Federal Aviation Administration

Research, Engineering and
Development Advisory Committee

Report of the
Weather-ATM Integration
Working Group

October 3, 2007

Executive Summary

This report provides findings and recommendations of the Weather – ATM Integration Working Group (WAIWG) of the National Airspace System Operations (NAS OPS) Subcommittee, Federal Aviation Administration (FAA) Research, Engineering and Development Advisory Committee (REDAC).

The objective of this twelve-month study was to examine the potential benefits of integrating two highly inexact sciences; weather and air traffic management, and to provide research recommendations to the FAA where appropriate.

The working group members were from airlines, general aviation, NASA, the National Weather Service, national research centers and academia. The study results are based information gathered during visits to airline operations centers, terminal and en route air traffic facilities, and research centers.

In this report, integration is defined as translating traditional weather information into impact measures, such as capacity or flow rates, and automatically or semi-automatically incorporating that data into traffic flow advisory information to improve the system capacity and safety in the face of weather hazards.

Few instances of integrated tools exist: time-of-flight estimates incorporating winds aloft; storm free departure times at one airport, and winter deicing timing. All other NAS decision tools use weather manually, as traffic display overlays or on separate displays.

Aviation weather forecasts have much more accuracy in 0-2 hour, tactical time frame, than the 2-10 hour, strategic time frame. However, the size and shape of the 0-2 hour solution space is much smaller and with increasing congestion, more decisions will have to be made in the latter. Conversely the more the tactical solution space can be expanded, the more decisions can be delayed adaptively and traffic optimized to meet business objectives.

A key finding, based on an analysis of several 2005-2006 convective events, is that as much as two-thirds of the weather related delay is potentially avoidable.

Another key finding is that a risk management approach with adaptive, incremental decision making, based on automatically translating weather forecasts into air traffic impacts, presents a major new opportunity for reducing weather related delays in the future NAS.

The key recommendation is that a cross cutting research program, involving public and private sector air traffic management and aviation weather experts, is needed to exploit these key findings.

Summary of Recommendations

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 AWRP requirements to support integration efforts

Research Recommendations: Near Term - IOC 2010

- Identify and quantify avoidable delay.
- Translate convective weather into ATC impacts
- Improve AFP 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 adaptive integrated ATM procedures for tactical trajectories
- Develop flexible airspace for weather impacts as a fundamental and initial ATM design requirement

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

FAA and NextGen Enterprise Architectures

- Ensure that direct ATM automation-weather integration is a key focus of the development of OEP/NAS Enterprise Architecture operational and technical views for the transition to NextGen.

Aviation Weather Research Program

- Increase support to enable participation in joint weather – ATM integration research
- Restore the National Ceiling and Visibility Program

Dedication

This study was organized by the late Jerry Thompson at a 2006 summer meeting in Boulder, Colorado, of the NAS Operations Subcommittee, FAA Research, Engineering and Development Committee. That so many contributed to this work is a tribute to the importance of this issue and to Jerry.

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1. Introduction

This report provides findings and recommendations on the integration of weather information into air traffic management (ATM) processes and systems. It was developed by the Weather/ATM Integration Working Group (WAIWG) under the direction of the National Airspace System Operations (NAS OPS) Subcommittee and its parent body, the Federal Aviation Administration (FAA) Research, Engineering and Development Advisory Committee (REDAC).

The objectives of the twelve-month study included examining the potential benefits associated with a higher degree of integration between two dissimilar and fundamentally inexact sciences, namely, weather and air traffic management, and with providing specific research recommendations to the FAA that were considered most likely to lead to better, more efficient ATM solutions, in the face of weather constraints.

The members of WAIWG believe this report to be complementary to the Next Generation Air Transportation System (NextGen) vision as espoused by the Joint Planning and Development Office (JPDO). The report is also seen as timely, especially when viewed in light of (1) current and projected future increases in demand for airspace system capacity, (2) the escalating difficulties associated with convective weather constraints in the NAS, and (3) the current state of ATM in the NAS.

With respect to the latter, it is useful to acknowledge that current ATM processes and toolsets are only partially automated, and when they are, the underlying algorithms are almost always based on nominal (no weather impacts) system conditions. Therefore, in the presence of weather constraints in the NAS, most ATM personnel discard available automated tools and their solutions and revert to the use of manual solutions. Every ATM decision maker has a different level of experience and mental capacity. This, combined with the inconsistencies naturally associated with human decision making under periods of high mental workload and stress, results in ATM solutions in the face of weather constraints which are inconsistent, unpredictable and often rigid.

Additionally, the common coping strategy for the human ATM decision maker is to devise solution sets that are applicable to a large number of flights (flow-based solutions) instead of tailored to the individual impacted flight (flight-based solutions). Unfortunately, a widely applicable solution set is not the best solution set for many, if not most, individual flights. Consequently, this strategy results in the perception among users of the airspace that NAS resource allocation decisions are not equitable.

A response to the overall ATM decision making problem is to incorporate more advanced automation systems that capture the impacts of weather.

As used in this report, integration means that weather information and forecasts must be translated from words, pictures or probabilities into quantifiable airspace capacity impact values which are then appropriately incorporated into ATM processes and technology. One component of this translation will involve gaining a better understanding of pilot actions in the face of weather phenomena such as thunderstorms and turbulence. These weather-related airspace capacity impact values must then be automatically incorporated into aircraft, airline operations center (AOC) and ATM toolsets and processes in such a way so as to improve system capacity and safety in the face of weather hazards. Many of the study's findings and recommendations are related to this area.

There are but a few examples of current ATM tools and processes in which weather information is integrated.

- Existing time-of-flight estimators which incorporate winds aloft are used by FAA systems today.

- Certain ATC facilities use a tool which provides storm free departure times from a particular airport.

- Winter deicing times are predicted in certain airports.

All other NAS ATM decision support tools and traffic management processes use weather information manually, as storm depiction overlays or from separate, stand-alone displays.

Aviation weather forecasts have much more accuracy in the zero to two hour ("tactical") time frame, than in the two to ten hour ("strategic") time frame. However, the number of viable solutions in the zero to two hour solution space is much less than in the two to ten hour space, and the available solutions themselves are also much different. With increasing congestion, it would seem that more decisions will have to be made strategically, from two to ten hours before departure. If, however, the tactical solution space can be expanded by increasing the number of possible solutions, then more decisions can be delayed adaptively and more flight trajectories can be optimized against business objectives. As will be reported in Section 6, this type of risk management approach with adaptive decision making presents a major new opportunity for reducing weather related delays and operating costs in the future NAS.

2. Study Description

This study was organized at a summer, 2006, meeting of the NAS OPS Subcommittee with the following terms of reference:

- Recommend development priorities for integration of Weather and ATM covering near (IOC 2010), intermediate (IOC 2015), and long term (IOC 2025).

- Consider requirements for the flight deck (weather in the cockpit), Air Navigation Service Providers and Flight Operations Centers.

- Recommend incorporation of the requirements into the FAA Enterprise Architecture and the NEXGEN Enterprise Architecture.

- Recommend changes to the Aviation Weather Research Program's to support study recommendations.

A study team 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.

Details on the membership, schedule, relevant literature and briefing sources are provided in Appendix A.

3. Background

This section provides background information on the evolving challenge of weather and congestion, aviation weather products, their use in air traffic management, earlier integration initiatives, and issues related to cockpit weather.

The Weather and Congestion Challenge

Weather has always been a major constraint to air transportation but its impact has grown in recent years. The National Airspace System of the United States is the most efficient in the world because, unlike other systems, it is allowed to operate at full capacity until weather or other constraints require throughput to be reduced by traffic management initiatives. Despite a 6% traffic reduction at major airports between 2000 and 2006[1], overall delays have grown due to increased enroute traffic volumes and growing enroute congestion. The higher enroute volumes result in much more difficult ATM decision making than those in response to terminal impacts or constraints.

The FAA S2K (Air Traffic Control System Command Center) home site states: "Even under the best weather conditions, overall increases in airspace demand and significant increases during peak demand periods routinely leads to congestion, which can have a ripple effect throughout the NAS. When areas of high demand are impacted by convective weather, the volume and complexity issues are extended dramatically requiring a system-wide choreographed effort to minimize service disruption."

The challenge is clear: how should Air Traffic Management systems and procedures be modernized, and integrated with aviation weather and new airspace designs, to minimize disruptions and enable the natural growth of the air transportation industry.

Aviation Weather

The concerted efforts of FAA, NOAA/NWS, DOD and NASA in the past several decades have resulted in the deployment of many new weather sensing systems including Geostationary (GOES) and polar (POES) satellites, and NEXRAD, ASOS, TDWR and ASR-9 WSP ground systems.

Using the new sensor data, and advances in computing, image processing and weather modeling, the FAA and National Weather Service have made significant

[1] Mitre OPSNET report

improvements to forecasting icing, turbulence, ceiling and visibility, and convection events. The integration of NEXRAD sensors enabled the creation of new products such as the Collaborative Convective Forecast Product, used for strategic traffic planning. The integration of a broad set of terminal area sensors to improve the prediction and detection of wind shear led to the Integrated Terminal Weather System (ITWS). Similar motivation for en-route or regional domains led to the prototype Corridor Integrated Weather System (CIWS).

The NWS has created a suite of digital weather products on the Aviation Digital Data Service (ADDS), which includes a national convective product called the National Convection Weather Forecast (NCWF), and a large variety of other products.

Since convection is historically the major reason for delay, especially in the summer, an automated 0-1 hour storm motion product (Terminal Convective Weather Forecast – TCWF) was developed and, later, a 0-2 hour storm product for regional use was created. These tactical products are self scoring, providing a metric on their recent performance, which air traffic managers are finding useful. Current FAA sponsored research is focused on a developing a single integrated convection and wintertime storm product for 2012.

Additional progress in weather automation has occurred: Preflight briefings of icing and turbulence hazards are now automated and can be tailored for specific routes and altitudes to simplify go-no-go decisions. An experimental ceiling and visibility tool for helicopter medical flights has been deployed. A challenging sensor integration and modeling effort was completed at San Francisco to predict marine stratus burn off.

Air Traffic Management and Aviation Weather

With few exceptions the use of the various single and integrated weather products by air traffic managers have followed traditional methods and procedures: separate displays of weather imagery are examined and air traffic flow decisions made by manually estimating the impact of weather based on mental models and experience. This may have been adequate in the past, but with the growing traffic and greater fragility of the NAS to disruptive weather, better means to leverage existing weather products are needed.

Accordingly, new approaches were developed and have already enjoyed some success, evolving ATM toward a more integrated approach with weather impacts. The CCFP enabled traffic managers and operators to move beyond arguments over convective forecasts. The FEA/FCA process enabled areas of flow, impacted by weather, to be isolated from nominally useable airspace. This capability was combined with the lessons learned from Ground Delay Programs

and the Flight Schedule Monitor to create the Airspace Flow Program capabilities.

FAA sponsored R&D, the CDM group and others have contributed these and other important building blocks in ATM but the following example illustrates an opportunity that was identified at New York to take weather integration to the next level:

When the one hour Terminal Convective Weather Forecast (TCWF) product was first deployed in 1998, ATC personnel had to mentally extrapolate the forecast and calculate the future aircraft locations for each planned departure. This proved impractical so a Route Availability Planning Tool, RAPT[2], was developed that automates these mentally taxing calculations, making accurate departure impact predictions readily available to the supervisors and air traffic flow managers. It effectively translated weather information into traffic flow constraints. It was subsequently enhanced to account for storm tops, continues to be used and refined at New York, is used in associated in air route centers, and is being considered for other FAA control facilities.

RAPT was possible because of the greater accuracy of the 0-1 hour TCWF forecast period. Although conceptually simple, it is difficult to extend into enroute airspace because of airspace structural rigidity and coordination problems. It also highlights the problem of deciding what weather is acceptable to penetrate based on radar observations that measure precipitation and not turbulence, and variations in pilot reactions. However, it exhibits a key finding of this report which cannot be over emphasized: weather can be translated into impact <u>and</u> converted to an advisory in ATM terms, at least for tactical situations.

Previous Integration Initiatives

Research on weather and ATM Integration has been consistently stifled due to a lack of requirements from FAA operations offices. Consequently, atmospheric scientists, engineers, and ATM researchers conducted ad hoc efforts to establish interest in this area.[3]

Since May, 2000, groups of weather and air traffic management researchers have held five Weather–ATM Integration Workshops, designed to identify integration opportunities and stimulate interest within FAA and NASA. The last, in October of 2004, identified ten research recommendations which are provided in Appendix B.

[2] See Appendix F for description.
[3] Section 5 of this report will address the requirements problem.

Until recently, neither the FAA nor NASA responded to the recommendations of these workshops. A common reaction by FAA air traffic operational offices was to insist that weather forecasts be first improved, especially in the 0-6 hour time frame before committing to integration efforts. Another reaction was resignation, or the suggestion that weather presents an unavoidable disruption to traffic flow. However, NASA has recently responded with new research in this area, reported in Appendix B.

As previously stated, with the exception of a departure tool at New York, and a winter deicing 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. [4]

Weather in the Cockpit

The growing use of data-linked weather information in general aviation aircraft and, shortly, in air carrier cockpits, presents both challenges and opportunities to the aviation community and the FAA.

There is both government and industry concern about up linked weather information, regarding its' quality, consistency, and use by both general aviation and air carrier pilots, especially for storm avoidance. Another concern is that the airline cockpit weather demonstrations designed to show how the cockpit weather products can lead to better pilot decision making have been conducted in situations where congestion was not an issue. When airspace congestion is a major concern, pilot decision-making must be done in coordination with the current NAS management strategy.

To identify the key issues associated with the use weather in the cockpit, the WAIWG held a special one day session with representatives from the FAA's Aviation Safety (AVS) organization, the airlines, general aviation, ALPA, the National Business Aircraft Association (NBAA), and a helicopter medical airlift group.

[4] Mitre Survey

4. Avoidable Weather Related Delay

A key issue considered by the committee was the extent to which today's weather delays could be avoided if weather and air traffic management were more effectively integrated. Accordingly, the study examined recent convective events in view of the higher level of weather related delays in the summer.

The avoidable delay for actual weather delay cases was determined by a three step process:

(i) The actual weather characteristics (e.g., ceiling/visibility, airport winds, and 3 D weather radar reflectivity) were translated into the capacity reductions in the associated en route sectors, terminal airspace, and at airports[5],

(ii) The time history of available terminal and en route capacity and the traffic demand were input into an fully automatic broad-area ATM strategy generator[6] to determine reroute strategies or, when necessary, minimally disruptive ground or airborne delay programs that could have been utilized to minimize overall NAS delay

(iii) The actual delays and airspace utilization for that date were compared to the optimized capacity utilization and its associated delays to determine where and when capacity was not fully utilized, and how much of the actual delay was "avoidable" where the avoidable delay = actual delay – delay for the optimized ATM strategy.

Since the ATM strategy generator has knowledge of both the current and future weather, this is equivalent to assuming the availability of perfect weather forecasts as well as the use of optimal ATM responses to that weather. The latter, therefore, also assumes that there is perfect coordination between the various ATC facilities and between the FAA and airspace users.

In practice there will always be underutilized airspace capacity in the face of weather constraints due to inaccurate forecasts, the suboptimal use of those weather forecasts in the development of ATM strategies, flawed coordination between various decision makers, communications and infrastructure limitations, and/or suboptimal implementation of the strategies (e.g., from delays in modifying flight plans, or because a particular aircraft is unable to fly the prescribed route due to mechanical issues).

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[5] The method by which this was done will be discussed subsequently.

[6] Bertsimas, D. and S. Stock-Patterson, The Air Traffic Flow Management Problem with En Route Capacities, Operations Research, 46, 406-422, 1998

As such, one must carefully look at the circumstances associated with the suboptimal use of available capacity in order to judge whether the existence of additional usable capacity could have been reasonably anticipated by real-time decision makers, given the accuracy of the weather forecasts and other ATM decision support then available to the decision makers. Beyond the formation of ATM strategies, one must also be aware that the current system infrastructure negatively impacts the air traffic manager's ability to communicate and execute an ATM decision once made.

With those caveats in mind, an analysis was done [7] for several significant convective events in 2005 and 2006. Table 1 shows the results.

Although the magnitude of the avoidable delay was quite high in two of the three cases, the fact that much of the actual delay could have been avoided is encouraging for weather-ATM integration, since the accuracy of short term (e.g., 0-2 hour) convective forecasts is much better than the accuracy of longer lead time forecasts and, may be easier to improve in the future.

Details of this analysis are provided in Appendix E.

	7/16/05 Actual	7/16/05 Possible	7/27/05 Actual	7/27/05 Possible	7/27/06 Actual	7/27/06 Possible
Ground Delay >15 min	31%	4%	25%	4%	42%	5%
Air Delay** >15 min	9%	5%	10%	9%	3%	7%
Total Delay (hours)	3997	69	5630	1840	6452	2236
# flights	13,340		15,648		16,328	

** Includes reroute time 1

Table 1 Preliminary results of determining unavoidable delay for three severe weather events in 2005 and 2006.[8]

[7] MIT Lincoln Laboratory 2007 study
[8] Ibid

5. Findings and Recommendations - Overarching

A. Crosscutting Research Program

Finding: There is virtually no funded, cross cutting, research taking place in the integration of weather information into ATM decision support systems automation.

There is a robust community of researchers and significant funded research activity in the ATM DSS automation arena. The same is true of aviation weather research, albeit at a much smaller support level. But there is virtually no identified or funded research on integrating weather information into ATM decision support system automation. Not a single interdisciplinary approach to such research, with members of the weather, ATM DSS automation and user communities working together as a team to develop an integrated weather/ATM capability, could be identified. If considered at all in ATM research, weather is, in effect, an afterthought or extension to an ATM tool.

Recommendation: Initiate and fund a crosscutting research program in Weather/ ATM integration and insure that weather aspects are an integral part of all new ATM initiatives from the beginning.

Specific research recommendations are provided Section 6.

B. Leadership

Finding: The support of senior leadership is vital for promoting the development of integrated weather – air traffic management capabilities.

As with any organization, public or private, the clear interest and commitment of senior management is needed for the success of a significant new effort such as integrating weather information and forecasts and air traffic management automation systems. This was emphasized in the REDAC Transitioning Research Study and is equally valid for the subject of this study, especially since past efforts have not been successful, in part for lack of management support.

Recommendation: Establish Senior Leadership oversight.

Senior leadership oversight of all major weather – ATM integration development efforts should be established to insure progress and overcome traditional resistance that has been resident in the middle management levels of the FAA.

Recommendation: Establish REDAC monitoring.

The REDAC should be directed to annually monitor weather/ATM integration initiatives to ensure adequate progress.

Finding: Related research at NASA is important to the development of weather – ATM integration.

NASA is currently conducting research directly connected to integrating weather and air traffic management processes and automation, although at a modest level of effort. This work is informally connected to FAA sponsored research and at risk given recent changes in NASA Aeronautics priorities. Additionally, it was found that this level of effort is far below the level required to insure the necessary cross-disciplinary connection to FAA Weather ATM integration work.

Recommendation: Revitalize joint advisory committee reviews of FAA and NASA joint research such as weather/ATM Integration.

FAA and NASA should hold joint meetings of their advisory committees and include the identification of current and future cross agency research opportunities in support of integrating advanced aviation weather and air traffic management tools. Furthermore, a Memorandum of Understanding (MOU) or Agreement of Understanding (AOU), between FAA and NASA, and encompassing weather and ATM research, may be needed to clearly elucidate the needed connection between these agencies.

C. Requirements Process

Finding: Current Weather Research Requirements do not include weather – ATM Integration.

Finding: ATM research only considers weather as an extension or afterthought, and that a new approach where weather is considered up front is needed.

While many of the existing aviation weather research efforts are important, they do not include work on weather integration with ATM, because the AWRP leadership does not have requirements from ATO to move in that direction. Additionally, the working group was not made aware of ATM requirements for weather integration, and could not find examples in the operational or research offices of the FAA where integration was considered a requirement.

Recommendation: Develop requirements for weather ATM Integration participation within the AWRP.

6. Findings and Recommendations: Weather – Air Traffic Management Integration

This section provides findings and recommendations regarding weather – air traffic management in nine areas:

Near Term: IOC 2010

- A. Assessments of Avoidable Delay
- B. Translating Weather Data into ATC Impacts
- C. Improve weather input into Collaborative Traffic Flow Management
- D. Weather Information and Pilot Decision Making
- E. Integrating Weather Impacts with Airport and Terminal TFM

Mid Term: IOC 2015

- F. Adaptive integrated ATM procedures for incremental route planning
- G. Weather Impacts and Tactical Trajectory Management Systems
- H. Design Airspace for Weather Impacts

Far Term: IOC Post 2015

- I. Advanced Integrated ATM Approaches

It is important to recognize that the research elements for each epoch must start now, in order to meet the Initial Operating Capability dates indicated.

While certain key human factors issues are highlighted for these different time frames, because many of those issues cut across near-, mid- and far-term epochs, most of the human factors considerations are documented in a separate section (Section 7).

Near Term: IOC 2010

A. Assessments of Avoidable Delay

Finding: Weather related delay may be significantly reduced through improved integrated decision tools.

As described in Section 4 and Appendix E, an analysis of recent convective events indicates that opportunities exist to significantly reduce weather related delay if weather and ATM functions are integrated and provided to decision makers.

It is important that research continue to improve understandings of the characteristics of avoidable delay and support the development of integrated methods to exploit these phenomena.

The analysis process cited provides explicit flight profiles for each aircraft (that could be provided to traffic flow management play back facilities) operational facility domain experts could provide useful feedback on the practicality of the automatically generated ATM strategies.

Recommendation: Research is needed to identify and quantify avoidable delay.

Quantitative research studies of "avoidable" delay, should be conducted each year, based on significant summer or winter storm events, to identify opportunities to reduce delay and to evaluate the performance of weather – ATM integration capabilities as they are developed and fielded.

Recommendation: ATM/TFM/AOC/FOC Involvement is needed.

Operational user feedback on the feasibility of the ATM strategies developed by the automatic planner described in Section 4 should be provided.

B. Translating Weather Data into ATC Impacts

Finding: Initial efforts on translating weather data into ATC impacts have shown some success, but additional research is needed.

A key research question is the translation of current weather data and weather forecasts into ATC impacts, i.e., airspace that pilots will seek to avoid and the associated airspace capacity impacts. Since this is an important topic, an example is provided here; a more detailed description is provided in Appendix E.

For this analysis, the integration of weather and ATM is shown architecturally in Figure 1. The process begins with descriptions of pilot behavior and weather, translates them into capacity impacts, using airspace and operational descriptions, and provides the results to algorithms that incorporate user demands and response strategies to develop decision advisories.

A pilot weather deviation model, shown in detail in Figure 2, was developed from over 500 flight-storm encounters in the Midwest.

The pilot weather deviation (avoidance) model can be combined with real time weather radar data and convective weather forecasts to generate graphical depiction of the regions that pilots will seek to avoid. These regions of high

likelihood of pilot deviation can used to forecast which routes will be blocked and hence the reduction in en route sector capacity.

The pilot weather deviation (avoidance) model can be combined with real-time weather radar data and convective weather forecasts to generate graphical depictions of the regions that pilots will seek to avoid. These regions of high likelihood of pilot deviation can used to forecast which routes will be blocked and model the associated reduction in enroute sector capacity.

To this point, a very limited amount of validation of the pilot weather avoidance region models and sector capacity models, as supported by NASA “foundational research” funding, has taken place. However, good agreement has been shown for many cases of level flight in en route airspace, but there are a number of situations where the models clearly are not adequate.

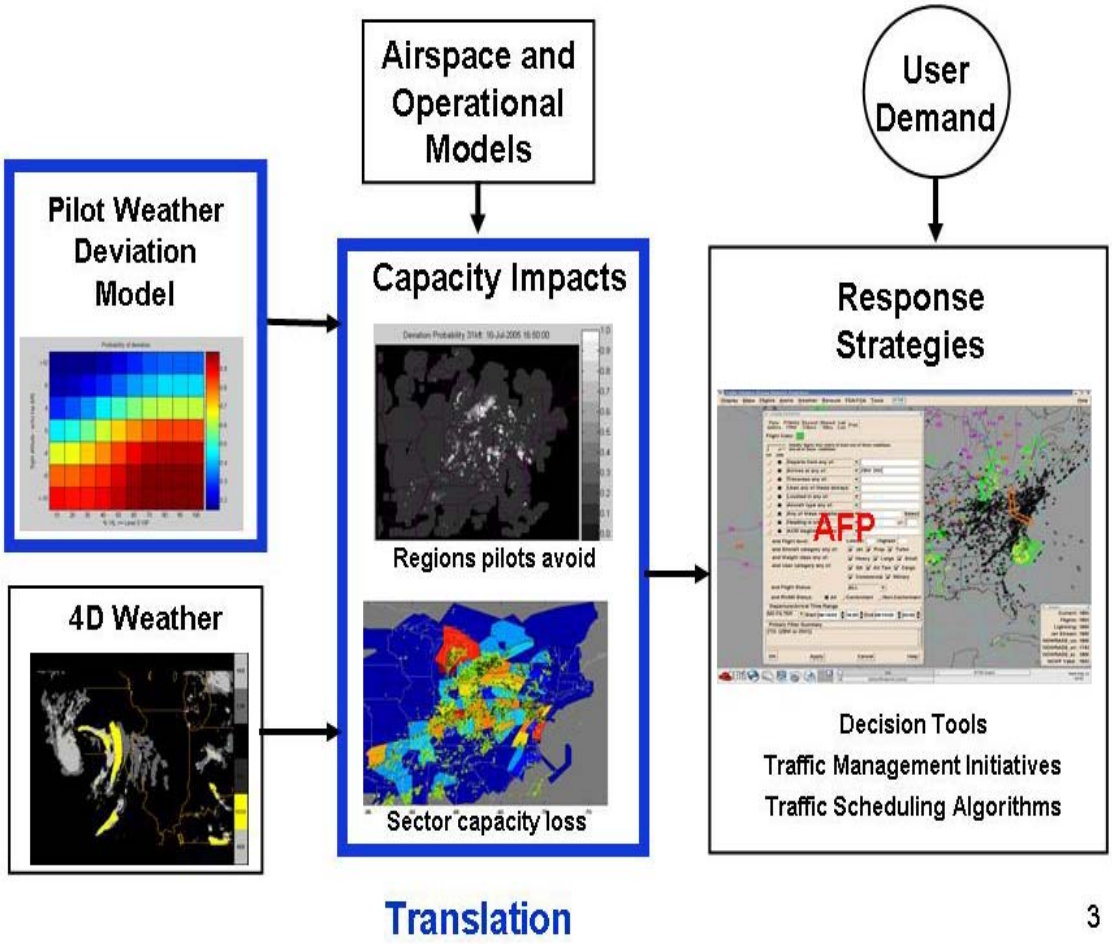

Fig. 1 Weather – ATM Integration Architecture. Shows the translation from weather impact and pilot preferences to capacity impact (dark blue boxes), and then to ATM decision support.

There are significant research questions, such as whether the architecture in Figure 1 is the best model, how to characterize the turbulence associated with storms, and pilot human factors questions such as the impact of information provided to the cockpit via data link on pilot decision making. Pilots flying for different airlines or with different equipment may make different decisions in the same weather situations. But of more concern, the same pilot may make different decisions when placed in two identical weather situations.

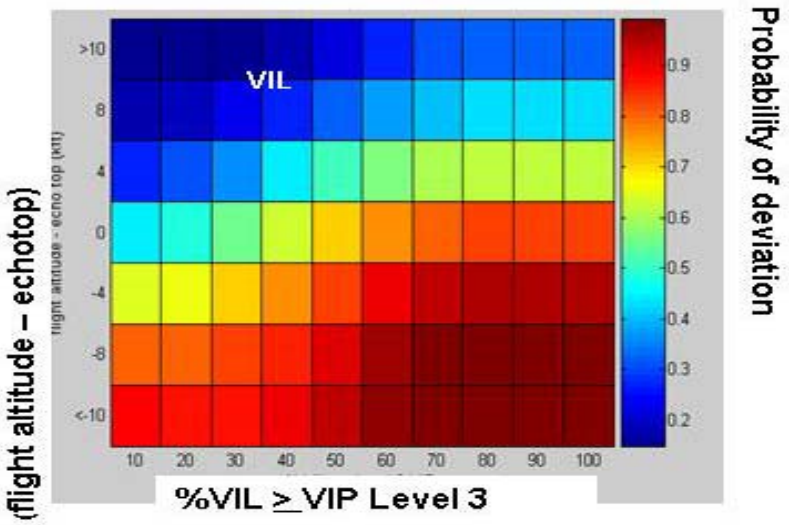

Figure 2. Pilot Deviation Model. Typical results for pilot avoidance of storms as a function of the flight path coverage of high reflectivity storms and the aircraft altitude relative to the storm radar echo tops. The plot shows the probability that a plane will deviate around a storm as a function of the fractional VIP level 3 or high reflectivity coverage and the difference between the flight altitude and the highest radar echo tops within the box.

Recommendation: Expand research on the translation of convective weather impacts into ATC impacts so that this information can be used to effectively support decision making.

Research should be conducted to address the following elements:

a. Improve the models for convective weather impacts, e.g. route blockage and airspace capacity.

b. Determine if pilot thresholds for weather conditions that lead to deviations can be reduced, since unexpected deviations around storm regions in high density airspace can lead to prolonged, unnecessary route closures

c. Determine if the data link transfer of ground derived weather and ATC domain information (spatial boundaries acceptable for maneuvering) to the pilot achieve a more consistent pilot response to convective weather

d. Determine if the airspace usage differs between various en route facilities [e.g., the Jacksonville Center (ZJX) appears to have very different procedures for convective weather ATM than many of the ARTCCs in the northeast].

e. Develop models for storm impacts on arrival and departure flows in both en route and terminal airspace.

C. Improved weather input into Collaborative Traffic Flow Management

Collaborative Decision Making is a Government - Industry Partnership, which has been advocated by the White House Commission on Aviation Safety and Security. It has been successful in making procedural and cultural changes in Traffic Flow Management during disruptive congestion and weather events in the NAS.

Finding: The collaborative use of the Airspace Flow Programs (AFP) and other Traffic Management Initiatives (TMI) in response to thunderstorm related airspace constraints, requires a strategic convective weather forecast that provides a translation of those constraints into flow impacts.

The AFP has improved the FAA's response to weather impacts but is limited by the existing aviation weather forecasts for decisions on the timing, scope and duration of AFP traffic metering and other TMI's. The need for more consistent and accurate forecast information remains. Even with better forecasts, this information would be far more useful if automatically translated into flow or capacity impacts.

When traffic flow managers have high-quality integrated weather information they can execute very effective tactical adjustments to airspace and traffic. However, effective strategic planning requires traffic management decisions to be made under high levels of uncertainty. The approach needs to be adaptive and control actions need to be limited and distributed across the multiple facilities and

operators. More consistent interpretation and control actions can be expected if weather impacts are automatically provided.

Recommendation: Develop a six-eight-ten hour convective forecast for strategic flow management decisions with automatically generated and updated forecasts of flow impacts.

This should be a joint program between the AWRP and the TFM R & D programs with involvement by representatives of the CDM Weather Team.

Finding: Probabilistic TFM research ongoing at NASA and MITRE could be leveraged during weather impacts to shift route/trajectory responsibilities back to the operator community and free traffic managers to focus on their core business: managing capacity and throughput within their airspace.

Finding; Traffic managers today are often too preoccupied rerouting aircraft to focus on fine tuning their airspace and maximizing throughput in spite of convective weather and other weather impacts.

Recommendation: Improve the Traffic Management interaction with AOC/FOC's during weather impacts.

Develop collaborative TFM systems that allow operators to better manage risks in meeting their own business objectives. Specifically, collaborative TFM systems should be developed that give operators the following capabilities:

- Enable visibility into probabilistic TFM weather mitigation strategies through robust TFM data feeds for integration into their own internal systems via CDMnet and eventually System Wide Information Management (SWIM).

- Electronically pre-negotiate multiple trajectory options with Traffic Managers.

- Select viable route/altitude/delay options during severe weather impacts.

- Integrate and ingest ATC-approved trajectories onto the flight deck for execution consistent with their own corporate infrastructure, business objectives and regulatory requirements.

- Expand collaboration to include flight deck capabilities and decision making tools consistent with NextGen and within the corporate infrastructure, business objectives and regulatory requirements of the operator.

D. Weather Information and Pilot Decision Making

This section addresses the use of weather information, including data linked weather, on pilot decision making. This is a very important aspect of integrating weather and air traffic management decision support tools.

Finding: Pilots' response to weather situations can be inconsistent. Pilots flying for different airlines or with different equipment may make different decisions in the same weather situations. But of more concern, the same pilot may make different decisions when placed in two identical weather situations.

Finding: FAA, AOC/FOCs, and flight crews often make decisions using different weather information. Today, automation in the FAA, AOC/FOCs, and the cockpit is seldom effectively linked. Furthermore, consistent weather information is not shared across these communities for joint decision making. An example is turbulence, which is validated via subjective pilot reports (PIREPs) or aircraft-specific automated turbulence observations, and as such may provide inconsistent information from different classes of aircraft or from different pilots.

Finding: Decision processes do not provide for the joint determination of appropriate weather mitigations.

The pilot, dispatcher and air traffic control decision making process, one of the cornerstones of the CDM concept, does not automatically or easily take into account flight limitations and preferences, aircraft capabilities, operator routing preferences and delay tradeoffs, in conjunction with mitigating disruptive weather.

Finding: Pilots may not understand the aviation system consequences if an aircraft significantly deviates from its current flight plan in congested airspace.

For example, deviations into airspace being used by a stream of traffic going in a different direction can result in major routes being closed by ATC which in turn results in major delays for many flights.

Recommendation: Initiate a research program to develop procedures and guidance on the integration of weather and airspace congestion information for preflight and in-flight decision making tools.

The program should include the following objectives:

Develop appropriate rule sets for weather avoidance decision making in both non congested and, highly congested airspace.

Develop ways to incorporate the same rule set into preflight, cockpit, AOC/FOC, and ATM decision support tools.

Develop methods to integrate and/or display current and forecast weather impact to flight profile, airspace congestion information, and weather decision support information in preflight and cockpit systems to enable greater shared situational awareness and improved collaborative decision making.

Conduct research on the direct, machine to machine, information transfer among cockpit, FOC, and ATM computing systems and determine whether this will facilitate consistent and expeditious decision making. This will place the users more “over the loop” than “in the loop” with respect to weather decision making.

E. Integrating Weather Impacts with Airport Surface and Terminal Management Systems

Decision support systems for the airport surface and terminal air space domains are not effectively integrated with weather information. With the exception of the Route Availability and Planning Tool (RAPT), weather information for terminal and surface operations is provided by a separate display or an overlay on ATC and ATM displays.

Utilizing all available capacity at major airports during bad weather is very challenging and failing to do so results in schedule disruptions, passenger frustrations, and economic losses to airlines and affiliated business.

To ensure each arrival and departure slot is used, extensive coordination and the utilization of multiple and separate weather sources is required. But manually estimating the impact of a departure or arrival decision, with in the face of dynamically changing weather in real time is impractical and results in unused capacity.

Finding: Integrating Airport Surface and Terminal Area Weather and ATM Tools could improve system performance and capacity.

Surface and terminal airspace operations could be improved if weather and traffic information were combined into a single system that computes the impact of the weather on potential traffic management decisions and provides the results in simple, easily understood display of decision options.

The Route Availability and Planning Tool (RAPT) successfully integrates weather and ATM for departures, but has only been deployed in a single region and is not integrated with automated surface movement systems, or the FAA’s Departure Flow Management (DFM) initiative. In addition, the provisions of a similar

capability in TMA has not been explored.

Surface surveillance systems are gaining acceptance among NAS operators, but the deployment and use of systems such as ASDE-X lags behind industry versions. Furthermore, operators report that air traffic decisions makers are often under-informed on actual surface and terminal conditions.

Coordination with airline and other operations centers is critical to successful optimization of terminal operations.

Current TAF forecasts are inadequate for efficient surface and terminal decision-making during anticipated and actual weather impacts. ITWS is an outstanding terminal and surface tool but is not integrated with other decision support tools.

Recommendations: Expand the use of route availability tools to integrate airport and terminal area weather data and ATM Tools.

Expand the deployment of integrated tools, such as route availability, to additional airports and terminal regions to improve NAS performance at the largest airports impacted by convective activity.

Conduct research on enhancing the Traffic Management Advisor (TMA) to achieve a weather sensitive arrival planning tool.

Integrate RAPT, ITWS, DFM and TMA with surface management systems to provide a singular terminal management tool spanning departures, arrivals and surface movement. Consider common use by air traffic and operators for collaborative decisions.

Support CDM and other efforts to provide meaningful and integrated terminal and TRACON specific weather forecast information.

Mid Term: IOC 2015

F. Adaptive Integrated ATM procedures for Incremental Route Planning

Uncertainty about weather, traffic and infrastructure constraints present major challenges to air traffic management. A new approach, to take better advantage of available airspace and airport capacity, is to manage traffic adaptively. This is motivated by the relationship, over time, between the effectiveness of alternative control actions for individual flights and the predictability (level of uncertainty) of events (both traffic and weather) that are causing the need for control.

Ideally control decision points should be delayed as late as possible to allow the accuracy of the prediction to improve. However, delaying the decision may reduce the control options and their effectiveness. While this may be straight forward for one aircraft, it can become vastly more complex as multiple flights with varying decision points are considered.

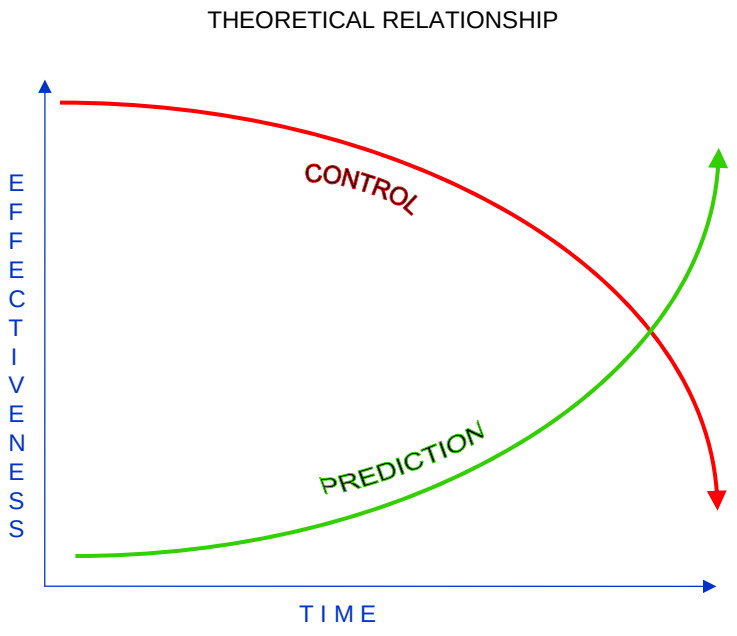

Figure 3. The relative relationship between the accuracy of predictions (weather, flight movement) and control effectiveness over time.

An example of today's approach to "flow level" traffic management is demonstrated in the figures below, captured from Flight Explorer. The current solution to a traffic overload of the southeast arrival corner post at Chicago O'Hare (ORD) is to reroute all ORD-bound flights which originate in the Miami (ZMA) and Jacksonville (ZJX) ARTCCs westward via St. Louis (STL) to the southwest arrival corner post. The associated reroute advisory is disseminated well before most of the affected flights are dispatched, without taking into consideration any circumstances that may have, in the meantime, affected the ability of an individual flight to fly the new route.

A "flight level" traffic management solution would delay this type of rerouting decision until it was time to dispatch the affected flight, and it would do so while taking into consideration whether that flight has already been delayed because of involvement in some other TMI due to, for example, an enroute weather constraint or a technical (communications outage) constraint. Instead of negatively impacting such a flight with two TMIs, that flight could be given priority to be one of the flights using the southeast ORD corner post, allowing it to fly on the normal route, and reducing its flying time by about 10%. In this manner, by delaying decisions until they need to be made, and by making them at a flight-specific level, adaptive traffic flow management can make decisions that are better informed.

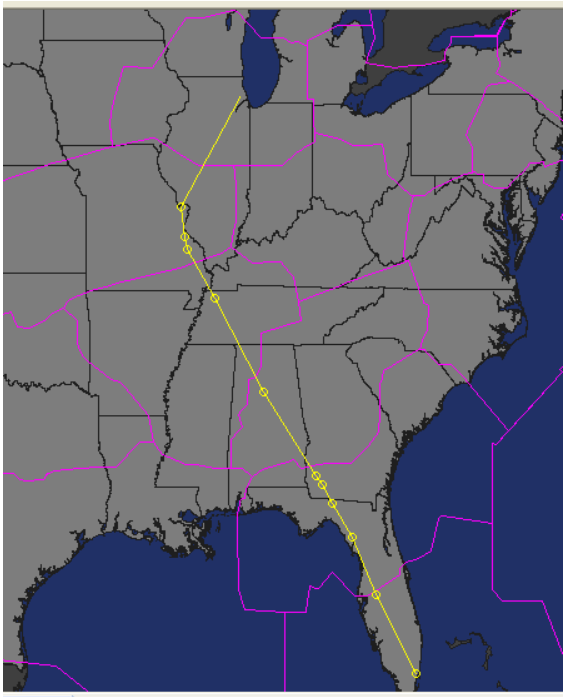

Figure 4. ORD OXI-ROYKO Playbook Route. Moving flights to the Southwest ORD arrival fix.

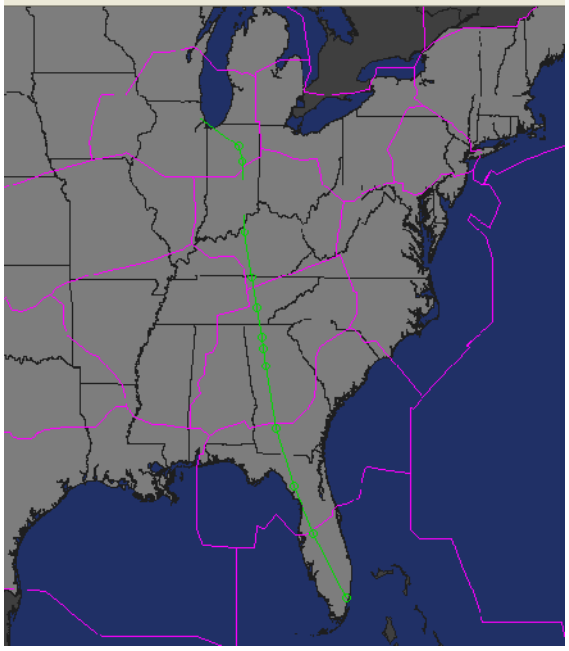

Figure 5. The normal preferential (required) route for flights from south Florida to ORD.

Another situation arises when weather is forecast to block a section of a planned route resulting in a “no routes available” response from the air traffic control authorities. An alternative is to offer the operator the option of departing with a partial flight plan, and enough fuel to accept some level of deviation, based on the presumption that the weather will be better known as the aircraft proceeds towards its’ destination, and can select the mid and final routes as their availability becomes more certain. This incremental route planning and filing approach is not unlike what was in common practice in the past, and requires more agility by the operator and air traffic control facilities, but will reduce the impact of weather on capacity.

Finding: The use of adaptive ATM decision-making offers opportunities to reduce delays.

Uncertainty is a critical characteristic of weather and traffic forecasts. Furthermore, the level of uncertainty changes over time. For example, while there may be a great deal of uncertainty about whether thunderstorms will delay the departure of a particular flight out of EWR 3 hours before its scheduled departure time, that uncertainty is likely to be significantly reduced at 20 minutes before its scheduled departure time. We therefore need to refine existing TFM procedures, as well as develop new TFM procedures, that are flexible, making it possible to adapt plans as uncertainty is reduced.

Some of following findings and recommendations reinforce several cross-cutting recommendations elsewhere in this document. In particular, in order to develop an effective adaptive TFM system, it is critical to pursue those general findings regarding the representation of uncertainty in weather and traffic forecasts and concerned with translating such information into meaningful decision parameters.

Finding: The inequitable approaches to the allocation of scarce NAS resources is a major impediment to Adaptive TFM and other Traffic Management Initiatives.

While NAS resources are far from a completely equitable allocation on fair weather days, weather impacts create major dislocations of NAS resources and tend to highlight equity issues among the diverse NAS operators.

Ideally, the equity issues should be addressed in the automation and not distract the traffic manager or operators from working together to address the weather impacts themselves.

Recommendation: Develop Weather Impact Forecasts versus Time.

Develop weather forecasting capabilities that incorporate representations of the uncertainties associated with different weather phenomenon for different planning horizons. This should be included in the research recommended in Section 6 B, translating weather into ATM impacts.

Recommendation: Develop Adaptive ATM/TFM Procedures.

Develop TFM procedures that are adaptive, and that take advantage of changes in uncertainty over time. These procedures should incorporate distributed work strategies that match the locus of control for a specific decision with the person or group that has access to the knowledge, data, motivation and tools necessary to effectively make that decision. Such adaptive procedures require an integrated approach to strategic planning and tactical adaptation.

Recommendation: Manage at the Flight Level.

Take advantage of trajectory-based management so that control actions and their impacts can be more directly and precisely localized at the points in the system where they are required to deal with a given scenario. In particular, this means that tools and procedures need to be developed to adaptively manage at the flight level instead of traffic flows, and that the air traffic management user does not need detailed meteorology experience.

Recommendation: Translate weather information and forecasts to parameters relevant to decision support tools.

Develop decision support tools that translate the implications of probabilistic weather forecasts into the decision parameters that are relevant to the application of particular TFM procedures and in a way that the air traffic management user does not require significant meteorological training.

Recommendation: Develop human-centered designs.

Develop human-centered designs for these decision support tools that enable their users to understand the current state of the relevant parts of the NAS, and that support these users in understanding the basis and implications of recommendations generated by their decision support tools that automatically generate options for users to consider.

Recommendation: Develop tools and automation enabling operations and implementation.

Develop computer-supported communication tools and automated decision support tools that enable effective coordination and collaboration in this distributed work system, and that enable timely implementation of the decisions that are made.

G. Weather Impacts and Tactical Trajectory Management

Finding: There are few examples of seamless integration of weather information into ATM DSS Automation.

The objective of ATM/Weather Integration is a seamless and transparent system that accounts for weather effects in all of the ATM algorithms. This objective is far from satisfied.

A good example of the seamless integration of weather information involves the forecast grid winds which are embedded in a variety of operator and ATC automation systems and which are a key component of the aircraft trajectory computation algorithms of these systems. The trajectories are used by pilots, aircraft dispatchers and controllers, and by algorithms such as conflict detection, without the users explicitly being necessarily aware of the exact wind component forecast that was included in the calculation. However, other useful weather information such as the probability of a thunderstorm hazard, turbulence or icing is not directly incorporated into automation tools

Recommendation: Implement Tactical Trajectory Management with integrated weather information.

Develop a highly automated advanced Tactical Trajectory Management (TTM) decision support capability integrated with convective weather and turbulence to decrease controller and pilot workload, and increase safety. This would be a mostly automated system. This capability would assist the controller in a shared severe weather separation responsibility with the pilot.

Recommendation: Investigate the human factors issues (communication, information display, safety nets, cognitive complexity, and mental workload) associated with new paradigms for tactical trajectory management.

H. Airspace Designs for Weather Impacts

The current NAS Airspace and infrastructure were designed to maximize throughput under ideal conditions. Weather considerations have yet to be fully incorporated into current airspace design and ATM control systems. As a result, the NAS airspace is mostly structured around rigid, stratified, and directional routes. The ATC automation that supports tracking and flight data processing operates as a carbon copy of the airspace, was designed to operate under perfect conditions, and has its own set of rigid processing logic developed in the early 1970's. Both the airspace and supporting automation systems are inherently inefficient during a weather event. The ERAM effort, while essential to future progress, will begin with a replication of the existing NAS structure and automation.

Finding: Existing Airspace Design profoundly influences and contributes to weather related delays.

The development of airspace designs, such as the dynamic reconfiguration of airspace, must allow flexible and efficient routing during adverse weather conditions, and not just when conditions are nominal.

Airspace design tends to bind the ATM solution space. Rigid airspace, procedures, and antiquated infrastructures contribute to system inefficiencies during weather events. The resultant delay is proportional to traffic density and the complexity of an impacted area.

Service providers and users have an array of decision support capabilities that support flight planning and execution decisions; however, these sophisticated tools are of marginal value in weather situations because weather information is not sufficiently integrated and utilized at the service delivery points. Further, these decision support capabilities are not developed in a congruent approach with airspace design.

This lack of integration forces ATM decision-making and solutions in the face of weather to be overly conservative and does not scale to predicted traffic volumes in the future.

The impact of adverse weather on the airspace system is inherently non-linear. As a result, if localized decisions are made without consideration of the impact on the local or national airspace system, local inefficiencies can be greatly magnified at the system level. Conversely there are artificial limitations on the ability of operators and local facilities to allow regional approaches to help achieve system benefits. The working group was quite alarmed about this finding, because without an integrated approach early on, it could preclude the use of weather as a more advanced system develops, just when the criticality of weather integration is known to be vital to capacity enhancements of NextGen. The lack of weather integration will severely hamper effective decision-making using increased levels of automation required by larger traffic volumes.

It is critical that weather information and functionalities be incorporated in the development of airspace structural design and decision support systems in the initial stages of development. Addressing these goals as an afterthought has been historically ineffective. These capabilities must be considered in the design of the airspace itself. NexGen air traffic control systems and airspace must be designed from the beginning with capabilities that support Traffic Flow Management in making flexible and efficient responses to common weather impacts.

Recommendation: Airspace designs should enable route flexibility during adverse weather conditions.

If the vision of 4D trajectories is to become a reality, the airspace must be designed to support seamless adjustments of the route of flight in all four dimensions, as required by weather impacts.

The development of ATM decision support tools must be done jointly with the weather research community so that decisions will adequately address impacts of adverse weather. Foundational efforts that reach across the disciplines of airspace design, weather translation into ATM impact and ATM decision support are required to achieve effective integration.

Recommendation: Investigate the human factors issues associated with the dynamic reconfiguration of airspace, including issues associated with information display, training and cognitive complexity.

FAR TERM: IOC Post 2015[9]

I. Advanced Weather ATM Integration Concepts

The NAS can be considered a network of airports, waypoints and fixes. This network can be disrupted due to weather constraints such as convective activity, resulting in a loss of capacity in an airspace region. Thunderstorms contributes the most to delays in the NAS so a method needs to be created to estimate the loss of capacity in an airspace region using both deterministic and probabilistic weather forecasts for short and longer range planning.

Finding: Modern, risk management methods are being applied to address uncertainty and guide the integration of weather and ATM tools.[10]

Recent NASA sponsored research[11] which employed a Maxflow / Mincut theory used for network flow problems, showed that the maximum amount of flow is equal to the capacity of a minimum cut, e.g., the bottleneck of a system defines the maximum flow. Applying this to ATM, the number and widths of flight lanes can be computed in the presence of weather constrained regions using this theory. The capacity of those regions can be estimated by adding assumptions of aircraft navigational performance and the permeability of convective regions using a convective weather translation model. Navigational performance will determine the number of available flight lanes with narrower flight lanes being reserved for aircraft with higher navigational performance.

The Maxflow/Mincut theory can be applied using either deterministic or probabilistic weather information. Deterministic information is most appropriate for short look-ahead times and probabilistic for longer look-ahead times beyond about one hour. Probabilistic forecasts for look-ahead times beyond two hours may require the use of scenario-based probabilistic forecasts which are being developed. An enhancement to this work can include changing altitude to traverse weather constrained regions allowing the development of flight tubes instead of 2D flight lanes and including crossing-flows in the determination of capacity.

Recommendation: Develop methods which combine the use of both probabilistic and deterministic forecasts, and observations, to maximize throughput using multiple dynamic flight lanes or "tubes" in weather impacted areas.

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[9] The Study Group felt that a far term defined as post 2015 was preferred.

[10] Initial versions of some of these capabilities can be implemented by 2015

[11] METRON analysis presented at WAIWG meeting

Recommendation: Develop methods to transition from a probabilistic trajectory or flight envelope to a 4D trajectory which is useable for separation and safety assurance.

Recommendation: Establish an independent bi-annual review of this work to determine the potential benefits and costs to aviation.

Finding: Current weather sensing often relies on surrogate measure of hazard versus actual hazard detection. This sometimes causes an overly conservative approach to weather avoidance and results in the quarantine of much more airspace than necessary. At other times, it may cause the routing of an aircraft through a real hazard not adequately represented by the surrogate measure.

Recommendation: Conduct research into replacement of surrogate weather indicators such as radar reflectivity with reflectivity with actual indicators such as turbulence, icing, lightning, or wind shear, and an estimate of ATM impact. For example, radar reflectivity can be translated to ATM impact by estimated airspace pilots will avoid and the associated airspace capacity loss.

Finding: Gridded and scenario based weather forecasts each have potential for integration with ATM decision making tools and processes.

There are probabilistic weather forecast products available today for convection and stratus which estimate the probability of a specific outcome at a specific location that are often referred to as gridded probability forecasts. ATM decision algorithms that use these products typically threshold the probability values to use them deterministically for decision making. Other types of probabilistic data, such as scenario based probability forecasts, and more sophisticated uses of probabilistic data are being developed. Scenario based forecasts shows several potential weather outcomes and associated uncertainty for each outcome. More sophisticated decisions can then be based on the likelihood that each outcome will actually occur.

Recommendation: Develop methods to use gridded and scenario based probabilistic weather data for ATM decision making.

Develop methods to translate deterministic and probabilistic convective forecasts to ATM impact for use in network based capacity estimate models.

Determine the reduction in capacity of an airspace region due to convective weather using a network model.

Recommendation: Investigate the human factors issues associated with the integration of such probabilistic modeling into decision-support tools.

7. Human Factors Considerations for Integrated Tools

Human factors issues are a pervasive consideration in developing a more integrated approach to dealing with the impacts of weather on ATM. As technologies are developed to provide access to probabilistic weather information, and to help translate it into critical decision parameters, a key challenge is the need to understand the strengths and weaknesses of these technologies, and to develop a resilient, cost-effective design that integrates human expertise with such advanced technological support.

Finding: Need to balance human and technology roles.

The complexities associated with representing uncertainty in the weather and reasoning about its implications on ATM decision making indicate a need for decision support tools that help the human user process such information. However, these very same complexities mean that such technologies must be assumed to be brittle, as it will be very difficult for designers to anticipate all of the scenarios that could arise and to encode effective responses. Thus, it is necessary to balance the strengths and weaknesses of the operators who are dealing with situations in real time, with the strengths and weaknesses of the technology developers, who must try to anticipate all of the situations that could develop, and support effective responses through their technologies. (To err is human, and both system operators and system designers are human.)

Recommendation: Develop advanced information sharing and display concepts for the design of integrated decision-support tools.

Develop strategies for information representation and display that enable people to maintain situation awareness regarding weather and traffic impacts, develop shared mental models, and evaluate inputs to the decision process provided by technology.

Of particular importance is the need to conduct research on strategies for representing, integrating and displaying probabilistic information about uncertainty regarding weather and traffic constraints and its predicted impacts as a function of look-ahead time. Equally important is the need to research new strategies for risk management that make use of such information. Research on the effective use of probabilistic information by ATC, TFM and FOCs is a major challenge that needs to commence in the near term in order to obtain short term benefits and to enable more powerful solutions in the longer term. This research needs to consider human factors as well as technology development challenges.

Recommendation: Develop new approaches and strategies for effective distributed decision making and cooperative problem solving.

Develop effective strategies and technologies (decision support and communication tools) to enable distributed decision making to address the interaction of weather and traffic constraints, and to adaptively respond to situations as they evolve. This requires consideration of cognitive complexity, workload, and the ability of people to develop and maintain necessary levels of skill and expertise. It requires consideration of the need to design a resilient system that provides effective safety nets. And it requires system engineering decisions concerning when to design the system to provide coordination as a result of the completion of independent subtasks and when to design the system to support collaboration in order to ensure that important interactions occur.

Develop technologies that support cooperative problem solving environments that allow people to work interactively with decision support technologies and with each other to assess situations as they develop, and to interactively generate and evaluate potential solutions.

Recommendation: Develop methods for implementing human-centered designs for decision-support tools.

Develop effective procedures and technologies to ensure effective communication and coordination in the implementation and adaptation of plans in this widely distributed work system that includes meteorologists, traffic managers, controllers, dispatchers, ramp controllers and pilots.

8. Implications on Air Navigation Service Providers

A. Training on New Integrated Tools

Finding: New integrated tools will bring changes to all aviation segments.

As weather information is integrated into the decision tools used by TFM's, FOC's, ATC facilities, and flight decks, the procedures, responsibilities, and supporting technologies for each group will change. It is vital that each group, at every level, have a clear understanding of their new capabilities and responsibilities, and their relationships with other groups and stake holders to enable a shared common situational awareness.

Recommendation. Proactively enable new training on integrated tools.

The FAA and aviation industry should proactively develop training curricula for controllers, traffic managers, pilots, dispatchers, and weather personnel which cover

- The new roles and responsibilities in the use of supporting technologies
- The roles, responsibilities and expectations of other decision makers with whom each group must interface
- The training doctrine, developed in concert with the integrated tools development, leveraging that real-world experience to maximize early benefits and refinements.
- The training cadre, deployed to all major new facilities as the tools are deployed to both assist in training and to maximize early benefits and identify problems.

The resulting procedures and rules must be translated into controlling documents such as the Federal Air Regulations (FARs), the Airman Information Manual (AIM), Air Traffic Manuals, Flight Manuals, and Aircraft Manuals.

B. Best Practices in Weather Mitigation

Finding: Some FAA facilities have very effective ATM methods during weather impacts while others do not.

Operators maintain that there are significant differences in the performance of air traffic facilities during severe weather events. Although differences in geography, special use airspace, and regional weather do exist, some facilities are consistently recognized for their innovative and proactive responses to weather events. The successful facilities approach bad weather events through flexible

airspace and route utilization coupled with pragmatic flow management techniques. These informal “best practices” provide significant gains in efficiency and delay reductions.

Other facilities are less successful. They are limited to practices which include an insistence upon pre established practices, the refusal to cross flows, an inability to mix operations, and the inability to dynamically modify airspace when there are clear benefits. Also, the inherent risks of convection result in tendencies to avoid engagement, citing workload, airspace rigidity, and procedural reasons.

An examination of, the performance of the more successful facilities reveals an integrated approach to weather impacts, where the careful selection and application of initiatives appropriate to the developing conditions minimizes disruptions.

Recommendation: Identify best weather practices of air traffic facilities and train these practices system wide.

Identify facilities with superior performance and develop best practices guidance for use by other facilities. Do not limit benchmarking to NAS facilities only. Seek global examples and new visions of innovative weather management techniques.

Develop and train ARTCC and TRACON ATC and TFM staff on “best practices” during the introduction and first five years of all new weather and weather-ATM integrated tools

Establish metrics which compare alternative processes.

9. Implications on Airline and Flight Operations Centers

Finding: The integration of weather into ATM operations, consistent with NextGen Concept of Operations and the Operational Evolution Partnership (OEP), offers all classes of network operators in the NAS a significant opportunity to improve their operational performance.

NextGen is expected to provide Network operators, including large airlines and charter operators, greatly expanded opportunities to optimize the operation of their fleets at the system level. These opportunities will include not only greater route freedom and metering options for individual flights, but also, with better forecasts of weather impacts, a greater ability to reduce system risks across groups of interdependent flights, subject to multiple TMI's.

This enhanced visibility into the risks associated with weather impacts implies a greater responsibility for the consideration of multiple trajectory options, and the supporting technology and infrastructure to communicate with the service provider, in advance trajectory negotiations, rather than today's singular expression of intent (e.g., the filed ATC Flight plan).

While the service provider can enable shared situational awareness through the development of open systems, large network operators are in the best position to integrate weather and ATM information into their internal systems and to use that information to develop system strategies and tactics on tradeoff of multiple trajectory options and TMI's during periods of uncertain weather impacts. These tactics and strategies will likely include the manipulation of flights in all four dimensions.

Recommendation: Ensure strong industry participation in CDM and NextGen concept development and implementation and consider expanding industry participation on review boards.

Industry must have voice and buy-in to future developments to ensure that internal corporate infrastructure and business systems can support, blend with and interact effectively with the NAS service provider systems.

Joint development of these systems is possibly the key component of a successful future capability

10. Implications for FAA and NextGen Enterprise Architectures

Finding: The integration of weather into ATM operations, including directly into advanced automation tools, is a fundamental component of NextGen and must be a focus of the Concept of Operations, the Operational Evolution Partnership (OEP) and NAS Enterprise Architecture (EA) development.

The NextGen Concept of Operations establishes the mitigation of weather as a major focus for enhancing capacity and improving safety. The concept specifies the need for direct integration of "common" weather information into air transportation decisions making, with emphasis on direct integration of weather into advanced decision support tools. Other NextGen products (e.g. R&D Plan, Integrated Work Plan, and EA) further define these concepts and specify multi-agency actions to develop and implement the needed capabilities.

The OEP is the FAA's response to transitioning the NAS to NextGen, and weather impact mitigation is a key focus area and defined by the "Reduce Weather Impact" solution set. The OEP is an evolving operational view, and a companion technical view (systems, algorithms, performance requirements, evolution strategy, concepts of use, etc) is needed to be embodied in the NAS Enterprise Architecture. Both the operational and technical views are necessary to driving investment decisions within the FAA, and to enabling continuing dialogue with the NextGen stakeholders on plans and progress related to ATM-weather integration.

Recommendation: Ensure that direct ATM automation-weather integration is a key focus of the development of OEP/NAS EA operational and technical views for NAS transition to NextGen.

To achieve the capacity and safety goals for NextGen, weather and ATM automation developments must become aligned and focused to define the operational and system views for the evolution to highly automated weather impact analysis and solution-generation system, where the human operators are no longer the "glue" for trajectory level decisions. This is a necessary and fundamental shift from today where weather display and human interpretation is the norm. The resultant operational and technical views must be reflected in the OEP and companion NAS EA in order to enable timely investment decision on deploying these needed integrated automation-weather capabilities. This information must also be (constantly) coordinated with NextGen concept and EA development to ensure consistency.

11. Implications for FAA Aviation Weather Research Program

Finding: The Aviation Weather Research Program continues to be very important to efforts to improve the capacity and safety of the National Airspace System, but support has declined.

The FAA Aviation Weather Research Program (AWRP), in collaboration with the NOAA National Weather Service, has been very successful in sponsoring and implementing weather research capabilities focused on the real world needs of aviation.

While the progress in forecasting, especially in the tactical, 0-2 hour period, has been significant, aviation continues to need increased accuracy for longer time periods, in convection, turbulence, icing and ceiling/visibility products.

The current effort to develop a single convective forecast tool, that incorporates the best techniques from the several existing products, for the 0-8 hour forecast period, is an important effort and will help efforts to integrate weather with air traffic management on a national level.

Support for the AWRP has declined in recent years, causing the reduction or cancellation of programs and an overall concern about its' future by the various research organizations affiliated with this area.

The major reduction in the National Ceiling and Visibility Program has caused an important flight advisory product, designed to help helicopter emergency medical evaluation flights, to be initiated with no forecasting component. Other programs such as Oceanic Weather have been eliminated.

Recommendations: *Support for the AWRP should be increased beyond* previous levels.

Support for the AWRP should be increased to enable further improvements in the 0-8 hour forecast time frame, and to allow the weather research community to enter into joint collaborations with the automation research community in integration of weather information into ATM DSS. Additionally, the FAA ATO-P organization should reexamine the R&D goals for AWRP in light of the needs of NextGen.

Support for the National Ceiling and Visibility Program should be restored. Related efforts to support and benefit individual sectors of the industry should be prioritized and addressed. For example:

1. Development of the Helicopter Emergency Medical Evacuation System (HEMS) tool.

2. Rewriting FAR 121 limitations regarding Ceiling and Visibility such as FAR 121.619 (also know as the “1, 2, 3 Rule” for alternate fuel specifications

Finding: Common metrics for the most significant aviation en route weather hazards should be expeditiously adopted by all systems measuring, reporting and/or forecasting the hazard. The following are listed in priority order:

1. Turbulence (convection induced)
2. Turbulence (clear air and mountain wave)
3. Lightning
4. Icing and Hail

Recommendation: Conduct research to develop improved methods of sensing turbulence taking advantage of a multi-sensor approach using radar, profilers, anemometers, satellite imagery, GPS, and instrumented aircraft to improve the forecasting and now casting of convective and non-convective turbulence.

12. Summary

This study examined the proposition of integrating weather and air traffic management to determine potential benefits and where appropriate recommend FAA research and development activities.

In this report, integration is defined as translating traditional weather information into weather impact measures, such as capacity or flow rates, and automatically or semi-automatically incorporating that data into both individual aircraft and traffic flow advisory information to improve the system capacity and safety in the face of weather hazards.

Aviation weather has much more forecast accuracy in 0-2 hour, tactical time frame, than the 2-10 hour, strategic time frame. However, the size and shape of the 0-2 hour solution space is much smaller than 2-10 hour space, and with increasing congestion, more decisions will have to be made in the latter. Conversely the more the tactical solution space can be expanded, the more decisions can be delayed adaptively and traffic optimized to meet business objectives.

It was found that opportunities exist to reduce the current weather related delay for both tactical 0-2 hours and strategic 2-10 hour planning horizons.

The study also found that a risk management approach with adaptive decision making and incremental route planning, presents a major opportunity to reduce weather related delay.

An integrated, cross disciplinary research program involving both aviation weather and air traffic management researchers will be needed for research on these initiatives to be successful.

Finally, this research will take place and succeed only with the enthusiastic support of senior leadership.

13. Acknowledgements

The study group is very grateful for the support provided many individuals and organizations that served on the study and hosted meetings.

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Jerry Thompson Associates

John Rekstad and Richard Heuwinkel, for being the designated FAA Federal Officials for the study.

Gloria Dunderman for administrative support at all of the meetings

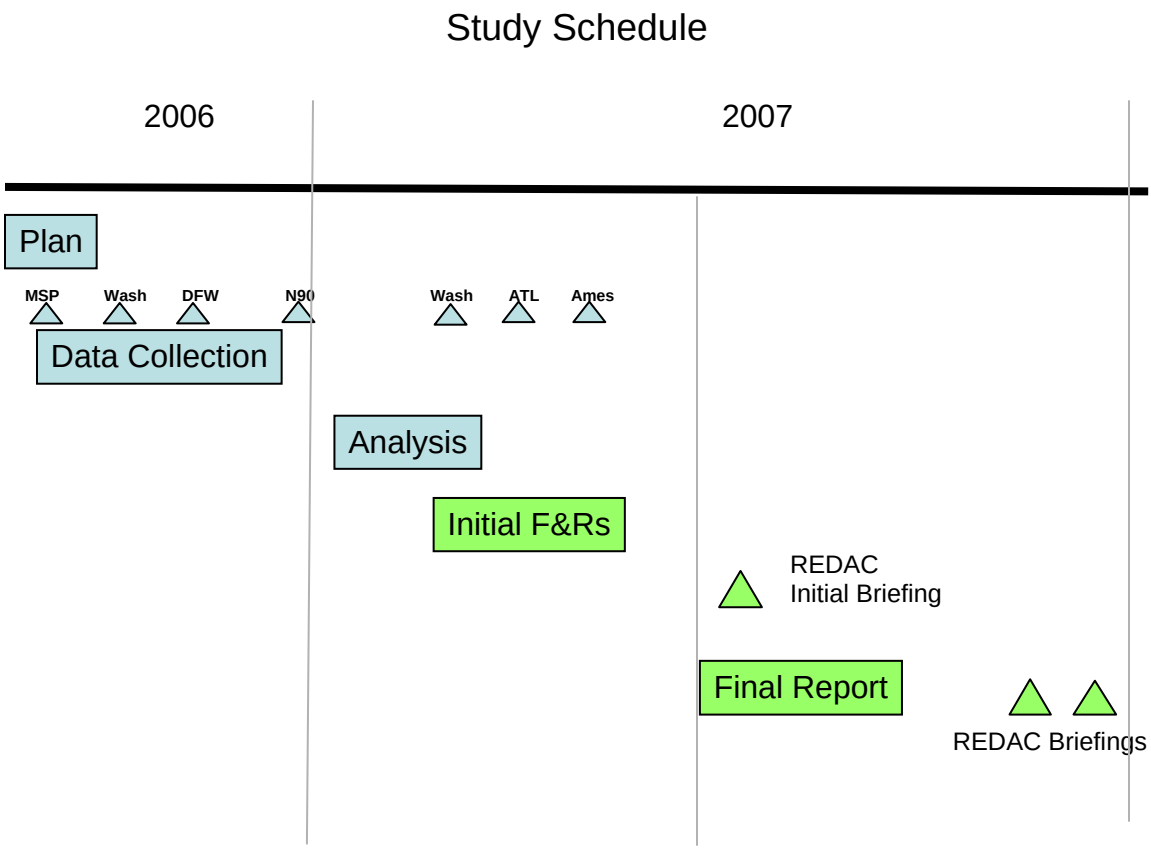
Denise Davis for travel support

We appreciate those who provided the briefings listed in Appendix A

Appendix A. Study Description

Working Group Membership

NAME	AFFILIATION	WAIWG ROLE
Bill Leber	Northwest Airlines	Chair
Ray LaFrey	Retired MIT - LL	Co-Chair
Richard Heuwinkel John Rekstad	FAA FAA	DFO Deputy DFO
Roger Beatty	American Airlines	Member
Steve Brown	NBAA	Member
Bruce Carmichael	NCAR	Member
Gloria Dunderman	FAA	Member
Jim Evans	MIT LL	Member
David Frame	JTA	Member
Matt Fronzak	Delta Air Lines	Member
Kevin Johnston	NOAA/NWS	Member
John McCarthy	Aviation Weather Associates, Inc.	Member
Philip Smith	OSU	Member
Eugene Wilhelm	MITRE CAASD	Member
Steve Green	NASA Ames	Member


Study Schedule
2006
2007
Plan
MSP
Wash
DFW
N90
Wash
ATL
Ames
Data Collection
Analysis
Initial F&Rs
REDAC
Initial Briefing
Final Report
REDAC Briefings

Literature List - Partial

- ""Next Generation Air Transportation System – Integrated Plan", Joint Planning & Development Office, December 2004

- "Next Generation Air Transportation System, Weather Concept of Operations", Version 1.0, May 13, 2006

- "An Operational Systems Vision for Aviation Weather-in-the-Cockpit Data Link", FAA AVS Office, 2006

- "Weather in the Cockpit Concept of Operations" DRAFT 10/7/2006, Tenny Lindholm, NCAR

- "FAA Flight Plan" 2007-2011, FAA

- "Implications of a Successful Benefits Demonstrations for Integrated Weather/Air Traffic Management (WX/ATM) System Development and Testing", Conference Paper J3.3, 12th Conference on Aviation, Range, and Aerospace Meteorology, AMS, Atlanta, GA, Jan 2006 , J. Evans, MIT Lincoln Laboratory, January 2006

- "TRACON Weather Forecast Requirements Recommendations", Collaborative Decision Making (CDM), Weather Evaluation Team (WET), Version 14, December 20, 2006

- "Tactical Weather Decision Support to Complement 'Strategic' Traffic", The Fourth
  International Air Traffic Management R&D Seminar ATM-2001 J. Evans, MIT Lincoln Laboratory 2001

- "Recommended HEMS Current and Future FAA/NWS Aviation Weather Product Development", Air Evac EMS, Inc., Association of Air Medical Services, January 21, 2007

Briefings to Study Group

Gene Wilhelm, et al	Mitre CAASD	TFM Weather Mitigation, Probabilistic Weather, Cockpit Weather
Harry Swenson, et al	NASA Ames.	Technical briefings of weather integration efforts in technical elements of NASA's Airspace and Airportal Projects
Bruce Carmichael	NCAR	Weather ATM Integration Issues
J. Wetherly, D. Sims	FAA ATO	Views on Wx-ATM Integration
M. Sammatino	FAA ATO	Views on Tactical Wx mitigation
M. Klopfenstein	Metron	Wx and TFM Strategies
M. Ball	U of Md	Equity of NAS Delays
S. Green	NASA ARC	Delay Banking
M. Andrews	JPDO WxIPT	Process for Wx RE&D Management
T. Fahey	Northwest Airlines	Airline Weather Issues
L. Sherrtz	NOAA	Weather Information Decision Aide
R. Beatty	American Airlines	Airline Weather Issues
L. Pruzak,	N90	N90 Operations, RAPT, CIWS, ITWS
R. Tamburro C. Gallo	N90 TMO	Tour N90 TFM
R. Klarmann	Continental Airlines Wx	EWR Hub Tower Operations in

M. Weber,et al	MIT Lincoln Lab.	Integrated Systems Decision Support, RAPT, Rapid Prototyping, CIWS Re-engineering

Weather in the Cockpit Briefings

T. Lindholm	NCAR	Weather In the Cockpit
Capt. J. Burns	United Airlines	Electronic Flight Bag
S. Young	NASA Langley	Integrated Intelligent Flight Deck
Robert Ruiz	FAA AVS	Processes for Approval of WIC
S. VanTrees	FAA AVS	AVS Vision for WIC
Cathy Bigelow	FAA AVS	Air-Ground Certification
Capt.T. McVenes	ALPA	ALPA Views
Matt Fronzak	Delta Airlines	WIC Views
S. Brown	NBAA	NBAA Views
Eric Lugger	Air Evac LifeTeam	Helicopter Medical Flight Issues
E. Dash	Raytheon	R&D for WIC

Appendix B. Previous Integration Initiatives

Five ATM/Weather Integration Workshops were held to encourage better use of aviation weather in air traffic management:

Workshop #1 – May 2000
Workshop #2 – July 2002
Workshop #3 – January 2003
Workshop #4 – June 2003
Workshop #5 – October 2004

The following recommendations were developed during the October 2004 Workshop. Instances where NASA has responded to the recommendations are noted.

ATM/Wx Integration Workshops
"10 Key Research Recommendations"

- Define Convective Impact and Constrained Areas for Evaluating Convective Forecast Products and Developing Air Traffic Decision-Support Tools
  - Provide observation field definitions to represent convective activity and its effects in support of TFM and Air Traffic Control (ATC) DS tools; forecast guidance products; and verification methodologies that provide operationally-relevant information

    Note: NASA is co-authoring an ATIO paper to verify Convective Weather Avoidance Model (aka Convective Storm Flight Deviation Model).

- Integrate Departure Management System for Severe Convective Weather
  - Provide route availability guidance for individual flights based on the filed flight plans, explicitly identify pathfinders, and present the salient decision information for alternative routes when the filed path is blocked by severe convective weather

- Develop Convective Storm Flight Deviation (CSFD) Model & Incorporating Algorithms into Multiple ATM Decision Support Capabilities
  - Develop an advanced model of CSFD that correlates (predicts) traffic flow deviations from convective forecast products, and integrate the model into research prototypes of DS tool capabilities

Note: NASA is supporting research to develop CWAM2 and integrated CWAM into a research version of FACET for automated routing studies (not an overlay and in early stages of maturity). NASA is also investing efforts to use CWAM in ATM decision-making and improving this model using human factors information.

- Develop Probabilistic Scenarios-Based Event Forecasting with TFM
  - Integrate the uncertainty in weather forecasts with strategic TFM planning

    Note: *NASA is supporting research to develop these forecasts and to use these data in TFM decisions.*

- Develop Fast-Time Simulation Tool Integrated with the Corridor Integrated Weather System (CIWS)/National Convective Weather Forecast (NCWF) Products
  - Study the impact of weather on air traffic using an integrated fast time simulation tool

- Incorporate Convective Weather Forecast Products for Use by ATM DS Capabilities
  - Integrate and evaluate convective forecast products into DS capabilities for en route/departure/arrival operations (e.g., time-based metering and 4D trajectory negotiation)

- Integrate TFM and Probabilistic Weather Forecasts
  - Continue and extend initial research efforts, concentrating on developing concepts for using probabilistic weather forecasts to predict the impact of weather on National Airspace System (NAS) capacity

    Note: NASA has proposed funding an external group to use these forecasts in TFM decisions.

- Develop En Route Weather Integration and Resolution Capabilities
  - Continue and extend current research efforts to provide sector controllers with integrated tools to support the pilot in the identification and avoidance of severe weather areas

- Integrate CIWS into an En-route Analysis Platform
  - Develop an operational concept for using advanced weather forecast technology (e.g., CIWS) in conjunction with aircraft

trajectories and traffic demand to identify and mitigate the impact of hazardous convective weather during high traffic demand periods

- Develop a Fast-time Simulation Analysis of TFM/Collaborative Decision Making (CDM) Integrated with Probabilistic Convective Forecast
  - Fast-time simulation analysis of traffic scenarios to determine the sensitivity of flight/flow deviation decisions through convectively-constrained airspace using a probabilistic forecast of convective strength

Appendix C. Glossary of Terms

AIRMET	Airman's Meteorological Information
ARSR	Air Route Surveillance Radar
ASOS	Automated Surface Observing System
ATOP	Advanced Technology and Oceanic Procedures
AVN	Aviation Forecast
CIP	Current Icing Potential Product
CCFP	Collaborative Convective Forecast Product
CIWS	Corridor Integrated Weather System
DOTS	Dynamic Ocean Track System
DSP	Departure Spacing Program
DSR	Display System Replacement
DUAT	Direct User Access Terminal
DUATS	Direct User Access Terminal Service
ERAM	En Route Automation Modernization
ETMS	Enhanced Traffic Management System
FIP	Forecast Icing Potential
GTG	Graphical Turbulence Guidance
pFAST	Passive Final Approach Spacing Tool
METAR	Meteorological Aviation Report
NCWF	National Convective Weather Forecast
NEXRAD	Next generation weather Radar
OASIS	Operational and Supportability Implementation System
RAPT	Route Availability Planning Tool
RUC	Rapid Update Cycle
RVR	Runway Visual Range
SIGMET	Significant Meteorological Information
STARS	Standard Terminal Automation Replacement System
TAF	Terminal Area Forecast
TFM-M	Traffic Flow Management Modernization
TMA	Traffic Management Advisor
URET	User Request Evaluation Tool
WSDM	Weather Support to Decision Making

Appendix D. Avoidable Delay Analysis

A key issue considered by the committee was the extent to which today's weather delays could be avoided if weather and air traffic management were more effectively integrated.

Avoidable delay has been recently examined quantitatively using Resource Utilization, one of three proposed metrics currently under study by the FAA and airlines. Resource Utilization is defined by the S2K/RTCA Customer Metrics Working Group as "the safe and efficient use of available airport or airspace capacity."

The focus of the initial analysis was on convective events in view of the higher level of weather related delays in the summer and predictions by FAA analyses that convective delays could result in the loss of airline profits by 2014 unless the overall NAS capability to manage convective weather was improved.

Measurement of capacity utilization and, the extent to which incomplete capacity utilization resulted in avoidable delays, is particularly difficult during convective weather since storms reduce capacity in both en route and terminal areas. In particular, en route capacity loss results in network congestion that must be addressed by a combination of aircraft altitude adjustments, route adjustments and metering delays on the ground and air. Determining the appropriate mix of trajectory adjustments and delays is a very difficult computational challenge.

The avoidable delay for an actual weather delay case was determined by a three step process:

1. The actual weather characteristics (e.g., ceiling/visibility, airport winds, and 3 D weather radar reflectivity) were translated into the capacity reductions in affected en route sectors, terminal airspace, and airports[12],

2. The time history of available terminal and en route capacity together with the traffic demand were input into an fully automatic broad-area ATM strategy generator[13] to determine reroute strategies or, when necessary, minimally disruptive ground or airborne delay programs that could have been utilized to minimize overall NAS delay

3. The actual delays and airspace utilization for that date were compared to the optimized capacity utilization and its associated delays to determine where and when capacity was not fully utilized,

[12] The method by which this was done will be discussed subsequently.
[13] Bertsimas, D. and S. Stock-Patterson, The Air Traffic Flow Management Problem with En Route Capacities, Operations Research, 46, 406-422, 1998

and how much of the actual delay was “avoidable” where the avoidable delay = actual delay – delay for the optimized ATM strategy.

Since the ATM strategy generator has knowledge of both the current and future weather in its strategy development, this is equivalent to assuming both perfect weather forecasts as well as optimal ATM responses (including perfect coordination between the various ATC facilities and, between the FAA and airlines).

In practice there will be underutilized capacity due to inaccurate weather forecasts as well as non optimal use of the weather forecasts to develop ATM strategies, flawed coordination between various decision makers, communications and infrastructure limitations, and/or non optimal implementation of the strategies (e.g., from delays in modifying flight plans).

Hence, one must carefully look at the circumstances associated with non optimal use of available capacity to understand whether the existence of usable capacity could have been reasonably anticipated by real time decision makers given the forecasts and other ATM decision support then available to the decision makers. Beyond the formation of ATM strategies one must also examine the infrastructure limitations to communicate and execute an ATM decision once made.

Computations of “avoidable” delay together with analysis of circumstances associated with non optimal use of available capacity have been carried out [14] for several significant convective events from 2005. Table 1 shows the results of these computations.

Comparison of the flight tracks determined with the optimized ATM strategy generation algorithm with the flight tracks for the same aircraft on the actual weather event (figures 1-3) showed that much of the avoidable delay arose from the inability of the decision makers during the real time operations to utilize capacity that had become available after weather impacts ended. Although the magnitude of the avoidable delay was quite high in two of the three cases, the fact that much of the current delay could have been avoided by relative short lead time ATM actions is quite encouraging for weather-ATM integration since the accuracy of short term (e.g., 0-2 hour) convective forecasts is much better than the accuracy longer lead time forecasts and, may be easier to improve in the near term.

The post event analysis tool described above could also be used to quantitatively assess the performance improvement provided by integrated ATM-weather system under test. Since an integrated ATM-weather decision support system should help the decision maker better utilize available capacity, one could use as

[14] MIT Lincoln Laboratory 2007 study to be published in 2007

a metric the degree to which capacity was fully utilized when needed before and after an integrated ATM-weather decision support system was deployed[15].

	7/16/05 Actual	7/16/05 Possible	7/27/05 Actual	7/27/05 Possible	7/27/06 Actual	7/27/06 Possible
Ground Delay >15 min	31%	4%	25%	4%	42%	5%
Air Delay** >15 min	9%	5%	10%	9%	3%	7%
Total Delay (hours)	3997	69	5630	1840	6452	2236
# flights	13,340		15,648		16,328	

** Includes reroute time 1

Table 1 Preliminary results of determining unavoidable delay for three severe weather events in 2005 and 2006. [16]

[15] An alternative metric – comparison of delays before and after an integrated ATM-weather decision support system was installed- is very difficult to use in practice since the "unavoidable" delay is an uncontrolled variable that depends on the exact time-space distribution of storms as well as the demand.
[16] MIT Lincoln Laboratory Study; to be published in 2007

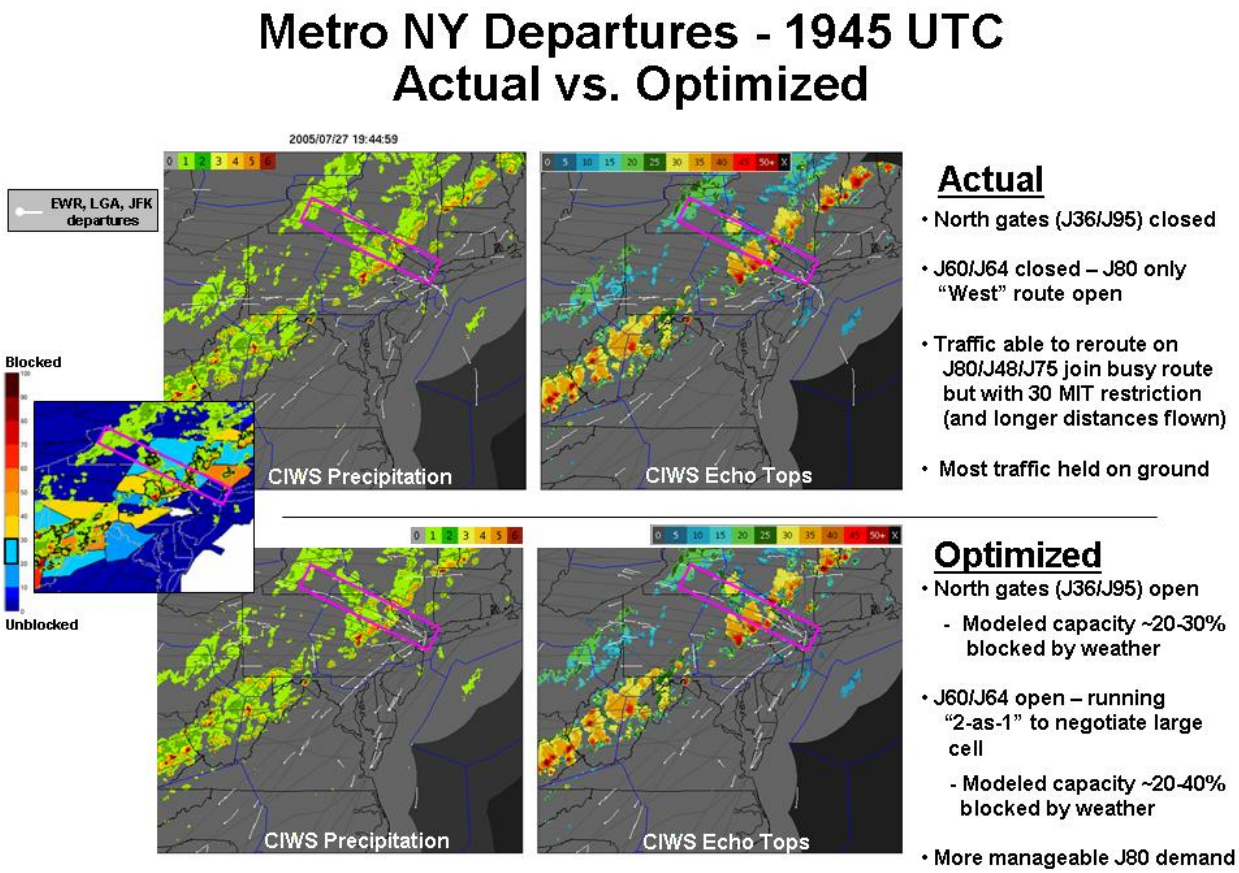


Fig. 1 Example of comparing capacity utilization in real time with optimized use of available capacity by post event analysis tool for a severe weather event on 7/27/2005.

The left hand large plots show flight trajectories (in white) overlaid on CIWS precipitation product; the right side large plots show flight trajectories (in white) overlaid on CIWS echo tops product. The small insert on the left hand side shows the fractional loss in sector capacity based on blockage of principal routes through the various sectors as determined from the CIWS reflectivity and echo tops products. The purple boxes show a region where there was a significant difference in airspace usage.

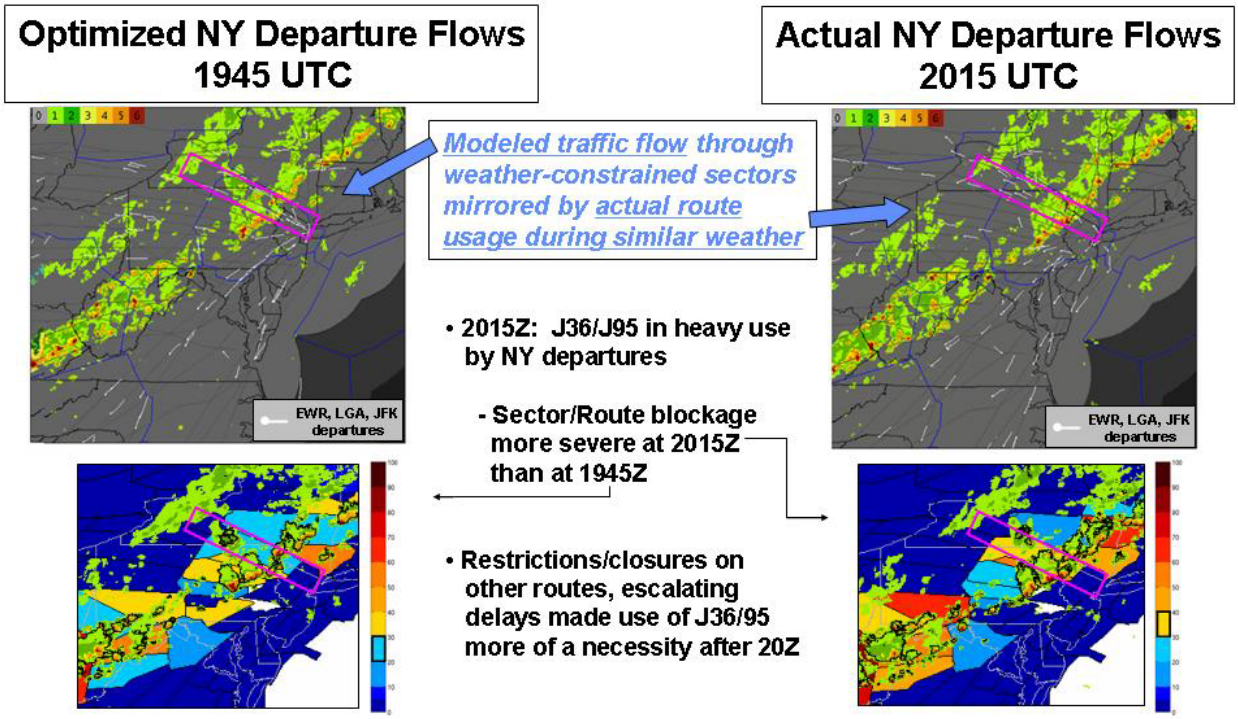


Fig.2. Verification of the validity of the assumed airspace availability in the post event analysis.

The upper plots show flight trajectories (in white) overlaid on CIWS precipitation product; the two lower plots shows the fractional loss in sector capacity based on blockage of principal routes through the various sectors as determined from the CIWS reflectivity and echo tops products. The purple boxes show a region where there had been a significant difference in airspace usage at 1945Z. The weather in purple box region was more severe and the fractional capacity loss was greater at 2015Z than at 1945Z. The conclusion is that the ATC system was at least 30 minutes late in utilizing available capacity near J36/J95 after 1945Z.

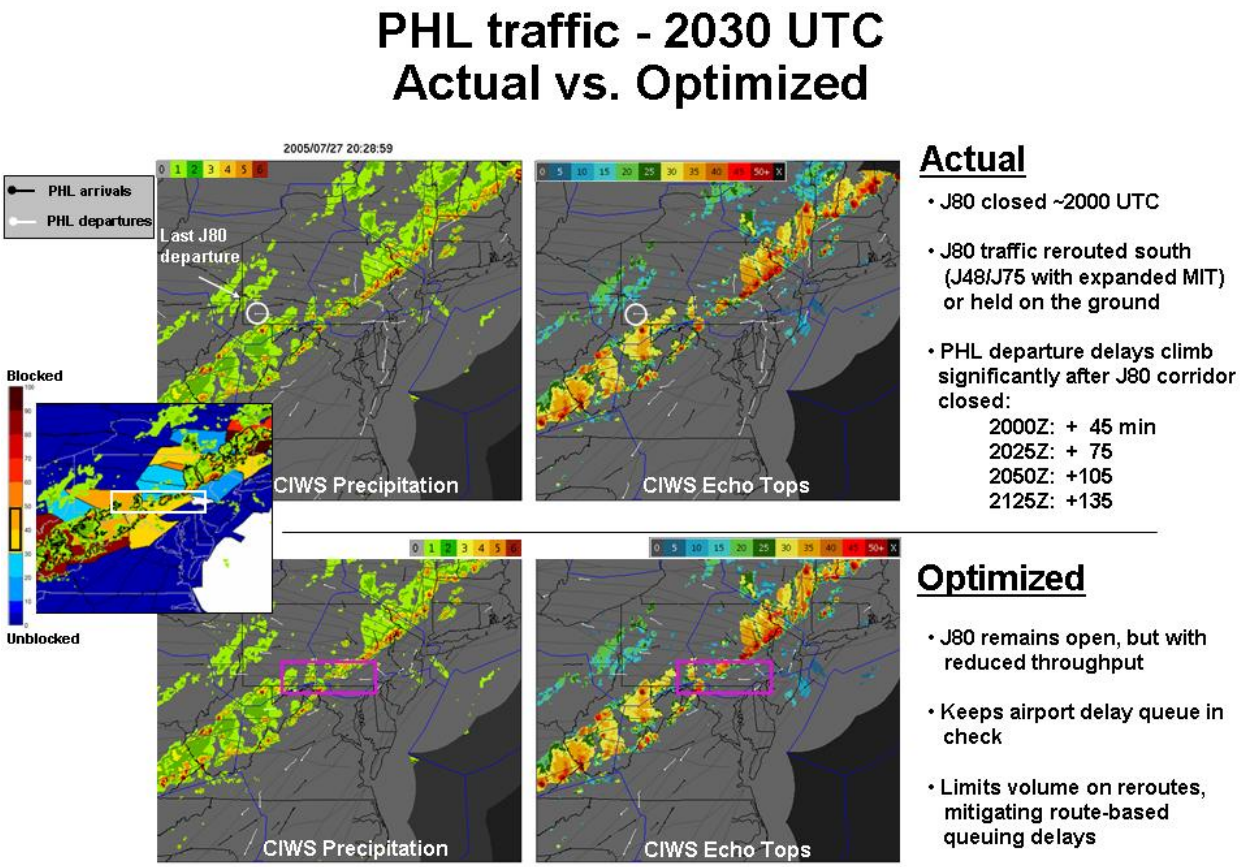


Fig. 3 Additional example of comparing capacity utilization in real time with optimized use of available capacity by post event analysis tool for a severe weather event on 7/27/2005.

The left hand large plots show flight trajectories (in white) overlaid on CIWS precipitation product; the right side large plots show flight trajectories (in white) overlaid on CIWS echo tops product. The small insert on the left hand side shows the fractional loss in sector capacity based on blockage of principal routes through the various sectors as determined from the CIWS reflectivity and echo tops products. The purple boxes show a region where there was a significant difference in airspace usage.

Appendix E. Weather Impact Analysis

A key element of an integrated ATM/weather decision support system (figure 1) is the translation of current weather data and weather forecasts into ATC impacts, i.e., airspace that pilots will seek to avoid and the associated airspace capacity impacts.

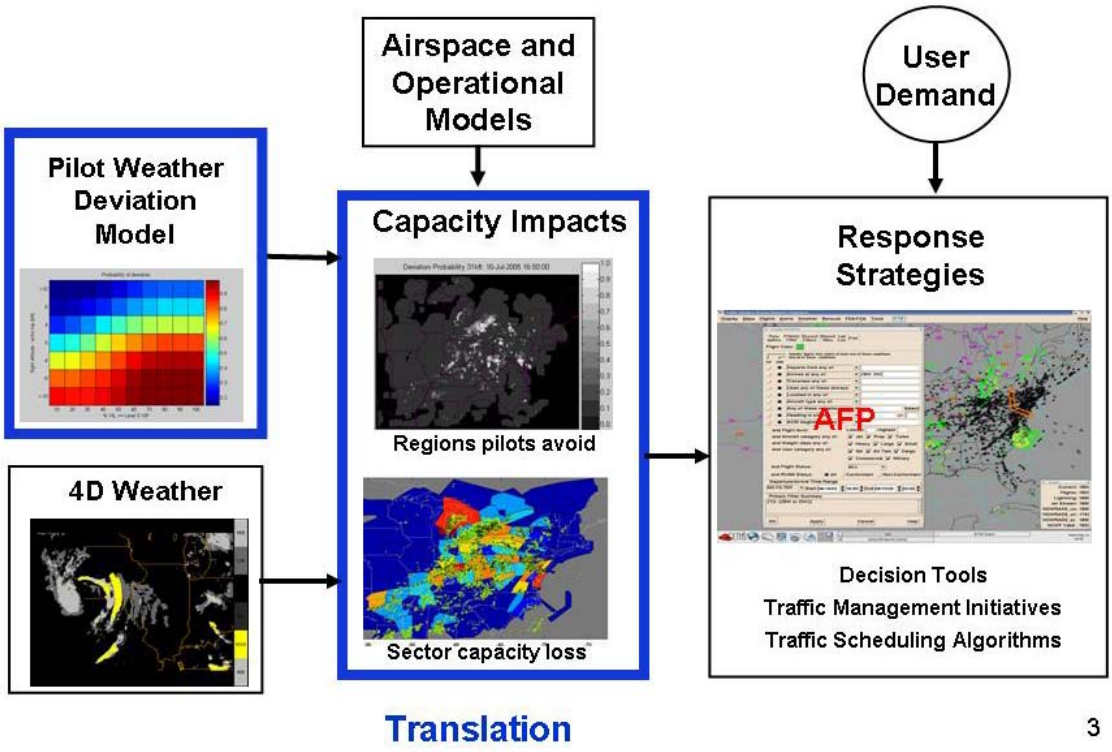


Fig. 1 Relationship of the translation from weather impact to capacity impact (dark blue boxes) to the overall use of weather information for ATM decision support

The principal focus for the committee study was on translation for convective weather given the high level of delays associated with convective weather and, the current state of knowledge on the relationship of convective weather characteristics to capacity impacts. In view of the importance of this topic for the practical utilization of integrated weather-ATM decision support tools and the lack of previous FAA funded research in this area, this section will include a relatively detailed summary of the status of knowledge to date before discussing the recommended research program.

Current state of technology in translation from weather impacts to ATC impacts

It is clear from figure 1 that determining the regions of airspace which pilots will/should avoid is a critical first step. The FAA Aeronautical Information Manual (AIM) suggests that pilots avoid thunderstorms characterized by “intense radar echo” in en route airspace by at least 20 nautical miles (40 km).

However, an initial study (Rhoda, et. al., 1999) of pilot convective weather avoidance decision making at Dallas-Ft. Worth showed that many air carrier arrivals would penetrate high reflectivity cells when within 10 nm of the airport. A follow up study (Rhoda, et. al., 2002) of pilot behavior in both terminal and en route airspace near Memphis, TN confirmed that arrivals often penetrate high reflectivity storms when near the airport and, that pilots fly over high reflectivity cells in en route airspace and penetrate lower cells whose reflectivity is less than VIP level 3.

NASA has funded some initial “foundational” research to develop a quantitative model that would predict when a pilot will deviate around convective weather in en route airspace as well as estimating the storm-aircraft separation associated with deviations. These models were determined from analysis of several hundred air carrier flight – convective storm encounters in the Midwest of the type shown in figure 2

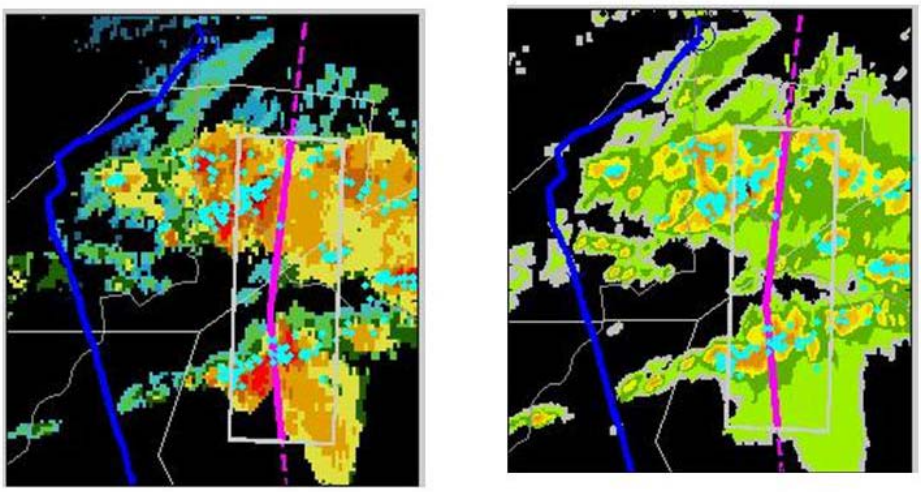


Fig. 2 Example of plane encounters with convective weather in the Indianapolis ARTCC (ZID). Blue trace is an aircraft that deviated; pink track is an aircraft that penetrated (or, over flew) the storm. Left hand side background is color coded CIWS echo tops (yellow is 30 Kft.); right hand side plot background is CIWS radar reflectivity (yellow is VIP level 3 equivalent). Blue crosses on right hand side plot are lightning strokes. The white box indicates the weather characteristic analysis box.

The results from over 500 encounters of the type illustrated in figure 2 were put into a statistical classifier package to determine which combination of radar reflectivity, echo tops and lightning data best explained whether a plane would penetrate or, deviate around a storm. Typical results of the statistical classification are shown in figure 3.

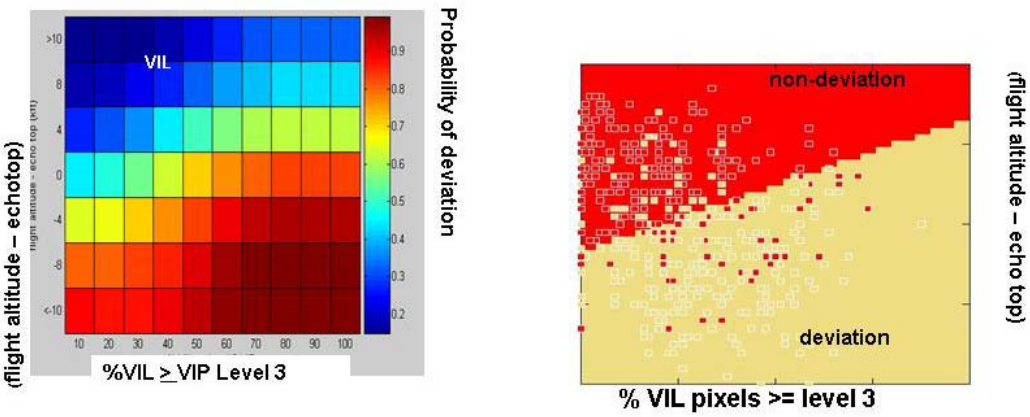


Figure 3 Typical results for statistical classification. The left hand plot shows the probability that a plane will deviate around a storm as a function of the fractional VIP level 3 or high reflectivity coverage of the weather analysis box shown in figure 3 and the difference between the flight altitude and the highest radar echo tops within the box. The right hand plots show a best fit delineation of the tradeoff between coverage by high reflectivity weather and flight altitude relative to echo tops.

We see that aircraft whose altitude is less than the echo tops altitude will generally deviate at relatively low fractional coverage. However, aircraft whose flight altitude is at least 5 Kft. above the echo tops typically will not deviate around the storm region.

The best fit models of pilot deviation as a function of the convective weather characteristics can be used to generate spatial fields of the likelihood of pilot deviation as a function of location as shown in figure 4.

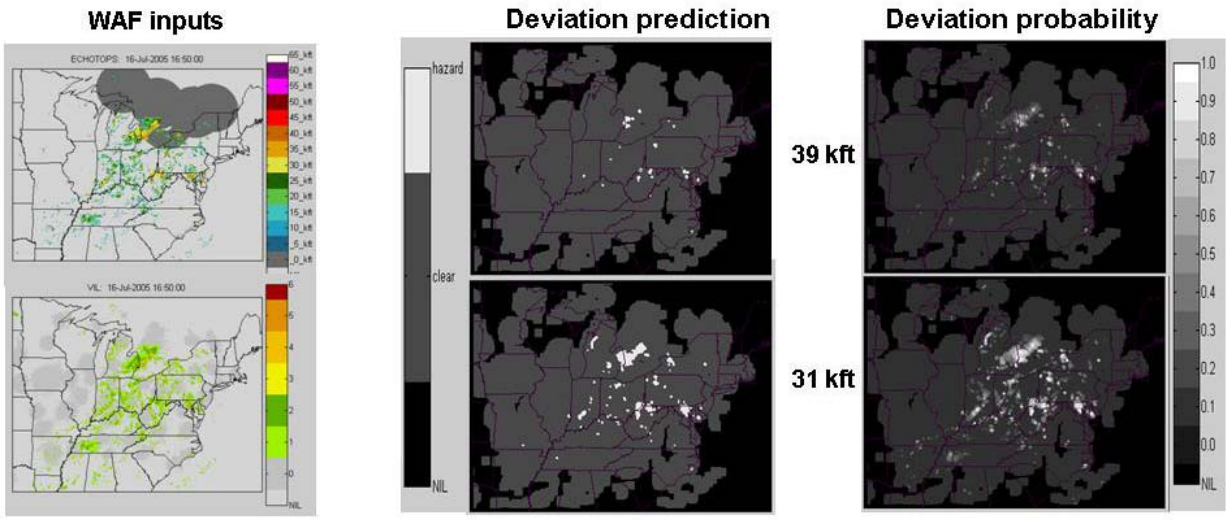


Figure 4 Translation of CIWS reflectivity and echo tops spatial fields into fields of regions where pilots are likely to deviate (middle plots) and fields of the probability of pilot deviation (right hand plots) as a function of the aircraft altitude. Note that the region of likely deviations is much smaller for aircraft at 39 Kft. than for aircraft at 31 Kft. The deviation spatial fields have been termed “weather avoidance fields” (WAF). Results from a conference paper by DeLaura (2007)

The WAF can be validated by seeing if flights do in fact deviate around the high WAF regions that were computed from radar and lightning data alone. Figure 5 shows an example of the data used to validate the deviation fields.

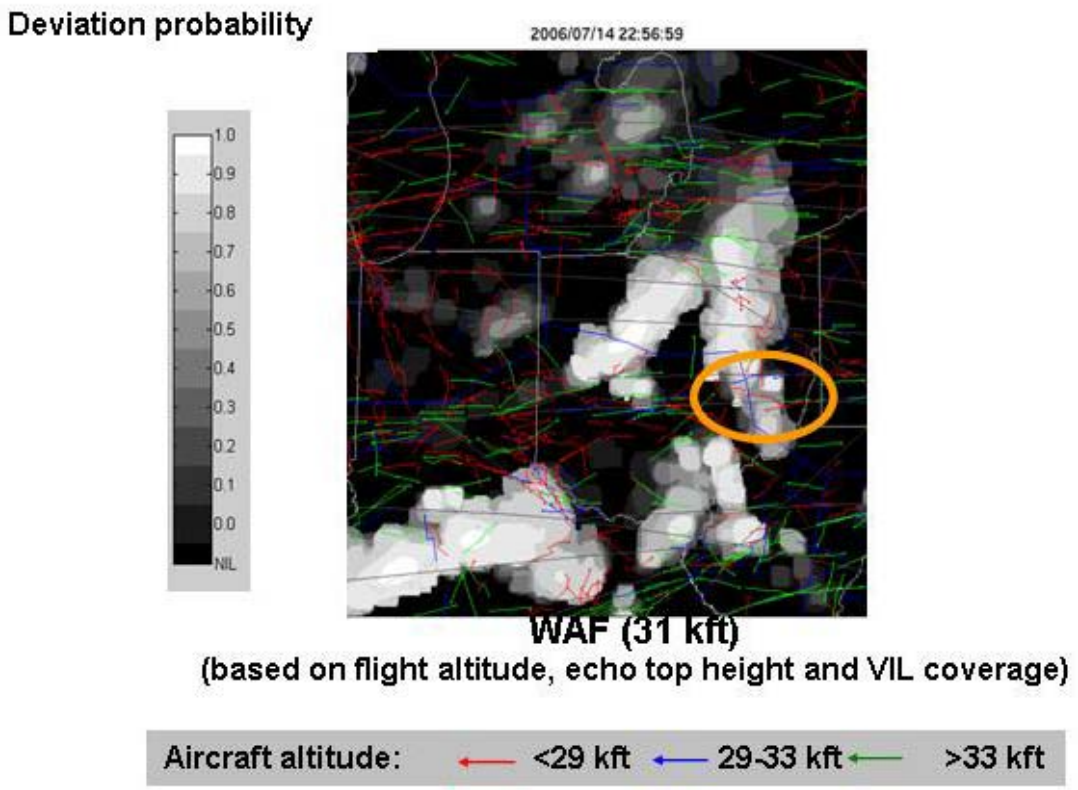


Figure 5 Example of a weather avoidance field (WAF) validation test. Tracks of aircraft are overlaid on the WAF determined from weather radar and lightning data alone to see if aircraft are deviating around storms as predicted. The region with the orange oval contains a number of tracks that did not deviate around an area where the echo tops was well above the flight altitude.

It is evident from figures 3 and 5 that there were flights that deviated around weather they could have over flown and aircraft that penetrated regions of storms at flight altitudes lower than the radar echo tops. In figure 5, we see that the unexpected storm penetrations occurred principally in one region as opposed to being randomly distributed over the regions of high values of deviation probability.

A major objective of the future research in this area should be to reduce the spread in pilot thresholds for weather conditions that lead to deviations (especially the ones where a pilot seems very conservative) since unexpected deviations around storm regions in high density airspace can lead to prolonged, unnecessary route closures.

There are two known sources of variability in pilot decisions to deviate around storm regions:

1. We may not currently be considering the best set of weather predictors, and

2. One pilot may be deviating for a smoother ride and then others will follow that pilot's track.

For the case shown in figure 5, meteorological analysis found that the region in the orange oval was a region of storm decay. It is well known meteorologically that decaying storms tend to have mainly weak downdrafts aloft with relatively low turbulence. Hence, research is currently underway to see if the inclusion of storm growth/decay information might improve the performance of the deviation prediction model.

Another apparent anomaly in pilot decision making was noted in testing of the Route Availability Planning Tool (RAPT) in the summer of 2007 as shown in figure 6.

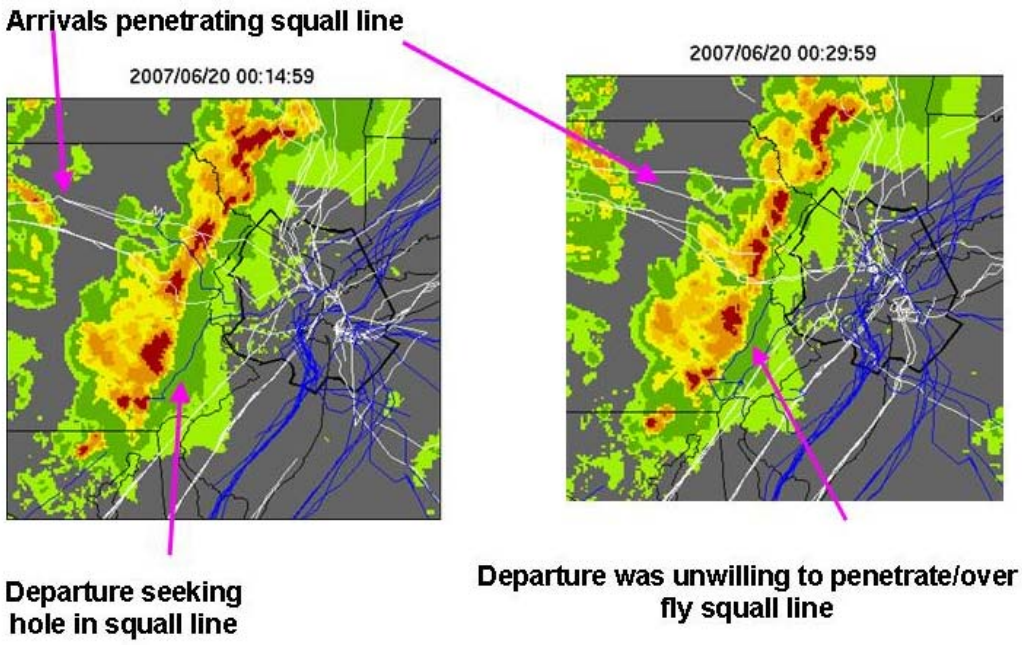


Figure 6 Example of a significant difference in storm deviation behavior between arrivals (white tracks) and departures (blue tracks observed at New York on 20 June 2007 at around 0000Z (8 pm local time). Arrivals penetrated regions of high reflectivity and storms tops over an extended time period during which departures would not penetrated the same storm. Differences in pilot behavior cannot be explained by aircraft altitude differences.

There are various possible explanations for the differences in deviation behavior shown in figure 6. ATC personnel have suggested that an important factor may be the difference in the visual depiction of the storms between having the storms back lit by the sun (departures) versus the storm depiction with the sun behind the pilot (arrivals).

Unexpected deviations around storms are a major concern for convective weather ATM in general and particularly for integrated ATM-weather decision support systems. If deviations around storm regions in congested airspace of the type shown in figure 6 result in the deviating aircraft interfering with other aircraft, ATC will often shut down the use of the route that was being used by the deviating aircraft. Reopening such route after weather impacts have ended can be very time consuming and result in a significant loss of usable capacity.

A concern here is that a pilot deviating simply to get a somewhat smoother ride may not understand the implications of an unexpected deviation on route usage by other aircraft. Alternatively, a pilot may attempt to penetrate a severe storm without fully understanding the hazard in such a storm and then request significant deviations in an effort to avoid additional difficulties in flight management.

Data link transfer of weather and ATC domain information to the pilot could be very useful in achieving a much more consistent pilot response to convective weather:

(1) ground derived weather characteristics (e.g., storm growth or decay, likelihood of hail) that should be of concern to the pilot

(2) a visual depiction of spatial boundaries that would be acceptable to ATC as a "normal" maneuvering region

Since traffic flow management (TFM) decision support tools typically require as an input an estimate of future capacity, one must translate the WAF information into estimates of loss of en route and terminal capacity.

(Song, et. al., 2007) state that “Sector capacity can be defined in terms of the number of aircraft which may enter a sector within the given time period, without causing excessive sector controller workload; that is, the maximum number of aircraft that can be safely handled by the controller. Controller workload reflects the overall level of demand for controller’s perceptual and cognitive resources.”

The translation from WAF to sector capacity requires assumptions on use of the airspace including the relationship of the structural flows in the sector when convective weather occurs. Estimates of the sector capacity with convective weather have been made with two rather different models:

(1) (Martin, et. al., 2007) estimate the effective sector capacity by determining the fraction of routes that are not blocked by convective weather (including consideration the fair weather demand on those routes). The basis for that assumption is that the complexity/workload for sectors is well understood only if the normal structural flow is maintained. If the flow spatial structure is quite different from the normal structure, controllers typically cannot not manage the normal number of aircraft in their sector due to lack of experience with the flow pattern.

(2) (Mitchell, et. al., 2006) estimate the throughput of aircraft flying in a single direction (e.g., west to east) through a sector which contains convective weather assuming that the planes can fly along undulating parallel “tubes” through the weather. An implicit assumption is that aircraft separation is provided by a fully automatic algorithm and, no results are shown for the situation where there are crossing and/or merging routes within a sector.

The sector throughput of the (Mitchell, et. al.) “tube” model for airspace usage is clearly much higher for a given spatial distribution of weather than the estimate based on blockage of the normal routes. However, since the assumptions (Mitchell, et. al) make regarding separation of aircraft from other aircraft do not seem applicable to today’s human based plane separation system, it is not possible to validate their estimates of capacity by comparison with today’s flight usage.

Figure 7 shows a typical result for en route sector capacity during convective weather determined by the method discussed in (Martin, et. al., 2007).

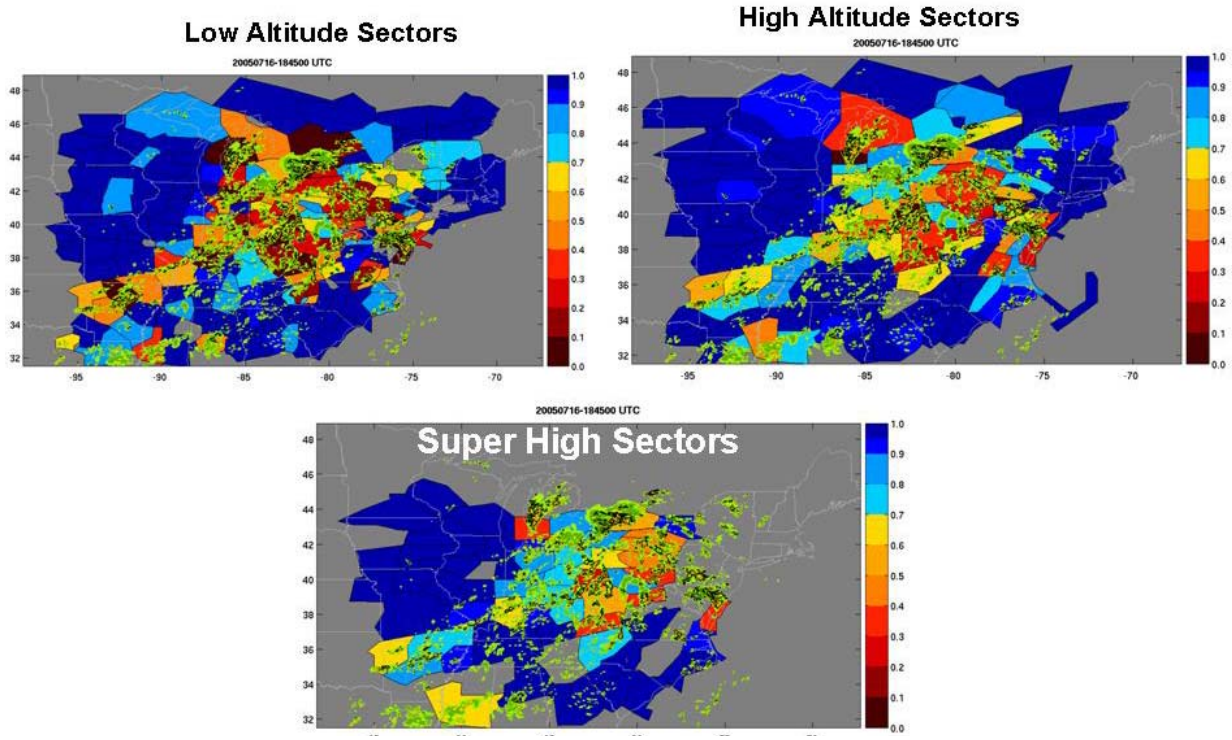


Fig. 7. Fractional capacity loss for a number of the en route sectors in the northeast portion of the US on 16 July 2005. The capacity loss was estimated using the CIWS reflectivity and echo tops data for 1845Z together with the pilot weather avoidance and RAPT route blockage models.

Some limited comparisons have been made between the actual uses of en route sectors during convective weather with the predicted use based the route blockage sector capacity model described above. An initial result is shown below in fig. 8

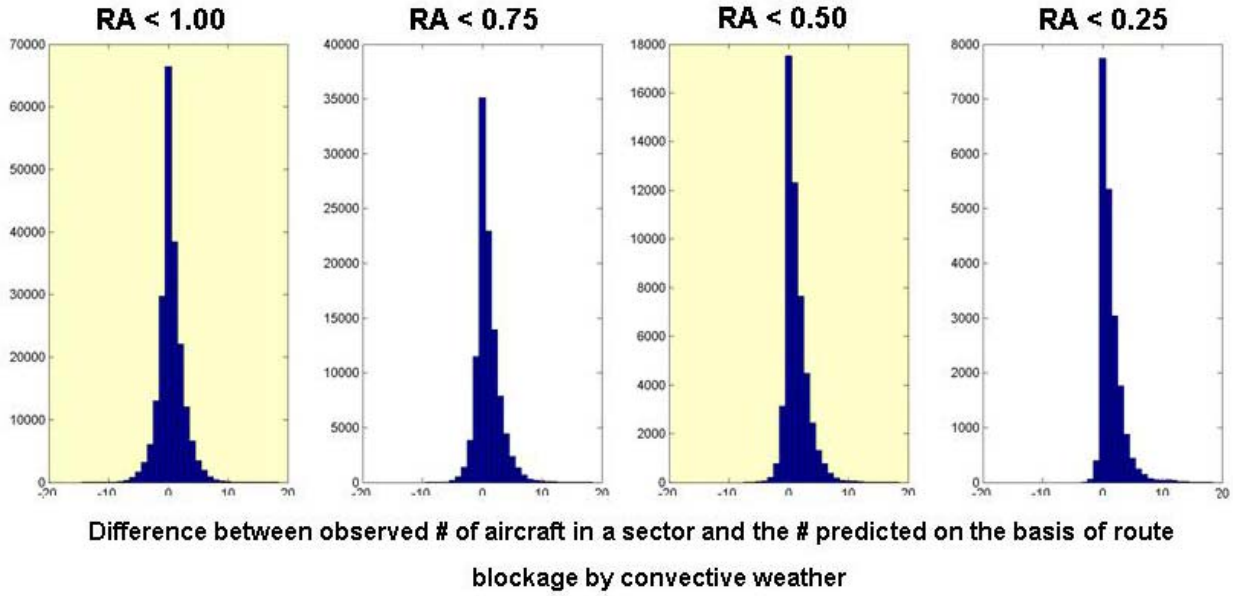


Fig. 8 Comparison of aircraft counts over a 15 minute periods for a number of convective weather events in the sectors shown in figure 7 with the aircraft counts predicted from CIWS weather data alone as a function of the predicted fractional route blockage (RA).

The mode of the distributions is zero (no error). However, for higher fractional blockages, the number of observed aircraft is often less than the predicted number of aircraft. This result is expected for the reason shown in figure 9.

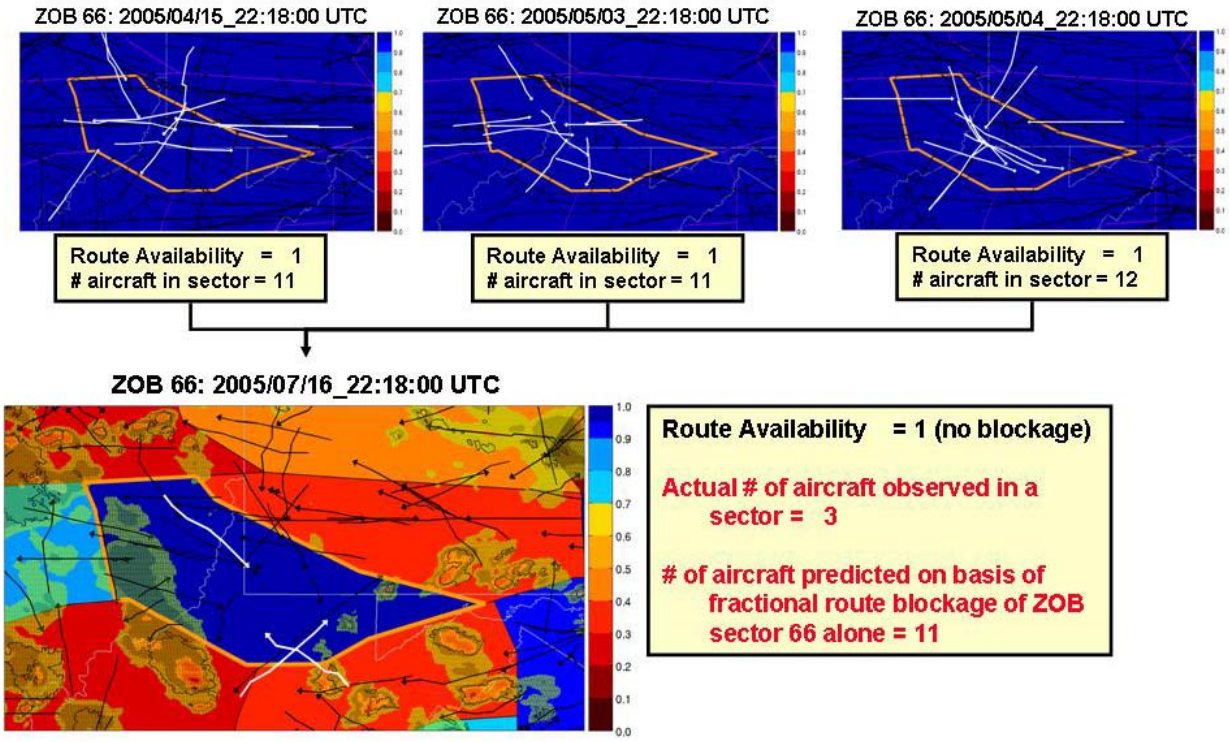


Fig. 9. A major cause of differences between predicted number of aircraft in a sector during convective weather and the observed number of aircraft in the sector is the impact of convective weather in adjacent sectors. The top 3 plots show that on fair weather, the observed number of aircraft in the Cleveland en route sector 66 at a given time of day (2218 Z) was very consistent. The bottom figure shows the (fair weather traffic normalized) fractional route blockage for sector 66 and its surrounding sectors on 16 July 2005 when there was extensive route blockage by convective weather. We see that although there is essentially no route blockage in sector 66, many of the surrounding sectors have very significant route blockage. Hence, it is not surprising that the number of aircraft actually observed in sector 66 on 16 July was much less than would be expected by considering only the characteristics of the weather within sector 66.

We see from figure 9 that experimental validation of sector capacity estimates in convective weather needs to consider the constraints on usage of a sector under examination by convective (and, non convective) weather elsewhere in the NAS. Hence, validation of the models for sector capacity in convective weather can necessitate a very detailed understanding of NAS dynamics.

The above discussion has provided a short summary of the current state of knowledge in this very important area of translation of weather information into ATC impacts. We view the validation results shown above as fairly promising given the very low level of funded research in this area to date. However, there clearly are major research needs that we will now briefly discuss.

Recommended research on translation of convective weather impacts into ATC impacts

The development and validation of models for pilot weather avoidance is clearly critical to both ATC impact determination and decision support tool development. As was noted above, there are a number of convective weather factors (e.g., storm growth / decay, how to best characterize the turbulence associated with storms, and visual cues) that need to be considered. Also, there are pilot human factors issues that also need consideration (e.g., whether the flight is delayed, alternatives to penetration of a storm, airframe differences, airline, etc) as well as the possible impact of information provided to the cockpit via data link on pilot decision making.

To date, WAF modeling have only considered en route level flight. Clearly, there needs to be consideration of ascending and descending aircraft as well as terminal area pilot decision making including landing and takeoff operations.

The models for airspace usage (including models for route blockage and, the importance of use of normal routes) are in a very preliminary state. Only en route sectors have been considered to date with the aircraft principally in level flight. Additional ARTCCs need to be studied to determine if the airspace usage is differs between various en route facilities [e.g., the Jacksonville Center (ZJX) appears to have very different procedures than many of the ARTCCs in the northeast].

Also, it is necessary to study the management of arrival and departure flows in both en route and terminal airspace. It appears that terminal areas have a much higher propensity to routinely operate in convective weather with routing that is very different from the normal fair weather routes. Hence, determining the effective capacity for various different storm spatial distributions within a terminal area will be a significant undertaking.

One of the important questions in the research is how accurate the translation modeling needs to be to support the successful utilization of integrated convective weather-ATM decision support tools (i.e., the right hand side of figure 1). The required accuracy will clearly depend on the specific DST and its intended function.

At this point, there are a very limited number of such tools in experimental operational use. It will be important for the FAA to take advantage of the ongoing operational testing of DSTs such as RAPT to get insights into the required accuracy for translation process so that the DST output quality is high enough to achieve operational user acceptance.

It will also be important to start identifying the additional model accuracy requirements that may be generated through innovative longer lead time approaches to ATM such as discussed by (Mitchell, et. al.)

Appendix F. Route Availability Planning Tool

Current departure decisions in the presence of convective weather require ATC to estimate whether the aircraft will have a storm free flight.

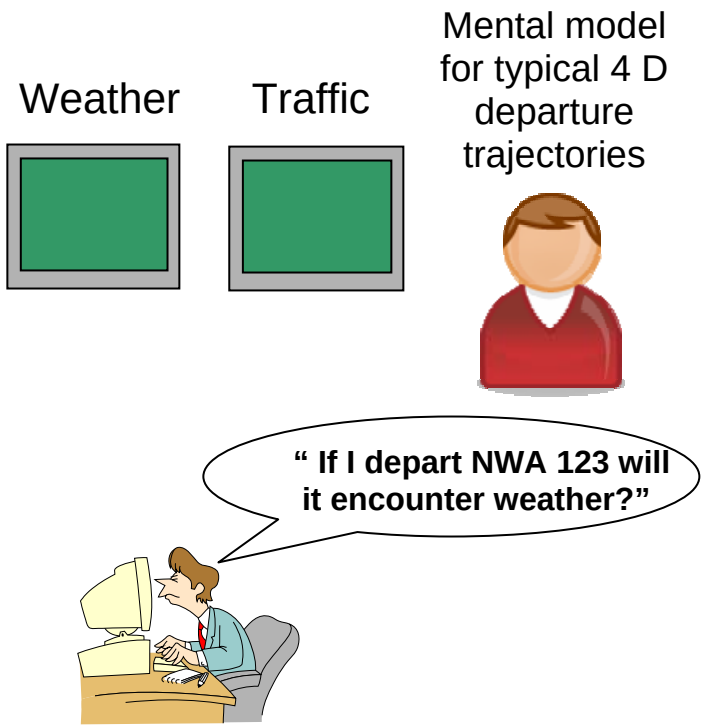


Figure 1. Existing Decision Process

The Route Availability Planning Tool uses the Terminal Convective Weather Product storm motion forecasts and typical departure flights along defined Standard Instrument Departure (SID) Routes to determine if an aircraft would encounter a storm for departure times in the next thirty minutes. The information

is color coded in a display, one row for each SID, where red indicates a likely encounter with a storm and green a safe departure.

Since its' first deployment, the tool has incorporated storm echo tops as well and is continuing to be refined as experience is gained.

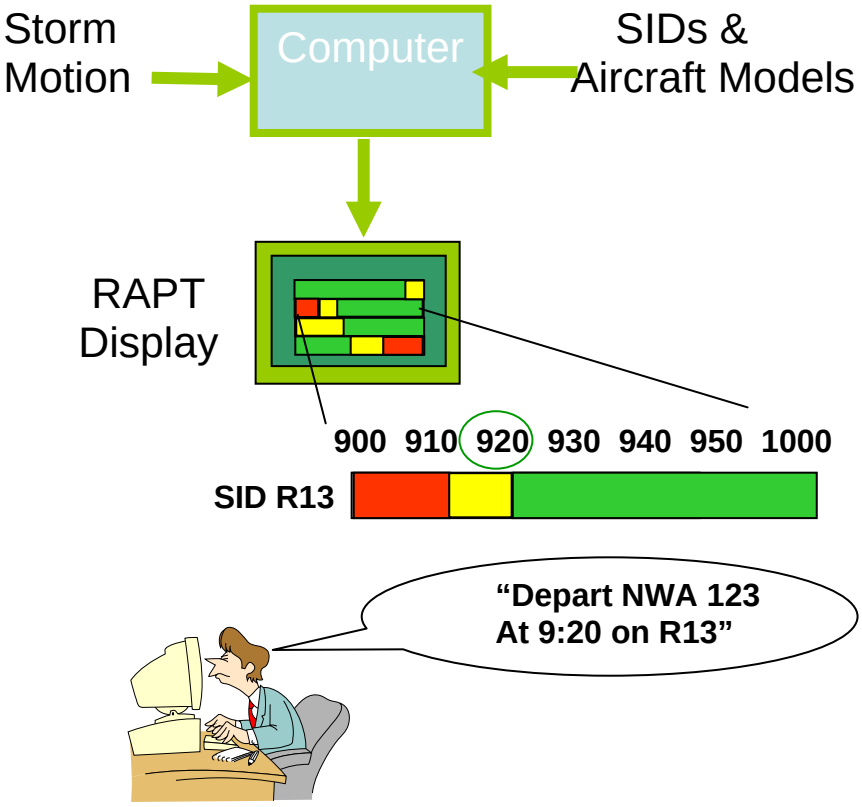


Figure 2. Route Availability Planning Tool

The RAPT display indicates, by color coding, if an aircraft departing at some time in the next 30 minutes will encounter a storm during the first 30 minutes of flight.