Improving Air Traffic Management Group Decision-Making During Severe Convective Weather*

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Abstract

There is an urgent need to enhance the efficiency of United States (U.S.) air traffic management (ATM) decision-making when convective weather occurs. Thunderstorm ATM decisions must be made under considerable time pressure with inadequate information (e.g., missing or ambiguous), high stakes, and poorly defined procedures. Often, multiple decisions are considered simultaneously; each requiring coordination amongst a heterogeneous set of decision-makers. Recent operational experience in the use of improved convective weather decision support systems in the Northeast quadrant of the U.S. is reviewed in the context of literature on individual and team decision-making in complex environments. Promising areas of research are identified.

I. Introduction

The main contributions of this paper are to briefly present the convective weather ATM decision-making problem, discuss some of the germane literature on individual and team decision-making in complex environments, and to discuss, in the context of the decision-making literature, recent experience with quantitative studies of improved air traffic management in the Northeast quadrant of the United States. Our overall objective is to identify promising directions for improving ATM decision making for convective weather. This topic is of particular interest at this time given the difficulties encountered by the U.S. Federal Aviation Administration (FAA) in reducing delays during the months of the year characterized by thunderstorms (see Figure 1). The challenges continue despite a number of FAA initiatives since 1999 to reduce convective weather delays. The FAA is also concerned that anticipated increases in air traffic will result in much worse convective weather season delays by 2014 (Hughes, 2006).

The paper first considers principal challenges in achieving efficient and productive ATM during thunderstorm conditions, focusing principally on tactical (0- 2 hour) traffic flow management (TFM) decision-making. We conclude that these decisions must be made in difficult, non-routine situations involving real-life constraints such as time pressure, high stakes, unclear goals, and inadequate information. Additionally, the team aspect of decision-making appears to be very important, since actions taken in response to the weather disruptions in one spatial region may cause significant traffic management problems in another spatial region.

To the best of our knowledge, there have been no detailed studies of TFM decision-making during convective weather. (Davison and Hansman, 2001) discuss convective weather briefly in their study of ATM communications and coordination issues. Research in the area of difficult decision-making in complex environments offers several theoretical concepts describing models for decision-making, shared situational

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awareness and interpretation of team phenomena that are applicable to management of convective weather impacts on the flow of air traffic. The work by Klein and his colleagues (Klein, 1999) on the use of a recognition-primed decision (RPD) model for making decisions in "difficult" situations is shown to be germane.

An important aspect of TFM decision-making is the collaboration required between a large set of heterogeneous decision-makers. The concept of the "team mind" (Klein, 1999) offers insight into improving this complex TFM decision-making process. Additionally, studies of decision-making by groups support the critical role of communication, particularly the quality of the group communication (Hirokawa, Erbert and Hurst, 1996).

Next, we look at recent experimental data on TFM decision making in the context of the literature on decision making. Recent studies of tactical TFM decision-making with the Corridor Integrated Weather System (CIWS)] are particularly useful since quantitative metrics were obtained on the effectiveness of the TFM decision making. The CIWS results suggest that key elements in improving ATM during thunderstorms are identifying key decision-makers, providing them with appropriate decision support products, and providing sufficient training. Initial operational experience with an integrated weather/air traffic decision support system, the Route Availability Planning Tool (RAPT), to improve decision making for departures from major airports is also presented. The paper concludes with recommendations for improving convective weather ATM by applying some of the principles from the decision making literature.

II. ATM Decision-Making in Convective Weather

A. Convective weather impacts

Understanding the mechanisms by which convective weather delays arise is essential for understanding key features of the convective weather ATM decision-making problem. An important issue is the relative importance of the roles of terminal and en route convective weather. For example, if the delays principally arise because storms close airport runways [as suggested by (Bond, 1997)], then it may not be possible to reduce the delays through improved ATM. Detailed studies of convective weather operations at New York (Allan, Gaddy and Evans, 2001) and Atlanta (Allan and Evans, 2005) found that terminal convective weather is a significant factor in airport delays (e.g., 20% of the delays at EWR), but that closure of all the runways at an airport is relatively infrequent.

Contrarily, we conclude that high altitude en route airspace congestion during convective weather is increasingly the major cause of delays in the U.S. during thunderstorm season, based on the following:

1. FAA initiatives focused on en route, strategic TFM [e.g., the use of the 2-6 hour Collaborative Convective Forecast Product (CCFP) (Huberdeau and Gentry, 2004) and the 2006 introduction of the Airspace Flow Program (AFP) (FAA, 2006)]

2. Analyses of convective weather events in the Northeast U.S. (Robinson, Evans, Crowe, Klingle-Wilson and Allan, 2004) reveals the importance of mitigating convective weather impacts on en route airways to reduce overall delays

3. Major increases (in excess of 20% between 2000 and 2005) in demand[1] of high altitude en route airspace in a time period where the operations into major airports decreased (Knorr, 2006)

The growing importance of network congestion has significant implications for convective weather ATM. Thunderstorm impacts in a congested air traffic network require greater coordination between traffic management facilities for TFM planning (Figure 2). Additionally, even with more devoted time and effort to coordination, it is much more difficult to develop effective ATM strategies due to the computational difficulty of understanding the network implications of candidate weather mitigation strategies.

Another important factor in decision making is inadequate input information arising from uncertainty as to the capacity impact of the weather. This uncertainty arises from a combination of convective weather forecast inaccuracies, and the variability that arises in translating convective weather impacts into capacity impacts.

The scientific difficulties in accurately forecasting convective weather 2-8 hours in advance have been documented in detail (National Academy of Sciences, 2003). The 2-6 hour CCFP, which is currently used as the input for strategic TFM decision-making in the U.S., generally over-predicts the amount of convective weather (Seske and Hart, 2006; Kay, Mahoney, and Hart, 2006). Also, the CCFP has very coarse quantization of the fractional convective weather coverage in a region which further increases the Air Traffic Control (ATC) impact uncertainty.

A conceptual framework for ATM in convective weather is shown in Figure 3. Weather forecasts are combined with a model for pilot avoidance of storms to determine the regions that pilots will seek to avoid [i.e., the weather avoidance field (WAF)]. Using WAF information in concert with operational airspace usage models, blockage of specific routes and the related impact on en route air traffic sector capacity can be determined. These forecasts of capacity impacts are used to develop convective weather ATM strategies. Variability in the translation of convective weather impacts into capacity impacts arises both from the differences between pilots in their propensity to penetrate storms, and from the variations in the spatial structure[2] of convective weather.

Determination of the weather avoidance field (WAF) is discussed by (DeLaura and Evans, 2006). For en route airspace, the aircraft altitude in relationship to the altitude of the radar-depicted storm echo top has been shown to be a key factor in pilot avoidance of storms (DeLaura and Evans, 2006; Rhoda, Kocab, and Pawlak, 2003). When the flight altitude is at least 1.5 km above the storm radar echo top altitude, most aircraft will fly over a storm, even if much of the spatial region ahead of the aircraft has high reflectivity returns at altitudes below the aircraft altitude. In the context of TFM decision-making, these are important results since the weather depiction and convective weather forecast tools provided to traffic managers in the past typically showed only two-dimensional (lateral-space) storm intensity information.

Figure 4 shows a typical result for the high altitude capacity loss at several points in time over a one hour period due to convective weather in the Northeast U.S computed by the method described in (Martin, Evans and DeLaura, 2006). This time-space variability of sector capacity loss in convective weather is a major challenge for effective ATM. For example, flow patterns that were feasible at 1700 UTC would need to be significantly altered by 1730 UTC. At 1700 UTC, the convective weather impact on sectors along the East Coast is minor, and therefore represents alternative routes for excess traffic from the Midwest. By 1745 UTC, those East Coast sectors have been significantly impacted by convective weather while the Midwest

[1] A very significant factor in the high altitude demand increase was the widespread adoption of regional jets (Mozdzanowska and Hansman, 2004).

[2] For example, squall lines typically cause greater capacity loss than does "popcorn" convection for a given fractional weather coverage (Martin, Evans, and DeLaura, 2006).

impacts have also changed significantly. Hence, there would need to be significant changes in the traffic flows between 1700 UTC and 1800 UTC with significant coordination between the various ATC facilities.

ATM decision-making for tactical convective weather impact mitigation (i.e., plans executed 0-2 hours in advance) is the primary focus of this paper. Although the bulk of the publicized FAA initiatives for convective weather ATM have been on strategic TFM, study results such as is shown in Figure 4 suggest that efficient and high-quality short lead time ATM is needed to handle the rapid time variations in sector capacity (Evans, 2001). Realistically, strategic TFM may only provide an estimate of a space/time average capacity loss in a region 4-8 hours in the future so that an appropriate number of aircraft will transition the convective weather impacted airspace (e.g., establishing an appropriate AFP flow rate). However, accurately estimating the space/time average capacity loss from the CCFP for use in an AFP is very difficult due to the inaccuracies in the CCFP that were discussed above.

Figure 4 also shows the difficulty in relating a current pattern of convective weather impacts to previously encountered convective weather events (e.g., to determine an appropriate ATM decision by comparing the current weather situation to a data base of previous cases). In the example illustrated in Figure 4, approximately 20 sectors are impacted by convective weather with no obvious relationship between the capacity losses in adjacent sectors. If the fractional capacity loss were quantized into four levels (as opposed to the 10 fractional capacity loss levels shown in the figure) and the capacity impacts are assumed to be independent statistical events, simple combinatorial mathematics suggests there are over 10^{12} possible convective weather capacity impact spatial patterns in the region shown in Figure 4. Hence, the ATM decision maker must be addressing relatively unique challenges every day that convective weather occurs.

B. TFM Considerations

The traffic management coordinators (TMC) and sector/area supervisors have significant personal responsibility for insuring that the workload of the various controllers is consistent with a very high level of safety. As noted earlier, the number of aircraft being handled by the controllers is only one factor in the overall complexity assessment. Violations of the standards for separation of different aircraft are a major safety metric for the ATC system and it is very important that the controller workload be proactively managed so as to avoid circumstances that might lead to separation violations. At the same time, the TMCs and traffic management officer (TMO) also are responsible for achieving an efficient air system operation with as few delays as possible

The procedures for TFM decision making given a time changing pattern of airspace capacity impacts such as shown in Figure 4 are poorly defined. Although there are benchmarks for the capacity of major terminals as a function of the ceiling/visibility conditions and runway configuration, there are no such benchmarks for the capacity of either en route or terminal airspace when impacted by convective weather. Written guidance as to how to solve the problem of aircraft allocation in the capacity-impacted network is also unavailable.

Additionally, the detailed goals for TFM are not well defined and can change significantly over the course of a day. For example, the relative priority of traffic that originates or terminates within a given ATC facility (e.g., an en route center) relative to aircraft that are passing through the facility may change. At times, the overall aviation system control center may seek to give priorities to aircraft departing from a major airport owing to concerns about “gridlock” on the airport surface. Different airlines can and do contact the TFM decision maker seeking to get priority of some of their flights (e.g., for a flight that has been unduly held on the ground).

The interactions between various individuals that are involved in TFM decision making and implementation (recall Figure 2) can be very different inside an ATC facility from those between adjacent ATC facilities and interactions between ATC and the aviation system users (e.g., the airlines). Within a facility, the various decision makers typically have known each other for a number of years and can fairly easily talk face-to-face. However, the TFM decision makers in different ATC facilities generally would not have the same degree of familiarity, rarely talk face-to-face, and may be not have the same goals (e.g., decision makers in a facility may have a tendency to give priority to flights originating or departing within the coverage of their facility). Airline – ATC facility interactions also can differ significantly from the interactions that occur within a given facility.

III. Models for Decision Making

The classical model for decision-making (Klein, 1999; Hirokawa, Erbert and Hurst, 1996) is rational choice strategy (RCS) in which one:

- Decomposes a situation or problem into smaller elements, each of which can be analyzed
- Develops a model to represent the system for which decisions must be made
- Conducts formal, logical, and statistical analyses using the data together with the system model to compare the consequences of various alternative decisions
- Describes analyses and recommendations to facilitate review by others

(Klein, 1999) conducted observations of real time decision making for decision making problems that are characterized by:

Time pressure
High stakes
Personal responsibility
Inadequate information (e.g., missing and/or ambiguous)
Ill-defined goals
Poorly defined procedures

Klein concludes that decision-making by experienced decision makers for these “difficult” problems are best represented by a “recognition-primed decision” (RPD) model in which the decision-maker makes an intuitive assessment assignment of the current situation to an analogue problem and then evaluates various possible actions according to a mental simulation of possible outcomes. A set of expectancies, relevant cues, plausible goals and typical actions are used in the recognition process.

(Klein, 1999) discusses when these two different strategies-RPD and RCS-for decision-making are typically used. In Table 1, Klein’s predictions (drawing on the observations from his real-life studies) as to when the various strategies would be used are compared with our assessment of the convective weather ATM decision making task conditions.

Table 1. Comparison of convective weather ATM decision-making environment with Klein's predictions for which decision-making model would typically be applicable for specific task conditions

Task Condition	Convective weather ATM decisions	Recognition-primed decisions (RPD)	Rational choice strategy (RCS)
1. Greater time pressure	Yes	More likely	
2. Higher experience level	Yes	More likely	
3. Dynamic conditions	Yes	More likely	
4. Missing / uncertain information	Yes	More likely	
5. Ill-defined goals	Yes	More likely	
6. Need for justification	Unclear		More likely
7. Conflict resolution	Desirable		More likely
8. Optimization	Desirable		More likely
9. Greater computational complexity	Yes (but, may not be computable)		More likely
10. Team decision-making	Yes	Not explicitly discussed by Klein	Not explicitly discussed by Klein

A few comments are in order on our assessment of the task conditions associated with convective weather ATM decisions. It is unclear how much formal justification is required for these ATM decisions. This is because an ATC facility decision, that it cannot accept more aircraft for reasons of safety, generally is not formally challenged. This may cause great inconvenience to other facilities and to the users of the aviation system, but we are unaware of any formal subsequent review of the decision. Similarly, conflicts between different FAA facilities and/or within a facility can always be resolved by simply reducing the number of flights to a lowest common denominator, but settling disputes on traffic flow in this manner can significantly reduce the efficiency of the aviation system.

The manual optimization of flight routing and delays given a time varying NAS capacity profile such as in figure 4 was found to be very difficult even in non-real time in the CIWS 2003 benefits analysis (Robinson, Evans, Crowe, Klingle-Wilson and Allan, 2004). The use of numerical optimization techniques for determining how to best utilize the available capacity is attractive, but the computational load can be daunting, especially if there is uncertainty on the future convective weather impacts (Evans, Weber, and Moser, 2006).

It appears from the first nine task conditions shown in Table 1 that the convective weather ATM decisions would principally be better modeled as RPDs. If in fact, RPD is an appropriate model for convective weather ATM decision making, there is a significant challenge in gaining acceptance for improved, alternative ways of accomplishing effective weather ATM because the decision-makers will tend to prefer approaches for solving problems that have become readily-recognizable and intuitive.

For example, much of the tactical convective weather ATM in the past was being accomplished by decision-makers without access to reliable short term weather forecasts and high-quality information on the storm vertical structure. Without this information, the decision-makers often would adopt a "reactive" ATM strategy wherein planes would be allowed to continue using a route as weather approached until one or more aircraft would refuse to penetrate a storm at which point the route would be declared to be "closed." Commencing the use of the route at a later time would involve finding a flight willing to be a "path finder" that would attempt to use the route. If the "pathfinder" reported that the route was flyable, other aircraft would then be released to use the route. This process could easily result in a route being closed for 1-2 hours after the weather impact had ended (e.g., 60 minutes to locate a candidate pathfinder and have it probe the route; 60 minutes to get a significant flow along the route by other aircraft). Transitioning the ATM decision-making from this "reactive" approach to a more proactive approach requires both higher quality information being provided to the decision-makers and a willingness of the decision-maker to consider the use of an alternative approach to problem solution that was not used previously. If the real-time decision-making is being accomplished by an RPD approach, it may be very difficult to obtain acceptance for a new alternative approach.

The necessity to coordinate between the different ATC facilities, as well as various elements within a given ATC facility, in arriving at and implementing an ATM decision induces <u>both</u> decision making process complexity <u>and</u> an opportunity to improve the overall ATM decision-making. The time required to coordinate between various ATC facilities and airlines (per Figure 3) is a hindrance to effective solution development and implementation. However, the coordination process itself creates opportunities for the creation and use of alternative solutions to a convective weather impact.

(Klein ,1999) discusses the power of the "team mind" to create new and unexpected solutions, options, and interpretations provided that team cognition is enhanced through:

1. Effective communication of intent.
2. Shared understanding (including a chance for team members to voice divergent views).
3. An appropriate time horizon for looking ahead and anticipating problems.
4. Appropriate management of uncertainty.

Klein notes that the most important elements of developing an effective "team mind" is the development of team competency, identity, cognition and metacognition[3] over time. The "team mind" seems feasible to develop within an ATC facility where the various members work together daily over a long period of time. However, development of a similar "team mind" capability between decision-makers in various ATC facilities (e.g., between sector managers in different en route centers) and between ATC decision-makers and airline dispatchers seems much more difficult.

Another aspect is the role of communications and communications processes between the decision makers as a factor in improved decision making. (Davison and Hansman, 2001) noted the importance of common access to appropriate graphical weather products as a factor in improving the communications associated with TFM decision making on adverse weather. (Klein, 1999) does not explicitly discuss communication processes as a factor in teams making difficult decisions.

It would seem that many of the coordination decisions made between different ATC facilities and between the FAA facilities and the airlines might be better modeled as group decision making as opposed to team decision making. Hence, one can look at the extensive literature on group communications and group decision making for insights into improving ATM decision making through better communications. (Hirokawa, Erbert and Hurst, 1996) note that although many investigators suggest that the quality of communications that occurs as a group attempts to reach a collective decision may well be the most important influence on the decision-making outcome (page 272). It has been difficult to relate group communications to group decision-making performance (Hirokawa, Erbert and Hurst, 1996 page 295). (Hirokawa, Erbert and Hurst, 1996) suggest research to determine if it is possible to enhance decision

[3] Klein (1999) defines metacognition as "thinking about thinking" wherein a team has the ability to monitor its own performance and select strategies that avoid weaknesses and capitalize on strengths (pp. 244-245).

making by altering the communication process between the various group decision makers [e.g., by providing a group decision support system (GDSS)].

IV Operational Experience with ATM in Convective Weather

In this section, we discuss results from studies to determine whether more effective ATM was being achieved during convective weather with enhanced, integrated convective weather decision support systems.

A. Operational Use of the Corridor Integrated Weather System (CIWS)

The CIWS (Evans and Ducot, 2006; Wolfson and Clark, 2006) fuses data from over 100 Doppler weather sensing radars with satellite data, surface observations and numerical weather models to provide state-of-the-art, fully automated, high-resolution animated 3-D 0-2 hour forecasts of convective weather (including explicit detection and display of regions where storms are growing or decaying). Real-time forecast accuracy scores are provided on both the precipitation and echo tops forecast animation displays so that traffic managers can determine how much credence to give to the forecast information at various forecast lead times. Additionally, the user can view the past 30, 60 and 120 minute forecasts for the current time overlaid on current weather to better understand the spatial distribution of the forecast errors.

Intensive observations of real time tactical convective weather ATM decision making have been accomplished as a part of the CIWS operational benefits assessments conducted in the high-demand Northeast quadrant of the U.S. airspace system. The operational usage of the CIWS for tactical convective weather ATM was assessed in both 2003 (Robinson, Evans, Crowe, Klingle-Wilson and Allan, 2004) and 2005 (Robinson, Evans and Hancock, 2006). The methodology used in this assessment is shown in Figure 5. Knowledgeable observers were present in facilities for a number of different days. For example, in 2005, observations were conducted on 14 convective weather impact days over a 3 month period. During convective weather impact events, observers at select en route centers obtained feedback from traffic managers (and Area supervisors) on:

1. Convective weather impact mitigation decisions made using CIWS products
2. The workload associated with monitoring existing convective weather impact mitigation initiatives
3. The workload associated with the mitigation plan development, coordination, and execution process in relation to the workload expected for similar convective events prior to CIWS

Given the coordination efforts associated with TMC weather impact mitigation plan development and execution (see Figure 2), we had hypothesized that use of CIWS by supervisors in facility controller Areas [in addition to the primary use of CIWS in the facility Traffic Management Unit (TMU)]would improve ATM decision-making. The facility observation scheme used in 2005 allowed us to explicitly explore this hypothesis:

- Washington en route center (ZDC): CIWS available in TMU and all Area supervisor positions
- Cleveland en route center (ZOB): CIWS available in TMU and 4 of 8 Area supervisor positions
- Minneapolis en route center (ZMP): CIWS available in TMU and 5 of 6 Area supervisor positions
- Boston (ZBW), Chicago (ZAU), and New York (ZNY) en route centers: CIWS available in TMU only

Observations were conducted in the TMU in all cases and in the sector Areas at facilities where CIWS was available to Area supervisors.

A key metric for assessing the effectiveness of the convective weather ATM decision-making process was the number of times a facility made a decision that benefited the system users. Figure 6 is a typical result for frequency of various beneficial decisions at the various CIWS user facilities. Figure 6 clearly shows the importance of providing the CIWS products to the Area supervisors in the en route facilities, as well as the traffic management unit (TMU) personnel.

The number of times per convective storm day that decisions to proactive reroute planes and keep routes open was found to increase at ZOB by about 70% when the Area supervisors also had access to the CIWS products[4]. We attribute this improved ATM effectiveness to improved situational awareness when the TMU decision-makers coordinate with the Area supervisors in developing and implementing convective weather impact mitigation plans as well as permitting a more effective "team mind" to develop at ZOB. With access to CIWS in both the TMU and controller Areas, there was a shared understanding of near term changes in weather impacts which in term facilitated consideration of options that were different from the long standing intuitive RPD model decisions. Area supervisors, with access to the same high-quality, high-resolution weather depiction and forecast information as the TMU, were also empowered to identify opportunities for improved convective weather ATM, thus assisting the TMU during high-workload periods and actively contributing to the overall improvement of ATC efficiency.

The improvement of convective weather ATM through the use of CIWS has required much more extensive training than is normally done for TFM weather products[5]. Since 2002, iterative refresher training has been conducted at least twice per year at all ATC facilities and airline operations centers with access to CIWS displays. Typically, 2-3 users are trained at one time for 30-45 minutes followed by 15-30 minutes of discussion. These very small groups facilitate informal dialog on experiences in use of CIWS for decision making as well as discussions between the users on possible applications of new capabilities that were introduced in the training session. The training sessions have often evolved from "training" to "information-sharing". In addition to these "classroom-training" sessions, key facilities were also visited during active weather to provide "on-the-spot" training in real-life convective weather decision making situations.

As operational user familiarity with CIWS has increased, "new" decisions for enhanced convective weather ATM efficiency became "standard" plans for weather impact mitigation. Described previously was the scenario where en route airways were closed as soon as pilots deviated around convection on the route. Reopening these airways after the "reaction" to close them is time consuming and requires extensive coordination (and thus increased workload). Decision-makers now monitor the CIWS storm top heights and short-term forecasts of vertical storm development to identify circumstances where airways can remain open, despite local "along-route" deviations, because they can better visualize the pilot information environment. Also, the users routinely use CIWS forecast information to proactively plan for changing conditions. The decision to keep air traffic routes open despite minor local flight deviations around storms has become a standard practice of a number of the en route ATM decision-makers with access to CIWS.

In fact, this and other CIWS-derived weather impact mitigation decisions now appear to have become largely intuitive in some ATC facilities (as suggested by the RPD model). For example, when interviewed by phone after weather impact events, and asked to identify specific applications of CIWS, some traffic managers now have difficulty identifying specific uses, stating that CIWS has become so ingrained in their operational

[4] The areas in the ZOB did not have access to CIWS in 2003, but did have access to CIWS product displays in 2005. By comparing the change in benefits frequency between 2003 and 2005 at ZOB and ZDC respectively, we concluded that providing area supervisors with access to CIWS had significantly increased the ATM effectiveness at ZOB. (Robinson, Evans and Hancock, 2006) describe the observed differences in ATM decision making at the areas within the ZOB which had CIWS versus the decision making involving the areas within ZOB that did not have access to CIWS.

[5] CIWS refresher training was provided in spring 2006 to 284 Traffic Managers and Area supervisors at 18 ATC facilities, as well as to dispatchers and air traffic coordinators at 10 airline operations centers. By contrast, there was no formal retraining on the use of the CCFP in 2006.

protocol that they rely on it for almost all convective weather-related decisions, and now use it "without thinking about it".

B. Operational Use of the Route Availability Planning Tool (RAPT)

For effective convective weather ATM, it is necessary to translate the current and forecast convective weather into air traffic capacity impacts. At this point in time, the only real-time system that provides explicit capacity impacts using the conceptual model shown in Figure 3 is the Route Availability Planning Tool (RAPT) which is an experimental system that has operated at New York since 2002 (DeLaura and Allan, 2003). RAPT grew out of the realization that a major cause of delays at the New York airports was the inability to get departures out of the airports when there was convective weather in the en route airspace surrounding the terminal area (Allan, Gaddy and Evans, 2001). RAPT uses the CIWS precipitation and echo tops forecasts, together with models for the 4-D trajectories of aircraft departing from the New York airports, to determine whether there will be a 4-D intersection of storms and aircraft as a function of the departure time for each major departure route.

The ATC decision-makers in airport towers, terminal control facilities (TRACONs) and en route centers, along with airline users, can view both a time line that depicts appropriate departure times from an airport along various departure routes plus an animation of projected aircraft and storm locations to optimize departure planning. The departure time window considered by RAPT is currently 0-30 minutes in the future.

The animation feature in RAPT is very interesting in the context of the RPD decision model. The display shows at various times in the future the projected location of aircraft that have taken off at a given departure time and the forecast locations of the storms. One of the key elements in Klein’s RPD model is the evaluation of candidate actions by mental simulation [see figure 3.2 on page 27 of (Klein, 1999)]. The decision-maker imagines how given actions will play out in the future. It had been hypothesized that the users had difficulty in carrying out this simulation in their minds; hence, the computer software carried out the simulation for them. One of the anticipated benefits of explicitly carrying out this simulation and making the results available to the user was that the decision-maker could better assess the controller workload risk of a take-off decision time for an aircraft by being able to see the expected spatial relationship of the aircraft to the storm situation (e.g., to assess what other options for in-flight routing might be available if the forecast of no route blockage turned out to be in error).

RAPT operational testing (Evans, Weber and Mosier, 2006) determined that although operationally benefits were being achieved on a number of occasions, the frequency of RAPT benefits per day when there were convective weather events was much lower than anticipated. One of the principal reasons for the lower than anticipated effectiveness was the model for the key decision makers. At first, it was thought that managing departures from an airport was principally the responsibility of terminal users. Hence, RAPT had been designed using inputs and feedback from terminal users. After several years of RAPT operational usage, together with the CIWS benefits studies discussed above, it was realized that decisions by en route centers to accept the departures were critical to the overall success of RAPT. One impediment to the use of RAPT by the en route center was that the spatial extent of a route probed by RAPT in en route airspace was relatively short. Also, the role of Area supervisors in en route centers in the decision to reopen closed routes had not been appreciated when RAPT was initially designed.

In 2007, the RAPT products will be provided to Area supervisors in en route centers, as well as to en route traffic flow managers, and the extent of en route airspace probed for aircraft-weather intersections will be more than doubled. The hope is that ATM effectiveness of RAPT will be significantly increased due to improved situational awareness when the TMU decision-makers coordinate with the Area supervisors in managing departures as well as permitting a more effective "team mind" to develop at the facilities that handle departures from the New York airports.

RAPT usage also revealed that the pilot weather avoidance model and the models for terminal and en route airway usage in convective weather need to be refined. Also, it was realized that decision support is needed to facilitate rapid determinations of alternative routes when the filed route for an aircraft about to depart is blocked.

The RAPT operational experience has shown the need to consider both human factors considerations and improvements in the quality of the information provided to the decision maker when seeking to improve ATM decision-making in convective weather.

V. Summary

The need for more effective ATM during convective weather has become increasingly urgent in the U.S. as a consequence of the increase in high altitude congestion and the expectations of significant traffic growth in the future. We have shown that thunderstorm ATM decisions must be made under considerable time pressure with inadequate information (e.g., missing or, ambiguous), high stakes, poorly defined procedures, and extensive coordination required between a heterogeneous set of decision-makers.

Despite the importance of the TFM decision-making to the overall ATM capability, there are very little published studies of the TFM decision-making process for convective weather ATM. It appears from the literature that the most applicable model is the recognition-primed-decision (RPD) model developed by (Klein, 1999). However, operational use of the RPD decision making approach may inhibit the effective use of improved weather and integrated weather-ATM information since the tendency of the decision-maker will be to principally consider solutions that were used in the past.

Recent operational experience in the use of improved convective weather decision support systems in the Northeast quadrant of the U.S. was reviewed in the context of literature on individual and team decision making in complex environments. It appears that there is research on the "team mind" and group decision making that suggests very promising approaches to improving the overall ATM decision making. In particular, the significant improvement in the operational effectiveness of CIWS that was achieved by providing Area supervisors in en route centers with CIWS product displays suggests that facilitating the effective development of a "team mind" for convective weather ATM is a fruitful avenue of research. Training tailored to improving the real time decision making (including "in situ" informal training during convective weather events) has been a key component of improving the use of CIWS).

(Klein, 1999) discusses the development of a "team mind" through explicit training. This has not yet been attempted in convective weather ATM, but seems like a logical next step. It will be important to determine appropriate training to develop a "team mind" within an ATC facility. It is not clear that the interactions between different ATC facilities and between the airlines and the FAA in convective weather ATM can be usefully modeled as team decision making. If these interactions might be better modeled as "group" decision making, then we need to consider whether the training and decision support system (DSS) might need to be different than the training/DSS used within an ATC facility.

Another broad area of research is how to better design the display of weather products and integrated weather-ATM decision making tools (such as RAPT) to better match the decision processes used by the key decision makers. For example, if the RPD model is applicable to convective weather ATM, providing a "what if" simulation capability to reduce the workload associated with mentally simulating the consequences of a given decision might reduce the time required to reach a decision. Such a "what if" capability might need to have features that would facilitate tailoring to better match the decision making process of different individuals (similar to the ability of CIWS users to save default configurations of weather display overlays that meet their specific decision making needs).

The identification of missed opportunities in the effective management of traffic during convective weather events would insure that the decision-making research is targeted toward the most important decisions that are not being made effectively today. A very promising approach to this identification of missed opportunities is the use of large scale ATM optimization techniques for post event analyses to determine where opportunities to better utilize available capacity were missed (Evans, Weber and Moser, 2006).

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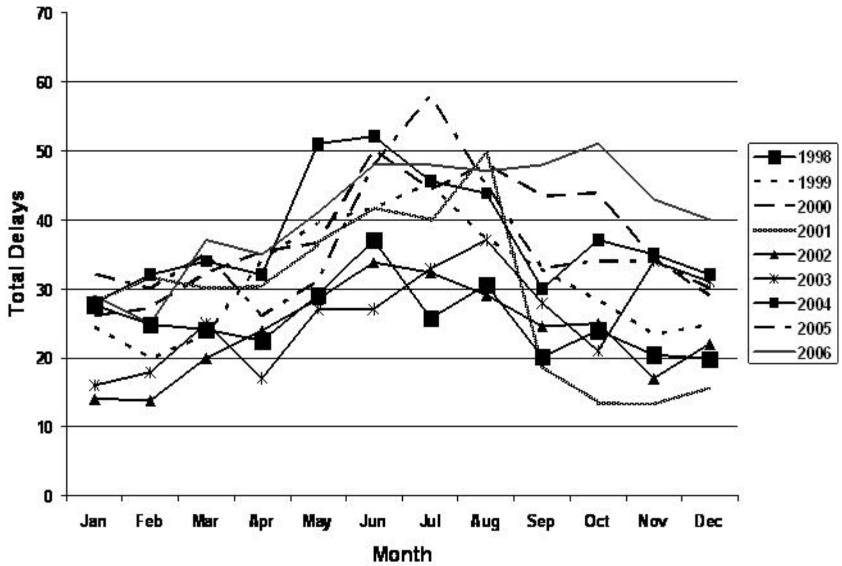


Figure 1. U.S. OPSNET delays by month for a period of 9 years. OPSNET delays reported by the FAA's Air Traffic Operations Network are delays of 15 minutes or more.

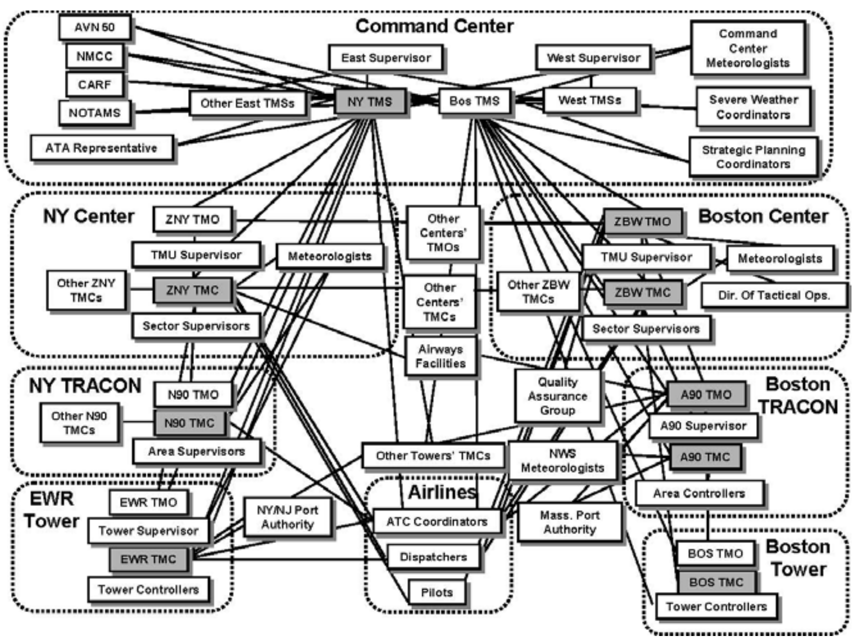


Figure 2. Interactions between various FAA facilities and airlines in addressing congestion problems related to the Newark International Airport (EWR) (from Davison and Hansman, 2001). The traffic management coordinators (TMCs) play a key role in addressing NAS network problems, but they must coordinate with many other potential aviation weather forecast users. Note that airline dispatchers are an important component of the coordination process. This is because rerouting and other adjustments to filed flight plans may be necessary to address the combination of weather and congestion problems.

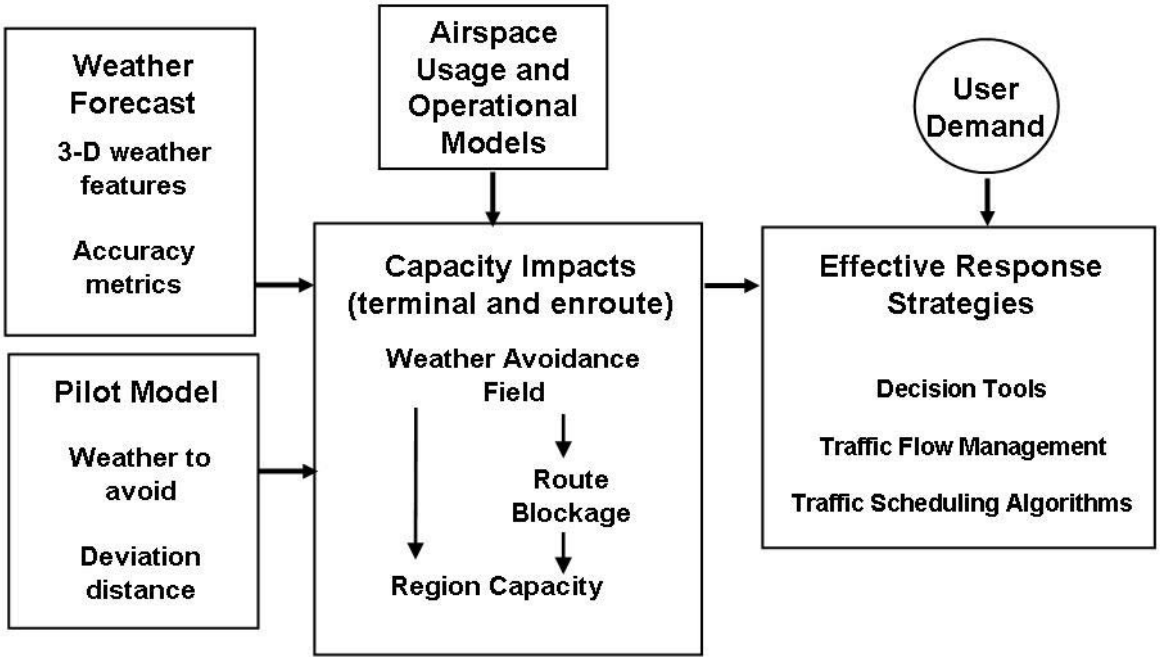


Figure 3 Conceptual framework for convective weather ATM. Uncertainty in the weather forecasts and additional ambiguity that arises in translating the convective weather forecasts into forecasts of capacity impacts further complicates the ATM decision-making problem.

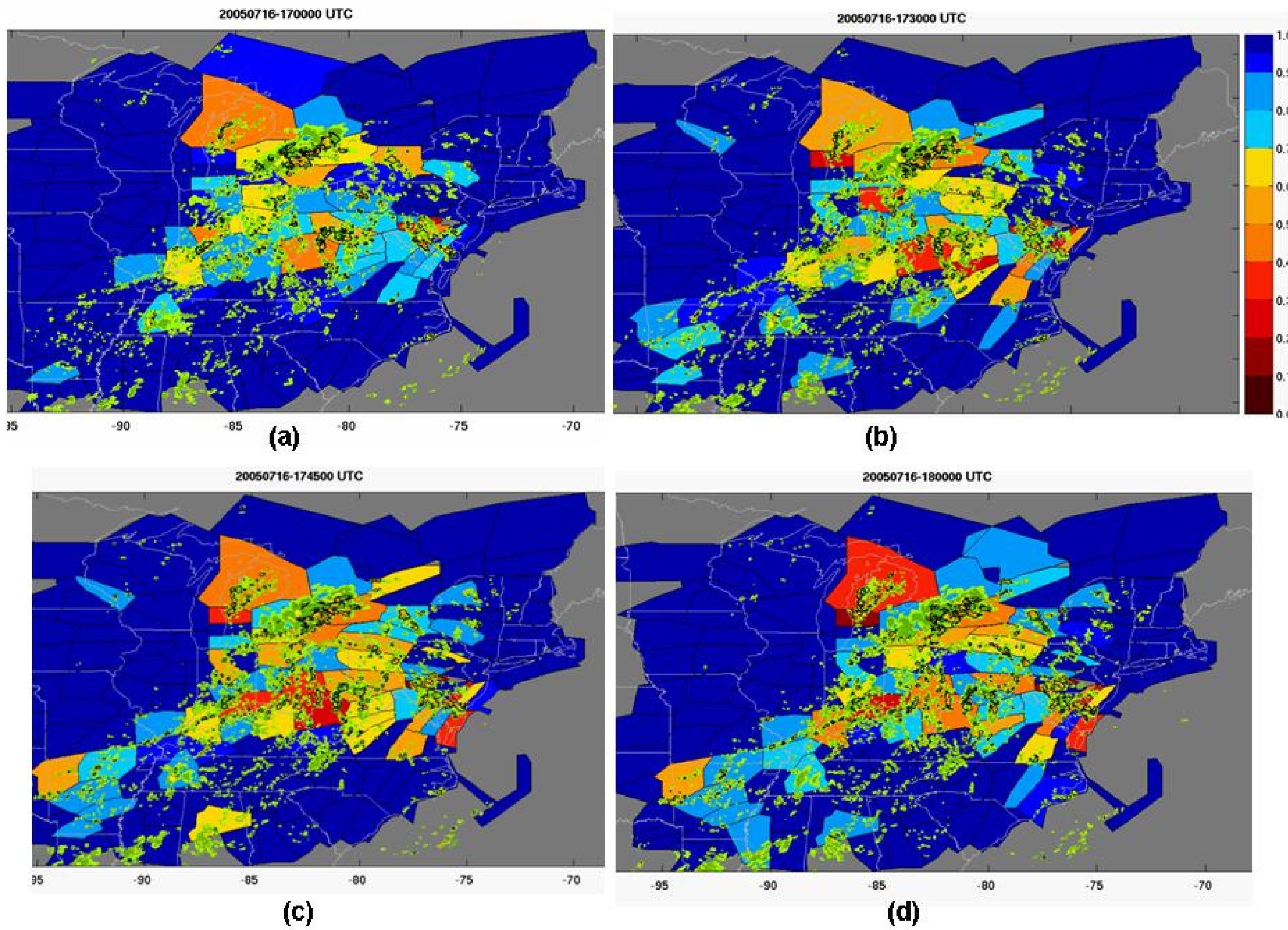


Figure 4 Capacity loss due to convective weather in the Northeast quadrant of the U.S. at (a) 1700 UTC, (b) 1730 UTC, (c) 1745 UTC, and (d) 1800 UTC on 16 July 2005. Overlaid atop capacity loss estimates is CIWS precipitation. The color bar in the right-hand corner indicates effective capacity of a sector as a fraction of the sector fair weather capacity (dark red is fully "blocked" while dark blue is fully "open").

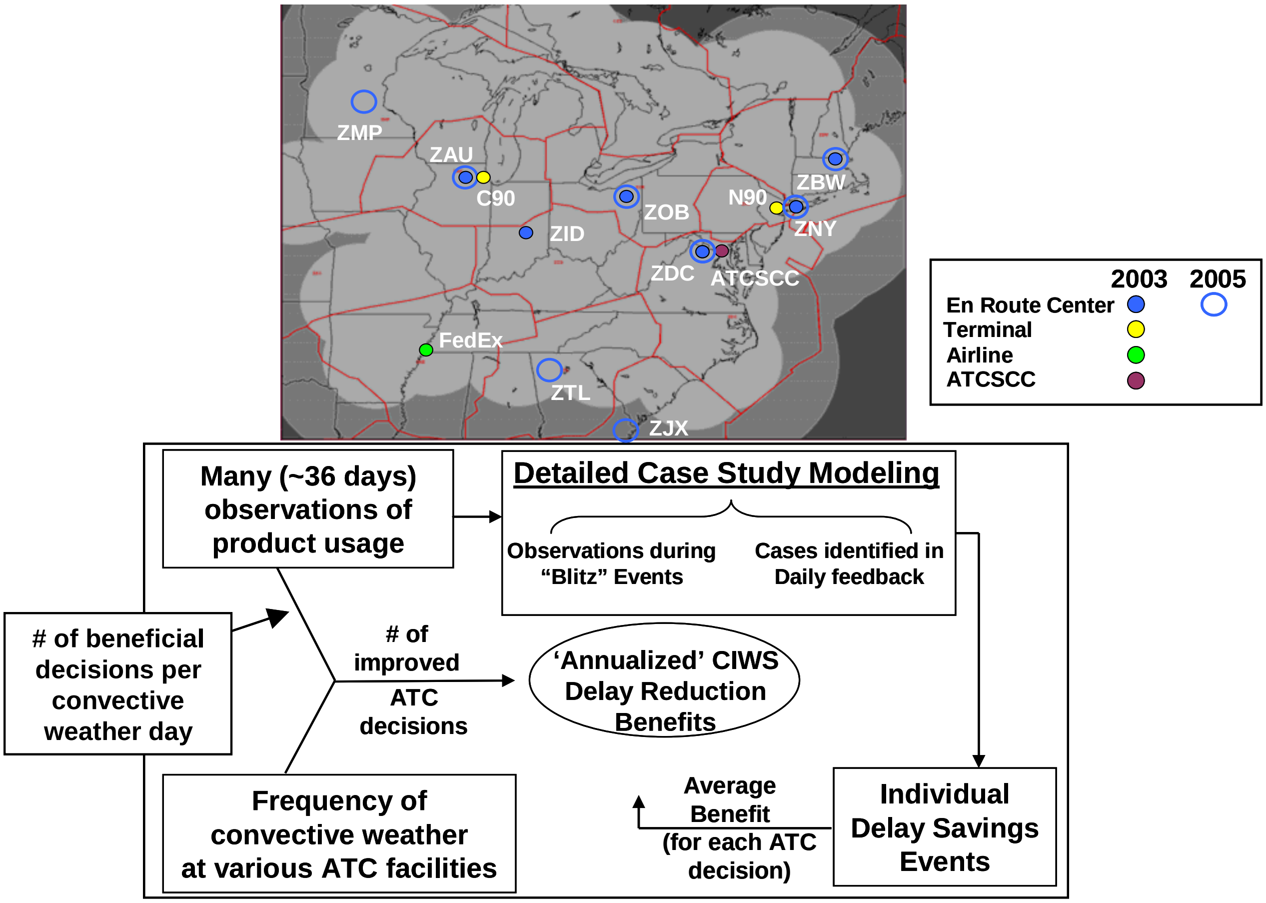
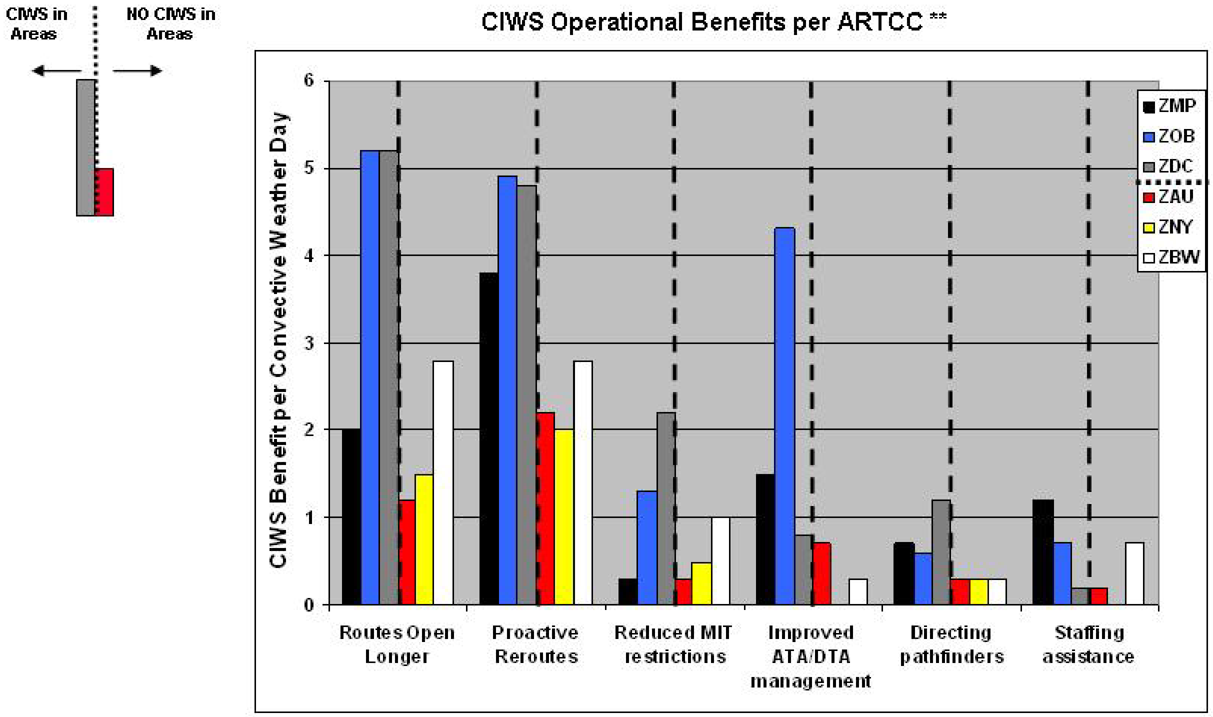


Figure 5. Methodology for CIWS operational usage observations and data analysis (Robinson et al., 2006). Facilities shown were assessed in the observations in 2003 and 2005.



** *Includes most significant CIWS en route delay reduction benefits categories + FAA staffing assistance category*

Figure 6. Frequency with which an improved ATM decision was made per thunderstorm day for various identified benefits. The Minneapolis en route center (ZMP) was a new user of the CIWS, while the Boston en route center (ZBW) had several very intensive users of CIWS in the TMU. Note that the experienced CIWS uses facilities [Cleveland (ZOB) and Washington (ZDC)] had a much higher rate of capacity enhancing uses of CIWS than the other ARTCCs. The much higher rate of management of weather impacts on the terminal arrival and departure fixes (ATA and DTA) at ZOB reflects the availability of CIWS at the major terminals within ZOB.