ACRP 11-04

Prediction of Terminal-area Weather Penetration based on Operational Factors

Authors: Yi-Hsin Lin*, Hamsa Balakrishnan
Massachusetts Institute of Technology
77 Massachusetts Avenue, 33-328
Cambridge MA, 02139

Submission date: 16 September 2013
Word count: 5627 words, 5 figures, 2 tables

*Corresponding author contact information: y_lin@mit.edu, 617.329.1361

Abstract

Convective weather is known to reduce airspace capacity, but the extent of the impact is not well understood. Understanding how weather impacts terminal area capacity is essential for quantifying the uncertainty in weather forecast, determining how accurately the weather needs to be forecast, for developing an optimal mitigation strategy. Prior research has focused on the overlap between convective weather cells and air routes, but has not sufficiently analyzed the differences that arise due to factors such as aircraft types and pilot behavior. This paper examines the interactions between convective weather and aircraft trajectories in the arrival airspace surrounding Chicago O'Hare International Airport. Case studies based on operational data are used to determine potentially relevant operational factors, and a predictive model is built using these factors to forecast if a flight will pass through hazardous weather. The results of the analysis suggest that these operational factors are secondary compared to the weather itself in determining whether a pilot will deviate from or penetrate hazardous weather.

1 Introduction

The increasing demand for air travel in the United States has strained the capacity of the National Airspace System (NAS). Any further reduction in capacity due to weather or other disruptions can result in significant delays. This is especially true of summer convective weather systems, which can grow and decay rapidly, and are difficult to forecast. The impact of these storms is compounded by the fact that they occur in summer, when the demand for air travel is at its highest.

Although convective weather is known to impact air traffic operations and reduce airspace capacity, the extent to which capacity is reduced as a result of weather is not well understood. Prior research has mostly focused on the types of weather that disrupt traffic, rerouting around weather, and the effect of convective weather on controller workload, without considering flight-specific factors. An examination of weather and trajectory data shows that while pilots typically avoid hazardous weather, some pilots do penetrate severe weather cells, both enroute and within the terminal area. This paper explores operational factors that may drive pilot behavior associated with the deviation from, or penetration of, weather. The analysis focuses primarily on weather penetration behavior within the terminal-area surrounding airports.

2 Background

Summer convective storms, commonly known as thunderstorms, occur in many parts of the continental United States, and typically form in the afternoon. Convective storms are associated with heavy rain and severe turbulence. Because they grow and decay relatively quickly, they can be difficult to forecast.

The Convective Weather Avoidance Model (CWAM) has been previously developed at the MIT Lincoln Laboratory [3, 4, 7]. This model forecasts Weather Avoidance Fields that predict the probability of pilot deviation based solely on weather-related features such as the height and intensity of the storm. For weather inputs, the model considers the Vertically Integrated Liquid (VIL) and the echo top height. The VIL represents the total amount of liquid in a vertical column of the atmosphere and is divided into six levels, chosen to correspond to pilots' perceived threat levels in previously used weather displays [9]. Level 3 VIL corresponds to a 'yellow' threat level; Level 6 corresponds to a 'red' threat level. The echo top height is the altitude of the highest clouds containing weather.

Several versions of the CWAM have been developed and refined, depending on the type of airspace considered. For enroute traffic, the most important indicator of pilot deviation was found to be the difference between the flight altitude and the echo top height followed by Level 3 VIL coverage within 16 km. Recent results for arrival flows have found that because pilots are not typically able to fly over storms, the absolute echo top height was a good indicator of weather avoidance in the terminal-area, in addition to the weather coverage within 4 km [8]. The terminal-area version of CWAM is used in the studies presented in this paper.

2.1 Weather Avoidance Field (WAF)

To understand how the Weather Avoidance Field identifies areas of weather that pilots are likely to avoid, it is instructive to look at an example. Figure 1 shows the VIL, echo tops, and resultant WAF in the ORD terminal area on June 12, 2008, at 20:17:30Z. The arrival trajectories are color-coded according to the maximum WAF penetrated in the terminal area; all departures are grey. The WAF eliminates much of the light rain that has little to no effect on aviation. Furthermore, not all VIL pixels of Level 3 or above translate to high WAF: some of the smaller cells have low echo tops, which the CWAM has found likely to be penetrated by pilots; these are accordingly assigned a lower WAF.

The WAF encapsulates a pilot's willingness to penetrate severe weather solely on the basis of weather features. However, it is believed that there are operational factors that may influence pilot decision-making. This paper explores whether these operational factors are in fact significant, and attempts to predict based on operational features when flights will be willing to penetrate regions of high WAF.

2.2 Comparison with actual weather

Since some pixels with low-level VILs possess high WAFs simply because of their proximity to higher VIL levels, it is possible that aircraft passing through high WAFs are not actually penetrating weather. Another possibility is that they are flying over weather. It is therefore interesting to check whether flights are actually flying through severe weather when they penetrate high WAFs. To this end, the distribution of the actual VIL penetrated by each flight, sorted by the WAF value, is plotted in Figure 2. For example, for all pilots who flew through a given WAF, the figure shows the VIL levels that they actually penetrated. The left bar in each pair indicates the VIL distribution; the right bar removes those instances in which a flight was at or above the echo top height.

Figure 2 validates the use of the WAF. First, overflying is rare and does not skew the results. In over 95% of cases, aircraft do not overfly weather in the terminal area, likely because they are in descent. Second, there is a strong correlation between high WAFs and high VIL levels. Aircraft that penetrate WAFs of 80 or more have a greater than 80% chance of actually penetrating Level 3+ VIL. Flights that flew through WAFs of 80 or more, but only penetrated Level 1 or 2 WAF, flew within 4 km of Level 3+ VIL.

2.3 Terminal-area operations

This paper focuses on arrival operations in the terminal-area, using the example of Chicago O'Hare (ORD) International Airport. Although Terminal Radar Approach Control (TRACON) facilities are typically irregularly shaped, a circular region simplifies analysis. Characteristics that define the terminal area and may influence pilot behavior are considered in determining the radius. Aircraft trajectories are more constrained, both vertically and horizontally, in the terminal-area. Aircraft frequently fly over convective weather in enroute airspace; an aircraft that has already begun its descent may not be able to do so. Furthermore, arrival routes are quite structured, especially at congested airports such as ORD, and air traffic controllers may be less willing to allow aircraft to deviate. While it is difficult to quantify the degree to which pilots have flexibility to deviate from established flight paths, one can determine when arrivals typically begin their descents. Aircraft landing at ORD typically begin their descent sequence about 200 km from the airport. Excluding routes less than 300 km, most flights begin their descent sequences between 200 and 250 km away from the airport. Based on the above observations, the terminal area is defined as a circle of radius 200 km around the airport.

3 Methodology

The methodology adopted in this paper combines case study analysis with predictive modeling. Case studies are used to identify potentially relevant features, and a predictive model is built to evaluate their relevance. The following section discusses the case studies undertaken, focusing on instances in which aircraft penetrated severe weather. Along with observations from air traffic controllers and other researchers studying pilot behavior regarding weather, these case studies inform the identification of features used in the predictive model.

4 Case studies

Case studies and discussions with people in the field have been very helpful in guiding the development of this research, both for understanding the evolution of weather throughout the day and how this affects the terminal, and for identifying features that affect pilot behavior. This section is divided into two parts. First, it describes one of the eight case days in the study so the reader can get an idea of how weather evolves throughout the course of the day and what impact this has on traffic. Second, it lists some of the recurring “themes” that are frequently observed in the case studies or mentioned by people familiar with the field as possible reasons for severe weather penetration.

4.1.1 Overview of case day: July 2, 2008

This section describes one of the eight case days in the dataset, July 2, 2008. Similar analyses were performed for each of the other case days, with comparable results. As is fairly common during the summer, convective weather affected the Chicago O’Hare terminal area from about 1500Z (10AM local time) until about 0300Z the next day (10PM local time). Figure 3 gives a brief overview of the case day. The bars indicate the number of flights landing at the airport at any given time. They are colored according to the maximum WAF penetrated by the aircraft within the terminal area. Grey indicates that the aircraft did not fly through any weather at all. The red line indicates the percentage of the terminal area containing WAFs of 80 or greater; this is roughly the severe weather coverage in the terminal area. Figure 4 shows a series of snapshots in time, showing the evolution of WAFs over the course of the day.

Generally speaking, as the amount of weather in the terminal-area increases, the number of flights decreases. During the peak of the weather impact, from about 2200Z-0000Z, traffic drops quite severely. Furthermore, most of these flights penetrate severe weather. While the drop in traffic can be attributed to the ground delay and ground stop programs in place for ORD, the relatively large fraction of flights that penetrate weather during the convective weather event suggests that the airspace was likely close to capacity.

It is not universally true that flights are more likely to penetrate severe weather when there is greater severe weather coverage in the terminal area, although these quantities are correlated. Few flights penetrate weather, and even then only the lower WAF levels, in the early part of the day, while the weather is still growing in coverage and intensity. During the latter part of the day, as the weather is decaying and moving out of the terminal-area, more flights penetrate high WAFs, even WAFs of 80 and above, despite there being fewer flights. It is unclear if this is due to the nature of the weather (decaying weather may pose less of a threat) or due to operational reasons.

A detailed case study will shed light on how weather and terminal-area procedures interact to determine aircraft penetration of, or deviation from, severe weather. In each subplot of Figure 4, the black circle indicates the terminal area, a circle of radius 200 km around ORD. The solid lines are the trajectories up to that time, and the dotted lines are the future trajectory points. A triangle indicates the current position of each aircraft. Gray trajectories are departures. Similar to Figure 3, arrivals are color-coded according to the highest WAF that the aircraft penetrates within the terminal-area. The color bar to the right represents the background WAF.

Generally speaking, as the amount of weather in the terminal-area increases, the number of flights decreases. During the peak of the weather impact, from about 2200Z-0000Z, traffic drops quite severely. Furthermore, most of these flights penetrate severe weather. While the drop in traffic can be attributed to the ground delay and ground stop programs in place for ORD, the relatively large fraction of flights that penetrate weather during the convective weather event suggests that the airspace was likely close to capacity.

It is not universally true that flights are more likely to penetrate severe weather when there is greater severe weather coverage in the terminal area, although these quantities are correlated. Few flights penetrate weather, and even then only the lower WAF levels, in the early part of the day, while the weather is still growing in coverage and intensity. During the latter part of the day, as the weather is decaying and moving out of the terminal-area, more flights penetrate high WAFs, even WAFs of 80 and above, despite there being fewer flights. It is unclear if this is due to the nature of the weather (decaying weather may pose less of a threat) or due to operational reasons.

A detailed case study will shed light on how weather and terminal-area procedures interact to determine aircraft penetration of, or deviation from, severe weather. In each subplot of Figure 4, the black circle indicates the terminal area, a circle of radius 200 km around ORD. The solid lines are the trajectories up to that time, and the dotted lines are the future trajectory points. A triangle indicates the current position of each aircraft. Gray trajectories are departures. Similar to Figure 3, arrivals are color-coded according to the highest WAF that the aircraft penetrates within the terminal-area. The color bar to the right represents the background WAF.

4.1.1.1 Detailed chronology

On July 2, 2008, ORD was affected by several small lines of convective weather cells which severely disrupted operations. Weather first entered the terminal area around 1400Z; however, this first line stayed mostly to the north of the airport with minimal affects on traffic: only three arriving flights penetrated WAFs over 80. The weather did not impact most standard arrival routes due to its position.

Air traffic flow managers noted the impending arrival of a second series of convective cells that was expected to pass almost directly above the airport. These cells were less severe than the first line, but caused a far greater disruption due to their location. At 1534Z, well before the arrival of the second series of cells, a ground delay program (GDP) was initiated. The GDP, which affected all flights departing from the continental US and Canada, was scheduled to take effect at 1800Z, when the second series of cells was expected to enter the terminal-area.

The second series of storms entered the terminal-area around 1915Z, traveling due east. These storms had cells of Level 5 and Level 6 VIL, and correspondingly had WAFs of 100. They also grew in size as they moved eastwards towards the airport. Figure 4 shows that the departures streams shifted south in response to this weather. Furthermore, because of the ground delay program, the number of flights attempting to land at ORD had begun to decrease.

At the same time, the first line of weather to the north began to impact the northeast arrival streams. These streams first shifted south in an attempt to fly around the weather, and were eventually rerouted behind the storm through lower WAFs. It is probable they were vectored through the storm by air traffic controllers in a continuous flow. As the weather intensified, fewer and fewer pilots approached from the northeast, and the cornerpost was shut down entirely.

The second line of cells from the west continued to progress towards the airport, reaching ORD shortly after 2100Z. This line was smaller in extent than the first, but of similar intensity. As this storm front approached the airport, over twenty aircraft penetrated severe weather within the terminal-area. The situation quickly became untenable, and a ground stop was put into place at 2103Z and extended at 2121Z. It was downgraded to a GDP at 2151Z.

These ground stops were triggered, at least in part, by the large number of aircraft penetrating severe weather. In most cases, as Figure 4 shows, flights simply had no other choice if they wanted to land at ORD, particularly once the storm was directly over the airport (for example, around 2200Z). In some cases, pilots attempted to deviate around a large cell, but instead penetrated the cell at some point. This behavior is partly due to the nature of approach paths: aircraft arriving from the west had to fly around the weather in order to use the active runway.

After 2200Z, the weather cells began to decay and moved out of the terminal-area. Nevertheless, several flights flew through severe weather. While some streams are still visible, the overall patterns are unstructured enough that pilots likely chose their own paths through weather. For example, at 0100Z an aircraft briefly flew through a WAF of 100, although most others in the same stream did not. Observations such as these suggest that there is variability in the risk tolerances associated with pilots flying through weather.

Even when the weather is decaying, its location relative to the airport is important. At 0100Z, when the weather was farther from the airport, relatively few pilots penetrated severe weather. Most of those that did intersected the boundaries of the weather cells, and did not fly directly through. Yet when the same weather reaches the airport around 0300Z, aircraft that wished to land had no choice but to penetrate severe weather. This observation partially explains why there are more severe weather penetrations when the weather is decaying than earlier in the storm.

By 0240Z, the weather in the terminal-area had sufficiently decayed for the ground delay program to be cancelled. The decreased levels of traffic meant that individual flights had greater flexibility to deviate around weather. Given these factors, a surprising number of flights flew through WAFs between 40 and 100. During such periods, it is interesting to investigate whether operational factors influence why certain flights penetrated severe weather, while others avoided it.

4.1.1.2 Case study conclusions

Many factors influence whether a pilot in the terminal-area will choose to deviate around weather; indeed, many factors influence whether a pilot will even be in the terminal-area at the time of a weather event. First, traffic flow management (TFM) initiatives will reduce the number of flights into an airport during the worst weather [2]. The reduced traffic may give the remaining flights greater flexibility to deviate. The specifics of TFM initiatives can also provide insight into the capacity of the airspace. For example, the initiation of a ground stop at 2103Z indicates that air traffic controllers felt the need to reduce the number of flights in the terminal-area. Second, the proximity of severe weather to the airport is an important factor in determining whether pilots choose to deviate. When the severe weather is unavoidable, many pilots appear to be willing to penetrate it. Third, at least one time-period in which pilots made a variety of choices on whether or not to penetrate severe weather was identified on this case study day. Situations such as these may help identify operational factors that influence aircraft penetration of severe weather, and the associated decision-making by pilots.

While the previous discussion focused on a particular case study day, similar assessments were conducted for eight days in 2008, all of which witnessed significant convective activity in the Chicago area.

4.2 Factors potentially influencing severe weather penetration

The previous section described evolution of weather through a case study day, and the response of air traffic managers to changing weather conditions. This section lists additional factors that may contribute to pilot willingness to penetrate severe weather. These observations combined guide the feature extraction process.

4.2.1 Proximity to weather cells

Aircraft frequently fly close to severe weather, in some cases within a few kilometers of very heavy storms. As a consequence, aircraft may occasionally penetrate a severe weather cell for brief periods of time. Furthermore, since the kernel for the WAF is 4 km, it may occasionally appear as if an aircraft is flying through severe weather, when it is only flying very close to it.

4.2.2 Aircraft size

Several domain experts hypothesized that large aircraft might be more likely to penetrate severe weather. In addition to being less able to withstand severe weather conditions, small aircraft on shorter routes may be more frequently subject to ground delays during weather events.

4.2.3 Apparent gaps in storm fronts

Aircraft were frequently seen flying through lines of severe storms, deviating as needed to avoid the worst weather. Even lines of severe thunderstorms have small gaps in the weather that pilots or air traffic controllers are able to observe and exploit to reduce the impact of weather.

Although it is difficult to identify these gaps from the data, indicators associated with this behavior may be detectable. Pilots behaving in this manner may fly longer routes than usual. These aircraft may also be more likely not to belong to a traffic stream, since they would individually find their way through gaps in the weather.

4.2.4 Perturbation of traffic flows at the onset of severe weather

As severe weather moves across the terminal-area, it is common to see aircraft flows deflect slightly to avoid passing through it. Eventually, aircraft are seen to fly behind the storm, as seen in Figure 4 around 1900Z and again around 0100Z.

4.2.5 Flight delays

Another potential factor influencing a pilot's decision to deviate from weather is the delay status of the flight. A pilot who has already been significantly delayed may risk penetrating weather rather than delaying the flight further by flying around the weather.

5 Predictive model of severe weather penetration

The case studies described in the previous section identified several factors that may increase the likelihood of severe weather penetration. A predictive model using random forests was developed to determine which of these factors had statistically significant skill, and to quantify their predictive power.

Much of the input traffic data for the predictive model was taken from the ETMS and ASPM databases [10]. Trajectories in the ETMS database were matched to their corresponding flights in the ASPM database with a 97% success rate. The unmatched flights were not included in the modeling. While some potential features such as aircraft type or delay status can be directly extracted from the ETMS or ASPM databases, other traffic-based indicators are more difficult to extract. The next section will describe how some of these more complex features were determined. Once the features were extracted for each trajectory, a random forest prediction model was used to evaluate their relative skills.

5.1.1 Cornerposts and traffic flows

Aircraft flows at many major airports are routed into the terminal-area through sets of gates known as cornerposts. The first step in identifying traffic streams is determining active cornerposts, and how close flows are around each of them. Each cornerpost is approximately 50 km from the airport; this distance is used for all cornerposts for consistency. The position of each flight in a certain time period when it is 50 km away from the airport is considered. Using these points, a k-medians clustering algorithm is used to determine the locations of the active cornerposts [5]. Typically there are four cornerposts at ORD, although some of them may be closed due to weather. Their locations are generally stable to within a few degrees. The k-medians clustering algorithm is run with $k = 1, ..., 8$, and the value with lowest error is used to identify cornerposts.

Normally, flights arriving from different directions will be merged into a single stream before they reach a cornerpost. During fair weather, these streams are quite precise; once merged into the stream, each pilot follows almost exactly the same trajectory. However, during convective weather events, pilots may deviate significantly from the path defined by the preceding aircraft, despite being assigned to the same cornerpost. Therefore, the deviation distance between subsequent pilots on each cornerpost is also measured. Groups of pilots that follow nearly identical paths are considered substreams.

Once the substream has been identified, several additional features can be extracted. For example, it is possible to compare an aircraft's weather penetration behavior with that of the one immediately preceding it, or consider whether an aircraft is the first or last in that particular substream. A pilot penetrating severe weather may notify the air traffic controller of turbulence, which might cause subsequent aircraft to be routed differently to avoid the weather. If this is a common occurrence, severe weather penetrations may be associated with being the last pilot in a given substream.

5.2 Random forest model

Once the potential features were extracted, a random forest model was constructed to evaluate the impact of these operational factors on weather penetration. The model was a binary predictor of whether or not a particular flight would penetrate severe weather, that is, a WAF threshold of 80% or more, within the terminal-area.

Random forests are a natural extension of decision trees, and were first described by Leo Breiman in 2001 [1, 5]. Random forest models were chosen because they are very robust, and can handle many correlated variables. The diversity of random forests also avoids the problem of overfitting that is sometimes encountered with decision trees.

A random forest works by creating many decision trees using random subsets of the features and the data in each one. The model developed in this research used 500 trees in each forest, with each tree drawing 4 predictors at random. The trees were trained on oversampled subsets of flights, each with equal numbers of flights that did and did not penetrate severe weather. Each tree then voted on the outcome of the prediction variable: The sensitivity of the model could be altered by adjusting the threshold for a “yes” vote.

The model was trained and tested using eight random partitions of the dataset. A summary of results is shown in Table 1 for several vote thresholds. The random forest model appears to perform reasonably well on the test dataset, achieving accuracy rates of up to 90%. The overall accuracy was, however, skewed towards the negative prediction. The lack of oversampling in the test data explains the high false alarm rate.

5.3 Sensitivity analysis

The sensitivity of the model depends on the vote threshold, which controls the balance between false alarms and missed detections. The false alarm rate increases rapidly as the vote threshold is lowered. At the same time, decreasing the vote threshold lowers the number of missed detections. A reasonable balance point seems to be somewhere between 0.3 and 0.5, depending on the relative costs of missed detections and false alarms. The tradeoff is plotted in Figure 5.

5.4 Variable importance

The random forest model ranks features by skill. In order to do this, it randomly permutes the values of each variable and measures the decrease in accuracy of the resulting tree using a Gini index [1]. This process is repeated for all trees in the forest containing the variable in question; the resulting average is the variable importance. A higher value indicates greater skill. These importance values were computed for an arbitrary run of the random forest model with vote threshold 0.5, and are summarized in Table 2.

The model indicates that the most importance features remain weather features; these have greater significance than all but one operational feature. The time spent in the terminal area is a significant feature, with longer terminal times correlated to higher likelihood of weather penetration. However, it is worth noting that this feature can only be known after the flight has landed. A flight of longer range is also associated with higher likelihood of penetrating severe weather. There are several possible reasons for this phenomenon: First, longer distances are correlated with larger aircraft, which may be better able to penetrate severe weather. Second, flights arriving from farther away are less likely to be impacted by ground delay programs or ground stops; as a result, there may be a larger proportion of long-haul flights during severe weather periods. Comparable in skill to the flight range is the number of preceding aircraft on the same approach path, with higher numbers corresponding to increased likelihood of severe weather penetration. This observation supports the hypothesis that pilots tend to follow established paths, perhaps through worsening weather. Despite these weak correlations, it is important to note that operational factors are not as significant as weather features in determining whether an aircraft will penetrate severe weather.

6 Conclusions

This paper explored the relevance of operational features in predicting instances when an aircraft would fly through severe weather. Several potential features were evaluated and were found to have statistical significance: the two most significant non-weather features were the flight range and the total time spent in the terminal-area. Several flow-based features were also found to have weak skill in predicting pilot behavior.

The random forest predictive model indicates that these operational features are a secondary effect, and that the most important determinant of pilot behavior is the intensity and location of the weather itself. The results support the operational practice of treating all flights as equal when developing tactical weather mitigation strategies, since they can be expected to behave in relatively similar ways in terms of weather penetration behavior. They also validate the use of Weather Avoidance Fields (WAFs) in the terminal-area. Finally, this study provides insights into the secondary operational factors that explain the variability in pilot behavior during severe convective weather events.

7 Acknowledgements

This research was supported by the ACRP Graduate Research Award Program on Public-Sector Aviation Issues. The authors wish to thank Larry Goldstein at the FAA, Dr. George Hunter at Saab Sensis, Dr. Annalisa Weigel at MIT, and Linda Howard formerly of the Texas Department of Transportation for their support and feedback throughout the project. We would also like to thank Mike Matthews and Rich DeLaura at MIT Lincoln Laboratory for useful discussions, and for providing the weather data used in this study.

8 References

[1] L. Breiman. Random forests. *Machine learning*, 45(1):5–32, 2001.

[2] Chang, K., K. Howard, R. Oisen, L. Shisler, M. Tanino, M. Wambsganss. 2001. Enhancements to the FAA Ground Delay Programs under Collaborative Decision Making. Interfaces 31 57–76.

[3] R. DeLaura and J. Evans. Exploratory study of modeling enroute pilot convective storm flight deviation behavior. In *12th American Meteorological Society Conference on Aviation, Range and Aerospace Meteorology*, Atlanta, GA, 2006.

[4] R. DeLaura, M. Robinson, M. Pawlak, and J. Evans. Modeling convective weather avoidance in enroute airspace. In *13th American Meteorological Society Conference on Aviation, Range, and Aerospace Meteorology*, New Orleans, LA, 2008.

[5] T. Hastie, R. Tibshirani, and J. Friedman. The Elements of Statistical Learning: Data Mining, Inference, and Prediction, 2nd edition. Springer, 2009.

[6] A.K. Jain and R.C. Dubes, Algorithms for Clustering Data: Prentice-Hall, 1981.

[7] M. Matthews and R. DeLaura. Evaluation of enroute convective weather avoidance models based on planned and observed flights. In *14th American Meteorological Society Conference on Aviation, Range, and Aerospace Meteorology*, Atlanta, GA, 2010.

[8] M. Matthews and R. DeLaura. Modeling Convective Weather Avoidance of Arrivals in the Terminal Airspace. *American Meteorological Society Special Symposium on Weather and Air Traffic Management Integration, Seattle, WA*. 2011.

[9] M. Robinson, J. Evans, and B. Crowe. En route weather depiction benefits of the NEXRAD vertically integrated liquid water product utilized by the corridor integrated weather system. In 10th American Meteorological Society Conference on Aviation, Range and Aerospace Meteorology., Portland, OR, 2002.

[10] ETMS data was obtained from the John A. Volpe National Transportation Systems Center. ASPM data is available at https://aspm.faa.gov.

9 List of tables and figures

Table 1: Summary of results from random forests with several different vote thresholds. Standard deviations are given in parentheses.

Table 2: Variable importance as given by the random forest model.

Figure 1: VIL, echo tops, and resultant WAF in the ORD terminal area with overlaid trajectories on June 12, 2008, at 20:17:30Z.

Figure 2: VIL distribution for each WAF value. The right bar in each pair removes the flights that were at or above the echo top height.

Figure 3: Overview of the July 2, 2008, case day. Bars indicate flight counts; the line indicates the fraction of the terminal containing WAFs of 80 or greater.

Figure 4: ORD terminal area on 2-3 July 2008, showing the evolution of WAFs.

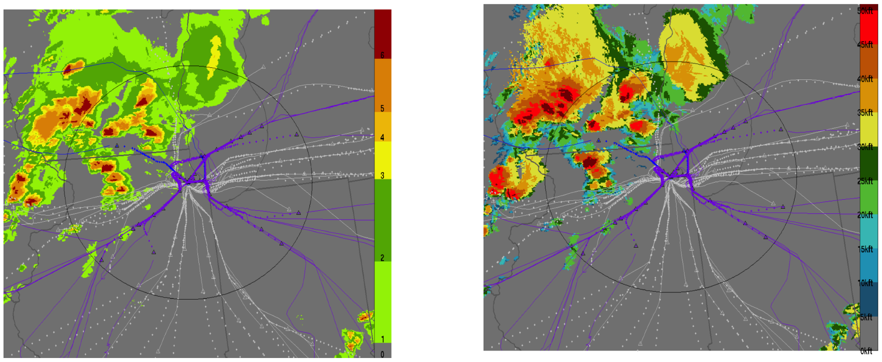
Figure 5: Sensitivity curve summarizing tradeoff between false alarms and missed detections, parametrized by the vote threshold.

Table 1: Summary of results from random forests with several different vote thresholds. Standard deviations are given in parentheses.

Threshold for yes vote	Predicted	Actual yes	Actual no
0.7	Yes	34 (3)	145 (28)
	No	33(6)	4235 (59)
0.5	Yes	51 (4)	556 (56)
	No	15 (4)	3823 (70)
0.3	Yes	63 (5)	1728 (186)
	No	4 (4)	2651 (206)
0.1	Yes	66 (7)	3662 (300)
	No	0 (0)	717 (293)

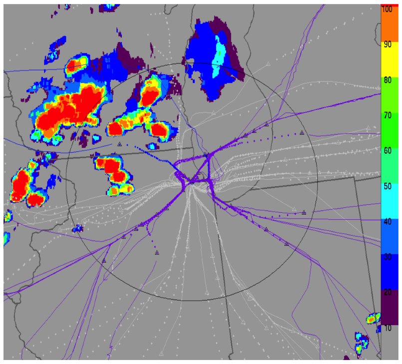
Table 2: Variable importance as given by the random forest model.

Variable	**Feature Importance**
Weather coverage within 50 km of the airport	22.7
Time spent in the terminal-area	16.3
Weather coverage between 50 km and 200 km from the airport	12.3
Weather coverage within 200 km of the airport	11.6
Flight range	10.6
Number of aircraft on the same stream in the past 30 min	10.6
Number of aircraft in the terminal-area	7.6
Airline	6.9
Number of aircraft on the same stream in the next 30 min	6.7
Airborne delay	5.5
Wheels-off delay	5.4
Pushback delay	3.9
Runway	3.2
Cornerpost	2.8
Aircraft type	0.3



1a: VIL

1b: Echo tops.



1c: WAF

Figure 1: VIL, echo tops, and resultant WAF in the ORD terminal area with overlaid trajectories on June 12, 2008, at 20:17:30Z.

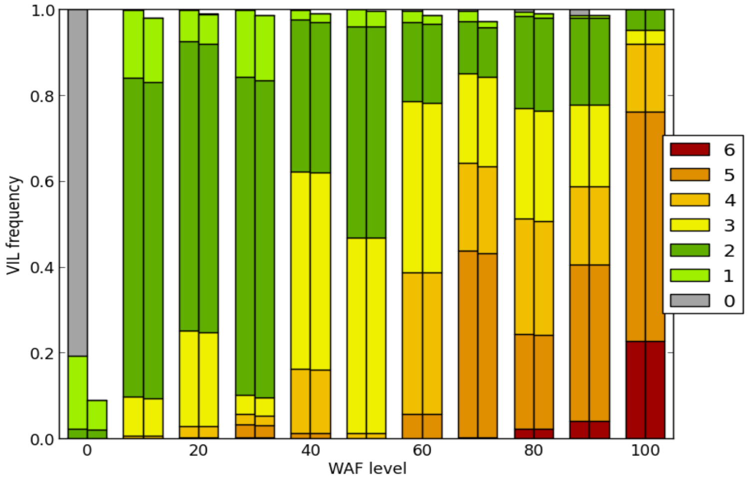


Figure 2: VIL distribution for each WAF value. The right bar in each pair removes the flights that were at or above the echo top height.

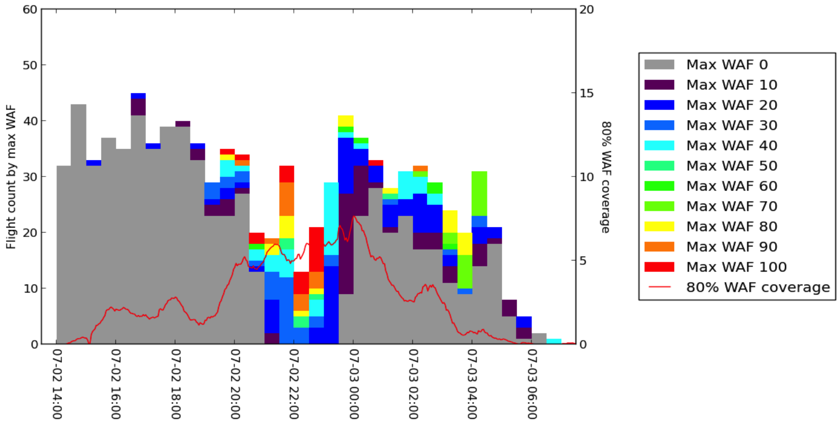
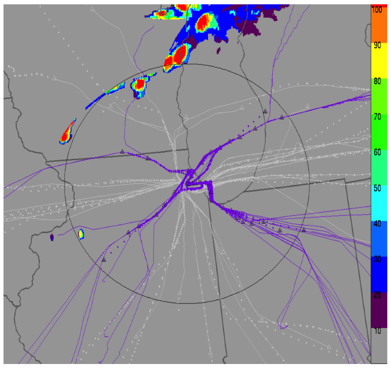
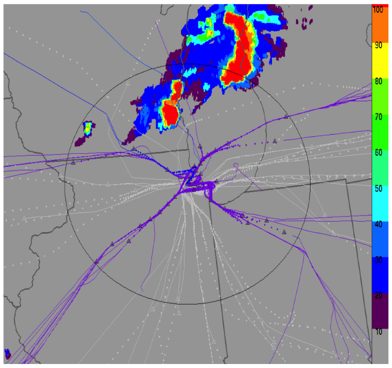


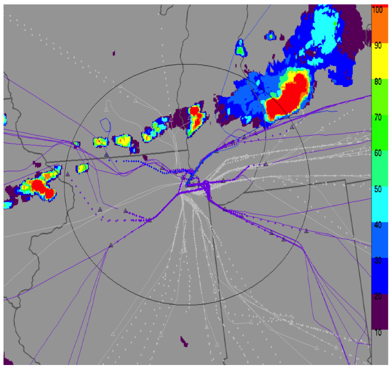
Figure 3: Overview of the July 2, 2008, case day. Bars indicate flight counts; the line indicates the fraction of the terminal containing WAFs of 80 or greater.



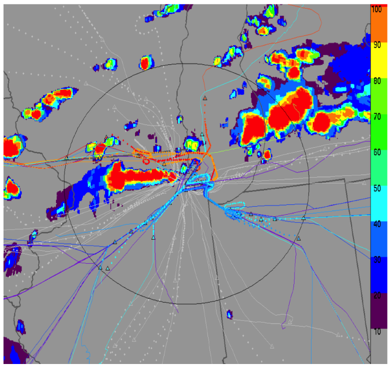
4a: 1500Z.



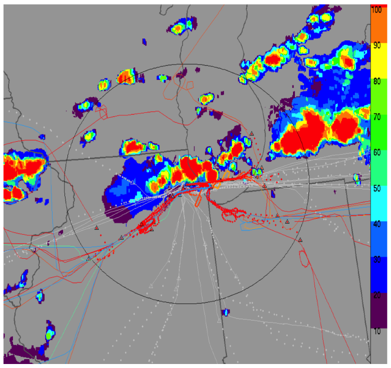
4b: ORD terminal area at 1700Z.



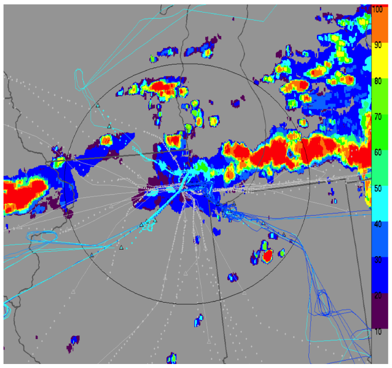
4c: ORD terminal area at 1900Z.



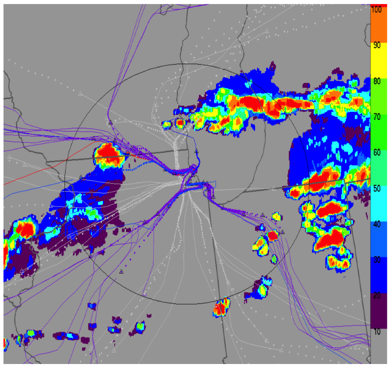
4d: ORD terminal area at 2100Z.



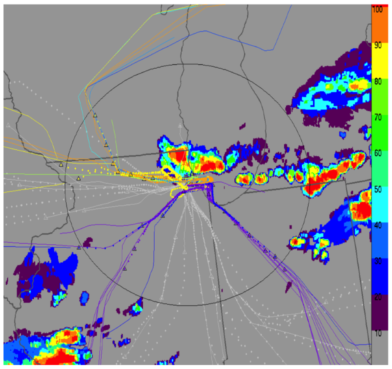
4e: 2200Z.



4f: ORD terminal area at 2300Z.



4g: ORD terminal area at 0100Z.



4h: ORD terminal area at 0300Z.

Figure 4: ORD terminal area on 2-3 July 2008, showing the evolution of WAFs.

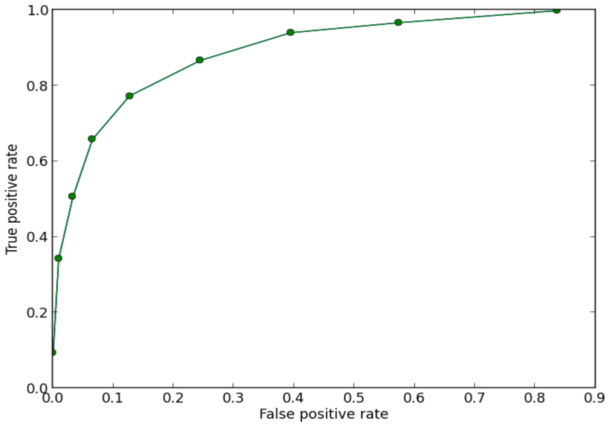


Figure 5: Sensitivity curve summarizing tradeoff between false alarms and missed detections, parametrized by the vote threshold.