INITIAL VALIDATION OF A CONVECTIVE WEATHER AVOIDANCE MODEL (CWAM) IN DEPARTURE AIRSPACE

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Abstract

The Convective Weather Avoidance Model (CWAM) translates gridded, deterministic weather observations and forecasts into Weather Avoidance Fields (WAF). The WAF gives the probability, at each point in the grid, that a pilot will choose to deviate around convective weather at that location. CWAM have been developed and validated for en route, high altitude, level flight [1,2], low altitude level flight [3], and for descending arrivals [4]. A heuristic CWAM for departures was also developed and deployed as part of the Route Availability Planning Tool (RAPT) prototype development in New York and Chicago [5,6]. This paper presents an evaluation of the departure CWAM that is currently deployed as part of RAPT, based on an analysis of departure traffic in the Chicago terminal area during convective weather events.

The validation of the CWAM in departure airspace is challenging, since it requires the inference of pilot intent from flight track and weather data. This task is particularly difficult in terminal airspace, because of the high degree of flexibility that pilots and air traffic controllers have in vectoring aircraft around storms and through the airspace. We describe our approach in solving 3 problems:

- Automation of weather avoidance detection in terminal airspace
- Validation of the WAF for departure flights between 20 and 120 km from the airport
- Interpretation of results to identify potential sources of error in the CWAM and weather avoidance strategies employed in departure airspace

To validate WAF, we automatically classify trajectory avoidances and intersections of WAF contours, determine the WAF probability associated with the weather that is avoided and intersected for each flight, and compare the observed probability of weather avoidance to the avoidance probability predicted by the WAF. The validation is based on the analysis of several test days from the summer of 2010 in the Chicago O'Hare departure airspace (Figure 1). In addition to the calibration of WAF avoidance probabilities, this paper will present an analysis of WAF-based deviation prediction errors, and observed weather avoiding tactics in the departure airspace.

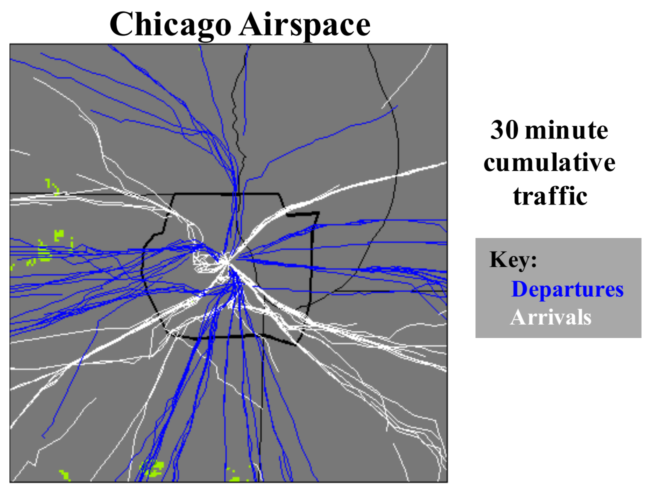

Figure 1. Chicago Departure Airspace

Methodology

Deviation probabilities predicted by CWAM were calibrated against flight trajectories observed in the Chicago departure airspace. Flight trajectories were taken from the Enhanced Traffic Management System (ETMS), which provides flight plan information and one minute updates of observed aircraft position. An automated trajectory analysis algorithm, described below, identified the maximum WAF deviation probabilities, calculated using observed weather products from the Corridor Integrated Weather System (CIWS), that each observed trajectory avoided and intersected. Note that WAF values range from 0.0 to 1.0, in increments of 0.1.

Observed weather avoidance probabilities were compared to predicted weather avoidance based on the WAF encountered along the planned departure trajectory. Data from five days in 2010 (7/7, 7/28, 9/1, 9/2, and 9/18) were analyzed to ensure a variety

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of storm scales and spatial distributions were considered. In total, 560 weather avoidances and 423 weather intersections were identified and analyzed. 'Weather avoidances' refers observed trajectories that maneuvered to avoid weather in their path; 'weather intersections' refers to trajectories that encountered WAF deviation probabilities greater than 0.

No attempt was made to analyze weather avoidance within 20 km of the airport. ETMS data lack sufficient resolution to identify weather avoidance maneuvers on such a small scale. Furthermore, within 20 km of the airport, aircraft trajectories are determined by the operational procedures (e.g., climbout) that are difficult to extract from available data. Finally, weather impacts within 20 km of the airport most often result from storms that are a 'direct hit' over the airport surface, and decisions about traffic management more likely reflect critical safety imperatives, such as microbursts, lightning strikes, or runway conditions, rather than pilot decision making.

Automated Trajectory Analysis

Unlike en route airspace, where planned trajectories can be readily identified by connecting the waypoints along the filed flight plan, planned trajectories in the TRACON are much more difficult to infer. Between climbout and merge into overhead streams in en route airspace beyond the departure fix, pilots and air traffic control have considerable leeway in coordinating flight trajectories to accommodate different climbout procedures, potential conflicts with traffic from neighboring airports, and weather avoidance preferences.

Figure 2 illustrates weather-related decisions that were considered in the validation. Pilots may elect to penetrate storms without altering course (Figure 2a). In other instances, the pilot may choose to deviate around the storm, without substantially altering course (Figure 2b). Finally, the pilot may choose to alter course significantly to avoid weather impacts over or near the departure fix (Figure 2c).

An automated trajectory classification algorithm was developed to identify flight trajectory changes that are intended to avoid weather, and to associate the avoidance decision with the WAF contour that the pilot is trying to avoid. Intersection with weather is also identified. However, weather avoidance by pre-departure reroute or pilot refusal was not captured in this algorithm or in the probability calibration analysis that follows.

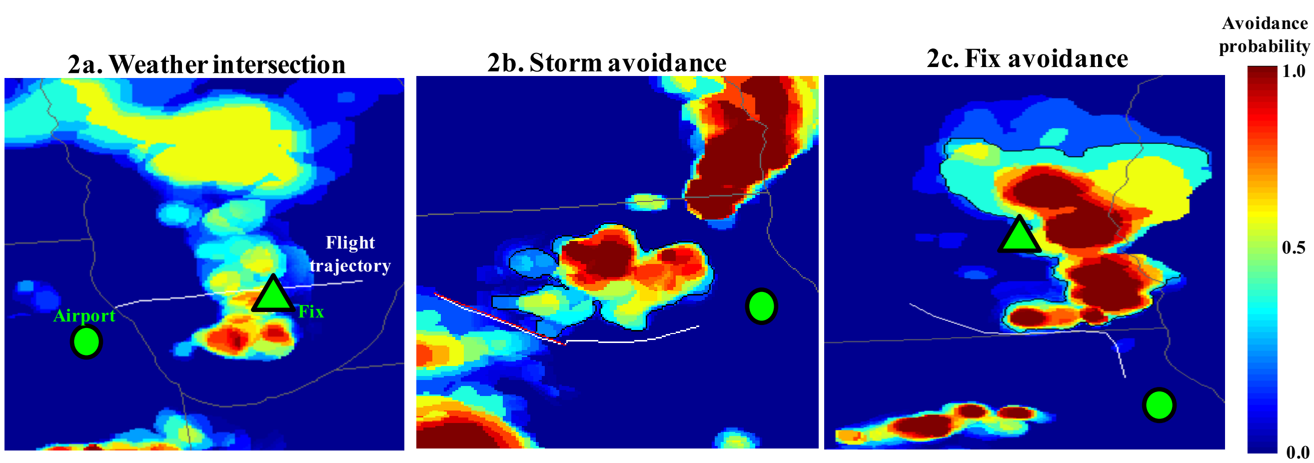

Figure 2. Illustrations of Pilot Responses to Weather

Observed trajectories and WAF are analyzed in 10 minute blocks: a WAF that is valid at time t0 is associated with the trajectories of all flights that departed between t0 and t0 + 10 minutes. The algorithm is implemented on each observed trajectory in the analysis block as follows (see Figure 3):

- Identify the maximum intersected WAF intersection by picking the maximum of all

WAF deviation probability contours intersected by the trajectory (Figure 3a).

- Identify instances of 'storm avoidance' (weather avoidance along the departure trajectory path) using the 'ray algorithm': a trajectory is classified as an avoidance if the trajectory does not intersect a WAF feature in its path, but there is an imaginary line connecting two points of the observed trajectory that intersects the WAF contour defining the feature. The avoidance is characterized by a minimum avoided WAF, which is the deviation probability associated with the outermost WAF contour identified by the ray method, and a maximum avoided WAF, which is the maximum WAF value contained inside the minimum WAF contour (Figure 3b). If multiple avoidances are identified for a single trajectory using the 'ray' algorithm, only the avoidance with the greatest maximum avoided WAF value is retained. Although the algorithm can discount trajectories where multiple avoidance decisions were made, multiple avoidances are rarely observed and clearly identifiable in the phase of flight – departure climb between 20 and 120 km of the airport – to which the departure CWAM applies.
- Identify avoidance of weather on the departure fix ('fix algorithm'), if the filed departure fix is within 140 km of the airport. If a line drawn between the departure fix and the closest trajectory point intersects a WAF contour, the trajectory is classified as a weather avoidance. The minimum avoided WAF is the minimum WAF contour intersected by the connecting line, and the maximum avoided WAF is the maximum WAF contour enclosed by the minimum avoided WAF contour (Figure 3c).

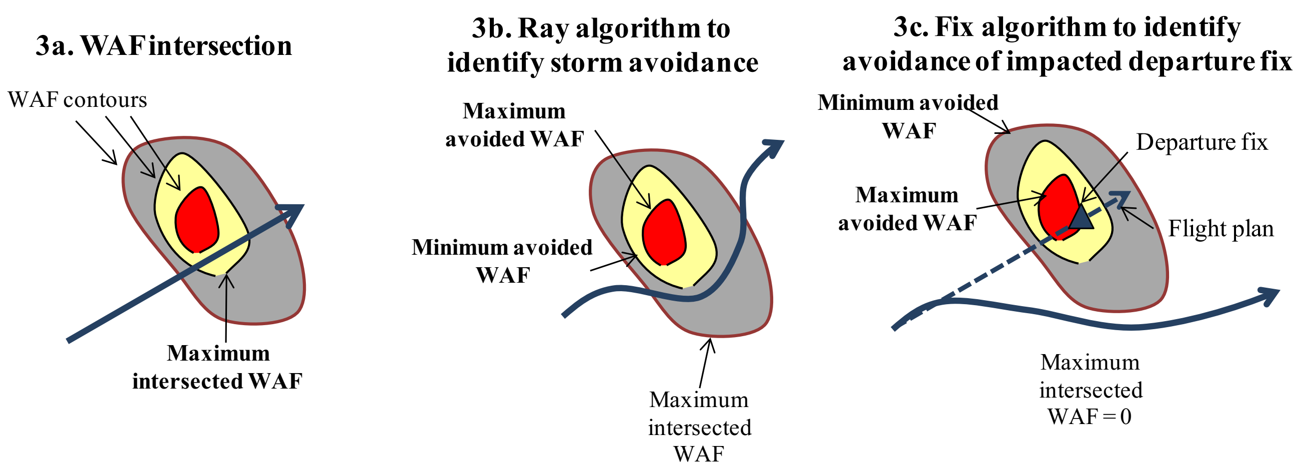

Figure 3. Illustrations of Automated Weather Decision Classification Algorithm

Figure 4 illustrates a weather intersection (Figure 4a), departure fix weather avoidance (Figure 4b), and storm avoidance (Figure 4c).

The trajectory classification algorithm was evaluated using visualizations that overlay the flight trajectory on the contours identified in the algorithm, and detection errors were identified and categorized, but were not edited out of the dataset. Visualizations of 316 automated classifications were reviewed to validate the algorithm; the error rate was estimated at ~20%. Two error modes were identified: WAF contour fragmentation, small misclassified deviations, and double counting due to contour 'shadowing'.

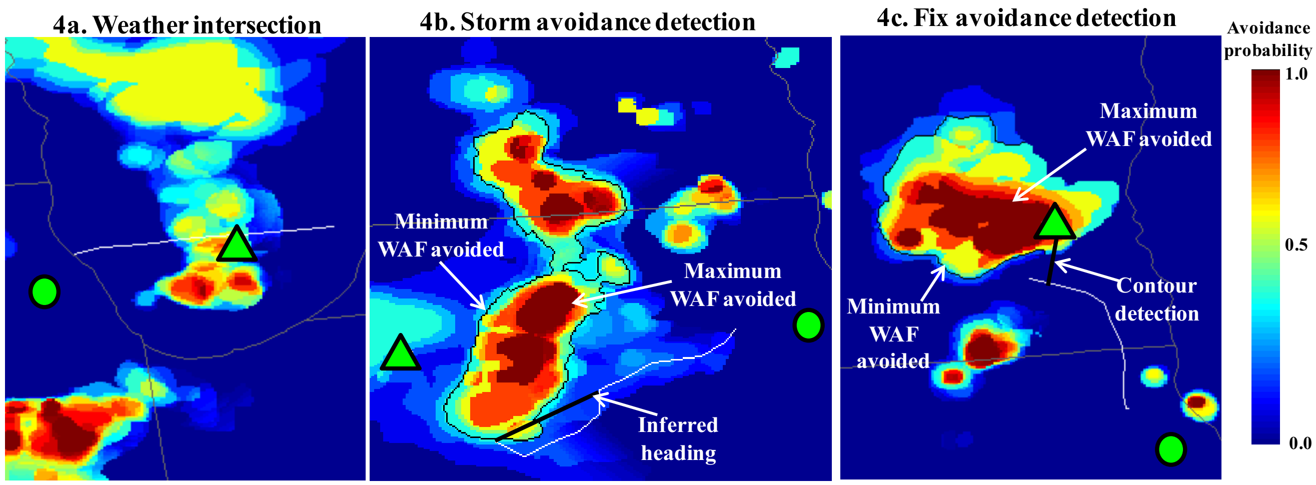

Figure 4. Illustrations of Weather Avoidance Classifications

In some instances, noise in the WAF resulted in WAF deviation probability contour fragments that were misidentified by the ray algorithm as the contour most likely responsible for the avoidance decision (Figure 5). Contour fragments most often were small deviation probability values on the edges of regions of high deviation probability contours, and tended to increase the error in the avoidance probability calibration by overestimating the observed avoidance probability for the lower forecast probability associated with the fragment, while underestimating the observed avoidance probability associated with the higher forecast probability associated with the higher region.

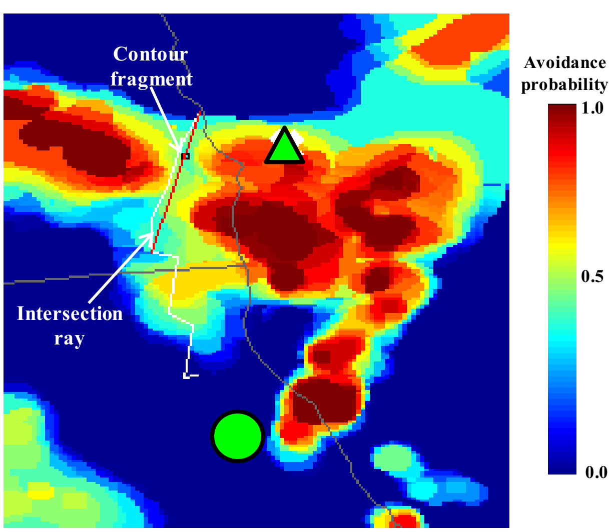

Figure 5. Decision Classification Misidentifies WAF Contour Being Avoided

Several errors were due to the ray algorithm identifying small deviations due to slight variations in trajectory heading, and associating these deviations with small WAF contours (Figure 6). These 'deviations' are more likely a result of noise in the trajectory data, and tend to overestimate the impact of lower WAF values on avoidance decisions.

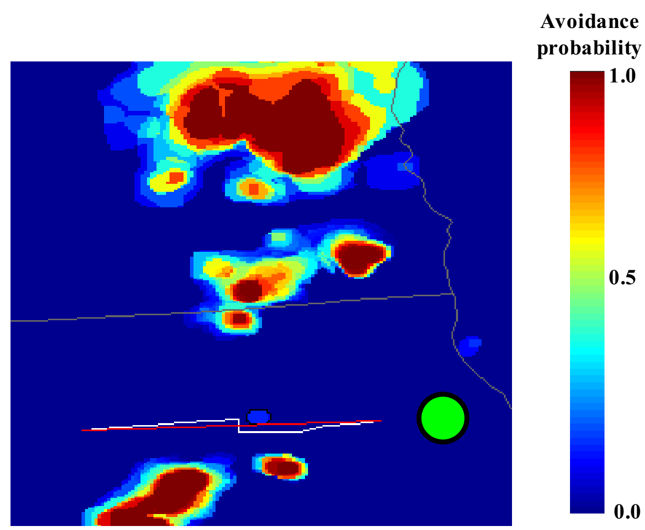

Figure 6. Erroneous Classification of Small Deviations

The classification algorithm can, in some instances, predict two classifications for a trajectory: one from the ray algorithm and another from the fix algorithm. Currently, there is no automated means to determine if both classifications are valid, and both classifications are included in the database. Figure 7 illustrates a classification error that results when one algorithm (in this case, the fix algorithm) identifies an avoidance contour that is overshadowed by a more significant contour identified by the other algorithm (in this case, the ray algorithm). In these cases, perceived avoidances of small 'shadowed' contours tended to overestimate the actual avoidance of lower WAF deviation probabilities.

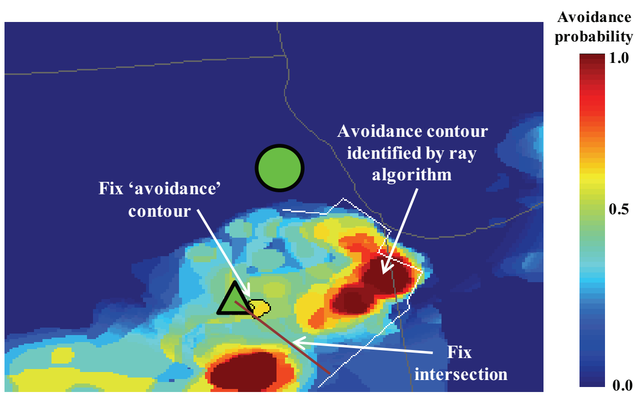

Figure 7. Shadowed Fix Avoidance Identified and 'Double Counted' in Addition to Weather Avoidance Identified by the Ray Algorithm

Results

The trajectory classification algorithm classifies each trajectory as a weather avoidance, weather intersection, or null (if no WAF contours are avoided or intersected). The maximum avoided WAF is assumed to dictate the avoidance decision, the minimum avoided WAF is assumed to be related to the avoidance strategy. In the probability calibration, each weather avoidance is associated with the maximum avoided WAF, and each intersection is associated with the maximum intersected WAF.

Figure 8 presents the deviation probability calibration results from Chicago. For each avoidance probability on the x-axis, the total number of flights that encountered that level of avoidance probability – avoidances plus intersections – were tallied (the tally is presented at the top of each bar), where 'encounter' is defined as the maximum avoided or intersected WAF. The observed avoidance probability is simply the percentage of the encounter tally classified as weather avoidances.

The departure CWAM appears to be reasonably well-calibrated, although the observed avoidance probability dips for predicted avoidance probabilities of 0.6 and 0.8 are difficult to explain. The tendency of observed avoidances to be higher than predicted for low prediction probabilities (0.1, 0.2, 0.3) are due, in part, to the automated classification errors that tend to overestimate the observed avoidance probability for low-probability weather features. It is also important to note that the dataset captures avoidance decisions made by pilots willing to depart during terminal area weather impacts; some pilots may have made the decision to remain on the ground or reroute to avoid weather impacts. If pilots who were more likely in general to avoid weather remained on the ground, one might conjecture that the observed avoidance likelihood would be somewhat less than predicted, particularly where the model predicts a higher probability of avoidance.

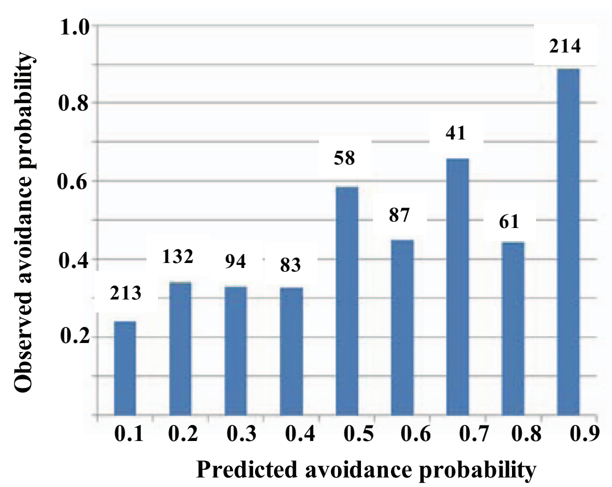

Figure 8. Calibration of Departure CWAM from Chicago

The decision to avoid weather is only one characteristic of pilot behavior; another important characteristic is the avoidance strategy that the pilot is likely to choose. In the weather-avoiding examples shown in Figures 2b and 2c, the pilots chose different avoidance strategies. In Figure 2b, the pilot chose an avoidance trajectory that avoided the storm core but encountered less severe weather in the vicinity. In Figure 2c, the pilot chose to avoid all weather and to fly in clear air. The choice the pilot makes about where to fly when avoiding a storm may depend on several factors, including the ability to identify a storm boundary visually, the quality of available avoidance options, the extra distance that the pilot is willing to fly, etc.

In order to characterize observed weather-avoiding strategies, we examined the maximum intersected WAF for all avoidances whose maximum avoided WAF was 0.9. The results are plotted in Figure 9. Almost 30% of flights that avoided WAF of 0.9 avoided *all* weather, and almost 60% avoided WAF with values > 0.3. This suggests that pilots will avoid weather near a storm that they would otherwise fly through if that weather were isolated and not associated with the storm.

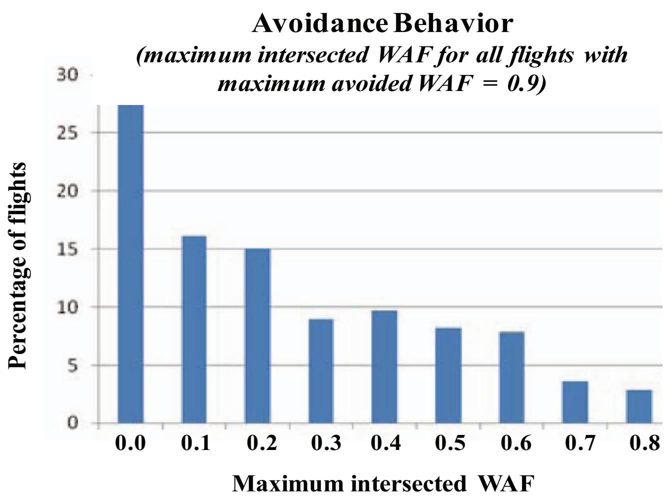

Figure 9. Maximum Intersected WAF for All Flights Avoiding WAF Probabilities >= 0.9

Conclusions and Future Work

The Convective Weather Avoidance Model (CWAM) for departure airspace creates a Weather Avoidance Field (WAF) that gives the probability at each grid point that a pilot flying through the departure climb and transition to en route airspace will deviate around weather. A heuristic departure CWAM, developed as part of the Route Availability Planning Tool (RAPT), was evaluated based on data from 5 days of operations in Chicago during the 2010 summer. The evaluation included the creation of an automated weather decision classification algorithm and the calibration of the departure WAF against observed weather avoidance behaviors.

The classification algorithm classified departure trajectories as weather avoidances or weather intersections. Avoidance of weather along the trajectory path and over the departure fix was captured. The classification error was estimated at 20%, with most of the errors tending to overestimate the observed avoidance probability for regions of low WAF values, and underestimate the observed avoidance probability for regions of high WAF values. Classification errors were not edited out of the evaluation dataset.

The departure CWAM produces a reasonably well-calibrated WAF. Observed avoidance probabilities were higher than expected by CWAM for low WAF, but some of that error was a result of the avoidance classification algorithm described above. Observed avoidance probabilities were typically higher for high WAF values.

Avoidance behavior – the WAF intersections for pilots avoiding WAF features with avoidance probability of 0.9 – was also analyzed. Approximately 60% of pilots avoiding storms intersected WAF regions with avoidance probabilities < 0.3, suggesting that where possible, pilots seek to avoid all weather impacts, particularly those associated with very strong storms, not simply to reduce them to an ‘acceptable’ level.

There are several areas of future work:

- **CWAM evaluation in different departure airspace.** An evaluation of departures in New York is currently underway, to determine if the underlying airspace structure affects pilot avoidance behavior.
- **Development of a single combined departure / arrival CWAM for terminal airspace.** An effort is currently underway to evaluate the performance of a single terminal area CWAM that would apply to both arrivals and departures. A single terminal CWAM with acceptable performance for both arrivals and departures would be easier to implement in decision support systems and more readily understood by users.
- **Evaluation of departure CWAM performance based on forecast weather.** Operational uses of CWAM for departure management and planning will require WAF forecasts in addition to WAF diagnostics. Departure CWAM forecast performance may be improved by modification of CWAM parameters (e.g., spatial filter window sizes) to account for

different characteristics of actual and forecast weather.

- Enhancements in the automated decision classification algorithm. Classification errors should be addressed, and further work should be done to adapt the algorithm for use in other airspaces.

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