

# Automated CB and TCU detection using radar and satellite data: from research to application

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## Abstract

The turbulence and lightning associated with Cumulonimbi (CB) and towering cumuli (Tcu) form a hazard for aviation. Their detection especially in aerodromes is a requirement by ICAO to limit hazardous flying conditions.

The Cb and Tcu observations are predominantly done by human observers. In 2007 at two small airports in the, Maastricht-Aken (EHBK) and Eelde (EHGG) the visual observations are replaced by automated observations. The automated detection of Cb and Tcu is based on an algorithm using radar signals as input. The Probability of Detection and False Alarm Rate of this algorithm shows ample space for improvement.

It was therefore considered as a priority at the KNMI to improve the algorithm.

This paper presents a detection algorithm of Cb and Tcu based on a synergetic system using radar reflectivities and satellite observed radiances. Only radar and satellite observations provide the spatial and temporal coverage required to identify and track Cb and Tcu in the aerodromes. The spatial coverage of the observation systems allows for detection outside the aerodromes.

Like the human observer the lack of solar illumination during the night hampers the detection of CB's and Tcu by the algorithm. The main challenge here is to cope with the difference in information content between day and night time. During daytime HRV radiances from SEVIRI contribute significantly to the detection rate, while during night time only infrared radiances can be used, next to radar reflectivities.

The study will present the method to discriminate the Cb and Tcu from other occurring cloud types. The research version achieved a detection hit rate of 65 % and a false alarm rate of 35 % under summer daytime conditions.

## Introduction

The occurrence of strong turbulence forms a hazard for aviation. Observations of turbulence are a prerequisite for safe aviation conditions, especially around airports. Here an unexpected vertical movement of an aircraft can have serious consequences.

Direct observations of turbulence are not common in meteorology. There are indirect methods using for example the radiosondes to determine the stability and the likelihood of turbulence. The radiosonde network, however, has a drawback: it is too coarse in spatial - temporal resolution.

Another indicator of turbulence though indirect is the occurrence of convective clouds, towering cumuli and Cumulonimbi hereafter referred to as Tcu and Cb. For aviation at aerodromes in the Netherlands the embedded cumuli, the towering cumuli and Cumulonimbi are relevant. Not only the turbulence associated with these clouds forms a hazard to aviation, but also the associated precipitation, super cooled water occurrence and lightning are a threat.

It is therefore a primary requirement by ICAO to include the occurrence of Cb or Tcu in the METAR (Meteorological Aerodrome Report or MÉTéorologique Aviation Régulière) of an airport to limit the risks for aviation. The METAR report is predominantly given by an observer.

In 2007 an automated Cb/Tcu detection system, hereafter referred to as the operational algorithm-2007, became operational at EHBK and EHGG. The algorithm-2007 uses radar and lightning observations. Its

performance is not optimal, a study by The ( 2006), showed a probability of detection of 50 % and a False Alarm ratio of 70 % as averaged values over the whole year.

This paper describes a study to develop an algorithm that will have a better performance than the algorithm-2007. The presently proposed algorithm is based on a synergy of both radar and satellite observations. The satellite information is provided by the SEVIRI imager on the Meteosat satellites operated by EUMETSAT. The radar information stems from the two operational radars used at KNMI. The goal of the study is an algorithm that detects Cb/Tcu in all seasons with a relatively low false alarm ratio and high probability of detection at four different airfields.

A master thesis study performed in the same period as this study within the weather research department overlaps with this work, (Carbajal-Henken et al.,2009). Carbajal-Henken studied the summer season for one airfield but for four years. The thesis study indicated logistic regression to be a successful approach in the classification of Cb-Tcu.

This paper describes the observation methods, the algorithm development, the statistical logistic regression method, the verification method, the predictor selection, results and ends with the conclusion.

## Observations

Only Radar and satellite observations have the temporal and spatial coverage required to observe convection.

### *Radar (Radio detection and ranging)*

In the Netherlands two Doppler radars are operated primarily for precipitation detection. The C-band radar emits and receives pulsed 6 Ghz radio waves with a wave length of around 5 cm. The lowest inclination of the radar beam is 1 degree. Therefore the part of the atmosphere not observed by the radar increases with the distance to the radar position.

The observed reflections are obtained from a distance from the Radar site (varying from 0-320 km) and at moderate altitude (0.8-3 km) above surface of the earth. The reflection signal is proportional to the sixth power of hydrometeor diameter, when the particles are smaller than the wavelength, Holleman (2000). Due to the sixth power the variance of the reflectivity value is huge. Therefore a decibel or logarithmic unit is used to represent the signal. The radar reflections are projected on a grid with grid cells of 2.5 by 2.5 km.

It is relevant to note some considerations about radar observations in relation to Cb/Tcu detection:

- the operational radars are sensitive to precipitation and not to cloud occurrence. Therefore developing convection without precipitation can not be observed by the radar. Hence the probability is small that the radar will observe Tcu correctly.
- Additionally the radar cannot distinguish between heavy non convective precipitation or convective precipitation. This may lead to false alarms when for example strong frontal related precipitation occurs.

### *Satellites*

Meteorological satellites provide an instantaneous view of the atmospheric state. The geostationary satellites are an invaluable source of information for nowcasting. The latest generation of operational geostationary satellites provides an image each 15 minutes over Western Europe. They are operated by EUMETSAT. The Spinning Enhanced Visible and Infrared Imager (SEVIRI) on board the METEOSAT 8 and its follow-on observes the world since January 2004. SEVIRI is a passive instrument, it does not emit a signal, opposite to the radar. SEVIRI observes the reflection of the earth in spectral bands from 0.5  $\mu\text{m}$  to 3.9  $\mu\text{m}$  and the emission from the earth in spectral bands ranging from 3.9  $\mu\text{m}$  to 13.4  $\mu\text{m}$ . Next to the eleven spectral bands, there is a high resolution visible (HRV) channel, 0.4  $\mu\text{m}$  - 1.1  $\mu\text{m}$ . The sampling grid distance in the nadir point of the satellite is 3 km for the eleven channels and 1 km for the HRV channel. The observation cycle consists of a 12.5 minutes scan of the earth from south to north. Then the scan mirror returns to its starting position and calibration occurs in 2.5 minutes remaining from the 15 minutes cycle.

Further details on the satellite platform and the SEVIRI instrument can be found at [www.eumetsat.int](http://www.eumetsat.int).

It is relevant to note here some consideration about satellite observations in relation to Cb/Tcu detection:  
-Satellite view is obscured when higher cloud layers block the view to the lower atmosphere. Cirrus may hamper a correct interpretation of the satellite data.

- The lack of the HRV and other reflection channels in the night period, when there is no in-solation, affects the detection of clouds.
- The satellite only observes the top layer of the cloud.
- The horizontal spatial resolution degrades when moving away from the nadir point. At the latitude of the Netherlands, the spatial resolution is approximately 3.5 km West East and 6 km North South, for the 11 channels and 1.2 by 2 km<sup>2</sup> for the HRV channel. Clouds smaller than the pixel size can not be classified correctly.
- One should correct for the slanted view of the satellite to collocate radar and satellite signals when both are used. A correction requires shifts up to several radar pixels.

## Algorithm development

Interviews with the KNMI R&D department of instrumentation revealed that there is no knowledge of instrumentation with proven ability to detect Cb/Tcu at time of writing available which can detect Cb/Tcu with a similar spatial coverage as an observer and at acceptable costs. The exploration into other instrumentation is therefore not pursued in this study. The consequence of this choice is that only radar and satellite observations can be used in this algorithm development.

The satellite based methods given in the literature all require at least a significant number of pixels to come to reliable statements on convection. Most of the discussed articles focus on severe or intense convection occurring frequently in the USA, Mecikalski (2004), and mountainous areas in Europe, Zinner (2008). The early stages of convection are not captured by these algorithms.

The goal of this study is to detect both early and mature convection. The early convection will occur in a small number of pixels, with a low or no intensity in the radar signal. The detection of the early convection category is a larger challenge, in comparison to developed severe convection detection.

The algorithm presented here to meet this challenge, uses the synergy between radar and satellite information to come to classification between Cb/Tcu and non- Cb/Tcu cases. This implies that the radar information can not be used as a source for validation studies as done by others, e.g. Zinner (2008) and Mecikalski (2004). This a point of consideration for future evaluation.

As radar nor satellite observations can discriminate between Cb and Tcu both cloud types are treated as one category Cb/Tcu further used as the predictand in the algorithm development.

As the vicinity of the aerodrome is not uniquely interpreted two radii of collocation areas are considered, 15 and 30 km radii around the aerodrome point of reference. The data of both radar and satellite observations within the collocation areas are used in the algorithm.

Partly based on the literature studies a large number of predictors were determined from the original data. The data involved :

The original radar reflection given in dBZ

The satellite radiances expressed in reflection and brightness temperatures.

For two different radii 15 and 30 km of the collocation area the following variables were calculated as predictors:

-radar contours varying from 14 dBZ to 56 dBZ ( in 16 steps of 2.5 dBZ)

-satellite 10.8  $\mu\text{m}$  channel brightness temperature contours varying from 213 K to 258 K

-satellite high resolution visible reflection contours corrected for the solar zenith angle varying from 59 % to 100 %.

From these distributions also the sum of the pixels, mean, median, minimum, and maximum values were determined, next to the maximum occurring contour, sum and a weighted sum of the occurring contours. The weighted sum here consists of the sum of the occurring contours multiplied by their order number, i.e. 1 x first contour + 2 x second contour + ...etc.

Additionally a rudimentary cloud mask was introduced for the smaller area (15 km radius).

First the difference between the 12.0  $\mu\text{m}$  and the 10.8  $\mu\text{m}$  channel larger than -3K is evaluated to flag those pixels probably containing cirrus. For those pixels with a brightness temperature in the 10.8  $\mu\text{m}$  channel lower than the two meter air temperature minus 20 K and not flagged as cirrus contaminated the average temperature and its standard deviation is determined.

In a future version the SAF-NWC cloud mask could be implemented here leading to an improvement of both cloud mask and cirrus mask.

In the development study of the algorithm also other predictors derived from satellite observations were evaluated, e.g. difference between 6.2  $\mu\text{m}$  and 10.8  $\mu\text{m}$ , difference between 3.9 and 10.8  $\mu\text{m}$ , difference between 13.4 and 10.8  $\mu\text{m}$ . Also the difference between the reflection channels 0.6  $\mu\text{m}$  and 1.6  $\mu\text{m}$  was evaluated. Unfortunately these predictors did not show a correlation with the predictand of Cb-Tcu occurrence over the time period considered. The precursor signals as given by Mecikalski and Bedka, (2006), to study convective initiation were not found to have an explanatory power in this study. Presumably because the convection in their study is has a higher intensity than can occur in the mid latitude climate studied here. Convection with regular occurrence of super cells is a rare phenomenon in the Netherlands.

### Logistic regression

Nearly two hundred potential predictors are determined to classify the binary predictand: Cb/Tcu or non Cb/Tcu. A successful approach to come to binary results is the Logistic regression, Wilks (1995) and Carbajal-Henken et al (2009). Logistic regression models result to a classification or prediction of a binary predictand while the predictor variables can be of any type. A non-linear equation can fit the predictand  $c$  using a multiple number of predictors  $x$ .

$$P(c) = \frac{1}{1 + \exp(-(b_0 + b_1 x_1 + b_2 x_2 + \dots + b_n x_n))}$$

With  $P(c)$  the probability that  $c$  occurs,  $b_i$  the regression parameters and  $x_i$  the predictor variables. The function is bounded between 0 and 1 due to its mathematical form allowing only for properly bounded probability estimates. The function drawn will always result in a S- shape curve. Logistic regression is in meteorological research commonly applied, e.g. for severe thunderstorm occurrence Schmeits et al (2008).

It is not possible a priori to indicate which predictors will lead to the best result in the desired classification. The dependencies and correlations between them are too complex. Commonly used is the forward stepwise regression, Wilks (1995). In each step a predictor is added to the equation and based on the statistical scores it is decided if the additional predictor contributes to the overall performance. It is up to the user to decide how many steps or predictors contribute significantly to the classification performance. Using all predictors may lead to an over-fit regression, Wilks (1995). In an over-fit regression too many predictors are used in the equation to describe the observations. The regression will fit to the used observations but the equation may fail to describe other observations not used for its determination.

To assess the performance of the obtained equation it is recommendable to split the data set in two parts: one part is referred to as dependent set, the other part is the independent set. By logistic regression predictor variables and regression parameters, also called coefficients, are determined on the dependent part. The performance of the derived predictors and coefficients are tested and evaluated on the independent set.

### Verification

Cb/Tcu occurrence is a dichotomous phenomenon. The frequency of Cb/Tcu occurrence is relatively low in comparison to the total number of METARs. The value of a forecast or classification can be assessed by comparison to an observation. Frequently used for assessment is the contingency table 1. Here the occurrences of forecast/classification in comparison to observations are represented.

	observed yes	observed no
classified yes	hits	false alarms
classified no	misses	correct negatives

**Table 1. Contingency table,( Wilks 1995). Relationship between the number of observed and classified cases of a dichotomous phenomenon. The sample size is the sum of the hits, misses, false alarms and correct negatives.**

From the table a number of scores can be calculated. Given the large number of correct negatives for this specific Cb-Tcu classification this number is not incorporated in any of the scores used in this report. It may lead to an incorrect interpretation of the results.

Considered are, the Probability of Detection (POD= Hits/ (Hits + Misses) ), The False Alarm Ratio (FAR=

False Alarms / (Hits + False Alarms)) the Critical success index ( $CSI = \text{Hits} / (\text{Hits} + \text{Misses} + \text{False Alarms})$ ) or threat score, and the BIAS ( $= (\text{Hits} + \text{False Alarms}) / (\text{Hits} + \text{Misses})$ ).

## Predictor selection

For predictor selection the **Statistical Package for the Social Sciences** SPSS package is applied on the data set for four aerodromes divided in four subsections, summer day, summer night, winter day and winter night.

A forward stepwise regression selection method is applied. Starting with a constant-only model at each step a predictor is selected with the largest statistical score (likelihood ratio based) and a significance less than 0.05. The selection and inclusion is stopped when the significance of the remaining predictors is more than 0.05. Should during the inclusion a predictor obtain a significance of more than 0.10 then this predictor is excluded from the further steps of the evaluation. Forward stepwise regression selects the predictors purely on statistical criteria. The regression is capable to identify groups of predictors which individually contribute only weakly to moderately to the explanatory power but as a group contribute significantly.

It is unlikely that a unique set of predictors will be found describing all the occurrences in a perfect model. As the method does no physical interpretation the predictors should be scrutinized for their physical relation to the predictand. This could lead to the removal of predictors which have a high statistical correlation with the predictand but lack a physical explanation.

For the used dataset of 2005 42 Different predictors were found to contribute to the Cb detection. There were differences between seasons, day versus night, and stations. Frequently these different predictors have a similar information content, e.g. the range of the HRV value was selected for EHAM, and EHRD, where the maximum and minimum HRV value appeared for EHBK and EHGG for the summer day season. As the minimum HRV value always had a negative coefficient, the information content of the combined HRV maximum minus the HRV minimum is similar to the HRV range predictor. The hypothesis was that the combination of HRV maximum and the HRV minimum can be applied at all stations and can replace the HRV range as a predictor.

In other cases a single contour value of satellite or radar was selected as predictor. The predictors summarising the contour information can capture the single value information.

The predictors summarising the contour information were expected to wrap up the information of a number of the single value contours. Therefore the contour summarising predictors were applied there were a single value contour appeared as a predictor.

By careful examination of the set of predictors the number could be reduced. To facilitate the interpretation and communication over the predictors for the different stations it is expected that a high degree of uniformity is beneficial both for the development and for the end-use. Where it was acceptable the remaining set of predictors were reduced to comply with uniformity.

For the summer day uniformity was achieved. In table 2 the chosen predictors are summarised for each station and category. For the summer night the lack of sufficient data enabled uniformity only for EHAM and EHRD. In wintertime the EHGG predictors differ slightly from the EHAM and EHRD predictors. This may be due to a difference in climate or lack of sufficient night time data, please note the METAR from EHGG does not cover the full night.

## Results

The results are evaluated per category: summer, winter, day, night per aerodrome. For each case a set of two graphs are determined from the independent data: the *POD*, *FAR*, *CSI*, and *BIAS*, as function of the probability threshold, summarised in one figure and the attributes diagram both as function of the predicted probability. A graph of one of the better and one of the worse obtained results is included to illustrate the variation in the results.

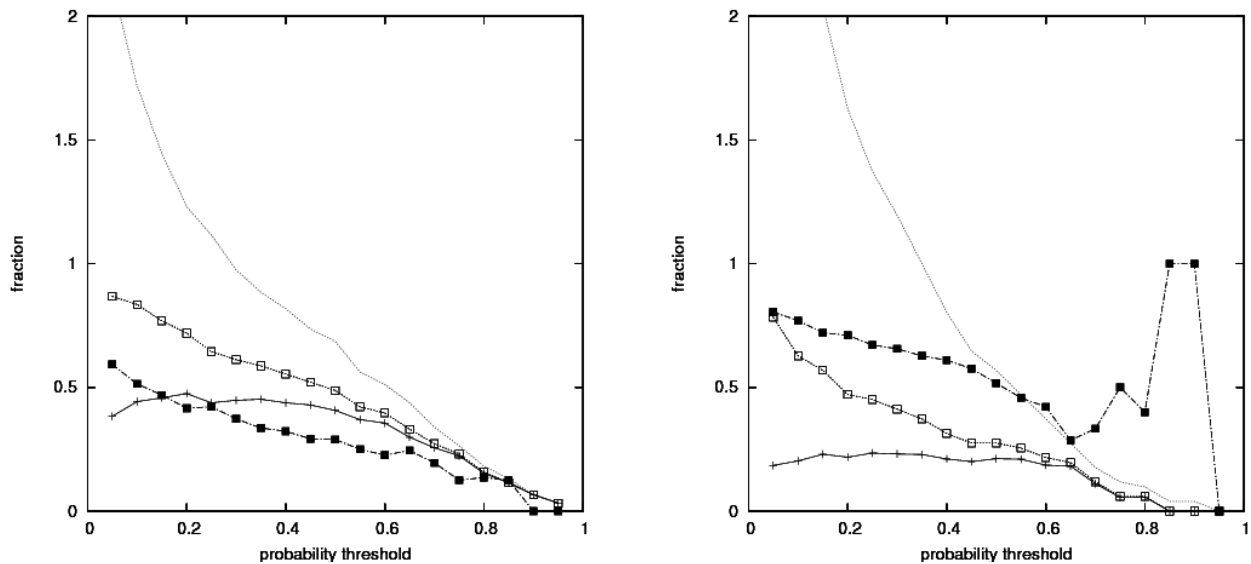
From the *POD*, *FAR*, *BIAS* and *CSI* diagrams a threshold can be determined on which the classification can be based. The wide variety occurring within the graphs shows that one fixed value of threshold for all categories cannot be determined. For each season and day/night situation a threshold can be derived.

The attributes diagram compares the predicted probability to observed relative frequency. The predicted values are binned into 10 percent bins, the occurrence number is given in the diagram and also in the histogram. The no-resolution line relates to the climatology, in this study the number of Cb occurrences

compared to all reported METARS in the category. The no-skill line is halfway the no-resolution line and the perfect reliability line, which is represented by the diagonal.

	Winter day	Winter night	Summer day	Summer night
EHAM	a,b,c,d,f	b,f,g	a,b,c,d	a,b,e
EHRD	a,b,c,d,f	b,f,g	a,b,c,d	a,b,e
EHGG *	b,c,d,f	b,f,g	a,b,c,d	
EHBK *			a,b,c,d	

**Table 2** Used predictors for each category with a) the maximum radar contour within the 15 km radius, b) the maximum radar contour within the 30 km radius, c) the minimum value of HRV within 15 km, d) the maximum value of HRV within 15 km radius e) the averaged brightness temperature with in the cloud inside the 15 km radius, f) the standard deviation of the brightness temperature within the cloud inside the 15 km radius, g) the weighted sum of radar contours, which is related to the maximum radar contour within the 15 km radius. \*For EHGG and EHBK there was not sufficient data to make a statistical analysis for all the cases.



**Figure 1** Scores for EHAM summer day (left) and EHRD summer night (right). POD (open squares), FAR (black squares), CSI (pluses) and BIAS (dashed lines) as a function of the probability threshold.

In Figure 2 for EHAM a significant number of the results contribute to the skill of the model. Points to the left of the perfect reliability line indicate a too low predicted probability in comparison to the observed relative frequency. And vice versa for the points to the right of the diagonal. For EHRD a significant number of points have a large distance to the perfect reliability line, and are closer to the no-resolution line. These points contribute marginally to the skill of the model.

The final results are summarised in Figure 3 in a POD FAR diagram for EHAM only for the uniform applied predictors.

### Conclusions.

Since 1-8-2007 an operational algorithm-2007 is implemented at the airports EHBK and EHGG to detect Cb and Tcu. It uses the radar reflection observations and lightning observations as input. The detection of Cb Tcu is relevant for aviation and therefore a requirement by ICAO. The performance of the algorithm-2007 is evaluated and considered as poor in terms of POD and FAR. This study was initiated to develop an improved algorithm.

An automated Cb-Tcu detection algorithm based on the synergy between radar and satellite observations is developed. The algorithm uses logistic regression to determine the probability of Cb-Tcu occurrence.

Within logistic regression a forward stepwise approach is applied. The predictors selected by the forward stepwise regression method are related to the highest radar contour occurring in the 15 and 30 km radii collocation area, and to the satellite observations, reflection range of the high resolution visible channel, the averaged cloud temperature and its standard deviation. The latter three all in the 15 km radius collocation area.

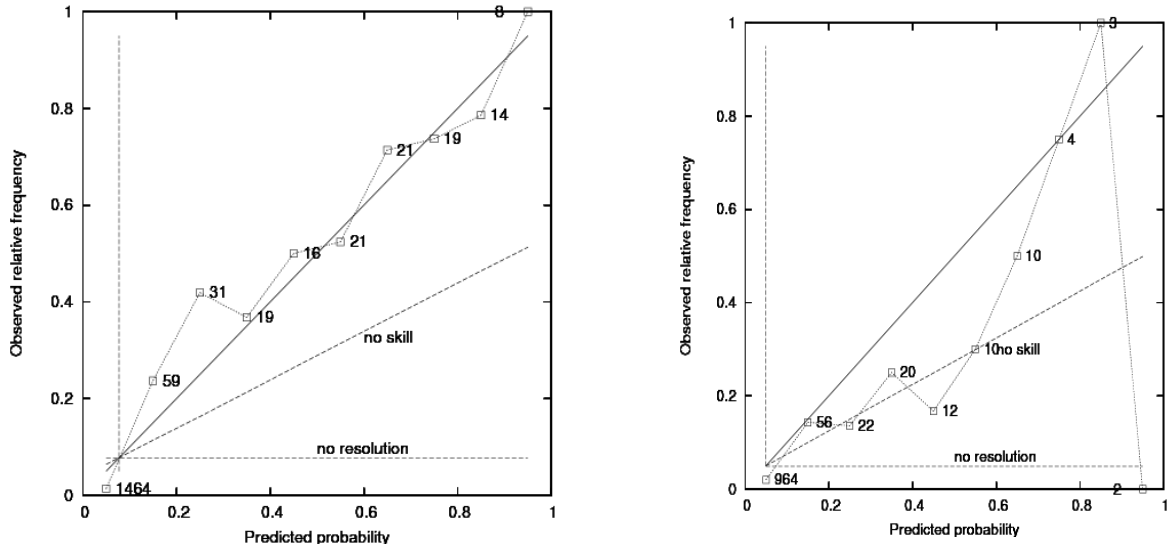


Figure 2. The attributes diagrams for EHAM summer day (left) and EHRD summer night (right) as a function of the predicted probability. The numbers in the figure indicate the number of cases per 10 percent bin. The no resolution line relates to the climatological Cb occurrence, different for each station and season. The perfect reliability line is the diagonal. The no skill line is halfway the diagonal and the no resolution line.

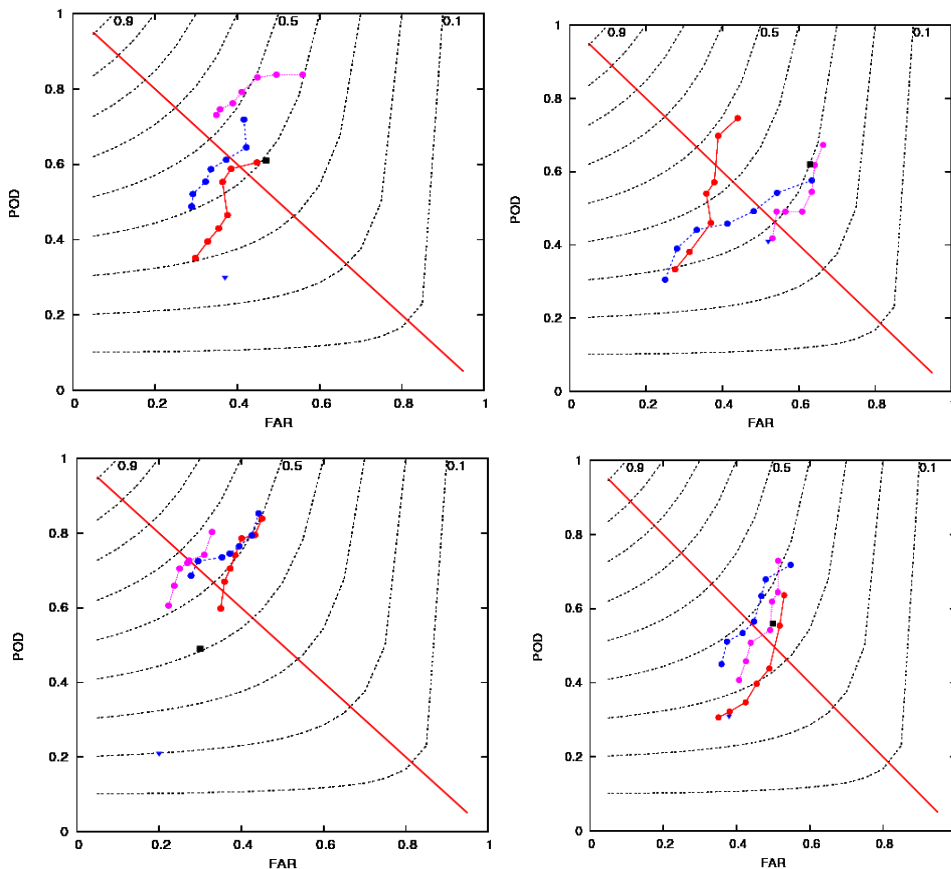


Figure 5.6 As Figure 5.4 for all cases at EHAM summer day (upper left), summer night (upper right), winter day (lower left) and winter night (lower right). The black square represents the autometer score for Cb-Tcu for a 30 km radius of the collocation area, the triangle gives the autometer result for a 15 km radius of the collocation area.

The obtained results show in general an improvement in performance of the developed algorithm in comparison to the operational algorithm results. The performance of the developed algorithm is dependent on season and day-night conditions. The best performance is achieved in the Summer day category followed by the winter day category, with the summer defined from April till October. Surprisingly the summer night category shows the worst performance, not significantly better than the operational algorithm-2007.

Although the algorithm is developed for EHBK and EHGG no year round evaluation was possible for those airports because of the lack of sufficient Cb occurrences, required for a statistical analysis. Especially for the EHBK airport data was lacking. This hampers an operational application for EHBK.

Note that since there is no other observation which covers both the required spatial and time dimensions a future assessment of the performance of the algorithm is not possible. The METARs are the most reliable and continuous source of Cb and Tcu observation, but they are terminated at EHGG and EHBK. However at EHAM and EHRD they are still continued.

Based on the results of this study an improved operational algorithm can be defined. The probability threshold selection will determine the performance of the algorithm. For the daytime categories a conservative estimate for POD is 65 % and for FAR is 35 % appears feasible in the summer and winter day categories. For the night time a POD of 60 % and a FAR of 40 % appears achievable.

Future work will address, next to more research, the evaluation of 2009 and evaluate the performance of the METAR by using a dataset interpreted by a forecaster.

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