MODELING CONVECTIVE WEATHER AVOIDANCE OF ARRIVALS IN THE TERMINAL AIRSPACE*

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1. ABSTRACT

For several years, efforts have been underway to correlate pilot weather avoidance behavior with observable weather parameters available from convective weather forecast systems. To date, the development of Convective Weather Avoidance Models (CWAM) has focused primarily on the en route airspace used by aircraft at cruise altitude [1]. The en route CWAM translates observed or deterministic forecasts of echo tops and vertically integrated liquid (VIL) into a probabilistic forecast of the likelihood of pilot deviation at each point in the forecast grid. In recent years, the WAF has been cited as a reliable indicator of the impact of convective weather on air traffic operations [2,3], and has been incorporated into the Route Availability Planning Tool (RAPT) operational prototype [4].

This paper will present a CWAM for arrivals, starting from the top of descent in en route airspace and continuing into the terminal airspace to touchdown. The arrival CWAM was based on the analysis of a database of convective weather impacts, determined from the observable weather products from the Corridor Integrated Weather System (CIWS) [5] and arrival trajectories from several major terminals in 2009. Past studies of terminal weather impact [6,7] have identified aircraft that penetrated severe weather or made clear deviations around convective cells within the terminal. In this study, the definition of weather impact and avoidance was expanded to include pilot and air traffic control (ATC) decision making occurring when the aircraft is *outside* of the terminal with regard to the expected weather *impact upon arrival in the terminal*. Examples include rerouting to an alternate corner post, holding in en route airspace, or diverting to an alternate airport when weather is expected along the planned terminal trajectory. These types of terminal weather avoidance decisions can often be made when the aircraft is many miles outside of the terminal.

The en route CWAM uses spatial filters applied to the echo tops and VIL to obtain the best correlation between the weather and pilot behavior. This paper will evaluate the current CWAM filters and identify alternate spatial filters or additional weather products that may best correlate pilot and ATC weather avoidance decision making in the terminal. Ultimately the goal of this work is provide air traffic managers and automated decision support tools with a weather avoidance field for effective management of arrival traffic during convective weather impacts in terminal and near-en route airspace.

2. INTRODUCTION

The prediction and avoidance of convective weather impacts when they occur in major metroplex arrival airspaces is critical to the maintenance of efficient traffic flow throughout the National Airspace System (NAS). Management of arrival airspace during convective weather is particularly challenging for several reasons. As flights transition from en route to terminal airspace, the flight planning and trajectory constraints increase, the number of weather avoidance options decrease, and the tactical procedures for avoiding weather become more difficult and disruptive. Flights may be low on fuel, further reducing the number of options and increasing the urgency to act. High resolution, precise forecasts of impacts are needed, since the scale of potentially disruptive thunderstorms in arrival airspace can be very small; a 20 – 30 km. wide storm located near an arrival corner post or between the corner post and airport can disrupt the flow of an already airborne stream of arrival traffic for 30 minutes or more. If unpredicted weather impacts make a corner post unavailable, these flights must be quickly rerouted to another arrival corner post, a tactic that may require closing departure airspace to accommodate the rerouted arrivals and disrupting the arrival flow on the alternate arrival corner post (figure 1). The consequences of these disruptions may include

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widespread airborne holding, a buildup of departure demand on the surface while impacted arrivals are managed, surface gridlock and ground stops that throttle demand to the impacted airport and create time to enable operations to recover.

Arrival management is further complicated by the need to plan for arrival impacts far in advance. Flight plans, including the choice of arrival corner post, may be filed one or two hours in advance of departure time, possibly several hours before the flight is expected to enter arrival airspace. For example, for a flight from Atlanta to Chicago, the time between filing and entering the arrival corner post airspace may be 3 – 4 hours. So arrival CWAM must not only predict pilot and air traffic control behavior in the presence of convective weather impacts, but also be reasonably robust when applied to weather forecasts that may be highly uncertain.

Given the particular flight and airspace constraints of arrival traffic, it is reasonable to expect that the factors most important in weather avoidance decisions may be different for descending arrival traffic than for level, high altitude en route traffic. Furthermore, the different airspace constraints of different metroplex TRACONs may lead to different behaviors. In order to ensure that the arrival CWAM accounts for these potential differences, this study considered arrival traffic to several different metroplex TRACONs, on several case days where the nature and scale of weather impacts varied considerably. This study focused on decisions affecting flight from roughly the top of descent (25 – 30 kft. altitude and approximately 150 km. from the airport), and included weather avoidance decisions in response to weather impacts in that airspace made by the pilot, air traffic control, and / or airline dispatchers.

Identifying the convective weather that will impact terminal operations has been of interest to researchers before. Rhoda et al. [6] analyzed which weather variables were correlated with arriving pilots' convective cell penetration/deviation behavior in Dallas Fort Worth. The authors collected a data set of 63 hours of aircraft and weather information over nine days from the spring and summer of 1997. A total of 4,300 arriving aircraft were studied with 1,952 weather encounters (642 deviations, 1,310 penetrations) from 1,279 aircraft. The authors also collected the data from three different radar systems within the DFW TRACON: the ASR-9, NEXRAD, and TDWR. A manual process was used to identify aircraft deviating around convective storms and an analyst drew a box around the weather that was assumed to be causing the deviation. It is important to note that the authors were identifying the most obvious cases were aircraft were observed making tactical deviations in close proximity to the storm.

The study did find a link between the storm intensity and pilots' deviation behavior. This is intuitive as pilots are trained to avoid storms with an NWS VIP level of 3 or greater (scale of 0-6). The authors also identified a correlation between the spatial coverage of the precipitation intensity in the quadrant that the aircraft entered the TRACON. However, the most often quoted finding from the analysis was a correlation between the distance from the airport and the intensity level of the precipitation that pilots are willing to penetrate. The probability of deviation is lower the closer the aircraft is to landing. The authors also noted a correlation to a pilots' willingness to penetrate heavy weather if the aircraft was 1) following another aircraft; 2) more than fifteen minutes behind the nominal flying time scheduled for the trip and 3) flying after dark.

This study extends the previous work in several ways. Arrival traffic in several TRACONs is analyzed, and a larger set of weather products from CIWS are included in the analysis. Weather avoidance decisions are more generally defined to include air traffic control and airline dispatch. The goal and context of this study is also somewhat different. The arrival CWAM is intended to provide a weather avoidance probability that is based solely on weather factors and applicable generally to arrival operations in all major metroplex TRACONs. Factors specific to a particular pilot decision that are not directly related to the weather are not considered. Such factors include the possibility that pilots may be more willing to penetrate weather of a certain severity if they are very close to the airport, if they are low on fuel, or if they are running late. These factors may be considered in a separate risk model for individual flight decisions that takes into account the CWAM and other operational factors not related directly to weather impacts.

The arrival CWAM analysis is presented in the following sections. The Methodology section includes a description of the weather avoidance decisions and the weather factors that were considered in developing the model. The Results section presents the weather avoidance statistics and the CWAM derived from them. Finally, the Summary and Future Work summarizes the study and presents several follow-on efforts to validate and apply the arrival CWAM to air traffic management decision support needs.

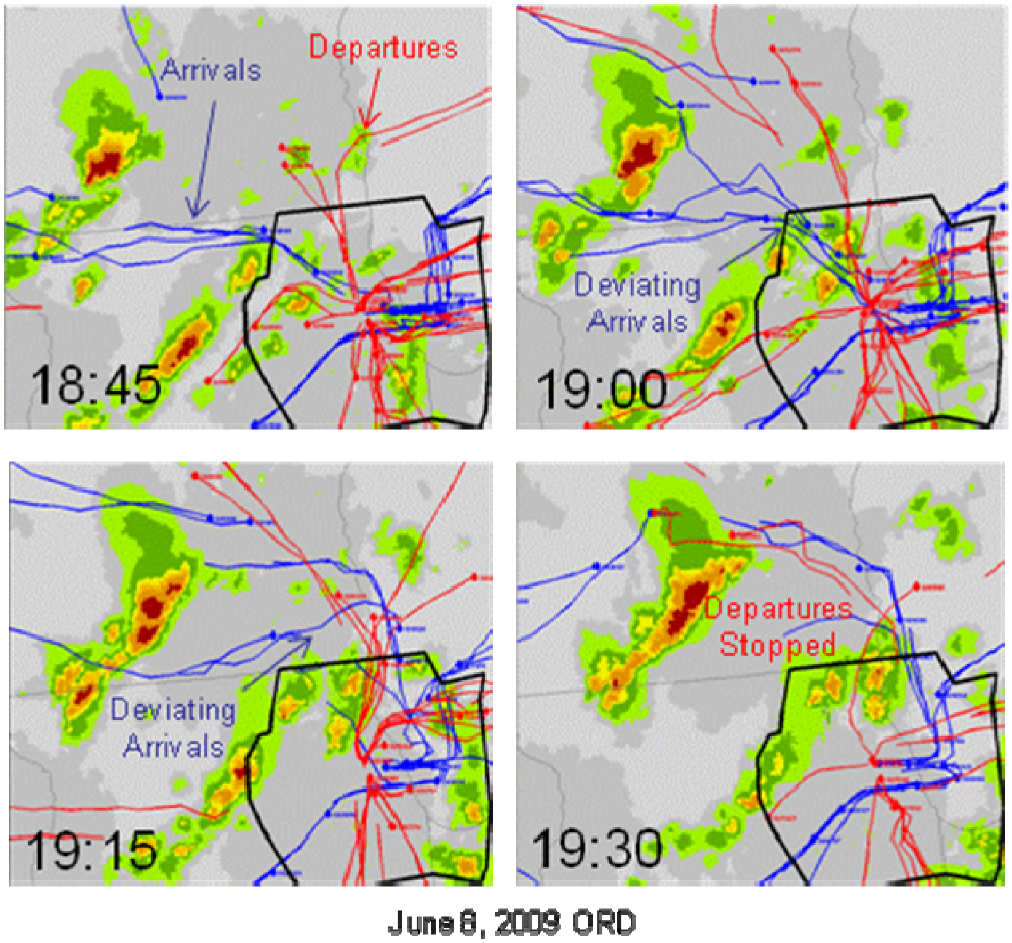

Figure 1. Arrivals (blue) and departures (red) at Chicago O'Hare International Airport on June 8, 2009 during a convective weather impact. Storms impacting the arrival stream on the northwest corner of the TRACON require arriving aircraft to deviate to the north and east. The deviating aircraft cross the departure flow at 19:15Z and all departures are stopped.

3. METHODOLOGY

The methodology used in this study was similar to that used in the en route Convective Weather Avoidance Model studies. Weather that pilots avoid was identified by comparing the planned flight trajectory with the actual and correlating the observed pilot behavior with weather variables extracted along the planned path from the CIWS suite of weather products. However, in en route airspace, aircraft generally follow well-defined planned trajectories with the aircraft moving from fix to fix along straight line segments, and, as a result, weather-avoiding deviations can be identified via automated means and simply reviewed by an analyst to ensure correct identification. The challenge of identifying weather avoidance in terminal airspace is more complicated; once aircraft reach the arrival fix of a typical corner post TRACON, any number of paths can be used to arrive at the runway. Figure 2 illustrates one factor that makes it difficult to clearly identify the planned trajectory for an incoming flight. An aircraft enters the Chicago TRACON on the northwest corner post (KRENA) and follows a relatively direct route towards the runway on descent. As the aircraft approaches the airport and is still at an altitude of 5,000 feet, the aircraft turns left to begin the downwind leg to merge with the traffic arriving from the east. The turn onto final is completed on the east side of the airport to land with a headwind towards the west.

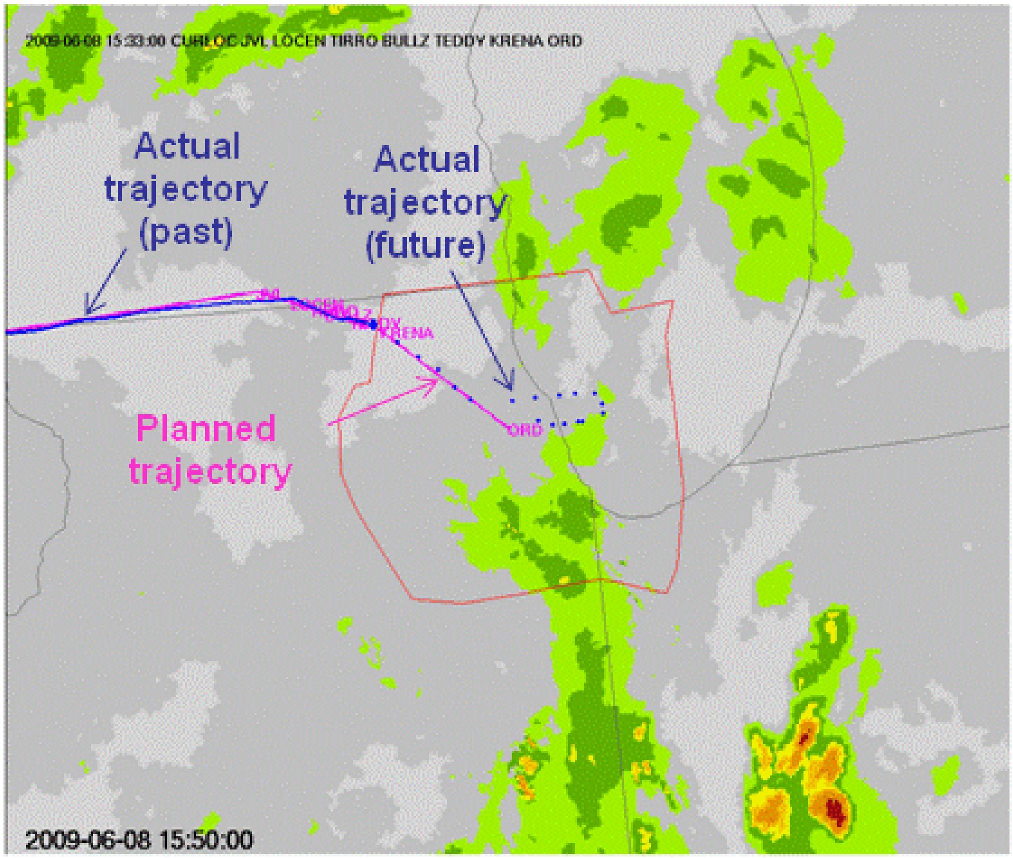

Figure 2. Aircraft arriving at the Chicago International Airport on June 8, 2009. The aircraft enters on the northwest corner post and lands on a northwest orientated runway. A downwind leg is performed to merge with other aircraft arriving on the north east corner post.

The choice of arrival trajectory in the TRACON is dependent upon many factors such as runway configuration, winds, traffic volume and interactions with nearby airports. Furthermore, air traffic controllers have considerable flexibility to maneuver aircraft to avoid weather, manage congestion, and / or to ensure proper spacing on final approach. As a result, it is extremely difficult to develop automated algorithms that reliably identify planned arrival trajectories and pilot deviations within the terminal airspace. Every possible standard landing trajectory would need to be captured and a method to automatically identify the preferred path would be required. Thus, much like the previous efforts in this area, a manual method was used to identify pilot avoidance.

Another challenge is the limited amount of tactical weather-avoidance decision making by pilots in the terminal area. Once pilots begin to avoid convective weather in the terminal area, controllers will shut off the arrival stream and begin rerouting aircraft away from the impacted airspace. The closing of arrival airspace by ATC is a weather avoidance decision that is effectively the result of pilot decision making, and should be accounted for in the development of a CWAM for arrival airspace. In order to account for all different types of weather avoidance decision making, this study identified a total of eight weather avoidance decision types that are both strategic and tactical decisions made by pilots, air traffic controllers, air traffic planners, and airline dispatchers. Instances of all types of weather avoidance were identified manually and incorporated into a weather decision database for analysis and model building.

a. Identifying Terminal Weather Avoidance

The first weather avoidance decision identified is called a planning decision. The decision can be identified when a flight plan is filed for an aircraft that follows an atypical route to avoid weather at an arrival corner post. Most likely this means arriving at the TRACON on a corner post that would not be typical for this origination-destination pair. For instance, a flight from Atlanta to Chicago will, in the absence of weather, use the southeast corner post. However, if weather is impacting the southeast corner post at departure time, the dispatcher in conjunction with the pilot may chose to file a flight plan that brings the aircraft in on a different arrival corner post. Figure 3 depicts the flight plan for a flight on June 19, 2009 originating in Atlanta and destined for Chicago. Typically flights departing Atlanta will take the shortest route over Tennessee and Kentucky arriving on the southeast corner post. At the departure time convective weather is impacting the southeast corner of the TRACON so the planned trajectory brings the aircraft further west and entering the TRACON on the southwest corner post. When the aircraft arrived at the Chicago TRACON, the weather had cleared and new storms were developing on the western edge of the TRACON. Since planning decisions are made at departure time for flights that will take longer than an hour to reach the destination, they were often observed to be out of phase with the weather impacts.

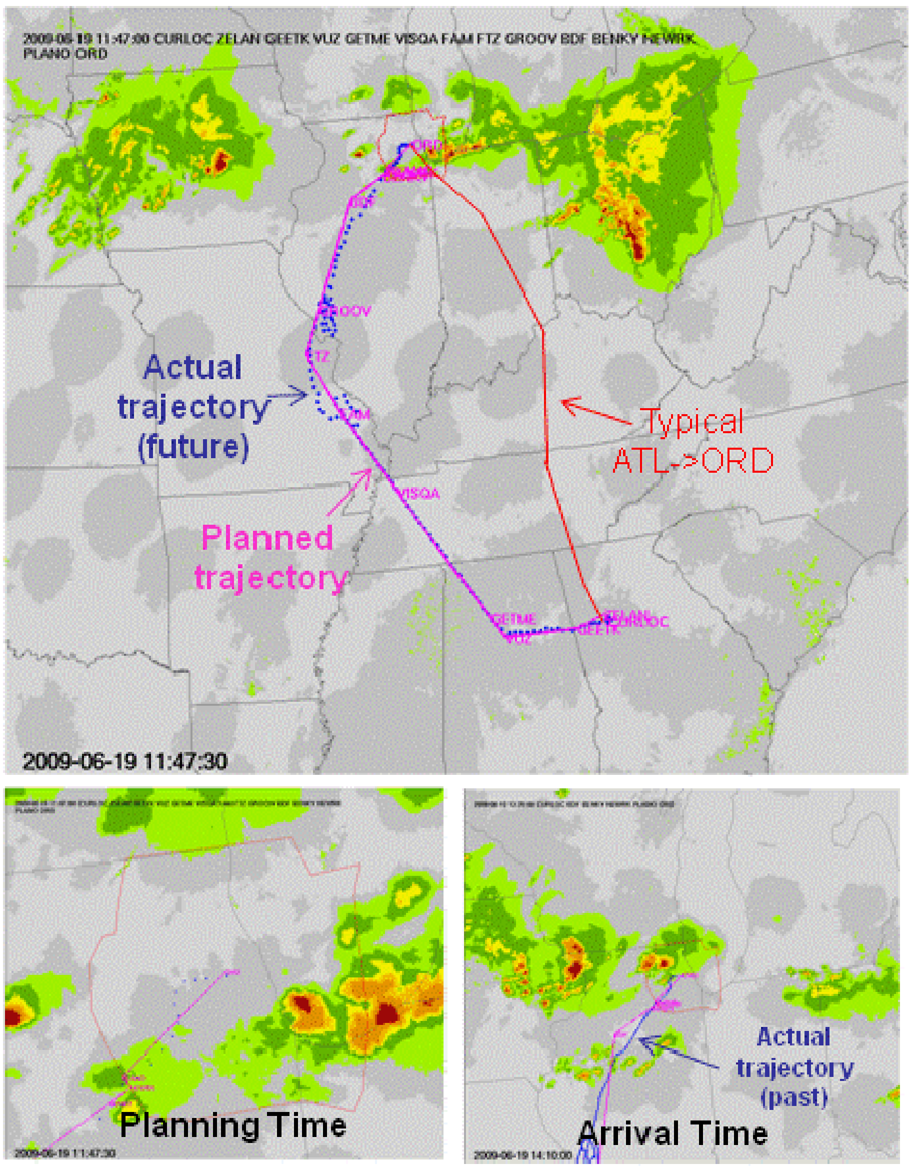

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Figure 3. Weather avoidance decision at planning time. A flight from Atlanta to Chicago files an atypical flight plan due to weather on the south east corner post at departure time of the flight.

The next weather avoidance decision identified is a reroute decision. The decision can be identified when a flight plan is changed and a new corner post is chosen for the arrival. These decisions are made while the aircraft is en route to the destination TRACON and are most likely made by the air traffic planners working the TRACON or surrounding ARTCC when a corner post is closed due to weather impacts. In most instances, these decisions are made with little input from the pilot, although the decision to close the corner post may have been made in response to deviations by other pilots entering the corner post airspace during the weather impacts. Figure 4 shows how weather avoidance is accomplished by rerouting the aircraft from one corner post to another. In this case a strong level six storm has blocked the northwest corner post and the aircraft is rerouted to the northeast corner post.

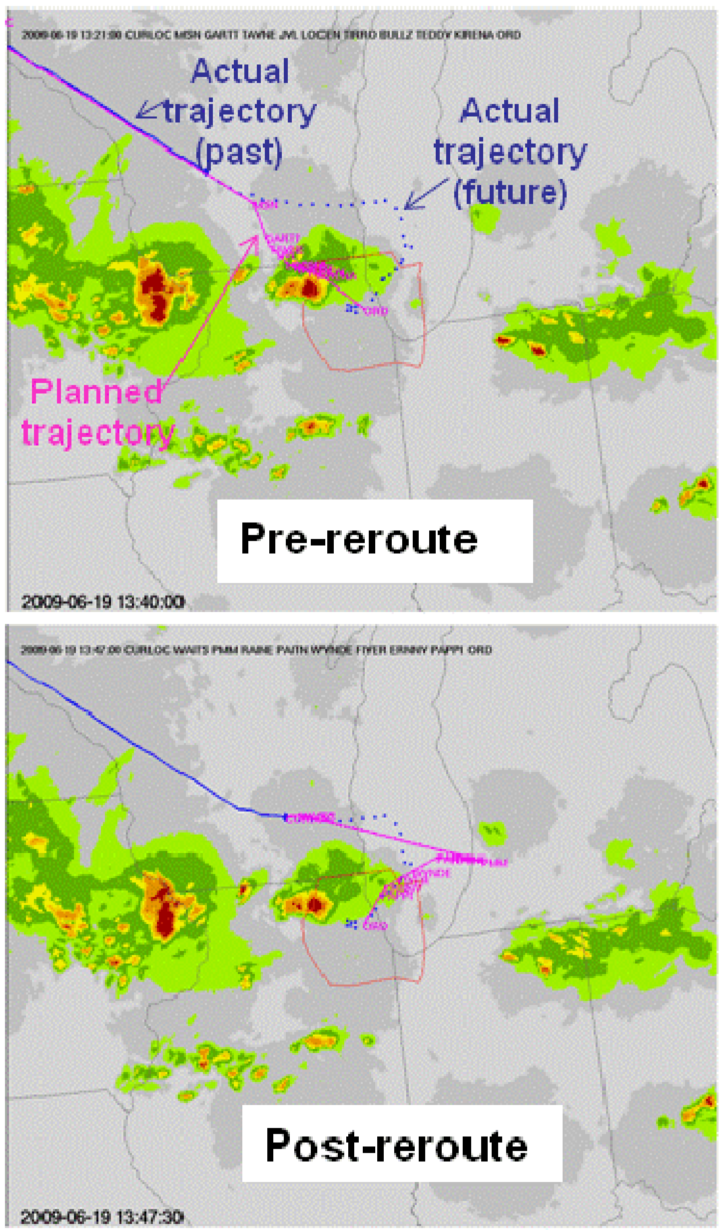

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Figure 4. A reroute weather avoidance decision. An aircraft with a flight plan to land on the north west corner post is modified to bring the aircraft in on the north east corner post.

Another common weather avoidance decision is to place aircraft into airborne holding to wait out the weather. In the event of a closed corner post it may not be possible to reroute the aircraft to a different corner due to traffic volume or the reroute may require an excessive flight time. In these instances placing the aircraft into holding may allow for the flight to continue on its filed plan after the weather clears, or to merge the aircraft into the heavy volume at another arrival corner post.

Figure 5 illustrates a flight from Long Beach to Chicago holding as a weather avoidance decision. As the aircraft approaches the northwest corner post, a strong line of storms is blocking the arrival. The aircraft is placed into holding on two occasions in the ARTCC. At this time both western arrival streams are closed due to the weather and the only alternative is an excessive reroute to the southeast. Eventually, the weather impacts the airport and the flight is diverted to Detroit.

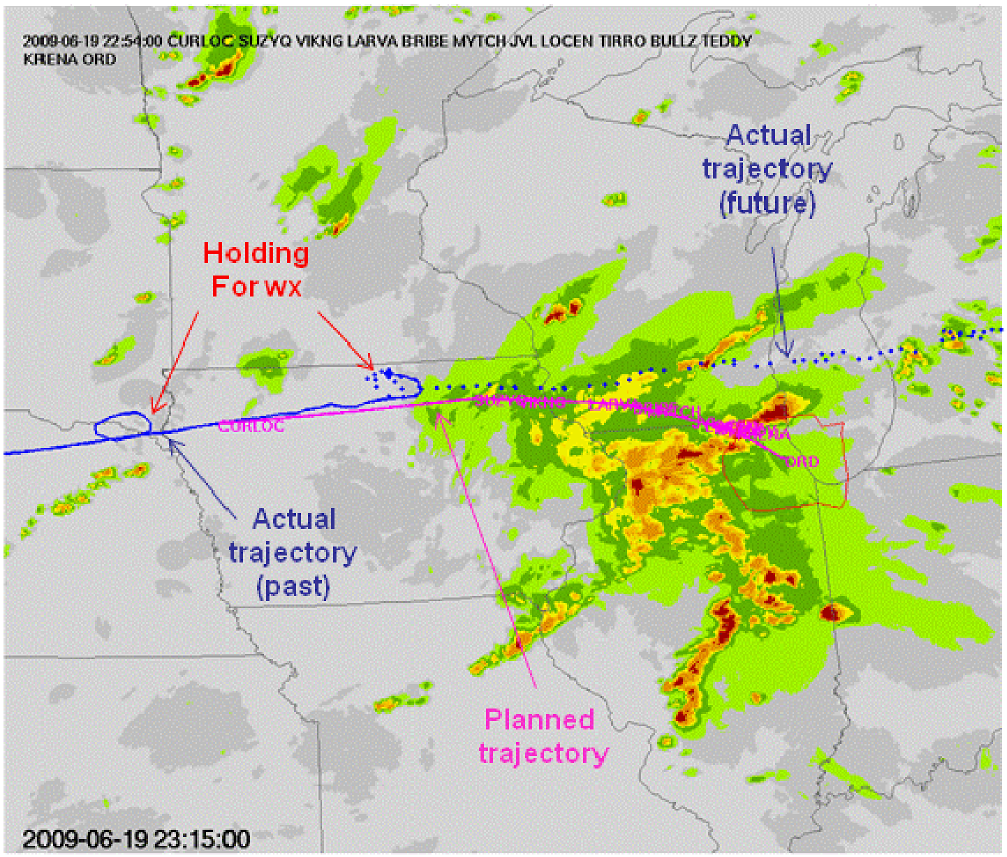

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Figure 5. A holding weather avoidance decision. An aircraft with a flight plan to land on the northwest corner post is placed into holding to avoid the weather along the planned trajectory.

Another weather avoidance decision is an aircraft performing a maneuver to delay its arrival at a corner post. The maneuver will create some additional flying time that will reduce the demand on a corner post by spacing aircraft farther apart. This will usually be done by ATC without coordination with the pilot. This paper will refer to this type of a weather avoidance decision as a slowdown. Figure 6 depicts a slowdown weather avoidance decision for an aircraft landing at Denver International Airport. As the aircraft approaches the corner post it makes a sharp S-turn maneuver in the en route airspace to delay the arrival on the weather impacted corner post. In many ways this avoidance decision is similar to holding in that it delays the arrival time of the aircraft.

The classic weather avoidance decision is to deviate to avoid a storm along the planned trajectory. Deviations are identified by comparing the planned flight path with the actual. Figure 7 depicts two deviations at the Chicago TRACON on two different days in the summer of 2009. The deviations are easily identified in this study by aircraft that are not entering the TRACON at the fix identified in the flight plan.

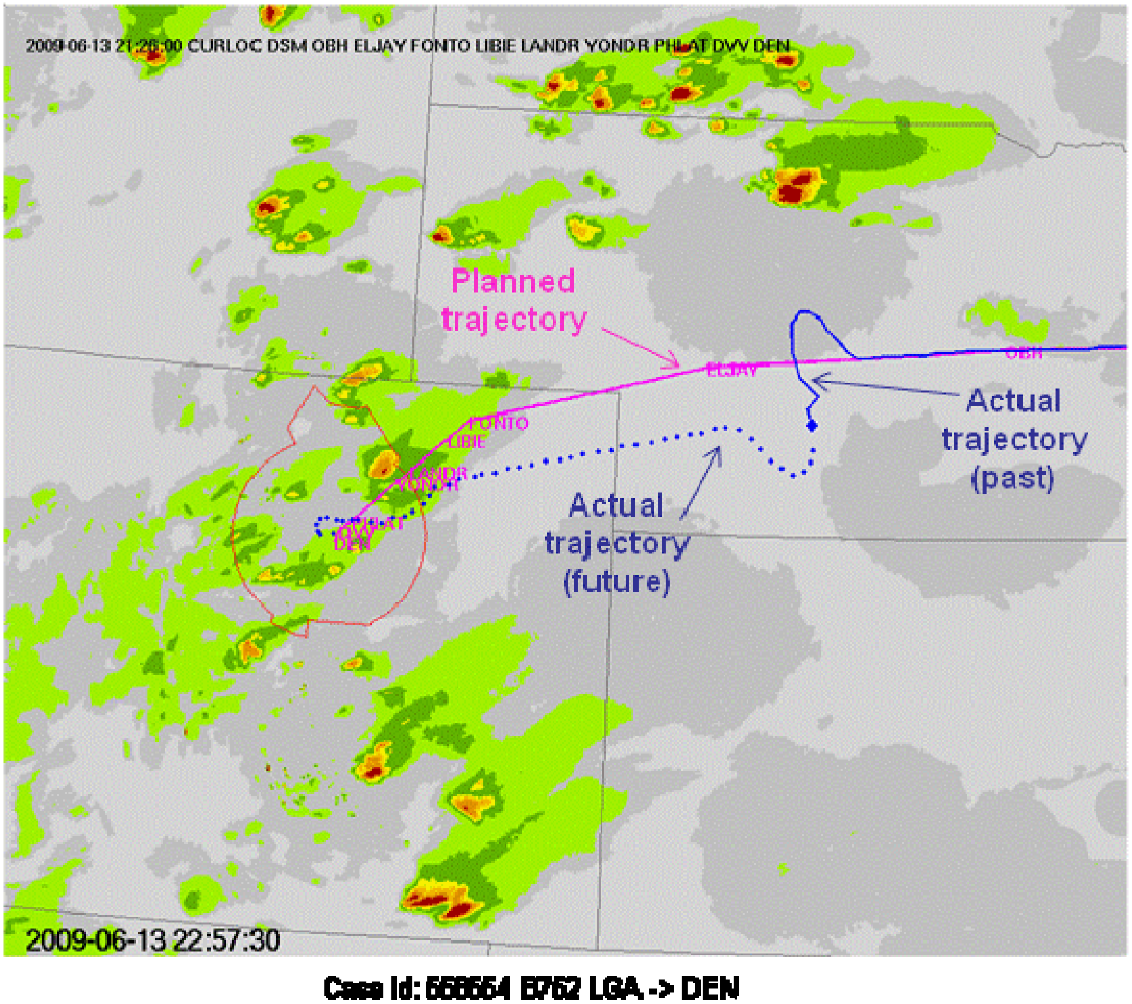

Figure 6. An example of a slowdown weather avoidance decision. An aircraft landing at Denver International Airport veers from the planned flight path to delay the arrival time into a fix impacted by weather.

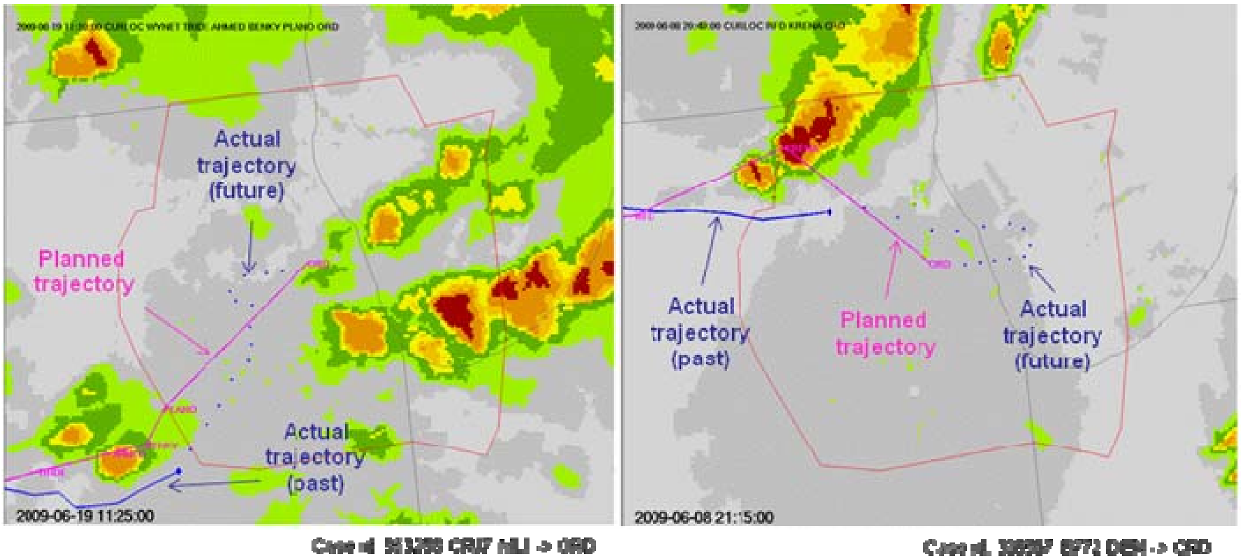

Figure 7. A classic deviation weather avoidance decision. An aircraft deviating around convective weather at the Chicago southwest corner post on June 19, 2009 at 11:25Z ***(a)*** *and an aircraft deviating around a storm on the northwest corner post on June 8, 2009 at 21:15Z* ***(b).***

A less desirable weather avoidance decision is for once a pilot has entered the TRACON to tactically search for gaps within convective storms. Such a decision is referred to as path finding. In these instances a coordinated effort between air traffic controllers and pilots is required to find an acceptable path from the corner post to the runway. This weather avoidance decision is easily identified by two characteristics. First, the pilot will have entered the TRACON on the planned corner post and secondly the actual track can be observed passing through a gap in convective cells. This weather avoidance is similar to a classic deviation. In these instances, a considerable amount of coordination must be done between ATC and the pilot increasing the workload on air traffic controllers. Figure 8 shows an aircraft within the Dallas TRACON that enters on the planned corner post (FEVER) but then must cross a line of storms to land at DFW in a southern configuration. The aircraft can be seen clearly flying in a gap between two very active convective storms. On this day a number of aircraft are holding outside the south west corner post waiting to enter the TRACON and find a path through the storms to the airport.

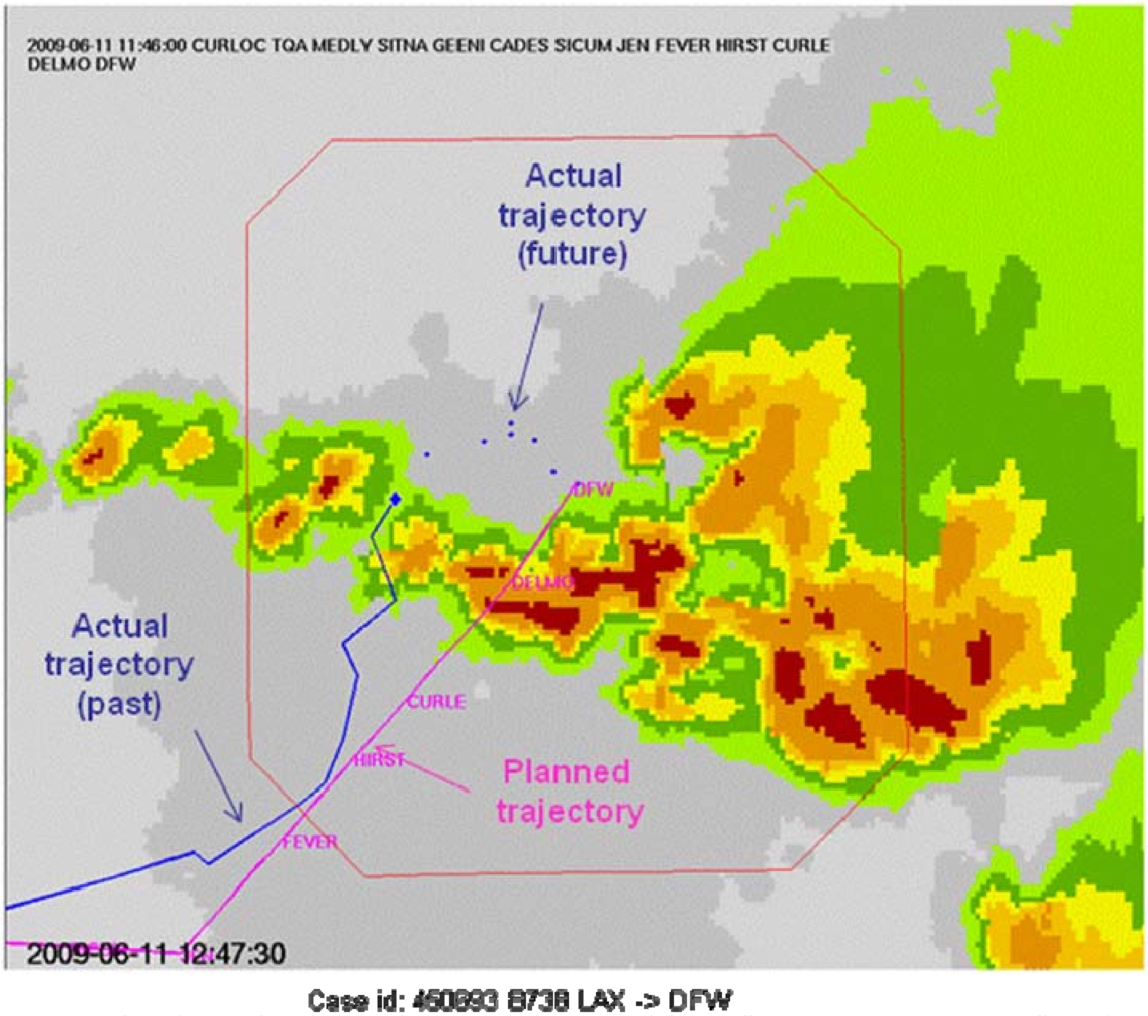

Figure 8. An aircraft entering the south west corner post of the Dallas TRACON crosses a line of storms to land at DFW. This is an example of a pathfinding weather avoidance decision.

The last two weather avoidance decisions are more commonly associated with weather impacts immediately at the airport. The first is a missed approach to the runways. In the event that the weather on final approach is severe enough to jeopardize the safety of the flight the pilot can declare a missed approach and begin to climb out of the final descent phase. A limited number of missed approaches were observed in the data set with an example shown in figure 9. The second is a diversion. If an aircraft is unable to land at the destination airport due to weather impacting the runways or weather blocking the route through the TRACON a pilot can divert to another airport to wait out the storm. Diversions are observed in the data set by a flight plan change to indicate the new destination airport along with an actual trajectory to a different destination. Figure 10 depicts an aircraft destined for Chicago O'Hare that is impacted by weather at the airport. At this time the airport has been closed and all aircraft are holding or diverting to outlier airports. For this particular flight the aircraft entered a holding pattern for approximately twenty minutes prior to the decision to divert to Milwaukee.

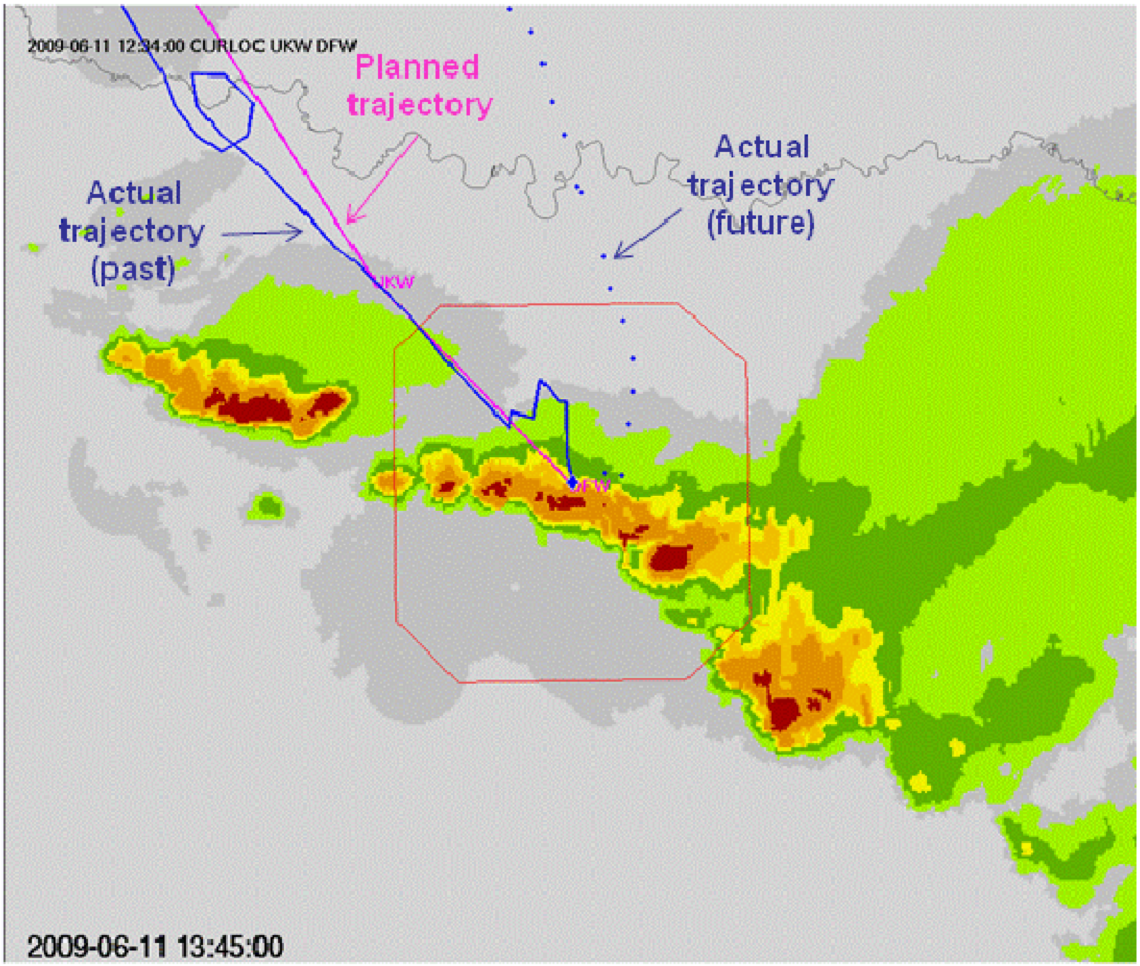

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Figure 9. A missed approach weather avoidance decision. An aircraft attempting to land at DFW is impacted by severe weather on final approach forcing a missed approach by the pilot.

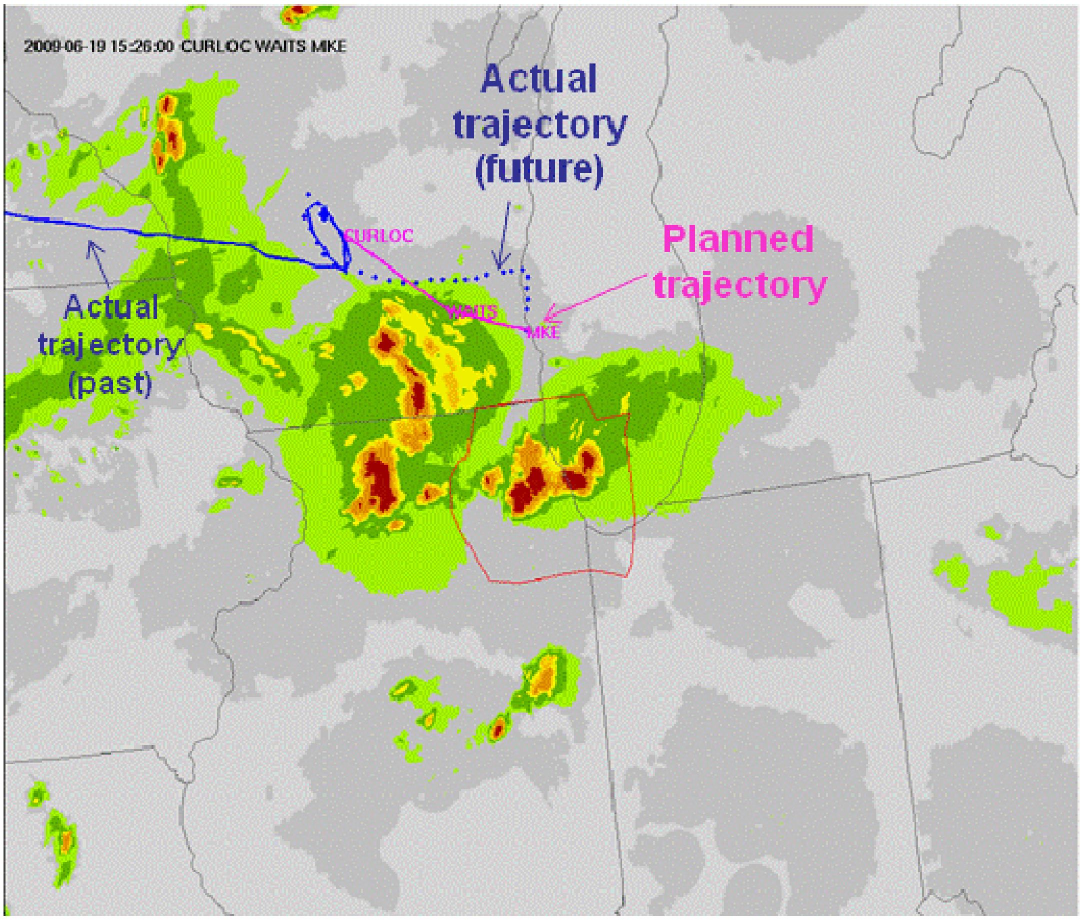

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Figure 10. An aircraft diverting to Milwaukee due to weather impacting Chicago O'Hare International.

b. Avoidance Modeling

The next step in the data collection process was for an algorithm to extract several weather variables that are associated with each weather avoidance decision. For this study, the weather variables were the unfiltered VIL and echo top field along with a 90th percentile VIL and echo top over a 17 km neighborhood. For each corner post avoidance decision the maximum VIL and echo top of the unfiltered and filtered weather along the planned trajectory from 150km to 10 km from the runway will be recorded. For the airport weather avoidance decision the VIL and echo top (unfiltered and 16km 90th percentile) at the airport reference point is recorded.

The final step in the data collection was for an automated process to extract the weather within the TRACON for all aircraft that did not make weather avoidance decisions. For example, an aircraft that entered the TRACON at the planned corner post and followed a typical trajectory to the runway. Figure 11 shows an aircraft penetrating a storm cell at the south east corner post of Chicago. This process finds the maximum weather impact (unfiltered and filtered VIL and echo tops) along the actual trajectory from 150km to 10km from the runway for all corner post impacts and at the airport reference point for airport impacts.

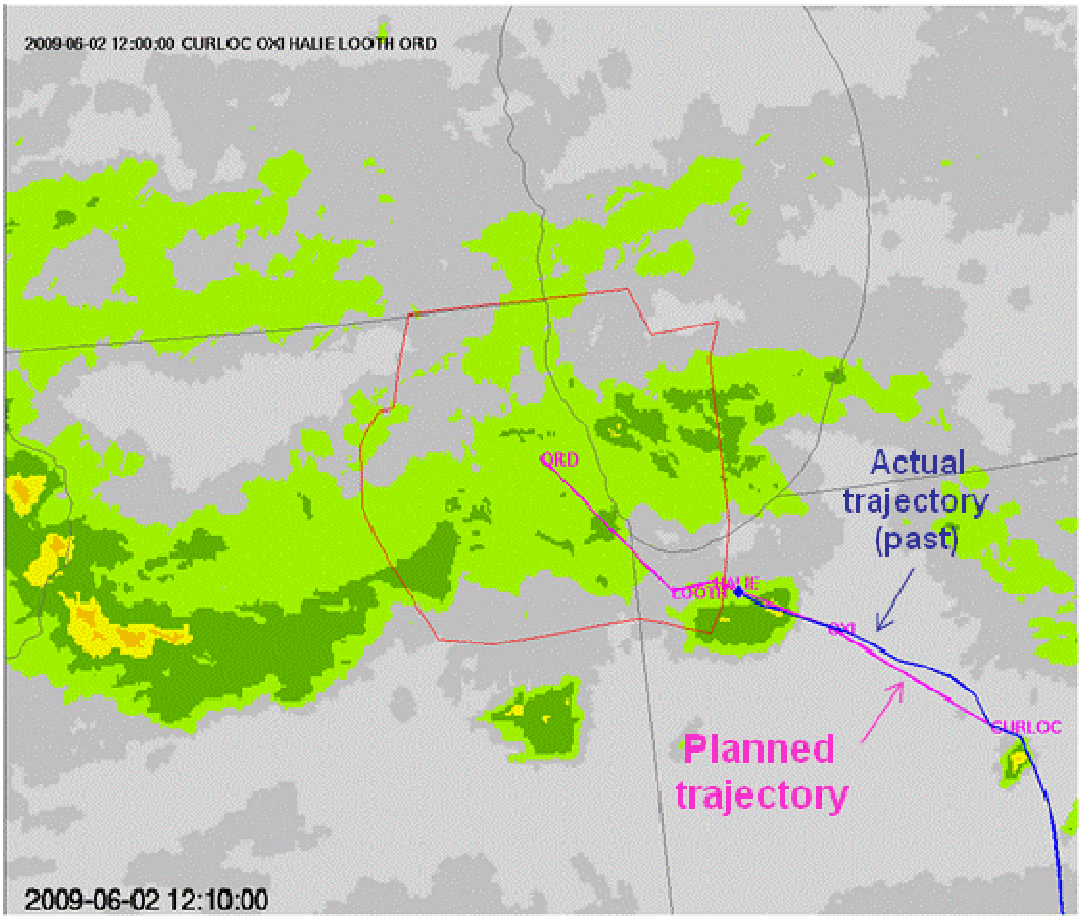

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Figure 11. An aircraft penetrating a storm cell at the southeast corner post of the Chicago TRACON.

4. RESULTS

For the study, a total of five days were analyzed from seven major airports across the country. The planned and actual trajectories for over 11,000 flights were plotted along with the six level precipitation images every 2 ½ minutes. In the event of a change in the planned trajectory the plots would reflect this update. For each trajectory an analyst observed the planned and actual trajectory and recorded all weather avoidance decisions discussed in the previous section. The analyst also noted weather avoidance decisions associated with weather during the climb and cruise segments of the flights. In all, over 4000 weather avoidance decisions were observed with approximately 1,800 of those occurring due to weather impacting the TRACON or airport operations. Table 1 summarizes the number of aircraft trajectories analyzed and the total number of weather avoidance decisions from the seven major airports. Table 2 breaks out the location of the weather decisions (corner post and airport), as well as the type of weather avoidance decision.

From table 2 it is observed that almost 1200 weather avoidance decisions were made with weather near the corner post. The most common weather avoidance decision in response to corner post impacts is the reroute of an already airborne aircraft, presumably by air traffic management, to avoid an oversupply of aircraft at a corner post impacted by weather. The second most common avoidance decision to avoid a corner post impacted was the filing of an alternative route (proactive pre-departure rerouting). This may be less than ideal because during flight the weather may move and therefore may very well not be a factor when the aircraft arrives at the corner post. For weather at the airport a total of 662 weather avoidance decisions were made. The most common type of decision was to enter a holding pattern with the second most common to be diverted to another airport. It is important to note that a single weather event may be responsible for several weather avoidance decisions (i.e. two aircraft enter holding at the same time). Also important to note, a single aircraft may be responsible for several weather avoidance decisions (i.e. holding then diverting).

Table 1. Total aircraft arrival trajectories and weather decisions analyzed from seven major airports on five days in the summer of 2009.

Totals	Trajectories	Wx Decisions
ORD	5602	1937
DFW	2358	1061
CLT	679	328
DEN	811	395
JFK	780	149
LGA	565	136
MDW	349	147
TOTALS	11144	4153

Table 2. A summary of the type of weather avoidance decision made for weather impacting the TRACON corner post and the airport for seven major airports on five days in the summer of 2009.

	Planning	Reroute	Deviation	Holding	Slowdown	Pathfind	Missed	Diversion	TOTALS
Cornerpost	237	426	218	108	39	71	0	33	1132
Airport	0	7	0	394	35	0	10	226	672

The output of the arrival CWAM is a Weather Avoidance Field (WAF) that predicts the likelihood of a pilot avoiding the convective weather encountered between the top of descent and runway. The WAF is based on a two dimensional look-up table with the observed probabilities of weather avoidance partitioned by VIL and echo tops. Unlike the en route CWAM analysis, the arrival CWAM analysis did not consider flight altitude as a factor in weather avoidance decision making, because it is assumed that pilots have few options to avoid convective weather by changing altitude once they begin their descent into arrival airspace. As a result, the arrival WAF is inherently two-dimensional, unlike the en route CWAM which varies with flight altitude.

The arrival CWAM analysis included all observed weather avoidance decisions except the planning decision described in section 3.1. The planning decision is not included at this point because its inclusion would require a robust analysis of all the typical origination-destination pairs in order to compare the set of possible (and rejected) flight plans to the one that was eventually filed. This analysis has not yet been done.

Two dimensional histograms of the terminal weather avoidance decisions are shown in figures 12 through 15. The data for JFK, LGA and MDW were eliminated due to the complexity of the airspace in NYC and the limited number of analyzed trajectories from Midway. In figures 12 and 13, the corner post weather avoidance decisions are shown for the spatially filtered weather data (90th percentile over 16km kernel) and the non filtered weather. The histograms are broken down into the different weather avoidance decision types in the top row. The deviation, missed approach and path finding decisions are combined as these are very similar tactical decisions primarily made within the cockpit. The reroute decision is shown separately, as this decision is most commonly made by air traffic managers rerouting airborne traffic away from a closed corner post. The holding and slowdown weather avoidance decisions are combined into one histogram. These types of decisions are commonly a tactical decision made by air traffic control and may be used when the corner post is open but demand is being slowed due to weather constraints. Finally diversions are shown independently and represent the worst case scenario. The second row depicts the flights that did not perform any weather avoidance (actual trajectory), the total of all weather avoidance decisions, the total of all trajectories, and the probability of impact. Figures 14 and 15 show the impact decisions of weather at the airport.

The results support the commonly held belief that pilots will avoid VIP level 3. The probability of weather avoidance jumps dramatically between level 2 and level 3 for the unfiltered corner post impacts. This strong delineation is not as evident in the spatially filtered weather suggesting that the pilots will operate closer to the weather in the terminal air space. Unlike in en route airspace, the pilots have less flexibility due to the congested spatial constraints in the terminal environment. A correlation with echo top height can also be observed. Weather avoidance is observed for level 3 storms with forty thousand foot echo top but for storms with lower tops the pilots are more willing to penetrate the storm. In fact for the small number of aircraft that encountered level 4 storms with low tops (~25kft) the decision was to penetrate the storm. It is also important to note that weather avoidance does occur for aircraft encountering VIP level 2 but not at a high probability. A similar observation is made for airport impacts. VIP level 3 is a very good indicator that the airport operations are impacted by shutting down or slowing operations. However, a high level of impact is also observed for level 2 weather with high tops (>40kft). Although pilots flying into arrival airspace are not able to observe echo tops directly because they are descending into and through the clouds, it is likely storms with higher echo tops are accompanied by significant updrafts, downdrafts, convectively induced turbulence, and lightning – all weather characteristics that pilots are likely to avoid.

The arrival CWAM lookup table was created by manually smoothing the 2D avoidance histogram from the unfiltered VIL and echo tops (figure 16 and table 3). Two arrival WAF (AWAF), one generated from this lookup table and a second generated from a lookup table based on the 16 km. filtered VIL and echo tops, are depicted in figure 17 for the DFW TRACON on July 11, 2009. At this time the TRACON is heavily impacted by convective weather with the eastern corner posts both closed due to the weather, and a line of storms impacting the arriving flights on the southwest corner post. Notice the aircraft maneuvering between cells or performing path finding weather avoidance. The AWAF based on the spatially filtered weather is smoother, but fills the gaps between storms that the aircraft are using on arrival.

Corner Post Weather Avoidance Decisions

Spatial Filter: 90th Percentile over 17km kernel

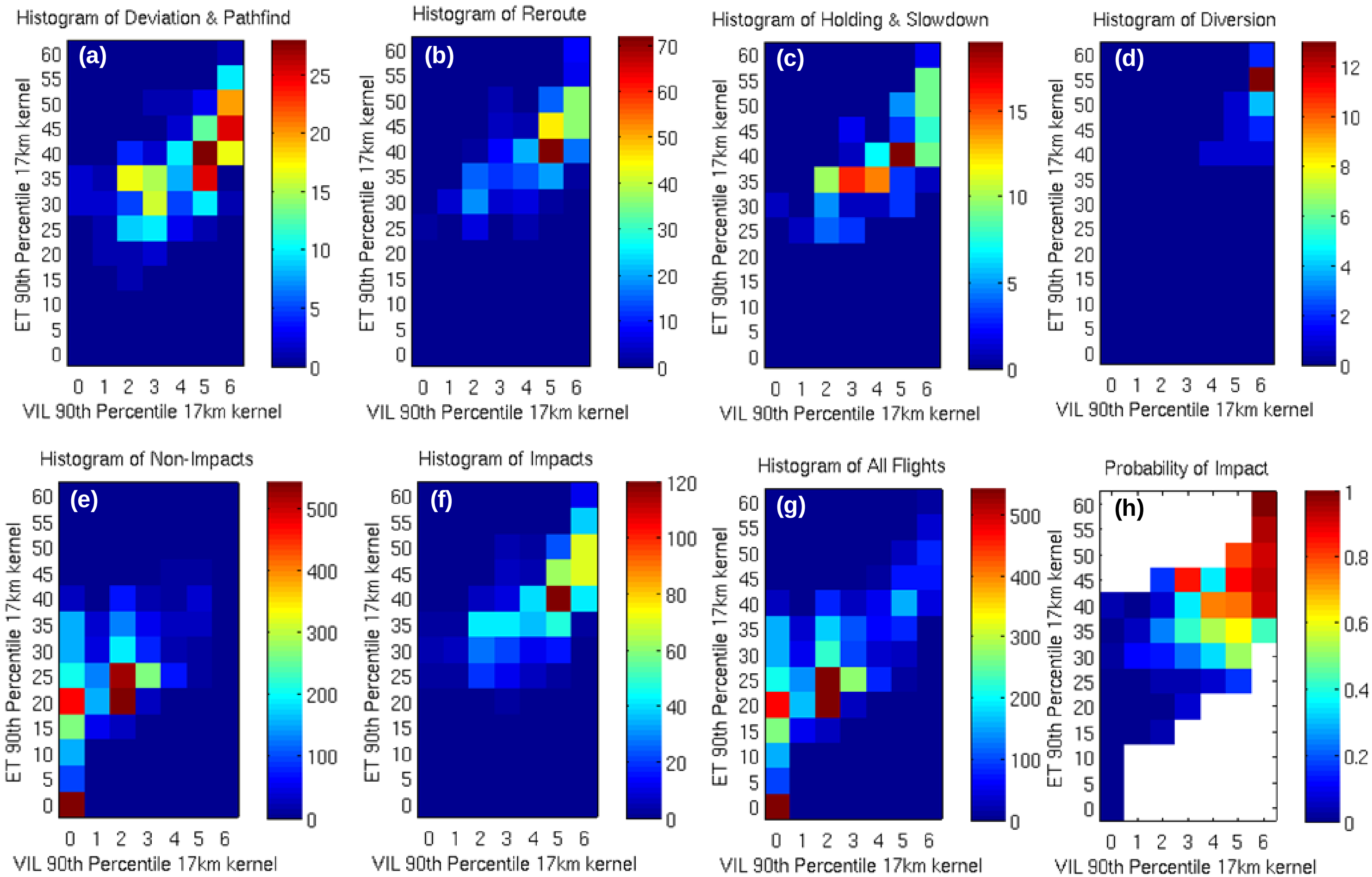

*Figure 12. 2D histograms of corner post weather avoidance decisions for deviation and path find counts **(a)**, reroute counts **(b)**, holding and slowdown counts **(c)**, diversion counts **(d)**, non-impact counts **(e)**, sum of deviation, path find, reroute, holding, slowdown and diversion counts **(f)**, sum of non-impact and impact counts **(g)** and observed probability of impact (percentage of flights in each histogram bin that were impacted)**(h)** for a 90th percentile spatial filter on a 17km kernel. White bins in **(h)** indicate input data intervals that were not present in the dataset.*

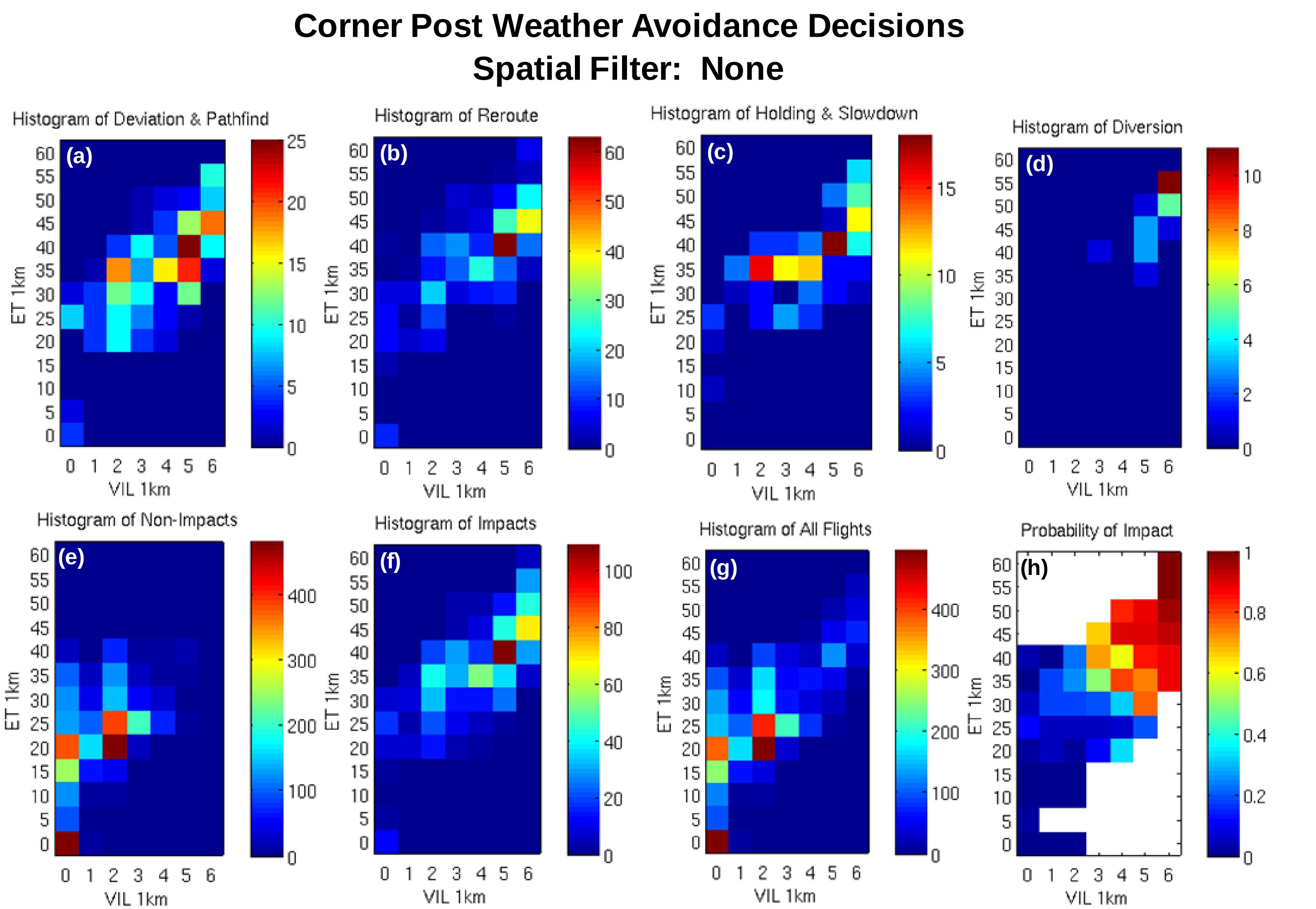

*Figure 13. 2D histograms of corner post weather avoidance decisions for deviation and path find counts **(a)**, reroute counts **(b)**, holding and slowdown counts **(c)**, diversion counts **(d)**, non-impact counts **(e)**, sum of deviation, path find, reroute, holding, slowdown and diversion counts **(f)**, sum of non-impact and impact counts **(g)** and observed probability of impact (percentage of flights in each histogram bin that were impacted)**(h)** for the unfiltered VIL and echo tops. White bins in **(h)** indicate input data intervals that were not present in the dataset.*

Airport Weather Avoidance Decisions

Spatial Filter: 90th Percentile over 17km kernel

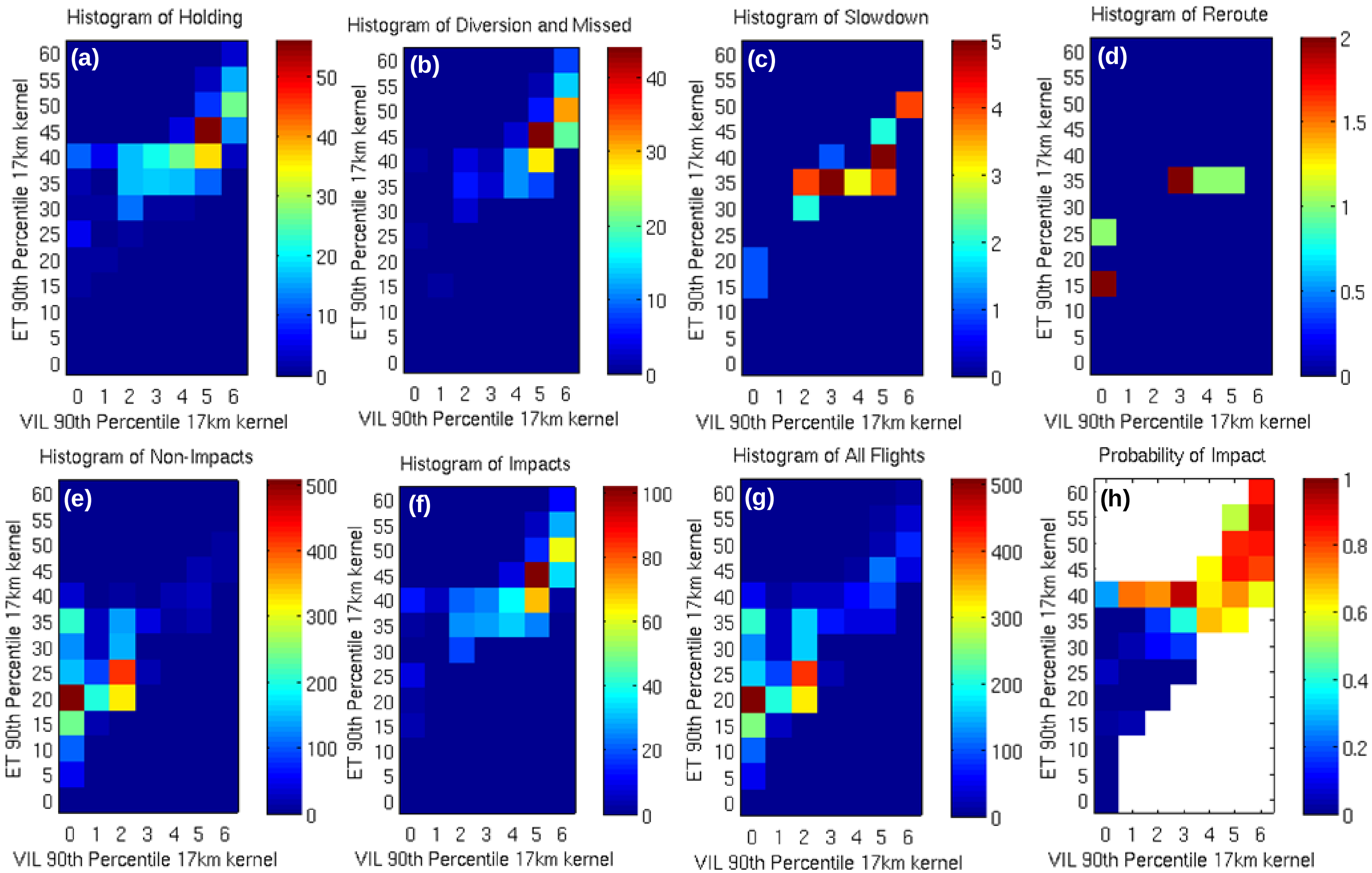

*Figure 14. 2D histograms of airport weather avoidance decisions for holding counts **(a)**, diversions and missed approach counts **(b)**, slowdown counts **(c)**, reroute counts **(d)**, non weather avoidance counts **(e)**, sum of holding, diversion, missed, slowdown and reroute counts **(f)**, sum of non-impact and impact counts **(g)** and observed probability of impact (percentage of flights in each histogram bin that were impacted)**(h)** for a 90th percentile spatial filter on a 17km kernel. White bins in **(h)** indicate input data intervals that were not present in the dataset.*

Airport Weather Avoidance Decisions
Spatial Filter: None

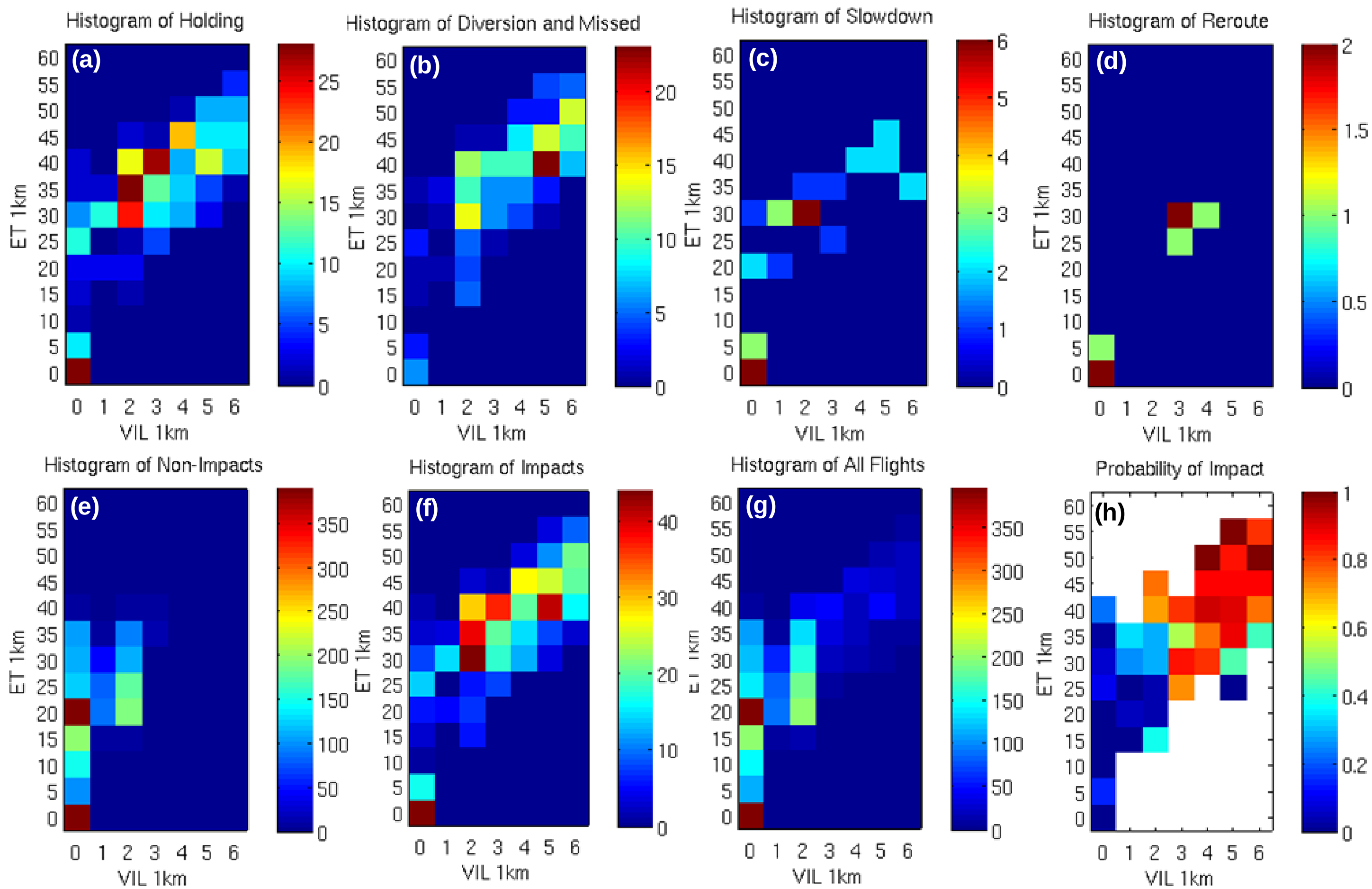

Figure 15. 2D histograms of airport weather avoidance decisions for holding counts ***(a)****, diversions and missed approach counts* ***(b)****, slowdown counts* ***(c)****, reroute counts* ***(d)****, non weather avoidance counts* ***(e)****, sum of holding, diversion, missed, slowdown and reroute counts* ***(f)****, sum of non-impact and impact counts* ***(g)*** *and observed probability of impact (percentage of flights in each histogram bin that were impacted)****(h)*** *for the unfiltered VIL and echo tops. White bins in* ***(h)*** *indicate input data intervals that were not present in the dataset.*

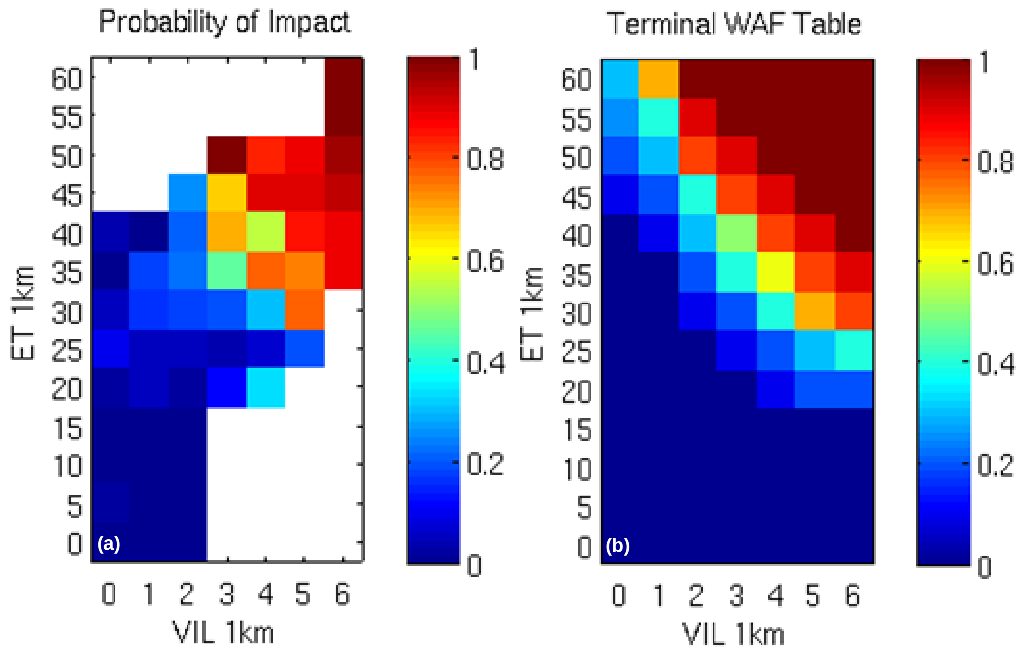

Figure 16. 2D histograms of corner post weather avoidance decisions for all impact types ***(a)****,and proposed terminal weather avoidance field look-up table* ***(b)****.*

Table 3. Proposed arrival CWAM look-up table.

WAF Probability	VIL Precipitation Intensity (VIP Level)							
		0	**1**	**2**	**3**	**4**	**5**	**6**
Echo Top Height (kFT)	0-17.4	0	0	0	0	0	0	0
	17.5-22.4	0	0	0	0	10	20	20
	22.5-27.4	0	0	0	10	20	30	40
	27.5-32.4	0	0	10	20	40	70	80
	32.5-37.4	0	0	20	40	60	80	90
	37.5-42.4	0	10	30	50	80	90	100
	42.5-47.4	10	20	40	80	90	100	100
	47.5-52.4	20	30	80	90	100	100	100
	52.5+	30	40	90	100	100	100	100

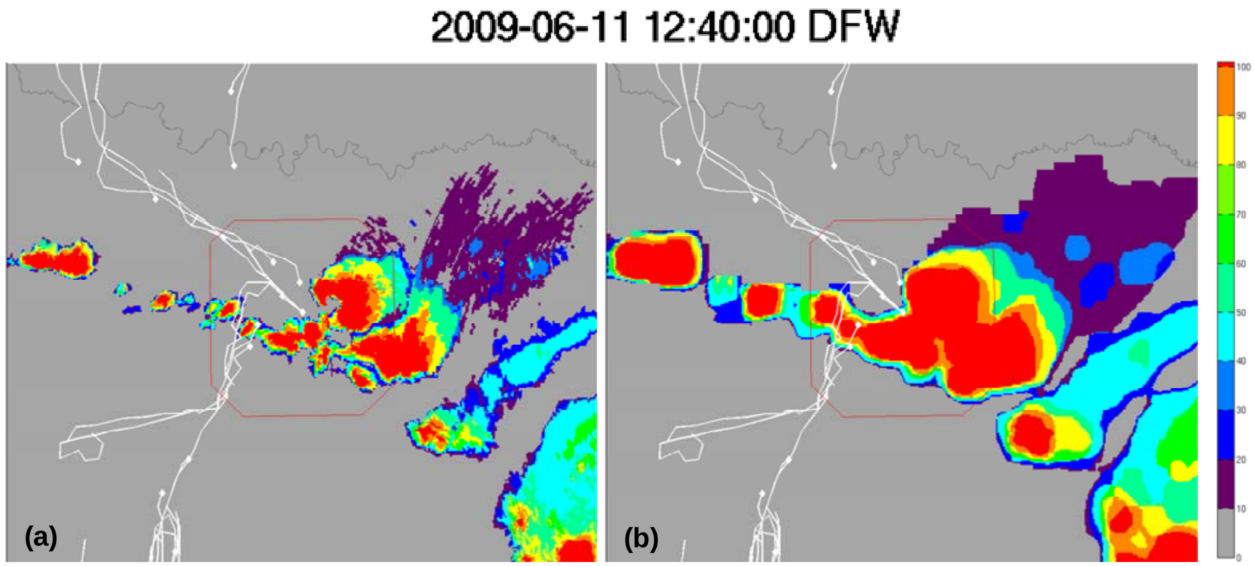

Figure 17. Terminal Arrival Weather Avoidance Field (AWAF) from 1km VIL and echo tops ***(a)*** *and 16km 90th Percentile VIL and echo tops* ***(b)*** *on June 11, 2009 at 12:40Z for the Dallas/Fort Worth TRACON. Aircraft are shown as white diamonds with a tail of 15 minutes. The TRACON is impacted by weather with the northeast and southeast corner posts closed and aircraft finding gaps in the storms on the southwest corner post.*

5. CONCLUSIONS AND FUTURE WORK

This report presented the results of a study that correlated observed weather avoidance decision making for aircraft arriving at large metroplex airports with observable and predictable weather parameters. A data set of weather avoidance decisions was assembled from five days during the summer of 2009 for four (Chicago, Dallas, Denver, Charlotte) major terminal environments. The definition of weather impact and avoidance included pilot decision making occurring within the terminal airspace (between en route airspace near the arrival corner post and runway) in response to terminal area weather impacts (tactical), and decisions made by air traffic management and / or airline dispatch well outside of the terminal in response to the weather expected upon arrival at the terminal (strategic). Tactical decision making includes deviations, missed approaches, and path finding through convective storms. Strategic decision making includes rerouting to an alternative corner post, holding in en route airspace, and diverting to an alternate airport. Strategic weather avoidance decisions were often made many miles outside of the terminal.

A total of over 11,000 aircraft trajectories were analyzed with almost 1,900 weather avoidance decisions for weather in the terminal air space. The most common weather avoidance decision in response to weather impacts near the arrival corner post or in the terminal airspace is to reroute aircraft to a different corner post. This type of weather avoidance accounts for almost half of all avoidance decisions. When weather impacts were observed directly over or very near the airport, placing the aircraft into holding was the most commonly observed weather avoidance decision, accounting for 60% of all avoidance observed.

The results show a strong correlation between precipitation intensity (VIP level) and weather avoidance with a secondary correlation with the storm height (echo tops). Generally, pilots avoided VIP level 3 weather with an echo top height greater than 35kft. However, in some instances level 2 weather with echo tops greater than 40kft. impacted pilot decision making. It is speculated that these storms with higher tops may have lightning embedded within the storm, or were accompanied by convectively induced turbulence that resulted in pilot requests to deviate. Also, data suggested that pilots will penetrate storms with higher precipitation intensity if the echo tops are low enough, perhaps indicating a less convective or turbulent storm. The results also indicate that the use of weather characteristics based on unfiltered VIL and echo tops as weather avoidance predictors were better correleled to observed avoidance behavior. This may indicate pilots' willingness to fly closer to the storms in terminal airspace as compared to the en route airspace, perhaps due to tighter constraints on flight trajectories within the terminal.

From these correlations a proposed arrival Convective Weather Avoidance Model (CWAM) has been developed to provide air traffic controllers and automated decision support systems with a likelihood of the weather impacting terminal operations. The arrival CWAM does not require any spatial filtering of the 1 km. resolution VIL and echo tops products obtained from the CIWS or CoSPA weather forecasts. The arrival CWAM presented is a 2 dimensional lookup table with observed or forecast VIL (VIP level) and echo top height providing the indices.

There are several areas for future research:

1. **Validation, based on observed weather.** The arrival CWAM should be validated against an independent data set, to quantify its accuracy in predicting weather avoidance, false prediction rate, etc.
2. **Validation, based on forecast weather.** In operational use, CWAM must be applied to forecast weather to predict and develop plans to mitigate future weather impacts. Weather forecast error will add to the inherent CWAM error in predicting avoidance behavior with 'perfect' (observed) weather information. Validation against forecast weather is necessary both to determine the robustness of the CWAM against small errors and noise in weather forecasts, and to guide the use of WAFs based on the arrival CWAM in operational decision support.
3. **Characterization, quantification, and development of a model to predict uncertainty in the prediction of weather avoidance based on forecast arrival WAF.** The predicted weather impact in arrival airspace is a critical element in decision support for strategic planning of traffic management initiatives and individual flight plans. The required forecast horizon may be several hours, and measures, characterizations, and predictions of forecast uncertainty appropriate to different decision support systems (fully automated, human in the loop, etc.) must be developed.
4. **Exploration of concepts for arrival CWAM application in decision support, traffic management tools, and time-based metering applications.** Arrival CWAM is likely to be a part of both tactical traffic management and strategic planning decision support systems, and different concepts of use, algorithmic post-processing, and display are likely to be developed.
5. **Identification of key terminal airspaces for CWAM site adaptation (if necessary) and deployment, and development of software architecture to incorporate arrival CWAM processes and arrival WAF distribution into the NextGen Weather Processor.**

6. REFERENCES

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