

An Algorithm to Identify Robust Convective Weather Avoidance Polygons in En Route Airspace*

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The paper describes an algorithm for constructing convective weather avoidance polygons. The algorithm combines weather avoidance fields (WAF) from the en route convective weather avoidance model (CWAM) with edges automatically detected in the echo tops field, clustering, convex hull fitting and wind data to build weather avoidance polygons. Results for 2 case days with significantly different weather patterns were classified and studied.

I. Introduction

THE Federal Aviation Administration (FAA) is currently handling nearly 120,000 flights a day through its Air Traffic Management (ATM)¹ system and air traffic congestion is expected to increase substantially over the next 20 years². Weather-induced impacts account for 70% of all delays with convective weather accounting for 60% of all weather related delays³. The management and control of air traffic in congested airspace, which is difficult even under ideal conditions, becomes extremely challenging in the presence of thunderstorms, which are often very dynamic and difficult to predict. Air traffic management problems are further compounded by the fact that many tools used routinely during nominal conditions (e.g., time-based metering) are of limited value during periods of convective weather, since they do not take into account the impacts of thunderstorms on air traffic and flight trajectories.

The first step in developing convective weather-aware decision support is the translation of weather information into statements about aviation impact. An en route convective weather avoidance model (CWAM) transforms gridded, deterministic forecasts of radar echo top height and vertically integrated liquid (VIL – a measure of precipitation intensity) into three-dimensional weather avoidance fields (WAF), which give the probability at each grid point that a pilot will choose to deviate around the weather at that point ('deviation probability')⁴ (figure 1). The use of CWAM and WAF in the Route Availability Planning Tool (RAPT), an operational, weather-aware departure management decision support prototype that has been deployed in New York, has resulted in significant improvement in predictions of weather impacts on departure routes⁵. Recent studies found that CWAM showed skill in predicting which aircraft would deviate to avoid convective weather in their planned path^{6,7}.

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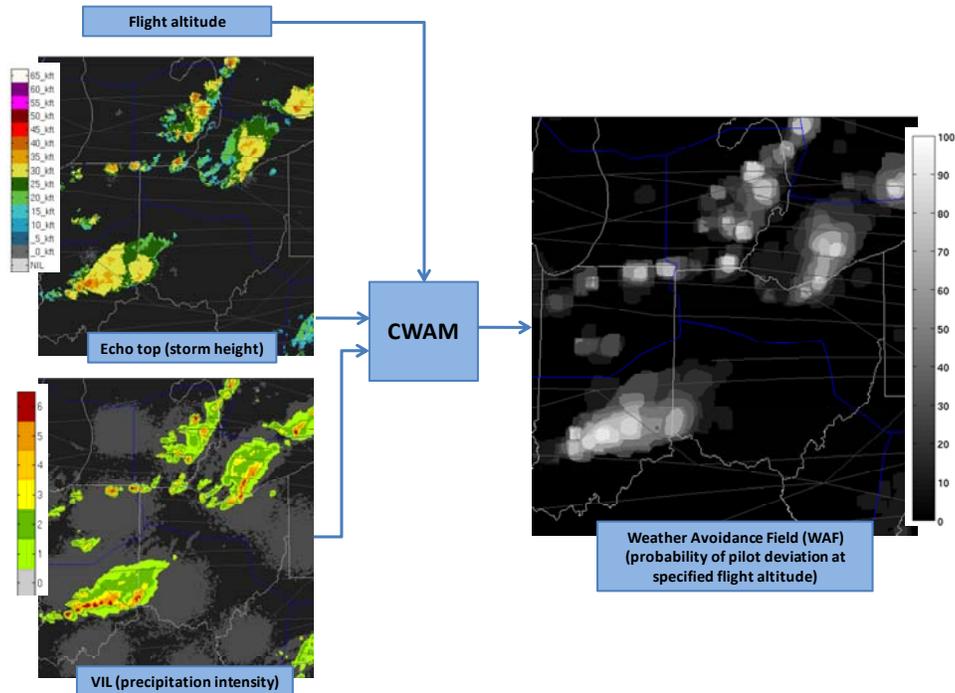


Figure 1. Illustration of a Weather Avoidance Field (WAF).

However, two significant problems reduce the effectiveness of CWAM in the prediction of weather-avoiding trajectories for time-based metering applications, where WAF contours must be converted to two- or three-dimensional polygons that flight trajectories are likely to avoid ('avoidance polygons'). Defining avoidance polygons as a particular deviation probability contour in the WAF sometimes results in noisy avoidance fields that, in turn, result in overly complex and unrealistic weather-avoiding trajectories (figure 2). Even though deviation can be predicted fairly well by identifying the maximum deviation probability that a flight will encounter along its planned trajectory, WAF contours do not always predict the boundaries of the avoidance polygons that deviating pilots follow.

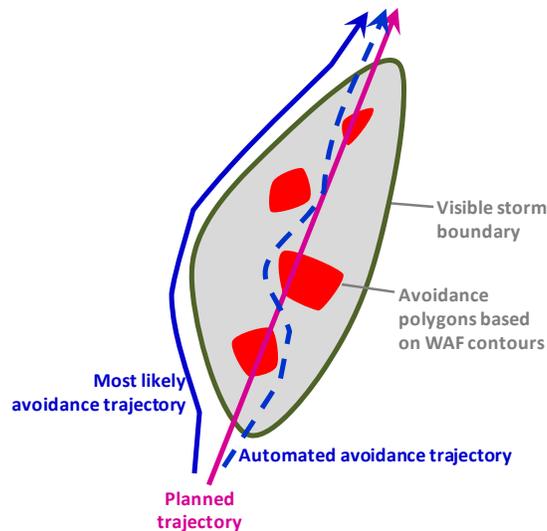


Figure 2. Notional illustration of a 'noisy' weather avoidance polygon field, based on simple WAF deviation probability contours that result in overly complex weather-avoiding trajectories.

This shortcoming arises from the fact that CWAM identifies regions of vigorous convection that pilots wish to avoid (high-topped thunderstorms), based only on local measurements of echo top height and VIL. CWAM does not attempt to identify boundaries of thunderstorms that pilots may be able to see outside the cockpit, and that may be used as a guide for safe and comfortable weather-avoiding trajectories. In some instances, pilots may still choose to fly gaps between thunderstorm ‘turrets’ that are part of a single storm complex, but more often, pilots will choose to avoid the storm altogether, if possible (figure 3).

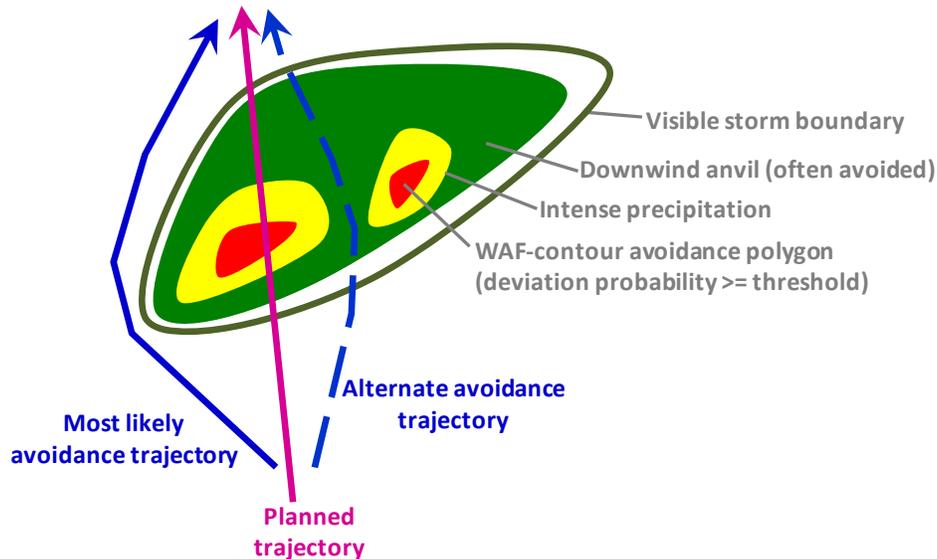


Figure 3. Notional illustration of a ‘typical’ thunderstorm and possible weather-avoiding trajectories.

In order to increase the effectiveness of en route CWAM in time-based metering applications, WAF must be enhanced to create more robust convective weather avoidance polygons (CWAP). Robustness implies that avoidance polygons contain convective weather that pilots wish to avoid, and that the preferred weather avoiding trajectory will follow the boundary of the polygon closely. Hence, automatically generated weather avoiding-trajectories based on robust weather avoidance polygons will have a high likelihood of acceptance by pilots. As a result, pilot behavior may become more predictable, and the workload required to coordinate weather-avoiding deviations should be reduced.

This paper describes an algorithm that combines WAF with automatically detected edges in the echo top field and winds at flight altitude to identify CWAP that roughly approximate storm boundaries observable from the cockpit. Results are illustrated from two case study days, and a qualitative evaluation of algorithm performance is presented. The paper concludes with a summary and suggestions for future work.

II. CWAP Algorithm Description

The CWAP algorithm is based on two central assumptions. First, it is assumed that high deviation probability contours in the WAF identify the convective ‘cores’ of the severe thunderstorms that pilots wish to avoid. This assumption is based on a recent CWAM evaluation study⁷ and operational experience with WAF in the Route Availability Planning Tool (RAPT)⁵.

The second assumption is that edges in the echo top field image approximate the visual boundary of storms that pilots, in many instances, choose to follow when they deviate to avoid thunderstorms. This assumption is not easily validated. However, observation of flight trajectories overlaid on weather has provided evidence that deviating pilots often follow echo top edges. Recent studies that compare WAF with observations from a research aircraft flying in and around thunderstorms^{8,9} also support this assumption. The weather inputs (observed VIL and echo tops) were provided by the Corridor Integrated Weather System (CIWS)¹⁰.

The steps of the algorithm are as follows (figure 4):

1. Detect edges in the echo top field image using automated edge detection.

The echo top image is run through a Canny edge detector¹¹. The Canny detector requires the setting of a gradient threshold to identify edge pixels in an image. Two statistical approaches^{12,13} to automatically determine gradient thresholds were examined. Unfortunately, the results were not satisfactory, so the gradient threshold was tuned heuristically.

2. Cluster edge pixels found in step (1).

Edge pixels from step 1 are clustered using the DBSCAN¹⁴ algorithm. The DBSCAN algorithm requires the setting of only two parameters: distance, and the number of edge pixels encountered in that distance (hence, the parameterization may be interpreted as a threshold density of edge pixels). A high density of edge pixels indicates what is likely to be a coherent storm edge boundary. The threshold parameters were tuned heuristically.

3. Enclose each cluster from step 2 in a convex hull.

Making CWAP convex hulls ensures that weather-avoiding reroutes that follow the bounds of the CWAP will be efficient.

4. Remove CWAP that do not enclose a region of WAF deviation probability greater than the deviation probability threshold, P_{\max} .

CWAP must be associated with thunderstorm cores that are sufficiently severe that pilots will wish to avoid them (defined as those with deviation probability $\geq P_{\max}$). CWAP that do not enclose sufficiently severe weather are assumed to be penetrable, and therefore are filtered out of the avoidance field. The deviation probability is taken from the WAF at flight altitude.

5. In order to capture potentially turbulent downwind thunderstorm anvils that pilots often choose to avoid, CWAP remaining after the filtering step (step 4) are extended downwind following the pilot's 'rule of thumb' for downwind anvils: one nautical mile downwind from thunderstorms for each knot of wind speed at flight level.

Because downwind anvils tend to have radar signatures characterized by fairly low precipitation intensities and echo tops that are lower than the thunderstorm cores, CWAM often do not assign high deviation probabilities to these regions. Setting P_{\max} deviation thresholds low enough to ensure that anvil regions are identified as hazards results in an unacceptable level of incorrect deviation prediction, since many regions of relatively benign rain (low intensity precipitation accompanied by non-convective echo top heights) will be classified as hazardous.

Algorithm

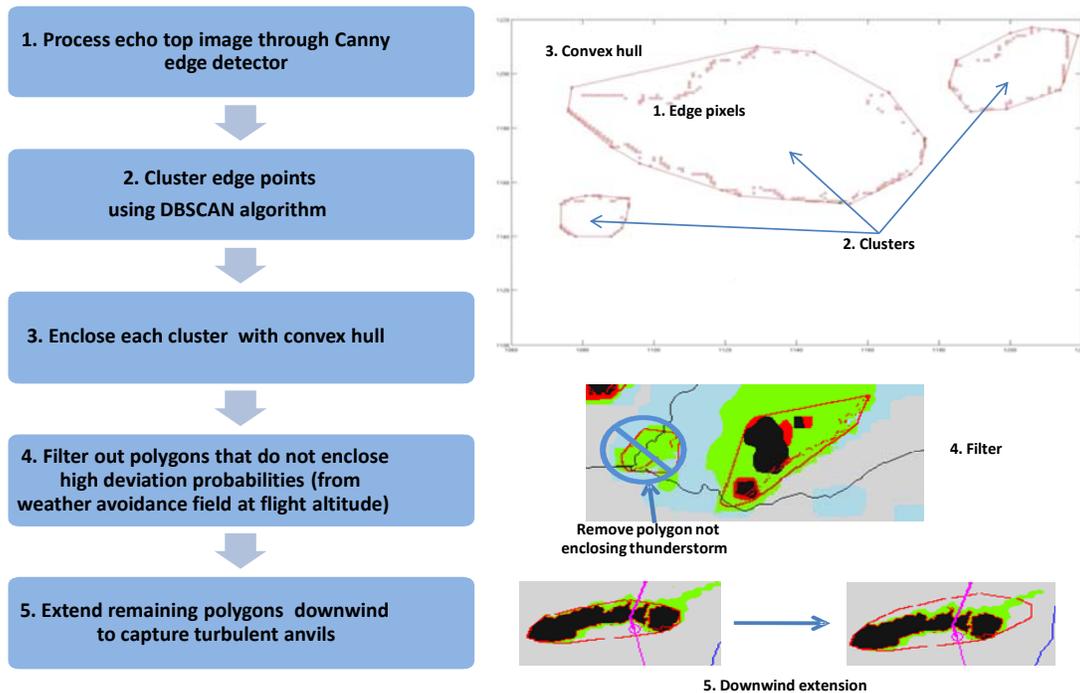


Figure 4. The Convective Weather Avoidance Polygon (CWAP) algorithm.

III. Case Study Results

The CWAP algorithm was applied to weather data from two different convective weather case days from 2006: 19 June and 14 July. The scale and spatial organization of thunderstorms on these two days was sufficiently varied, so that the algorithm was exercised in circumstances where pilots were likely to exhibit a range of weather avoidance behaviors. Storm types included organized, large-scale thunderstorms (figure 5a) and complexes of unorganized convection: small, intense thunderstorm cells, some of which were embedded in larger regions of rain (figure 5b).

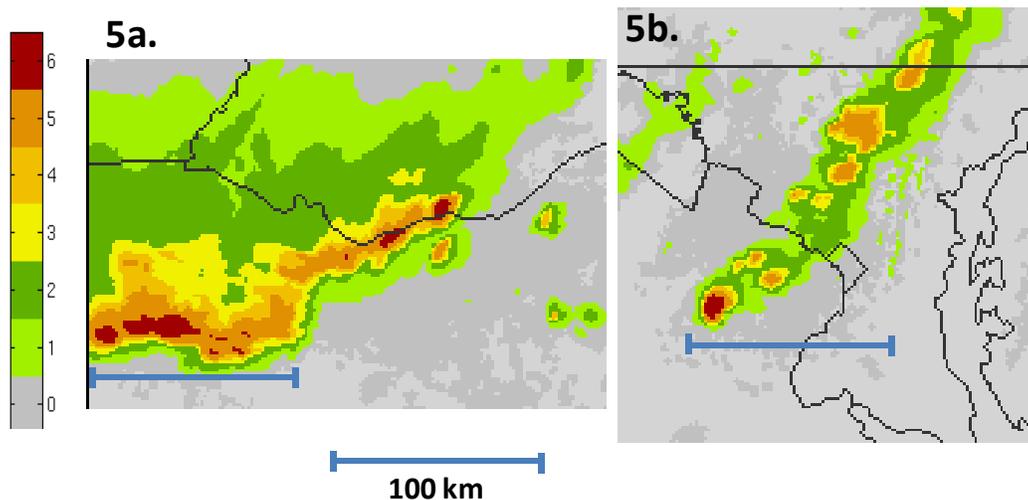


Figure 5. Illustrations of two different weather regimes from the case study days (radar-derived precipitation intensity shown).

Two different variations of CWAP were tested. In both versions, WAF was created using a modified version of the original CWAM published in⁴, in which the spatial filtering of weather inputs was omitted. The spatial filters used in the CWAM tend to extend the influence of storm features identified in the weather radar fields, creating more and larger potentially hazardous regions (those with deviation probabilities $\geq P_{\max}$). Since spatial filters were not applied, WAF used in step 4 of the CWAP algorithm tend to identify smaller, and in some cases more numerous, thunderstorm cores than the original model. In the NO_WIND version, step 5 (downwind extension) was not applied. Downwind extension was applied in the WINDY version.

Figures 6-8 illustrate flight trajectories overlaid on weather, WAF and CWAP derived from each of the CWAP versions. In each of these figures, the planned aircraft trajectory, based on data from the Enhanced Traffic Management System (ETMS) is shown in magenta. The actual flight trajectory, also from ETMS data, is shown in blue. The leftmost panel illustrates the trajectories overlaid on maps of observed precipitation intensity (VIP intensity levels 0-6). The other two panels show the trajectories overlaid on WAF and CWAP derived from each of the two CWAP model variations (NO_WIND, WINDY). Regions with WAF deviation probabilities $\geq P_{\max}$ (here chosen to be 0.7) are shown in black, and regions with WAF deviation probabilities ≥ 0.2 are shown as green. The approximate prevailing at flight level, based on the nearest radiosonde atmospheric sounding, is also shown. The CWAP are shown as red polygons.

Figure 6 shows a fairly large, isolated thunderstorm that is characterized by vigorous convection (level 6 precipitation and radar echo tops > 45 kft). Winds are blowing from the west, creating a downwind anvil with echo top heights ranging between 30-35 kft to the east of the thunderstorm core. The WINDY CWAP clearly identifies the anvil boundary that the deviating pilot appears to follow; CWAP_NO_WIND fails to capture the anvil and consequently underestimates the deviation distance from the storm core. It is interesting to note that the commonly used rule of thumb for thunderstorm avoidance – 20 nautical miles from the boundary of regions with precipitation intensity of VIP level 3 – is not being applied.

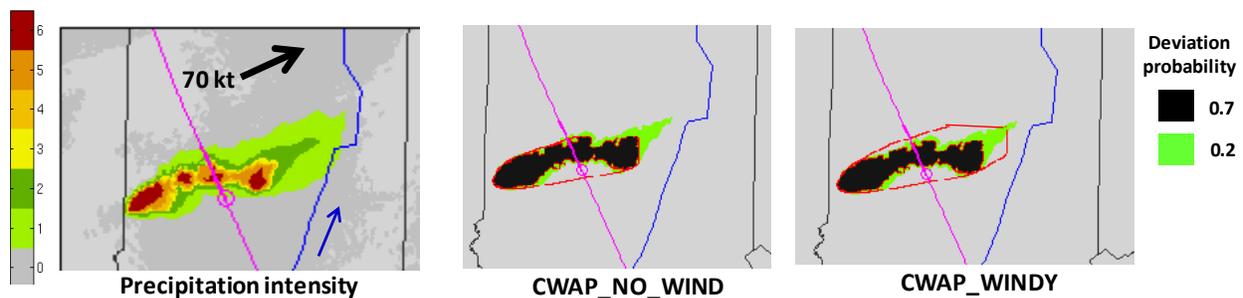


Figure 6. *Precipitation intensity, CWAP_NO_WIND, CWAP_WINDY avoidance polygons, with planned (magenta) and actual (blue) flight trajectories overlaid. Figure illustrates pilot avoidance of a downwind thunderstorm anvil.*

Figure 7 shows several small, intense thunderstorm turrets that have been aggregated within the storm boundary identified by the CWAP polygon. The deviating pilot follows the CWAP edge, rather than trying to navigate around each separate thunderstorm individually. In this instance, the winds are light, and the differences between the NO_WIND and WINDY CWAP are negligible. Figure 8 illustrates an example of ‘over-aggregation’, where the CWAP encloses several thunderstorm cores and obscures a passable gap.

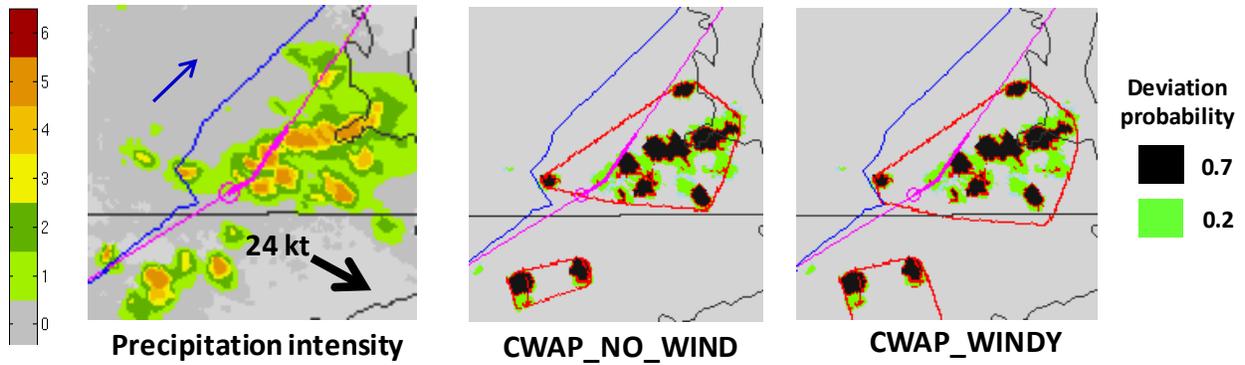


Figure 7. Several small thunderstorm cells

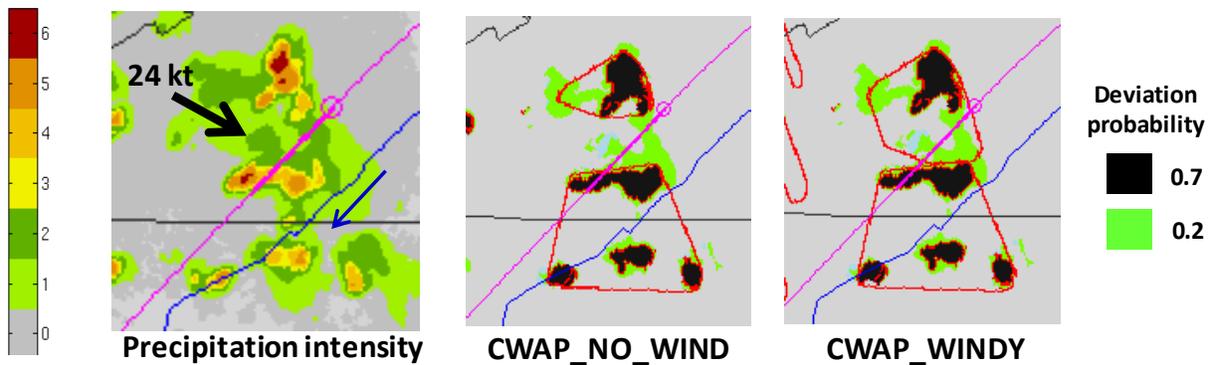


Figure 8. Navigable gap between thunderstorm cells that is obscured by CWAP 'over-aggregation'.

We studied 222 trajectory encounters with CWAP from 19 June and 305 trajectory encounters with CWAP from 14 July 2006. In order to evaluate the quality of CWAP, we classified CWAP_WINDY polygons based on an analysis of result pictures like those shown in figures 6-8, using the following categories: GOOD, CORNER-CUTTING, FLY-THROUGH, and FAR. GOOD means that actual trajectory follows the polygon closely, CORNER-CUTTING means that the actual trajectory 'cuts a small piece' from the polygon, FLY-THROUGH means that the actual trajectory penetrates and crosses the polygon, and FAR means that the actual trajectory is far from the polygon. GOOD and CORNER-CUTTING are considered successful CWAP, FLY-THROUGH and FAR are considered failures. Figure 9 illustrates each classification. Table 1 illustrates the results.

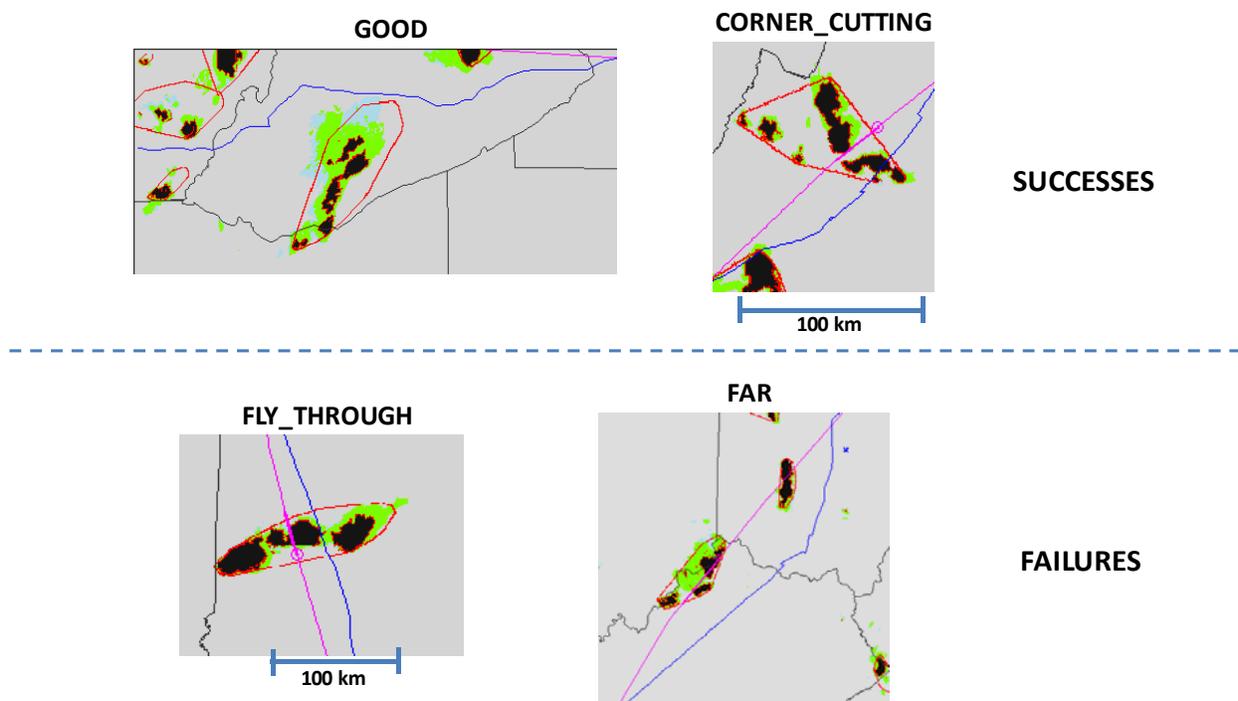


Figure 9. Illustration of CWAP evaluation classifications.

Table 1. Results of CWAP evaluation.

	June 19, 2006	July 14, 2006
GOOD	76 % (177)	51% (157)
CORNER-CUTTING	9% (20)	15% (46)
FLY-THROUGH	9% (20)	31% (94)
FAR	6% (15)	3% (8)

There was a significant difference in CWAP performance between the two case days. Eighty five percent (85%) of CWAP identified on 19 June were successes, while only sixty six percent (66%) of CWAP identified on 14 July were successes. The weather on 19 June was characterized by larger scale, better organized storms and stronger upper level winds, resulting in a less ambiguous delineation between passable and impassable airspace. The weather on 14 July was characterized by smaller scale ‘popcorn’ convection, and CWAP tended to over-aggregate storms and obscure passable gaps between them.

We noticed that FLY-THROUGHS tended to occur with very small or very large polygons. We suggest two possible explanations for the small polygon FLY-THROUGHS. Edge detection and / or the downwind extension may simply over-extend the CWAP for storms that are small enough that the pilot can see the full extent and severity of the storm out the window; in these circumstances, the pilot may choose a relatively small deviation because (s)he is confident that a large deviation is unnecessary. Alternatively, the mismatch between CWAP and observed deviation may be the result of the time lag between the displayed CWAP and flight track. The weather data used in the CWAP calculation is updated once every 5 minutes, enough time for changes to occur in a small thunderstorm that may affect the pilot’s decision.

For large polygons, the probable reasons for FLY-THROUGHS are different. Here, a pilot must choose between the cost of a lengthy reroute along the polygon and the likelihood of an acceptable ride through the weather encounter during the FLY-THROUGH. In these instances, the flying strategy appeared to depend on the mutual orientation of the planned trajectory and the avoidance polygon. If the longer side of the polygon was roughly parallel to planned trajectory, the pilot was more willing to fly along the polygon boundary. If the planned trajectory crossed the minor axis of the polygon, the pilot was more likely to fly through. The pilot estimation of the

acceptability of the ride may be related to the integral of WAF field or a similar metric that takes into account both the severity of the weather encountered and the length of the encounter. Low cost trajectories (those with relatively small deviations) that traverse avoidance polygons may provide acceptable alternatives to high cost trajectories that follow the boundaries of large avoidance polygons. The development of models for the ‘encounter acceptability function’ is a key area of future research.

IV. Conclusions

Figures 6-9 illustrate the complexity of modeling pilot decision making based on remotely sensed data and the inference of pilot intent based on observed flight trajectories. The decision making environment of the cockpit in the vicinity of thunderstorms is very fluid, and the pilot’s perception of the risk of a particular trajectory through or around rapidly developing weather may change quickly¹². In these circumstances, prediction errors are inevitable.

However, if the CWAP are considered in the context of a concept of operations that includes sharing of CWAP between air traffic control on the ground and the pilot, the number and impact of prediction errors on operations might be reduced. Figure 10 illustrates robust, automated weather avoiding trajectories that could be calculated using CWAP. If these examples were presented to the pilot several minutes before a predicted weather encounter, the pilot could choose simply to follow the ‘safe’ suggestion and accept the automated route (solid purple trajectories in figure 10). The result would be a more predictable pilot response, reduced workload for both the pilot and air traffic controller, and improved trajectories for use in time-based metering applications. If the pilot still wishes to choose a different route based on his assessment of the situation from the cockpit the route generator could present alternatives to the default route (dotted purple trajectories in figure 10), based on a more nuanced analysis of the weather enclosed inside the CWAP, and an alternative formulation of the pilot cost function. In such a system, CWAP need not provide the single, correct avoidance trajectory; it must only provide a small set of feasible trajectories, of which one is acceptable. The result would be a quickly and accurately identified avoidance trajectory that could improve the prediction of flight trajectories through convective weather, and support more effective use of time-based metering during convective weather.

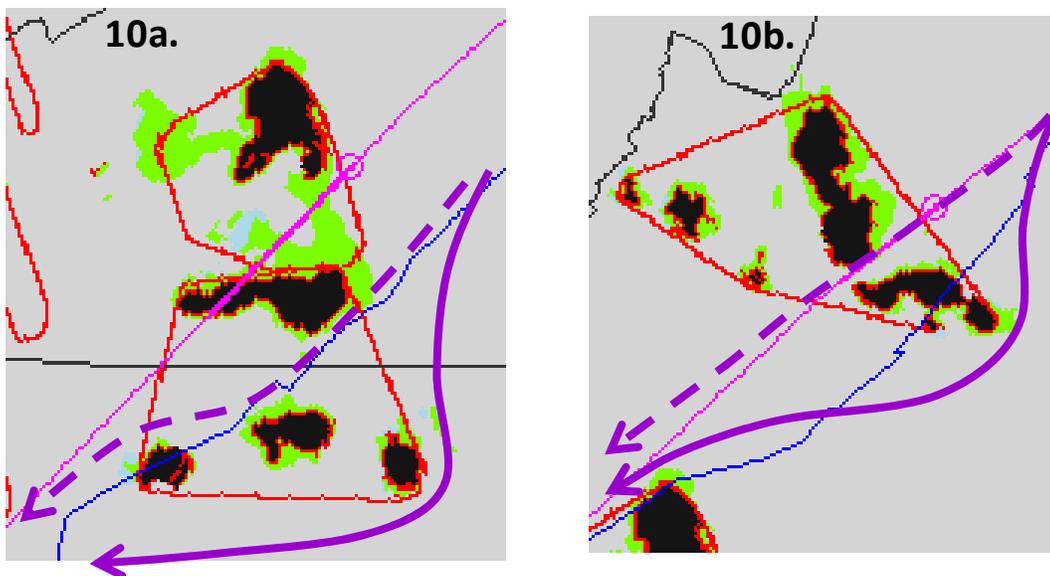


Figure 10. Illustration of a concept of operations for the use of automatically generated weather avoidance polygon options. Solid purple trajectories suggest the lowest risk options with the highest likelihood of pilot acceptance. Dotted trajectories show potentially flyable options that are more likely to encounter weather that a significant percentage of pilots are likely to avoid.

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