1.5 DEVELOPMENT OF BENEFITS-DRIVEN CONVECTIVE WEATHER DECISION SUPPORT SYSTEMS FOR IMPROVING SAFETY AND EFFICIENCY IN THE ATC SYSTEM THROUGH 30 YEARS OF CONTINUOUS USE OF REAL TIME FUNCTIONAL PROTOTYPES*

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1.0 INTRODUCTION

The July 2018 Aeromexico accident flight at Durango, Mexico, and the many flight delays/cancellations along the east coast in 2018, serve as a reminder that convective weather remains a major safety and efficiency challenge for the aviation system. A key need continues to be decision support to help manage the traffic congestion that arises from the loss of airspace and airport capacity, while also improving the safety of operations.

This paper describes a 30-year program of providing convective weather decision support products in real time to major Air Traffic Control (ATC) facilities, airlines, and pilots to improve safety and efficiency in the US airspace system using MIT Lincoln Laboratory-developed prototypes as a part of an iterative, benefits-driven system development process shown in Figure 1.

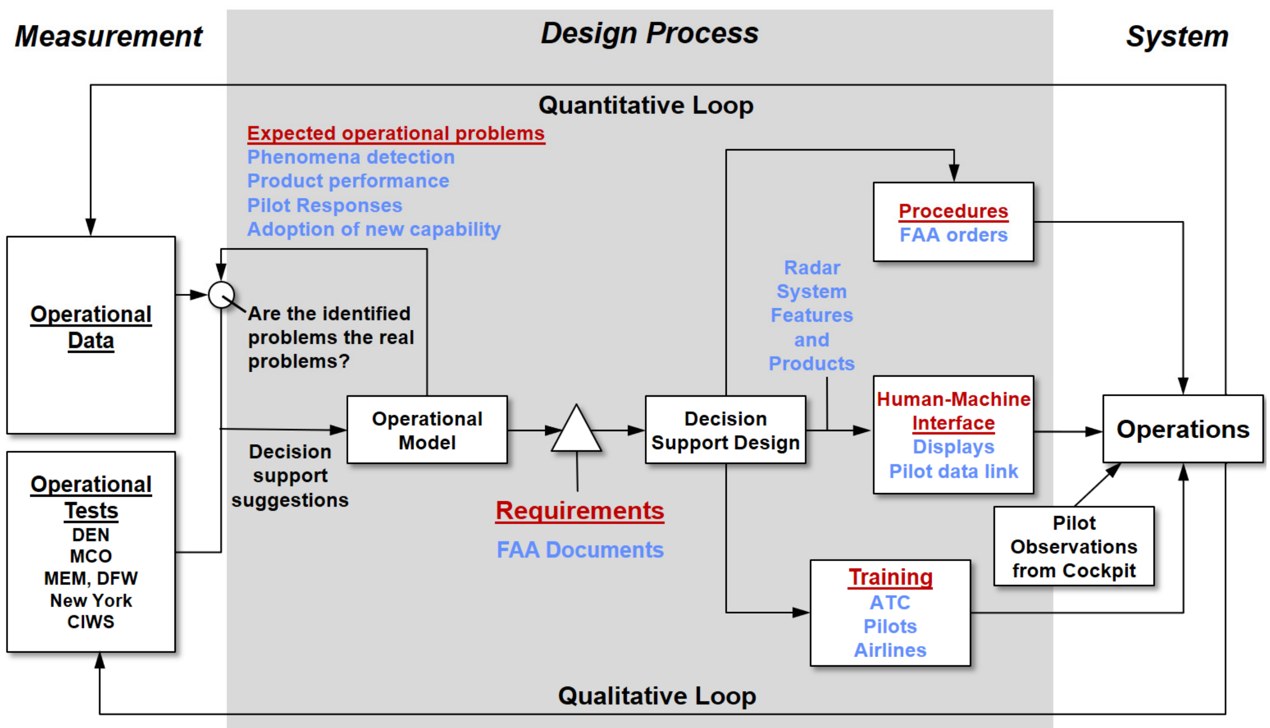

FIGURE 1. The benefits-driven, decision support design process underlying 30 years of real time convective weather decision support using prototype systems. The process has provided a means of both qualitatively and quantitatively iterating upon a decision support system to achieve quantifiable operational benefits [original process diagram from (Reynolds, et al., 2012)]. Various Federal Aviation Administration (FAA) documents [e.g., (FAA, 1987; FAA, 1995)] have high level functional system requirements such as probabilities of detection and false alarm for wind shear alerts.

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In this paper, we describe:

1. The principal operational problems that motivated this long-term effort,
2. How the real-time experimental decision support functional prototype evolved as a result of ongoing operational user feedback,
3. The key role of benefits assessment coupled to training in achieving increased operational benefits, and
4. Real-time operations of the prototypes and operational user training

The paper concludes with a discussion of how this approach might be applied to address high priority remaining problems of mitigating weather impacts on the National Airspace System (NAS).

1.1 Operational Problems that Motivated the Work

There are two U.S. National Airspace System (NAS) operational problems that motivated this program:

1. Air carrier accidents due to low altitude wind shear – especially microbursts (Table 1 and Figure 2) – became a major concern in the 1970s and 1980s. Initially, there had been much skepticism that short-lived storms could generate operationally-significant low altitude wind phenomena. And, it took several scientific experiments to demonstrate that the phenomena existed and could be of concern for airline aircraft [e.g., (Fujita, 1985; Hjelmfelt, 1988). However, it was only with the deployment of fully automated microburst detection using pulse Doppler weather radar that the high frequency of microburst events at airports in the US became evident, as shown in Figure 3.
2. The need for improved decision support for tactical Air Traffic Management (ATM) (e.g., 0-2 hour lead times) to facilitate the safe utilization of the available system capacity when convective weather impacts airports and highly congested US airspace (Figure 4) had not been fully appreciated for a number of years. The need for terminal ATM at busy airports with frequent convective impacts became clear in the testing conducted by Lincoln Laboratory in Orlando, FL in the early 1990s.

En route congestion during convective weather increased significantly in the late 1990s when airlines switched from operating a relatively small number of turboprop aircraft (operating at altitudes well below that of the longer distance flights) to the widespread use of regional jets that operated at the same altitudes as larger jets (Evans and Ducot, 2006)

The focus for tactical ATM in en route airspace depends on the type of weather shown in Figure 5[1] and the location of the weather. With unorganized convective weather in low to moderate density airspace, ATC can effectively route traffic around the isolated cells. However, organized convection clearly could block many of the high traffic routes in the eastern half of the US. This level of route blockage requires a portfolio of strategies such as routing around the region of convection, maximizing the use of gaps in lines of storms, and overflying storms when that can be safety accomplished. In both types of convective weather, it is especially important to start using airspace and airports promptly when the storm impacts have ended.

Providing effective decision support for such ATM decision making in high congested airspace requires high space and time resolution information on the usable airspace (including accurate forecasts).

TABLE 1. U.S. Aircraft Accidents With Fatalities or Injuries Attributable Specifically to Microburst Low Altitude Wind Shear (Wolfson, 1988; Evans and Weber, 2000).

Date	***Airport***	***Aircraft***	***Fatalities***	***Injuries***	***Uninjured***
24 June 1975	New York (JFK)	B727	112	12	0
7 August 1975	Denver (DEN)	B727	0	15	119
23 June 1976	Philadelphia (PHL)	DC-9	0	86	20
9 July 1982	New Orleans (MSY)	B727	153	9	7
2 August 1985	Dallas (DFW)	L-1011	135	28	2
2 July 1994	Charlotte (CLT)	DC-9	37	20	0

[1]Details on the convective weather classification shown in Figure 5 are provided in section 4.3 of (Robinson, et al., 2004)

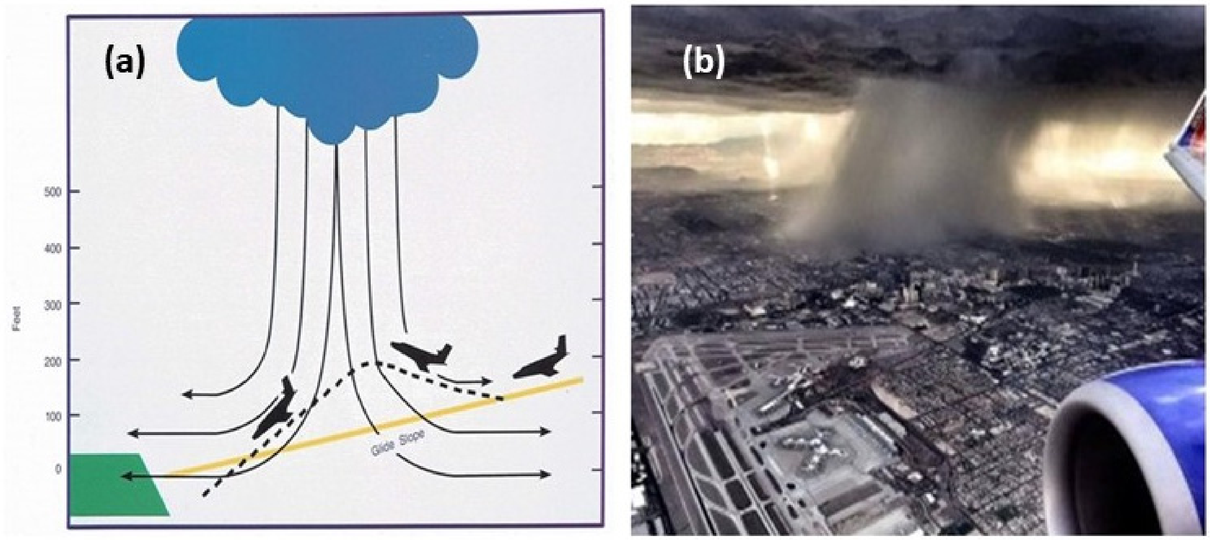

FIGURE 2. Downdraft and outflow from a thunderstorm: (a) schematic of an aircraft microburst encounter and (b) photograph of a microburst-producing thunderstorm in Las Vegas. The pilot first encounters a head wind (increase in lift), and then a downdraft (loss of climb) and finally a tail wind (decrease in lift), which causes the plane to lose airspeed. The adjustments a pilot might make in encountering a head wind (e.g., slowing down and/or dropping the nose) can put the plane in a poor configuration to manage the loss of lift and altitude due to the downdraft and tail wind. In the picture, one can see that the rain reaching the ground is spreading along the ground due to the storm outflows.

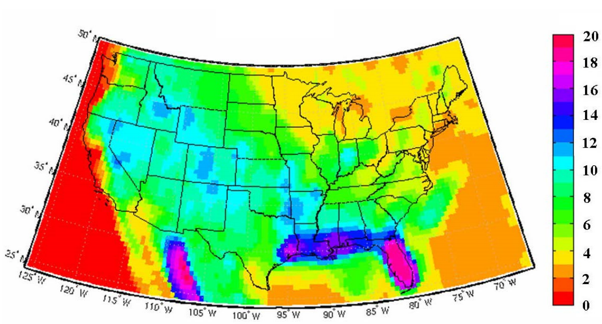

FIGURE 3. US map of annual microburst exposure (1000s of minutes of alerts at an airport) using measured microburst detections by the Lincoln Laboratory-developed Terminal Doppler Weather Radar (TDWR) at a number of major airports as an input to a model developed by R. Hallowell of Lincoln Laboratory (Hallowell, et al., 2009).

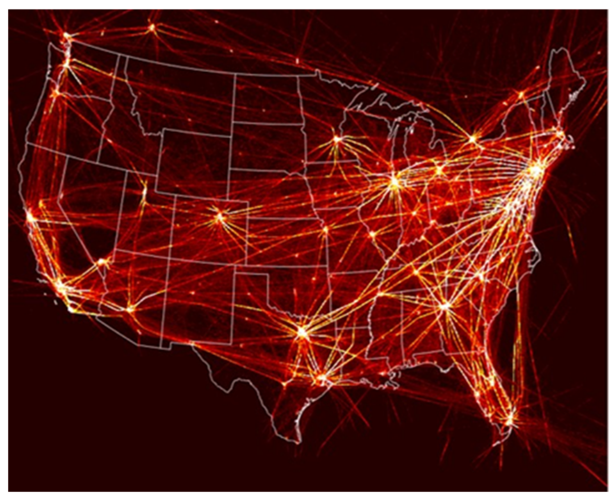

FIGURE 4. Density of IFR aircraft in the US aviation system on a fair weather day in October 2015. High densities of aircraft (indicated by the white areas) coincide with major airport complexes and very heavily used routes between airports. The triangle between Boston, Chicago, and Washington is particularly congested and, sensitive to convection. For example, the major airports in that triangle had only 27% of the FAA core airport traffic, but experienced half the core airport airborne holding and 2/3 of the core airport departure delays between March and Sept. of 2012 through 2016.

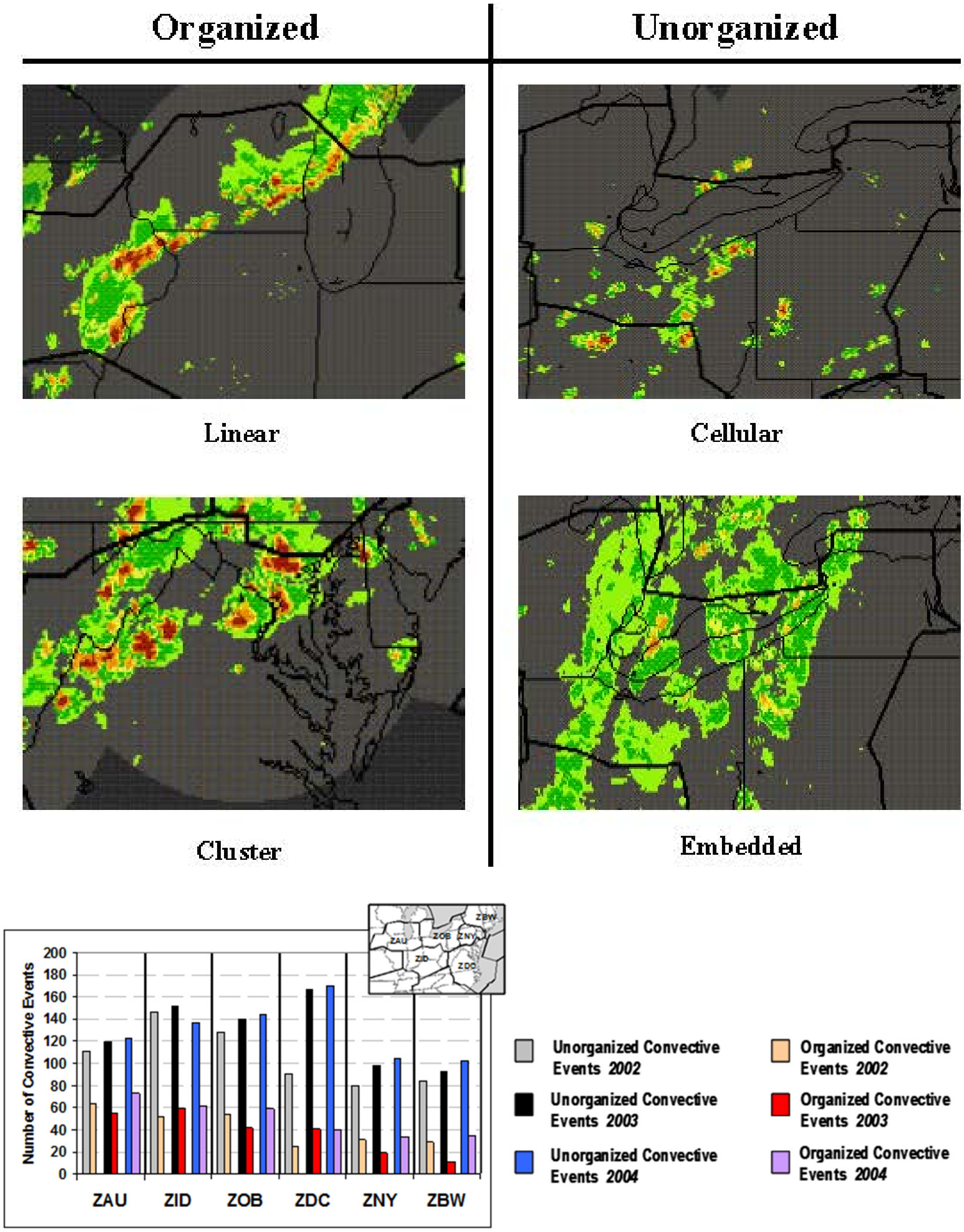

FIGURE 5. Frequency of various types of convective weather patterns observed in the northeast quadrant of the US in 2002-2004 (Robinson, et al., 2004). Yellow or red in the radar reflectivity plots are storm regions that pilots will typically avoid in en route airspace.

2.0 LOW ALTITUDE WIND SHEAR DECISION SUPPORT

When the Lincoln Laboratory work commenced, pulse Doppler fan beam radars had for many years been used to provide precipitation information on ATC displays. Pencil beam Doppler weather radars had been used for scientific weather studies of convective weather since these radars offered a unique ability to remotely measure the three dimensional structure of precipitation and wind velocity within storms. At the same time, the Next Generation Weather Radar (NEXRAD) program was in the process of implementing a pencil beam Doppler weather radar that would make azimuth scans at multiple elevation angles.

The NEXRAD radar might have been used for low altitude wind shear detection. But, the network of NEXRADs generally were not sited to provide the requisite low altitude coverage near major airports. Deploying more NEXRADs would be difficult due to the need to get additional frequency allocations for S band radars.

The FAA determined that a dedicated C-band pencil beam pulse Doppler radar – the Terminal Doppler Weather Radar (TDWR) – sited at locations near major airports that had a high likelihood of microburst activity, would best meet the operational need for reliable, timely microburst warnings.

Accomplishing automated, reliable, timely detection of low-altitude low-reflectivity phenomena such as microburst outflows would necessitate significant advances in a number of areas:

1. Detecting low-reflectivity outflows and measuring their Doppler velocity would have to be accomplished in the presence of significant ground clutter and out-of-trip weather returns[2], and
2. Fully automated reliable pattern recognition of the Doppler/reflectivity features of phenomena such as microbursts had not been demonstrated.

Another major concern was the human-machine interface (e.g., product displays and distribution of displays), procedures, and training that would be needed to achieve the desired operational outcomes given that there was little or no past FAA experience with this type of weather decision support.

Operational data germane to several key elements of a microburst wind shear decision support system including

- Warning strategy (e.g., microburst severity and locations of operational concern that warranted providing warnings to pilots)
- Human-machine interface (an alphanumeric display for warnings to be read out by a tower controller and a color situation display showing locations of microbursts, gust fronts, and operationally significant precipitation),
- Operational procedures by ATC and airlines associated with real time usage, and
- An initial set of relevant operational data (e.g., where is low altitude wind shear phenomena of concern to pilots?)

were available from the Classify, Locate, and Avoid Wind Shear (CLAWS) real-time demonstration conducted by a team from NCAR at Denver's Stapleton Airport in 1984 (McCarthy and Wilson, 1985). During CLAWS, the locations and severity of microbursts were determined by real-time analysis of Doppler reflectivity and Doppler displays by highly experienced radar meteorologists and then radioed to researchers in the control tower. The tower researcher showed ATC controllers where there were microbursts, and ATC provided warnings to the pilots with the estimated horizontal wind change across an outflow and the location relative to the runway. The observed responses of the pilots to these warnings, together with feedback from the tower ATC personnel, were used to define an initial alerting strategy, operational procedures, and human machine interface including the displays shown in Figure 6.

However, an end-to-end operational demonstration including fully-automated detection of low-altitude wind shear and generation of tower displays was necessary for the TDWR to proceed to full scale development.

FIGURE 6. Displays for the TDWR for the 1988 real-time operational demonstration at Denver. The color display on the left is the Geographical Situation Display (GSD) used by the tower and TRACON supervisors. The GSD depicted the location of wind shear and gust front wind-shift events as well as radar derived precipitation products. The alphanumeric display on the right provided runway-oriented text messages for local controllers which were read directly to pilots in real time during the demonstration.

Lincoln Laboratory developed a functional [3] Terminal Doppler Weather Radar (TDWR) testbed to be used for the formal TDWR operational demonstration in Denver, CO in 1988.

That operational demonstration confirmed the soundness of the initial concept for warning strategy, human-machine interface, and operational procedures.

[2] Out-of-trip returns are of much greater concern for weather sensing than is the case for point targets because the signal return from weather drops off as $1/(\text{range})^2$ as opposed to the $1/(\text{range})^4$ dependence for point targets. And, the use of C-band would necessitate a shorter unambiguous Doppler range.

[3] The bulk of the TDWR development was accomplished with a C-band radar with 0.5° beam width in both planes that scanned in azimuth at a number of different elevation angles.

However, it was determined early in the operational demonstration that there needed to be a shear criterion as well as a surface wind change criterion for declaring microburst events so as to not alarm on spatially large low shear surface divergences (Merritt, et al., 1989).

Most importantly, the operational demonstration at Denver provided concurrent major operational safety benefits, as summarized in the box below.

Following the successful Denver real-time operational TDWR testing, the prototype TDWR was used to conduct a real-time operational test at Kansas City, MO in 1989 and then moved to Orlando, FL for operational testing from 1990-91.

At Orlando, it became evident that the criteria that had been successful at Denver for deciding when a microburst alert should be issued for a runway was too conservative for the Orlando environment. A key factor in the pilot real-time evaluation of the wind shear warnings was that the spatial extent of microbursts in Orlando was visually apparent to pilots (e.g., as in Figure 2) whereas in Denver, a significant fraction of the microbursts had few if any visual clues for the pilot. There were also factors associated with the Denver microbursts (e.g., asymmetry in the surface divergent outflows) that warranted a very conservative alerting strategy at Denver.

The practical consequence of these differences in the pilot perception of the risk associated with a storm outflow and the nature of the storm surface outflows in Orlando was that pilots started ignoring the TDWR-generated microburst alerts in Orlando. Adjustments were made to the alerting strategy that resulted in an operationally acceptable microburst decision support system (Evans and Bernella, 1994).

Additionally, a number of wind shear enhancements were tested at Orlando that were incorporated into the Integrated Terminal Weather System (ITWS) system such as improved gust front detection (Delanoy and Troxel, 1993; Troxel et al., 1996) and a microburst prediction capability (Wolfson, et al., 1994).

3.0 IMPROVING EFFICIENCY IN ATC OPERATIONS DURING CONVECTIVE WEATHER

3.1 Terminal Operations

The use of gust front detections and tracking to provide forecasts of surface wind changes at an airport for proactive management of runway configuration changes had been identified as an operational benefits capability in the CLAWS testing at Denver. However, due to the relatively poor automated gust front detection performance in the 1988 Denver tests, there was only limited use of the TDWR prototype in real time for improving the efficiency of operations.

The interaction with the Orlando ATC terminal facilities arising from their real-time operational use of the TDWR testbed products led to a major shift in the focus of the real-time decision support system from principally

Success in Improving Safety at Denver Shortly After the Start of the TDWR First Operational Demonstration

The TDWR testbed Doppler weather radar had a major impact on aviation safety, but never more than so on July 11, 1988, the ninth day of the Stapleton operational demonstration. It was a hot and humid afternoon in Denver, Colorado. At 4:07 pm local time, the TDWR testbed detected microbursts near the approach end of a runway being used for landing. The initial warning was for a microburst with a 40 knot loss on one mile final. The microburst intensity increased to 50 knots and then to 80 knots.

Traffic was heavy; five United Airlines aircraft were on the approach.

A few days earlier, United had issued a bulletin to its pilots that instructed them to not take off or land if a microburst was reported. But out of the five pilots approaching Denver, only one remembered the portion of the bulletin dealing with microburst advisories.

Within the next six minutes, two of the pilots who attempted to land during the microburst lost altitude in a critical phase of flight. Flight 395 (which had received a warning for a 40 knot loss, but continued its approach) dropped to less than 100 ft above ground level, at a distance of more than a mile from the end of the runway.

A second aircraft, Flight 236 (which had received an alert for a 50 knot loss at two mile final), lost almost 3000 feet of altitude, but remained safely above the airport surface. Only Flight 862, flown by the one pilot who responded correctly to the microburst advisory with an avoidance maneuver, was unaffected.

The TDWR was credited with preventing at least one accident on this event.

A film “The Day All Hell Broke Loose” was produced by the FAA and the National Center for Atmospheric Research that includes the audio of the air-to-ground discussions as well as interviews with the Denver tower controller who issued the microbursts alerts and key researchers.

focusing on safety enhancement to also including a major effort to provide decision support for the proactive management of convective storm impacts on flight operations to and from the Orlando international airport.

The ATM decision support needs identified by the operational users at the Orlando tower and TRACON included:

a. Storm movement information and short-term forecasts of the future spatial extent of storms and microbursts,
b. Better precipitation information than that provided by either the TDWR (which generally used a sector scan pattern that resulted in relatively slow updates plus poor coverage of storms in some sections of the TRACON) or, the Airport Surveillance Radar-9 (ASR-9) weather channel [which had operatically significant Anomalous Propagation (AP) ground clutter returns appearing in the precipitation product during convective weather [4]],
c. Information on storm features that would indicate a hazardous storm (e.g., storm tops, lightning, and the possibility of hail) that would warrant keeping aircraft at a greater distance than normal from the storm, and
d. Providing predictions of microburst occurrence (or, at least warnings that a currently weak microburst outflow was likely to intensify in the next few minutes) to assist in planning runway usage

The Orlando terminal facility also stressed that decision support needed to be provided to the Jacksonville Air Route Traffic Control Center (ARTCC) which handled en route traffic to and from the Orlando TRACON (Terminal Radar Approach Control) facility. This would facilitate communication and coordination between the ARTCC and terminal facility when storms impacted the airspace near the ARTCC-terminal interface and/or when storms (including wind shear activity) were reducing the airport capacity enough that it was necessary to hold arrivals in en route airspace.

Short-term forecasts of storm movements and future positions could have been generated from the TDWR precipitation product for the regions in which that radar had operationally useful coverage. However, addressing the other needs would necessitate accessing and utilizing information from a number of other radars (especially the ASR-9 at the airport and the National Weather Service NEXRAD), lightning sensors, numerical weather prediction models, surface observations, and weather data from aircraft.

The Orlando TDWR[5] prototype real time decision support evolved into an Integrated Terminal Weather System (ITWS) functional prototype in 1993 (Evans and Ducot, 1994). Figure 7 shows the Orlando ITWS display generated from real time integrated use of the Orlando ASR-9, the FAA production ITWS, and the NWS NEXRAD during a major hurricane event in 2004.

The rapidly improving computational processing capabilities (discussed in section 6) and major advances in radar imaging processing that grew out of the wind shear detection development[6] were used by a team led by Dr. Marilyn Wolfson of Lincoln Laboratory to make major advances in 0-2 hour convective storm forecasting.

An initial correlation tracker had provided operationally useful 0-20 minute forecasts of the future positions (Chornoboy, et al., 1994) of storm cells. However, coping with cells moving along a propagating squall line that was moving in a direction different from the direction of the storm cell movement (such as occurred frequently in Dallas and Memphis) led to the use of multi-scale storm tracking algorithms together with explicit consideration of storm growth and decay (Wolfson, et al., 1999; Dupree, et al., 2005). Additionally, real time information on the performance of the convective storm forecasts was provided, which has been found to be a reliable indicator of the accuracy of 0-1 hour convective storm forecasts (Evans, et al., 2009).

An important element of the change in focus to include decision support for the proactive management of storm impacts on flight operations was much greater utilization of the qualitative and quantitative feedback loops shown in Figure 1.

The operational impacts of convective weather on the terminal area are very sensitive to the runway configuration, structures of the routes within and outside the terminal area, and the traffic volume in relationship to the runway and airside capacity. To understand the user needs at major terminals other than Orlando, additional Lincoln Laboratory ITWS functional prototypes were deployed to Memphis, TN, Dallas, TX, and the New York region.

All of these prototypes provided experimental ITWS products in real time to the local terminal and en route ATC facilities as well as to major airlines (e.g., Northwest

[4] Since the ASR-9 precipitation product was the only precipitation product on the Orlando TRACON controller displays, the presence of Autopilot System (AP) ground clutter on the display during convective weather was an operational concern for ATC.

[5] The ITWS functional prototype at Orlando used the production TDWR as part of its sensor suite when the Lincoln Laboratory testbed TDWR was replaced by a production TDWR.

[6] Examples of advanced image processing techniques for low altitude wind shear detection and forecasting include (Delanoy and Troxel, 1993; Wolfson, et al., 1994).

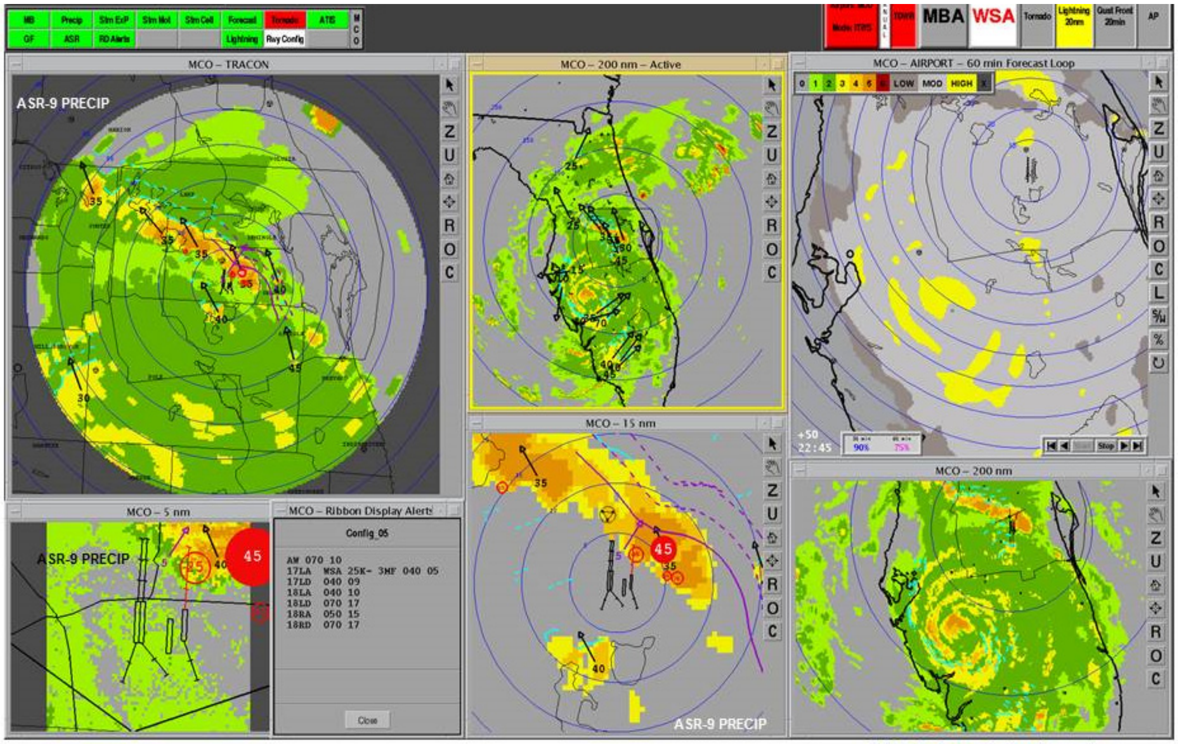

FIGURE 7. Orlando ITWS situation display during Hurricane Charlie in 2004. The upper left hand window and middle bottom window show the motion and extrapolated positions (dashed blue lines) of a squall line north of the hurricane eye. The solid red circular shapes are locations of strong microbursts; the red circle outlines are less intense microbursts. The numbers inside the microbursts are the surface wind change across the microburst (i.e., microburst intensity). The purple line in the center lower display is the current location of a gust front. The 10- and 20-minute forecasts of the gust front location are shown as purple dashed lines. The user has chosen to only show the most intense precipitation regions in the bottom middle display. The upper center window shows the NEXRAD long range precipitation with cell motions indicated by arrows. The lower right-hand window is the NEXRAD precipitation zoomed in to highlight the rain bands around the center of the hurricane. The upper right-hand window is the 1-hour forecast of heavy precipitation locations. The text box in the lower left-hand portion shows the situation display text. A wind shear alert is in effect for approaches to runway 17 Left.

and Fed Ex at Memphis). The principal results of the real-time usage and operational feedback are summarized in Table 2.

Clearly, Orlando and New York were the most important locations for determining operational needs and identifying approaches to achieve quantifiable operational benefits associated with terminal area operations. The insights gained at Orlando have been successfully utilized at nearly all of the major terminal complexes in the US except for New York and the west coast airports.

New York brought a very different set of issues and needs (Allan and Gaddy, 2001) that have been major drivers for decision support system development for the past 18 years:

1. The very high levels of congestion even in fair weather mean that convective weather can cause extensive air- and ground-side queues to develop. The magnitude of the flight delays that occur is very sensitive to the magnitude and duration of the loss in capacity due to convective weather. In particular, it is very important that operations recommence promptly as soon as capacity impacts end.
2. The structure of the NY airspace departures (Figure 8) is such that coordination and collaboration between many decision makers (Figure 9) is necessary. Maintaining the spatial structure of major traffic flows is essential in New York, whereas Orlando, Memphis and Dallas had considerable flexibility in both terminal and en route airspace to dynamically reroute traffic when storms blocked a normal route.

These major differences led to explicit weather/air traffic management tools that generate quantitative forecasts of capacity impacts on the system (as opposed to each decision maker relying on their past experience), development of longer lead time forecasts (to compensate for the time that must be allocated to communication and coordination) and enhanced training.

TABLE 2. Summary of key findings from ITWS functional prototype real-time operational testing. Years shown are the years during which the system design process shown in Figure 1 had its greatest impacts on the decision support system development.

	Terminal Area			
	Orlando	**Memphis**	**Dallas**	**New York**
Years	**1992-2000**	**1995-2002**	**1995-2003**	**1998-2006**
Type of convective weather	Unorganized	Mixture	Organized	Mixture
Other weather				Coastal Storms
Congestion in fair weather: Terminal	No	Once per day	Moderate	High to very high
En route	No	Once per day	Moderate	Very high in certain directions
Technical challenge initial identification	Microburst over warning		Squall line multiscale storm motions	NEXRAD coverage
	Anomalous propagation due to storm outflows		Detection of gust fronts from squall lines	Wind estimation
Initial identification of operational needs/insights	Storm tracking and forecasts	En route pilot storm avoidance	Terminal pilot storm avoidance	Explicit models for pilot storm avoidance
	Terminal/en route common situational awareness	Airline ops center (AOC) usage		Explicit ATM-weather integration (RAPT)
	Storm severity indication			Sheared winds aloft
	Microburst forecast			Echo tops forecast
	Pilot info via data link			Final approach winds
Decisions yielding greatest operational benefits	Management of convective impacts on arrival routes and airport runways			Management of convective impacts on departure routes
				High surface winds planning
				Vertical wind shear planning

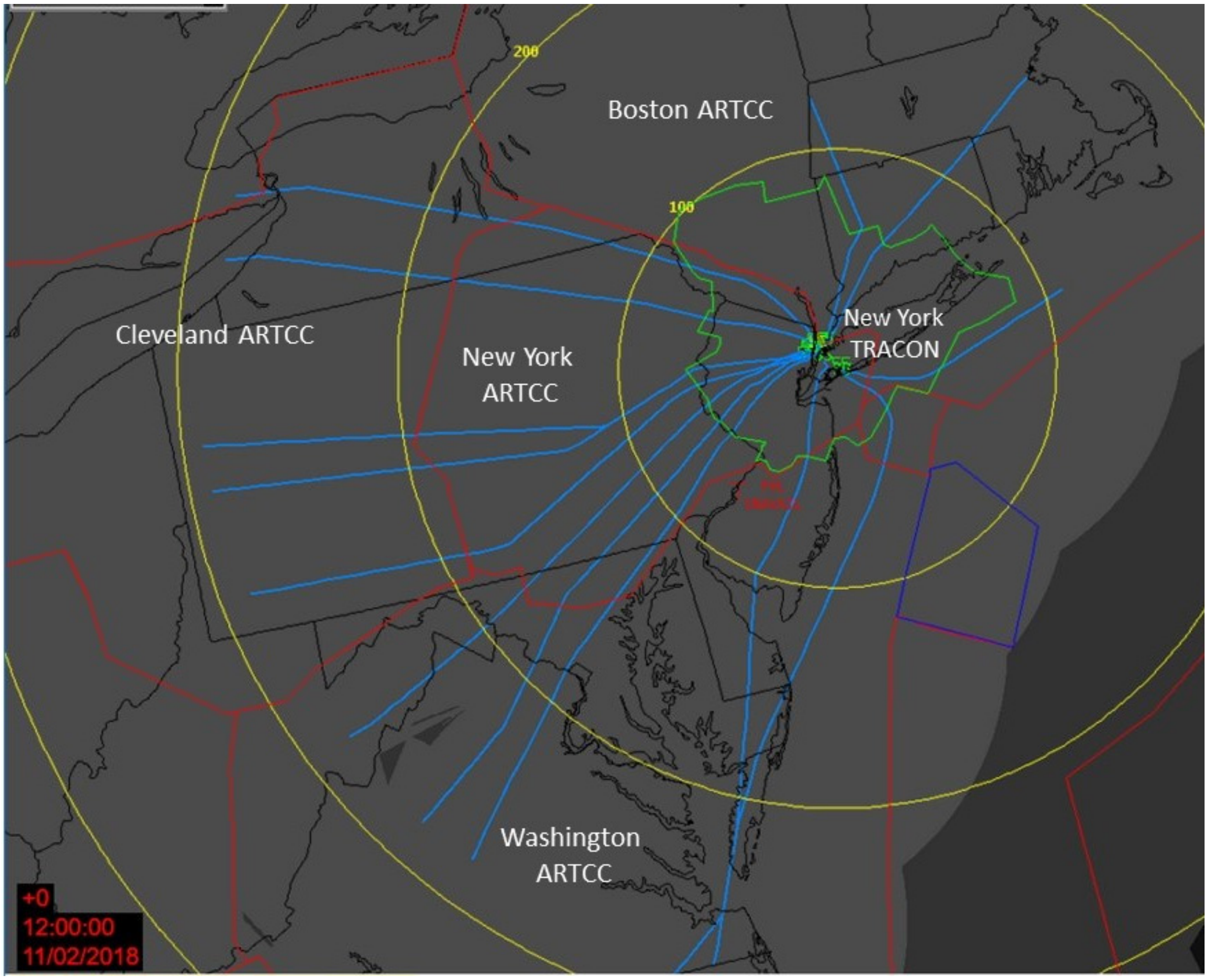

FIGURE 8. Departure routes from major New York City airports (JFK, LGA, EWR, TEB) (in blue) with ATC control center boundaries (in red and green) and 100 nmi range rings (in yellow). The New York TRACON (N90) is the green outline. Major arrival routes into N90 lie in the gaps between the groups of departure routes as well as between some arrival routes. The number of departures from New York airports in the southwest quadrant is over a factor of two greater than the maximum departures in a quadrant at any of the other major US airports (e.g., ATL, DFW, ORD). Deviations by an aircraft on these departure routes to avoid a convective cell in the airspace shown in this figure generally lead to conflicts with other aircraft. Hence, departures on a route are generally halted as soon as a plane deviates off that route on the blue route segments.

The displayed departure routes end when the local traffic density is sufficiently low that the plane can deviate around small storms without conflicting with other traffic. Note that the ends of many of the departure routes to the west and south are nearly 300 nmi from the airports. By contrast, most other major airports experiencing convective weather (e.g., Dallas, Atlanta, Orlando and Chicago) have airspace available for departure deviations within 50-75 nmi from the airport.

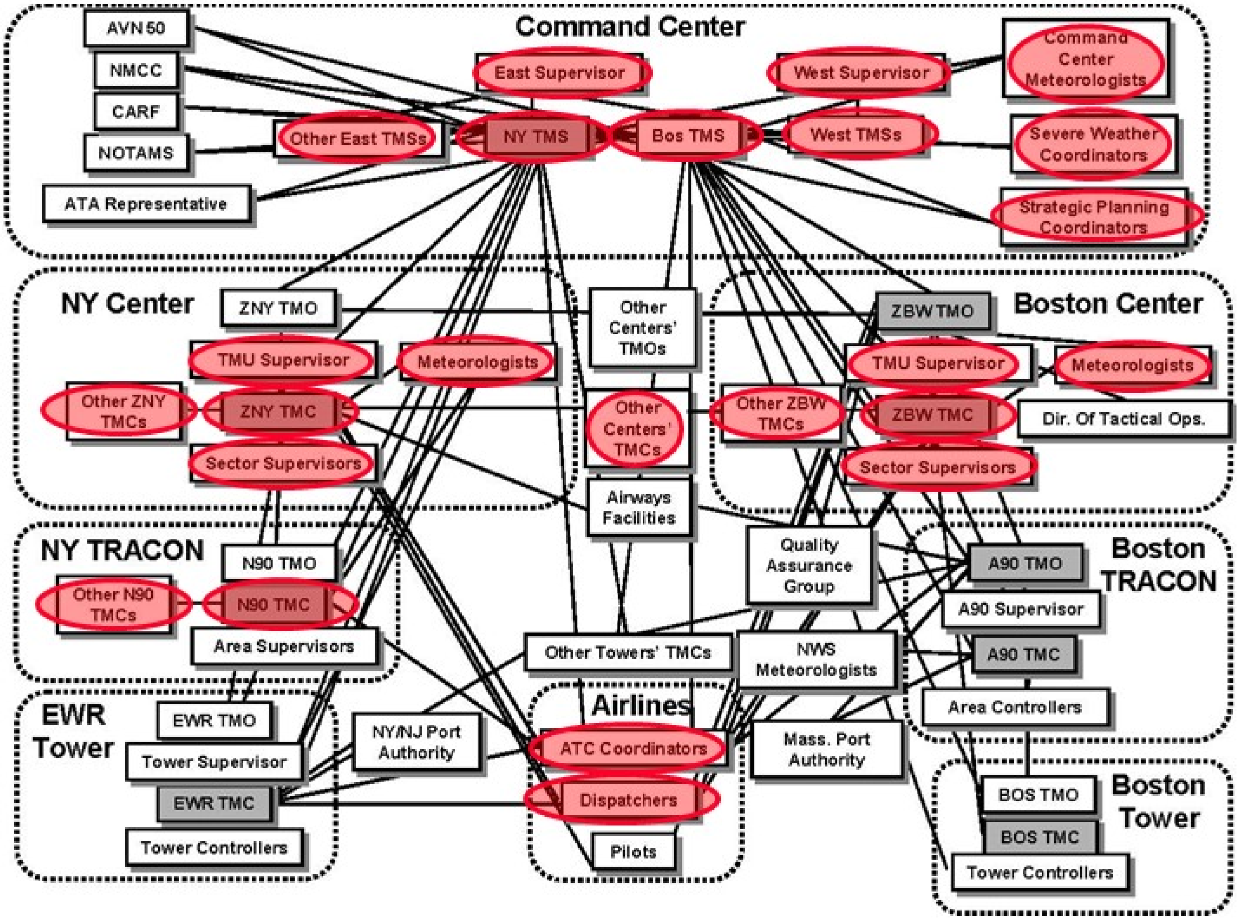

FIGURE 9. Interactions between various ATC facilities when managing convective weather impacts in or near the NY TRACON (from Davison and Hansman, 2001). NY Center is the NY ARTCC (ZNY), Boston Center is the Boston ARTCC (ZBW). Not shown are the Cleveland and Washington ARTCCs (ZOB and ZDC). The red highlights show key participants in resolution of convective impacts on NY arrivals and departures. Achieving consensus between so many decision makers places a premium on real-time common situational awareness between the various decision makers.

3.2 Explicit Weather-ATM Integration to Improve Departure Operations at New York Airports in Convective Weather

The Route Availability Planning Tool (RAPT) is an example of explicit weather-air traffic management integration to facilitate departures when convective weather is impacting departure routes. Getting agreement between two ARTCCs and the NY TRACON as to when a departure can take off and not encounter a storm when the storms are moving can require such extensive communication and coordination that opportunities for departures are often missed. Figure 10 shows the RAPT user display

RAPT carries out explicit computations of the space-time intersection between departures on various routes and convective storms using the Corridor Integrated Weather System (CIWS) forecast precipitation and storm echo tops fields (DeLaura, Robinson and Underhill, 2009). The RAPT determination of route blockage uses the results of years of studies of pilot decision making on continuing on a route that passes near or through storms versus deviating to avoid the storm encounter, as a function of the plane altitude and the storm precipitation and storm echo tops fields at the time of storm encounter (DeLaura, et al., 2008; Matthews and DeLaura, 2010). A key factor in the RAPT development was that the precipitation and storm echo tops forecast images were essentially identical to the real-time measured storm reflectivity and storm echo tops images used in the pilot storm avoidance studies so that it was straightforward to provide forecasts of regions a pilot was likely to avoid.

3.3 Improved Decision Support for En Route ATM in Convective Weather

3.3.1 Tactical ATM (0-2 hour) decision support in regions covered by NEXRAD

Providing operationally effective decision support for New York arrival and departure operations during convective weather resulted in an ever-increasing

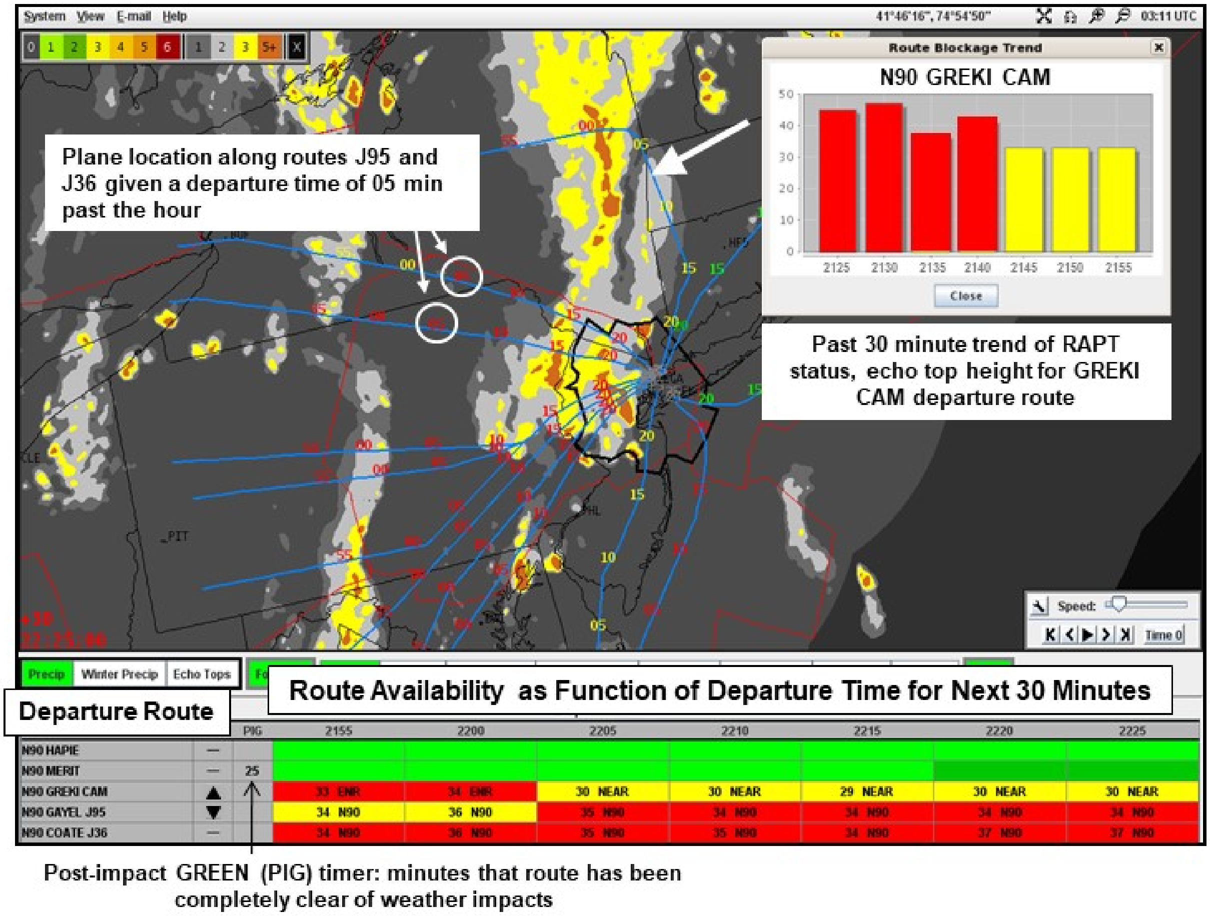

FIGURE 10. The Route Availability Planning Tool (RAPT) user real time interface consists of RAPT timelines and a weather animation window. Each row of the timeline display corresponds to a departure route. Each column corresponds to a future departure time, starting at the current time and extending out to 30 minutes into the future in five-minute intervals. The color of each timeline bin represents the departure status. Yellow and red bins have text with annotations giving the trajectory phase and the echo top height at the location where the route will be blocked for the given departure time. The animation window overlays show the predicted locations of departing aircraft on forecasts of precipitation or storm echo tops. Additional information on the blockage associated with a specific route can be obtained by clicking on the route as is illustrated for the GREKI-CAM departure route to the north.

number of NEXRAD radars being used in the NY ITWS mosaic. Finally, it was realized that a separate integrated weather decision support system was needed for en route airspace. This led to development of the CIWS prototype (Evans and Ducot, 2006) shown in Figure 11.

Over a seven year period, the CIWS coverage grew until it covered nearly all of the lower 48 states in the US as well as southern Canada. Note that both the forecast lead times and the ability to provide height information on storms increased significantly as our understanding of en route decision support needs evolved.

At this point in time, the CIWS functional prototype is providing the real-time radar precipitation and echo tops mosaics for the lower 48 states on the FAA Traffic Flow Management System (TFMS) displays.

3.3.2 Strategic en route ATM (2-8 hour) convective weather decision support

The management of arrivals into the highly congested northeast airspace (Figure 4) during convective weather needed longer lead time forecasts than were provided by CIWS since aircraft from the major western airports (e.g., LAX, SFO, SEA, SLC, and DEN) were a major contributor to the arrivals at northeast airports. For example, one needed to determine whether

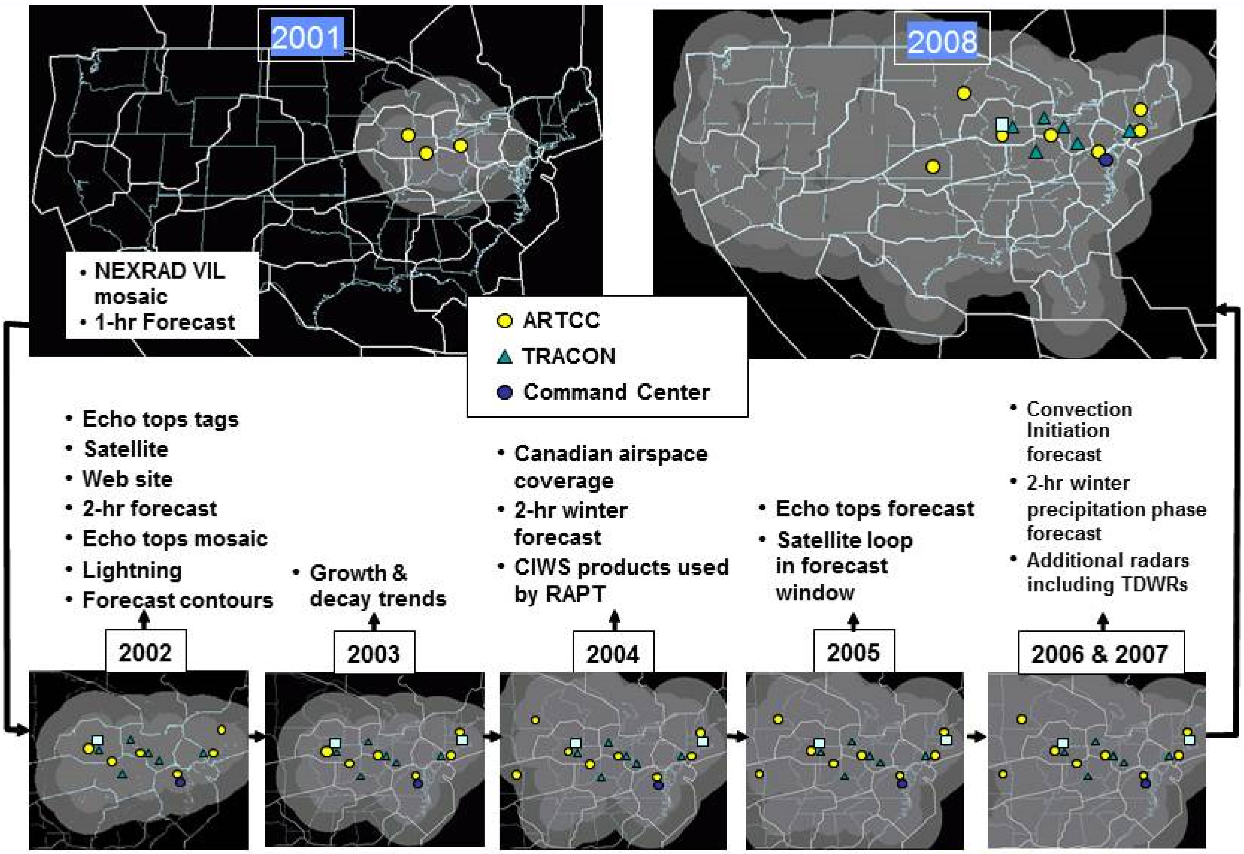

FIGURE 11. Evolution of the CIWS prototype demonstration system capabilities for tactical ATM decision support. Note the significant increase in ATC facilities using the CIWS products that occurred in 2002.

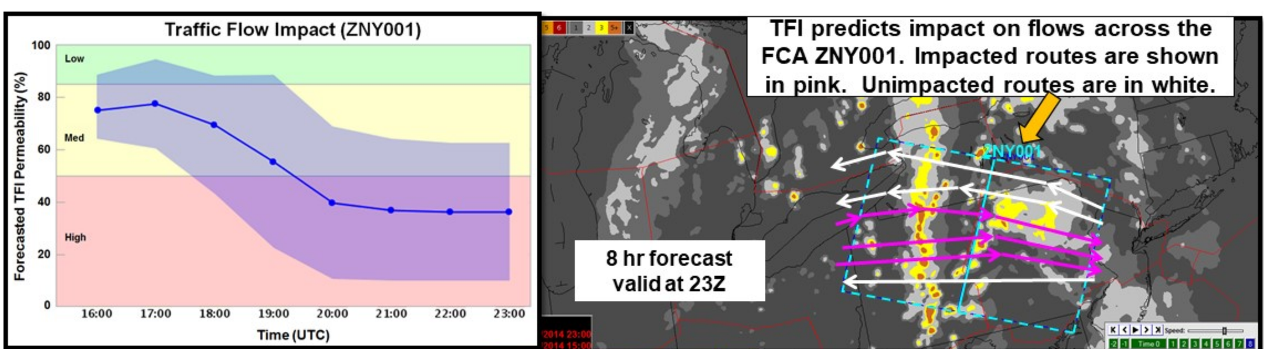

FIGURE 12. An example of a new decision support capability recently receiving feedback from users: statistical forecasts of the flow through a Flow Constrained Area (FCA). The left-hand side shows forecasts of the factional traffic flow (i.e., “permeability”) as a function of time. The solid blue line is the median estimate. The shaded area shows the 20% and 80% bounds on the forecast throughput. The right-hand side shows the region associated with the FCA as well as principal east- and west-bound flows overlaid on the CoSPA 8 hour precipitation forecast. The route blockage computation considers plane altitude and storm echo tops as well as the precipitation forecast (Matthews, et al., 2015).

a major reroute[7] might be needed or whether the plane needed to be held at the origin. The forecast lead time required to support this decision is on the order of the flight time plus an hour.

The National Oceanic and Atmospheric Administration (NOAA) development of the High-Resolution Rapid Refresh (HRRR) numerical model with real-time 3-km resolution updated every 15 minutes, together with algorithms to blend the numerical model output with the CIWS forecasts and real time precipitation products, appeared to be a viable approach to generating RAPT like route availability displays for much longer lead times.

This led to the use of the CIWS real time prototype to generate Consolidated Storm Prediction for Aviation (CoSPA) 2-8 hour forecasts (Wolfson et al., 2008; Dupree et al., 2009; Pinto, et al., 2010). However, the uncertainty in the timing and duration of convective storm impacts on individual routes 2 hours or greater in the future was found to be too great to be directly usable for decision making.

The operational strategic planning decision support technology in 2008, of forecasts of regions of convective weather coverage,[8] could not be readily translated into forecasts of airspace capacity since the forecast weather representation was so different from the actual weather spatial patterns.

As a solution, work was begun on developing statistical forecasts of the available capacity hours in advance. Fortunately, the FAA and airlines had determined that it would suffice to forecast the throughput for families of roughly contiguous routes (e.g., 5-10). These groups of routes were called Flow Constrained Areas (FCAs) (Doble, et al., 2006). Research (Matthews, et al., 2015) has showed that:

1. Given time series of actual storm reflectivity and echo tops spatial fields, one can reliably forecast the observed traffic flows through an FCA, and
2. Reliable statistical forecasts of traffic through an FCA could be made through supervised machine learning algorithms operating on the CIWS, HRRR, the Localized Aviation MOS Program (LAMP), and the Storm Prediction Center's Short Range Ensemble Forecast (SREF) Calibrated Thunderstorm Probability Field.

An example of a statistical flow through an FCA is shown in Figure 12. These objective, quantitative statistical forecasts of permeability[9] for an FCA [called the Traffic Flow Impact (TFI)] commenced real time experimental use in 2015 and operational assessments are underway (Venuti and Klingle-Wilson, 2017).

3.3.3 Offshore convective weather decision support

Flights across the Gulf of Mexico (e.g., Texas to Miami) and south of Florida into the Caribbean frequently encounter convective weather. However, the NEXRAD weather radar coverage does not include much of the offshore airspace, as shown in Figure 13.

The Offshore Precipitation Capability (OPC) provides radar-like depictions of precipitation intensity and storm height in offshore regions where weather radar coverage is incomplete or unavailable by use of non-radar data sources[10]:

- Lightning detections,
- Geostationary satellite visible and infrared imagery, and
- Outputs from numerical weather prediction models.

Results from the OPC data fusion are blended with outputs from existing radar-based systems to create seamless mosaics of weather systems that extend into offshore and oceanic regions as shown in Figure 14.

The prototype OPC commenced providing real-time products in 2017 and has been found to be useful operationally by the Miami, Houston, and New York ARTCCs, the San Juan Combined Center Radar Approach Control (CERAP), and the FAA's ATC System Command Center. OPC was particularly helpful in managing flight operations into San Juan following Hurricane Maria in Sept. 2017 after the Puerto Rico NEXRAD was destroyed during the hurricane.

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[7] For example, when organized convective weather blocks routes in Pennsylvania and upstate New York as shown in Figure 4, flights from Los Angeles (LAX) may be routed to New York via Atlanta. This is a much longer flight than the normal routing and necessitates extra fuel onboard.

[8] Since 2000, NOAA, the FAA and the airlines have produced 4, 6, and 8 hour forecasts every 2 hours for regions where the coverage by heavy precipitation and storm echo tops will exceed a certain coverage threshold (e.g., 25%).

[9] Permeability is discussed extensively in (Matthews, et al., 2006). A figure in that paper shows that permeability is closely related to flow rates through an FCA when the convective weather impacts are principally within the spatial region for the FCA model.

[10] The supervised machine learning methodology used in OPC applies advanced analytics and machine learning to fuse multiple heterogeneous datasets (Veillette, et al., 2016). The technology was developed and validated by use of data sets from regions where NEXRAD weather radar coverage is available. OPC applies a motion-tracking algorithm to estimate storm motion so that the features obtained from satellite imagery and numerical models can be spatially shifted to keep the mosaics up to date.

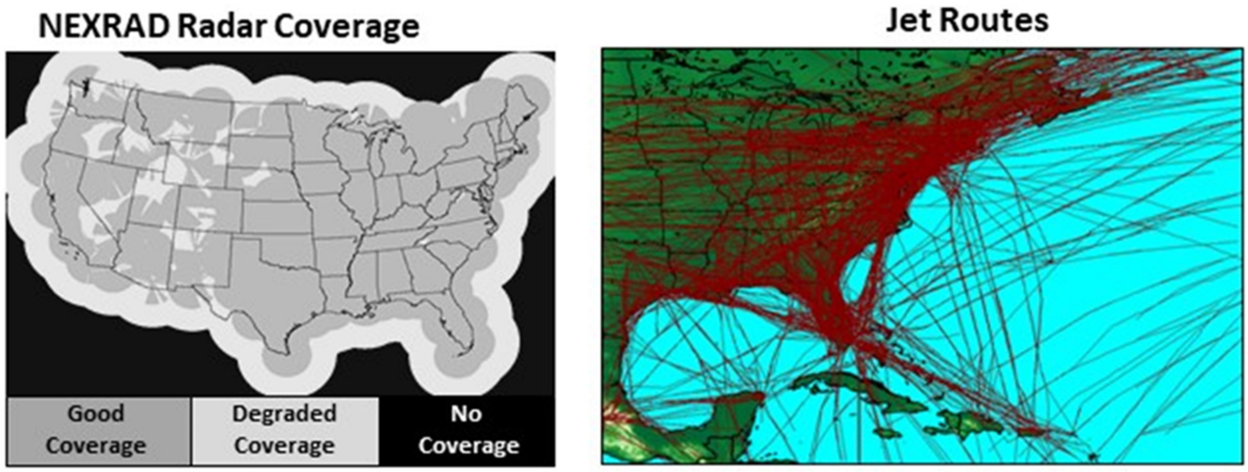


FIGURE 13. Comparison of NEXRAD coverage with major offshore routes for commercial aircraft in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea.

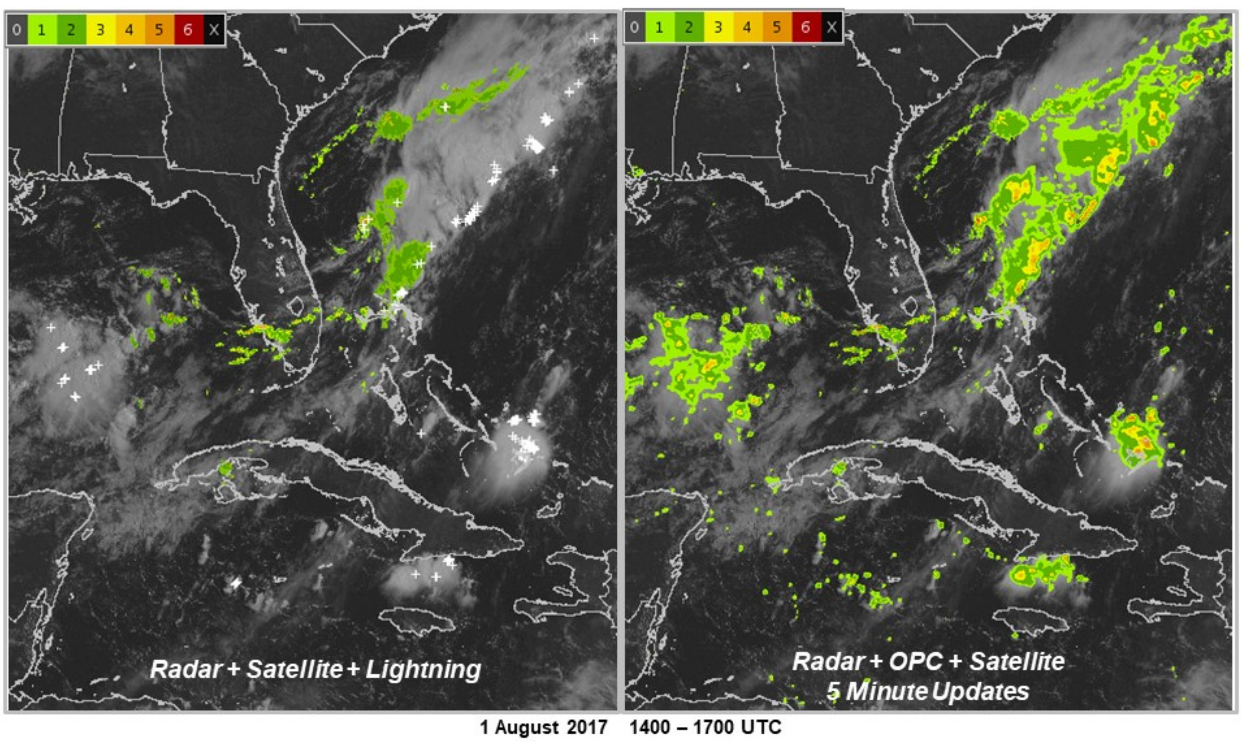


FIGURE 14. Comparison of the weather depiction for offshore aviation operations decision making provided by weather radar mosaics, satellite, and lighting (left hand picture) to the decision support provided by OPC together with radar and satellite data (right hand picture). Note the OPC depiction of intense weather in the top right of the right-hand figure corresponding to the regions of high density lightning strike activity in the same region on the left-hand figure.

4.0 TRAINING

Training has been an exceptionally important element of the prototype usage in facilitating the use of various decision support products so that operational benefits are achieved and in getting feedback via the qualitative feedback loop shown in Figure 1. We have found training and operational benefits assessment are most effective when tightly coupled. Hence, some of our training insights gained through operational benefits analysis of the prototype product usage are discussed in the following section.

Clearly, it is essential that the operational decision makers have a thorough understanding of the new product strengths and weaknesses, as well as the areas of uncertainty associated with the new information (e.g., how to assess the likely accuracy of a forecast that has just been issued).

This type of training generally has been achieved by standard training techniques. For the low altitude wind shear decision support, this level of training for ATC personnel was generally satisfactory given the operational concept for providing warnings: no judgment to be exercised by ATC---just read out the warnings displayed on a ribbon display.[11]

However, the training to achieve operational benefits to improve efficiency in ATM during convective weather is much more challenging due to the nature of the decision making and the desire to achieve measurable operational benefits.

Key elements of real-time tactical ATM decision making in convective weather include the following:

- Time pressure to make decisions quickly,
- High stakes for the outcomes of decisions,
- Personal responsibility for the decisions,
- Inadequate information on the future impacts of the convective weather and reactions of pilots,
- Ill-defined goals when there are conflicts between the needs and objectives of different ATC facilities and the airlines, and
- Poorly defined procedures in many cases for coping with the many different types of convective weather that were shown in Figure 5.

Additionally, the coordination and communication process shown in Figure 9 requires significant amounts of time during the decision making process.

(Klein, 1998) characterizes decision making with the above factors present as a "difficult" problem. He postulates that decision-making processes used by experienced decision makers in such situations follow a "Recognition-Primed Decision (RPD)" model. In RPD, the decision-maker makes an intuitive assignment of the current situation to an analogous past problem and then evaluates various possible actions taken in the past according to a mental simulation of possible outcomes for the current situation.

Under the RPD model, ATC decision makers may tend to solve convective weather impact problems by attempting to relate the current situation to prior convective weather impacts considering only the decision support information that has been used in the past, as opposed to also using the new decision support information in addition to the past information.

We have sought to address this problem of getting decision maker acceptance of new decision support capabilities through training geared toward:

1. Developing a "mental library" of past situations and actions with the new information (e.g., products and/or tools) so they can include the new information when they work out solutions to problems,
2. Helping operational users determine that the tool is in fact useful for their decision making, and
3. Providing an opportunity for the users to provide input/prioritization on decision support enhancements.

More information on this new approach to getting acceptance of new products is available in (Robinson and Evans, 2010).

In the early years of providing real-time products to ATC facilities, Lincoln Laboratory prototype operations were typically located physically close to the key ATC facilities. This made it possible for Lincoln Laboratory operations personnel to be present during convective events on a frequent basis and discuss in real time how various products might be used to address the current situation as well as to get suggestions for enhancements. In most cases, these interactions progressed over a multiple year period such that the Lincoln Laboratory operations personnel acquired a very good understanding of the key ATC decisions that needed to be made during different types of convective weather.

However, when the number of facilities involved in real-time ATM decision support grew as shown in the CIWS evolution (Figure 11), a much more organized process of training needed to be developed. This had two elements:

1. Site-specific scenario-based training (if possible) at facilities at the beginning of each convective season to review the products used in the previous year and discuss how new products might be used. This would typically involve 2-3 days per ATC facility, and
2. Periodically (e.g., 2-3 time per year) conducting an intensive real time operations observation program at a number of facilities [e.g., such as described in (Robinson, et al., 2004)] to gather operational data related to product usage and the operational benefits of the various decision support products. This offers an opportunity to discuss informally how one might use various products to make decisions on the convective weather ATM problems at that point in time and to note problems in product usage).

In the next section, we show some examples of how operational data analysis (per Figure 1) was used to develop changes to decision support products, product

[11] The major challenge in low altitude wind shear decision support training was training for the pilots in what actions to take when they got a wind shear warning. This has been accomplished by the airlines as a part of their pilot training programs.

dissemination, and training that resulted in significant increases in operational benefits.

5.0 QUANTITATIVE OPERATIONAL BENEFITS ASSESSMENT AND ITS USE TO IMPROVE DECISION SUPPORT SYSTEM DESIGN

Measurement of operational benefits and use of those results to improve the aviation convective weather decision support system became much more important in the late 1990s and reached its most intensive phase in the period 1999-2008. The initial studies were typically accomplished by end-of-season interviews with ATC (or, airline) decision makers who had used the products in real time and estimated the number of times per day that they would make certain beneficial decisions, the number of aircraft impacted, and the likely benefit per impacted flight.

The CIWS operational benefits studies conducted in 2003 broke new ground in terms of the methodology employed to assess convective weather delay reduction benefits (Robinson, et al., 2004). The 2003 data collection design used knowledgeable observers at a number of FAA facilities during convective weather events for real-time identification of operational CIWS uses. The data gathered during convective weather events included:

- Observations of traffic managers utilizing CIWS displays,
- User statements of ATC decisions made using CIWS products, and
- Expert feedback on what alternative decisions would have been made in that specific situation had CIWS not been available.

The metrics used included reduction in airborne and ground delay, reduced workload for ATC decision makers (as assessed by time to make decisions), and the number of beneficial decisions of various types made per day of convective activity in various facilities.

Another major advance occurred in the RAPT benefits assessment where the objective was to assess the timely reopening of departure routes that had been closed due to convective weather impacts (Underhill, et al., 2010). Two metrics were of particular concern:

- Time to first departure when the weather impact ended on a blocked departure route, and
- The departure rate on a route when the weather impact ended on a blocked departure route.

These metrics were automatically derived from two datasets:

1. Flight tracks from the Enhanced Traffic Management System (ETMS) to monitor the flight traffic, and
2. The RAPT route status timeline data shown in Figure 10.

We will show an example of the use of these metrics to make changes to the decision support system (especially training) in the next section. However, first we need to provide some perspective on the relationship of decisions made to desired operational outcomes such as reduced delays and carbon emissions.

The delay reduction benefits[12] generally could be characterized as some combination of two key delay reduction mechanisms (Robinson, et al., 2004; Evans, et. al., 2005):

1. Keeping air routes (and airports) open longer and reopening closed routes (or airports) sooner after closure by convective weather, and
2. Proactive, efficient reroutes of traffic around storm cells or to alternate routes if the normal route has become blocked.

The first mechanism can generally be computed using standard auto traffic deterministic queueing theory (e.g., Newell, 1982).

In the simplest case where effective capacity is reduced for a time T from Cv to Cw, the sum of delays to the aircraft that are in the queue can be shown to be given by

$$\Sigma = 0.5\, T^2\, (D - Cw)\, (Cv - Cw)/(Cv - D) \qquad (1)$$

where Σ = sum of delays to the various aircraft, D = demand per unit time, Cw = capacity during adverse weather[13], Cv = capacity during the (hopefully benign) weather following the end of the capacity impact, and T = effective capacity loss duration.

Note that the time of capacity impact is squared --- this highlights the importance of keeping T as short as possible when T is large. Note also that the delays are very sensitive to the fair weather excess capacity (Cv – D). Hence, airports which are operating very close to their maximum capacity in fair weather experience very large delays when there is even a short loss of capacity.

The New York airport departures when there is a Severe Weather Avoidance Plan (SWAP) in effect are a classical example of a queue delay dominated delay situation: when a departure route to the southwest (see Figure 8) is blocked by convective weather, the alternative routes are generally completely filled. In such a situation, Cw = 0, so the emphasis has to be on keeping T as short as possible and having a high rate of departures (i.e., Cv) when the route reopens.

The fraction of time that queueing is the major factor depends very much on the nature of the convective weather (per Figure 5) and the traffic density. For example, Orlando has a very high frequency of

[12] The discussion below will focus on delay time savings. The FAA has standard formulas for converting time savings for flights in the air and on the ground into monetary values for airline and passenger cost reductions as well as into reductions in carbon emissions.

[13] If the airport or route is totally closed, Cw = 0.

convective weather. But, much of that is unorganized convection, there are a number of runways that can be used whose separations are comparable to storm diameters, and there is available airspace within the TRACON and en route airspace to reroute aircraft around storms and to runways that are not impacted by storms.

For such airports, queue delays are relatively uncommon. But, efficient rerouting is very important due the large number of situations in which rerouting is needed during the course of a convective season. The delay reduction associated with efficient rerouting of aircraft for some length of time T to achieve a shorter distance flown that would have been the case with reactive rerouting is given by:

$$\text{Delay reduction} = D\ T\ S \quad (2)$$

where D is the number of planes per unit time that need to be rerouted, T is the length of time that a reroute action is needed and S is the time savings per reroute.

Efficient rerouting is by far the most frequently achieved improvement in efficiency though the benefits for a single incident are generally far lower than those for queue reduction (see, e.g., Robinson, et al., 2004). Hence, a key metric in assessing the decision support system effectiveness in rerouting is the number of times per convective weather day that efficient reroutes are accomplished.

We now will illustrate how the operational benefits considerations above were used to determine changes to the decision support system to increase the operational benefits

5.1 Use of Operational Benefits Metrics to Improve Departures from the New York Airports during Convective Weather Benefits

The first of these analyses involved queue reduction for departures from New York when convective weather was impacting the departure routes. Analysis of the time to first departure after a route's status changed from "red" (blocked) to "green" (not blocked) for at least 3 hours showed that on many occasions, there were very lengthy delays in getting a first departure out when the route status changed. All too often, this was accomplished by use of a "pathfinder[14]" which increased the effective capacity impact duration T in equation (1) by 30 minutes to an hour.

Analysis (DeLaura, Robinson, Underhill, 2009; Underhill, DeLaura and Robinson, 2010) showed that the delay reduction provided by RAPT would increase 6 fold if nearly all routes reopened within 15 minutes after a route transitioned from being blocked to being usable.

This analysis led to a focused effort to encourage more rapid use of blocked routes after the blockage had ended. Three changes were made:

1. The thresholds used for determining when a departure route status was red, green, or yellow in Figure 10 were changed to have the likelihood of major error in route status (e.g., red forecast when green was true and vice versa) very low,
2. The user display was changed to add a "post impact green" (PIG) timer that showed how long it had been since a route that had been red had transitioned to a green status, and
3. Training stressed that "green means go" as opposed to discussing how departures might be accomplished when the route status was yellow.

Figure 15 shows the results of the decision support system design changes plus training. Lengthy delays in commencing the use of a route at all were significantly reduced and the number of departures in the first hour as increased over 50%. In retrospect, one might have anticipated this result from inspection of Figure 8 where we see that communication and coordination for the most commonly used departure routes would generally involve at least 5 key participants in three facilities [Traffic Management Unit (TMU) in the New York TRACON, a TMU and an area supervisor in ZNY, and a TMU and an area supervisor in ZOB or ZDC]. When one needs to get agreement amongst that many people in different physical locations in a time critical situation, it is very important that human-computer interface interpretation be as simple as possible and closely integrated with the training.

It is important that training be focused on key decision makers for changing the metrics. In 2008, the timeliness of reopening routes after the route status went from red to green for several hours was examined (DeLaura, et al., 2009).

In particular, a Post-Impact Green (PIG) event was defined as one for which the entire RAPT timeline for a specific route (all 6 bins in the 30 min forecast period) was green for greater than or equal to three hours. In Figure 16 we show the principal departure fixes for departures from the NY airports and, the fraction of PIG events for which a first departure was greater or less than 15 minutes after the route status transitioned to green. First departures occurring greater than 15 minutes after the route status went green were termed "missed opportunities" and are colored in black.

We see that the missed opportunities were <u>not</u> equally distributed amongst the various departure fixes. Rather, certain fixes accounted for the bulk of missed opportunities. Quantitative data such as this is very important in carrying out the decision support system.

[14] When ATC is unsure of the usability of a route, they may seek to find a flight that will act as a "pathfinder". This single flight departs on the route and reports back if the route is usable. However, when the departure distance to be probed is on the order of 300 miles (see Figure 8), the use of a pathfinder typically results in only a single departure in the first hour.

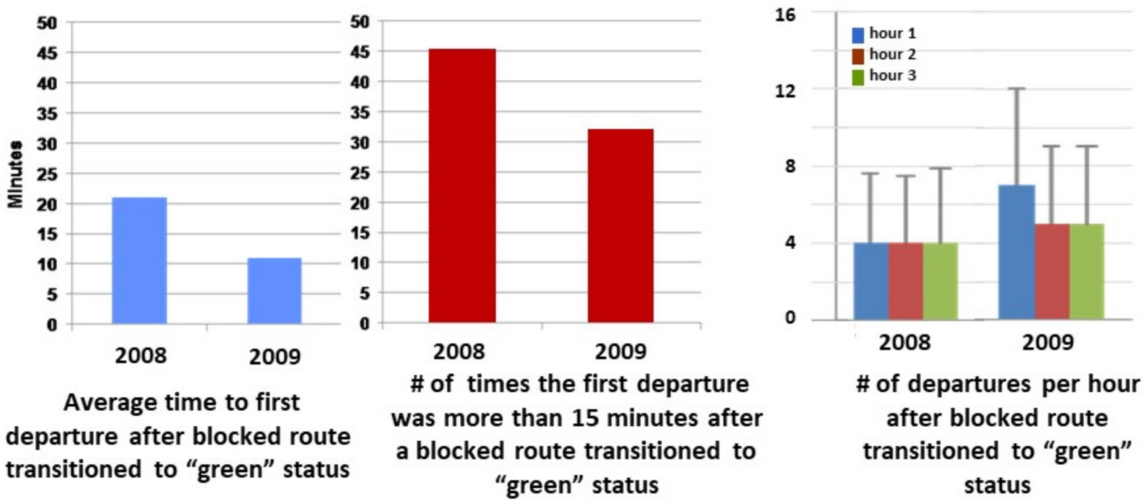


FIGURE 15. Comparison of some key statistics for departures from NY airports following convective storms on departure routes as a result of decision support system focus changes and coordinated training. The right-hand plot is a summary of departures per hour. The boxes show the mean departures in an hour with the top bar representing the standard deviation.

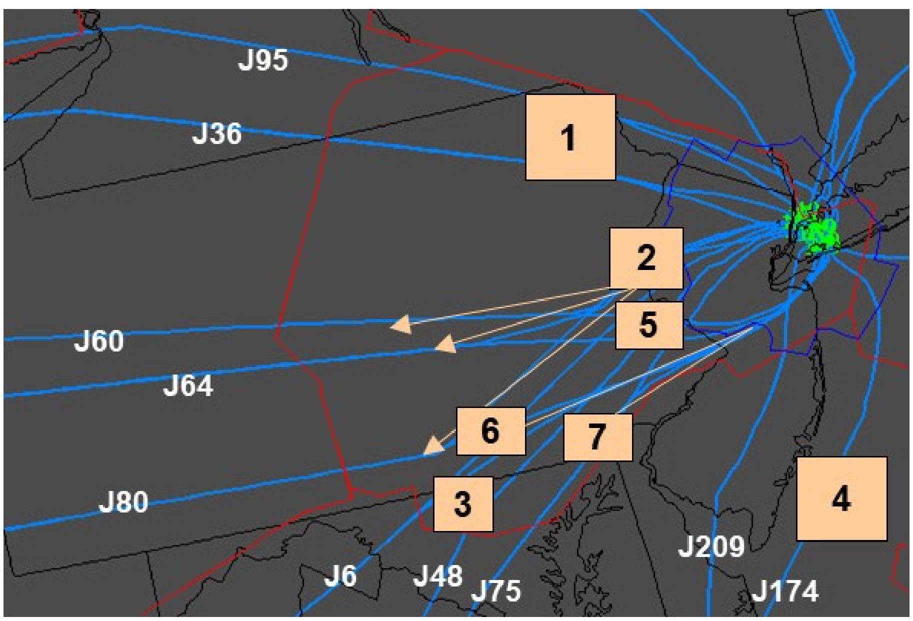


FIGURE 16a. Principal departure routes and fixes for RAPT route reopening "missed opportunities" study. The Robinsville fix (RBV, Fix 5) handles departures from JFK to J80, J6, J48, and J75. These JFK flights overfly departures from EWR and LGA to J80, J6, J48, and J75. Fix 4 (WAVEY) feeds J174. The fix allocation of flights from an airport to the desired route depends on the airport runway configuration. The allocation shown above is a common one in convective weather.

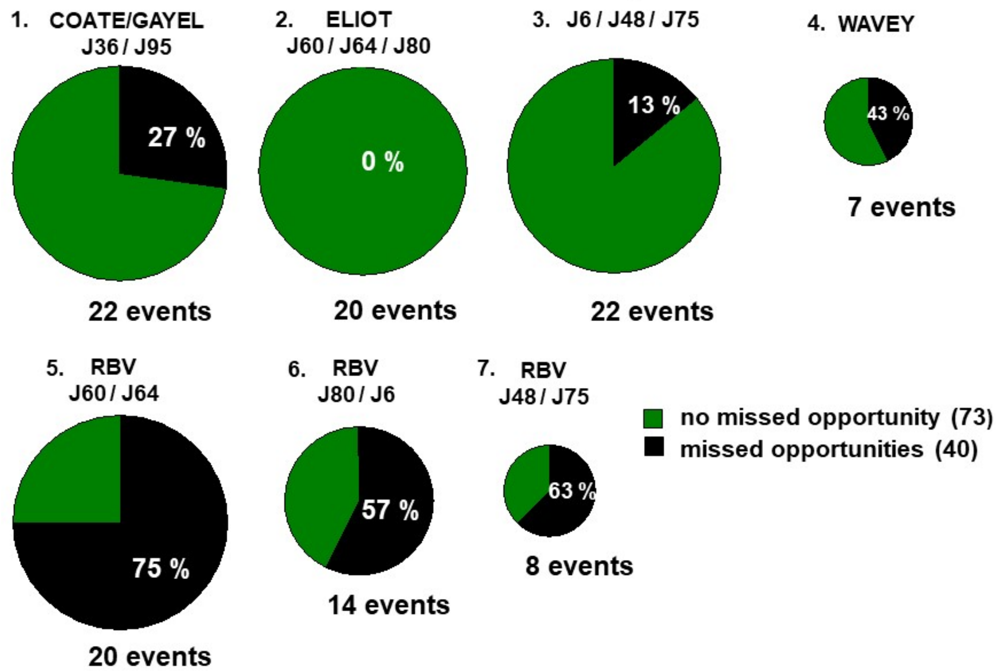


FIGURE 16b. Comparison of the frequency of Post Impact Green (PIG) missed opporturnities for key New York departure fixes in 2008.

design process shown in Figure 1 including determining the focus for enhanced training.

5.2 Use of Operational Benefits Metrics to Determine Who Needs Access to Convective Weather Decision Support Information

Another example of the use of quantitative metrics to focus convective weather decision support arose from analysis of the CIWS operational evaluation in 2003 (Robinson, et al., 2004). The operational benefits analysis that was conducted using knowledgeable observers at a number of FAA facilities during convective weather events for real-time identification of operational CIWS uses focused on two key delay reduction related benefits at the various facilities:

1. Keeping routes open longer and/or reopening closed routes earlier.
2. Proactive, efficient reroutes.

A key metric was the number of times each of these facilities made decisions yielding these benefits per convective day that (in the opinion of the facility decision makers) they would not have made prior to having CIWS.

When we analyzed the results at the end of the convective season in 2003, we were surprised to learn that the Washington ARTCC (ZDC) frequency of achieving each of these benefits per thunderstorm impact day on the ARTCC was higher than for ZOB. The difference was not readily explained by possible factors such congestion in the respective ARTCCs nor by skill of the personnel. And, the training, human-computer interface, and products were identical for the two ARTCCs.

But, there was one potentially important difference: ZDC had CIWS displays in each of the areas for use by the supervisors whereas none of the areas at ZOB had CIWS displays.

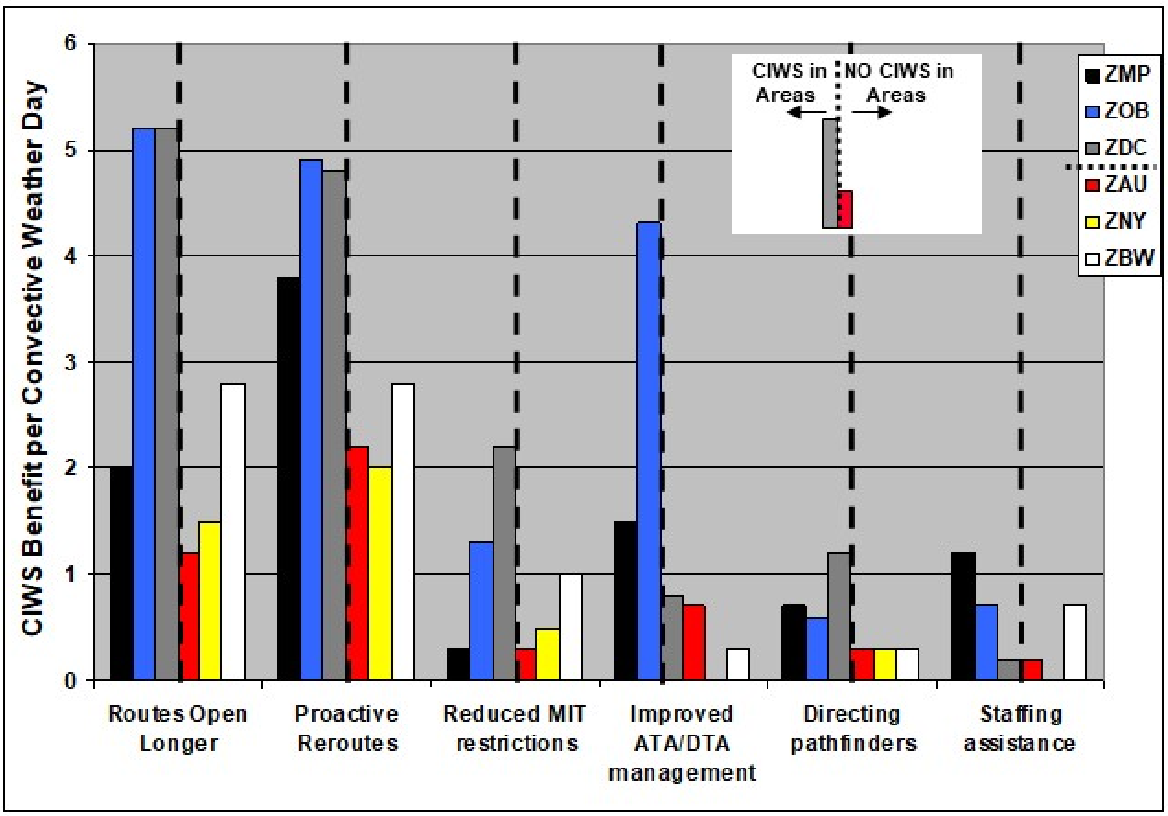
When there was a second CIWS operational evaluation in 2005 (Robinson, Evans, and Hancock, 2006), an experiment was conducted where CIWS at ZOB was made available in the TMU and 4 of 8 Area Supervisor positions. Observations by FAA observers during convective events in 2005 at ZOB when storms impacted the areas that had CIWS versus decision making when storms were impacted ZOB areas without CIWS confirmed that the shared situational awareness between the ZOB areas and TMU was very important in arriving at good decisions much faster than was the case where there was not shared common awareness.

There had been a number of enhancements to the CIWS decision support system (e.g., forecast capabilities) as well as greater familiarization by the users that applied to all the user facilities. What was striking was the change in frequency per thunderstorm day for the two benefits noted above between 2003 and 2005.

We see from Table 3 that both ZOB and ZDC made more beneficial decisions in 2005 per thunderstorm day. But, the ZOB increase in decisions made per thunderstorm day between 2003 and 2005 was noticeably higher than that of ZDC.

TABLE 3. Comparison of the frequency for key beneficial decisions per thunderstorm day at the Cleveland ARTCC (ZOB) and Washington ARTCC (ZDC) between 2003 and 2005.

Keeping routes open longer			Proactive reroutes		
Year	**ZOB**	**ZDC**	**Year**	**ZOB**	**ZDC**
2005	**5.2**	**5.2**	**2005**	**4.9**	**4.8**
2003	**1.9**	**3.4**	**2003**	**1.1**	**1.7**
ratio 2005/2003	**2.7**	**1.5**	**ratio 2005/2003**	**4.5**	**2.8**



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

FIGURE 17. Comparison of CIWS en route delay reduction benefits for various ARTCCs and decisions in the 2005 CIWS operational demonstration (Robinson, et al., 2006)

In Figure 17, we compare the frequency with which these two operational benefits were observed in 2005 along with some other operational benefits for the ARTCCs that were the focus of the 2005 testing. We see that the ARTCCs with CIWS available in the areas generally had the highest frequency of each observed benefit except for the Minneapolis ARTCC (ZMP). 2005 was the first year that ZMP had access to CIWS whereas the other ARTCCs generally had used CIWS for several years.

Figure 17 also illustrates another element of common situational awareness in ATM decision making: the ability to better manage the arrival and departure transition areas (ATAs) (also known as arrival and departure gates) between a TRACON and the surrounding ARTCC. In the 2006 testing, only ZOB had CIWS displays in major airports within ZOB (CLE and DTW).

6.0 REAL TIME OPERATIONS

The real time prototype decision support system, which has been a very important part of the system development process, has seen an enormous change over the 30 years of continuous operations. These changes extend from the initial prototypes which had to be located near user facilities in what was barely a step up from a scientific weather measurement program with Doppler weather radars to the current situation, which supports many different facilities, with 100s of user displays, and a multiplicity of capabilities – all operating from a single location. A few highlights deserve discussion.

6.1 Field Sites Located Close to Major Operational User ATC Facilities

The initial decision support capability - low altitude wind shear avoidance – was provided by the TDWR prototype system which operated in Denver, Kansas City, and Orlando. The real time processing and operations monitoring was housed in a transportable trailer. The technologies used were quaint by today's standards:

- Radar real time product generation: Perkin Elmer (PE)/Concurrent 32 bit super-mini computers and custom digital signal processor for data acquisition,
- Weather algorithms, alert generation, monitoring etc.: a collection of small Sun workstations,
- Microburst detection and alerts using features aloft: a LISP machine,
- Customized Ethernet broadcast to deliver base radar Doppler products from Concurrent to the workstations,
- VERY labor intensive system operation/monitoring needed by the staff at the prototype site, and
- Airborne "sneaker net" (that is manual transport) to get new software to site.

In the early 1990s, the TDWR real time prototype evolved into several ITWS prototypes that still operated near user facilities, but had far greater processing and communications capabilities as technology process evolved rapidly:

- The Lincoln Laboratory prototype radar was retired, ITWS was connected to one or more production TDWRs, one or more NEXRADs, and one or more ASR9s,
- The "processor" was now a network of Sun workstations,
- The software complexity evolved from 10s of algorithm processes and ~500KB domain size to 100s of processes and 5MB domain size, and
- A T-1 phone line to the site replaced the 9600 baud line and the "sneaker net".

Support of a multiplicity of sites simultaneously providing real time products was challenging, but a trip to a prototype had its redeeming virtue of allowing the visiting support team to participate in the field site culture highlighted in Figure 18.

6.2 Real Time Operations from a Centralized Location in Lexington MA

The wide area covered by the CIWS prototype that grew out of the NY ITWS prototype no longer had a single key ATC user. Hence, it was logical in 2001 to transition the real time prototype operations[15] to the Lincoln Laboratory main facilities in Lexington, MA. This presented a number of new operational challenges not yet encountered with the previously terminal-centric prototypes.

The increase in geographical coverage, spanning multiple time zones, meant that there were frequently weather and traffic issues occurring somewhere in the CIWS domain. As a result, there was no convenient time for the prototype to be taken off-line for maintenance. In addition, the size of the domain that extended across the US and into Southern Canada, required a re-engineering of the algorithms to accommodate both a new coordinate system for representing the products and new decomposition methods for meeting the time constraints when processing the larger grids. Some of the challenges were made easier due to the fact that CIWS was not responsible for the safety-critical alerts of the TDWR. However, the others required a concerted effort on the part of the development team to create the engineering environment for this prototype be able to live up to its promise.

Since the CIWS products generated by the prototype system are being used by the TFMS system, the target availability for the products to the external users is greater than 95%. The key elements of the current real time product generation system for CIWS, CoSPA, and OPC that make this possible are as follows:

- New software infrastructure that was required due to processing requirements (1000s of product generation processes) and large domain (~30MB),
- Enhancements to the monitoring and system maintenance functions to provide full automated monitoring ,
- A "hot" switchover capability, which allows a real-time swap between two copies of the real-time system for maintenance on one while generating live products with the other -- with no loss of products to the users,

[15] The New York ITWS and RAPT prototypes operated from a location near the NY TRACON until 2006 at which point the prototype operations were transferred to Lexington, MA.

FIGURE 18. “Culture” of real time convective weather decision support for terminal safety and air traffic management decision support in convective weather at field sites located near the principal ATC facilities. Top left-hand figure is the prototype TDWR inflatable radome in Orlando with black panels mounted inside the radome to create a 100 foot wide pumpkin for Halloween. Top right is the Orlando ITWS site with sheets covering processors after Hurricane Charlie damaged the roof. Lower right-hand figure is the New York ITWS real time operations installation team in the operations room. Lower left-hand figure shows the bathroom facility at the initial Orlando ITWS field site together with the production TDWR that was installed next to the Lincoln prototype TDWR site.

- A hardware upgraded to Virtual Memory (VM) clusters with thousands of CPUs,
- The adoption of contemporary real time software development processes,
- A transition to 24 hours per day/7 days per week operations (as opposed to weather conditional), and
- An installation of a large number of workstations at user facilities (127 as of winter 2018) as supporting real time web sites for CIWS, CoSPA, and OPC with approximately 4,150 accounts that are used by FAA, NAV CANADA, and airline real time operational decision makers.

The staff monitor the prototypes continuously for both technical and product quality issues. Specifically, there is Monitor-In-Charge (MIC) present at all times who covers all prototypes. This role is assigned on a rotating basis to staff from the real-time prototype team; these staff members are considered the prototype’s Subject Matter Experts (SMEs). Three shifts are defined: primary shift from 6 am to 6 pm to coincide with the periods of highest activity within the FAA facilities, evening from 6 pm to midnight, and overnight from midnight to 6 am. Although the MIC is in charge, additional members of the monitoring, real-time software and the system/network engineering teams are also monitoring the system in the background, making periodic health checks on the system, as well as responding to calls from the MIC and any alerts coming automatically from elements of the real-time systems.

The monitoring challenges faced by the team are divided into three categories, each with an increasing level of staff resources needed for resolution. The categories are:

- Routine (Level I) - can usually be resolved by the MIC with minor involvement from another member of the real-time team.
- Substantial (Level II) - although less time-critical, require more analysis than Level 1 and may require anything from minor to major involvement of other team members.
- Emergency (Level III) - require full and immediate attention from one or more additional monitors, prototype system analysts, engineers or system administrators in order to address a major hardware failure, networking issues, or software/system infrastructure failures that would cause system products to be unavailable.

Lincoln Laboratory SMEs address both Level I and Level III issues immediately regardless of the shift on which they occur. SMEs also address Level II problems, which might include input data quality issues or the replacement of an unreliable hardware element; however, if necessary, they may be deferred until the next primary shift. Depending on the nature of the problem, Operational staff notify the users in the case of system outages. The MIC must also communicate with the FAA's *TFM* Production Center (TPC) at the FAA William J. Hughes Technical Center (WJHTC) to discuss system status.

An important element of the real time monitors is to identify meteorological data quality problems and, unmet decision support needs. Many members of the real time SME team are meteorologists with substantive experience at use of Doppler weather radar data. Hence, they have the background to note inconsistencies between the products and other available synoptic information that warrant off line analysis. Additionally, a number of the real time SME team have participated in development of a number of the meteorological analysis algorithms running in the real time system.

One of the most important benefits of real time operations near an ATC facility was that the Lincoln Laboratory real-time site personnel (such as shown in Figure 18) could easily visit the ATC facility to provide training to new staff, observe real time decision making, and answer questions about products. This type of ongoing feedback about the operational use and utility of the decision support system is much harder to accomplish from a centralized location.

Our approach to facilitating the operational feedback from a centralized location has been to:

a. Have a number of the real time monitors participate in training at ATC and airline facilities as well as participating in intensive observations of decision making during convective weather of the type discussed in (Robinson, 2004) so they have an in depth understanding of ATC facility operations,
b. Monitor the FAA/airline Strategic Planning Teleconferences (SPTs) held every 2 hours to understand weather decision issues of immediate national concern,
c. Monitor aircraft tracks and weather displays in real time to note operationally undesirable situations (e.g., holding patterns or, delays in utilizing available capacity at the end of storm impacts) that occur, and
d. When FAA policy permits, contact facilities following salient convective impact events to understand the basis for various decisions made and whether the decision support provided was adequate.

Additionally, we are often contacted by the FAA TFM regional offices to support their analysis of decision making for major convective weather impact events.

7.0 SUMMARY AND FUTURE OPPORTUNITIES

There are a number of criteria one can use in assessing whether a sustained decision support development program such as described above was actually successful:

1. Has an operationally useful capability that provides measurable benefits been achieved?
2. Has that capability been successfully transitioned to operational systems, and
3. What are major unmet needs for decision support and, how might they be addressed?

Each of these will be discussed below.

7.1 Operational Benefits of the Decision Support Systems

There have been a number of major studies to assess the operational benefits of the major decision support systems using both the methodologies described above. In some cases, key numbers such as delay saving for reroutes of arrivals to ARTCC-TRACON interfaces in these studies were similar to those found by "direct measurement" approaches of the type discussed in (Howell, et al., 2008). A very brief summary is as follows:

1. TDWR/ITWS wind shear safety enhancement: there have been no fatal accidents due to low altitude wind shear at the TDWR equipped airports after the TDWR was installed.
2. The delay reduction benefits estimated for ITWS for Atlanta were assessed by two different methods: facility interviews and analysis of time of flight during convective conditions. Delay reduction benefits are summarized in Table 4.

There are additional ITWS benefits not discussed above (specifically, greater rate of arrivals into an airport following airport closure) that were identified by (Howell, et al., 2008).

TABLE 4. Quantitative delay reduction benefits per year for various decision support systems discussed in this paper.

System	Location	Direct delay savings (hr)	Airline DOC ($M)	Passenger value of time ($M)	Reference (lead author only)
ITWS	Atlanta	4,000	7	23	Allan, 2005
	New York	28,000	78	90	Allan 2001
RAPT	New York	3,075	6	7	Robinson, 2008 Robinson, 2009
CIWS	Northeast US	52,000	94	201	Robinson, 2006

DOC= airline Direct Operating Cost (mainly fuel and flight personnel) using FAA standard values at time of report

PVT= passenger value of time using FAA standard values at time of report

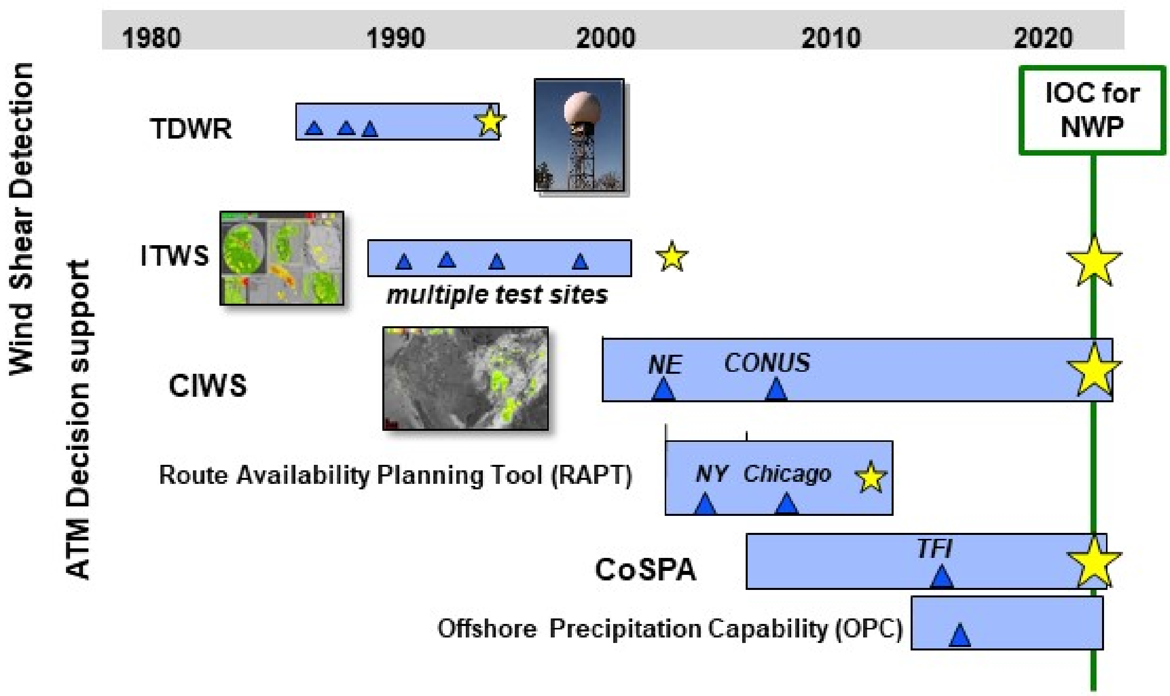


FIGURE 19. Summary of major convective weather decision support capabilities developed through real time product usage by ATC and airlines as part of the design process shown in Figure 1. Blue triangles indicate major prototype deployments and enhancements to various systems. Yellow stars indicate technology transfer of the functional capabilities developed through prototype usage to FAA production systems. The technology transfer to the NextGen Weather Processor (NWP) is particularly important since it involves combining of several different platforms into a single platform as well as upgrading the technology used in existing operational systems such as ITWS.

7.2 Transfer of the Technology Developed with Prototype Decision Support Systems to the FAA Operational System

The FAA is very concerned that the decision support capabilities developed using functional prototypes be transitioned to FAA production systems. In Figure 19, we summarize the transition of the decision support capabilities to FAA operational systems. A transition of the CIWS to a production system had been planned for implementation prior to 2010, but it was determined that the capability should be combined with CoSPA and implemented in the NextGen Weather Processor (NWP).

The operational implementation of the Offshore Precipitation Capability (OPC) is under active consideration. One option is to transition OPC to the National Weather Service (NWS) for operational usage. A global extension to OPC is also currently under development by the Air Force for operational deployment at Offutt AFB, NE.

7.3 Addressing Unmet Decision Support Needs

When the NWP achieves IOC, much of the impetus for the current real time prototype operations described above will go away. Two questions then arise:

- Are there still outstanding significant ATM-weather decision support needs that should be addressed by the prototype-centric system design process described above?
- Does the weather decision support system design process shown in Figure 1 (which evolved in an ad hoc manner over 20 years) make sense given contemporary thinking on ATM system development?

It would be nice to report that there has been a decrease in weather delays at major airports in the past few years. In Figure 20, we compare OPSNET weather delays for major airports highlighted in FAA NextGen program information on weather delays as of Nov. 2018. We see that weather delays in Chicago, Philadelphia, and Atlanta all decreased significantly in 2017 compared to 2013. However, the New York major airport weather delays in 2017 and much of 2018 generally were higher than in 2013. The results shown below have not been normalized for possible differences in weather impacts. (Venuti, et al., 2018) show that 2017 was very similar to the preceding three years in terms of high reflectivity impacts. It should also be noted that the delays at Philadelphia (in the Northeast Corridor close to New York) went down in 2017 whereas the New York delays went up.

The Northeast Corridor (especially the New York airports) has been flagged by the NextGen[16] Advisory Committee (https://www.faa.gov/nextgen/nac/) as a NextGen priority area. A North East Corridor (NEC) Advisory Committee (https://www.faa.gov/nextgen/snapshots/priorities/?area=nec) has been developing recommendations that would improve operations in this region, especially in adverse weather. However, only one of the near-term recommendations by the NEC addresses operations in adverse weather.

In section 3, we discussed the challenging problem of convective weather coupled with congestion as a major factor in the high delays experienced at the New York airports in the summer. One of the further challenging factors for the New York operations since 2013 has been a major loss of experienced traffic flow

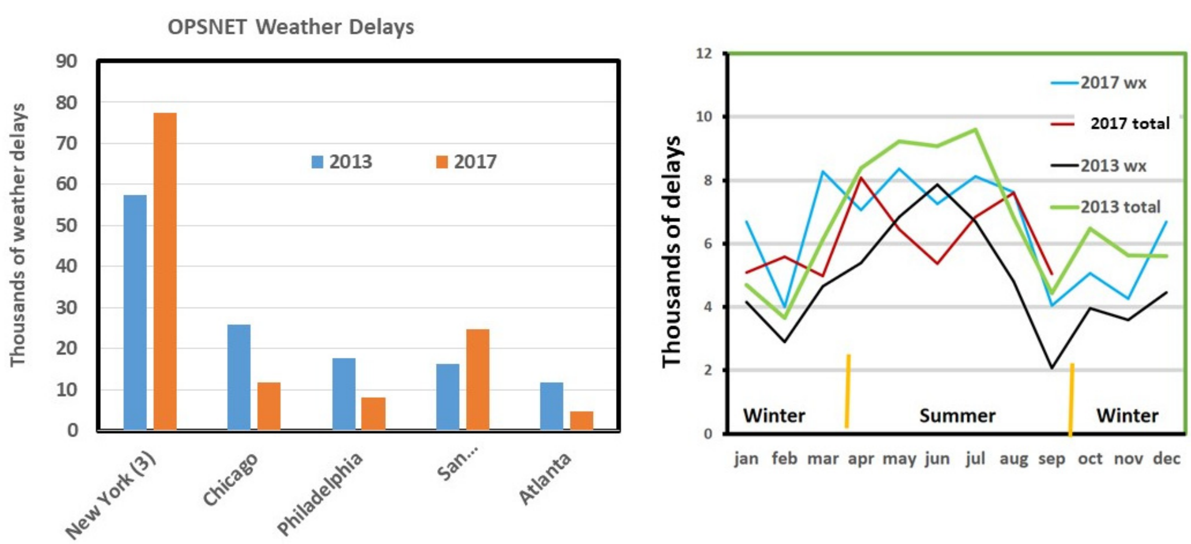


FIGURE 20. Comparison of OPSNET weather delays for major airports highlighted in FAA NextGen program information on weather delays as of Nov. 2018. The New York major airport OPSNET delays attributed to weather are generally about 70% of all the OPSNET delays reported for those airports.

[16] The Next Generation Air Transportation System, or NextGen, is the FAA-led modernization of America's air transportation system that is intended to make flying even safer, more efficient, and more predictable.

managers and area supervisors in key ATC facilities as controllers hired after the 1981 PATCO controller strike retire.

As noted above in section 4, ATC decision makers rely heavily on past experience when making tactical (0-2 hour) ATM decisions in convective weather. Hence the loss of experienced personnel can be a major problem when there is significant communication and coordination required.

An obvious approach to mitigating the loss of knowledge would be developing a training program of the type described above in section 4. Unfortunately, the current FAA approach to training for operationally deployed decision support tools such as the RAPT involves Computer-Based Instruction (CBI) that focusses primarily on how to access various display features as opposed to scenario-based training describing how the decision support tool might be used under realistic operational conditions in a particular facility.

From our very preliminary analysis of NY departures since focused, metric-based training ended in 2010 that as a consequence of the loss of experienced personnel and lack of training of the type discussed in section 4 above, the problem of long delays in resuming the use of New York departure routes after storm impacts ends (see Figures 15 and 16) appear to be increasing.

The FAA has recently embraced the Plan, Execute, Review, Train, Improve (PERTI) paradigm as the operating model for strategic ATM decision-making. It provides a best practice framework for a formal, holistic collaborative decision-making process for stakeholders as follows:

- **P**lan 1-3 days ahead for a given event (e.g., determining which subset of TMIs might be appropriate given the long-range weather and demand forecasts and prior experience).
- **E**xecute refined plans which build from the prior step based on updated demand, capacity and other relevant information available on and during the operational day.
- **R**eview the effectiveness of the ATM decisions through a formal process in the immediate aftermath of an event in order to identify good and bad plan elements and lessons learned with relevant stakeholders while the institutional memory of the event is still fresh.
- **T**rain to promote identified best practices and eliminate less effective strategies with appropriate ATM and airline personnel in a formal setting each year (e.g., at the end of the convective weather season).
- **I**mprove system outcomes in a continual fashion using the steps above, requiring the definition and tracking of appropriate operational performance metrics from year to year.

At this point in time, most of the PERTI focus has been on long lead time planning and it is uncertain how the training for convective weather operations would be accomplished as a part of PERTI. However, it is encouraging that such a paradigm is now being embraced operationally and future decision support tool technologies can be mapped to the different PERTI phases.

Additionally, it should be noted that arrival management into the Northeast Corridor during convective weather has continued to be a problem both for the tactical (0-2 hours) time frame and strategically (greater than 2 hours). As noted in (Venuti and Klingle-Wilson, 2017) and in (Venuti, et al., 2018), operational success in providing reliable quantitative permeability forecasts for forecast lead times greater than 2 hours has been difficult to accomplish.

Another significant problem at the NY airports is the lack of effective decision support for managing adverse surface winds and strong winds aloft especially when combined with convection, rain, or snow. This need was identified in the early years of the NY ITWS operations (Allan and Gaddy, 2000; Allan, et al, 2001), but has not been addressed nationally since the decision support problems are principally of concern at New York.

These many challenges to successful adverse weather decision support for the Northeast Corridor (especially for the New York airports) suggest that the Northeast Corridor operations in adverse weather might best be addressed by an ongoing prototype centric process of the type shown in Figure 1 as opposed to piecemeal implementations such as occurred with RAPT.

However, the question then arises as to what sort of system design process might be used and whether there are other examples of system design approaches to address difficult ATM problems.

In 2017 (about 23 years after we had commenced ATM decision support for coping with convective weather impacts), a paper “The ATM Acquisition Process: Fit for Purpose?” (Koslow, 2017) was published which argues the standard development approach of:

1. Program justifications,
2. Detailed requirements definition, followed by,
3. Contractual arrangements for building, testing and installation

has been used for over 40 years with a “remarkable lack of success if success was defined as on-time, within budget delivery of expected functionality”.

Koslow states that these problems in achieving success arise because the ATC systems needs could not be defined that well a priori especially when one had to consider the special needs of individual airspace, and argues instead that “continuous collaboration between experienced ATM operational personnel on the one hand, and ATM development personnel on the other” using functional prototypes is the best way to proceed.

The development approach that Koslow suggests seems very similar to what has been accomplished over the past 30 years through the succession of convective weather decision support systems described in this paper.

But, what is not discussed in the Koslow paper is the role of training and performance metrics (that is, the feedback loops shown in Figure 1) in achieving successful operational outcomes in both the initial use of a decision support capability and on an ongoing basis.

We believe that the results summarized in sections 5 and 6 above on coupling training and metrics make a compelling case for such elements being a key feature of any concentrated effort to provide improved adverse weather ATM decision support for the Northeast Corridor using real time functional prototypes.

8. ACKNOWLEDGEMENTS

The 30 year effort described above had a large number of major contributors as is indicated by the various references. We would like to particularly acknowledge the pivotal role of ATC personnel at Orlando, New York, Dallas, and Memphis in providing feedback and suggestions for products. Dan Strawbridge at the FAA headquarters provided support and encouragement for the very rapid evolution of capabilities that took place between 1990 and 2006. Leo Prusak was instrumental in the development of the NY ITWS prototype. Major airlines (especially Northwest, Continental, American, and United) also provided key insights and recommendations as the decision support evolved. More recently, Thomas Webster in the FAA has championed the continued use of the CIWS prototype system for eliciting user needs and identifying requirements that have directly led to significant improvements planned for the NextGen Weather Processor (now under the leadership of Alfred Moosakhanian) – while at the same time providing significant operational benefits.

We also would like to thank the Lincoln Laboratory real time systems and software developers that were led by Ms. Elizabeth Ducot for much of the 30 year period. Achieving very high availability of the real time products with software systems that could be fairly rapidly changed to address urgent issues and, being able to successfully transition the technology to production contractor were all critical elements of achieving 30 years of successful contributions to the safety and efficiency of the NAS.

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