike than the operational model, which has variable physics.

5.4. Skill scores for rerun model forecasts of helicopter-triggered lightning strikes

The skill scores examined in Section 5.2 were re-examined for the rerun cases. In the rerun cases, due to the lack of data assimilation, it was assumed that a forecast within 150 km is a hit, irrespective of the percentage of the domain highlighted at risk. This is shown in Table 6.

In all cases, the high hit rate indicates that the model has the potential to capture the triggered lightning strike conditions on the majority of occasions. However, as a consequence, the false alarm ratio is rather large. This is mainly because there is very little to distinguish non-strike days from strike days in the model data (and even the observational data).

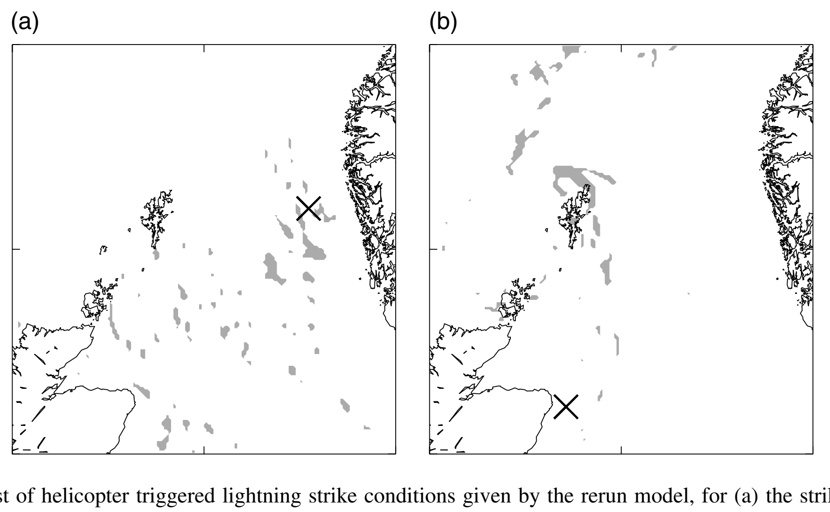

Figure 8. Example forecast of helicopter triggered lightning strike conditions given by the rerun model, for (a) the strike of 19 March 2007 and (b) the strike of 18 February 2010. The location of the triggered lightning strike is marked with the black cross and shaded regions indicate a strike risk.

Table 6. As Table 4 but for the rerun model.

Threshold	Hits	False alarms	Misses	Correct rejections	H.R.	F.A.R.	P.O.F.D.
Above 1 point	8	47	2	95	0.80	0.855	0.331
Above 1% of domain	8	38	2	104	0.80	0.826	0.268
Above 5% of domain	8	14	2	128	0.80	0.636	0.099
Above 10% of domain	8	6	2	136	0.80	0.429	0.042

5.5. Null data comparison with lightning sferics

Lightning observations, known as sferics, were obtained from ATDnet. These were examined subjectively and compared with the forecast maps of risk for the null data set. On each day the sferics that occurred between 1100 Z and 1300 Z were examined. Sferics were observed within the null data domain on nine occasions, as shown in Table 7.

The second column indicates whether or not the model forecast a triggered lightning strike in the area of the sferic (for a 'yes', the sferic had to lie on the region of high risk). This means that out of the 47 false alarms in Tables 4 and 6, 8 were observed to have natural lightning sferics in them. It could be argued that these cases should not be thought of as false alarms. However, as there was no record of a helicopter being struck by lightning, it was considered that the fairest approach was to remove these cases from the analysis.

Table 7. Dates when sferics were observed in the null data set between 1100 Z and 1300 Z, and whether the algorithm had forecast a strike to occur in the region of the sferic.

Date	Model forecast triggered strike
24 November 2010	Yes
28 November 2010	No
29 November 2010	Yes
19 December 2010	Yes
3 February 2011	Yes
15 February 2011	Yes
8 March 2011	Yes
9 March 2011	Yes
18 March 2011	Yes

Revised contingency tables for the operational model and rerun model results are presented in Tables 8 and 9, respectively. As can be seen, the false alarm ratio is reduced in all cases.

5.6. False alarms

Even after the natural lightning strikes were removed from the data, the false alarm rates are quite high. This would normally be a cause for concern. However, it should be noted that the absence of a triggered strike when one was forecast does not necessarily constitute a false alarm. It could be that conditions were ideal for a triggered strike but no helicopter flew in the right place at the right time to generate a strike. The concept of a false alarm is therefore academic to some extent, and the acceptability of the apparent false alarm rate should be evaluated by means of an operational trial.

In addition, a high false alarm rate can be tolerated provided that the operational impact is not significant. This would appear to be the case as the algorithm generally identifies relatively small regions of the operating area as at risk which can hopefully be easily avoided by rescheduling and/or re-routing the flight(s).

5.7. Forecasts for 8–10 March 2011

During the period of study, a cold air outbreak occurred, starting with a cold front that passed through the North Sea operating area on 8 March 2011, with strong convection lasting until 10 March 2011. Although there were no reported triggered lightning strikes, the helicopter operators were concerned about the risk of a strike and operations were shut down over part of the North Sea region for some time.

Figure 9 shows the synoptic chart for 0600 UTC on 8 March 2011; a similar cold front to that seen in Figure 3

Table 8. As Table 4, but after removal of natural lightning cases from the data set.

Threshold	Hits	False alarms	Misses	Correct rejections	H.R.	F.A.R.	P.O.F.D.
Above 1 point	6	39	2	95	0.750	0.866	0.291
Above 1% of domain	6	30	2	104	0.750	0.833	0.223
Above 5% of domain	6	11	2	123	0.750	0.647	0.082
Above 10% of domain	5	4	3	130	0.625	0.444	0.030

Table 9. As Table 6, but after removal of natural lightning cases from the data set.

Threshold	Hits	False alarms	Misses	Correct rejections	H.R.	F.A.R.	P.O.F.D.
Above 1 point	8	39	2	95	0.80	0.830	0.291
Above 1% of domain	8	30	2	104	0.80	0.789	0.223
Above 5% of domain	8	11	2	123	0.80	0.578	0.082
Above 10% of domain	8	4	2	130	0.80	0.333	0.030

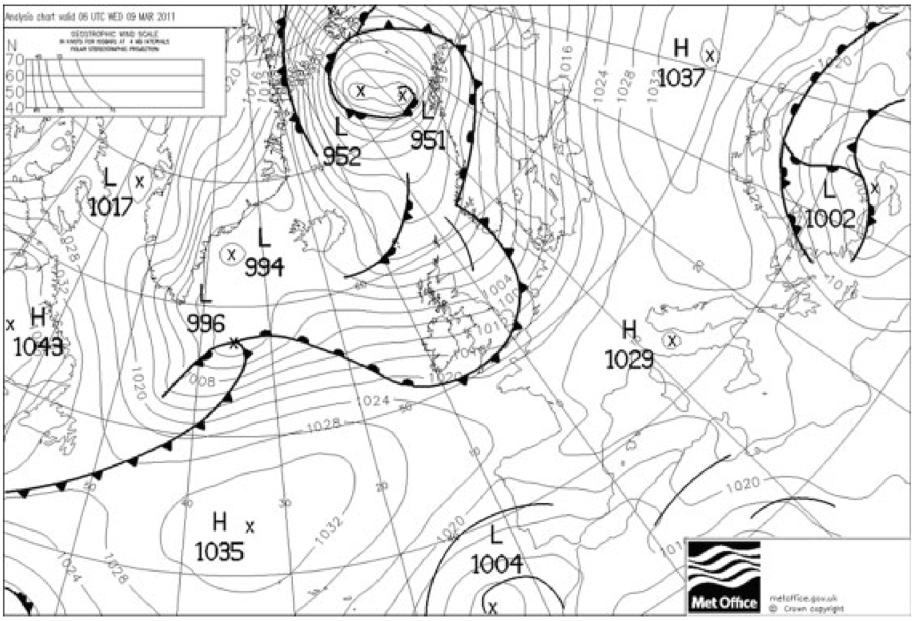

Figure 9. Analysis chart for 0600 UTC on 9 March 2011.

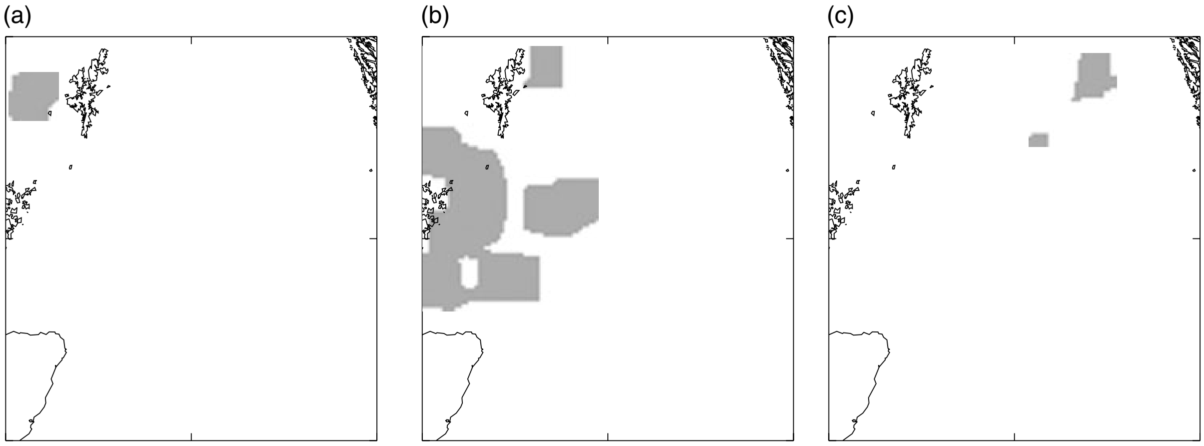

Figure 10. Sample forecasts for 1200 Z on (a) 8 March 2011, (b) 9 March 2011 and (c) 10 March 2011 for the null data region as defined in Figure 1. Shaded areas indicate triggered lightning strike risk.

has passed over the UK. Strong convection has been generated, including a front halfway between Iceland and the north of Scotland. This situation persisted for a couple of days, during which helicopter operations were partially suspended on 9 March. Figure 10 shows the forecasts generated from the null data set for 1200 Z on 8–10 March 2011. It can be seen that, starting on 8 March, some areas of the domain are highlighted by the algorithm. The peak is reached on 9 March 2011, and the area is reduced again by the 10 March 2011. These areas correspond roughly to the highest intensity echoes in the radar images and to the areas in which the helicopter operators decided not to fly.

6. Summary and conclusions

This study has examined the possibility of producing a triggered lightning algorithm using Met Office model data. After finding a lack of appropriate algorithms in the literature, an algorithm was developed based on specific conditions seen to be present at past triggered lightning strikes; notably temperature at typical flight levels, and total precipitation rate to give an indication of the location of convective cells. The model freezing level has also been used to ensure that the flight level is in the vicinity of where the precipitation starts to melt, which is thought to be a requirement for a helicopter-triggered lightning strike.

This study has found that the algorithm has the potential to forecast most triggered lightning strikes but, as a result, the model forecasts a potential for a triggered strike on 33% of days in the winter (47 out of 142 days). However, it is worth noting that in 8 of these 47 cases natural lightning was observed at the time and location indicated by the forecasts, implying that the algorithm could be generating false alarms on 27% of days (39 out of 142 days). In order to try and reduce this number, more criteria could be included in the algorithm. For example, if the criteria that 5% or more of the domain had to be indicated as a risk region were included then the model forecasts a strike potential on 8% of winter days (11 days out of 134). However, there is a risk that applying more stringent criteria would decrease the number of correct event detections

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and, indeed, the absence of a triggered lightning strike may not necessarily constitute a false alarm. Similarly, to capture the missed triggered lightning strikes using the algorithm would require a decreased precipitation threshold which would lead to more potential false alarms. So a balance will have to be struck and this will be influenced by the impact of alarms on operations. In future, this could be done using by creating many more contingency tables with different threshold levels of the domain at risk. The use of relative operating characteristic (ROC) curves, as described in Mason (1982) and Mason and Graham (1999) could then be applied to the analysis.

It is likely that the high proportion of forecast triggered lightning strike days during the winter is partially due to the nature of the events. In a typical winter there are probably around 10 cold air outbreaks in the North Sea operating area, each lasting around 3 days. This would mean that there are typically 30 triggered lightning strike-risk days *per* season, and assuming typically 100 flights by three operators in the North Sea operating area and typically two strikes *per* year there is a roughly 1 in 1500 chance of a helicopter being struck by lightning. This probability is low due to the fact that pilots are skillful in avoiding the areas of high risk, notably Cb clouds: most of the triggered lightning strikes have occurred when the pilots have not expected a strike (e.g. Cb embedded in Sc). The low probability will also be due to the rarity of high charge regions in clouds and the low potential for a helicopter to be caught either in the positive area of the cloud near the base, or underneath the anvil, or between two different charged areas.

The algorithm has shown potential in correctly forecasting eight out of nine events during the winter where natural lightning was observed in the domain. It has also correctly highlighted conditions likely to cause triggered lightning during a cold air outbreak in March 2011, during which some helicopter operators decided to suspend operations. The algorithm has the potential to warn of Cb activity for other purposes (e.g. to limit take-off of at airfields such as Komatsu airbase, in Kobayashi *et al*., 2007), but this has not been tested in the present paper.

Future upgrades to the operational model will naturally be made. It is hoped that a prognostic graupel variable can be added to the model in due course, which could allow further refinements to the algorithm.

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References

AAIB. 1997. Report on the accident to Aerospatiale AS332L Super Puma, G-TIGK, in North Sea south west of Brae Alpha Platform on 19 January 1995. Report No 2/1997, AAIB: http://www.aaib.gov.uk/sites/aaib/publications/formal_reports/2_1997__g_tigk.cfm (accessed 1 December 2011).

AAIB. 2005. Report on the accident to Sikorsky S-76A+, G-BJVX near the Leman 49/26 Foxtrot platform in the North Sea on 16 July 2002. Report No 1/2005. http://www.aaib.gov.uk/publications/formal_reports/1_2005_g_bjvx.cfm (accessed 1 December 2011).

Barthe C, Pinty J-P. 2007. Simulation of a supercellular storm using a three-dimensional mesoscale model with an explicit lightning flash scheme. *J. Geophys. Res.* **112**(D06210): DOI: 10.1029/2006JD007484.

Born GJ, Burke WF, Durbin EJ. 1972. A fundamental study of static electric phenomena (applied to helicopters). Technical Report, Princeton University: Princeton, NJ.

Broc A, Delannoy A, Montreuil E, Lalanda P, Laroche P. 2005. Lightning strike to helicopters during winter thunderstorms over North Sea. *Aerosp. Sci. Technol.* **9**: 686–691.

Browning KA, Reynolds R. 1994. Diagnostic study of a narrow cold-frontal rainband and severe winds associated with a stratospheric intrusion. *Q. J. R. Meteorol. Soc.* **120**: 235–257, DOI: 10.1002/qj.49712051602.

Cooray V. (ed.) 2003. *The Lightning Flash, IET Power and Energy Series, Vol. 34*. Institution of Electric Engineers: Stevenage.

Doswell CA, Davies-Jones R, Keller DL. 1990. On summary measures of skill in rare event forecasting based on contingency tables. *Weather Forecast.* **5**: 576–585.

Ely BL, Orville RE. 2005. High percentage of positive lightning along the USA west coast. *Geophys. Res. Lett.* **32**: L09815, DOI: 10.1029/2005GL022782.

Gaffard C, Bennett AJ, Atkinson NC, Nash J, Hibbett E, Callaghan G, Taylor P, Odams P. 2008. Observing lightning from the ground over large areas of the globe. *Proceedings WMO Technical Conference on Instruments and Observing Methods*, Vol. 1(16). WMO: St. Petersburg. http://www.wmo.int/pages/prog/www/IMOP/publications/IOM-96_TECO-2008/_PROGRAMME.HTML

Hardwick CJ. 1999. *Assessment of Lightning Threat to North Sea Helicopters: Final Report*. Paper 99007. Civil Aviation Authority: London.

Kitagawa N, Michimoto K. 1994. Meteorological and electrical aspects of winter thunderclouds. *J. Geophys. Res.* **99**(D5): 10,713–10,721.

Kobayashi F, Shimura T, Masuda K. 2007. Aircraft triggered lightning caused by winter thunderclouds in the Hokurika Coast, Japan – A case study of a lightning strike to aircraft below the cloud base. *SOLA* **3**: 109–112, DOI: 10.2151/sola. 2007-028.

Lande K. 1999. Lightning strikes on helicopters – effects, detection and avoidance. SAE Technical Paper Series 1999–01-2398.

Lee ACL. 1986. An operational system for the remote location of lightning flashes using a VLF arrival time difference technique. *J. Atmos. Oceanic Technol.* **3**: 630–642.

Mason BJ. 1953. The growth of ice crystals in a supercooled water cloud. *Q. J. R. Meteorol. Soc.* **79**: 104–111.

Mason I. 1982. A model for assessment of weather forecasts. *Aust. Met. Mag.* **30**: 291–303.

Mason SJ, Graham N. 1999. Conditional probabilities, relative operating characteristics and relative operating levels. *Weather Forecast.* **14**: 713–725.

Patton R. 1999. *Lightning Strikes to Helicopters Over the North Sea*. Paper 99008. Civil Aviation Authority: London.

Rakov VA, Ulman MA. 2003. *Lightning: Physics and Effects*. Cambridge University Press: Cambridge.

Rawlins F. 1982. A numerical study of thunderstorm electrification using a three dimensional model incorporating the ice phase. *Q. J. R. Meteorol. Soc.* **108**: 779–800.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice and night marine air temperature since the late nineteenth century. *J. Geophys. Res.* **108**(D14): 4407, DOI: 10.1029/2002JD002670.

Stolzenburg M, Rust WD, Marshall TC. 1998. Electrical structure in thunderstorm convective regions 3. Synthesis. *J. Geophys. Res.* **103**: 14097–14108.

Wilks DS. 2006. *Statistical Methods in the Atmospheric Sciences*. Academic Press: Burlington, MA; 264–265.