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Air Traffic Decision Analysis During Convective Weather Events in Arrival Airspace

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Decision making during convective weather events in the terminal area is shared among pilots and air traffic management, where uninformed decisions can result in wide-spread cascading delays with high-level impacts. Future traffic management systems capable of predicting terminal impacts will mitigate these unnecessary delays; however in order to realize this vision, it is important to understand the decision mechanisms behind convective weather avoidance. This paper utilizes an arrival adaptation of the Convective Weather Avoidance Model (CWAM) to investigate the catalysts for arrival traffic management decision making. The analysis is broken down by category of terminal airspace structure in addition to the type of decision. The results show that pilot behavior in convective weather is heavily dependent on the terminal airspace structure. In addition, pilot and air traffic management decisions in convective weather can be discriminated with large-scale weather features.

I. Introduction

THE National Airspace System (NAS) is a large interconnected system designed to safely and efficiently manage air traffic over the United States. The NAS is composed of many different levels of control that are intended to divide the responsibility of system operations over many different decision makers. The various stakeholders work together to determine the best use of resources in the NAS given estimates of system demand and capacity. Disturbances such as weather significantly impact normal operations, where 70% of all delays in the NAS are caused by weather, and of those delays, 60% are specifically accounted for by convective weather [1]. Convective weather disturbs the system by effectively reducing the amount of available airspace, which is a result of pilots avoiding thunderstorms above a given severity. Additionally, pilot avoidance of convective weather increases air traffic controller workload through an increase in radio communications and a loss of flow structure. To mitigate the increased workload caused by convective weather impacts, air traffic managers issue traffic management initiatives (TMIs) to limit the number of flights that encounter convection. Strategic TMIs such as ground delay programs (GDPs) and pre-departure reroutes are issued to flights before departure to limit flights through a given section of airspace during a specific period of time. Tactical TMIs such as in-flight holding, slowdown, and reroutes are typically made dynamically in response to observed pilot deviation.

In terminal areas, the NAS route structure is generally convergent into and divergent out of major metroplex airports. Arriving flights follow transition routes from en route airspace to terminal airspace to join Standard Terminal Arrival Routes (STARs), which essentially funnel arrival traffic through the highly dense terminal area. Arrival airspace is distinct from departure airspace, where departing traffic follows Departure Procedures (DPs). Convective weather impacts in the terminal area are generally more severe than en route impacts for a number of reasons. First, terminal airspace is characterized by a high density of air traffic and limited open airspace into which pilots could deviate. As a result, significant pilot deviation in the terminal area is followed by a decision to either reroute flights away from the weather or to assign in-flight holding until the storm passes. Complicating the situation, tactical reroutes of arrivals often cross departure flows, necessitating the closure of departure routes for arrival traffic. In severe cases, the closure of departure routes and the corresponding ground holding can lead to surface gridlock at the affected airport.

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This paper investigates the inherent decision mechanisms of pilots and air traffic managers during convective weather events in the terminal area. The analysis is based on traffic observations over six convective weather days, and weather avoidance decisions are scored using the arrival Convective Weather Avoidance Model (CWAM). One objective of this paper is to explore the specific catalysts for air traffic decision making in terminal areas with disparate airspace structures. Additionally, it is important to understand differences in decision making between the decision makers in the system. To this end, arrival CWAM is employed to generate a scored decision database to compare and contrast the decision making behavior of pilots and air traffic managers. The results of this paper are necessary to gain accurate insight into the causes and motivation of terminal area decision making to support the development of decision support tools for arrival operations.

II. Background

The effect of convective weather on operations in the NAS is fairly well characterized for en route operations by the Convective Weather Avoidance Model (CWAM), which is a probabilistic model of pilot deviation based on precipitation intensity and the difference between flight altitude and storm height [2]. In the terminal area, convective weather impacts are modeled on a variety of factors including pilot avoidance [3, 4], arrival fix-based ground delay programs [5], and terminal airspace capacity [6]. Recently, CWAM has been adapted to arrival and departure operations [7-9]. A unique feature of the arrival adaptation of CWAM is that it models multiple types of decisions made by both air traffic management and pilots. This provides a foundation to explore differences in the mechanisms for each decision type and decision maker in arrival flow management.

Arrival CWAM is based on the observation of over 23,000 flights and 4,200 terminal weather encounters for aircraft inbound to a variety of major metroplex airports (ORD, DFW, CLT, DEN, BOS, JFK, LGA, EWR, DCA, IAD) [10]. The output of arrival CWAM is a two-dimensional Weather Avoidance Field (WAF), which provides the probability of convective weather impact given a set of spatially filtered weather features along a flight's planned route. The dominant decision types in the model are reroutes and deviations, which are decisions typically made by air traffic management (ATM) and pilots, respectively. Figure 1 is a representation of a pilot deviation, where the magenta line shows the flight plan, the solid blue line is the flown trajectory, and the dotted blue line is the future trajectory.

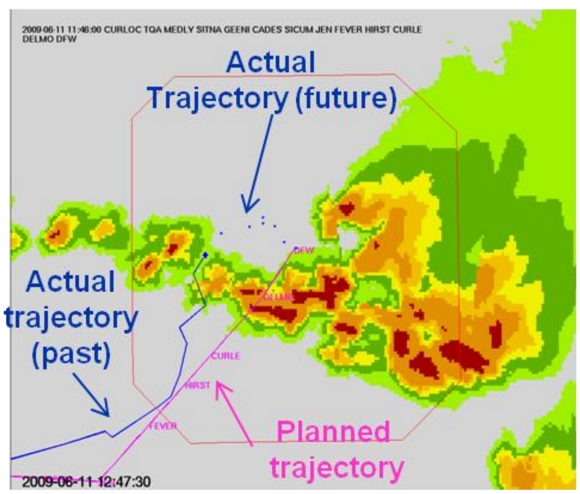

Figure 1. Example of a pilot deviation around weather. The magenta line shows the flight plan, the solid blue line is the flown trajectory, and the dotted blue line is the future trajectory.

Figure 2 shows a reroute decision, where the illustration on the left illustrates the time step before the decision and the illustration on the right shows the time step after the decision. The magenta line represents the flight plan, the solid blue line is the flown trajectory, and the dotted blue line is the future trajectory.

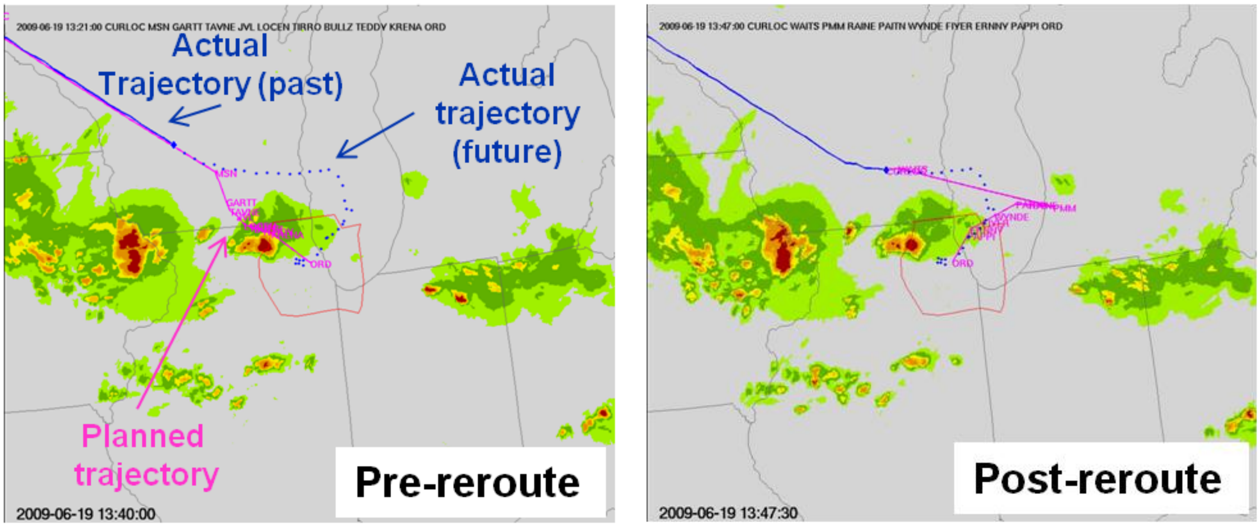

Figure 2. Example of a reroute around weather. The magenta line shows the flight plan, the solid blue line is the flown trajectory, and the dotted blue line is the future trajectory.

III. Results

This analysis employs arrival CWAM to generate decision statistics for reroute and deviation decision types in a variety of terminal areas. The results are based on a database of approximately 12,000 flights over six convective weather days in seven major metroplex areas (ORD, DFW, CLT, DEN, BOS, JFK/LGA/EWR, DCA/IAD). The database includes 534 terminal reroute decisions and 352 deviation decisions.

A. Decision Making in Different Terminal Airspaces

In most cases, the geometry of terminal airspace in different geographic regions is structured based on local airspace constraints such as the proximity of major airports and the nominal flow patterns. For example, the New York Terminal Radar Control (TRACON) area contains arrival and departure routes for five major airports and is bordered by an ocean. The resulting complicated terminal airspace is structured to interweave arrival/departure routes that are predominately on the western side of the airspace. This terminal airspace is contrasted with the Chicago TRACON, which is a simpler airspace structure with one dominant major airport and no major geographic constraints.

For this paper, terminal airspace structure is simplified by defining two terminal airspace categories: the corner post TRACON and the complex TRACON. A corner post TRACON is characterized by symmetric arrival fixes and relatively large margins of safety between arrival and departure flows. Examples of corner post TRACONS include ORD, DEN, DFW, CLT, and BOS. Complex TRACONs are characterized by unsymmetrical arrivals and higher density air traffic, typical of the New York and Washington DC areas. This airspace typically contains multiple high-volume airports and little margin between arrival and departure flows. Figure 3 presents an example of typical clear-weather arrival flows into a corner post TRACON and complex TRACON, specifically Chicago (C90) and New York (N90) in this example.

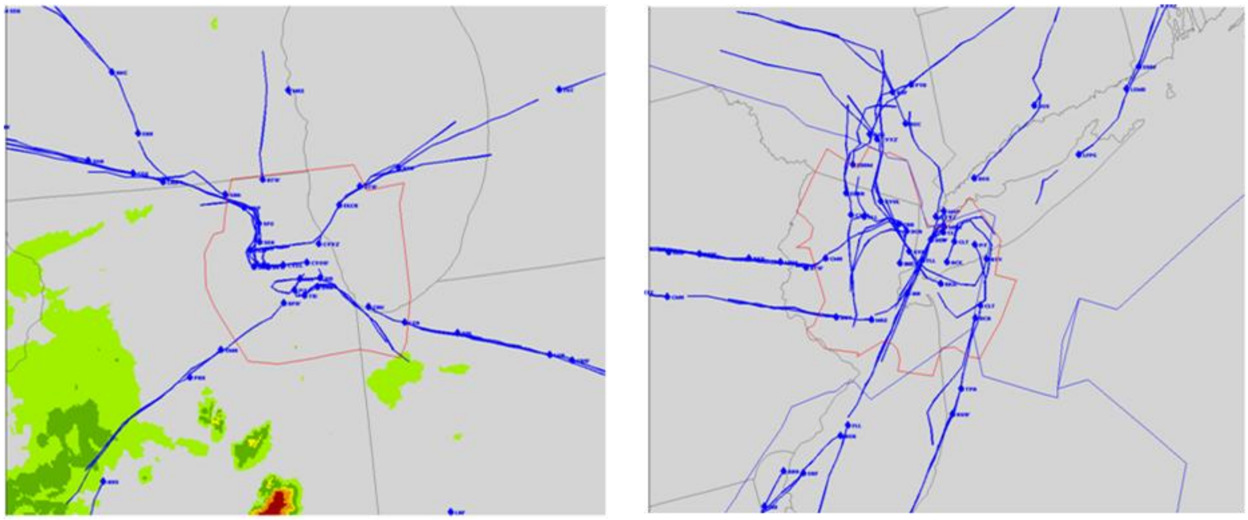

Figure 3. Typical arrival flows in a corner post type TRACON (Chicago, left) and complex TRACON (New York, right).

Weather avoidance decisions are scored using WAFs generated by arrival CWAM. Each weather decision in the database is mapped to a binary decision using a WAF decision threshold ($WAF_{threshold}$). First, the trajectories in the database are assigned WAF values for each time step k in the observed trajectory ($WAF_{actual}[k]$) as well as the corresponding maximum WAF value in the flight plan ($WAF_{plan}[k]$). Each avoidance decision at time step k_D is scored based on the difference between $WAF_{threshold}$ and $WAF_{plan}[k_D]$. If $WAF_{threshold} \leq WAF_{plan}[k_D]$ the decision is labeled a correct avoidance prediction (CAP) and if $WAF_{threshold} > WAF_{plan}[k_D]$ the decision is labeled a false penetration prediction (FPP). Trajectories that do not make an avoidance decision and are characterized by $WAF_{threshold} \leq WAF_{actual}[k]$ for any k, are labeled a false avoidance prediction (FAP). Likewise, if $WAF_{threshold} > WAF_{actual}[k]$ for all k the trajectory is labeled a correct penetration prediction (CPP).

This analysis focuses on pilot deviation decisions, where the quality of the decisions are described from the perspective of the decision maker, and Eqs. 1 and 2 are used to evaluate the decisions.

$$\text{Probability of Correct Avoidance Prediction} = \frac{CAP}{CAP + FAP} \tag{1}$$

$$\text{Probability of Correct Penetration Prediction} = \frac{\text{CPP}}{\text{CPP} + \text{FPP}} \tag{2}$$

CAP is a correct avoidance prediction, *FAP* is a false avoidance prediction of avoidance, *CPP* is a correct penetration prediction, and *FPP* is a false penetration prediction. In practical terms, the probability of correct avoidance prediction (PCAP) is the probability that a deviation prediction is true, given that a deviation is predicted. Essentially, it measures the accuracy of a deviation prediction. The probability of correct penetration prediction (PCPP) is the probability that a penetration prediction is true, given that a penetration is predicted. Figure 4 presents curves comparing the PCAP and PCPP generated by varying the WAF threshold for deviation in the model. The ideal predictor corresponds to a curve that has a point on the top-right corner, where the PCAP = PCPP = 1. The black curve shows the results using the complete dataset, the blue curve using the corner post TRACON partition of the dataset, and the red curve using the complex TRACON partition of the dataset. In general, the model is better at predicting *penetrations* in a complex TRACON, whereas it is better at predicting *deviations* in a corner post TRACON. The presumed explanation of these differences is that pilots have more freedom to deviate in a corner post TRACON because of the lower density airspace. Therefore, operations in corner post TRACONs experience more frequent deviation around seemingly benign weather, resulting in a lower probability of correct penetration prediction. On the other hand, fewer flights in a corner post TRACON penetrate seemingly severe weather, leading to a higher probability of correct avoidance prediction. For a fixed WAF threshold of 70, the model correctly predicts avoidance with 72% and 67% percent accuracy in the corner post and complex TRACONs, respectively.

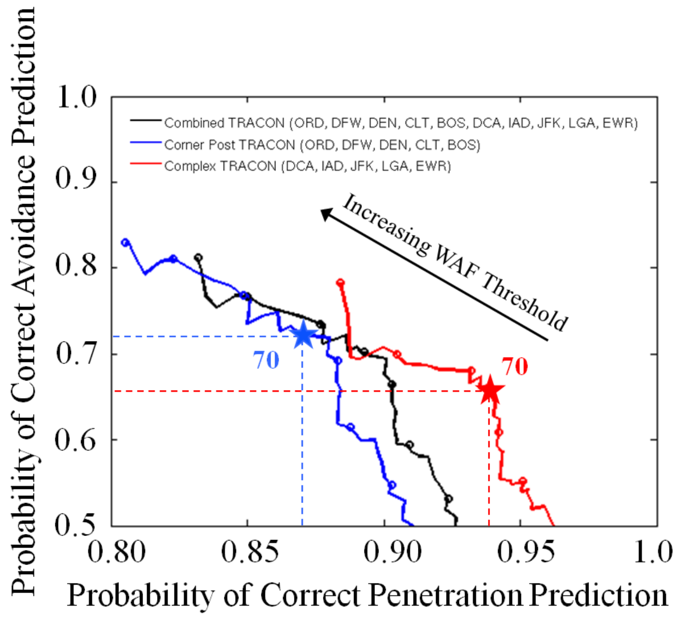

Figure 4. Arrival CWAM performance using difference partitions of the testing dataset. The inset figure shows a zoomed-in view of the top-right corner, where the stars indicate the location of the 70 WAF thresholds.

Weather penetrations are correctly predicted with 87% and 94% accuracy in the corner post and complex TRACONs, respectively. This behavior is also captured by departure CWAM, where pilots have displayed a greater willingness to penetrate severe weather in New York compared to Chicago [8]. Figure 5 shows a representative sample of traffic in the New York (complex TRACON) and Chicago (corner post TRACON).

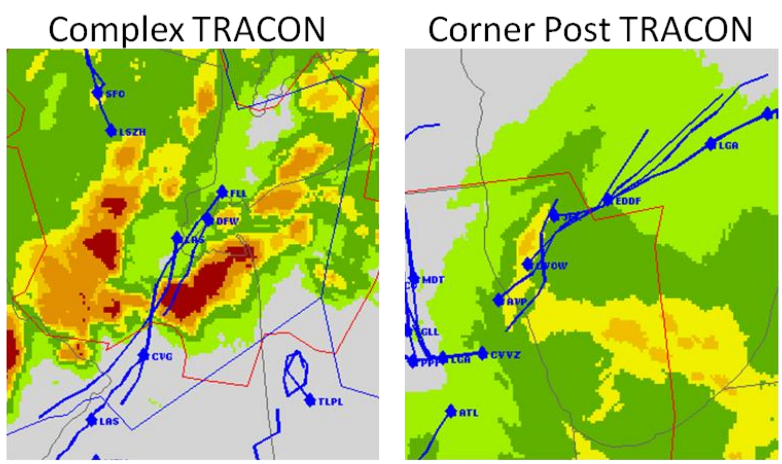

Figure 5. Examples of representative traffic in complex and corner post TRACONs. The traffic in the complex TRACON penetrated severe weather, whereas the traffic in the corner post TRACON deviates around moderate weather.

It is apparent from Fig. 5 that traffic is penetrating heavy weather on arrival to New York, whereas traffic is deviating around much weaker weather on arrival to Chicago.

B. Comparison of Deviation and Reroute Decisions

Air traffic decision making during convective weather events in the terminal area is distributed among pilots, air traffic controllers, and air traffic managers. In general, the decision makers do not make decisions independently – they work together to find the safest and most efficient paths for flights to avoid weather and reach their destination. However, in many cases the decision makers have different objectives occurring at different time scales (a pilot is typically concerned with the tactical maneuvering of his/her own aircraft, whereas an air traffic manager has to balance overall system efficiency by forecasting demand and capacity). The purpose of this section is to analyze differences in the decision making between pilots and air traffic managers to investigate the triggers for deviation and reroute decisions and address potential opportunities for improvement in air traffic management.

The analysis will concentrate on identifying the type of weather conditions that initiate deviation and reroute decisions, and then investigate mismatches in the decision making process. The objective of the analysis is to find mismatched decision triggers that potentially highlight the natural transition between tactical and strategic decision making, as well as identify situations where air traffic management is either over- or under-conservative in issuing traffic management initiatives.

Consider the set of decisions $D = \{d,r,n\}$, where d is a deviation decision, r is a reroute decision, and n is a decision to penetrate weather. Each decision in D corresponds to a set of spatially filtered weather features that occur along the flight plan. These weather features correspond to WAF values that are binned in increments of 10 from 0 to 100. Differences in decision making are inferred from differences in the likelihood that a specific decision is made given the binned WAF value that is encountered. The probability that a deviation decision is made given the maximum WAF value along the flight plan is given by Eq. 3

$$P(D = d \mid x_1 \leq WAF \leq x_2) = \frac{N_d}{N_d + N_n} \tag{3}$$

where N_d is the number of deviation decisions and N_n is the number of weather penetration decisions in the WAF bin defined by the edges x_1 and x_2. For the case of a reroute decision, a key assumption is made regarding the event that a reroute decision is *not* made and the flight encounters weather: the set of non-reroute decisions includes both weather penetration decisions and deviation decisions. The reasoning behind this assumption is that if the goal of a reroute is to avoid pilot deviation, then any flight that encounters and/or deviates around weather is the result of a decision to not reroute. The probability that a reroute decision is made given the maximum WAF value along the flight plan is given by Eq. 4

$$P(D = r \mid x_1 \leq WAF \leq x_2) = \frac{N_r}{N_r + N_d + N_n} \tag{4}$$

where N_r is the number of reroute decisions, N_d is the number of deviation decisions, and N_n is the number of weather penetration decisions in the WAF bin defined by the edges x_1 and x_2. Figure 6 illustrates the probabilities of deviation and reroute decisions given WAF values binned from 0 to 100 in increments of 10, where the error bars show the 95% confidence interval (2 standard deviations). Note that this analysis is based on actual, not forecasted, weather.

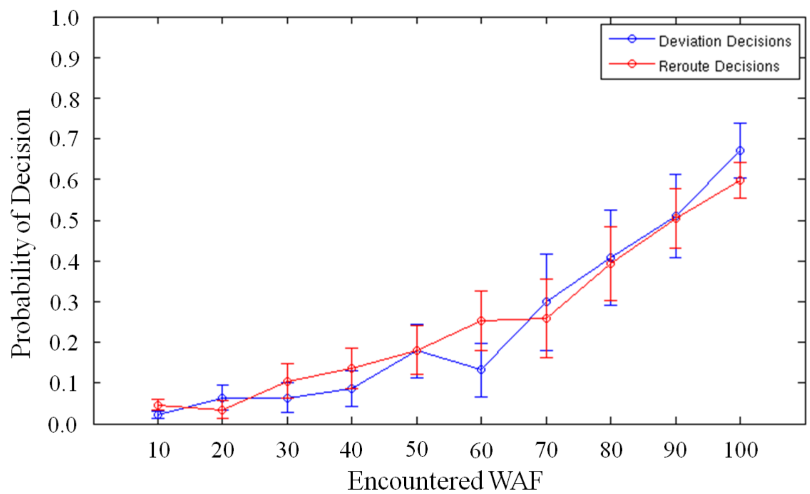

Figure 6. Probability of deviation and reroute decisions given a specific weather encounter.

In general, the probability of decision for both decision types shows a similar trend with the predicted WAF values along the flight plan. As expected, low WAF values correspond to low probabilities of weather avoidance decisions and the probability of both decision types increases with the WAF. Differences in the curves between decision types imply that one decision type is more likely to occur when a given WAF value is encountered. This is important to understand because differences in decision likelihood can potentially illustrate over- or under-conservative air traffic management decision making. For example, in Fig. 6 the likelihood that a reroute decision is made in the presence of WAF values between 30 and 40 is higher than the likelihood of a deviation decision. This potentially implies that some reroute decisions are being made in response to seemingly innocuous weather (compared to observed pilot behavior in similar conditions), resulting in an inefficient use of arrival airspace. Observation of ETMS data corroborates this hypothesis, where reroute programs frequently remain active even after the weather impact has passed. Figure 7 presents an example of a scenario where an arrival fix is underutilized. In this example, the SW arrival fix of Chicago is unused while it is clear of severe weather (approximated by the yellow contours on the image). Arrival and departure traffic are represented by red and blue lines, respectively.

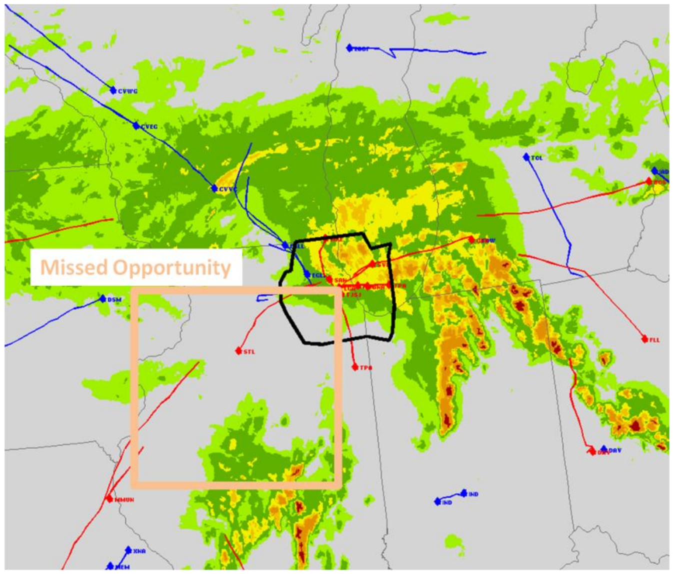

Figure 7. Example of unused arrival fix for Chicago. Arrival traffic is shown in blue and departure traffic is in red. Traffic is rerouted around the SW arrival fix while it is clear of severe weather.

An additional factor to consider when comparing the likelihood of deviation and reroute decisions is the scale of the weather in the terminal area. For this example, the scale of the weather is represented by the percent area coverage of the 70% WAF contour in a 32 x 32 kilometer kernel. Figure 8 shows the likelihoods of deviation and reroute decisions given the area coverage of the weather along the flight plan.

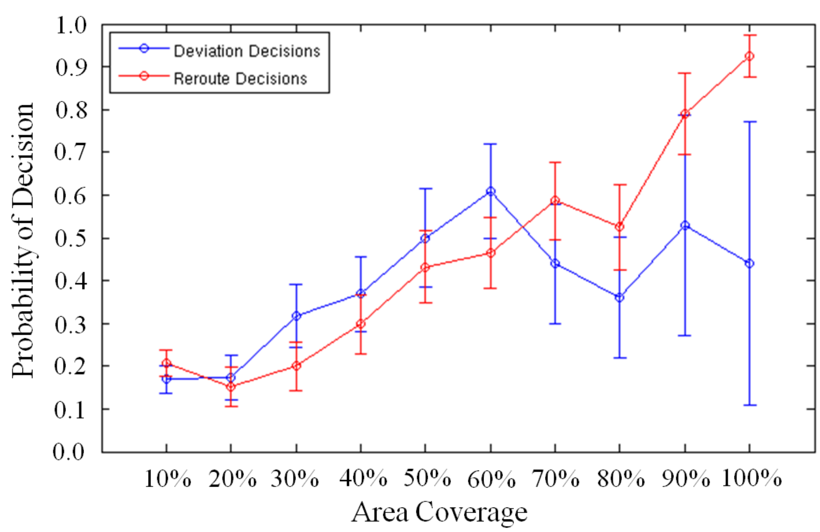

Figure 8. Probability of deviation and reroute decisions given the area coverage of the weather.

It is apparent from the figure that deviations are more likely when the area coverage is small and reroutes are more likely when the area coverage is large. Intuitively this makes sense because the potential impact of a deviation is what drives the decision to implement a reroute. Smaller areas of weather correspond to smaller deviations, leading to little impact, and in turn, no need to reroute. On the other hand, large areas of weather result in large deviations which have a significant system impact. This can be seen in the figure where the likelihood of deviation decisions plateaus or drops between 50% and 100% coverage, whereas the likelihood of reroute decisions increases consistently to 100% coverage. Essentially, at lower coverages, ATC is running tactically – they are letting pilots decide weather avoidance. At higher coverages, ATC is running strategically by rerouting flights in advance of the weather. Figure 9 shows representative terminal air traffic in the presence of convective weather with sparse and dense area coverage.

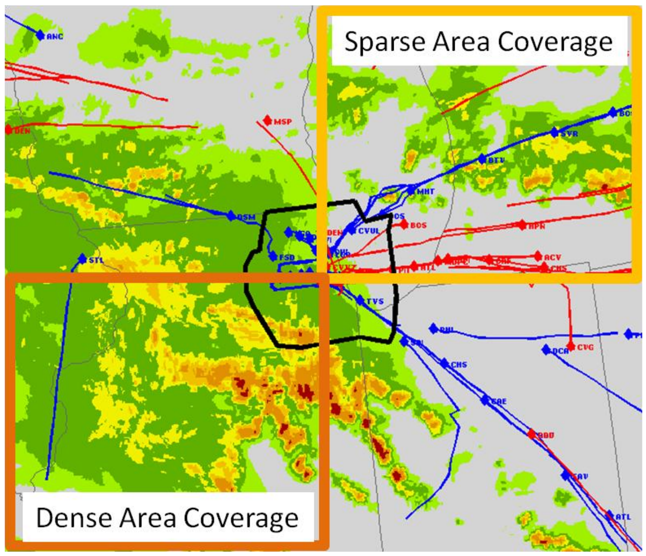

Figure 9. Example of representative air traffic in the presence of convective weather with sparse and dense area coverage in the terminal area. Notice aircraft continue flying through sparse area, whereas aircraft are rerouted around the dense weather area.

Arrival traffic is shown in blue and departure traffic is in red. In the figure, the north-east (NE) arrival airspace is covered by small and isolated storms and the south-west (SW) arrival airspace is affected by a large-scale system. The NE arrival flow is open, with convective weather avoidance handled tactically through pilot deviation. The SW arrival flow is closed, with inbound flight rerouted to neighboring arrival flows. This analysis is significant because, in essence, the crossover point of the curves represents a metric to describe the point at which tactical operations saturate controller workload. It is also worth noting that the large error bars on the deviation curve at high area coverage are a result of few deviation encounters. This is a result of consistently rerouting flights around weather with high area coverage, leading to few data points.

IV. Conclusions and Future Work

This paper presents an analysis of air traffic decision making for arrival operations durning convective weather events. Terminal airspace is categorized as either a corner post TRACON or complex TRACON, where the primary difference between these areas is that the complex TRACON is characterized by a higher density and more complex structure of arrival and departure traffic flows. A significant finding is that flights penetrate stronger weather in complex TRACONs than in corner post TRACONs. The likely cause of this behavior is fewer avoidance options in complex TRACONs. Additionally, differences between reroute and deviation decision making are investigated through an analysis of the likelihood that a specific decision is made given the weather encountered on the flight plan. A comparison between the likelihood of a reroute and the likelihood of a deviation reveals potential "missed opportunities" in air traffic management, where for a given weather feature, the probability of a reroute is greater than the probability of deviation. The effect of weather scale on decision making is a good discriminator between deviation and reroute decisions. For the example in this report, weather scale is abstracted by the area coverage (%) of 70 WAF contours in a 32 x 32 km kernel. It is apparent from this analysis that small weather coverage (< 60%) typically corresponds to pilot deviation, whereas area coverage greater than 60% results in reroute decisions. This potentially describes a metric to differentiate tactical and strategic decision making. Future work should concentrate on the investigation of additional WAF filtering techniques to further refine ATM decision prediction accuracy. Moreover, a similar analysis should be conducted using forecasted weather to explore the relationship between forecast and decision predication accuracy. An accurate ATM decision forecast will enable a significant increase in ATM decision support capability.

References

[1]Clifford, S.F., et al., "Weather Forecasting Accuracy for FAA Traffic Flow Management", The National Academies Press, Washington DC, 2003, pp. 2.
[2]DeLaura, R., Robinson, M., Pawlak, M. L., Evans, J. E., "Modeling Convective Weather Avoidance in Enroute Airspace," 13th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), New Orleans, LA, Amer. Meteor. Soc., 2008.
[3]Rhoda, D. and Pawlak, M., "An Assessment of Thunderstorm Penetrations and Deviation by Commercial Aircraft in the Terminal Area," Project Report NASA/A-2, June 1999, MIT Lincoln Laboratory.
[4]DeLaura, R., Robinson, M, Todd, R. F., MacKenzie, K., "Evaluation of Weather Impact Models in Departure Management Decision Support: Operational Performance of the Route Availability Planning Tool (RAPT) Prototype," 13th Conference on Aviation, Range, and Aerospace Meteorology (ARAM), New Orleans, LA, Amer. Meteor. Soc., 2008.
[5]Hoffman, B., Krozel, J., and Jakobavits, R., "Potential Benefits of Fix-Based Ground Delay Programs to Address Weather Constraints," AIAA Guidance, Navigation, and Control Conf., Providence, RI, Aug., 2004.
[6]Michalek, D., and Balakrishnan, H., "Building a Stochastic Terminal Airspace Capacity Forecast for Convective Weather Forecasts," Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, Phoenix, AZ, Amer. Meteor. Soc., 2009.
[7]Matthews, M. and DeLaura, R., "Modeling Convective Weather Avoidance of Arrivals in the Terminal Airspace," Second Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, Seattle, WA, Amer. Meteor. Soc., 2011.
[8]Rubnich, M., and DeLaura, R., "Initial Validation of a Convective Weather Avoidance Model (CWAM) in Departure Airspace," 30th Digital Avionics Systems Conference (DASC), Seattle, WA, Oct. 16-20, 2011.
[9]Matthews, M., Campbell, S., and DeLaura, R., "Evaluation of Convective Weather Avoidnace Models for the Terminal Area," Third Aviation, Range and Aerospace Meteorology Special Symposium on Weather-Air Traffic Management Integration, New Orleans, LA, 2012.
[10]Campbell, S., Matthews, M., and DeLaura, R., "Evaluation of the Convective Weather Avoidance Model for Arrival Traffic," AIAA Aviation, Technology, Integration, and Operations (ATIO) Conference, Indianapolis, IN, 2012.