ANALYSIS OF PROBABILISTIC WEATHER FORECASTS FOR USE IN AIR TRAFFIC MANAGEMENT

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1. INTRODUCTION

Convective weather is mainly responsible for large delays in the National Airspace System (NAS). Currently, deterministic convective weather products do not provide accurate forecasts in the two to six hour time frame, which creates inefficiencies in the decision-making process for that time period (Nilim, 2004). Air traffic managers and flight dispatchers believe that probabilistic weather forecasts can provide information, which can be used for alternate route flight planning decisions. The National Convective Weather Forecast (NCWF-6) Product (Wolfson, et al. 2004) creates probabilities of forecasted weather (precipitation) intensities for up to 6-hours (Megenhardt, et al. 2004 and Pinto, et al. 2008) including storm heights. To utilize these data for flight routing decisions, additional understanding for use of these products with probabilistic forecasts in the tactical (1-2 hours) and strategic (2-6 hours) is desired. Significant research and development is necessary for integration of these data in air traffic management, not only for assessing aircraft behavior around forecasted convective systems but also for flight routing and planning decisions in the short and long term.

In earlier research (Sheth, et al. 2007), probabilistic convective weather forecasts from the NCWF-6 were studied for applications of flight routing decisions in air traffic management. This previous work considered the entire continental United States, which was beneficial for understanding the aggregate behavior of aircraft around forecasted precipitation over a large area. The objective of that study was to derive the threshold of probability that could be used by decision makers for circumventing convective weather areas. By synchronizing air traffic data and probabilistic convective weather forecasts it was observed that aircraft largely avoid specific predicted probability value. This value was referred to as the Probability Cut-off Parameter (PCP). Using the PCP, a decision-maker could assess the probability that aircraft are willing to traverse, and in turn, the risk associated with traveling in the vicinity of forecasted convective weather intensity contours. That analysis showed that for a one-hour forecast, the 80th percentile value (PCP) for all aircraft flying through the probability field across the continental US was around 35% using four months of flight and weather data. The same probability limit value for a two-hour forecast was around 25%. The values for three and four-hour data were around 18 to 20%, while the five and six-hour data fell below 10%. Using the Corridor Integrated Weather System (CIWS) (Evans, et al. 2006), Delaura, et al. (2008) presented the Convective Weather Avoidance Model (CWAM) where probability of pilots deviating around bad weather are evaluated and verified through flight tests (DeLaura, et al. 2008). Current research and operational strategies tend to solve the rerouting problem at an aircraft level or at the national level, but not at an Air Route Traffic Control Center (ARTCC) level. It is desired to study the center-level strategies as it reduces the additional burden on centers along the path and potentially larger deviations for aircraft. Although the previous study by Sheth, et al. looked at the PCP value for the entire NAS, it is necessary to evaluate this parameter at the ARTCC or center level. The desire to analyze center-level data is additionally due to a previous study by Sridhar, et al. 2007, which indicated that a small number of centers experience a majority of weather impact in the NAS.

In current research, the probabilistic weather data are similarly analyzed with a more focused local spatial scope maintaining the temporal resolution of twenty-four hours. Results for this analysis are presented for all the twenty

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centers in the Continental US (ConUS) and additional details are provided for the Fort Worth (ZFW) Center to study the behavior of air traffic around weather in a localized region. Characterization of the behavior during various times of day, different altitudes, airlines and aircraft types are presented at a sector-level for a four-month period using one- and two-hour forecasts. Once these data were available, based on a specific scenario of arrival fix closures for the Dallas/Ft. Worth International (DFW) airport, alternate route strategies were identified and analyzed for air traffic impact. The Air Traffic Control System Command Center (ATCSCC) uses the Playbook routes for large convective weather situations around the country, where flights across the west and east coast are often simultaneously affected. In this research the idea of localized center-based reroutes is proposed for inclusion within the scheme of Playbook routes, called Center Routes. The results present a what-if analysis capability for the DFW weather scenario implemented in an air traffic management (ATM) simulation system for aiding ATM decisions.

The background for this research and its relevance to the current and future ATM environment is presented in the next section. The synchronization of probabilistic convective weather forecasts and air traffic data for the PCP analysis is described; along with a brief review of the Probability Cut-off Parameter evaluation in section 3. The next section presents the results of PCP computation for the 20 centers in the ConUS, along with the values in ZFW and seven high-altitude sectors of interest therein. Once these parameters are available, the need for using local rerouting is described and conceptual implementation is detailed in section 5. The results for a specific weather scenario in ZFW are also displayed in that section. The paper closes with some conclusions.

2. BACKGROUND

Based on air traffic delay results from the Federal Aviation Administration's (FAA) Operations Network (OPSNET) data, more than 70% of the National Airspace System reportable delays were attributed to convective weather. In the current ATM system, probabilistic weather data are not included for decision-making. The Weather-ATM Integration Working Group of the Joint Planning and Development Office has suggested that probabilistic convective weather forecasts be included in the System-Wide Information Management for the Next Generation of Air Transportation System (NextGen). The NCWF-6 forecast product utilized in this research is slated to be a component of the Consolidated Storm Prediction for Aviation (CoSPA) suite of weather data (Wolfson, et al. 2008), which is being considered as one of the weather products for the NextGen environment (Stobie, et al. 2008).

With probabilistic forecasts in mind, several studies have looked at the air traffic management problem under uncertainty. Steiner, et al. 2008 looked at probabilistic air traffic management decisions by considering ensemble forecasts for developing various evolution scenarios. Ramamoorthy, et al. (2006) considered probabilistic traffic flow management using the FAA provided Collaborative Convective Forecast Product data. Recently, Klein (2008) used the PCP value as the initial condition for analyzing impact of weather on airspace capacity through a method of scanning the airspace for presence of weather. In turn, the reduction of airspace capacity to accommodate demand, often referred to as the weather impact translation, was determined. Song, et al. (2008) discussed three different methods for determining the weather translation using CWAM. Another study by Wanke et al. (2007) presents the incremental, probabilistic decision making for en route traffic management. They present an approach of incrementally and explicitly using the prediction uncertainty for efficient air traffic management decisions through Monte Carlo simulations.

These studies address probabilistic aspects of flow management in the future. There are others who propose local rerouting around weather cells (Grabbe, et al. 2008, Sridhar, et. al, 2002), or larger deviations (Prete, et al. 2004) similar to the FAA's Severe Weather Avoidance Plan (SWAP) or Playbook routes. Based on these studies of decision-making with uncertain information, the need addressed in this research is to understand one probabilistic convective weather forecast product (NCWF-6) for the ATM impact and apply the knowledge for investigation of a center-based weather and rerouting scenario. This is accomplished through detailed analysis of aircraft traversing NCWF-6 forecast probabilities and study of a weather constraint scenario for current operations and future applications insight. This research focuses on how to translate the weather impact on ATM, rather than analyze the accuracy of forecasts.

3. ANALYSIS METHOD

3.1 Traffic/Weather Integration Environment

Air traffic data from the FAA's Enhanced Traffic Management System (ETMS) and probabilistic convective weather forecasts from the National Center for Atmospheric Research's (NCAR) NCWF-6 product were used. The data from May 1 through August 31 of 2007 were analyzed. The Future ATM Concepts Evaluation Tool (FACET), a simulation and modeling system for investigation of air transportation concepts, developed at NASA was utilized for this analysis (see Fig. 1). The integrated information is employed for visualizing the effects of weather in real-time, as well as for planning of flight routes around forecasted weather. The NCWF-6 data

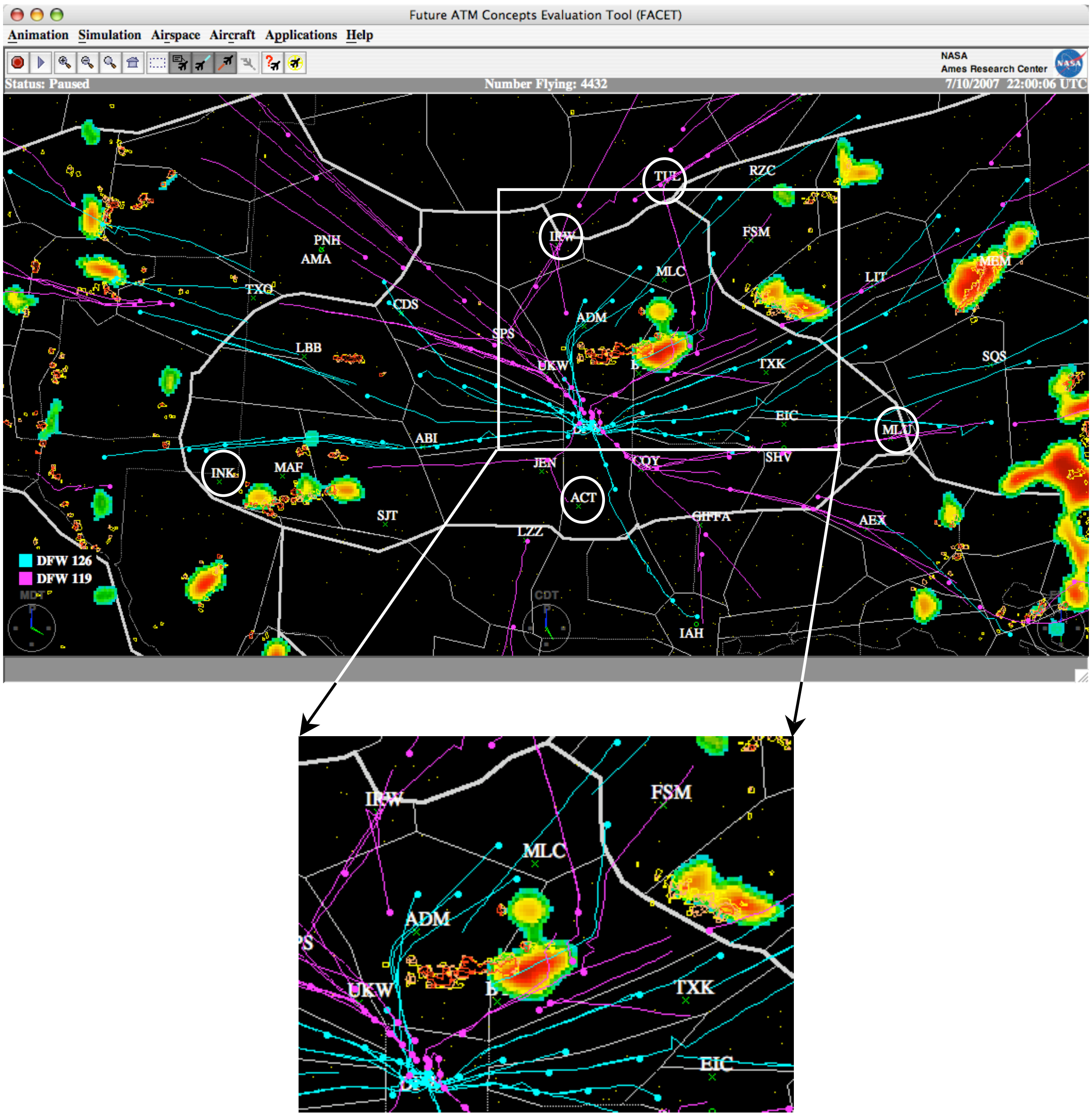


Figure 1. Integrated display of air traffic and convective weather over Ft. Worth Center with inset showing the NCWF-6 probabilistic weather (filled) contours and NEXRAD weather (unfilled) contours. The pink and cyan dots represent arrivals to and departures from DFW with their 20-minute histories as traces.

contain one, two, three, four, five and six hour forecasts with a continuous distribution of Vertically Integrated Liquid (VIL) level 3 or higher convective weather occurrence probabilities. These data are published approximately three times each hour. Figure 1 shows a snapshot of synchronized ETMS and NCWF-6 data displayed in FACET for 22:00 Coordinated Universal Time (UTC) or 5 pm Central Daylight Time (CDT) on July 10, 2007.

The Ft. Worth ARTCC is shown with some of the important fixes in the region (e.g., Tulsa (TUL) and Will Rogers (IRW) in the north, Monroe (MLU) in the east, Waco (ACT) in the south, Wink (INK) in the west, etc.), along with four DFW arrival fixes of Cedar Creek (CQY) (southeast), Glen Rose (JEN) (southwest), Bowie (UKW) (northwest) and Bonham (BYP), hidden under weather, in the northeast. The ZFW center boundary, in the middle, is highlighted in white. The one-hour NCWF-6 forecast data valid at this time are shown as filled polygons. The color map is continuously varying, and the probability of convective weather displayed varies from 25% (cyan) on the periphery to about 100% (dark red) at the center. The National Weather Service provided Next Generation of Radar (NEXRAD) unfilled contours of VIL level 3, 4, 5, and 6 (better seen in the inset) in yellow, orange, red and dark brown, respectively. NEXRAD data shows actual observations. The aircraft arriving at and departing from DFW are shown as pink and cyan dots, respectively, with their twenty-minute track histories. A key observation from this figure is that the track histories indicate that pilots find gaps in the weather to fly through or deviate around weather, as seen just northeast of DFW airport, which is in the center of the figure (and at bottom left of the inset).

3.2 Probability Cut-off Parameter (PCP)

Earlier research by Sheth, et al. (2007) described the process of determining probability value that aircraft tend to avoid. It is briefly repeated below for reference.

To compute the PCP, the air traffic data were ingested into FACET with the NCWF-6 forecast data, valid at the same time. Each aircraft track was checked for its height above the storm top. If the aircraft was below the storm top, and its location was contained within a 10% or higher probability contour, the aircraft was recorded as traversing through the probability field. For each aircraft, for its entire journey, the probability values, if any, were recorded in this manner. The maximum value of probability was then selected from all the probability values thus obtained. This process was conducted for all aircraft at all times for a four-month period. It should be noted that these data were recorded only if the probability forecast was valid at the current time instant and only if at that location a storm top value was available as suggested by Dupree, et al. (2006).

Once the aircraft data were recorded for the four-month period with one-hour and two-hour weather forecasts, the maximum probability traversal values of all aircraft were binned in a histogram ranging from 10% to 100% in 1% increments. The majority of aircraft (80th percentile number) of this histogram was called the Probability Cut-off Parameter (PCP) and was found to be around 35% and 25% for one- and two-hour forecasts. The significance of this PCP is that a large number of aircraft avoid this probability value. This PCP value can be used as the weather probability contour to avoid and for flight routing decisions. It should be noted that NCWF-6 data are forecasted values and pilots and dispatchers are not using them in current operations.

4. PROBABILITY TRAVERSAL ANALYSIS

4.1 Results for 20 Centers

In this study, the PCP value was derived for each of the twenty centers in the ConUS. The purpose of evaluating the PCP value for a center-based scope was to identify if the data demonstrated different behavior from the NAS-based analysis performed earlier.

Figure 2 shows the behavior of aircraft traversal for each of the twenty centers for the one-hour (left) and two-hour (right) forecasts. Each point on a curve represents the number of aircraft going around the corresponding maximum probability contour during the entire four-month data set. These data were recorded for all aircraft flying between 10,000 and 40,000 ft. It is seen from the one-hour plot on left that Atlanta (ZTL), Houston (ZHU), Jacksonville (ZJX), Miami (ZMA) and Ft. Worth (ZFW) Centers (all five neighbors in the southeastern part of the US) show large number of aircraft traversing through higher probability values. It is also seen from Figure 2 left that there appear to be three bands within which the data can be classified. The first one consists of those five southeast centers, ZFW, ZHU, ZTL, ZJX and

ZMA, with larger than 40,000 aircraft crossing the greater than 10% intensity contours, above the upper brown bar. The third consists of less than 10,000 aircraft crossing the greater than 10% intensity contours, below the lower brown bar. These are the 4 western centers, Los Angeles (ZLA), Oakland (ZOA), Seattle (ZSE) and Salt Lake (ZLC), where there's little convective activity. The middle band, between the brown bars, consists of the 11 remaining centers showing between 10,000 and 40,000 aircraft. From Figure 2 right for the two-hour forecasts, similar banded behavior is observed, with the same centers, but the middle band has between 20,000 and 70,000 aircraft. It should also be noted that as the forecast time increases, the probabilities smear and lower in value (due to increased uncertainty), which explains the curves' slide to the left. The Figure 2 (left) is an aggregation of over 600,000 data points, whereas Figure 2 (right) consists of roughly a million data points over the four-month set. As can be seen from the figure, Atlanta (ZTL) center (in solid pink line with square symbols) has about 80,000 probability traversal values in the one-hour data (left) and about 120,000 values in the two-hour (right) case. The computed PCP values for the one-hour forecasts were as follows: the minimum value was 18% (from the lower band centers), the maximum value was 33% (from the upper band centers), the median was 33% and the average was 29% for all centers. For the two-hour forecasts, the values were 13%, 23%, 23% and 20%, respectively.

In order to understand this aircraft traversal trend around probabilities, the number of grid cells with 10% or higher forecast probability values were counted for the entire four-month one- and two-hour NCWF-6 forecast data set. The NCWF-6 has a 2 nmi grid resolution, which implies that over the

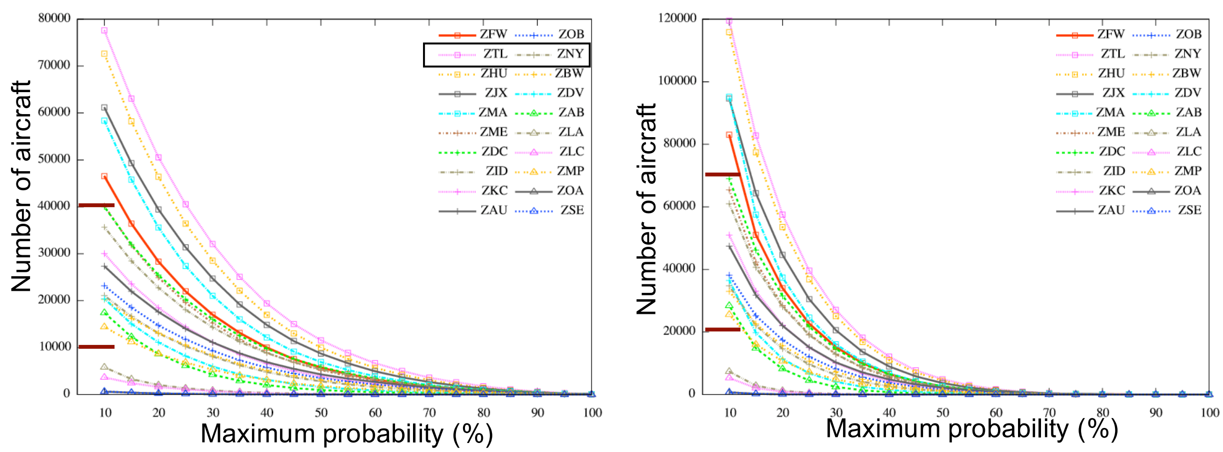


Figure 2. Number of aircraft crossing maximum probability values for the 20 centers in the continental United States for one-hour (left) and two-hour (right) forecasts over the four-month period.

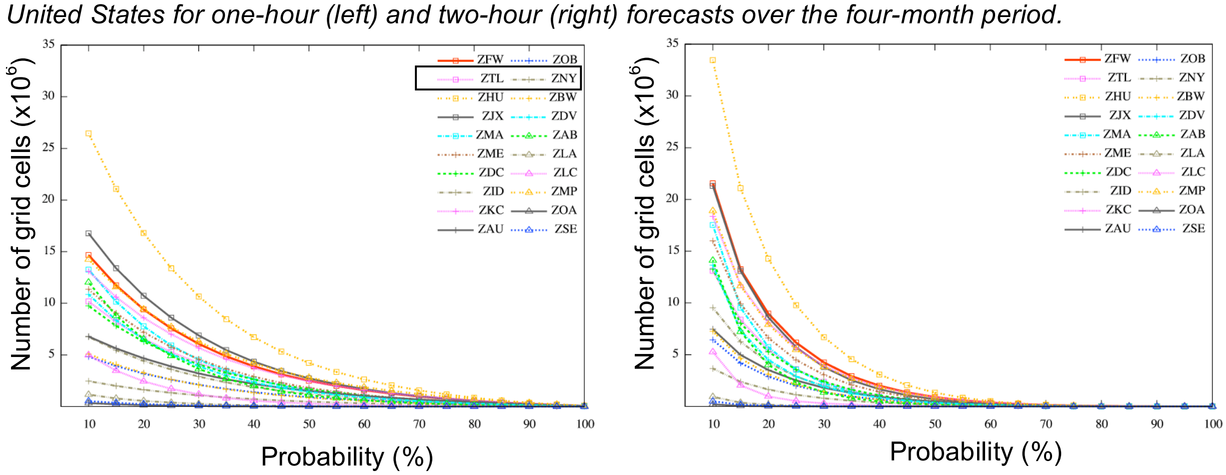


Figure 3. Frequency of convective weather cells the 20 centers in the continental United States for one-hour (left) and two-hour (right) forecasts over the four-month period.

continental United States, there are over 1 million grid cells at each instant of time. Only cells with a probability >10% were used for these statistics. The results for one-hour weather frequency forecasts are presented on the left, and the two-hour results are presented at right in Figure 3. With the exclusion of Atlanta Center and inclusion of Minneapolis Center, each of the five upper band centers has the most number of grid cells. This implies that those five centers experience most convective weather (at least for the data under consideration). It is observed that Atlanta and New York centers (shown with a box in Figs. 2 and 3 left) are exceptions where larger number of aircraft flying with higher probabilities in proportionately lower number of forecasted weather cells. The Figure 3 (left) is an aggregation of over 200 million grid cell values, while Figure 3 (right) consists of close to a billion data points. As can be seen from the figure, Houston (ZHU) center (in dashed yellow line with square symbols) has about 26 million individual grid cell values (>10% probability) in the one-hour data and about 34 million values in the two-hour data. It should also be noted that for PCP computation to be relevant, existence of large number of weather grid cells, as well as high air traffic is necessary.

4.2 Results for Ft. Worth Center

For this study, Ft. Worth Center was selected for further evaluation due to relatively high convective weather activity, it's central location in the NAS and observed probability traversal data. Figure 4 and 5 show the results for ZFW for different parameters for a one-hour forecast, four-month data set. Figure 4 (left) shows the number of aircraft at various altitudes starting from ground level up to flight level (FL) 500 in 10,000 ft increments. It is observed that more aircraft in the ZFW region traverse the probabilities in the bottom 10,000 ft (closer to the Terminal Radar Approach Control), and between flight levels 300 and 400. In the FL 100 to 200 range, mostly visual flight rules aircraft fly. In the FL 200 to 300 range, mostly the regional jets are present. The overflights largely traverse the center between FL 300-400. In the FL 100-200 and FL 200-300 ranges, 28% PCP was observed (shown by vertical lines in the figures) while in 0-100, 300-400 and 400-500 altitude bands, PCP values of 31-33% were observed. On the other hand, Figure 4 (right) shows the PCP for time of day statistics. The convective weather usually appears in the afternoon through evening hours. The 18-24 UTC (11 am through 5 pm CDT) and 0-6 UTC (5 pm through 11 pm CDT) times see intermediate probability traversal activity (PCP=30%). The 12-18 UTC (5 am through 11 am CDT) sees lower PCP of 28%, as there is lesser convective activity in the atmosphere. It is seen from the green curve that the hours of 6-12 UTC (11 pm through 5 am CDT) show PCP of 33% when there is minimal traffic activity.

Additionally, the behavior of different airlines and aircraft types was also studied. Again, the vertical lines show the corresponding PCP values. Figure 5 (left) shows the behavior of four dominant airlines in the Ft. Worth Center. The top-two users were mostly avoiding the 28-29% probability while the bottom two users were

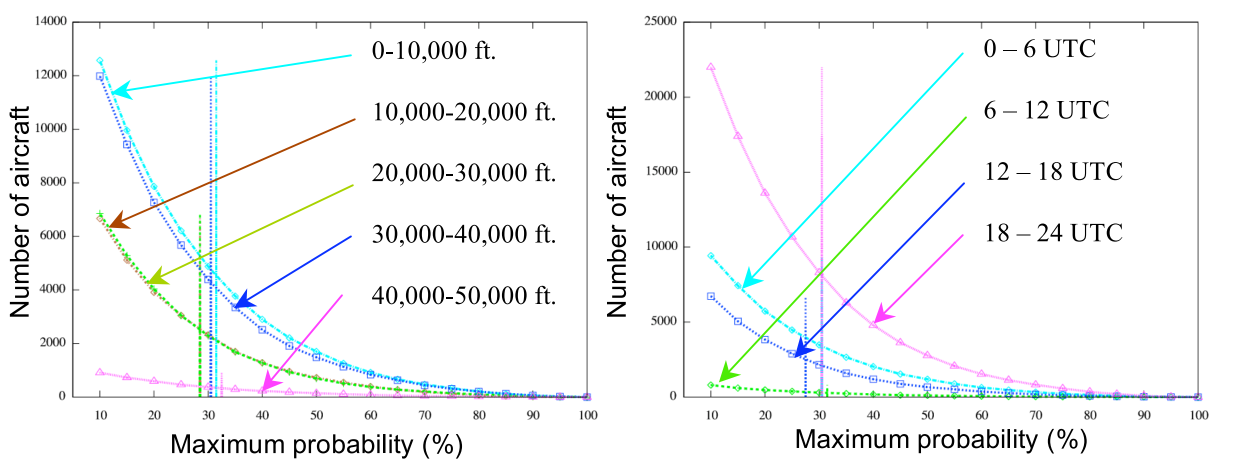


Figure 4. Number of aircraft crossing maximum probability values at various altitudes (left) and at different times (right) for Ft. Worth Center.

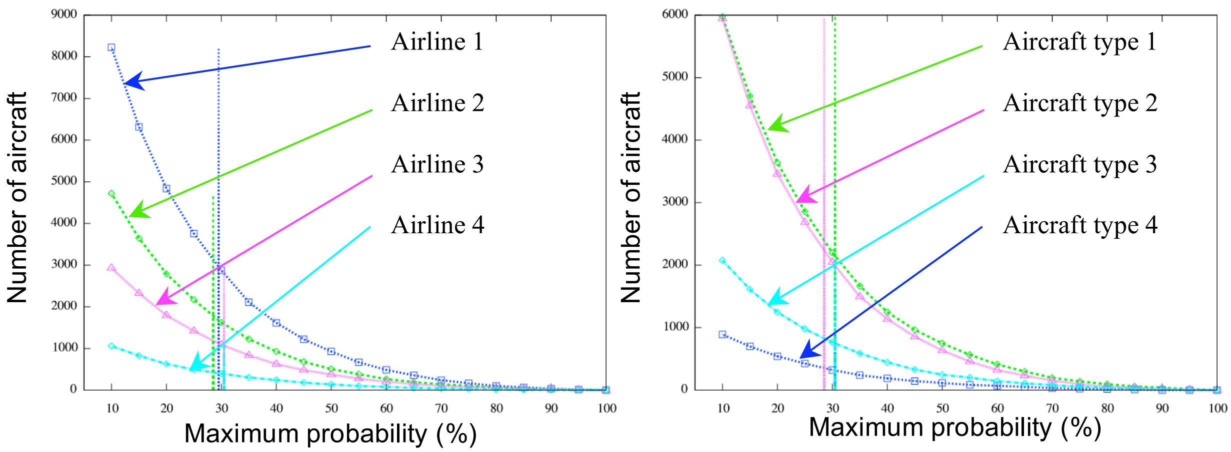


Figure 5. Number of aircraft crossing maximum probability values for four airlines (left) and four aircraft types (right) for Ft. Worth Center.

avoiding 31% value. The top users have DFW as the hub while the bottom two users do not, which is similar to findings of Rhoda, et al. (2002) that aircraft tend to venture more into convection closer to destination. On the other hand, Figure 5 (right) shows the number of aircraft crossing probability values for the four commonly occurring aircraft types in the center. The main observation was that the medium size aircraft type 2 appears to avoid the 28% contour value, but the three other aircraft types were avoiding the 31% intensity contours, including the smaller type 3 and larger type 4 aircraft.

The two-hour forecast data were processed as well and all the graphs behaved similarly to the one-hour cases. For altitudes, between FL 100-200 and FL 200-300, 18% PCP was observed, while all other altitude bands showed a PCP of 23%. For the 18-24 and 0-6 UTC (11 am to 11 pm CDT) a 23% PCP value was observed while the remaining times of 11 pm to 11 am CDT, it was 18%. The airline behavior was similar with the top two users showing 18% while the other two users had 23% PCP value. Following a similar trend to one-hour forecasts, aircraft type 2 showed 18% PCP while the others were avoiding 23% intensity contours.

4.3 Results for ZFW High-Sectors

In order to study the impact of weather in the Ft. Worth center, it seemed appropriate to compute the PCP value at a sector level as well. Figure 6 presents all the high-altitude sectors (all at and above FL 240) in the Ft. Worth Center, but highlights (in cyan) the 7 sectors for which data are presented in Table 1. These seven sectors, with names shown in cyan in Figure 7, contain the four main arrival fixes (shown in

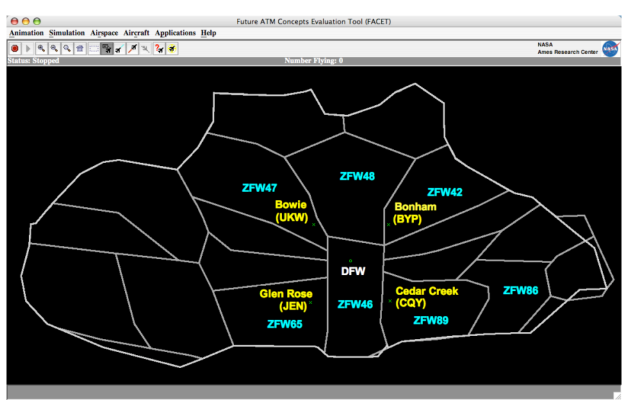


Figure 6. ZFW center with 7 high-altitude sectors highlighted in cyan for which results are presented in Table 1. The four main arrival fixes for Dallas/Ft. Worth International (DFW) airport are highlighted in yellow.

Sector	ZFW47	ZFW48	ZFW42	ZFW86	ZFW89	ZFW65	ZFW46
	(1hr, 2hr)	(1hr, 2hr)	(1hr, 2hr)	(1hr, 2hr)	(1hr, 2hr)	(1hr, 2hr)	(1hr, 2hr)
FL: 240-500	28, 18	29, 19	30, 19	30, 21	29, 19	28, 17	29, 19
Time: 0-6	26, 18	30, 20	34, 21	30, 20	32, 20	30, 18	30, 19
Time: 6-12	32, 17	32, 18	33, 14	25, 23	27, 22	32, 18	14, 15
Time: 12-18	30, 19	30, 17	29, 18	28, 18	30, 16	29, 19	24, 14
Time: 18-24	28, 18	29, 19	28, 19	31, 21	27, 19	27, 16	29, 19
Airline 1	27, 17	28, 18	28, 19	29, 19	27, 19	27, 18	31, 18
Airline 2	25, 18	33, 20	27, 18	27, 18	27, 19	25, 15	29, 19
Airline 3	27, 19	30, 20	31, 20	29, 21	30, 19	22, 19	28, 19
Airline 4	28, 18	27, 20	31, 21	35, 20	32, 19	27, 20	33, 19
Aircraft type 1	28, 18	30, 19	29, 19	32, 21	29, 19	24, 19	27, 19
Aircraft type 2	28, 18	27, 18	29, 18	29, 19	27, 19	27, 18	29, 18
Aircraft type 3	29, 20	29, 19	29, 20	34, 21	30, 19	28, 14	30, 17
Aircraft type 4	32, 18	32, 19	36, 18	27, 21	24, 19	28, 18	32, 20

Table 1. The PCP values for seven sectors (shown in Figure 6 above) in ZFW for one- and two-hour forecasts for altitude range, times of day, airlines and aircraft types.

yellow), as well as have more complex traffic patterns in the center (e.g., right-most sector ZFW86, and central sectors ZFW48 and ZFW46). The other sectors are either departure sectors or have lesser activity in them. Table 1 shows two numbers, which are the one- and two-hour forecast PCP (comma-separated) values. Since each of the sectors (presented in row 1) is a high-altitude sector, data from FL 240-500 is shown in row 2. The rest of the data are for times of day, airlines and aircraft types. It is worth noting that sector ZFW86 has a very complex traffic pattern due to arrivals from the east, departures from the south and multi-directional overflights. It's seen that mostly it has a PCP value, which on average, is at or above its peers for the altitude range shown. For times of day, each sector shows data based on its location and arrival/departure patterns. The highest one-hour PCP value noted is for aircraft-type 4 with 36% in ZFW42, while the lowest one-hour PCP value is 14% in ZFW46 between 6-12 UTC when there's little arrival or overflight traffic. For all ZFW sectors, one-hour values lie between 27 and 32% with a 30% average, while the two-hour values lie between 17 and 21%, with a 20% average. Overall, the average 30% (one-hour) and 20% (two-hour) values for this large case are independent of airline, aircraft type, altitude and time of day. A similar analysis can be conducted for three- through six-hour forecasts.

5. AIR TRAFFIC MANAGEMENT APPLICATION

5.1 The Local Rerouting Need

During the times when convective weather is predicted to occur, it obviously benefits the operators and users to assess the impact on air traffic. At the same time, it would be tremendously useful to have a what-if analysis capability available, to quickly evaluate possible rerouting options. It would be beneficial to have such a system for evaluating center-level routing strategies for a localized weather event. These single center-based rerouting options could potentially lower the workload of traffic managers in neighboring centers along the reduced flight paths of aircraft arriving at an airport with, for example, an arrival fix closure due to weather.

Once the probability cut-off threshold values have been computed, what-if evaluation analysis can be performed for various route options to assess the balance of demand and capacity. For example, if a fix for arrival traffic (e.g., Bonham, BYP) for DFW airport or overflight traffic transitioning through the ZFW

Center is forecasted for impact by convective weather in the next one through six hours, what kind of rerouting schemes could be employed? Which route options can be utilized to maintain the stream of aircraft flowing without schedule disruption through a ground delay program and minimal additional workload for controllers, while providing sufficient predictability? A simple and routine example is to reroute westbound flows from Texarkana (TXK) through Wichita Falls (SPS) to Childress (CDS) for alleviating delays due to weather effects, including the east-to-west SWAP Playbook routes. In general, while using the Playbook routes, there is national and multi-center impact on large number of aircraft, with associated potential loss of schedule integrity. For local weather scenarios of a center-level scope, it is desired that the impact on other centers be minimized. The proposal is to reduce the burden on other centers while the impacted center works cooperatively with the Air Traffic Control System Command Center.

5.2 Local Reroutes Concept

A contribution of this paper is to provide a decision-support system for evaluation of options for flight routing decisions based on probabilistic forecasts. A local center-based rerouting what-if analysis concept is proposed, where the centers can employ local and predefined routes for assessing the impact of various strategies, in coordination with the ATCSCC. A simulation environment like FACET could be employed to appraise such strategies. While implementing the National Playbook, generally the aircraft's flight plan is completely modified from origin to destination, resulting in larger scale deviation from nominal operations. The concept of Center Routes proposed here, keeps the flight plan unchanged until the point of entry into the locally impacted center. Only after the last fix before entry into the affected center, the flight plan is changed with the planned local reroute up to the destination (for arrivals) or exit from center (for overflights). This provides a level of predictability (assuming a satisfactory level of forecast accuracy) to the dispatcher as well as the controller. It also eliminates the need to route each aircraft individually and maintains the flow in the form of a stream of traffic. Since the probabilistic convective weather data are available up to six hours in advance, such strategies could constantly be evaluated for air traffic management planning decisions in the long term.

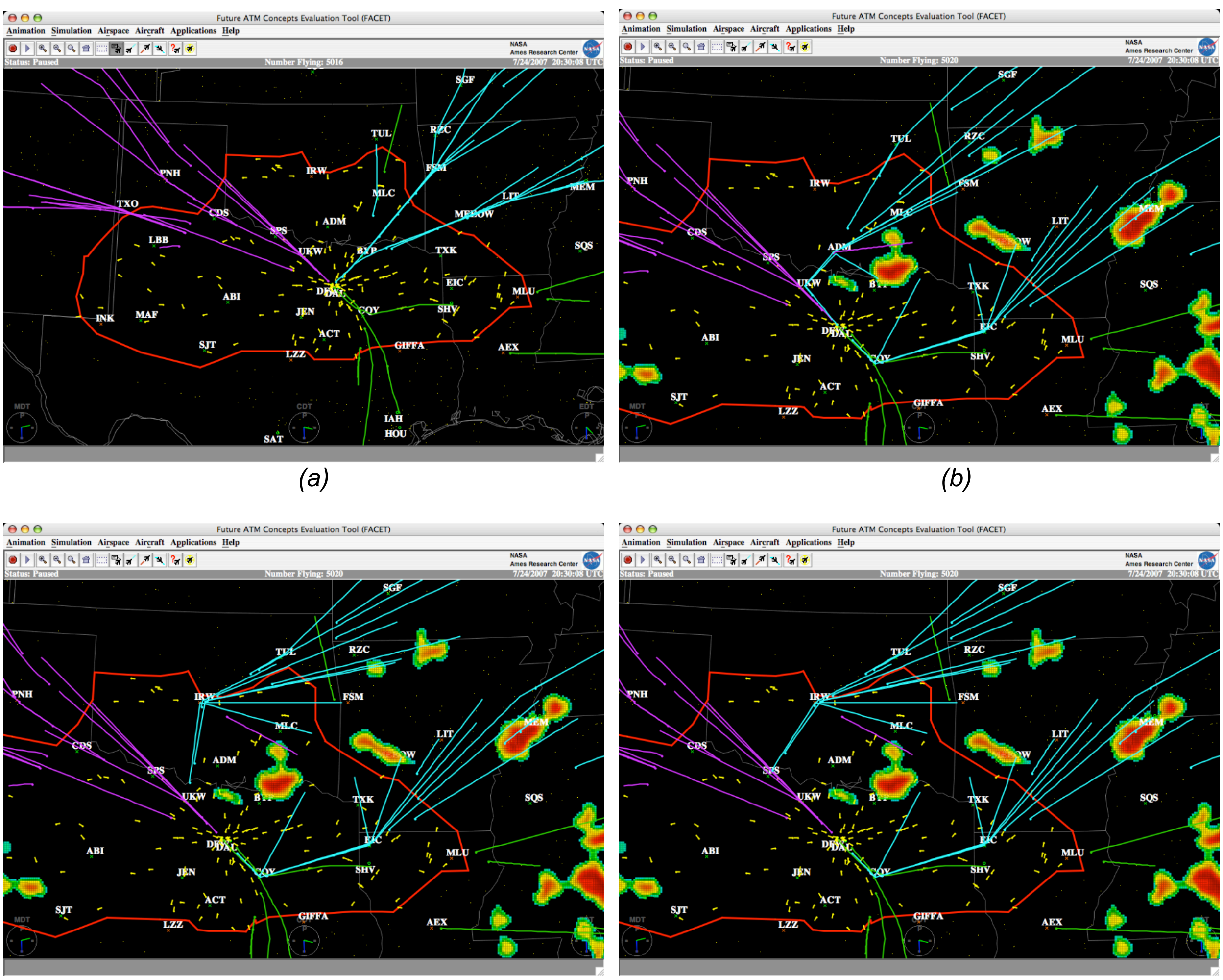
In the case of Ft. Worth Center, traffic enters from four neighbors. The traffic from Albuquerque (ZAB) Center (at left) mainly enters ZFW through Wink (INK), Panhandle (PNH) and Texico (TXK); from Kansas City (ZKC) Center (above) through Will Rogers (IRW) and Tulsa (TUL); from Memphis (ZME) Center (at right) through Munroe (MLU), Little Rock (LIT) and Ft. Smith (FSM); and from Houston (ZHU) Center (below) through Alexandria (AEX), Lampasas (LZZ), and GIFFA fixes. In this study, local routes were designed for the scenario where one of the arrival fixes (e.g., Bonham, BYP) was closed, as in the events of July 10, 2007. These local strategies were implemented in the FACET software through its Application Programming Interface. Consider a flight plan for an aircraft arriving from Chicago O'Hare International Airport (ORD), routinely filed with the FAA as ORD..RBS..SGF..BYP.BYP5.DFW. In this implementation, the route would be modified, for example, as ORD..RBS..SGF..TUL..IRW..UKW. UKW9.DFW, using a potential route option incorporating alternate fixes and a non-impacted arrival fix (UKW). Once these routes were designed for arrivals into DFW, what-if analyses are conducted to study the impact on flights. Several metrics of delay, congestion, additional fuel, distance, etc. are then computed.

5.3 Results of Local Rerouting

Figure 7 presents a scenario when BYP (the northeast arrival fix for DFW) is closed, as was the case on July 10, 2007 (see Fig.1) with significant delays for DFW arrivals. The PCP values computed earlier were used to look at the area covered by 30% probability values over the BYP arrival fix. The traffic originally planned to arrive through BYP from various northeastern origin airports is rerouted along TUL, IRW, SPS and UKW to arrive into DFW. Figure 7 shows the situation before (top-left) and after (top right and bottom) implementation of these local reroutes through ZFW. In Figure 7, cyan lines show the arrivals at DFW through BYP, magenta lines show arrivals through UKW and green lines are arrivals through CQY. The reroutes for this BYP closure scenario were implemented using three different strategies, which would depend on the location and spread of predicted weather. First strategy (Figure 7b) rerouted aircraft to TUL/ADM and UKW to arrive into DFW. The second strategy rerouted through TUL, but additionally, to IRW and UKW; while the last strategy rerouted aircraft even further to go from

TUL, IRW, SPS and UKW to arrive into DFW. In each of the three strategies, aircraft coming from Ft. Smith (FSM) and north of it (upper cyan arrival stream in Fig. 7(a)) were diverted to the TUL/ADM arrival stream, while aircraft coming from Little Rock (LIT) and southeast of it (lower cyan arrival stream in Fig. 7(a)) were routed through Belcher (EIC) and Cedar Creek (CQY) into DFW. The EIC..CQY..DFW flight reroutes were held constant in each of the three strategies.

In order to understand how effective these routes are and what the impact on traffic is, what-if analyses were conducted for each of the three strategies and the results are presented in Table 2. The intent is not to compare the results of one strategy versus another, since each is applicable for a different weather impact and coverage scenario, but to understand the effect on traffic for each strategy, if the situation were to arise. The reroutes were implemented in FACET for a four-hour period from 20:00 to 24:00 UTC using data from July 24, 2007. Since the data from July 10, 2007 (a Tuesday) would be corrupted with controller input of rerouting the aircraft due to presence of convective weather over BYP; July 24, 2007 (another Tuesday) data were used for simulating reroutes. In each of the three cases, the number of impacted flights was 155. Table 2 provides the metrics for each of the three strategies. The aircraft incurred an average of 12, 15 and 18 minutes of delay; 794, 1,012 and 1,235 pounds of additional fuel; and 42, 54 and 66 nmi additional distance, per aircraft for the three strategies, respectively. It is worth noting that in each of the three cases, there was no



(a) (b) (c) (d)

Figure 7. (a) Original tracks of flights arriving into DFW through BYP (cyan), UKW (magenta) and CQY (green. Results for Strategies 1 (b), 2 (c) and 3 (d) are presented in Table 2.

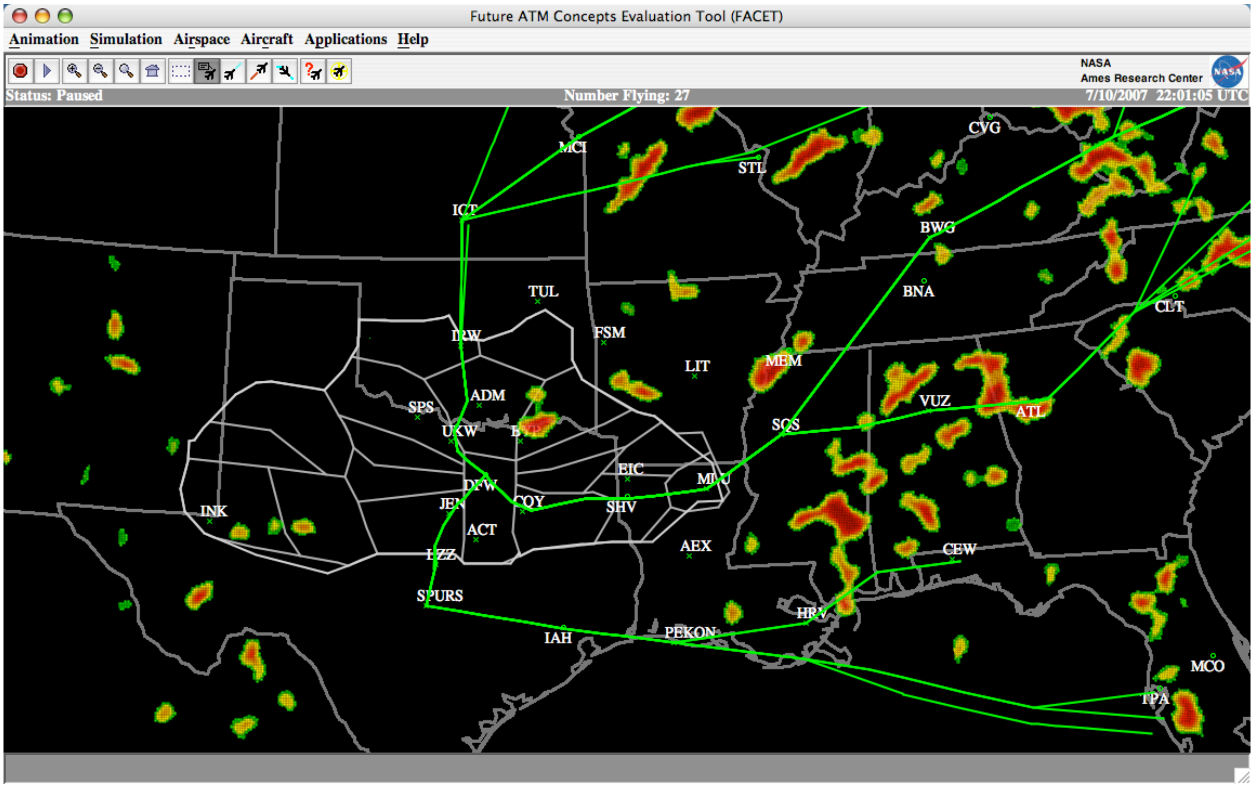


Figure 8. Description of the Bonham fix closure for DFW arrivals using the DFW_BYP1 Playbook route (green lines).

	Strategy1 (TUL.ADM. UKW)	Strategy2 (TUL.IRW. UKW)	Strategy3 (TUL.IRW.SPS. UKW)	DFW_BYP1 (Playbook route)
Number impacted flights	155	155	155	218
Total delay (min)	1,789	2,296	2,823	2,821
Total extra fuel (lbs)	123,108	156,992	191,388	185,833
Total extra distance (nmi)	6,520	8,343	10,287	13,186

Table 2: The total delay, extra fuel and extra distance metrics for Bonham arrival fix closure, for the three rerouting strategies as well as the National Playbook plan simulation.

congestion (number of aircraft above Monitor Alert Parameter) observed in the northwestern sector ZFW47 (where UKW lies) or in the southeastern sector ZFW89 (where CQY lies). This behavior is observed mainly due to a smaller number of aircraft present during the evaluation interval. However, this brings up an interesting issue that rerouting flights to the same region of airspace may not necessarily overload the airspace but may provide a reasonable alternative to dealing with the weather problem. This also validates the need for a capability that allows a quick evaluation of the rerouting strategies. The last column in Table 2 corresponds to the implementation of a published Playbook route, DFW_BYP1, for arrivals into DFW airport during a BYP closure event. The result indicates that 218 DFW arrivals flights are affected. The reason for a larger number of flights being impacted is that the current description of DFW_BYP1 modifies flights not only flying over BYP, but also over other arrival fixes, CQY and JEN. The use of DFW_BYP1 does not include other flights (e.g., overflights or arrivals at other airports) in the center and separate Playbook routes need to be implemented to account for all those flights. In the local rerouting concept implemented for this paper, flights flying over BYP, either arriving at DFW, DAL, Houston (IAH and HOU), or other nearby airports like San Antonio (SAT), etc. can all be accounted for with less than

10 minutes of flying time modification. The DFW_BYP1 plan could start modifying flight routes more than two hours in advance. Figure 8 shows the scope of the DFW_BYP1 plan. The green lines show the flight plan amendment that would be used for aircraft arriving at DFW airport from origins across the northern and eastern part of the country. The weather pattern shown is the same as in Fig. 7. It is clear from Figures 7 and 8 that the scope of local rerouting is smaller and much lesser impact would be felt by air traffic compared to the larger DFW_BYP1 or similar plan, especially for a convective weather problem of a local scope. It can be observed from Fig. 1 that on July 10, 2007, the aircraft from the north and east were arriving at DFW through IRW and SPS, which is closest to Strategy 3 implemented for this research. It is acknowledged that for larger, multi-center convective weather scenarios, the National Playbook provides appropriate predictability. The concept proposed here only addresses local weather events and associated local reroutes.

6. CONCLUSIONS

Previous research conducted at NASA was extended in this study to assess the behavior of aircraft in the vicinity of a field of forecasted weather probabilities. The present study provided the Probability Cut-off Parameter (PCP) values for all the twenty centers in the continental United States and investigated the aircraft behavior in detail in the Ft. Worth Center. It was observed that the 20 centers are divided into three bands with low, medium and high number of aircraft traveling through the forecasted probabilities. The Atlanta and New York Centers demonstrated higher number of aircraft flying through probability field with proportionately lower forecasted weather activity, while Minneapolis Center had higher weather occurrence but lower number of aircraft traversal through the probability field. The analysis also presented the PCP values for different altitudes, times of day, airlines and aircraft types for Ft. Worth Center and seven high-altitude sectors therein. Most of the PCP values observed were in the vicinity of 30% and 20% for the one- and two-hour forecasts, respectively.

Using the derived PCP values, a concept of center-level rerouting is presented. In the FACET simulation environment, such local reroutes can be implemented for a rapid what-if analysis and to estimate the impact on arriving and overflights. Results for a specific scenario of the Dallas/Ft. Worth's Bonham arrival fix closure are presented. The metrics include arrival delay, additional fuel and distance, and congestion in the airspace due to rerouting. It was observed that the total impact on affected flights is smaller compared to larger scope National Playbook plan. In the proposed Center Routes concept, for a small amount of additional fuel, deviation from nominal path and time traveled by individual aircraft for a specific scenario, the flights were maintained as flow streams handled by locally impacted center with no additional congestion. In the current study, the airspace complexity metric was not used for comparison and is a subject of future research.

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