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CLIMATOLOGY STUDY OF WORLD AIRPORTS IN THE CONTEXT OF WAKE VORTEX BEHAVIOUR CLASS

Paul Agnew* and Deborah J. Hoad
UK Met Office, Bracknell, UK

1. INTRODUCTION

The increasing capacity demands at major airports throughout the world continue to drive research in the civil aviation community into ways of increasing the number of hourly aircraft movements in a safe manner. At busy airports the frequency of movements is restricted by aircraft separation rules imposed due to safety concerns associated with wake vortex encounters. The current separation rules have been highly effective in reducing wake vortex encounters, however there are situations where they appear overly conservative. As a result there is considerable interest in developing a greater understanding of wake vortex evolution in order that a more flexible approach to imposing separations can be implemented. The European initiative S-Wake is a multi-activity research programme aimed at addressing these issues and comprises a variety of both experimental and theoretical studies. One important strand is concerned with understanding how local meteorological conditions influence the evolution of vortices. If meteorological conditions can be identified in which wake vortices are known to either dissipate quickly or be swept away from the path of following aircraft, and if those conditions can be reliably forecast sufficiently far ahead, then there exists the basis for a more flexible implementation of aircraft separation rules, which could lead to valuable increases in the frequency of movements in and out of busy airports.

Earlier work in this area by Frech et. al. (2000) concentrated on identifying and defining a small number of so-called ‘wake vortex behaviour classes’ (WVBC) with which a given level of risk can be associated. It was deemed desirable to introduce the concept of discrete classes (contrasting with the continuous range of meteorological conditions) in order that air traffic controllers should be able to work with a relatively small number of separation classes, as at present, dependent on the WVBC prevalent at any given time. This paper describes work concerned with establishing a climatology with respect to WVBC at selected sites. A wider ranging study involving around 45 airports world-wide (including major US airports) has been conducted. However here we give the more detailed results available for some major European airports. The various airports studied were selected on the basis of being sites where very high capacity aircraft are likely to land.

2. WAKE VORTEX BEHAVIOUR CLASSES

Frech et. al. (2000) have provisionally described the criteria for ascribing WVBC under given meteorological conditions, based on a combination of Brunt-Väisälä frequency, Richardson Number and vertical wind shear. The classes are designated turbulence, stable stratification, wind shear, null and cross wind. The first four are mutually exclusive. However the conditions for the cross wind class may be satisfied at the same time as those for either the turbulence, stable stratification or wind shear classes. The five categories are described fully below:

(i) Turbulence

The turbulence class is characterised by a Richardson Number, $R_i \leq 0.25$. In these conditions the wake vortex is expected to rapidly dissipate via its interaction with the turbulent atmosphere.

(ii) Stable Stratification

This class has Brunt-Väisälä frequency $N>0.014\ s^{-1}$ and $R_i \geq 1.0$. Enhanced decay is anticipated, via the baroclinic instability mechanism described by Holzäpfel et. al. (2001). However there also exists the possibility of reduced vortex descent velocity or even rebound due to the buoyancy characteristics of the ambient air.

(iii) Wind Shear

Weather conditions in this class are described by a vertical wind shear and an intermediate Richardson Number in the range $0.25< R_i <1.0$. Under these weakly turbulent conditions no enhanced vortex decay is anticipated. Furthermore the presence of wind shear offers the possibility of vortex rebound, since it is now generally accepted that a low level jet often favours subsequent lift of a vortex. The criterion for this class is currently determined solely by the range of R_i stated above.

(iv) Null Class

Any conditions not fulfilling the criteria for any of the above three classes are assigned to a null class, which is expected to be neutral with respect to wake vortex risk.

(v) Cross Wind

This class differs from the others in that it is site and runway dependent. In the presence of a cross wind a portion of the wind velocity vector is added to that of the descending vortices, resulting in downwind advection of the vortices. In many cases this reduces the risk of a wake vortex encounter because the vortices are swept off the runway. However if a parallel runway is present the level of risk may increase due to the possibility of one or both vortices being blown onto the adjacent runway. The criterion

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* *Corresponding author address:* Paul Agnew, Met Office, London Road, Bracknell, Berkshire, RG12 2SZ, United Kingdom;
e-mail: paul.agnew@metoffice.com

used for this class is that the cross wind should be greater than 3.11 ms^{-1} (equivalent to 6 knots). This value is justified in section 4.2.

3. METEOROLOGICAL DATA GENERATION

In order to determine the WVBC at a given location it is necessary to determine the value of the relevant meteorological parameters as a function of altitude. We have used the Met Office Site Specific Forecast Model (SSFM) to generate these profiles (Clark and Hopwood, 2001). The SSFM is essentially a single column version of the Met Office Unified Model (UM) which is routinely used for producing global weather forecasts. The SSFM has increased vertical resolution near the surface, with 54 levels up to an altitude of around 2km. This high resolution makes it ideal for studying processes occurring in the boundary layer.

The initial conditions for a forecast run are supplied by a combination of actual surface synoptic observations and upper air forcing data from the ECMWF Re-analysis Project, ERA-15. The ERA-15 project involved the re-analysis of archived meteorological data to produce a new and validated 15 year set of assimilated data for the period December 1978 to February 1993. The main advantage of such a data set is that it is produced consistently and is independent of any changes made to forecast models over the period. The consistency of the data set makes it ideal for applications involving longer-term climatological studies, such as the present investigation. The SSFM assimilates the synoptic data with the ERA-15 forcing data at 6-hourly intervals to produce a set of initial conditions at the forecast site which is consistent with both the local measurements and conditions at other locations.

Additionally, information describing the topography (including height of land, surface roughness and land use) in the neighbourhood of the airport is used in the SSFM. This will contribute to the differences between the climatologies of pairs of airports which are relatively close to each other, as will the differences in synoptic data (where the latter are available).

4. DATA ANALYSIS

4.1 *Evaluation of WVBC Criteria*

The data analysed consists of hour by hour values of meteorological variables over the 7 year period 1979 to 1985 for each of the sites studied: London Heathrow (UK), Toulouse Blagnac (France), Frankfurt (Germany) and Amsterdam Schiphol (Netherlands). Meteorological data are given by the SSFM at 77 pressure levels, although we have only utilised the first 54 levels.

Determination of the WVBC requires knowledge of the Richardson Number R_i and the Brunt-Väisälä frequency N. These parameters were evaluated from the wind components (u,v) and potential temperature θ at each height z according to the following equations:

$$R_i = \frac{N^2}{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}\, ;\, N^2 = \frac{g}{\theta}\left(\frac{\partial \theta}{\partial z}\right) \quad . \qquad (1)$$

4.2 *Evaluation of Cross Wind Criterion*

In order to determine the crosswind characteristics at a given level we adopt the following procedure. Assume the runway has an orientation defined by direction cosines (α,β), where α is defined with respect to a north pointing axis and β with respect to an easterly axis. Let the wind vector $\underline{V}$ have direction cosines (α', β'). The component of wind perpendicular to the runway is then

$$V_{cross} = \left|\underline{V}\right|\left(1-\left(\alpha\alpha' + \beta\beta'\right)^2\right)^{1/2} \quad . \qquad (2)$$

Our criterion for the cross wind class is that $V_{cross} >$ 3.11ms^{-1} (6 knots). According to Halsey (1998) this value is sufficiently high that all the vortices observed in an experimental study of ~100,000 wake vortices were swept well clear of the runway.

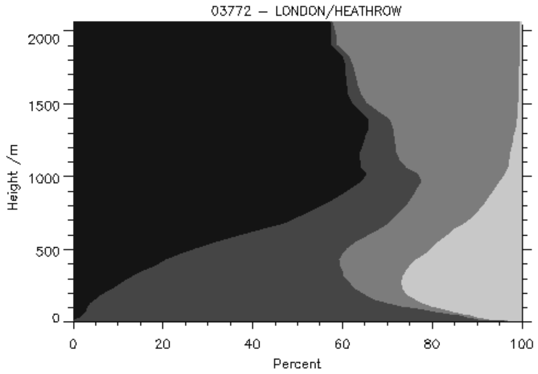
5. RESULTS

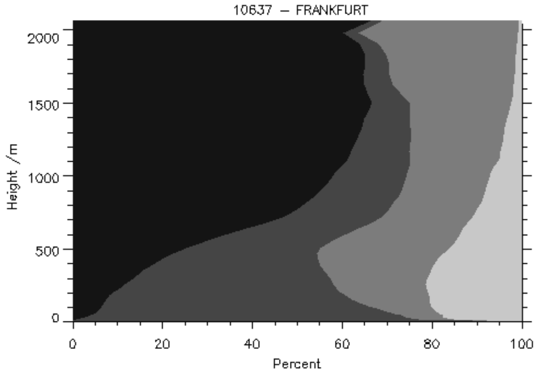
We have analysed meteorological conditions at each site, each hour of the day for seven years, at each of 54 pressure levels extending from the surface up to an altitude of around 2km. The results are presented overleaf. The outcome of each analysis has been to assign a weather class using the criteria described in section 2. Two figures are shown for each airport. The upper figure shows the proportion of null, turbulence, stable stratification and wind shear on a single plot. The horizontal extent of each band shows the proportion of time spent in each WVBC. The lower figure gives the results for the proportion of time spent in the crosswind class as a function of height.

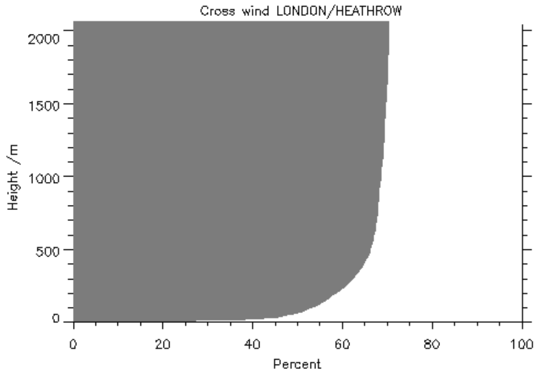
5.1 *General Observations*

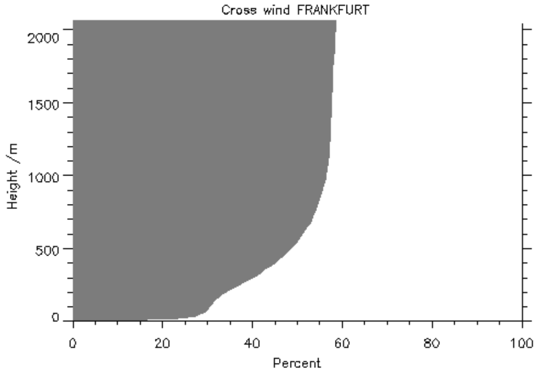
Some features of the results are readily apparent.

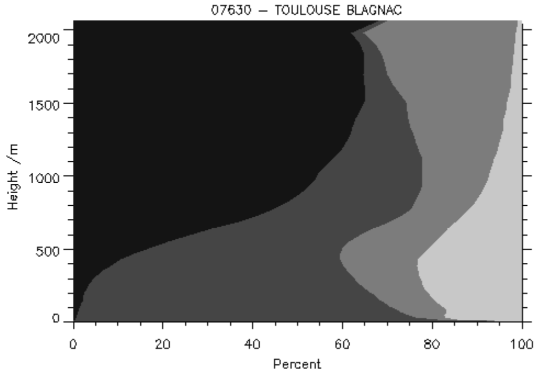
(i) The turbulence class is invariably dominant at the surface and decreases in frequency with increasing altitude. This is consistent with the usual boundary layer model of turbulence being generated close to the surface.

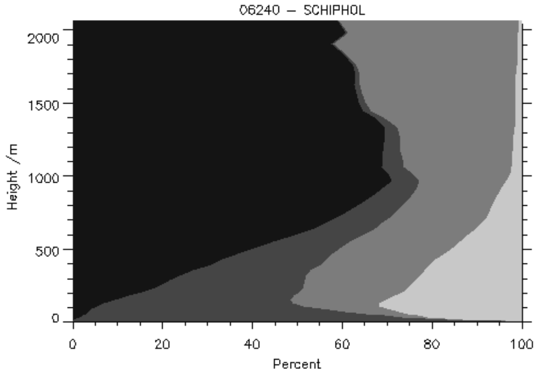


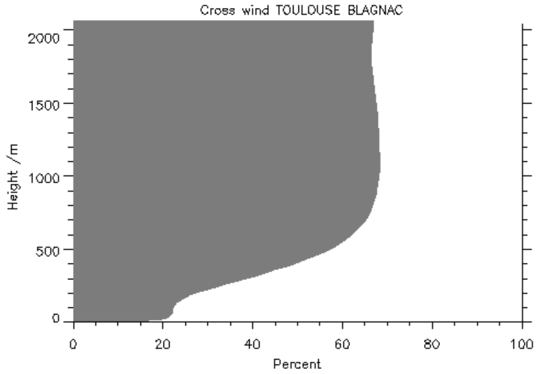


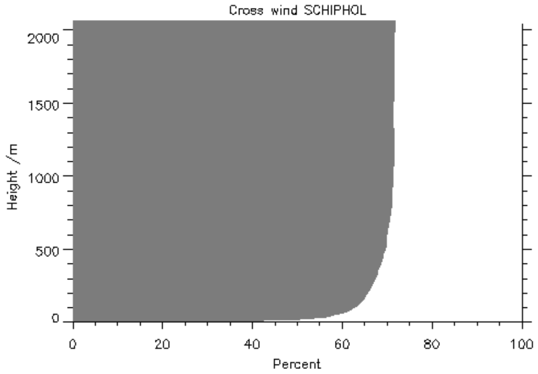












Legend for upper graph of each site:

Null---------------------------- ■
Turbulence------------------ ▓
Stable stratification--------- ▒
Wind shear------------------ ░

(ii) The wind shear class rises to a maximum within a few hundred metres of the surface and thereafter generally decreases in frequency with increasing altitude. This pattern is consistent with typical wind profiles in the boundary layer and simple theoretical models.

(iii) The stable stratification class is generally weak near the surface and becomes increasingly more frequent with increasing altitude. This is consistent with the fact that the surface is the main source of heat flux into the atmosphere at low levels, leading to greater levels of convection closer to the surface and more frequent stable stratification at greater altitudes.

5.2 *Cross Wind Weather Class*

With regard to the crosswind WVBC, we stress the point made earlier that the consequences of this class at any given site can only be determined with a careful study considering other runways and runway usage. As expected, the proportion of time spent in the crosswind WVBC increases rapidly with increasing altitude in the first 500m or so and then increases more slowly with further increases in height. For London Heathrow, Amsterdam Schiphol the value adjacent to the ground is around 30-40%, whilst for Toulouse and Frankfurt it is around 15%. For all of the sites the value at higher altitudes is in the vicinity of 60%.

6. DISCUSSION

6.1 *Evaluation of Safer Meteorological Conditions*

The aim of this climatological study has been to identify the relative frequency of occurrence of each type of WVBC. Having performed this analysis we are in a position to assess the frequency with which safer meteorological conditions occur.

Considering the crosswind class, the results for the four sites studied show that, for altitudes above around 500m, the criterion is satisfied for about 60% of the time. However in order to allow a reduction in separation it is necessary that safe conditions prevail all the way down to the surface. Frech et. al. (2000) state that the turbulence and stable stratification WVBC offer safer conditions (although we will discuss the latter class further below). In many of the sites studied these two WVBC taken together occur around 30% or more of the time, over the full range of altitude considered (approximately 0 to 2000m). In the range 0 to 500m these two classes typically occur for at least 40% of the time. It is likely therefore that a safe weather class is prevalent over the entire glide slope for a proportion of the time somewhere between 40 to 60%. The implication of this is that, providing the following aircraft fly on the same track, there is scope for reducing separations for a corresponding proportion of the time.

6.2 Re-evaluation of WVBC

The WVBC outlined by Frech et. al. (2000) were intended as provisional definitions and may need to be revised in the light of on-going research. In particular the stable stratification class may require a more detailed examination. Whilst numerical simulations, such as the recent work of Holzäpfel et. al. (2001), suggest that strong stable stratification can lead to shorter vortex lifetimes, other evidence (see for example Tombach, 1973) indicates that weaker stable stratification has relatively little effect on wake vortex dissipation but may actually increase the lifetime. Furthermore it also promotes increased vortex buoyancy, which can enhance the chance of a wake vortex encounter. It is not possible to reconcile both of these aspects of stable stratification within a single safety class. This is an area where more work is required and is likely to result in a sub-division of this WVBC.

References

Clark, P.A. and Hopwood, W.P., 2001: One-dimensional site-specific forecasting of radiation fog, Meteorol. Appl. 8, 279.

Frech, M., Gerz, T., Carriere, J. and Lunnon, R.W., 2000: A definition of wake vortex behaviour classes, S-Wake Technical Note 131-1.

Halsey, N.G.J., 1998: The prediction of crosswind components over very short periods in the context of wake vortex avoidance, Met Office Forecasting Research Technical Report 244. This is not the original reference for this work. The source cited by Halsey is: R.P. Rudis and D.C. Burnham, 'Crosswind measurement and forecasting requirements for aircraft wake vortex avoidance systems', Proc. 7th Aviation and Range Meteorology Conf. of the American Met. Soc., Long Beach CA (1997). However this paper is not published in the conference proceedings.

Holzäpfel, F., Gerz, T. and Baumann, R., 2001: The turbulent decay of trailing vortex pairs in stably stratified environments, Aerosp. Sci. Technol. 5, 95.

Tombach, I., 1973: Observations of atmospheric effects on wake vortex behaviour, J. Aircraft 10 (11), 641.