3.4 KEY RESEARCH ISSUES FOR NEAR TERM OPERATIONAL USE OF INTEGRATED CONVECTIVE WEATHER-ATM DECISION SUPPORT SYSTEMS*

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1. INTRODUCTION

Thunderstorm-related delays dominate the overall U.S. airspace delay statistics and continue to increase (Figure 1), even though a number of new weather information systems and air traffic management (ATM) decision support tools have been deployed since 1999. The FAA is also concerned that anticipated increases in air traffic will result in much worse convective weather season delays by 2014 (Hughes, 2006).

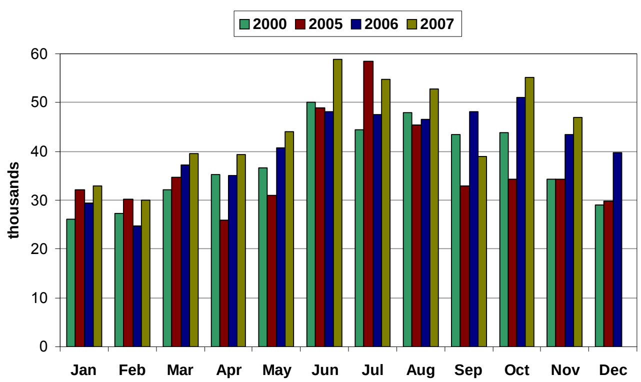

Figure 1. U.S. air traffic delays as measured by the FAA Air Traffic Operations Network (OPSNET) data base. OPSNET counts the number of delays of 15 minutes or more in a single Air Traffic Control (ATC) facility (including ground holds at the departure airport). 2007 had the greatest number of OPSNET delays of any of the years shown. The traffic at major airports in 2005 through 2007 was typically 7-8 % lower than the traffic in 2000. The number of ARTCC operations for 2007 were essentially unchanged from 2000.

A key factor in this persistence of significant convective weather delays has been increases in high altitude traffic due to the air carrier transition from turbo props to regional jets. As a consequence, when convective weather causes reductions in en route capacity, the high altitude traffic demand exceeds the available capacity [Evans and Ducot, 2006]. Operational decision makers must then mitigate the network congestion that arises while rapidly varying capacity losses occur in both en route and terminal airspace. Improving decision making in such an environment requires decision support tools that explicitly consider airspace structure, network impacts, weather forecast uncertainty, and pilot preferences for weather avoidance.

The NextGen initiative envisions weather assimilated air traffic management that would assist in improved decision making. The near term focus of NextGen has been:

(1) an operational concept and research agenda for 2025 that assumes that aircraft separation from other aircraft and weather avoidance is accomplished using a high degree of automation and
(2) development of a net-enabled weather information distribution infrastructure

Recent FAA presentations on NextGen at major ATM conferences [e.g. Cox, 2007] discuss the need for improved weather forecasts, for research on the impact of weather on NextGen concepts and, for improved weather sensors on aircraft. NASA has sponsored some "foundational research" on the translation of weather information into ATC impacts that is applicable to near term integrated convective weather-ATM applications.

In this paper, we consider research to achieve significant near term time frame (2010-2015) improvements in convective weather ATM where aircraft separation from other aircraft is provided largely by controllers and hazardous weather avoidance is accomplished by pilots using visual cues, reports from other aircraft, onboard weather radar, and ATC advisories.

Key elements of the research program to be discussed include:

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*This work was sponsored by the Federal Aviation Administration under Air Force Contract No. FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.
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1. Translating of convective weather products into ATC impacts (including handling of uncertainty in the convective weather forecasts).
2. Determining how much of this delay in the current NAS (using contemporary forecasts and ATC procedures), is considered avoidable.
3. Developing integrated weather-ATM decision support tools (DST) to enable decision makers to more fully utilize available capacity, and
4. Human factors [e.g., how individuals make real time decisions in collaboration with other decision makers (e.g., ATC, airlines, dispatch, pilots)].

The paper proceeds as follows. We briefly review the current status of work in key areas (including the major recommendations from the recent study of ATM-weather integration by an FAA advisory committee[1] and then discuss research initiatives in the four areas noted above.

2. BACKGROUND

Framework for convective weather-ATM integration

An overall framework for discussing research convective weather-ATM integration is presented in Figure 2.

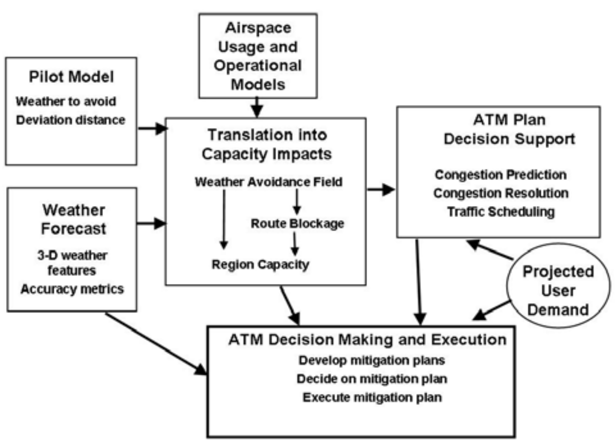

Figure 2. Key elements of convective weather-ATM integration (including the ATM decision process).

[1]The Weather – ATM Integration Working Group (WAIWG) of the National Airspace System Operations Subcommittee, Federal Aviation Administration (FAA) Research, Engineering and Development Advisory Committee (REDAC).

By integration, we mean that weather information and forecasts have been translated from a “conventional” weather representation (e.g., a spatial field of forecast storm reflectivity or echo tops or probabilities) into regions of airspace that pilots will seek to avoid which in turn have been used to estimate airspace capacity impacts. These weather-related airspace capacity impact products can either be used directly by decision makers, or act as an input to automated ATM plan decision support tools that accomplish functions such as automated congestion prediction and resolution.

Human decision makers typically use a combination of decision support information (e.g., conventional weather forecasts, capacity impact forecasts, and ATM plan generation decision support products) to arrive at an ATM decision. Understanding this decision process and its impact on issues such as product distribution, presentation, and training is extremely important if the desired objective of the integrated convective weather-ATM decision support development is measurable operational benefits (Evans, 2006).

The most pressing operational need for improved convective weather ATM is in congested airspace. In congested airspace, ATM convective weather impact mitigation plans often necessitate traffic being rerouted from the normal sectors/routes to alternative sectors and routes which will in turn have a significant impact on ATM in other regions of airspace. Hence, coordination and collaboration between different ATC facilities and airlines such as is shown in Figure 3 is a critical element of plan development and execution.

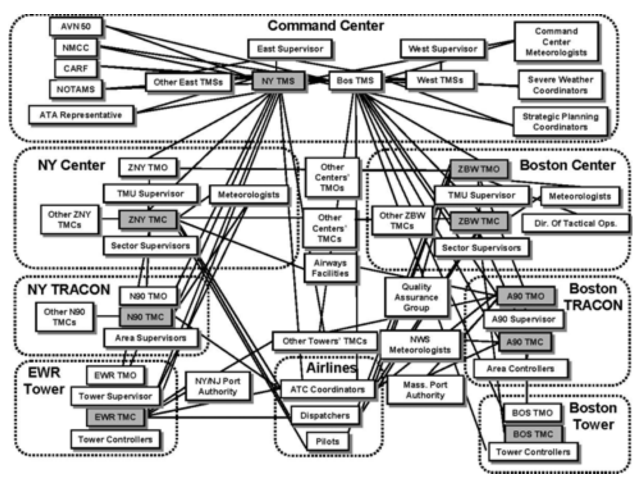

Figure 3. Interactions between various FAA facilities and airlines in addressing congestion problems related to the Newark International Airport (EWR) (from Davison and Hansman, 2001). The traffic management coordinators (TMCs) play a key role in address NAS network problems, but they

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.

2.1 REDAC WAIWG Study

The most comprehensive recent study of ATM-weather integration was carried out by the REDAC WAIWG. A study team[2] under the leadership of W. Leber and R. LaFrey was formed with representation from the airlines, general aviation, the research community, and experts from the weather and air traffic management community. The year long effort included meetings with the aviation community, FAA facilities and committee meetings at various locations. Forty-seven briefings were presented including eleven on weather in the cockpit.

The WAIWG found (FAA REDAC, 2007) that with the exception of the Route Availability Planning Tool (RAPT)[3] (a departure decision support system in operation at New York), and the Winter Weather (WSSDM) deicing decision support tool, no existing air traffic management tools are integrated with aviation weather beyond providing traditional weather depictions as an overlay on traffic displays or flight plans and using winds for flight time estimates.

An important consideration from the recommendations in REDAC WAIWG study was the recognition that the ability to accurately forecast convective weather impacts greater than an hour in advance is quite limited (Figure 4). One needs to explicitly consider this when deciding what type of ATM decision support tools have the greatest likelihood of achieving operational success (as measured in reduced delays) in the relatively near term.

[2]The author of this paper was a member of the REDAC WAIWG and benefited greatly from the briefings and discussions of the WAIWG. However, the analyses and recommendations of this paper are the responsibility of this author and do not necessarily reflect the WAIWG position.

[3]RAPT will be discussed subsequently in this paper.

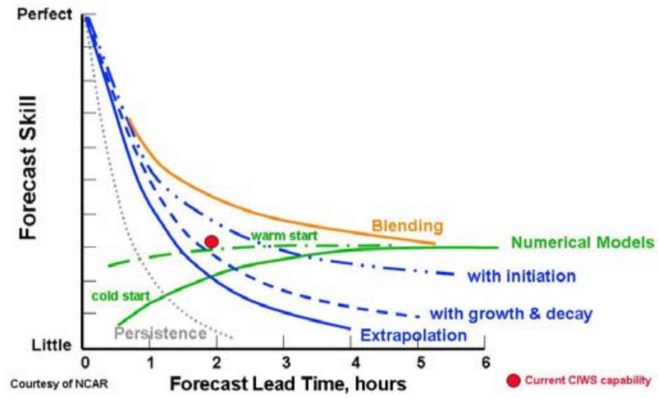

Figure 4. Projected accuracy of convective weather forecasts in the near term (Wolfson, 2008).

The principal emphasis thus far in the FAA-airline Collaborative Decision Making (CDM) efforts to improve convective weather ATM has been on strategic (2-6 hour) plan development using the Collaborative Convective Forecast Product (CCFP). Major difficulties have arisen in accomplishing effective ATM with such lead times due to the lack of accurate 4-6 hour forecasts at the key decision times times (e.g., mornings) for effective strategic planning [(Huberdeau, et. al., 2004), (Kay, et. al., 2006), (Seske and Hart, 2006)].

In view of the difficulties that had arisen in use of strategic ATM as the principal approach for convective weather ATM, the WAIWG suggested much greater focus on shorter lead time ATM. The major specific WAIWG recommendations were as follows:

(i) A risk management approach using adaptive, incremental decision making based on automatically translating weather forecasts into air traffic impacts, presents a major new opportunity for reducing weather related delays.

(ii) A cross cutting research program, involving public and private sector air traffic management and aviation weather experts, is needed to exploit these key findings.

Overarching Recommendations

- Initiate a crosscutting research program in ATM/Weather integration
- Establish Senior Leadership over-sight and REDAC monitoring
- Revitalize joint FAA-NASA advisory committee reviews of research including weather – ATM integration
- Develop FAA Aviation Weather Research Program (AWRP) requirements to support integration efforts

Research Recommendations: Near Term - IOC 2010

- Identify and quantify avoidable delay.
- Translate convective weather into ATC impacts
- Improve support for Airspace Flow Program (AFP)[4] by developing a 6-10 hour weather impacts forecast
- Improve Weather Input into Collaborative Traffic Flow Management
- Develop guidance on integrated tools for cockpit decision making
- Integrate airport and terminal area automation with weather

Research Recommendations: Mid Term - IOC 2015

- Develop adaptive integrated ATM procedures for incremental route planning
- Develop integrated ATM procedures for tactical trajectories
- Develop flexible airspace designs

Research Recommendations: Far Term - IOC Post 2015

- Replace surrogate weather indicators with true measures of flight hazards
- Conduct research on probabilistic and deterministic forecasts for multiple dynamic flight lanes.
- Conduct research on gridded and scenario based probabilistic weather data for ATM decision tools.

Human Factors

- Conduct research on the human factors aspects of weather – ATM integration
- Identify best weather practices of air traffic facilities and train these practices system wide

Since REDAC reports are recommendations to the FAA administrator and high level decision makers within the FAA, the level of technical detail in the REDAC report on various recommendations was necessarily quite limited. Hence, a more technical review of the current state of art in key areas identified by REDAC is warranted.

[4]Airspace Flow Programs are discussed in (Doble et al (2006).

2.2 Translation of convective weather products into ATC impact products

It is clear from Figure 2 that a key component of the translation from weather products to ATC impacts is explicit models for determining whether or not pilots will seek to avoid certain portions of the airspace and, the deviation distance from avoidance regions. A number of recent studies have been carried out on the relationship of pilot decision making for level flight in en route airspace on convective storm penetration versus deviations [DeLaura and Evans, 2006; Chan, Refai, and DeLaura, 2007; DeLaura, Robinson, Pawlak and Evans, 2008].

These studies [and, the earlier studies discussed in (Rhoda, et. al., 2002)] have consistently shown that the radar echo tops relative to the flight altitude is generally a much better statistical predictor of pilot deviations around a storm than is the storm reflectivity. This result is a very important factor to consider in design of convective weather forecasts to support integrated convective weather-ATM systems since nearly all convective weather forecasts developed for general use focus only on forecasting storm reflectivity fields.

(DeLaura, Robinson, Pawlak and Evans, 2008) found that pilot response prediction errors were greatest for trajectories whose flight altitude was near or slightly below the echo top height with the differentiation between ‘benign’ echo tops and those that pilot avoid remaining the major challenge in convective weather avoidance modeling for level en route flight.

Algorithms have been developed for finding paths through a field of weather regions to be avoided (Prete, et. al. 2004). However, the key issue in congested airspace is how many aircraft can safely traverse an area with convective activity, i.e., what is the capacity of convective weather impacted airspace.

Capacity typically corresponds to the maximum number of aircraft that can be safely handled in a region due to controller workload[5] (and, wake vortex) constraints. However, there is no standard metric for capacity. (Histon, et. al., 2002) discuss complexity metrics that are related to capacity metrics. Histon’s work emphasized the importance

[5]If one assumes that separation of aircraft from other aircraft is accomplished automatically, then controller workload complexity becomes a much less important consideration. (Mitchell, et. al., 2007) provide estimates of sector capacity if the principal constraint is the spacing between adjacent aircraft on nominally the same flight path.

of the geometry of principal traffic flows in a sector in determining the complexity. (Song, L., C. Wanke, and D. Greenbaum, 2007) extended the work of Histon, et. al., to quantify the importance of factors such as the major flow, and the number of flows, merging flows, climbing flows, and crossing flows in determining complexity.

The principal traffic flow management (TFM) decision tool [the Enhanced Traffic Management System (ETMS)] used today in the US characterizes the capacity by the number of aircraft that may be in a sector over a given period of time[6].

On the other hand, it is also quite common to find TFM control executed using miles-in-trail (MIT) spacing between aircraft on a route. *In-situ* real time observations of TFM decision making in congested airspace [e.g., (Robinson, et. al., 2006), (Robinson, et. al., 2008)] have consistently observed that TFM control is accomplished by manipulation of flows (especially, starting and stopping the use of a fix or route) as opposed to reducing the sector capacity limits used by ETMS.

Given the importance of MIT and flow start/stops as a principal mechanism for control of traffic flows in convective weather, route impacts of convective weather are of independent interest as a characterization of weather impact on capacity. The RAPT (DeLaura, Robinson, Todd and Mackenzie, 2008) utilizes route segment blockage forecasts to determine when aircraft can depart an airport on a given route.

A key research issue at this point is how to characterize the effective capacity of sectors during convective weather. There are two basic approaches that have been discussed in the literature to date:

(a) Ignoring all or most of the details of traffic flow within a sector (e.g., flow distribution, maximum flow, merges, and crossing points) within a sector, or
(b) Applying the complexity considerations used in fair weather to convective weather as suggested by (Song, L., C. Wanke, D. Greenbaum, and D. Callner, 2007). This involves considering in detail the flow structure within a sector including the spatial geometries of the various flows.

Examples of the first approach include:

(i) (Zobell, et. al., 2007) estimates sector capacity in convective weather by a linear function of the fractional coverage of the sector by high reflectivity weather,
(ii) (Mitchell, et. al., 2006) estimate sector capacity for unidirectional flow in a sector by a fluid flow argument (specifically, a max-flow, min-cut theorem from the mathematical literature[7]) that focuses on the narrowest available region that is at right angles to the traffic flow (i.e., akin to an obstruction in a pipe). (Song, Wanke, Greenbaum and Callner, 2007) extend the (Mitchell, et. al., 2006) approach to apply it to flows through a sector in different directions. (Song, Wanke, Greenbaum and Callner, 2007) assume that the reduction of the net flow in a given direction is linearly proportional to the maximum fractional decrease in effective sector width for each flow.

An example of the second approach is the model discussed in (Martin, 2007) which characterizes the reduction in sector occupancy by determining which specific routes in a sector are blocked (using a route blockage algorithm similar to that of RAPT) and, what fraction of the normal traffic in the sector operates over the blocked routes.

A key question is whether the additional complexity involved in understanding the details of the traffic flows within a sector and complexity factors is important in estimating the effective sector capacity during convective weather. Assuming that effective capacity is linearly proportional to the fractional coverage of weather within a sector is clearly not adequate in situations where the sectors are very long and narrow with the principal routes oriented along the long axis of the sector (e.g., west of New York city) since in such cases, a very small fractional weather coverage will block all of the principal flows within the sector.

[6]This is the monitor alert threshold (MAP) used by ETMS to identify possible excessive traffic densities.

[7]See, e.g., (Ahuja, et. al., 1993)

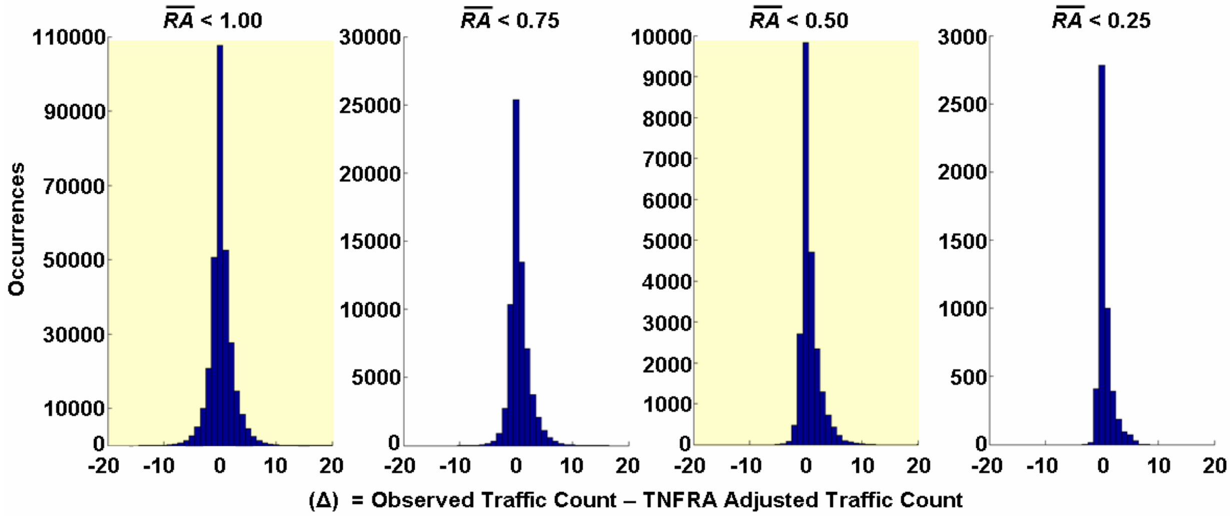

Figure 5. Comparison of estimated one minute traffic counts in 406 sectors within the Corridor Integrated Weather System (CIWS)[8] domain) using traffic normalized route blockages (TNFRA) computed from CIWS 3D storm data and, the actual observed one minute traffic counts for 27 July 2007 convective weather event. $\overline{RA}$ *is the fraction of routes within a sector that were blocked at the time of measurement. From (Martin, 2007). Reasons for the major differences between the predicted and actual sector usage are discussed in (Martin, 2007). A principal cause of overestimation of the traffic within a sector is the impact of storms on other sectors surrounding the sector under study.*

[8]See (Evans and Ducot, 2006) for a description of the CIWS and its spatial coverage

The best agreement reported to date between actual sector occupancy and sector occupancy predicted on the basis of 3-D weather radar reflectivity and echo tops are the results in (Martin, 2007) shown in Figure 5.

One of the important outgrowths of the validation of route blockage and sector occupancy estimates has been an improved understanding of important issues in the model of pilot weather avoidance. For example, the RAPT operational testing that there was a significant difference in pilot propensity to penetrate storms if the storm was backlit by the sun as opposed to the situation where the aircraft is between the sun and the storm. Flight level visual observations of the storms (DeLaura, Robinson, Pawlak and Evans, 2008) confirmed the hypothesis that the storms look very different as the plane-storm-sun geometry changes.

Similarly, the sector occupancy prediction validation testing (Martin, 2007) has shown that it is very important to gain a better understanding of routine operational ATC use of available airspace when routes are impacted by convective weather. For example, it was noted that when there are parallel adjacent routes in a given direction through a sector, transitions between the adjacent routes may be used to get aircraft around a short blockage on one of the routes (e.g., operating the group of routes as "two as one" or "three as one").

2.3 *How much of today's delay is in fact avoidable?*

A key question in determining the priority for near term investments in integrated convective weather-ATM systems and, various elements of an integrated system (e.g., en route versus terminal, tactical versus strategic, which sections of the country) is the extent to which the delays that occur today are "avoidable" in the sense that contemporary convective weather forecasts (e.g., accuracies similar to those shown in Figure 4), ATM decision support algorithms, and ATM decision maker capabilities could be expected to take advantage of availability opportunities.

The recent development of reasonably accurate estimates for sector capacity (e.g., as described in Martin, 2007) has made it possible to consider the use of fully automated algorithms for congestion resolution with time varying capacities. The principal data on the magnitude of convective weather "avoidable delay" considered by the REDAC WAIWG were Lincoln Laboratory studies of three convective storm events (Robinson, Moser, and Evans, 2008). Sector capacity estimates derived from the actual 3D CIWS weather products[9] were input into a objective, automatically-generated, broad-area airspace usage algorithm developed by (Bertsimas and Stock-Patterson, 1998) that considers the time-varying estimates of airspace capacity and the demand in determining optimal reroute strategies (and, when necessary, minimally disruptive ground or airborne delay initiatives). This algorithm provides explicit flight profiles and delays for each aircraft. By comparing the actual airspace usage with the airspace usage by the Bertsimas model solution, one can objectively assess the effectiveness of operational ATM during convective weather impacts. In all three cases studied in (Robinson, Moser, and Evans, 2008), the "avoidable" delay was at least 75% of the actual delay.

Studies of the specific scenarios are underway [see (Robinson, Moser and Evans, 2008) for some examples] to determine how much of the "avoidable" delay reduction could have been accomplished using contemporary convective weather forecasts (e.g., accuracies similar to those shown in Figure 4), ATM decision support algorithms, and ATM decision maker capabilities. This involves detailed studies of the ATM decision support information available in real time at various salient decision points in a given day. For example, if opportunities were missed for use of departure capacity for storms relatively close (e.g., within 30 minutes flying time) of the departure airport, one could readily envision providing near term decision support such as exemplified by RAPT. On the other hand, if a key difference between optimal ATM and actual ATM was the number of long distance flights routed through storms relatively close to the destination airport, achieving an improved ability to accurately forecast the capacity impact (and hence, long distance flight routing) hours in advance may not be feasible in the near term.

2.4 *Route Availability Planning Tool (RAPT) usage*

The RAPT grew out of the observation that a major benefit of the ITWS system at New York (Allen, Gaddy, Evans, 2001) was an increased effective departure capacity when there was convective weather near the New York terminal area. However, a significant limitation in the achievable benefit from such manual ATM decision making using the ITWS 0-1 hour forecasts was that the ATM decision maker had to continually translate

[9]It is very important to note that these computations are using the functional equivalent of perfect convective weather forecasts.

from storm impact times at various locations on a departure route to the corresponding departure time from the various New York city airports. In determining whether or not a route might be blocked at a point, the user would also need to consider the relative altitude of the aircraft and the storms at locations of potential blockage along a route.

It was suggested by the NY terminal ATC personnel that ATC domain information (i.e., the flight profiles typically used by departing aircraft and typically departure routes) could be combined with corresponding convective storm forecasts to determine when aircraft could depart from the various airports and not encounter convective storms. Initial testing of this integrated convective weather ATM system (DeLaura and Allan, 2003) showed that it was essential to consider the flight altitude relative to the storm echo tops and, to have a much better model for what constitutes blockage of a route in a given location (e.g., how wide is the feasible maneuvering region for a route and, what spatial distributions of storm reflectivity and echo tops within the maneuvering region typically results in operationally undesirable flight deviations).

Tests of an improved RAPT departure time algorithm were conducted in the summer of 2007 [(DeLaura, Robinson, Todd and MacKenzie, 2008) and (Robinson, DeLaura, Evans and McGettigan, 2008). These tests found that RAPT as tested was providing operationally useful benefits (RAPT delay reduction benefits in 2007 of 2,300 hours of delay saved with a corresponding cost savings of $7.5 M), but that the currently achieved benefit was a small fraction of the potential benefits. The RAPT technical issues that needed to be addressed included:

- Improvements in the RAPT route blockage use of storm reflectivity and echo tops (to reflect the results of research on pilot storm avoidance modeling)
- Provision of explicit information about RAPT route forecast uncertainty, including a better representation of weather deviation sensitivity for individual departure routes/fixes, and
- Addition of more departure routes

The most significant near term need was addressing a number of operational issues including:

Improved access to the RAPT decision support by key decision makers (especially the New York airport towers)

Reducing the adverse impacts of lack of common understanding of which departure routes were open or closed at a given time and, why various facilities were constraining departures at a given time.[10]

Training in the recognition of missed opportunities for departures during SWAP

2.5 Human factors issues

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 conceptual models for decision-making, shared situational awareness and interpretation of team phenomena that may be applicable to understanding the 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 seems to be particularly germane.

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, and
- Describes analyses and recommendations to facilitate review by others

[10] It was estimated that there were 440 instances in the News York 2007 convective weather season where ATM decision-makers were sufficiently uncertain of airspace availability status that available departure capacity was not utilized.

(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 concluded 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 assignment of the current situation to an analogue past situation and then evaluates various possible actions by undertaking a rapid mental simulation of possible outcomes.

If the RPD model is fact an appropriate model for convective weather ATM decision making, then there are very significant implications for the design, distribution and training for integrated convective weather-ATM decision support products. For example, if a new product is introduced, the decision-maker will not have a personal “library” of past situations that includes the new product as a piece of data. Hence, the new product might be ignored in the ATM decision making for a considerable period of time after its introduction simply because there had not been extensive past experience with the product.

(Evans, Robinson, and McGettigan, 2007) have interpreted the very impressive increases in the operational usage and benefits of CIWS at ARTCCs when CIWS weather products were provided to both area managers and traffic flow managers at the ARTCCs (Robinson, Evans and Hancock, 2005) as the use of enhanced situational awareness to facilitate partial use of RCS in a situation where otherwise only RPD would have been utilized.

3. RECOMMENDED RESEARCH PROGRAM

In this section, we discuss research issues that are particularly important for operationally successful experimental use of integrated convective weather-ATM decision support systems by 2015. By operationally successful, we mean that operational benefits such as reduced delays relative to an appropriate baseline can be demonstrated.

3.1 Translation of convective weather products into ATC impacts (including handling of uncertainty in the convective weather forecasts)

Both the validation testing of pilot storm avoidance modeling [(Chan et. al., 2007) and (DeLaura, Robinson, Pawlak, and Evans, 2008)] and operational testing of the RAPT (DeLaura, Robinson , Todd and MacKenzie, 2008)]) have shown that improvements in the model for predicting pilot deviation decisions as a function of ground derived weather features is urgently needed. It appears that the greatest uncertainty in pilot response occurs when the flight altitude is close to the radar echo tops altitude. Such variability is of great concern for the development of operationally useful convective weather ATM decision support systems since variability in pilot response translates into uncertainty in the ATC impact.

(DeLaura, Robinson, Pawlak, and Evans, 2008) suggest that upper level winds and satellite data warrant consideration as possible deviation predictors, and, that there may be better predictors than the current CIWS convective forecast algorithm growth and delay fields for capturing the convective storm growth and decay features at jet flight altitudes.

Concurrent research by the FAA Aviation Weather Research Program (AWRP) turbulence product development team (PDT) may be useful at developing additional robust deviation predictors as well as determining the level of turbulence around a storm near the radar echo tops altitude.

Another factor that could potentially be significant in improving the ability to accurately predict storm pilot deviation decisions is providing ground derived weather and airspace congestion products to the cockpit. It was noted by the test pilots for the flight tests reported in (DeLaura, Robinson, Pawlak, and Evans, 2008) that it is not easy to estimate the altitude of storms relative to the aircraft at distances of 20-40 miles. Hence, some variability in pilot deviation behavior may arise from differing subjective estimates of what might be required to fly over a cell. Ground derived storm information such as storm tops, an indication of which storms are growing or decaying, and explicit turbulence severity forecasts might help in achieving more consistent deviation behavior between different pilots.

Another candidate product for transmission to the aircraft would be information on current and expected congestion in the region ahead of a flight. In particular, it could be useful if pilots had a better sense of the consequences to the ATC system if their aircraft were to deviate into airspace used by aircraft on a standard route. For example, in the NY departure airspace, deviations of a departing airspace into the space normally used by arrivals often resulted in a shutdown of departures along the departure route for extended periods of time that cause acute problems for the subsequent departures. This is not to say that a pilot should not deviate around storms if there is a serious safety concern; but there needs to be improved pilot understanding of the ATC system consequences of flight deviations into airspace used by other aircraft flows.

It should also be noted that relatively well validated pilot storm avoidance models have been developed thus far only for level flight in en route airspace. These models need to be extended to consider both ascending and descending flights in both en route and terminal airspace. For example, departures climb at much steeper elevation angles than the typical arrival. Also, both passengers and cabin attendants are seated with seat belts on during climb out whereas cabin attendants may be in the aisles during the initial descent phase. Hence, one might imagine that the pilot desire to avoid convective turbulence could be higher for arrivals than for departures. Since many near term convective weather-ATM integration system capabilities (to be discussed later in this section) involve flights that are ascending or descending or, are in terminal airspace, it clearly will be necessary to extend the pilot response modeling analysis to these other flight regimes early on in the 2008-2015 time period.

3.2 Determining ATC impacts in the form of route blockage and reduced sector capacity

A number of areas for research in route blockage algorithms arising from the RAPT real time testing in 2007 are discussed in (DeLaura, Robinson, Todd and MacKenzie, 2008).

There is a broad urgent need to better understand how traffic managers handle situations such as storm impacts on merge and crossing points, ascending and descending flights, arrival and departure fixes, and storm impacts inside terminal areas. Some issues associated with modeling the impact of storms on departure fixes will be investigated as a part of the studies of how the RAPT algorithms (which currently reflect the atypical arrival and departure fix geometry of the NY TRACON) should be modified to allow RAPT to be used at "conventional" 4-corner TRACONs.

The sector capacity studies reported in (Martin, 2007) noted the need to handle transitions between adjacent flows of aircraft in the same direction when there was intermittent (but, not coincident) blockage of the various parallel routes.

One of the major challenges is the translation of convective weather forecast accuracy metrics into route blockage and sector capacity forecast accuracy metrics. The classical approach to characterizing inaccuracy of a convective weather forecast has been to provide a spatial pixel map of the likelihood of weather reflectivity exceeding a given threshold (typically 40 dBZ). However, to go from such a probability field to a computation of route blockage or, blockage of regions within a sector requires making some assumptions about the spatial correlation between the various probabilities in near by pixels. It is clear from looking at typically convective weather reflectivity fields that there is a much higher likelihood of high level reflectivity occurring in pixels near a pixel that has high reflectivity than there is in a pixel chosen at random. However, this spatial correlation between probabilities has not been quantified to date and is very likely to be very complicated.

Computations of route blockage and sector capacity uncertainty are much easier if the uncertainty in the convective weather forecast were to be characterized by a set of ensemble deterministic forecasts that are derived from the deterministic forecasts (e.g., such as generated by CIWS) together with recent history of forecast inaccuracy.

One can envision characterizing the forecast uncertainty in terms of storm advection velocity uncertainty, shape uncertainty (including cell growth and decay) and new growth. Work is underway to determine how this might be accomplished. In this respect, we call attention to the use of Monte Carlo simulations to generate fairly realistic looking spatial patterns of convective weather in the study by (Mitchell, et. al., 2006). Such a pseudorandom approach may be quite useful for generating realistic spatial distribution of new cell growth regions provided that there is sufficient quantitative guidance from numerical models, satellite data and front detectors to identify the likely regions of new growth.

In Figure 6, we show how the sensitivity of route blockage estimates to errors in the extent of storm cells (ΔR) and cross route velocity (ΔV_c) is related to the cross route velocity (V_c) of the storm cells. This simple example suggests that route blockage algorithms should consider the expected cross route velocity of the weather in determining how best to utilize the storm forecasts (e.g., how much time-space smoothing of forecast fields may be warranted).

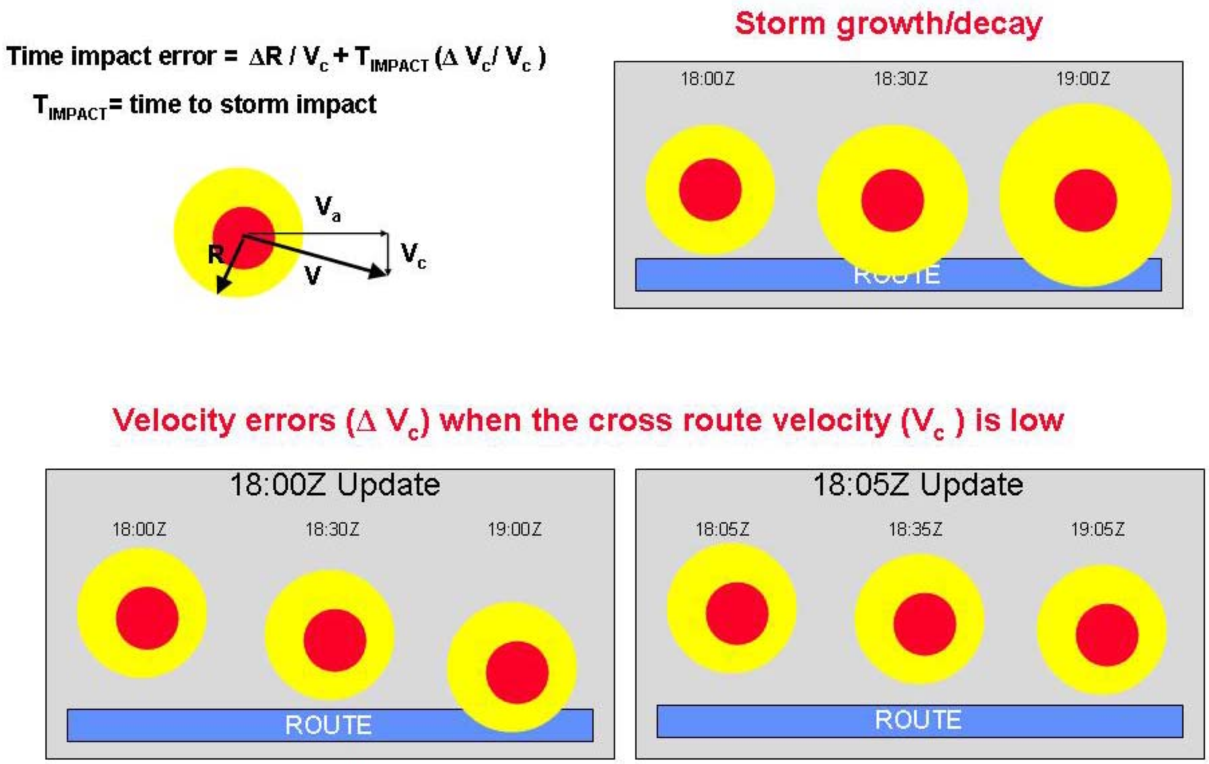

Figure 6. Illustration of the impacts of errors in storm size and cross route velocity errors on route blockage computations. When the cross route velocity (V_c) is small, the blockage times and occurrence is very sensitive to small changes in either storm extent (ΔR) or cross route velocity (ΔVc).

3.3 *Determining whether much of today's delay is in fact "avoidable" using contemporary forecasts and ATC procedures.*

An important element of the process to determine which candidate convective weather-ATM integrated tools should be developed in the relatively near future is a quantitative understanding of the likely operational utility of a given capability. The methodology for determining "avoidable delay" and analyzing the results to determine where the convective weather ATM missed opportunities occurred ATM described in (Robinson, Moser, and Evans, 2008) should be very useful for the prioritization process. Work is currently underway to use this methodology for generating initial estimates of candidate traffic flow management modernization (TFM-M) capabilities.

However, it is also necessary to improve the operational fidelity of the overall simulation described in (Robinson, Moser, and Evans, 2008). Some improvements will occur as a result of research into improving the pilot storm avoidance model and the sector/route capacity impact models that were discussed above. However, there are some larger scale traffic flow management strategies that may also need to be considered. These can best be understood by obtaining operational facility feedback on the overall traffic flow management strategies provided as inputs to the Bertimas-Stock-Patterson algorithm.

3.4 Developing integrated weather-ATM decision support tools (DST) to enable decision makers to more fully utilize available capacity

A number of TFM-M capabilities are under consideration by the FAA in areas such as automated congestion prediction, automated congestion resolution, departure flow management and time based flow metering. These capabilities typically include one or more of the elements discussed above: the pilot storm avoidance model, forecasting route impacts, forecasting sector capacity impacts. Figure 7 shows an example of a suite of weather-ATM decision support capabilities suggested by the REDAC WAIWG.

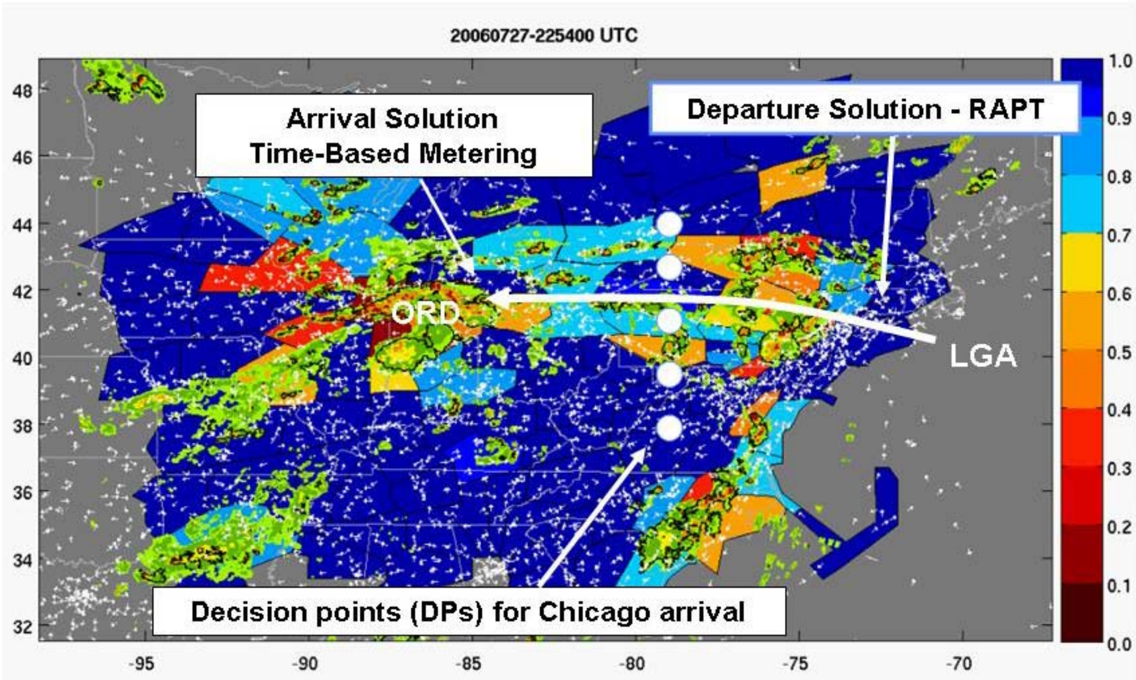

Figure 7. Example of increment adaptive integrated convective weather-ATM capabilities suggested by the Weather – ATM Integration Working Group (WAIWG) of the National Airspace System Operations Subcommittee, FAA Research, Engineering and Development Advisory Committee (FAA REDAC, 2007). The route availability planning tool (RAPT) is used to determine the best route for a departure from LaGuardia International airport (LGA) to Chicago O'Hare. At predefined decision points (DP), short term forecasts of route and arrival fix availability are used to decide which arrival fix into the Chicago terminal area should be used. As the aircraft nears the arrival fix, time-based metering that is aware of regions of airspace that pilots will seek to avoid is used to generate a flow of aircraft through the arrival fix that facilitates optimal use of the available runways at ORD. The color coding of en route sectors indicates the fractional sector capacity at this time. The overlay is CIWS storm reflectivity. The white dots are locations of flights.

Regarding Figure 7, the research needed for RAPT and to improve the ability for forecasting which routes would be available between the various decision points and an arrival fix has already been discussed. The chief new research required to achieve the capability shown in Figure 7 would be research on algorithms for determining the flight times for the various aircraft arriving at a departure fix when some (possibly all) of the flights may have to route around storms to some degree. This computation will require research into deviation flight profiles that would be acceptable to both pilots and controllers.

3.5 *Human factors initiatives*

The RAPT 2007 operational testing (Robinson DeLaura, Evans and McGettigan, 2008) showed that human factors issues such as collaboration inside an ATC facility and with other facilities can greatly influence the operational use of a convective weather-ATM decision support tool. There is also an urgent need to find methods for product presentation and training that will greatly reduce the time to achieve significant operational use of new capabilities.

There is research on the "team mind" and group decision making (e.g., (Klein, 1999), (Hirokawa, 1966) that seems applicable 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 (Robinson, Evans and Hancock, 2006) suggests that facilitating the effective development of a "team mind" for convective weather ATM is a fruitful avenue of research.

(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. If these interactions might be better modeled as "group" decision making, then we need to consider whether the training to improve collaboration in convective weather ATM should be different for inter facility interactions vs intra facility interactions.

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).

4. SUMMARY

There is an urgent need to improve convective weather ATM in the US air system. This is a very challenging problem due to rapidly changing nature of the convective weather induced capacity impacts, complexities of network management and difficulties in accurately forecasting convective weather impacts hours in advance. However, there has been major progress in the last 5 years in developing a framework for convective weather-ATM integration and a first order understanding of some key factors (e.g., a model for pilot avoidance of thunderstorms and initial models for convective weather impacts on routes and sector capacities). Additionally, some preliminary studies of how much of today's convective weather delays are potentially avoidable suggest that there is a large "benefits pool" available if both convective weather forecasts and ATM decision support could be improved.

These studies show that the convective weather forecasters need to provide forecasts for storm characteristics beyond storm radar reflectivity – in particular, improved echo tops forecasts information is needed for en route ATM. It is also essential that the forecast algorithms provide forecast uncertainty information in a form suitable for computation of ATC impact uncertainty. We suggest that the forecast uncertainty be represented by a set of deterministic sample spatial patterns of convective weather.

There is a very important role here for meteorologist insights into convective storm dynamics to help in determining the best set of predictions for pilot storm decision making. Data link transmission of ground generated storm information (and, possibly airspace congestion information) could help significantly in reducing the variability in storm avoidance decision making between different pilots.

Much better understanding of standard ATC practices for management of convective weather impacts on both en route and terminal airspace is needed to develop models for ATC impacts on various elements of both en route and terminal airspace.

Determining priorities for integrated convective weather-ATM capabilities could benefit greatly from detailed quantitative studies of how much of today's avoidable delay could be addressed with various candidate capabilities.

Finally, we have emphasized the importance of focused human factors research to reduce the time period for decision makers to make effective use of new weather-ATM capabilities and, to improve the collaboration between decision makers within an ATC facility as well as between different ATC facilities.

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