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Technical Report No. 304

Identification of Meteorological Wake Vortex Predictors

by

D. J. Hoad

March 2000

The Met.Office

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Abstract

Wake vortex safety considerations dictate aircraft separation limits at busy airports. If weather conditions in which wake vortices decay quickly can be identified and used reliably as "wake vortex predictors", there is potential for making the separation distances dependant on these predictors as well as aircraft weight. This could increase the capacity of airports in certain weather conditions.

This study uses the ETWIRL (European Turbulent Wake Incident Reporting Log) database, which contains data for wake vortex incidents reported by the air traffic control (ATC) authority at London Heathrow airport in addition to incidents occurring around the world reported by pilots. In this study, weather data for incidents occurring at Heathrow were extracted from the ETWIRL database and compared with weather data from a "null incident" database. This "null incident" database holds weather data from Heathrow airport on days on which no wake vortex incidents were reported by the ATC authority at Heathrow. This comparison identified some weather-related predictors, which could indicate whether a wake vortex incident is likely to occur. A statistical analysis was then performed to analyse the performance of these predictors.

Identification of Meteorological Wake Vortex Predictors

Contents

Nomenclature

C_p	= specific heat of water vapour at constant pressure
D	= distance between the wake vortices in the pair
dU/dz	= wind shear or rate of change of wind speed with height
F_m	= Monin Obukhov similarity function
g	= acceleration due to gravity (equal to 9.81)
H	= sensible heat flux
k	= von Karman constant (equal to 0.41)
L	= Monin Obukhov length scale
p	= pressure
p(0)	= pressure at sea level
p_0	= standard pressure (taken to be 1000mb)
q*	= ambient turbulence velocity
R	= Gas constant (equal to 287 J deg^{-1} kg^{-1})
T	= temperature
t	= time
U_z	= wind speed at height z
u*	= friction velocity
z	= height
z0	= roughness length
z'	= ratio of height to the Monin-Obukhov length scale
α	= angle wind direction makes with the runway
ρ	= density of air
ψ_M	= a stability function defined in Holtslag and Ulden (1983), and Holtslag and De Bruin (1988)

1. Introduction

Wake vortex safety considerations dictate aircraft take off and landing separation limits at busy airports. As the effect of wake vortices is dependant on the weight of the aircraft creating them and the weight of the affected aircraft, current separation limits are based on the weight of the leading and following aircraft. However, it is widely believed that wake vortices decay faster under certain weather conditions. If these weather conditions can be identified and used reliably as "wake vortex predictors", there is potential for making the separation distances dependant on these predictors as well as the weight of the leader and follower aircraft. This could increase in capacity at airports in certain weather conditions.

This study uses data from the ETWIRL (European Turbulent Wake vortex Incident Reporting Log) database. This database holds details of wake vortex incidents, such as the location, the type of aircraft involved and weather conditions. The database contains incidents reported by air traffic control (ATC) authorities at London Heathrow and Gatwick airports in addition to incidents occurring around the world reported by pilots. In this study, the data for incidents occurring at Heathrow were extracted from the ETWIRL database and compared with weather data from a "null incident" database. This "null incident" database holds weather data from Heathrow airport on days on which no wake vortex incidents were reported by the ATC authorities at Heathrow. This comparison identified some weather (or weather related) predictors which could indicate in future whether a wake vortex incident is likely to occur. A statistical analysis was then performed to analyse the performance of these predictors.

This paper is split into 6 sections. The next section describes the data used in this study, the predictors investigated and how these predictors were calculated. Section 3 presents and discusses the initial results, obtained from scatterplots of each predictor against height for all cases. Section 4 describes the statistical analysis of some of the predictors. Section 5 investigates the dependence of the predictors for incident cases on the aircraft separation distance. Section 6 discusses possible improvements to this work and suggests areas for future investigation. Section 7 presents a summary of the conclusions.

2. Identifying the Meteorological Predictors

2.1 Data Used in This Study

For this study a null-incident dataset and an incident dataset were created. Only incident or null incident events occurring at Heathrow were used in this study. This was for two reasons. Firstly, the direction of the parallel runways at Heathrow and the roughness length z0 at Heathrow are known. These two parameters are needed in the calculation of some of the predictors. Secondly, dates when no wake vortex incidents occurred at Heathrow could be determined as the ATC authority at Heathrow reports any wake vortex incidents for inclusion in the ETWIRL database.

The null-incident dataset held meteorological data from days when no wake vortex incidents were reported by the ATC authority at London Heathrow. This meteorological data consisted of the observed surface pressure, temperature, wind speed and direction at Heathrow and the Global model values for sensible heat flux, wind u and v components and temperature at 4 model levels (model levels 1000mb, 950mb, 925mb and 900mb).

The incident dataset contained wake vortex incident data for incidents where the height of the affected aircraft was known, and where the aircraft involved were using one of the parallel runways (runways 09L/27R,or 09R/27L). Incidents used in this study were also restricted to those that occurred at a height below the 900mb model level. The data for the incident dataset was extracted from the ETWIRL database. The incident dataset contained the altitude of the affected aircraft as reported by the pilot or by the ATC authority at Heathrow in addition to the same meteorological parameters as contained in the null-incident dataset.

2.2 Meteorological Predictors Investigated

The parameters calculated and compared in this study as potential predictors were the following:

i) The wind speed, U_z. This parameter was chosen for investigation as it has been demonstrated that if the wind speed exceeds 12 knots, wake vortices will decay to non-hazardous levels within one minute (Halsey 1998).

ii) The crosswind component, x_wind, to the runway. This parameter was chosen for investigation as it has been demonstrated that a crosswind exceeding 6 knots moves wake vortices out of the path of a following aircraft within a minute (Rudis and Burnham 1997).

iii) The wind shear (or change in wind speed with height), dU/dz. It was thought that this might show some indication of wake incident conditions from non-incident conditions, as the ambient wind shear affects the decay of the downwind vortex (Kantha 1998).

iv) The friction velocity, u*. This parameter was chosen as it gives an indication of turbulence (the more turbulent the atmosphere, the larger the value of u*), and turbulence is the main method of wake vortex decay (e.g. Greene 1986, Halsey 1996).

v) The term gamma3, which is a parameter taken from the equations in Kantha's empirical model of transport and decay of wake vortices, described in Kantha (1996) and Kantha (1998). It represents the decay of the downwind wake vortex by ambient wind shear, and is given by Equation 5 (see Section 2.3). This term was investigated as Kantha (1998) found that this significantly affected the decay of the downwind vortex parameter.

It was also intended to investigate three other predictors that are related to the turbulence of the atmosphere and the possibility of vortex decay due to Crow instability. (Crow instability is decay that happens when the two vortices touch, and so interfere, with each other. It is described by Crow and Bate (1976).) These parameters were to be calculated using an iteration method described by Holtslag and Van Ulden (1983). Unfortunately, the value of sensible heat flux obtained from the Global model was incompatible with that needed for the iteration scheme. This meant that the analysis of the other predictors could not be performed.

2.3 Calculating the Predictors

In the null-incident calculations, the predictors were calculated at 5 levels in the atmosphere: at 10m (where surface wind speed and wind direction is measured) and at the 4 model levels 1000mb, 950mb, 925mb, and 900mb. In the incident calculations, the predictors were calculated at the height of the incident. Before the predictors described in the section above were calculated, the following had to be determined:

i) The roughness length at Heathrow. This is reported to be approximately 0.1 m for north-easterly winds and approximately 0.4 m for south-westerly winds by Wieringa (1980). In this study, $z_0 = 0.1$ m if the wind direction was between the north and east, $z_0 = 0.4$ m if the wind direction was between the south and west, and $z_0 = 0.25$m for all other directions.

ii) The angle the wind direction makes with the runway at the height of the incident or null incident. This was determined using the observed wind direction (or wind components from the nearest model level) and the direction of the runways used. (The parallel runways at Heathrow are orientated at 274° (Halsey 1996)).

iii) The height of each of the model levels 1000mb, 950mb, 925mb, 900mb. These were determined using Equation 1.

$$p = p(0)\exp\left(\frac{-z}{7000}\right) \qquad (1)$$

iv) The pressure at the incident height and at 10m in the null-incident cases. These were calculated using Equation 1.

Once these parameters were determined, the predictors were calculated using the methods described below.

i) Wind speed (U_z), wind shear (dU/dz), and friction velocity (u*)

In the boundary layer under neutral conditions, the rate of change of horizontal wind speed is inversely proportional to the height. This gives Equation 2, which was used for calculating the wind shear:

$$\frac{dU}{dz} = \frac{A}{z} \quad (2)$$

Integrating this equation, and using the condition that the wind speed drops to zero at a height equal to the roughness length z0, gives the following equation for A:

$$A = \frac{u^*}{k}$$

and Equation 3 for calculating the wind speed U_z at height z:

$$U_z = \frac{u^*}{k}\ln(z) - \frac{u^*}{k}\ln(z0) \quad (3)$$

Using this theory, u* can be determined from the slope of the graph of U_z versus ln(z). This can be calculated using two measurements of wind speed, or using the roughness length and one measurement of wind speed. The theory described above can be found in boundary layer textbooks, e.g. Stull (1988).

This method of calculating U_z, dU/dz and u* was used for all incidents and null incidents occurring in the boundary layer. The height of the boundary layer depends on the roughness length (it is higher for rougher surfaces such as city centres) and the state of the atmosphere (it is higher for unstable conditions). A stable night-time boundary layer typically has a height between 50m and 100m, and an unstable boundary layer a height of about 1 km. A boundary layer height of 100m was chosen for this study. This depth was chosen to reduce the chance of accidentally using the boundary layer method above the boundary layer in stable nighttime conditions.

For incidents and null incidents occurring above 100m, the wind speed and wind shear were calculated by interpolating the values given at the nearest model levels. It was intended to calculate the value of u* using an iterative scheme described by Holtslag and Van Ulden (1983). Unfortunately, the sensible heat flux obtained from the Global model was unsuitable for use in this iteration scheme, so it could not be used. Therefore the results produced in this study for u* refer to incidents below 100m only.

ii) Crosswind, x_wind

The crosswind was calculated using Equation 4.

$$x\_wind = U_z \sin\alpha \quad (4)$$

For this predictor to be of use, it is assumed that both the flight paths of the leader and follower aircraft are in the same direction as the runway they were using at Heathrow.

iii) Gamma3

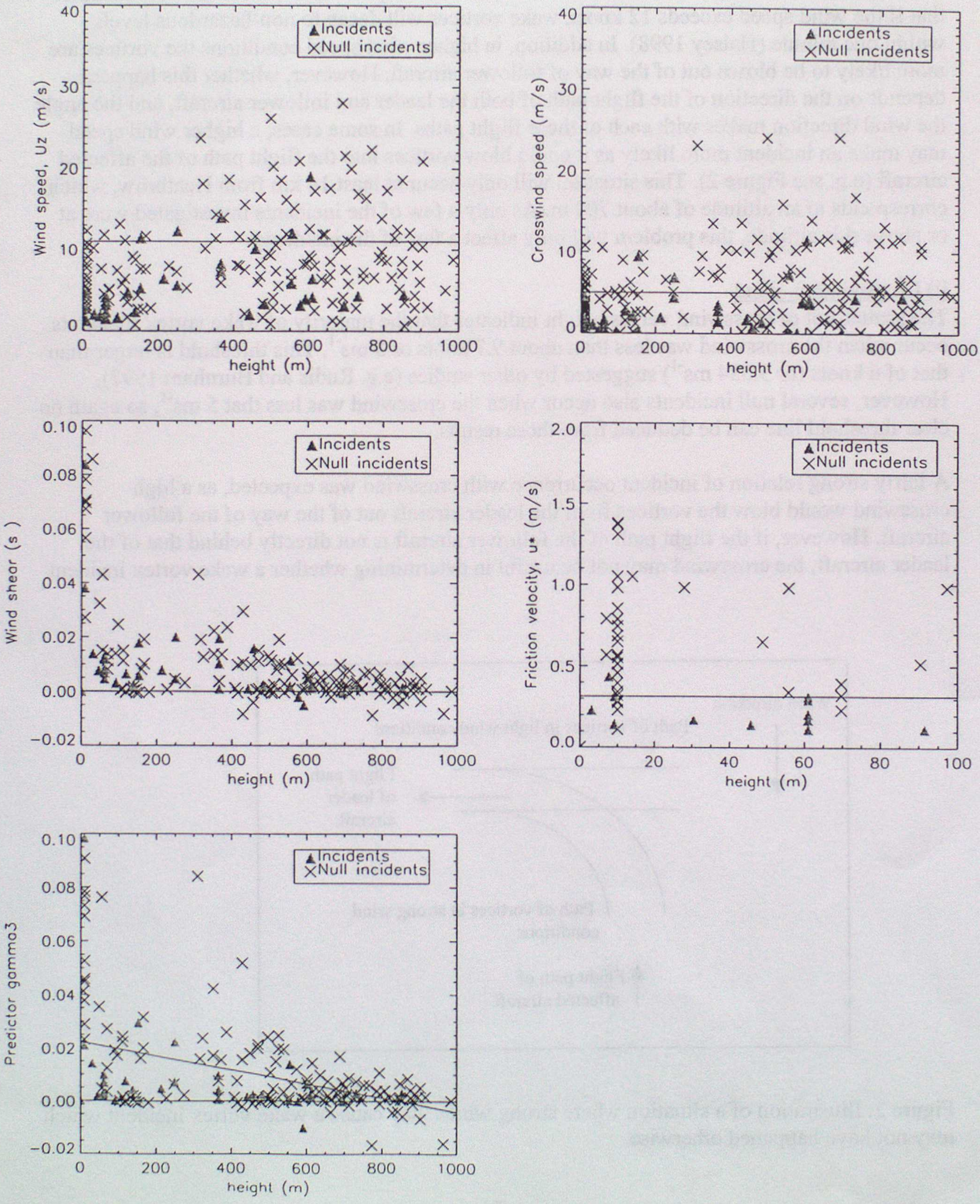
This was calculated using Equation 5.

$$gamma3 = 2.0(dU/dz)\sin\alpha \quad (5)$$

3. Discussion of Initial Results

For all events, each predictor value was plotted against the incident or null incident height, producing a scatterplot for each predictor. These scatterplots are presented in Figure 1. The scatterplot for the predictor gamma3 is plotted over the range $0 \leq$ gamma3 ≤ 0.1, although there are several null incident points and a few incident points above gamma3=0.1. This range was

Figure 1. Scatterplots of predictor values for incidents and null incidents. The line drawn on the wind speed, crosswind, friction velocity and gamma3 scatterplots indicate the threshold lines used in the statistical analysis in Section 4.



used because most of the incident and null incident points were below the value gamma3=0.03, so this range would give a clearer indication of any distinction between the incident and null incident values.

i) Wind speed, U_z

The scatterplot of wind speed versus height indicates that the majority of incident cases occur at lower wind speeds, particularly in the lowest 200m. However several null incidents also occur at lower wind speeds, therefore no clear threshold can be deduced from these results. Some relation of incident occurrence to wind speed was expected, as it has been demonstrated that if the wind speed exceeds 12 knots, wake vortices will decay to non-hazardous levels within one minute (Halsey 1998). In addition, in higher wind speed conditions the vortices are more likely to be blown out of the way of follower aircraft. However, whether this happens depends on the direction of the flight path of both the leader and follower aircraft, and the angle the wind direction makes with each of these flight paths. In some cases, a higher wind speed may make an incident more likely as it could blow vortices into the flight path of the affected aircraft (e.g. see Figure 2). This situation will only occur at least 14 km from Heathrow, which corresponds to an altitude of about 700 m. As only a few of the incidents investigated were at or above this altitude, this problem will only affect a few of the incidents.

ii) Crosswind, x_wind

The scatterplot of crosswind versus height indicates that the majority of wake vortex incidents occur when the crosswind was less than about 9.7 knots or 5 ms^{-1}. This threshold is larger than that of 6 knots (or 3.084 ms^{-1}) suggested by other studies (e.g. Rudis and Burnham 1997). However, several null incidents also occur when the crosswind was less that 5 ms^{-1}, so again no clear threshold line can be deduced from these results.

A fairly strong relation of incident occurrence with crosswind was expected, as a high crosswind would blow the vortices from the leader aircraft out of the way of the follower aircraft. However, if the flight path of the follower aircraft is not directly behind that of the leader aircraft, the crosswind may not be useful in determining whether a wake vortex incident

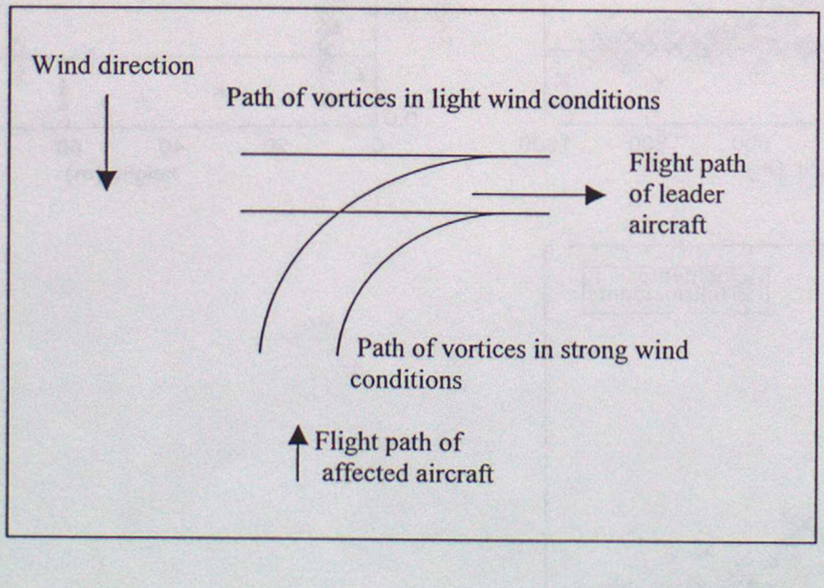


Figure 2. Illustration of a situation where strong winds may cause a wake vortex incident which may not have happened otherwise.

occurs or not. In addition, the crosswind has been calculated as the crosswind to the runway in this study. The flight paths of the aircraft involved in the incident cases are assumed to be parallel to the runway, but if that is not actually the case this would cause an error in the value of the crosswind.

iii) Wind shear, dU/dz

The scatterplot of wind shear versus height does not give a clear distinction between incident and non-incident conditions. It may be that there is a relationship between wind shear and the occurrence of an incident, but more values of wind shear in both incident and non-incident conditions are needed before it can be identified.

iv) Friction velocity, u*.

The scatterplot of friction velocity, **u***, versus height indicates in general that the value of u* tends to be lower in incident cases than in null incident cases. This is expected because the larger the value of u*, the more turbulent the atmosphere, the quicker vortices will decay (Greene 1986), and so the likelihood of an incident occurring will be less. However there were only a few incidents where u* could be calculated, so these results should be treated with caution. Further investigation with more incidents (and null-incidents) is needed before an accurate forecasting threshold is determined.

v) Gamma3

The scatterplot of gamma3 versus height indicates that the value of gamma3 tends to be lower in incident cases than in null incident cases. This was expected, as the larger the value of gamma3, the faster the decay of the downwind vortex due to ambient wind shear, and the less likely that an incident caused by this vortex will occur.

However, this parameter deals with a decay mechanism that only affects the downwind vortex. After the downwind vortex has decayed, the behaviour of the remaining vortex changes as it is no longer influenced by the downwind vortex. For example, a pair of vortices tend to move downwards, but a single vortex may move upwards. This changes the likelihood of an incident caused by the remaining vortex, but it is difficult to say whether the likelihood is increased or decreased.

4. Statistical Analysis of the Meteorological Predictors

A statistical analysis of the predictors U_z, crosswind, u* and gamma3 were performed using the thresholds described in the following paragraphs. In the cases of the U_z, crosswind and gamma3 predictors, this statistical analysis was performed to highlight the result that there were no clear distinctions between incident and null incident conditions.

i) Wind speed, U_z

For the statistical analysis, a threshold of Uz=11 ms^{-1} was used. Events where the wind speed was greater than 11 ms^{-1} were predicted to be null incidents and those where the wind speed was less than 11 ms^{-1} were predicted to be wake vortex incidents. A constant threshold was used because a wind speed threshold should be independent of height.

ii) Crosswind, x_wind

For the statistical analysis, a threshold of crosswind=5 ms^{-1} was used. Events where the crosswind was greater than 5 ms^{-1} were predicted to be null incidents and those where the crosswind was less than 5 ms^{-1} were predicted to be wake vortex incidents. A constant threshold was used because a wind speed (or crosswind) threshold should be independent of height.

iii) Friction velocity, u*

For a statistical analysis, a threshold of u*=0.315 was used. Events which had a value of u* above this line were predicted to be null incidents, and those which had a value of u* below this line were predicted to be wake vortex incidents.

iv) Gamma3

For the statistical analysis, the threshold line described by the equation

$$gamma3 = -(2.637E-5)z + 0.0223$$

was used. Events that had a value of gamma3 above this line were predicted to be null incidents, and those that had a value of gamma3 below this line were predicted to be wake vortex incidents.

4.1 Description of Statistical Measures Used

There are four possible outcomes of an event:

1/ A wake vortex incident was forecast by the predictor under investigation and the incident occurred;

2/ A wake vortex incident was forecast by the predictor under investigation but the incident didn't occur;

3/ A wake vortex incident was not forecast by the predictor under investigation but the incident occurred;

4/ A wake vortex incident was not forecast to occur by the predictor under investigation and the incident didn't occur.

For each predictor under investigation, the value of the predictor at each incident and null incident was compared with the threshold value. This comparison was used to decide which of the four categories above the event was in. The counts for each predictor then added together

		Observed	
		Air sector closed	Air sector open
Forecast	Air sector closed	**a**	**b**
	Air sector open	**c**	**d**

n = total number of forecasts = a + b + c + d and entered into a 2x2 contingency table (as illustrated on the previous page) for each forecast range. (The contingency table values for each predictor tested can be found in the Appendix.)

Several statistical forecast quality measures were calculated from this table. The description of these measures below is taken from Hoad (1999). For a more detailed description see Wilks (1995). The values calculated for each of these statistical measures were then plotted as a bar chart.

Accuracy

Accuracy measures sum up the quality of a set of forecasts by comparing individual pairs of forecasts and observations. There are several scalar measures of accuracy, described in the following paragraphs.

1. Hit Rate or Proportion Correct

This represents the fraction of times when the forecast was correct. It is calculated using:

$$HitRate = \frac{a+d}{n}$$

2. Critical Success Index (CSI)

The Critical Success Index (also known as the Threat Score) can be used as an alternative to the Hit Rate. It is particularly useful in cases where the event to be forecast occurs less frequently than the non-occurrence of the event. It represents the hit rate once the "wake vortex incident was not forecast to occur and didn't occur" values were removed.

$$CSI = \frac{a}{a+b+c}$$

3. False Alarm Rate (FAR)

This is the fractional number of times that the event was forecast occur and it didn't occur. (The best False Alarm Rate value is zero and the worst is one.)

$$FAR = \frac{b}{a+b}$$

4. Probability of Detection (POD)

This is the fraction of times when the event was forecast when it had been observed. (The best POD value is one, and the worst zero.)

$$POD = \frac{a}{a+c}$$

Bias

This is measured by comparing the average forecast with the average observation. This is not an accuracy measure, as it does not compare forecasts and observations for individual occasions.

Bias is determined by the bias ratio. In this study, it is the ratio of "wake vortex incident" forecasts to "wake vortex incident" observations.
A perfectly unbiased forecast has a bias ratio of 1. This means that closure of the air sector was forecast the same number of times as it was observed.

If the bias ratio is greater than one, wake vortex incidents were forecast more often than observed ("overforecast"). If the bias ratio is less than one, wake vortex incidents were forecast less often than observed ("underforecast").

$$Bias\ Ratio = \frac{a+b}{a+c}$$

Forecast Skill

Another way of measuring the accuracy of the forecasts is by comparing them with a set of control or reference forecasts. Common forecasts that are used for this are random forecasts.

The forecast skill is then given by:

$$Forecast\ Skill = \frac{F - F_{ref}}{F_{per} - F_{ref}}$$

where F_{per} = probability of perfect forecast being correct (which equals 1)
F_{ref} = probability of reference forecast being correct
F = probability of forecast under test being correct

A number of skill scores have been developed which are based on this idea. The one used in this study is the Kuipers Skill Score (or KSS) described by Wilks (1995). In this skill score, the rarer the event to be forecast the more influence a correct forecast of this event has on the skill score.

The Kuipers Skill Score was developed using unbiased random reference forecasts. It is given by:

$$KSS = \frac{ad - bc}{(a+c)(b+d)}$$

KSS is 1 for perfect forecasts, zero for random forecasts and negative for forecasts that are inferior to random forecasts. In addition, constant forecasts (i.e. always forecasting wake vortex incidents) have a KSS of 0.

4.2 Discussion of Results

The bar charts in Figure 3 show the values of each statistical measure for each predictor investigated.

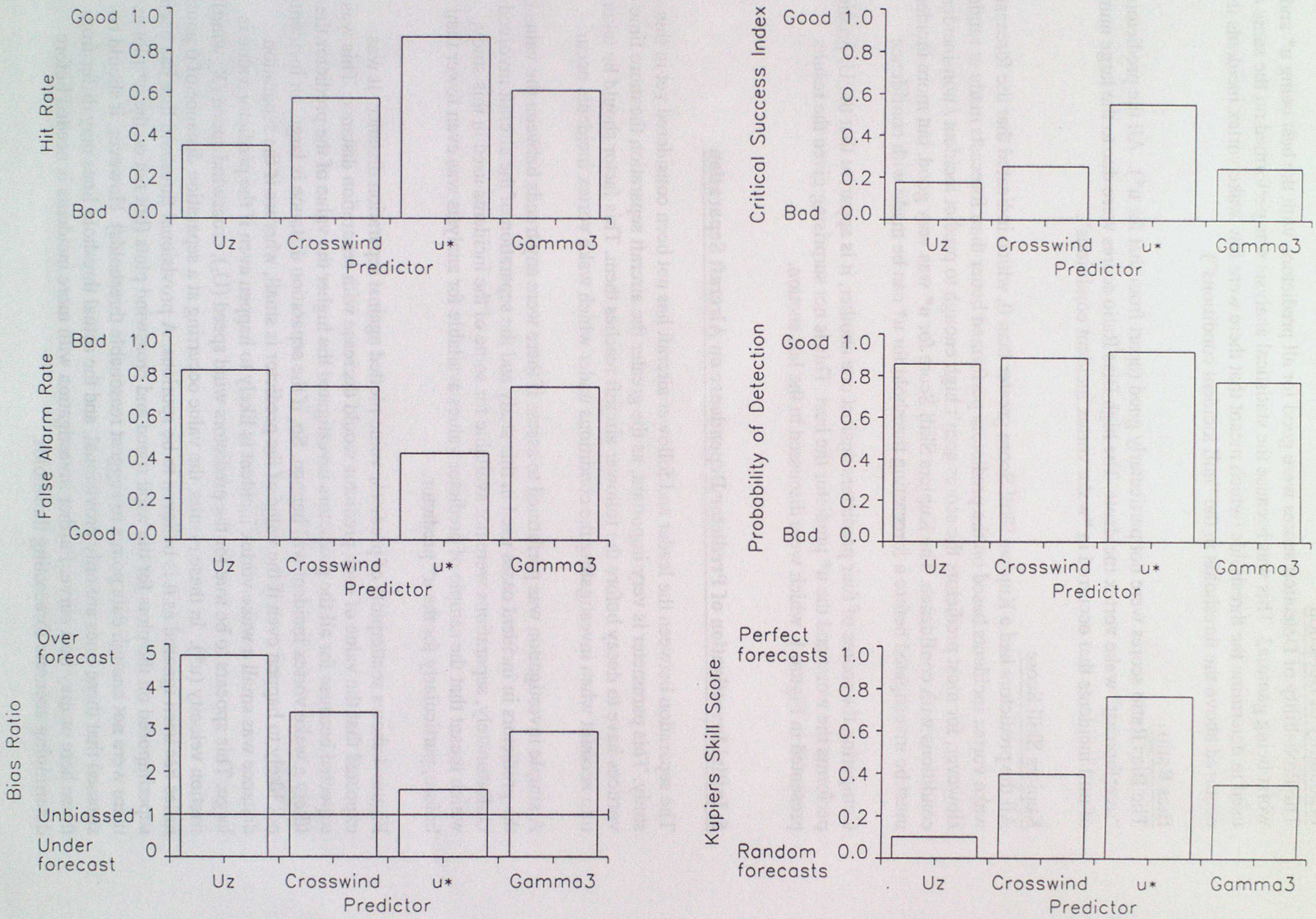
Hit Rate and Critical Success Index

The Hit Rate and Critical Success Index scores were not particularly good for all the predictors except u* (with those for U_z being the worst). This was due to the large number of null incidents which occurred in "wake vortex incident" conditions, particularly for the U_z predictor case. The results for u*, although encouraging, should be treated with caution as only a few incidents and null incidents were investigated for this predictor.

False Alarm Rate

The False Alarm Rate scores were quite high (i.e. not very good) for all predictors, except for the u* predictor. The False Alarm Rate scores were expected to be high in all the predictor cases (except u*) because of the large number of null incidents which occurred in "wake vortex incident" conditions.

Figure 3. Bar charts for each statistical measure used showing the scores obtained by each predictor.



Probability of Detection

The Probability of Detection scores were good for all predictors, with the best being u* and the worst being gamma3. This was because the statistical analysis was performed on the same data used to determine the thresholds (which meant that there were few wake vortex incidents that occurred above the thresholds in the "null incident conditions").

Bias Ratio

The Bias Ratio scores were not particularly good (apart from that for u*). All the predictors "overforecast" wake vortex incidents. The high Bias Ratio scores were due to the large number of null incidents that occurred in "wake vortex incident conditions".

Kupiers Skill Score

All the predictors had a Kupiers Skill Score greater than 0, which indicated that the forecasts of wake vortex incidents based on the predictors performed better than forecasts made at random. However, for most predictors the scores aren't high enough to predict incident / non-incident conditions with confidence. The Kupiers Skill Score for u* was very good, but more incidents must be investigated before a forecasting threshold for u* can be made with confidence.

Comparing the scores of four predictors against one another, it is apparent that the U_z predictor performs the worst and the u* predictor the best. This is not surprising given the results presented in Figure 1, which were discussed in the last section.

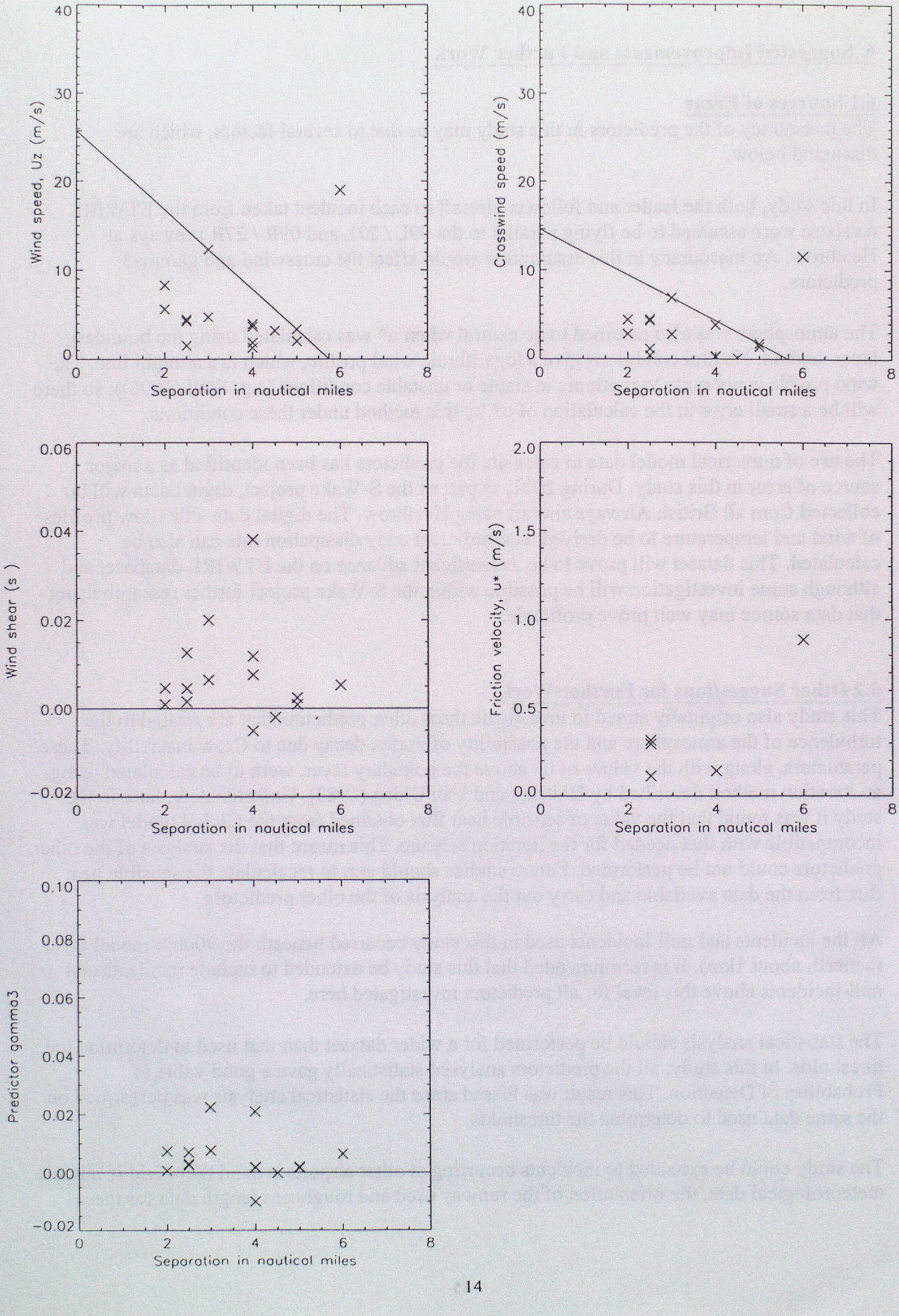
5. Initial Investigation of Predictor Dependence on Aircraft Separation

The separation between the leader and follower aircraft has not been considered yet in this study. This parameter is very important, as the greater the aircraft separation the more time the vortices have to decay before the follower aircraft reaches them. This factor should be taken into account when investigating the conditions under which wake vortex incidents occur.

A simple investigation was performed to assess if there were any trends between the value of the predictors in incident cases used in this study and the separation of the aircraft involved. Unfortunately, separations were not available for some of the incidents used in this study, which meant that the sample of predictor values available for analysis was even fewer than before, particularly for the u* predictor.

Figure 4 shows scatterplots of predictor value plotted against separation distance. It was expected that the value of each predictor would decrease with separation distance. This was expected because for all the predictors investigated the higher the value of the predictor the less likely a wake vortex incident will happen. So, if the separation distance is large, an incident is not likely to happen even if the value of the predictor is small, whereas if the separation distance was small a wake vortex incident is likely to happen even if the predictor value is large. This appears to be true for the predictors wind speed (U_z), crosswind speed (X_wind) and friction velocity (u*). In these results, the value occurring at a separation distance of 6 nautical miles has been ignored as it is believed to be spurious. A provisional threshold line has been superimposed on the plots for the wind speed and crosswind plots (but not on the u* plot as there were not enough data points to suggest reasonable thresholds). However, it should be stressed that these lines are only provisional, and the actual threshold lines may differ from those here or may be a curve. Further investigation with more incidents is needed before determining accurate forecasting thresholds.

Figure 4. Scatterplots of predictor values for incidents plotted as a function of aircraft separation.



The results for the wind shear and gamma3 predictors are well scattered. However if more incidents are investigated in the future a trend may be identified.

6. Suggested Improvements and Further Work

6.1 Sources of Error

The inaccuracy of the predictors in this study may be due to several factors, which are discussed below.

In this study, both the leader and follower aircraft in each incident taken from the ETWIRL database were assumed to be flying parallel to the 09L / 27L and 09R / 27R runways at Heathrow. An inaccuracy in this assumption would affect the crosswind and gamma3 predictors.

The atmosphere was also assumed to be neutral when u* was calculated using the boundary layer method. Neutral conditions give a logarithmic wind profile, which is a straight line. The wind profile is not quite logarithmic in stable or unstable conditions (e.g. Stull (1998)), so there will be a small error in the calculation of u* by this method under these conditions.

The use of numerical model data to calculate the predictors has been identified as a major source of error in this study. During 2001, as part of the S-Wake project, digital data will be collected from all British Airways aircraft using Heathrow. The digital data will allow profiles of wind and temperature to be derived, and turbulent eddy dissipation rate can also be calculated. This dataset will prove to be a significant advance on the ETWIRL database, and although some investigation will be possible within the S-Wake project further research using that data source may well prove profitable.

6.2 Other Suggestions for Further Work

This study also originally aimed to investigate three other predictors that are related to the turbulence of the atmosphere and the possibility of vortex decay due to Crow instability. These parameters, along with the values of u* above the boundary layer, were to be calculated using an iteration method described by Holtslag and Van Ulden (1983). Unfortunately, later in the study it was found that the value of sensible heat flux obtained from the Global model was incompatible with that needed for the iteration scheme. This meant that the analysis of the other predictors could not be performed. Future studies should aim to recalculate the sensible heat flux from the data available and carry out the analysis of the other predictors.

All the incidents and null-incidents used in this study occurred beneath the 900mb model layer (beneath about 1km). It is recommended that this study be extended to include incidents and null-incidents above this level for all predictors investigated here.

The statistical analysis should be performed for a wider dataset than that used to determine the thresholds. In this study, all the predictors analysed statistically gave a good value of Probability of Detection. This result was biased since the statistical analysis was performed on the same data used to determine the thresholds.

The study could be extended to incidents occurring at other airports around the world if reliable meteorological data, the orientation of the runway used and roughness length data for these airports could be obtained. The null incident dataset could also be extended to other airports if dates when no wake vortex incidents occurred could be determined accurately.

The previous section analysed the dependence of the predictors on the separation of the aircraft involved in the incident cases. Although the results for the wind speed, crosswind and friction velocity predictors were encouraging, results for only a small number of incidents were available. Further investigation with more incident data is needed before drawing any conclusions on this part of the study.

Whether wake vortex incidents occur also depends upon the type of aircraft involved. (In general, the heavier the leader aircraft, the greater the initial strength of the vortices. In addition, the lighter the follower aircraft, the more likely it will be affected by a wake vortex). Predictors that depend on these parameters (such as Crow instability link time, as given by Kantha (1998)) should be investigated. In addition, the predictors investigated in this study should also be used in conjunction with these parameters. A future study could re-analyse the predictors investigated here, investigating wake vortex incidents caused by heavy aircraft, light aircraft etc. separately. Other meteorological parameters not dependent on aircraft parameters could also be investigated.

7. Conclusions

Most of the predictors investigated did not give a clear indication of incident and null-incident conditions. The u* predictor did, but only a few incidents and null-incidents were available for the study of this predictor, so more data is needed before a forecasting threshold can be determined with confidence.

The investigation into the dependence of predictors on aircraft separation distances was also encouraging, although further investigation with more incidents is required before these results can be used to determine a forecasting threshold.

Whether wake vortex incidents occur also depends upon the type of aircraft involved. Further studies should be performed, either investigating predictors calculated from these parameters, or investigating the predictors used in this study for incidents created by different types of aircraft, etc.

There were several large sources of error in this study. Therefore this study should only be viewed as a preliminary study. Improvements should be made before suggesting forecasting tools from these results.

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Appendix: Contingency Table Values and Skill Measures

The following table contains all the contingency table values and skill measures for each predictor investigated, for all events.

Predictor	Incident forecast and occurred (a)	Incident forecast but didn't occur (b)	Incident occurred but not forecast (c)	Incident didn't occur and was not forecast (d)	Hit Rate	Critical Success Index	False Alarm Rate	Probability of Detection	Bias Ratio	Kuipers Skill Score
Wind speed, U_z	30	136	5	44	0.344	0.175	0.819	0.857	4.743	0.102
Cross-wind, x_wind	31	88	4	92	0.572	0.252	0.739	0.885	3.400	0.397
Friction velocity, u*	11	8	1	45	0.862	0.550	0.421	0.917	1.583	0.766
Gamma3	27	76	8	104	0.609	0.243	0.738	0.771	2.942	0.349