A Measure of Efficiency of Current Flight Operations in Convective Weather and Use of Weather Polygons in Fast-Time Simulation

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16. Abstract

In order to measure the potential benefits of planned weather improvements, researchers must first understand current practices with respect to weather avoidance. The objectives of this study are to calculate the proximity of aircraft to weather of different severity levels and to investigate the difference in this proximity between flight types (airlines, cargo, general aviation, and military flights). We will also identify specific aircraft which were rerouted due to highly convective weather and measure the additional flight distance incurred due to the reroute.

Given the known impacts weather has on flight operations, the capability to simulate weather in fast-time models is necessary to accurately evaluate NextGen concepts. Thus, the Concept Development and Validation Group (AJP-66) were tasked to satisfy the following business plan goal: Develop the capability to export convective weather polygons for use with current simulation models.

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NextGen, Weather, Efficiency, Reroutes, Fast-time Simulation

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Executive Summary

The Next Generation Air Transportation System (NextGen) is the solution to safety, capacity, and efficiency problems that will result from an expected increase in air traffic. The Federal Aviation Administration (FAA) is primarily responsible for the implementation of NextGen which includes improvements to the management of flight operations, pilot and controller situational awareness, terminal environment flexibility, environmental impact, and weather prediction and avoidance. Convective weather is a significant cause of flight delay as aircraft must avoid severe weather to ensure safety. Multiple enhancements to weather prediction and avoidance techniques are included in the NextGen plan and are expected to reduce flight delays and safety hazards caused by convective weather.

To measure the potential benefits of planned weather improvements, researchers must first understand current practices with respect to weather avoidance. In this document, the Simulation and Analysis Team (AJP-661) evaluates the current efficiency of flight paths during convective weather. The proximity of aircraft to weather of different severity levels is calculated and the difference in this proximity between flight types (airlines, cargo, general aviation, and military flights) is investigated. We also identify specific aircraft which were rerouted due to highly convective weather and measure the additional flight distance incurred due to the reroute. The results of these studies showed that the distance aircraft fly from weather increases with the severity of the weather. During weather of high severity levels, flights remain on average a maximum of approximately ten nautical miles from the weather. When necessary, flights will enter weather of low severity levels but generally avoid all weather if possible. Also, when flights are rerouted around weather, half of the flights deviate less than 21.5nm off their previous route, and cargo flights deviate less than airline, general aviation, or military flights. Overall, this activity demonstrated that today's operations during convective weather are efficient during weather of low severity levels; however, there is room for improvement in the efficiency of operations during severe weather.

Furthermore, the impact of weather on the National Airspace System (NAS) must be considered when analyzing NextGen concepts. In the concept development and validation process, fast-time simulation and modeling exercises are performed to examine system performance, obtain initial assessments of potential benefits, and to identify potential problem areas where real-time simulation studies are necessary for further exploration (Operational Concept Validation Strategy Document, 2003). However, weather has traditionally been excluded from fast-time simulation studies due to its complexity in modeling. To satisfy a need for the capability to model weather in a fast-time environment, the AJP-661 developed a tool which creates weather polygons to be imported into fast-time simulation models. The process of successfully using this tool in one fast-time simulation model, RAMS Plus, is documented in this technical note.

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1 Introduction

The Next Generation Air Transportation System (NextGen) is the solution to safety, capacity, and efficiency problems that will result from an expected increase in air traffic. The Federal Aviation Administration (FAA) is primarily responsible for the implementation of NextGen which includes improvements to the management of flight operations, pilot and controller situational awareness, terminal environment flexibility, environmental impact, and weather prediction and avoidance. Convective weather is a significant cause of flight delay as aircraft must avoid severe weather to ensure safety. Multiple enhancements to weather prediction and avoidance techniques are included in the NextGen plan and are expected to reduce flight delays and safety hazards caused by convective weather.

Furthermore, the impact of weather on the National Airspace System (NAS) must be considered when analyzing NextGen concepts. In the concept development and validation process, fast-time simulation and modeling exercises are performed to examine system performance, obtain initial assessments of potential benefits, and to identify potential problem areas where real-time simulation studies are necessary for further exploration (Operational Concept Validation Strategy Document, 2003). However, weather has traditionally been excluded from fast-time simulation studies due to its complexity in modeling. To satisfy a need for the capability to include weather in a fast-time environment, the Simulation and Analysis Team (AJP-661) developed a tool which creates weather polygons from recorded convective activity to be used in fast-time simulation models

1.1 Purpose

To measure the potential benefits of planned weather improvements, researchers must first understand current practices with respect to weather avoidance. The objectives of this study are to calculate the proximity of aircraft to weather of different severity levels and to investigate the difference in this proximity between flight types (airlines, cargo, general aviation, and military flights). We will also identify specific aircraft which were rerouted due to highly convective weather and measure the additional flight distance incurred due to the reroute.

Given the known impacts weather has on flight operations, the capability to simulate weather in fast-time models is necessary to accurately evaluate NextGen concepts. Current simulation tools consider wind conditions but are limited in their functionality for representing convective weather in a fast-time simulation environment. Thus, AJP-661 developed the capability to export convective weather polygons for use with current simulation models. We will show an example of how the weather polygon tool was used in a fast-time simulation model.

1.2 Background

Aircraft rerouting around weather have been the focus of many studies. The methodologies and results of the studies described below provide an extensive background for our current study.
A study conducted by ISA Software explored the potential benefits of a multi-sector planner (MSP) role in the efficiency of the trajectory flow management (TFM) process during weather events. The study compared the total distance of a flight during a clear weather day with the total distance of the same flights when weather was present. Reportedly, 3.5% of more than 62,000 flights flew up to 200nm greater than originally planned during convective weather activity[1]. The conclusions showed a small room for improvement in efficient TFM operations; however, the study included all flights, those affected and not affected by the weather, in the airspace.

Therefore, one could make the case that there were other causes of the added distance to the flights that are not considered in the MSP study.

A Massachusetts Institute of Technology (MIT) graduate research thesis was conducted in 1999 to determine distances between aircraft and precipitation of varying intensities. Distances were determined through pilot surveys and interviews as well as track data from the Dallas Fort-Worth area. The study concluded that aircraft increase their distance from weather as the intensity of the weather increases[2]. Traffic levels and aviation technologies have changed since the study was performed; therefore, it was appropriate to conduct a follow-on study.

Another MIT LL study described an en route convective weather avoidance model that includes an algorithm to transform gridded, deterministic forecasts of radar echo top height and vertically integrated liquid (VIL – a measure of precipitation intensity) into three-dimensional weather avoidance fields. This algorithm was studied and led to the development of the AJP-661 Weather Polygon Creator[3].

1.3 Scope

The first part of this study examines the proximity of aircraft in Washington (ZDC) and Indianapolis (ZID) Air Route Traffic Control Centers (ARTCCs) to weather at six different severity levels (defined in Section 2.1.1). Due to the FAA suggestion for pilots to remain at least 20 nautical miles (nm) away from weather, the analysis is limited to aircraft within 20nm of an active weather event at any severity level[4]. Since the primary interest is in aircraft that diverted from their planned route to avoid weather, only flight positions considered out of adherence from their planned trajectory are included in the analysis. Four different analysis days were chosen based on the location and severity of their weather events.

A second part of the study focuses on aircraft which were rerouted to avoid penetrating highly convective weather. This activity evaluates the entire set of aircraft in ZDC and ZID on the four chosen days, and the difference in distance flown by the rerouted aircraft is analyzed.

Additionally, the simulation of weather polygons in fast-time simulation models is tested using RAMS Plus. RAMS Plus is a fast-time simulation model that is commonly used by AJP-661.

1.4 Document Organization

The remainder of this document provides details of weather and air traffic data, tools used in this activity, analytical methods for the proximity to weather and weather reroute analyses, the results obtained, and the conclusions drawn. The fast-time simulation usability test case for the polygon creation tool is also discussed.

Section 2 provides detailed information on the data and tools used throughout this research activity. The methodology, results, and conclusions drawn from the proximity to weather and weather reroute analyses are discussed in Section 3.

Section 4 presents the test case performed for the Weather Polygon Creator developed by AJP-661 for use in fast-time simulation models. This section discusses the development of the Weather Polygon tool, the simulation model used for the activity, and the usability of the weather polygons in fast-time modeling.

2 Analysis Preparation

This study focused on calculating the proximity of aircraft to weather as well as identifying flights rerouted due to weather and measuring how far off their original route they actually flew. Extensive data preparation was required to process and filter weather and air traffic data for the analyses. Specific tools were required to do this and are detailed below.

2.1 Data

Both the proximity to weather analysis and the weather reroute analysis utilized and processed weather data and recorded air traffic data.

2.1.1 Weather Data

The first step in obtaining weather data for our analysis was finding weather days with severe weather in ZDC and ZID. To do this, an analyst viewed NEXRAD National Mosaic Reflectivity Images on the National Oceanic and Atmospheric Administration (NOAA) Satellite and Information Service website[5]. Users of the website can view animation of the weather maps per hour for a selected day to evaluate the location and severity of weather events. As a result of this activity, the analyst chose four days to examine: 6-12-2010, 8-5-2010, 8-18-2010, and 5-14-2011. Figures 1-4 below are screenshots of the chosen days on the NOAA website.

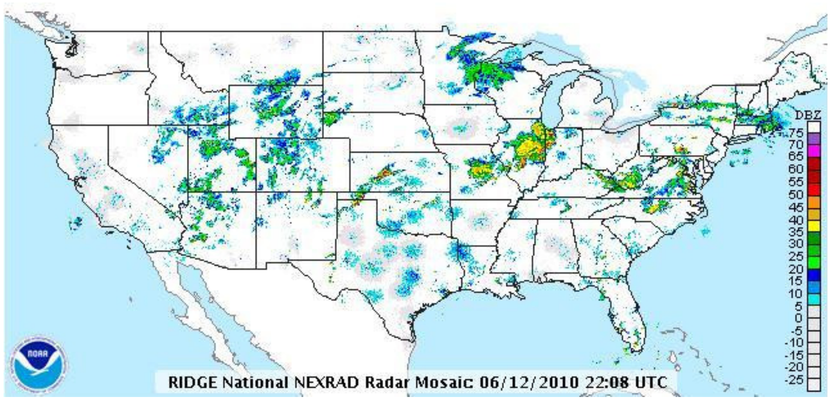

Figure 1. NEXRAD Weather Map for 6-12-2010[5]

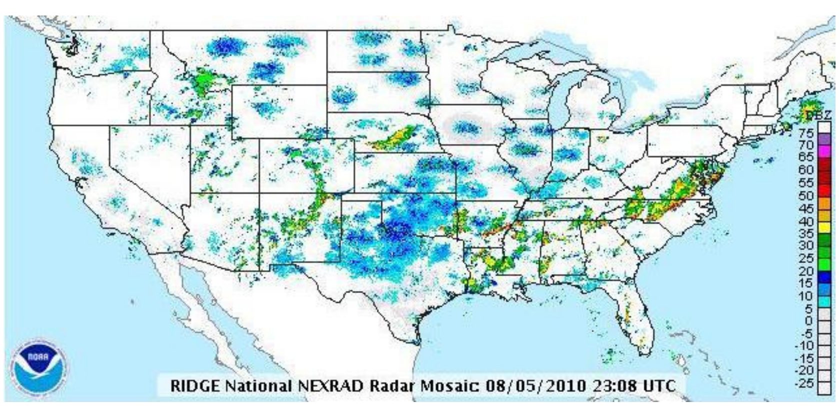

Figure 2. NEXRAD Weather Map for 8-5-2010[5]

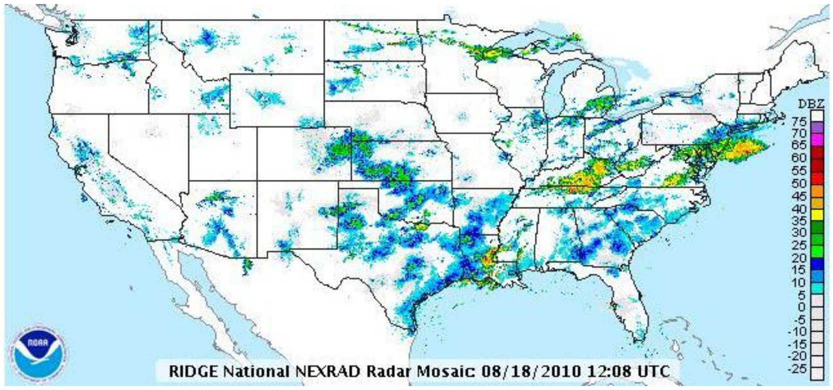

Figure 3. NEXRAD Weather Map for 8-18-2010[5]

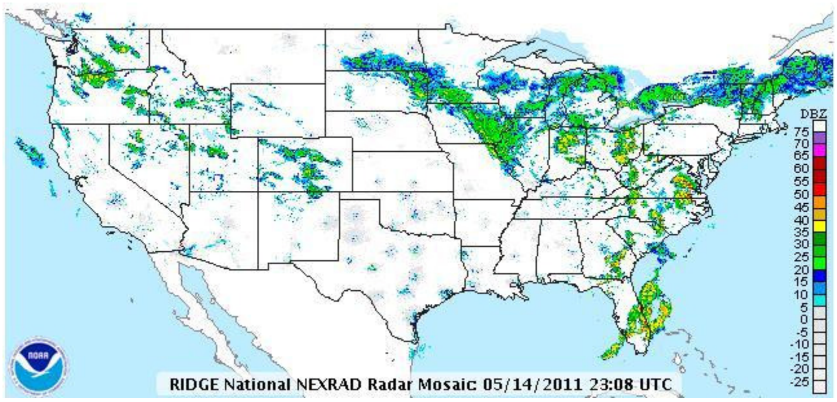

Figure 4. NEXRAD Weather Map for 5-14-2011[5]

Next, researchers in the FAA's NAS Weather Group (AJP-68) provided Multi-Radar/Multi-Sensor (MRMS)[6] weather data for the selected days in both ZDC and ZID ARTCCs. The MRMS data is provided in a binary format called NetCDF*. The data contains a four dimensional array that has a single value of radar reflectivity measured in dBZ† at each time, latitude, longitude, and altitude combination. In 2010, data measurements are taken every 2.5 minutes at each 0.01 degrees in each direction, with 31 altitude levels ranging from 1,600 ft to 50,000 ft. In contrast, weather data from 2011 provides these measurements every 2 minutes. This grid of data covers the continental USA and the lower half of Canada, but it is split into eight tiles in order to provide more manageable sizes (shown in red in Figure 5). The tiles used in this study were those covering the majority of the ZDC and ZID ARTCCs (shown in green in Figure 5) which contain 124 million and 62 million measurements, respectively.

* http://www.unidata.ucar.edu/software/netcdf/

† http://en.wikipedia.org/wiki/DBZ_(meteorology)

Figure 5. MRMS tiles overlaying the continental USA with ZDC and ZID boundaries

For this analysis, reflectivity values provided in the MRMS data were translated to hazard levels that align with the National Convective Weather Forecast (NCWF) Hazard Levels as shown below. Results are reported based on NCWF Hazard Levels.

Reflectivity (r)	NCWF Hazard Level
r <30	1
30 <= r < 41	2
41 <= r < 46	3
46 <= r < 50	4
50 <= r < 57	5
r >= 57	6

Table 1. Hazard Level Definitions of Reflectivity Value

2.1.2 Traffic Data

Data from several current operational systems (e.g., ARTCC Host systems, ETMS) are regularly recorded by the FAA to keep a historical record of the National Airspace System (NAS) activity. For this study, Host Air Traffic Management Data Distribution System (HADDS) traffic data was obtained for the days identified in the previous section. This operational data is processed through AJP-661 internal tools which smooth the traffic data and perform key performance calculations for each trajectory (see Section 2.2.1). Table 1 below lists the original total aircraft count for each scenario as well as the total number of flights analyzed in each part of the study (proximity analysis and reroute analysis). The final data sets for the proximity analysis were obtained by extracting flights within 20 nm of any level of weather (see Section 2.2.2); whereas, the final sets of flights for the reroute analysis were selected using the Reroute Detection Tool described in Section 2.2.3. The number of aircraft in the proximity analysis scenarios is highly dependent on the amount and location of convective weather. Naturally, more flights are affected by a large amount of weather present in a major traffic flow than smaller amounts of weather or weather in an area of the ARTCC that is less frequently travelled.

Scenario		Total Number of Flights	Number of Flights in Proximity Analysis	Number of Flights in Reroute Analysis
Date	ARTCC			
6-12-2010	ZDC	5304	678	49
6-12-2010	ZID	4570	837	98
8-5-2010	ZDC	5893	1104	168
8-5-2010	ZID	5941	918	152
8-18-2010	ZDC	6140	4353	155
8-18-2010	ZID	6030	1235	24
5-14-2011	ZDC	5414	4100	33
5-14-2011	ZID	4373	3046	29

Table 2. Number of Flights per Scenario

2.2 Tools

The following tools were used to process and analyze the weather and air traffic data discussed above.

2.2.1 TrajTools

Recorded air traffic data in ZDC and ZID on the days specified for this analysis are processed in a suite of tools referred to as TrajTools. Using TrajTools, an analyst can validate and smooth the raw traffic data to fix issues with incomplete or incorrect flight data. Through this process, all VFR flights are removed, flight data is interpolated to create uniform 10 second intervals between track recordings, and several trajectory adherence metrics are calculated and stored in Oracle databases. For example, horizontal, vertical and time deviations of the actual flight path are measured against the current flight plan. Route amendments from Common Message Set (CMS) data are considered in these accuracy measurements to utilize the most current flight plan information. These route amendments are used in the determination of aircraft rerouted due to weather (see Section 2.2.3 for more details on the algorithm).

2.2.2 Weather Calculation Tools

Three tools were created to process the weather data.

2.2.2.1 MRMS Tracker

The first weather processing tool that was built is called the MRMS Tracker and calculates the distance from each flight's recorded track points to the nearest grid cell of MRMS data at multiple user-defined reflectivity bins. This study used the NCWF Hazard Level scale defined in Section 2.1.1. This tool uses the actual paths the flights flew, as recorded by the Host Computer System (HCS), as well as the raw MRMS 4-dimensional grid.

The recorded track data used in this tool is run through TrajTools to clean up the data, reduce the noise that was generated by the radar and interpolate to create uniform 10 second intervals between track recordings. When the MRMS Tracker runs, it takes each of these track points at the 10 second intervals and finds the closest point of weather that is within 20 nm, for each of the 6 defined hazard levels. This process is done by searching the MRMS grid outward in a circular pattern until a grid point is found that is at a particular hazard level. Because of the massive amount of data contained within the MRMS grid, this process typically takes several hours to run on a 12-hour scenario.

The process of running MRMS Tracker provides a good overview of the data and gives an idea of how close flights come to weather; however, because the MRMS data is such high resolution, and this process uses the raw MRMS data, it is susceptible to noise. Also, since the data is stored as grid points it does not have any volume, so the only way to determine how far into a weather cell an aircraft travels is by looking at a visualization of the data. Furthermore, because the lower levels of reflectivity are typically more common and the weather cells are larger, distances measured in this process are biased to be larger with higher reflectivity levels, and smaller with lower reflectivity levels.

2.2.2.2 Weather Polygon Creator

The Weather Polygon Creator converts MRMS weather data into three dimensional polygons to be used in fast-time simulations and other data processing tools. Since the MRMS data set is very large, the eight tiles (latitude-longitude grids) that comprise it are processed through the conversion tool individually. An MRMS file associated with each tile contains reflectivity values for 31 altitude bands every 2 or 2.5 minutes (depending on the year of the data). The files are processed concurrently.

During the conversion process, a polygon is created for each hazard level at each of the 31 altitude bands. Since there is a large amount of data, only reflectivity values at or above 18 dBZ are used. This value represents light precipitation and is the minimum reflectivity value considered for the creation of echo tops; thus, reflectivity values below 18 dBZ are assumed to be negligible. A reflectivity value is assigned to each cell in the grid. Within a specific altitude band, a cluster algorithm is used to group neighboring cells by reflectivity value. The algorithm groups cells with hazard level at or above the current level, starting with Level 1 and moving consecutively until Level 6. Figure 6 below illustrates this process. A polygon is created to encompass the cluster of cells for each hazard level, and the algorithm begins the same process for the next altitude band. The result is a collection of polygons at each altitude band that contains individual polygons representing weather at each hazard level. These polygons are stored in a database table and used in data processing and analysis tools such as the Reroute Detection Tool and FlightGUI.

In fast-time simulation, there is no need to distinguish between polygons of different hazard levels; only one polygon representing a cluster of severe weather is needed in order to model aircraft avoiding the weather. To adjust for this difference, the Weather Polygon Creator will group nested or combined polygons of hazard levels greater than 3 and create one polygon to represent severe weather.

This process is repeatable; data from another day or for another tile can be used as input to create new weather polygons. Once the tables have been populated, it is a simple process of formatting the data into the specific fast-time model file format to import the polygons into a fast-time simulation tool.

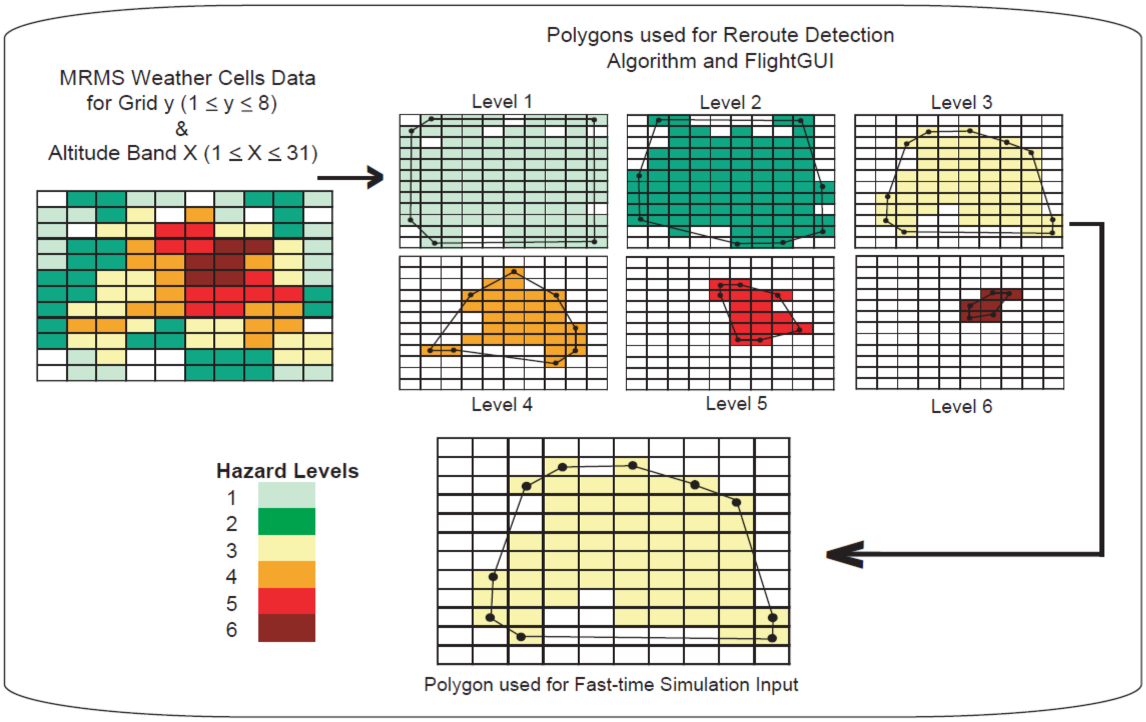

Figure 6. Weather Polygon Creator Process Diagram

2.2.2.3 Weather Polygon Tracker

Once the MRMS data has been processed into convective weather polygons using the Weather Polygon Creator, new opportunities are available for data processing. The Weather Polygon Tracker uses a similar method to the MRMS Tracker of measuring the distance at each recorded track point. However, the polygons give the weather data a volume and boundary; therefore, it can be determined how far into the weather polygon an aircraft travels. This information is an important key to determining when an aircraft reroutes around weather.

The Weather Polygon Tracker can be used to evaluate the recorded flight paths, similar to what was done with the MRMS Tracker, as well as predicted flight paths. The output data is much less susceptible to error than the MRMS Tracker because the Weather Polygon Creator is able to remove a lot of noise. The Weather Polygon Tracker is a key tool used in the Reroute Detection Tool algorithm.

2.2.3 Reroute Detection Tool

There is no existing data which states the cause of a rerouted flight. Thus, determining which flights were rerouted due to weather is not trivial. One method employed in other research[7] involves an analyst visually identifying flights with rerouted flight paths avoiding the weather. This method is viable for a relatively small sample size of flights; however, this study is focused on thousands of flights in each scenario. Therefore, we developed an algorithm to select flights rerouted due to weather.

The algorithm considers amendments to the flight path found in CMS data. Using an in-house trajectory predictor[8], predicted flight paths (trajectories) are created each time a new route amendment was generated by an Air Traffic Controller. The trajectory that is generated uses the current flight position, heading, speed, rate of climb or descent (when applicable), and clearance altitude to predict positions of the aircraft up to an hour into the future. The distances to weather polygons are then determined for each 10 second interval along these trajectories. Each flight may have several trajectories; thus, it is determined for each flight if at least one of these trajectories enters a severe weather polygon (41+ dBZ reflectivity). For each flight, if there are trajectories that enter into the severe weather polygons, then the trajectory that penetrates the furthest into the most severe weather is chosen as the “original route” to be compared against the actual flight path of the aircraft. If no trajectories for a particular flight enter severe weather polygons, then that flight is not determined to reroute due to severe weather. Figure 7 below provides an example of a weather rerouted flight; the solid, blue tube represents the flight’s planned route entering severe weather while the dotted path shows the actual flight path avoiding the weather.

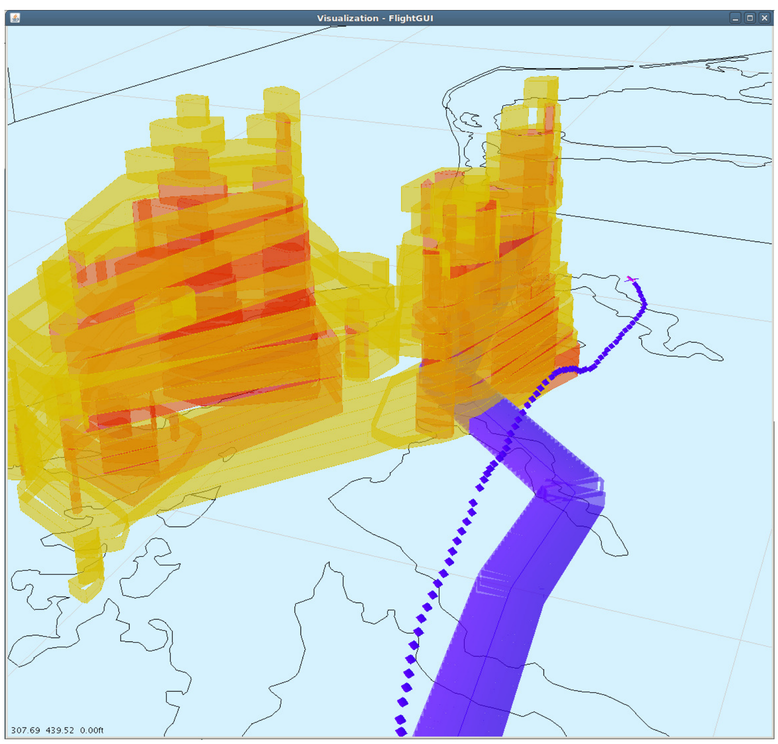

Figure 7. FlightGUI Visualization of Flight (blue, dotted path) Deviating from Planned Route (blue, solid tube) to Avoid Severe Weather

The algorithm was implemented in a program to automate the weather reroute detection process. The steps of the algorithm are as follows:

1. Generate a new predicted trajectory at each route amendment that follows the route at the flight's current altitude and speed.

2. Calculate distance of each predicted trajectory point (10 second sample time) to each of the four most severe reflectivity level (3-6) polygons.
3. Flights that possess at least one predicted trajectory which penetrates a weather polygon of hazard level 3-6 are flagged as weather reroutes.
4. For each flight, find the trajectory that goes the furthest into the maximum reflectivity polygon. This trajectory will be compared against the actual flight path of the aircraft.

2.2.4 Analytical Tools

Statistical software products JMP and Statistical Analysis System (SAS) are used to analyze the weather and traffic data. JMP is a product of the SAS Institute that provides a user-friendly graphical interface and allows the user to easily manipulate data tables and create meaningful graphs. SAS is also provided by the SAS Institute and allows an analyst to perform data entry and manipulation, statistical analyses, operations research, and create customized graphics through user-written codes in the SAS programming language.

FlightGUI is an interactive three-dimensional visualization tool for air traffic data built by AJP-661. For this project, the capability was added for 3D weather polygon visualization. Using this new option and its ability to show flight paths and trajectory predictions, users can view the air traffic data with the convective weather and see the reroutes from all angles with a high level of detail. The trajectory prediction display allows the analyst to see where the flight would have been if it had not rerouted around the weather. This tool was useful in validating the Reroute Detection Tool since the analyst could clearly see the aircraft avoid the weather as the reroute occurs. FlightGUI was also used to visualize the behavior of outliers in the proximity to weather analysis.

Figure 8 shows an example of one of the aircraft rerouting around the severe weather cells as it takes off. Since the reroute analysis only considers hazard levels of 3 through 6 (yellow, orange, red, and dark red), levels 1 and 2 are hidden in this visualization. The purple airplane is where the flight is located currently, and the diamond trail behind the aircraft is the actual flight path. The purple tube is the path the aircraft would have flown if it had not rerouted around the weather, and the darker purple marker inside the tube is where it would have been at the current time.

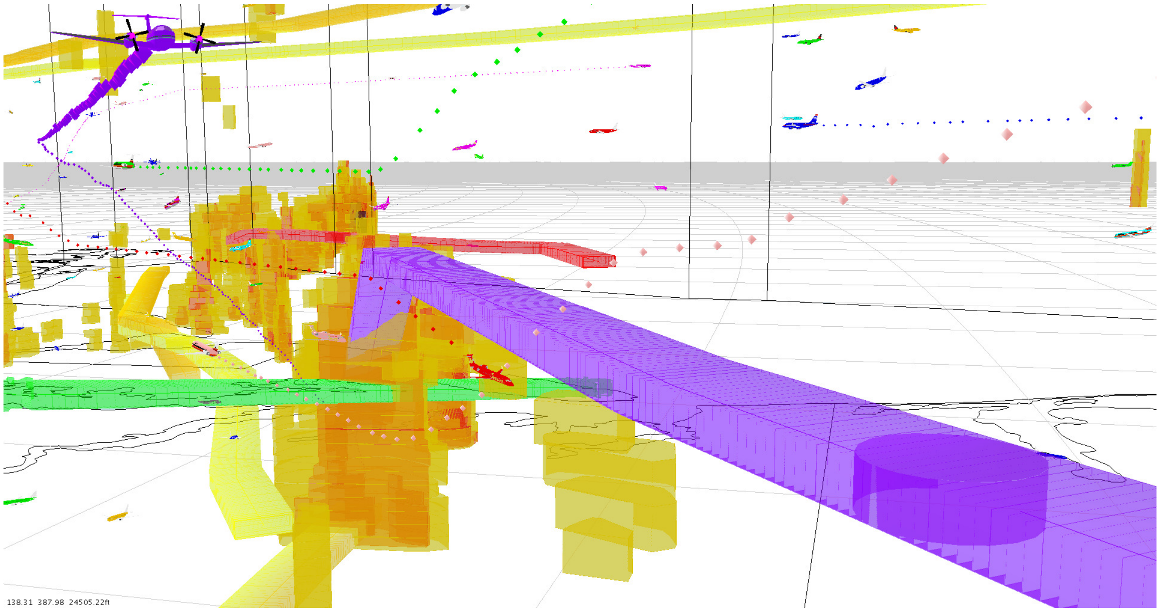

Figure 8. Aircraft Rerouting around Severe Weather Cells in FlightGUI

3 Analytical Methods and Results

Two analyses were conducted for this study: the proximity to weather analysis and the weather reroute analysis.

3.1 Proximity to Weather Analysis

One of the objectives of this study is to determine how close aircraft fly to different severity levels of weather. This analysis is particularly interested in aircraft that are not adhering to their current flight plan. Since the FAA recommends maintaining a safe 20nm distance from any weather, only flights within 20nm of weather are considered in this analysis.

The MRMS Tracker was used to identify flights within 20nm of weather and provided the distance of each flight to the six hazard levels of weather at 10 second intervals. Analysts used the adherence flag obtained through TrajTools for each track point of every flight to select only the instances where a flight was out of adherence from its current flight plan. Finally, JMP and SAS were used to identify the closest point at which each flight flew near the weather. The minimum distance to each level of weather was found for each flight, and the distribution of these results were reported.

It is important to note that a slight difference in data exists between 2010 and 2011 weather data. As previously mentioned, MRMS weather data from the year 2010 provides reflectivity values every 2.5 minutes; whereas, MRMS weather data from the year 2011 provides reflectivity values every 2 minutes. Also, due to the high number of charts produced for these analyses, only two of the chosen days will be reported in this section. Charts associated with 6-12-2010 show results that are similar to those of 8-5-2010 and 5-14-2011. The results for 8-18-2010 are also reported in this section since they indicate higher amounts of weather than the other days analyzed. All additional charts can be found in Appendix A.

3.1.1 Results and Conclusions of Proximity to Weather Analysis

The proximity to weather analysis examined the typical minimum distance to weather for a flight during convective weather. The analysis first considered all flights then evaluated the differences between flight types.

3.1.1.1 Proximity to Weather Results Overall

Figure 9 below provides the number of flights in ZDC which flew within 20nm of weather for each of the selected days. The chart shows the flight count for each of the severity levels of weather, and Figure 10 contains the same information for flights in ZID. It is apparent in both figures that many more flights travel within 20nm of weather at hazard levels 1 and 2 than at more severe levels. This result is expected based on previous research[2]. However, the number of flights within 20nm of more severe weather seems to be somewhat sporadic, changing with the day and ARTCC. It is assumed that this is due to the amount and location of severe weather present during each of the days analyzed. For example, 3.3% of the flights in the ZDC 8-5-2010 scenario flew within 20nm of level 4 weather while 7.7% of the flights in the ZID 6-12-2010 scenario flew within 20nm of the same level of weather. Since this is not a trend among the other days, it can not be concluded that more flights in ZID fly close to severe weather than flights in ZDC. Therefore, it is assumed that this difference is due to the inconsistency of weather day to day. This is the cause of the high flight count in both ZDC and ZID on 8-18-2010. An unusually high amount of weather was present on this day; thus, more flights were impacted and forced to fly within 20nm of the weather. Sector size and shape within each ARTCC could also play a role in how close aircraft flew to the weather.   Air Traffic Controllers may have restricted options for reroutes due to handoff location, point-outs, etc.

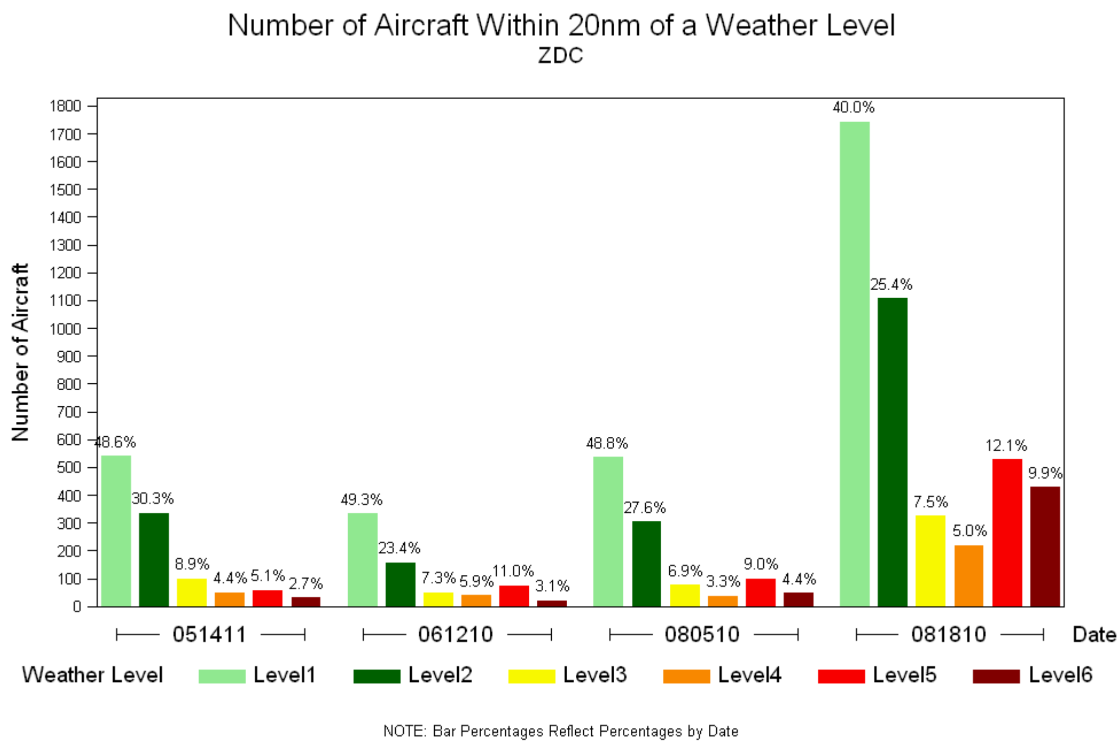

Figure 9. Number of Aircraft within 20nm of each Weather Level in ZDC

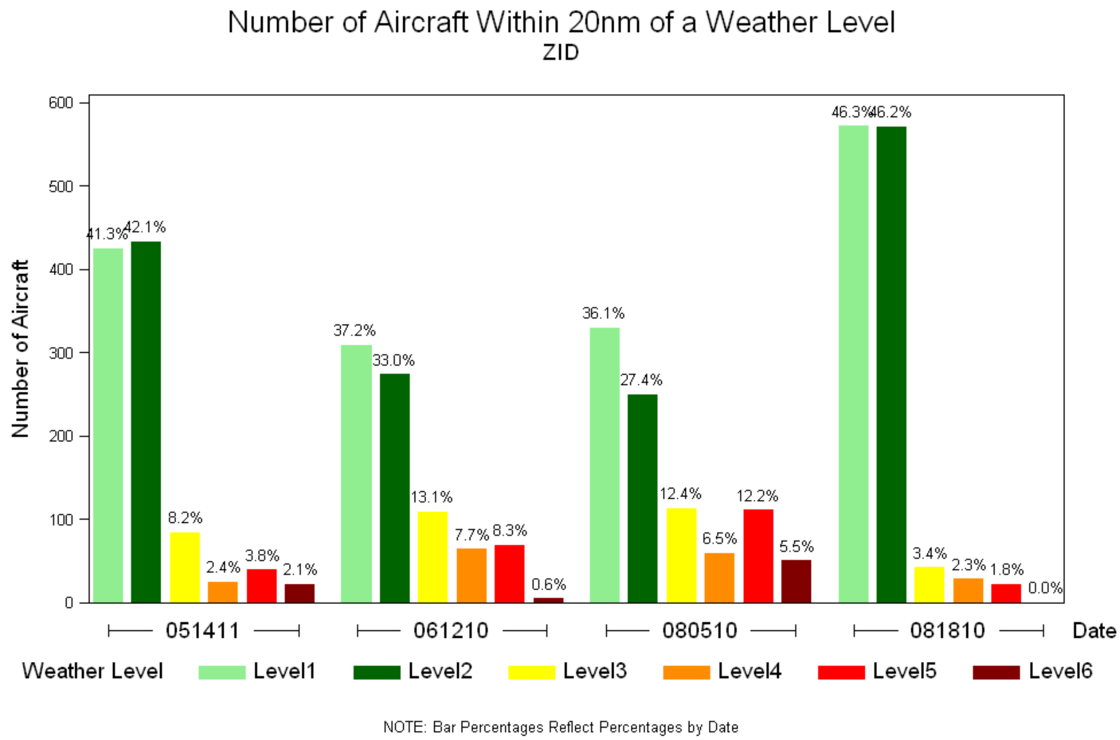

Figure 10. Number of Aircraft within 20nm of each Weather Level in ZID

The figures below show the overall results of this analysis. For each scenario (ARTCC and date combination), the first chart shows the distribution of the minimum distance to each weather level for the aircraft in the scenario. In other words, this is a snapshot of how close to weather each aircraft flew in the stated ARTCC on the stated day. The second chart shows the cumulative percentage of flights by the minimum distance to weather at each severity level. One can read from this chart, for example, that on 6-12-2010 in ZDC about 75% of the flights flew within 10nm of Level 1 weather.

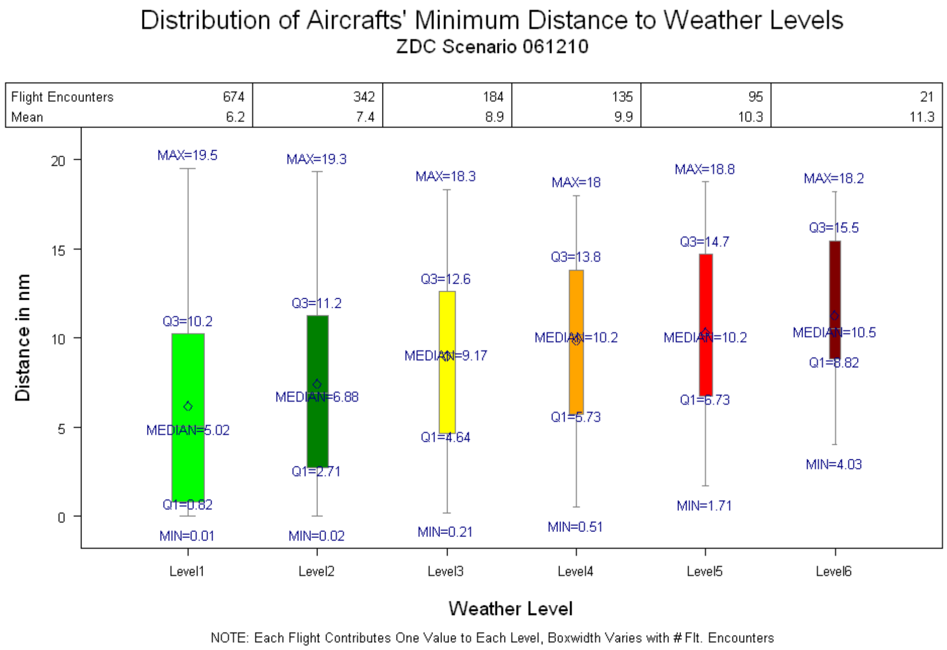

Figure 11. Minimum Distance of Aircraft to Each Weather Level on 6-12-2010 in ZDC

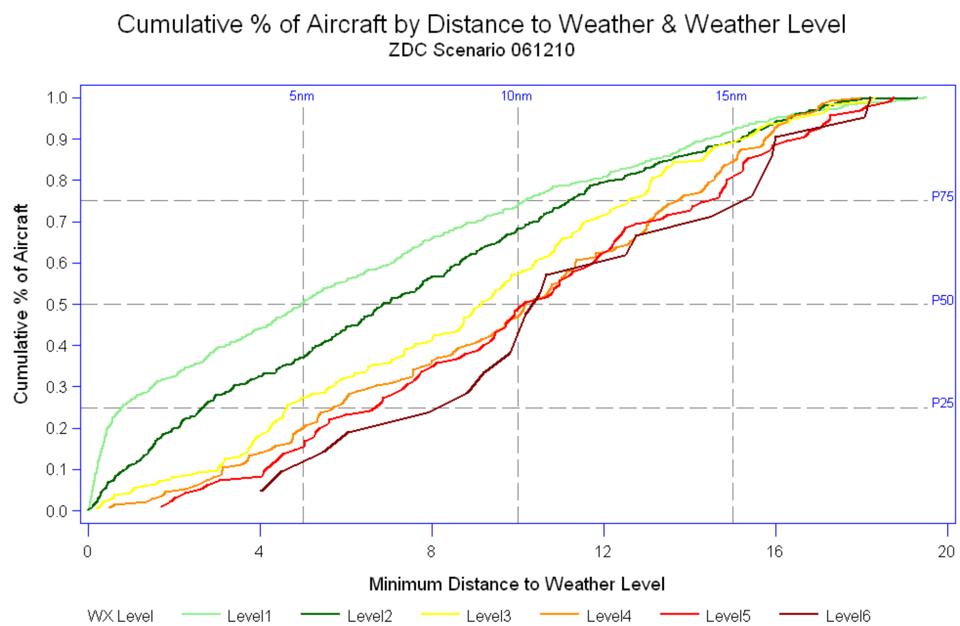

Figure 12. Percent of Aircraft by Minimum Distance to Weather Levels on 6-12-2010 in ZDC

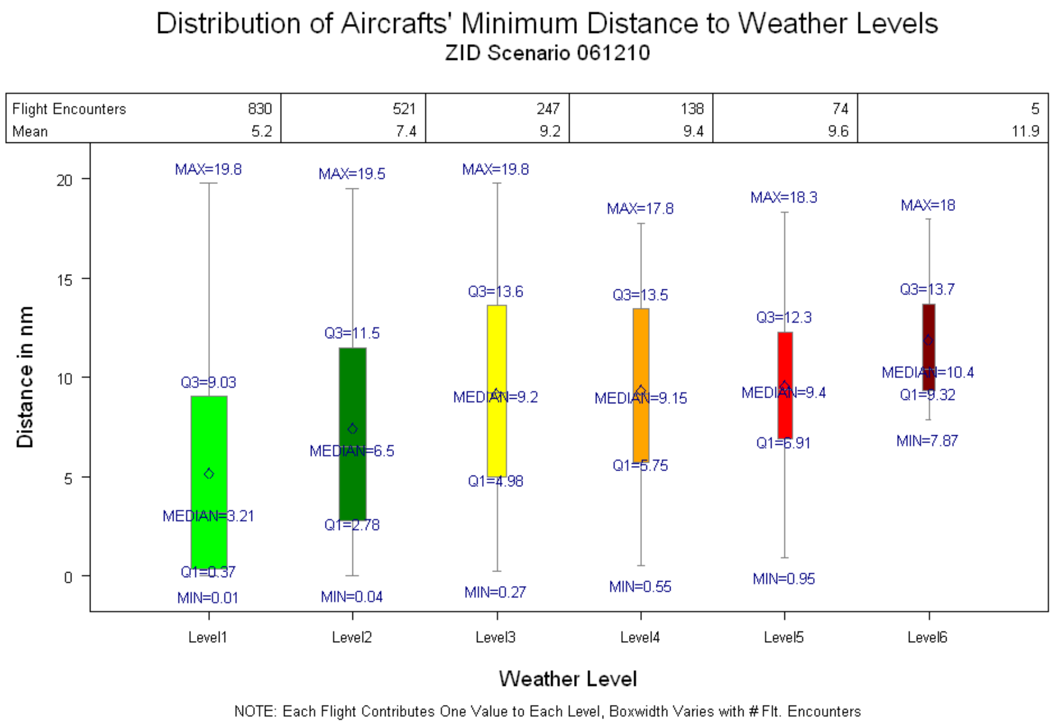

Figure 13. Minimum Distance of Aircraft to each Weather Level on 6-12-2010 in ZID

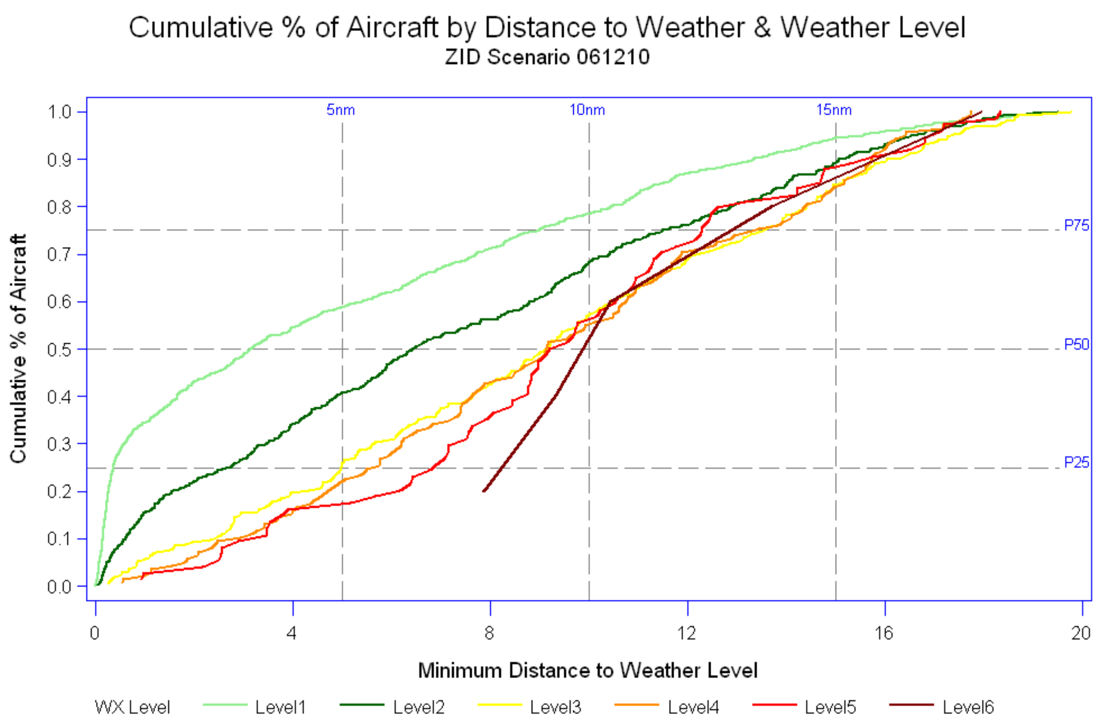

Figure 14. Percent of Aircraft by Minimum Distance to Weather Levels on 6-12-2010 in ZID

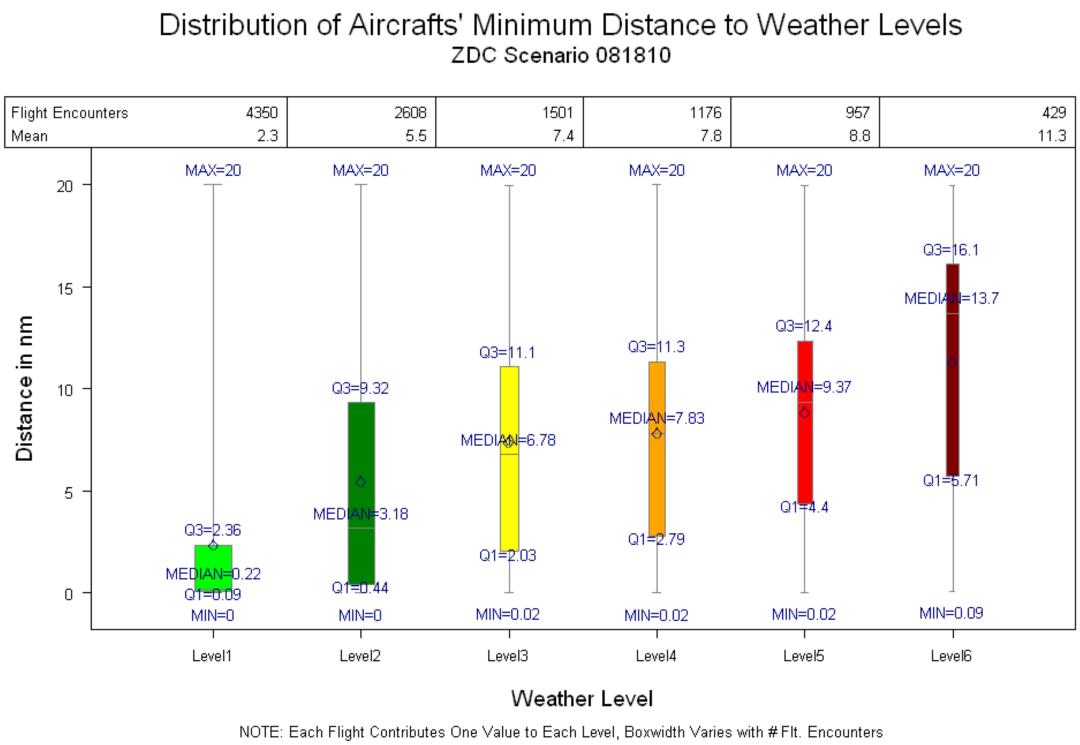

Figure 15. Minimum Distance of Aircraft to each Weather Level on 8-18-2010 in ZDC

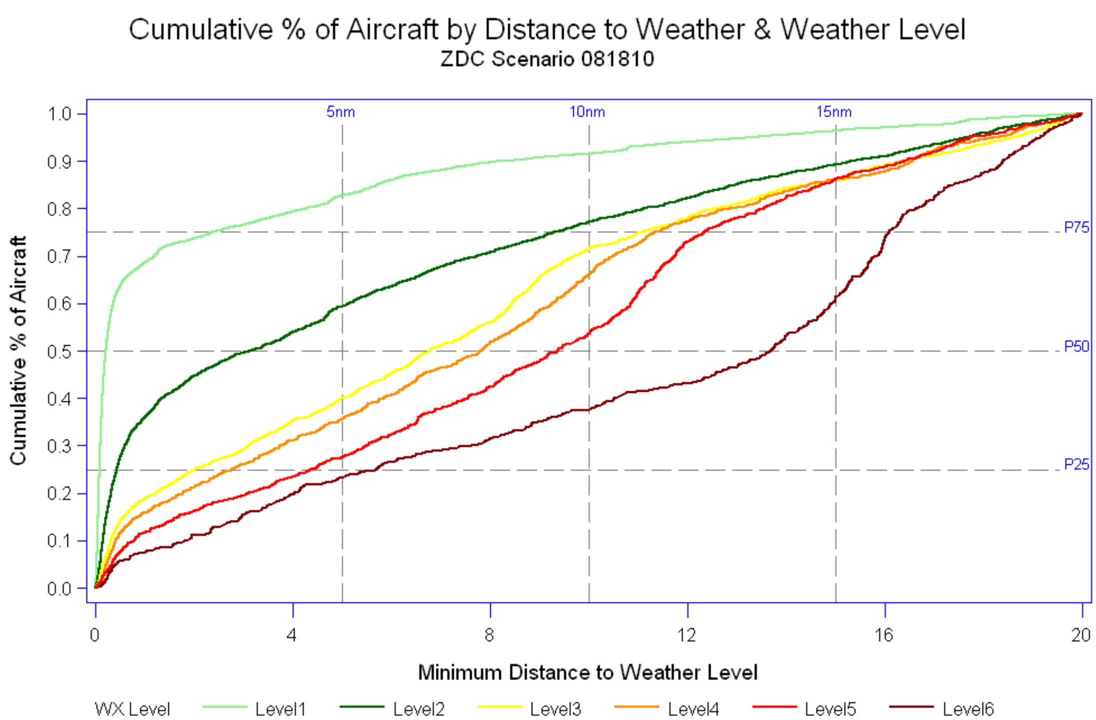

Figure 16. Percent of Aircraft by Minimum Distance to Weather Levels on 8-18-2010 in ZDC

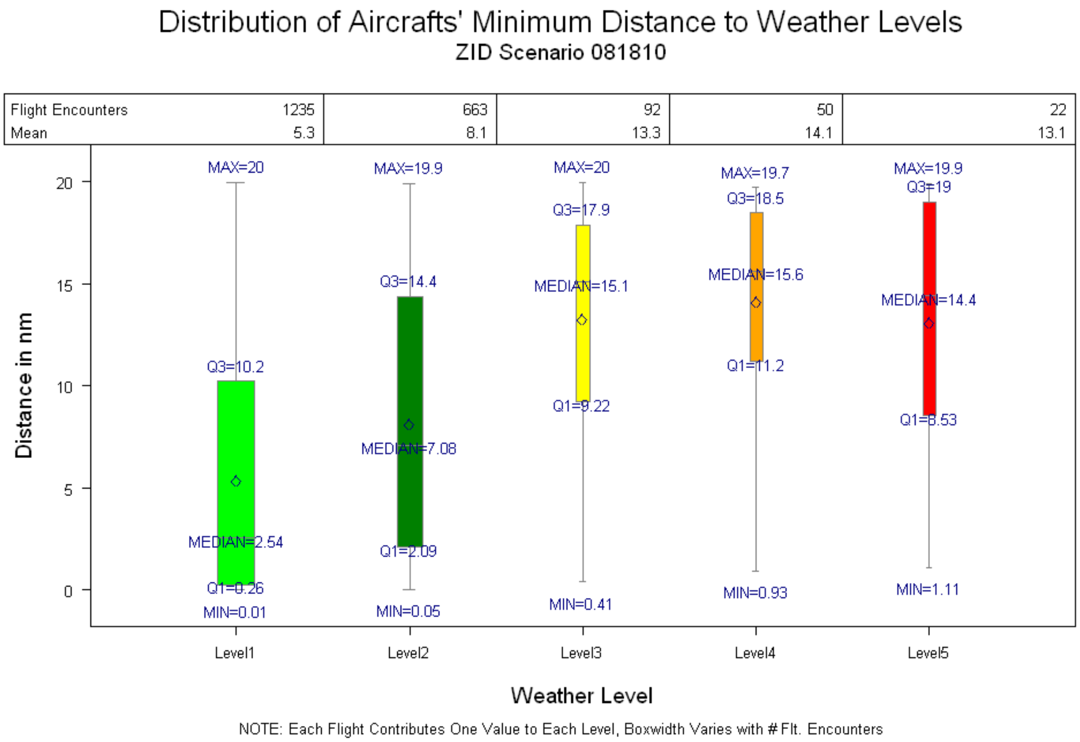

Figure 17. Minimum Distance of Aircraft to each Weather Level on 8-18-2010 in ZID

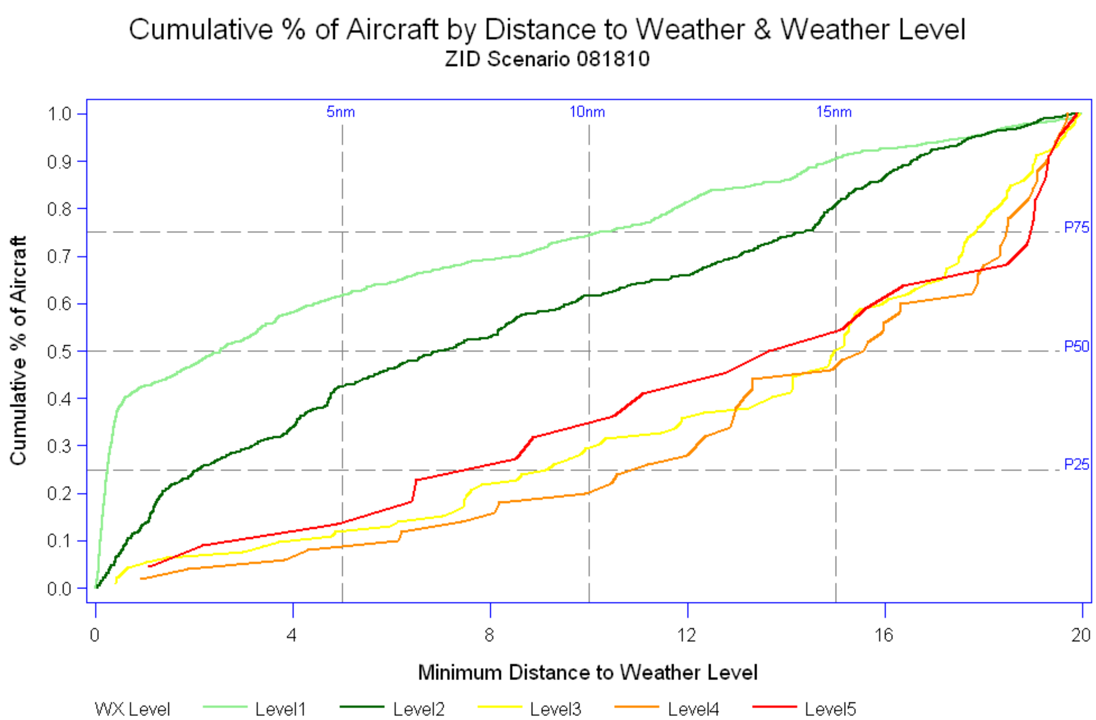

Figure 18. Percent of Aircraft by Minimum Distance to Weather Levels on 8-18-2010 in ZID

The box plots in Figures 11, 13, 15 and 17 provide the minimum, median, mean, and maximum values of the closest distance to each weather level. In general, these values increase as the weather level increases since aircraft tend to avoid higher levels of convection. The plots also show that on most days with convective weather, flights stay at least 2nm away from level 1 weather. However, when large amounts of convective weather are present, more aircraft fly through or very close to weather at low levels. On 8-18-2010 in ZDC, more than half of the flights (68.5%) flew closer than 1nm away from level 1 weather. This could indicate that aircraft will attempt to fly a safe distance (at least 2nm according to the data) from weather at low levels of severity; if this is not possible due to the amount of weather, they can and will fly directly through low levels of weather. This may be attributed to airlines wanting to stay on schedule as best as possible or Air Traffic Controllers being limited in rerouting options. This is not true for more severe levels of weather. Flights tend to fly a maximum of approximately 10nm away from weather at levels 4, 5, and 6. This is most likely due to the increase in turbulence and risk involved in flying through highly convective weather; however, it reflects an area of inefficiency that could possibly be improved in NextGen through improvements to weather prediction and awareness as well as operational improvements to traffic flow management.

3.1.1.2 Proximity to Weather Results by Flight Type

All flights in this analysis were assigned a flight type: airline, cargo, general aviation (GA), and military. This was done based on the aircraft's call sign and, in some cases, aircraft type. These flight type designators were used to examine potential differences in the proximity of the flights to weather. Figures 19 and 20 contain the count of flights within 20nm of weather for each flight type on each of the four chosen days. It is clear that a majority of the flights each day are airline, and general aviation flights account for the second highest percentage of flights.

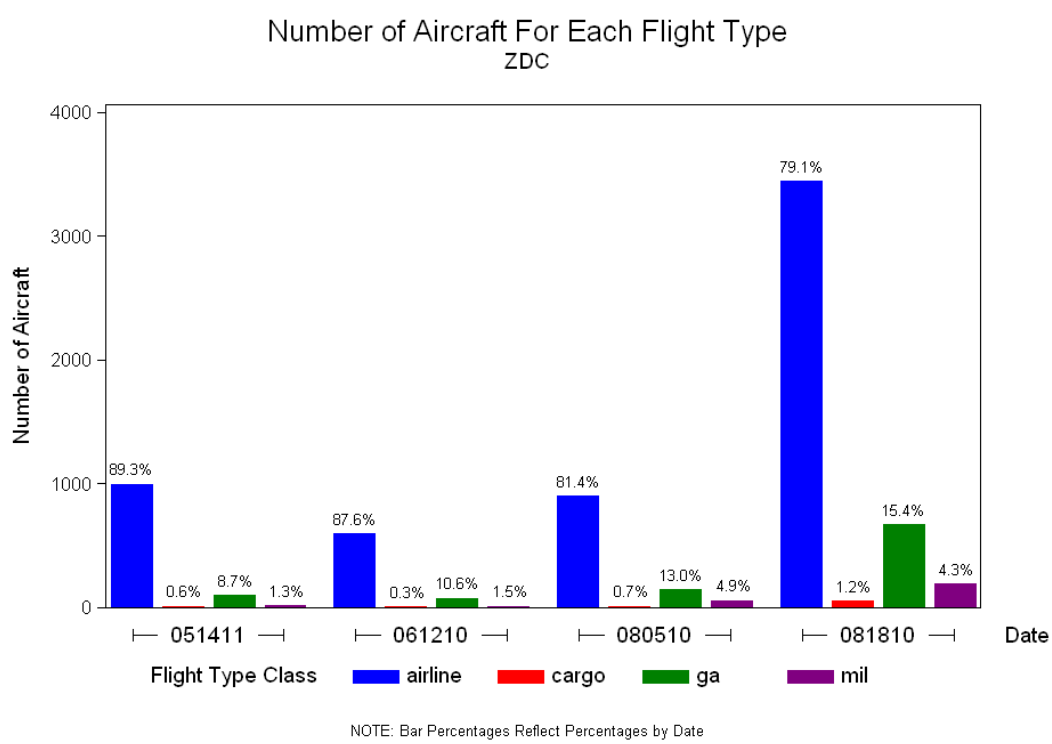

Figure 19. Number of Aircraft per Flight Type in ZDC

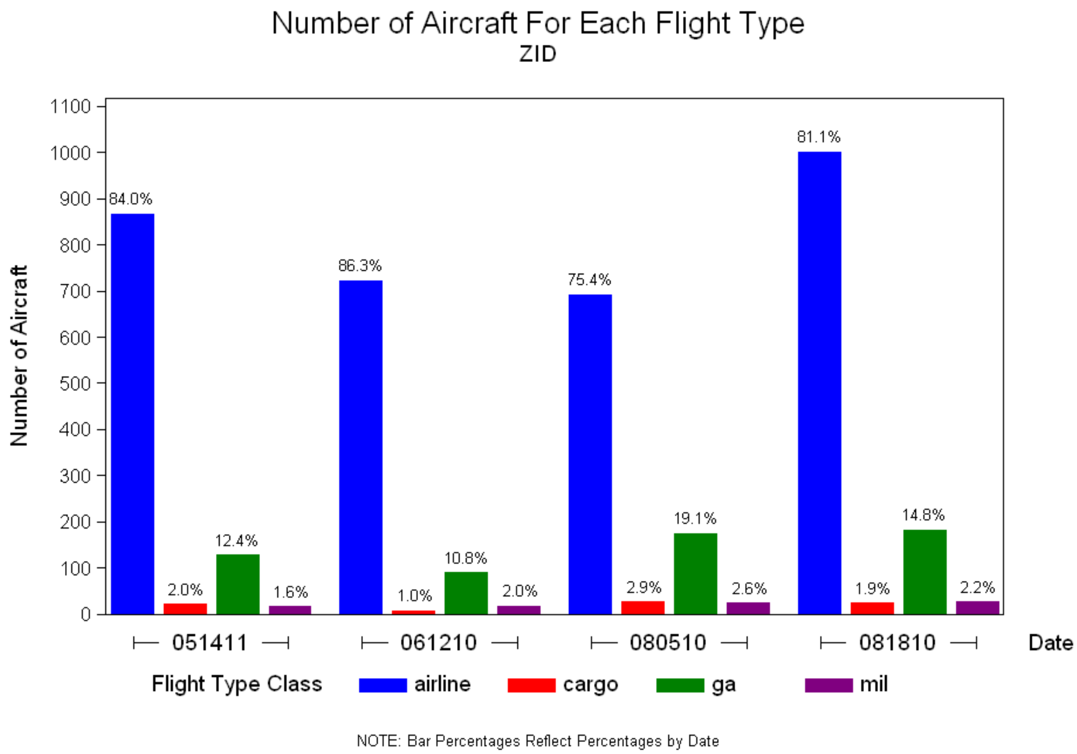

Figure 20. Number of Aircraft per Flight Type in ZID

It was assumed that airlines would fly farther away from weather than cargo, GA or military flights since the comfort of the passengers is a prime concern. Figures 21-24 below show how close aircraft of different flight types flew to different severity levels of weather. The median statistic is used. In some cases, no data exists for a particular combination of flight type and weather level in a scenario. These cases may indicate that no flights of the given flight type came within 20nm of the specific level of weather; alternatively, these cases could mean that none or very little of the specific level of weather was present.

One can conclude from these figures that airline and GA flights tend to fly roughly as close to each weather level. This result makes sense since both flight types may carry passengers who would prefer to avoid highly turbulent airspace. In some scenarios, GA flights flew farther away from the weather than airline flights, which can be explained by the fact that GA aircraft are typically smaller and more heavily impacted by convective weather. They also often do not have the onboard weather technology that many of the airlines have; thus, they rely on ATC weather reports or visual reference and may wish to allow more room for error. It is harder to detect a trend in cargo and military flights. This is partly due to the smaller sample sizes available, but another theory is that their operations near weather depend heavily on the type of cargo or on the military mission. Since this information is not available for this analysis, we can not make any conclusions on cargo and military flights.

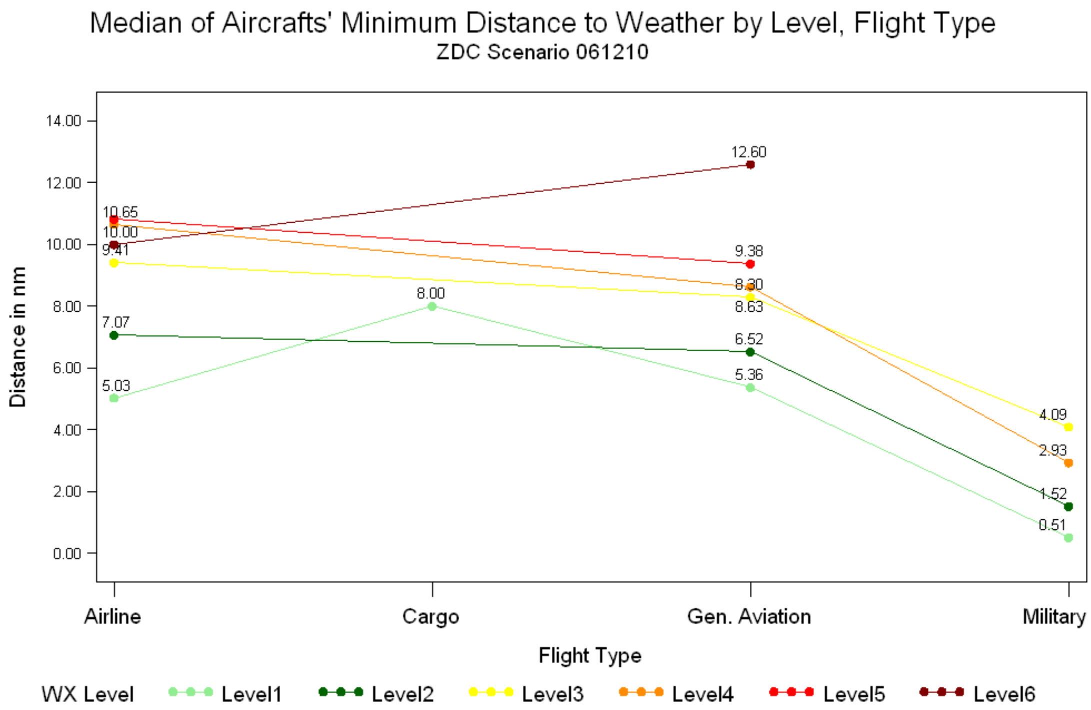

Figure 21. Minimum Distance to Weather by Flight Type on 6-12-2010 in ZDC

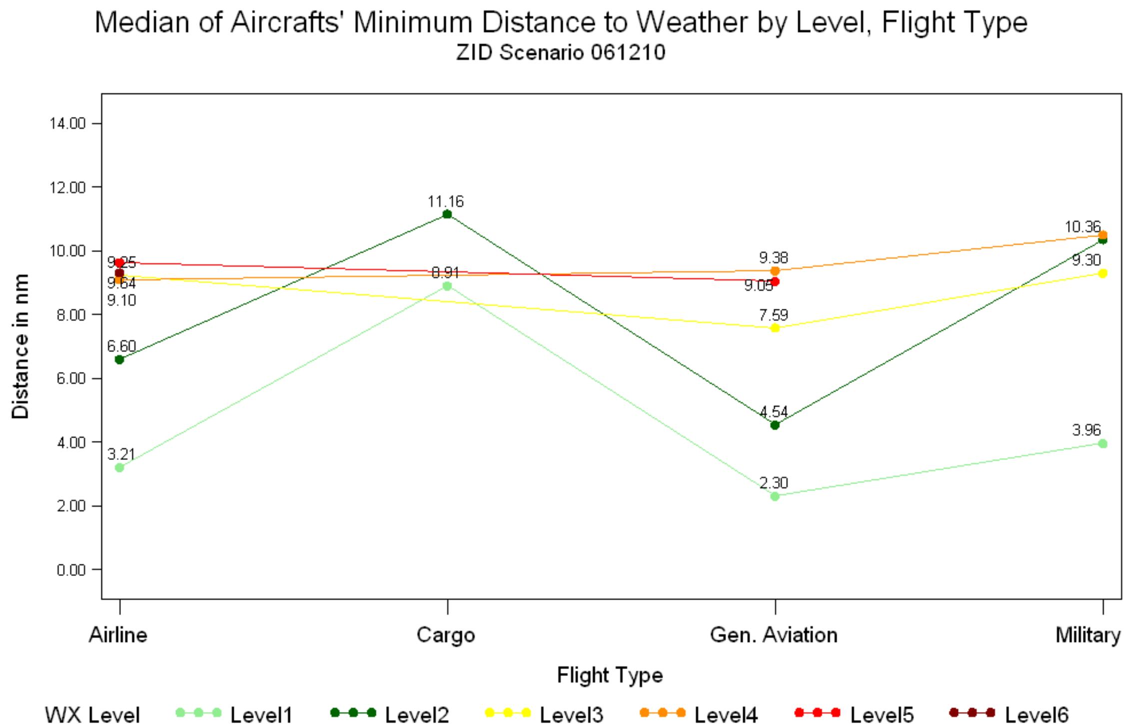

Figure 22. Minimum Distance to Weather by Flight Type on 6-12-2010 in ZID

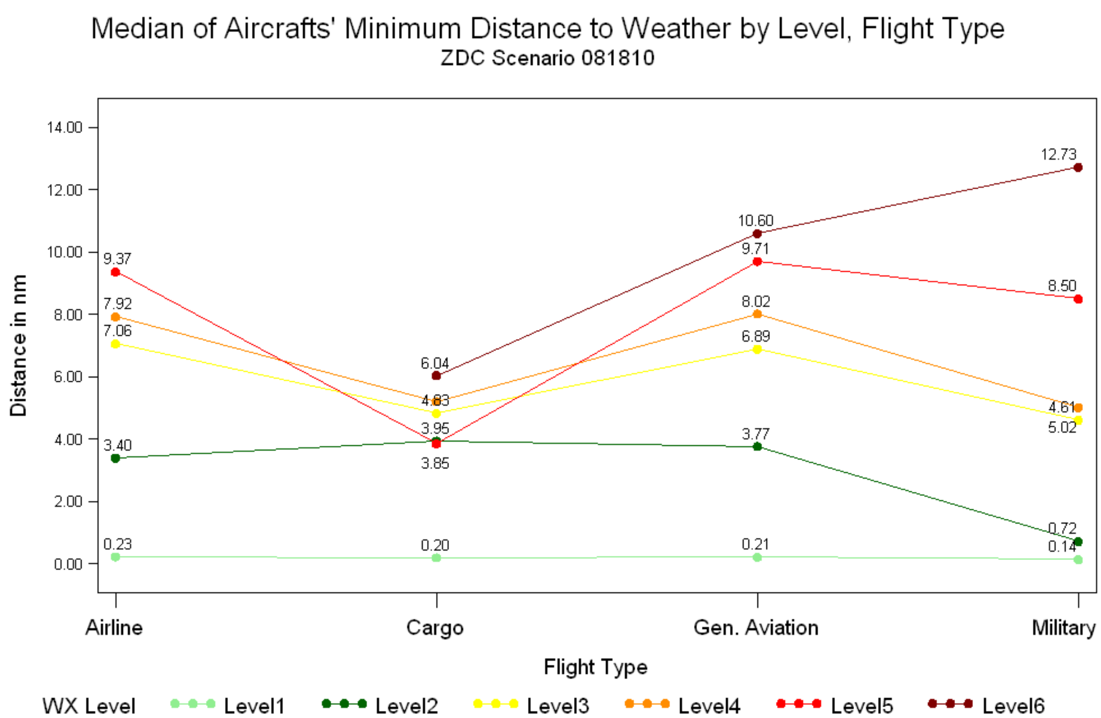

Figure 23. Minimum Distance to Weather by Flight Type on 8-18-2010 in ZDC

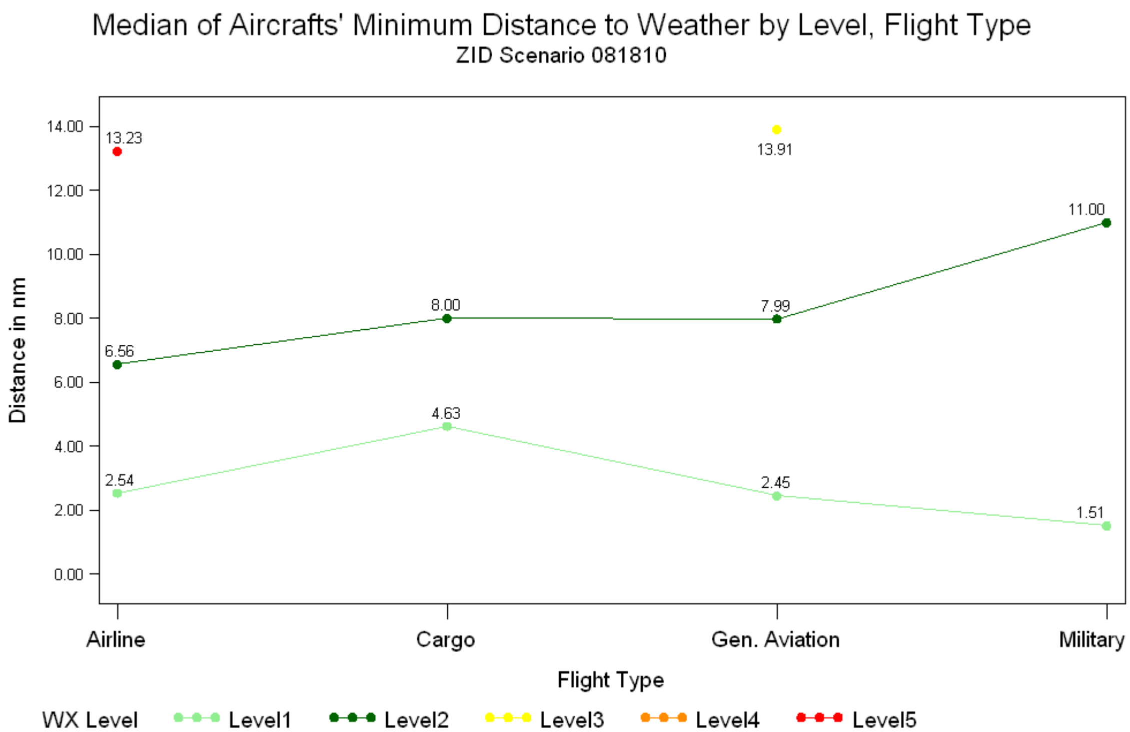

Figure 24. Minimum Distance to Weather by Flight Type on 8-18-2010 in ZID

3.2 Weather Reroute Analysis

A second objective of this study is to identify aircraft that were rerouted due to weather and to calculate the distance between the original route and the actual flight path.

To do this, the Reroute Detection Tool was used to identify weather reroutes and accuracy metrics obtained from TrajTools were used to analyze the distance flown off the original route. JMP and SAS were used to perform the analysis.

The key metric used for this analysis was horizontal deviation. This metric reflects the difference in horizontal location between the original route and the actual flown flight path at the same moment in time. Figure 25 below provides an illustration of the horizontal deviation, and details on the calculation of this metric can be found in "Implementation and Metrics for a Trajectory Prediction Validation Methodology[9]."

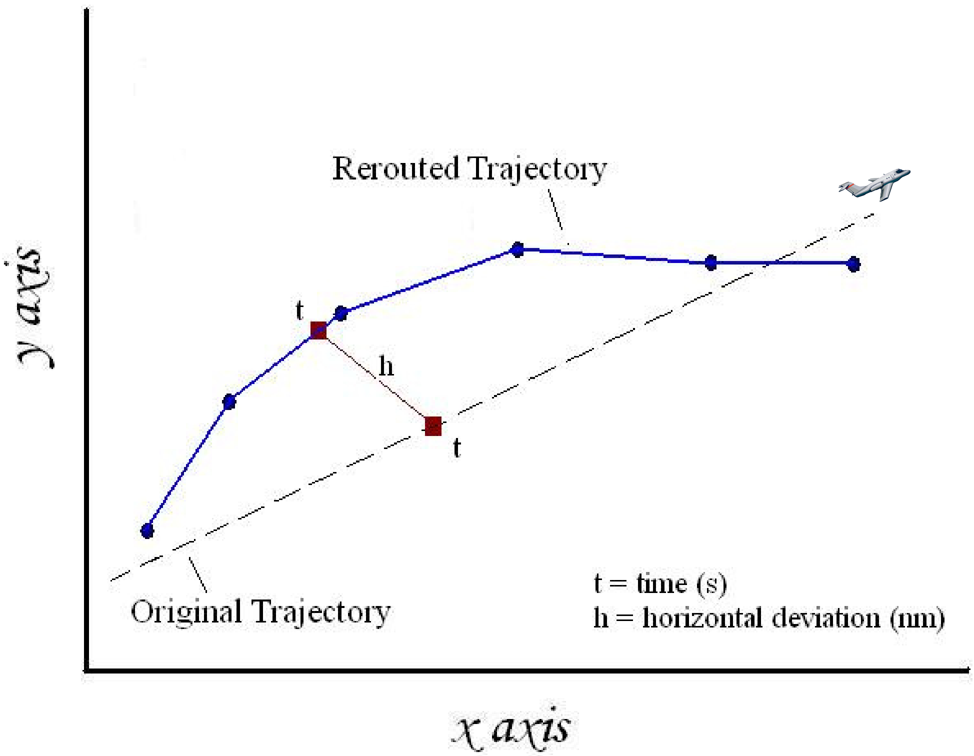

Figure 25. Horizontal Deviation Metric

The horizontal deviation for each flight was calculated every 10 seconds and recorded at each track point at which the original flight plan was inside a weather polygon of level 3 through 6. A large number of aircraft fly directly through weather at levels 1 and 2; these aircraft were not considered in this analysis to avoid a large dataset. The distribution of maximum horizontal deviation for each flight is reported below. This distribution was examined for differences among ARTCCs and dates. No patterns could be concluded from this analysis; thus, we have combined the data for all of the scenarios to examine the flights as a whole.

At each track point when the original flight path was predicted to enter the weather, the horizontal deviation of the actual flight path was calculated. Figure 26 below depicts this calculation. The maximum horizontal deviation for each flight was found and analyzed.

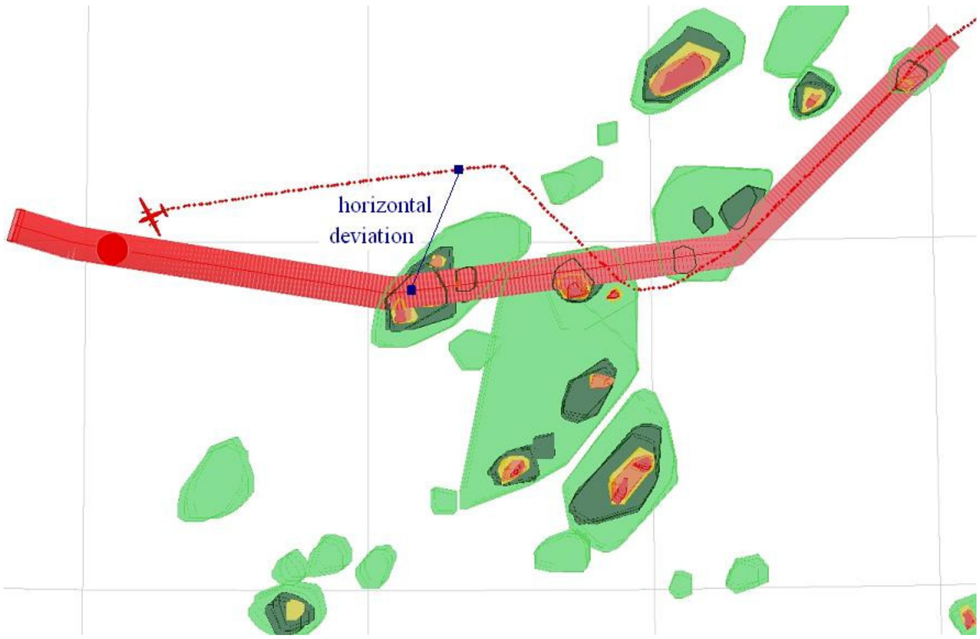

Figure 26. Horizontal Deviation of Weather Rerouted Flight showing Flight Plan (red, solid tube) and Actual Flight Path (red, dotted line)

Figure 27 below shows the distribution of maximum horizontal deviation for each of the weather rerouted flights. One can see in the histogram that the majority of weather rerouted flights strayed 25nm or less off their original route. In fact, the median value of maximum horizontal deviation is 21.5nm. Through exploratory analysis of individual outliers, it was determined that flights deviating more than 100nm from their original route were mostly airlines that went into a holding pattern to avoid the weather. Other outliers included a military flight that seemed to completely change its course once the weather was sighted.

Finally, we investigated the difference in maximum horizontal deviation for all flights by flight type. It was theorized that flights not carrying passengers may deviate from their original route less than airlines or general aviation aircraft. Figure 28 indicates this theory was correct. The box plot shows that there is little difference among the horizontal deviation values for airline, general aviation, and military flights; however, cargo flights generally fly closer to severe weather. The median values of maximum horizontal deviation for each flight type are as follows: airlines 23nm, GA 19.1nm, military 19.3nm, and cargo 7.4nm.

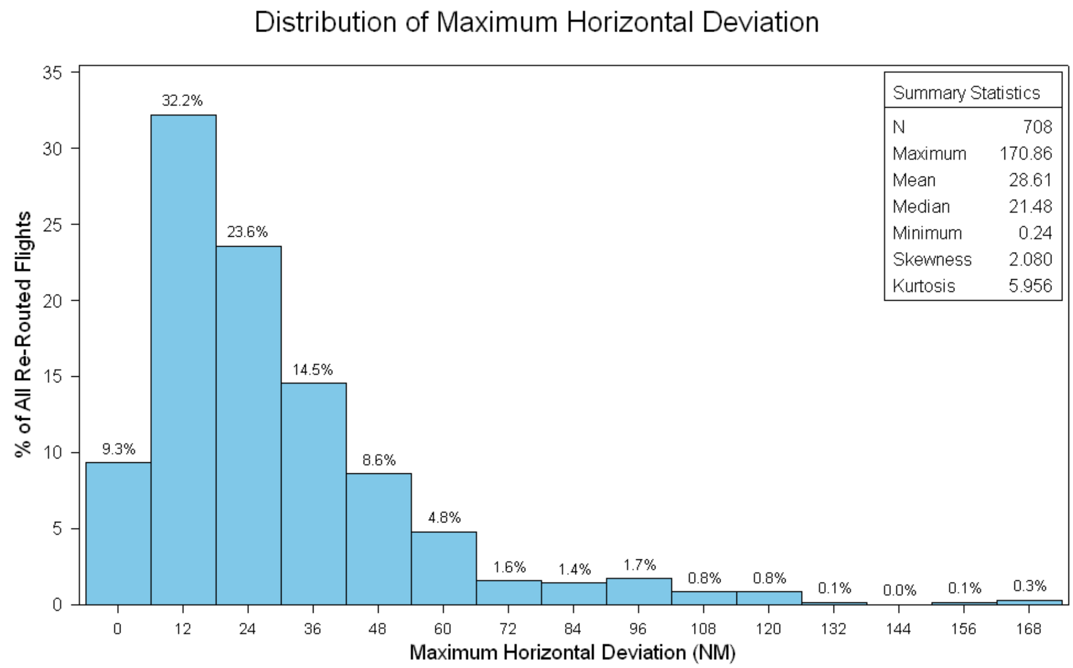

Figure 27. Distribution of Maximum Horizontal Deviation

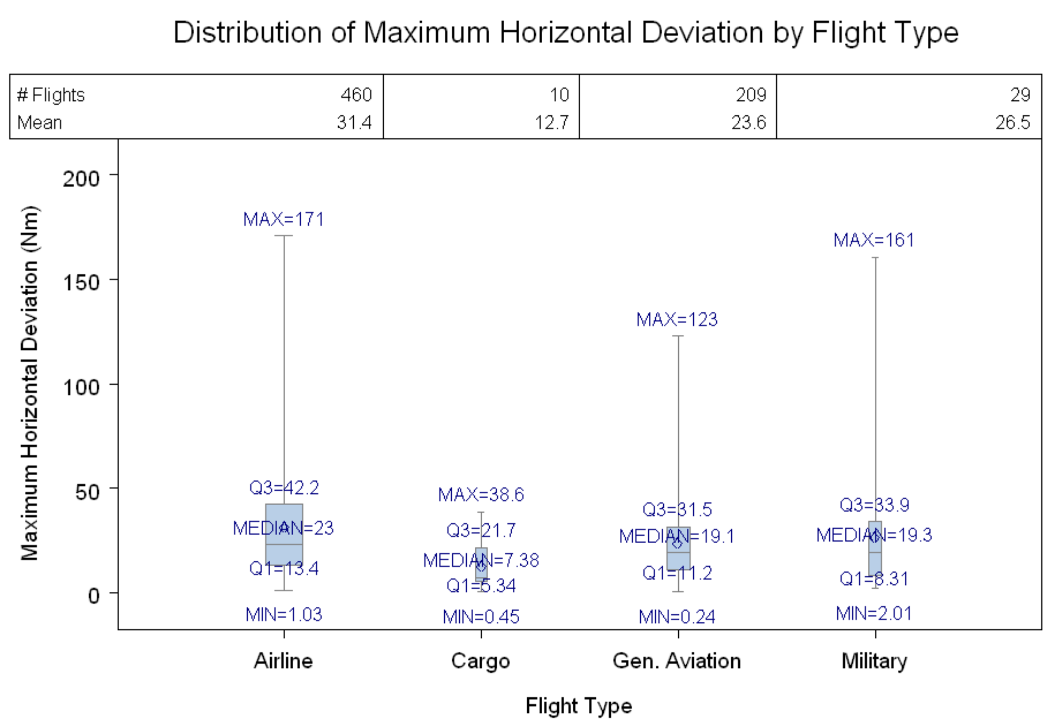

Figure 28. Distribution of Maximum Horizontal Deviation by Flight Type

4 Weather Polygons Usability Example in Fast-Time Simulation (RAMS Plus)

RAMS Plus is developed and supported by ISA Software and features 4-D flight profile calculation, 4-D sectorization, and 4-D spatial conflict detection and resolution (CD&R). Both enroute and terminal environments can be modeled in RAMS Plus, and traffic route flows and procedures can be easily modified by the analyst to fit any study. AJP-661 uses RAMS Plus to define and evaluate potential benefits of NextGen concepts.

One of the key features in RAMS Plus is the ability to reroute around restricted zones such as Military Operations Areas (MOA) and Special Activity Airspace (SAA). By importing weather polygons created in the Weather Polygon Tool, AJP-661 uses this feature to depict weather polygons as restricted zones. RAMS Plus can perform rerouting using user defined avoidance routes or automatically through the CD&R algorithms. For this proof of concept, AJP-661 elected to use the automated feature since defining an avoidance route around each polygon would be time consuming and inefficient.

To define the restricted zone(s), one must create polygons similarly defined as sectors with a boundary, floor, and ceiling. In addition, each polygon can be turned on or off by associating it with on and off times during the simulation. The creation of the polygons is performed by the Weather Polygon Creator defined in Section 2.2.2.2. When creating the polygons the user can specify the duration and time interval to sample the data. For example, the proof of concept test uses a one hour sample of weather data with a ten minute update interval. Figure 29 is a screen shot of the RAMS plus test scenario depicting the Air Traffic Control (ATC) sector boundary (blue), flight tracks (white), and weather polygons (red).

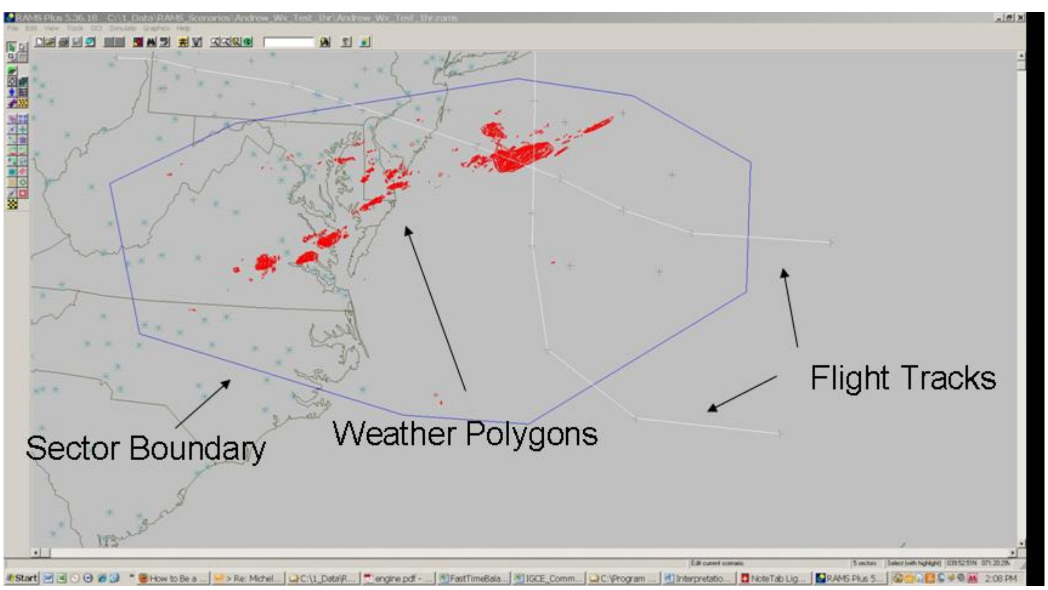

Figure 29. RAMS Plus Screen Shot with Weather Polygons

To test the proof of concept, a small traffic sample was created in which each aircraft's flight plan flew through the weather polygons. As the simulation progressed, the weather polygons turned on and off depicting the changes in the convective weather forecast. Once an aircraft entered a sector, RAMS Plus simulated controller actions, including CD&R. For this test RAMS Plus performed CD&R on both the restricted zones (weather polygons) and crossing traffic providing conflict free flight paths for the aircraft. AJP-661 concluded that this was a sound test of using the polygon tool in conjunction with a fast-time simulation tool.

However, there were two limitations identified in using the polygon tool for fast-time simulation. These limitations were a byproduct of the high fidelity of the MRMS data. First, the number of polygons created as restricted zones caused a degradation in RAMS Plus processing speed. Second, the number of polygons restricted the simulation time to one hour with ten minute intervals. To address these limitations, AJP-661 will determine a method of describing the polygons in less detail. Some of these limitations were experienced and identified by NASA Ames Research Center[10] when implementing weather polygons into the Airspace Concept Evaluation System (ACES).

5 Summary

The purpose of this activity was to understand the current operations of flights during convective weather and to develop the capability to model weather in fast-time simulation tools. There were three objectives for this research activity: to determine the proximity of aircraft to different severity levels of weather, to identify flights rerouted due to weather and examine their deviations from original flight paths, and to develop a tool to create weather polygons for use in fast-time simulations and demonstrate its use. All of these objectives were met using the tools and methods described above.

The first two objectives were met using MRMS weather data and air traffic data from four chosen days (6-12-2010, 8-5-2010, 8-18-2010, and 5-14-2011) in ZDC and ZID ARTCCs. It can be determined through analysis of this data that, in general, the minimum distance an aircraft will fly from weather increases with the severity of the weather. For low severity levels of weather (hazard levels 1 and 2), flights will remain at least 2nm away from weather if possible but will enter these low levels of weather when there is an extensive amount of highly severe weather (hazard levels 3 through 6) as on 8-18-2010. However, in all scenarios, flights remain a maximum distance of approximately 10nm away from more severe weather (hazard levels 4, 5, and 6). It can also be concluded that airline and general aviation flights generally fly farther away from weather than cargo and military flights.

Flights identified as reroutes due to weather were examined to determine how far off their flight plan they flew to avoid weather. The median difference between the flight plan and actual route flown by the aircraft was 21.5nm. Outliers with a maximum difference greater than 100nm were typically airline flights that were placed in a holding pattern to avoid the weather. It was determined that cargo flights deviate less from their original flight plan than airline, military, and general aviation flights to avoid weather. This research could be continued to determine the total flight delay incurred due to weather reroutes. To do this, the original flight path that would have penetrated the weather must be simulated and compared against the actual flight path flown. Additionally, a fuel burn analysis could be performed to determine the amount of extra fuel burned due to the reroute.

Finally, AJP-661 developed a tool to create weather polygons from MRMS weather data for use in fast-time simulation tools. The weather polygons were tested in the fast-time simulation model RAMS Plus. The usability test was successful on a limited sample of data. In the future, we will improve the method of defining the polygons to enable more data to be simulated as well as develop the capability to output the weather polygons to other fast-time simulation tools such as AWSIM, AirTOp and ACES. Also, a comparison test will be performed to compare actual weather and air traffic data with simulated data.

6 List of Acronyms

AJP-661	Simulation and Analysis Group
ACES	Airspace Concept Evaluation System
ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
CD&R	Conflict Detection and Resolution
CMS	Common Message Set
CONUS	Continental United States
FAA	Federal Aviation Administration
GA	General Aviation
HADDS	Host Air Traffic Management Data Distribution System
HCS	Host Computer System
MIT LL	Massachusetts Institute of Technology Lincoln Laboratories
MOA	Military Operations Area
MRMS	Multiple Radar/Multiple Sensor Weather Data
MSP	Multi-Sector Planner
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCWF	National Convective Weather Forecast
NextGen	Next Generation Air Transportation System
nm	Nautical mile
NOAA	National Oceanic and Atmospheric Administration
RAMS	Reorganized Air Traffic Control Mathematical Simulator
SAA	Special Activity Airspace
SAS	Statistical Analysis System
TFM	Trajectory Flow Management
Wx	Weather
ZDC	Washington, DC ARTCC
ZID	Indianapolis ARTCC

7 References

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[9] Paglione, M. & Oaks, R. D. (2007, August). *Implementation and Metrics for a Trajectory Prediction Validation Methodology.* American Institute of Aeronautics and Astronautics (AIAA) Guidance, Navigation and Control Conference and Exhibit. Hilton Head, SC.

[10] Karahan, S., & Zelinski S. (2007, August). *Creating Convective Weather Scenarios for Simulating Weather Reroutes.* American Institute of Aeronautics and Astronautics (AIAA) Modeling and Simulation Technologies Conference. Hilton Head, SC.

Appendix A: Results for Additional Days

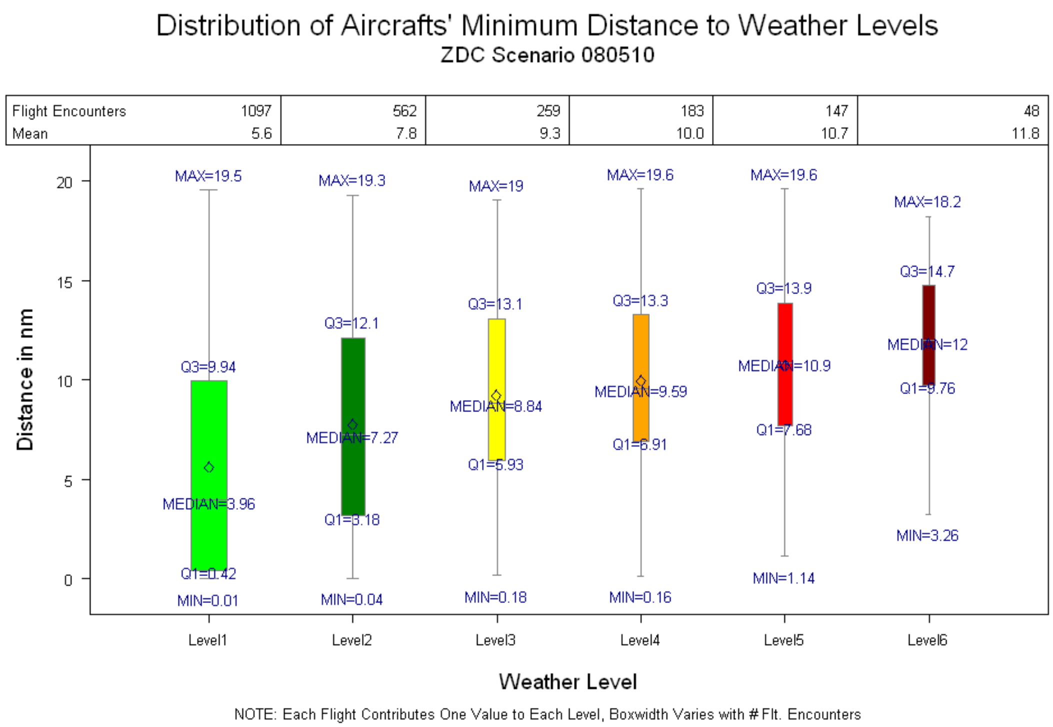

Figure 30. Minimum Distance of Aircraft to each Weather Level on 8-5-2010 in ZDC

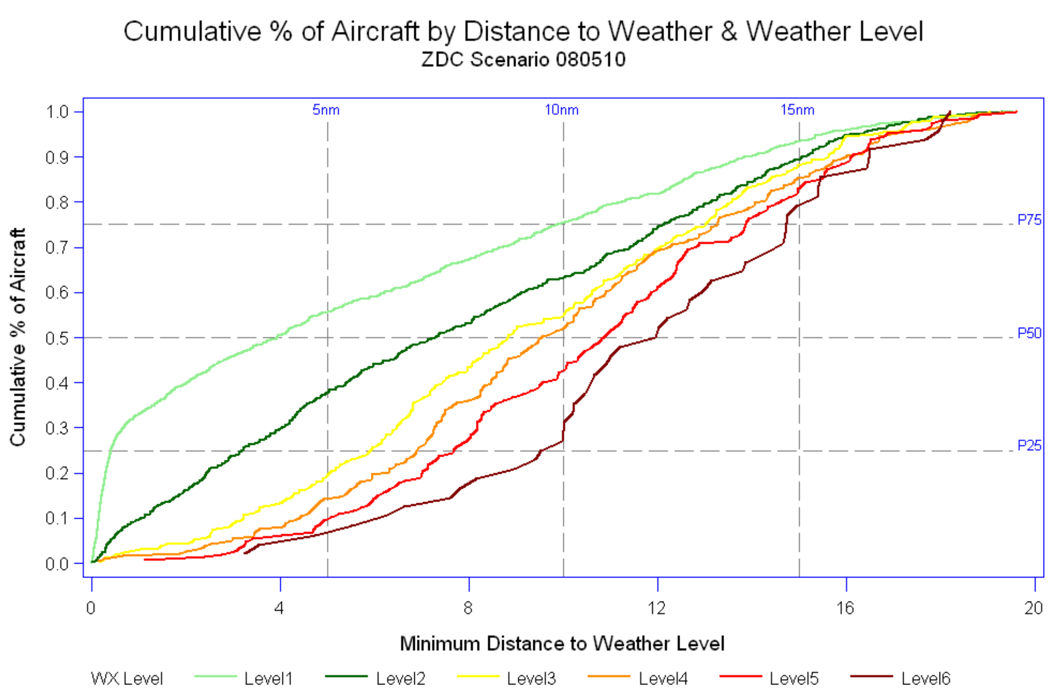

Figure 31. Percent of Aircraft by Minimum Distance to Weather Levels on 8-5-2010 in ZDC

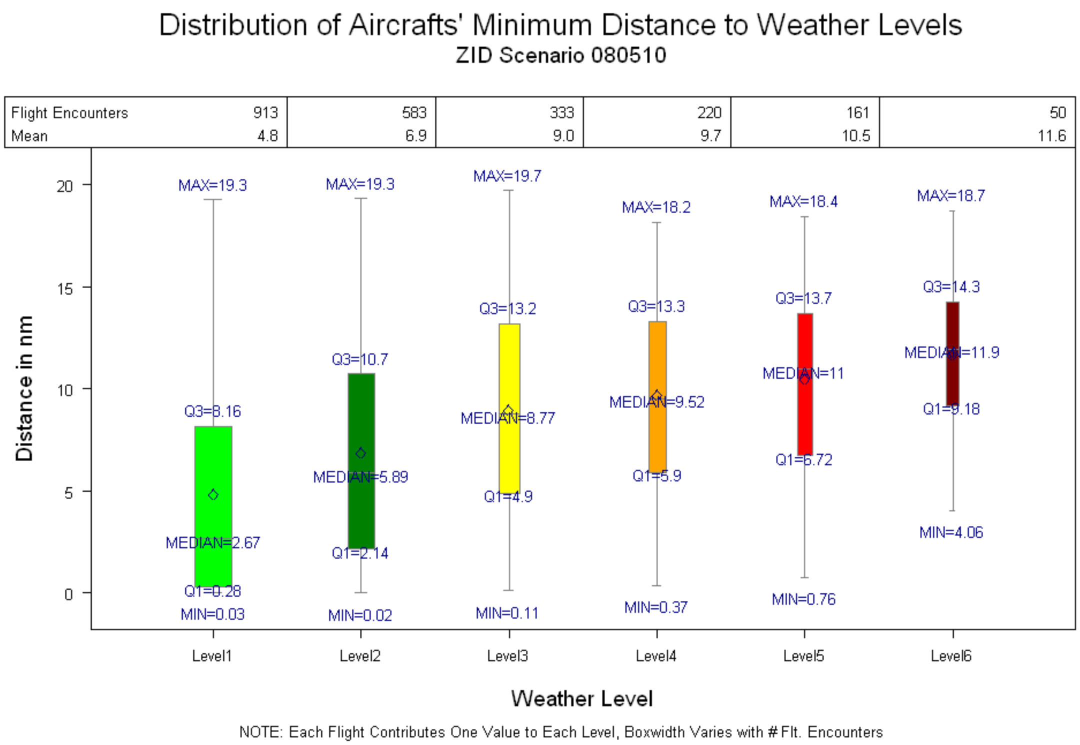

Figure 32. Minimum Distance of Aircraft to each Weather Level on 8-5-2010 in ZID

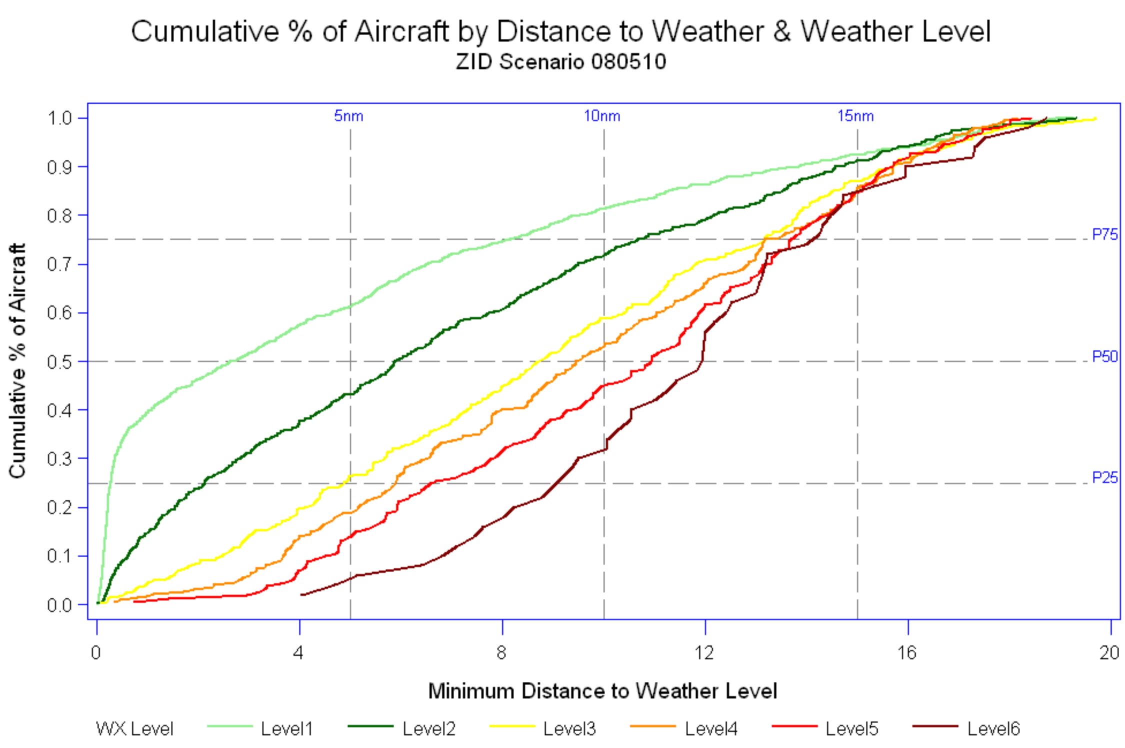

Figure 33. Percent of Aircraft by Minimum Distance to Weather Levels on 8-5-2010 in ZID

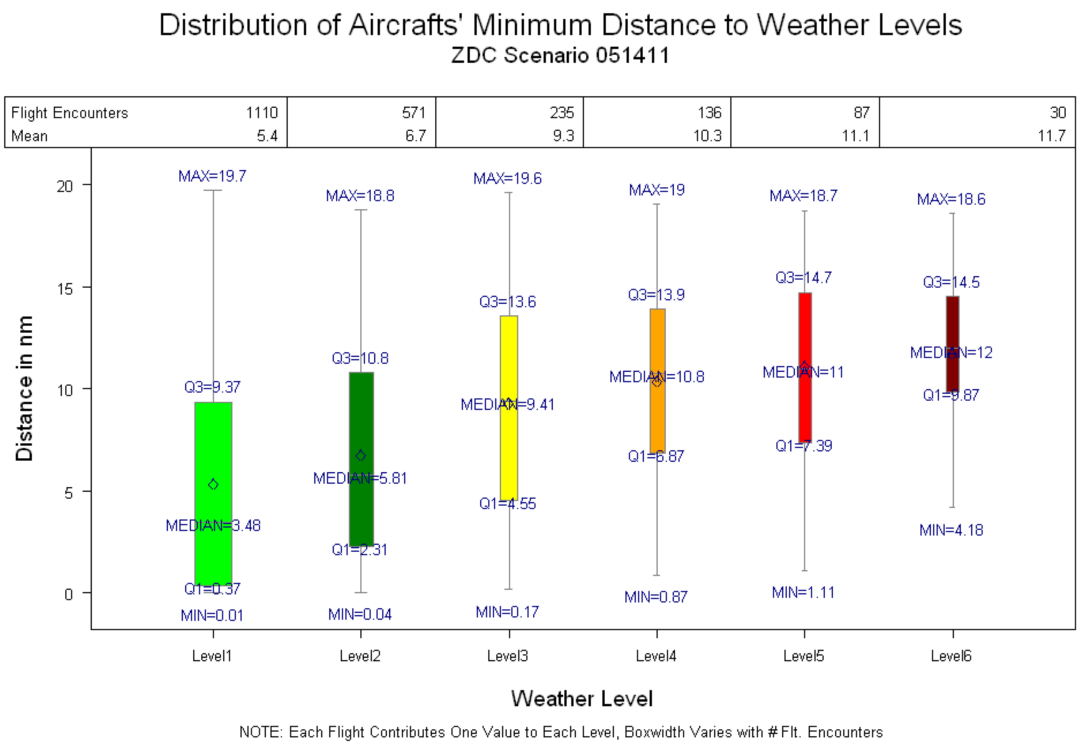

Figure 34. Minimum Distance of Aircraft to each Weather Level on 5-14-2011 in ZDC

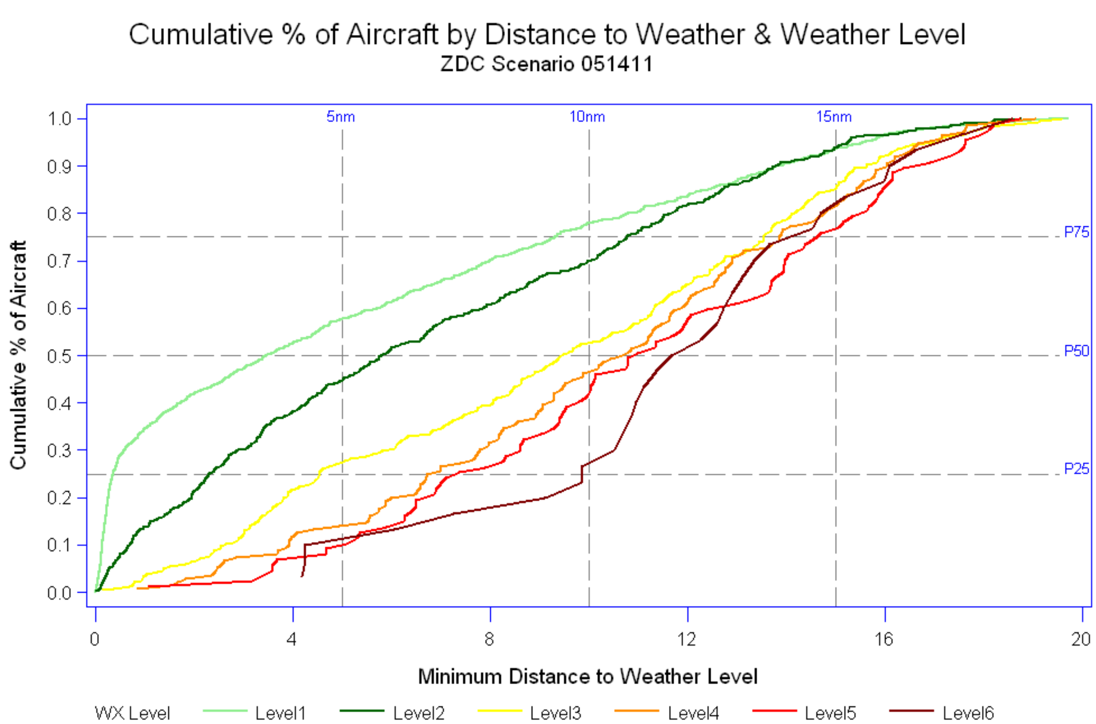

Figure 35. Percent of Aircraft by Minimum Distance to Weather Levels on 5-14-2011 in ZDC

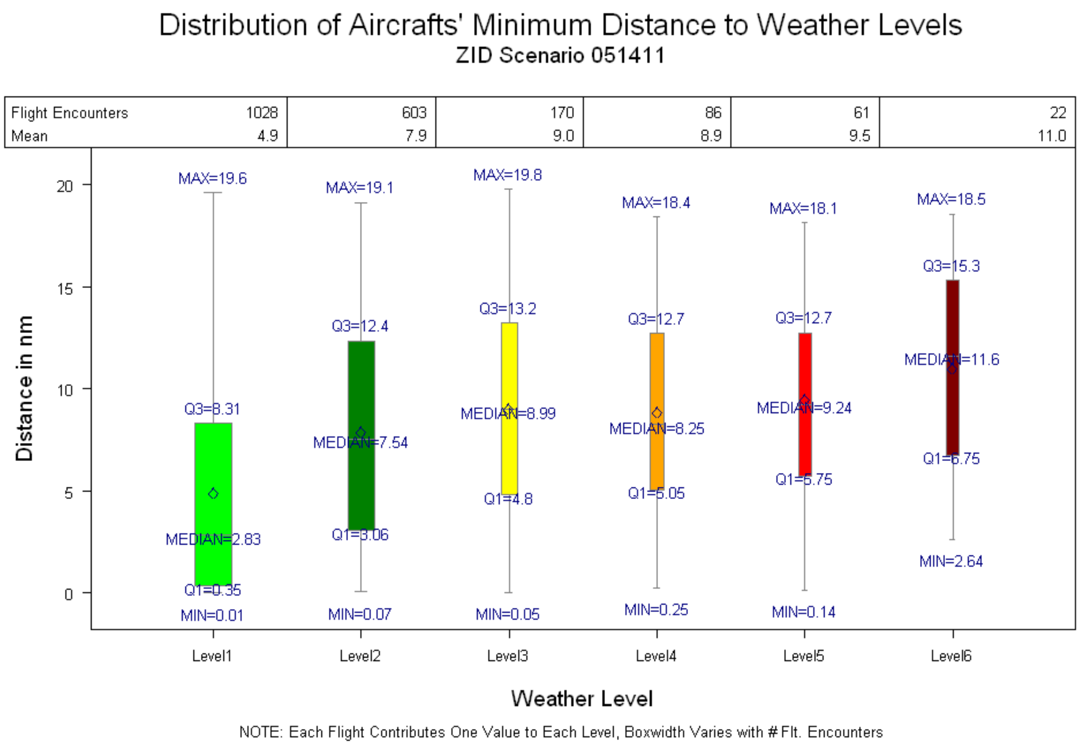

Figure 36. Minimum Distance of Aircraft to each Weather Level on 5-14-2011 in ZID

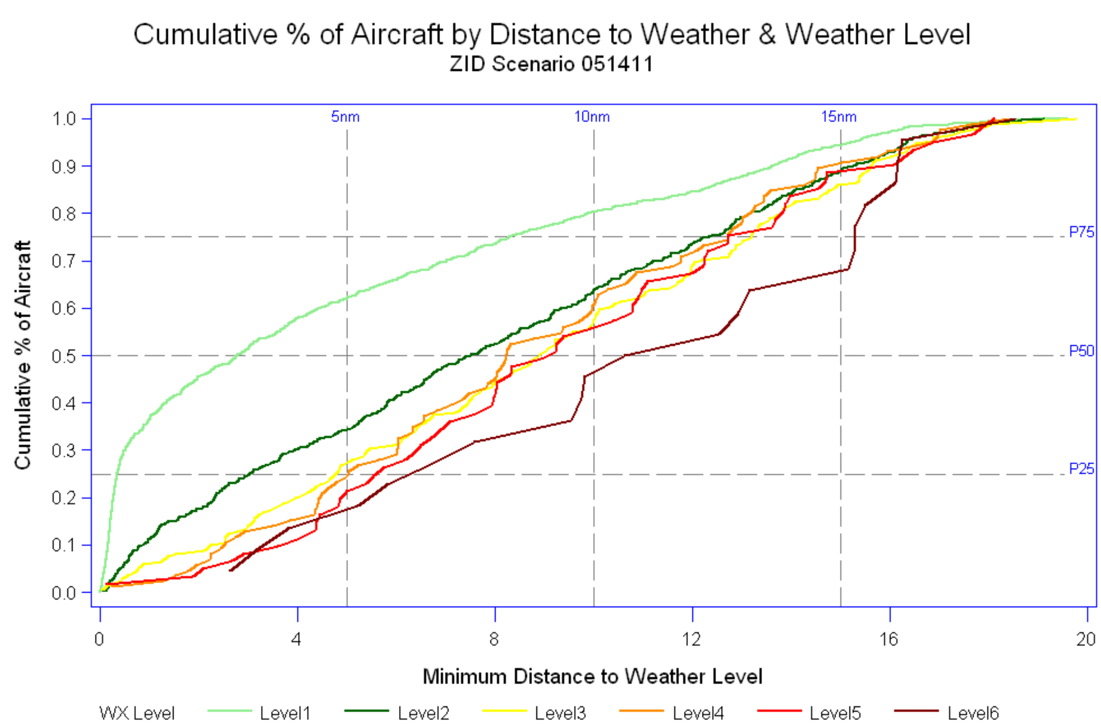

Figure 37. Percent of Aircraft by Minimum Distance to Weather Levels on 5-14-2011 in ZID

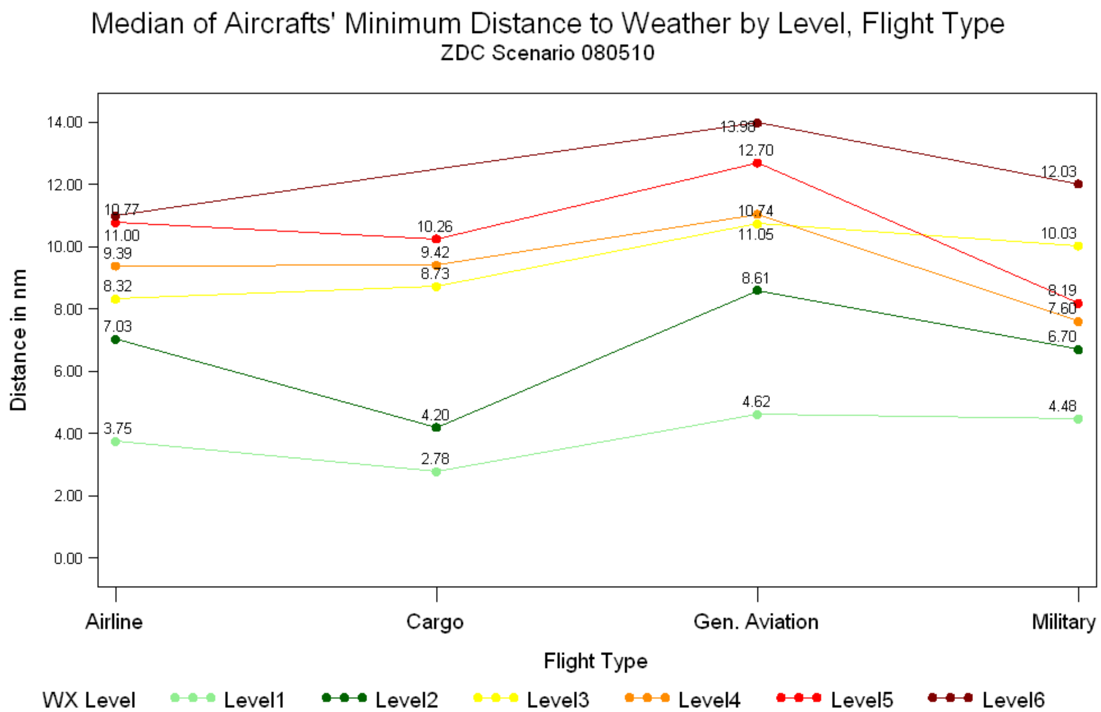

Figure 38. Minimum Distance to Weather by Flight Type on 8-5-2010 in ZDC

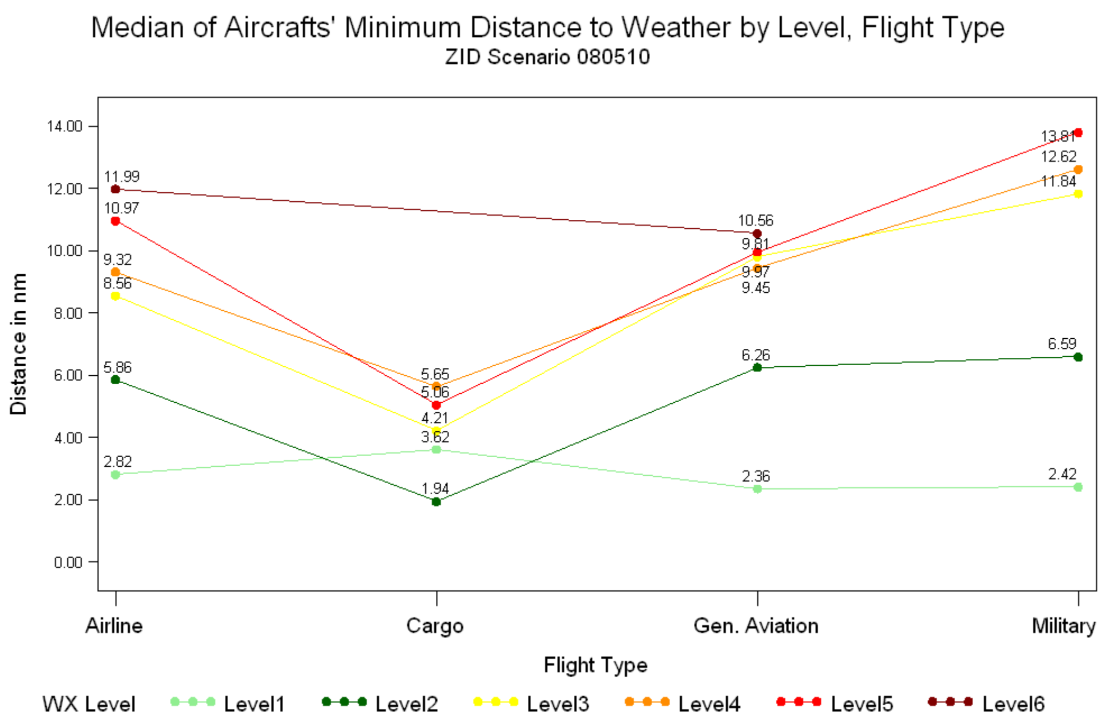

Figure 39. Minimum Distance to Weather by Flight Type on 8-5-2010 in ZID

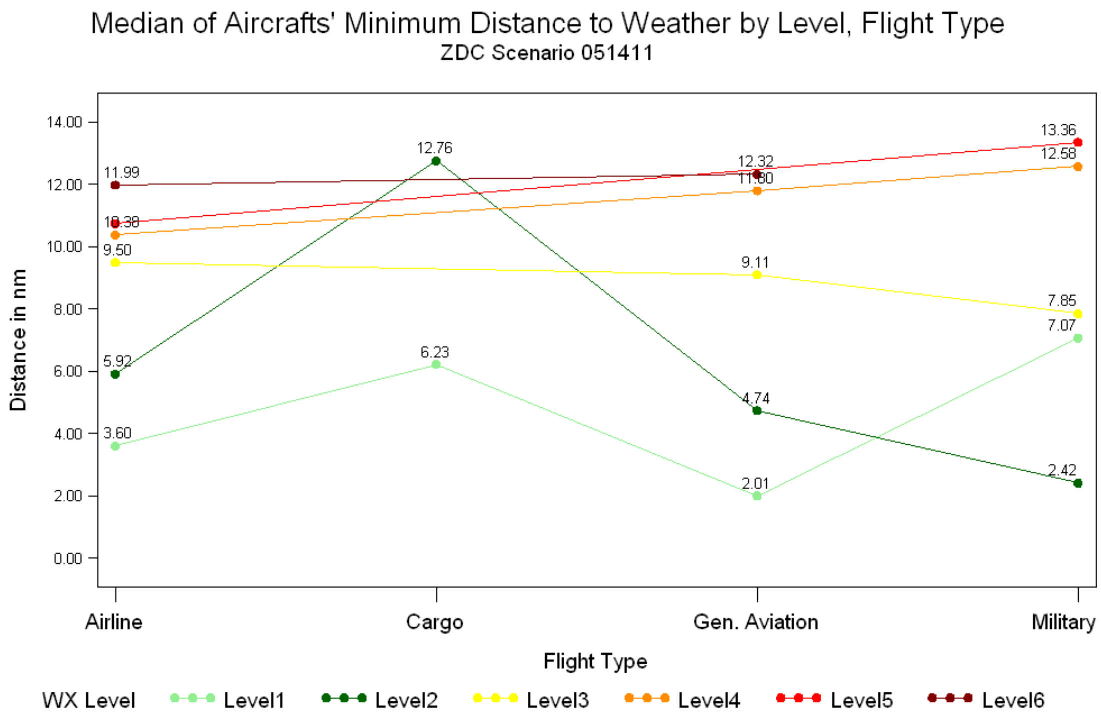

Figure 40. Minimum Distance to Weather by Flight Type on 5-14-2011 in ZDC

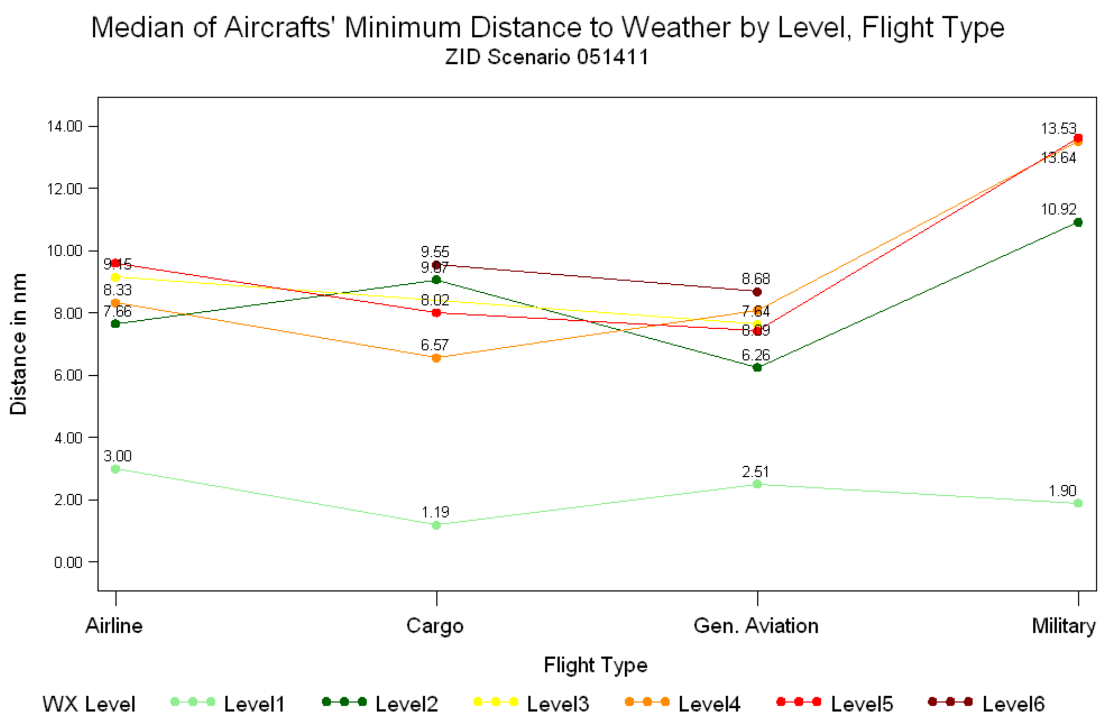

Figure 41. Minimum Distance to Weather by Flight Type on 5-14-2011 in ZID