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Tactical Weather Decision Support To Complement "Strategic" Traffic Flow Management for Convective Weather*

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Abstract

Reducing delays due to thunderstorms has become a major objective of the FAA due to the recent growth in convective delays. In 2000 the key new initiative for reducing these convective weather delays was "strategic" traffic flow management (TFM) using collaborative weather forecasts and routing strategy development. This "strategic" approach experienced difficulties on a number of cases where it was not possible to accurately forecast storm impacts on routes. This paper describes a complementary "tactical" capability using contemporary terminal and en route weather prediction systems plus traffic flow management and automation decision support tools.

We argue that a major paradigm shift may be required in the method by which aircraft routings are determined when there is convective weather in congested airspace. We propose a system where re routes and, routes for near term departures are frequently revised based on automatically generated storm predictions coupled to traffic flow and traffic conflict decision support systems with review and very limited swapping of routes by pilots and airline dispatch.

1. Introduction

Delay increases during the months of the year characterized by thunderstorms have been the principal cause of the dramatic delay growth in the US aviation system over the past 3 years as shown in Figure 1. In 2000 the key new initiative for reducing convective weather delays was "strategic" traffic flow management (TFM) through the Collaborative Convective Forecast Product (CCFP), the Strategic Planning Team, and Collaborative Routing (CR) (Figure 2). The "play book" shown in Figure 2 consists of collaboratively determined routes assuming that there are various regions of weather, which must be totally avoided.

This "strategic" approach has been quite successful in improving operations in many cases. However, in congested airspace, the inability to accurately forecast convective weather impacts requires a complementary tactical weather decision support capability. This paper describes tactical weather prediction systems plus traffic flow management and automation decision support tools to provide this tactical capability.

The paper proceeds as follows. In Section 2, we discuss some of the challenges that were encountered using the strategic approach shown in Figure 2. Section 3 discusses contemporary terminal and en route systems that create automatically generated short-term convective weather predictions through the integration of data from both terminal and en route sensors. Section 4 discusses complementary air traffic management (ATM) systems that would utilize the tactical weather products. We argue that a major paradigm shift may be required in the method by which aircraft routings are determined when there is convective weather in congested airspace. The final section

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summarizes the results and suggests a number of areas for further research.

2. Challenges Encountered Using a "Strategic" Approach to Convective Weather Traffic Management

The growth in demand relative to the capacity of the NAS has resulted in a growing emphasis on traffic flow management and collaborative decision making as the principal mechanisms for managing the flows of traffic. Accomplishing such planning and optimal use of the available resources necessitates estimating the capacity of terminals and en route sector, and the air routes on time scales comparable to the flight times of aircraft plus at least one hour.

A key question is then whether the collaborative forecasts shown in Figure 2 can reliably predict where the weather will be, and whether these predicted regions coincide with the various hypothesized weather regions.

Recent experience has shown three major challenges in using strategic traffic management as characterized in Figure 2 <u>alone</u>:

1. route decision making when the CCFP has spatially large regions with a relatively low predicted likelihood of weather impact to the various routes within the regions,
2. managing situations where weather unexpectedly occurs in critical locations, and
3. deciding what to do when weather is not present at the forecast times and locations.

Figure 3 shows an example where the CCFP was reasonably accurate in that weather occurred in much of the forecast region; however, there was no easy way to anticipate which routes would be available within the region of forecast weather. In Figure 3, the large extent of forecast activity made it infeasible to simply route all aircraft outside the forecast regions.

Figure 4 illustrates a case where the weather that occurred was much more widespread than anticipated. Here a tactical capability was clearly required. Figs. 3 and 4 should not be viewed as a criticism of the relative skill of the operational forecasters that created the CCFPs; rather, it is a reflection of the very difficult scientific challenge in multi-hour convective forecasting.

Figure 5 summarizes the current and projected accuracy estimates from the FAA Aviation Weather Research program convective weather development team. We see there is a very basic challenge facing the NAS operations: the ability to predict the capacity and route availability in congested airspace throughout the duration of many flights is <u>simply</u> <u>not</u> <u>available</u> when convective weather occurs.

3. Tactical convective weather decision support

Thus, there must be a complementary tactical convective weather decision support capability. But what is the essence of this capability and how does it relate to the strategic plan?

We propose assuming an effective tactical capacity for regions that may be impacted and planning to dynamically reroute using tactical weather products and ATM decision support tools. The tactical capacity depends critically on the tactical weather products, ATM decision support tools and, capability of the air traffic controller team and pilots/dispatch. A very important consideration is the need to avoid excessive controller workload situations that might result in aircraft separation violations. Such overload situations are more likely to occur when there is rapid new growth and/or rapidly moving cells that unexpectedly impact busy routes and/or terminals.

Eight years of analyses by Lincoln of convective weather operations at busy terminals have shown that both terminal <u>and</u> en route decision support are essential. The critical product needs for congested airspace are very accurate, timely information (e.g., update rates consistent with cell lifetimes as short as 15 minutes, minimal corruption by data anomalies such as clutter AP and, appropriate indices of storm severity) on the current and future locations of operationally significant weather. If these products need to be disseminated to terminal and en route facilities as well as to airline systems operations centers and pilots to facilitate collaborative decision making

Major terminal areas have historically been relatively accomplished at tactical responses because:

a. ATC controllers had timely (30 to 60 sec update rates) relatively high quality information on storm locations via the ASR-9 displayed on controller displays and the Terminal Doppler Weather Radar (TDWR) data on supervisor situation display, and

b. Rerouting in the terminal area was relatively easy to accomplish because no flight plan changes were required, the controllers involved are in close physical proximity, and very knowledgeable about each other's position.

The capability lacking in terminal airspace for tactical convective weather handling was short-term forecasts, and common situational awareness between the terminals, ARTCCs and, the airline systems operations center (SOC) dispatchers.

The tactical convective weather decision support for <u>en route</u> airspace has historically been less robust than the terminal capability. En route controllers have not had access to timely, high quality storm location and severity information. In many cases, the weather radar data provided to en route traffic managers was not timely and had data quality problems. Coordination of route changes in en route airspace can be very difficult due to the need to coordinate changes across sectors (and sometimes, ARTCCs), amend flight strips and, address traffic flow management constraints.

<u>Contemporary Terminal Capabilities</u>

A major improvement to tactical convective weather decision support system is provided by the Integrated Terminal Weather System (ITWS), which has been used operationally for over 7 years at four major terminal complexes (New York, Dallas, Orlando and Memphis). The ITWS provides high update (30 second) 3D information on storms by integrating ASR-9, NEXRAD and lightning data to provide 20-minute forecasts of storm movements and gust fronts that may cause airport reconfiguration[1]. Figure 6 shows the 10 and 20 minute storm extrapolated position forecast products provided by the initial ITWS. Typical accuracy for this product is over 80% for 10 minute predictions and about 66% for 20 minute predictions.[2]

A near term enhancement to the ITWS will be the Terminal Convective Weather Forecast (TCWF) (Figure 7), which provides 30-60 minute predictions for the future location of organized convection such as squall lines (Wolfson, et. al, 1999). The accuracy of the TCWF -30 and -60 minute forecasts depends critically on the type of convective weather; hence, a key TCWF feature is real time product performance scoring so that the TCWF user has a quantitative estimate of the useful time span of a plan generated using the TCWF.

A recent study of weather delay reduction at the New York terminal area (Allen, et. al, 2001) found that the NY ITWS with the TCWF capability achieves an <u>annual convective weather delay reduction of over 1.2 million minutes per year.</u> This is accomplished by enabling traffic flow managers and terminal facility supervisors to:

1. Achieve higher departure rates during convective activity by optimizing the use of gaps in the convective weather
2. Anticipate runway shifts,
3. Utilize shorter routes for arrivals and departures, and
4. Proactively end severe weather avoidance plans (SWAPs)

These benefits results are important as a guide to delay reduction investment decision making since they indicate areas where better terminal tactical decision making can achieve large delay reductions. The New York airspace is somewhat unusual in that the surrounding en route airspace is very congested such that it is difficult to re route aircraft from a convective weather impacted arrival fix to an alternative weather free arrival fix. By contrast, at other major terminal complexes (e.g., Dallas) that are less congested, we have found that the major convective weather delay reduction provided by ITWS is reduced delays for arrival reroutes to alternative arrival fixes into the terminal area[3].

[1] Additional information on production ITWS is available at www.faa.gov/AUA/. Information on specific ITWS products and usage can be found at www.ll.mit.edu/AviationWeather/. A national deployment of ITWS with the TCWF would provide over 4 million minutes of delay reduction per year.

[2] The criteria was whether the leading edge of the actual VIP level 3 precipitation was within 1 nmi of the leading edge of the precipitation forecast for that time.

[3] It should be noted that over half of the ITWS national delay reduction is achieved by better ARTCC TMU decision making.

Contemporary En Route Capabilities

The Weather and Radar Processor (WARP) currently provides displays of NEXRAD mosaics to ARTCC meteorologists, traffic flow managers and sector supervisors. The en route controllers should receive these mosaics on their DSR displays in 2002. WARP currently does not provide any accurate, automated short-term forecasts of future storm locations. The Aviation Weather Center provides the National Convective Weather Forecast (NCWF) with 1-hour forecast contours based on application of the TCWF technology to vendor provided NEXRAD reflectivity data. Cloud-to-ground lightning data is typically provided as strike locations.

The FAA is currently operationally evaluating the Corridor Integrated Weather System (CIWS) concept that would take advantage of the high density of existing FAA and NWS weather sensors in the congested en route corridors, and, the forecast technology developed for the ITWS program (Figure 8). Both terminal and en route weather sensors are used to create the CIWS products: the rapid update rate of the ASR-9 and ARSR-4 radar weather products (30–60 seconds) helps detect rapidly growing cells, while the NEXRAD provides 3-D storm information using AP edited vertical integrated liquid (VIL) as a measure of storm severity[4]. Data from lightning sensors (not shown) is also integrated with the radar data. Data from ASR-11s and ASR-9 Weather Systems Processor (WSP) would be used in CIWS when these systems are deployed. A Regional Convective Weather Forecast (RCWF) provides a TCWF like 30-60 minute forecast capability with regional performance scoring.

This use of the existing terminal sensors for en route tactical decision support provides much higher update rates than could be provided by NEXRAD alone, redundancy when NEXRADs are out of service, and (most importantly) the ability to forecast new storm development through much better sensing of the critical boundary layer. It is anticipated that the CIWS will commence providing 2-hour forecasts that include forecasts of cell development in 2002.

The CIWS NEXRAD sensors shown in fig 8 were used to create initial CIWS products for an operational demonstration that started 9 July 2001 and is continuing. The initial results show that many of the benefits associated with the ITWS are obtained with CIWS when the aircraft are relatively near airports. Much of initial evaluation was during the middle and late summer in which the storms had relatively low cell velocities. Hence, for over flight en route tactical management, the main benefit of the CIWS would be to help anticipate when gaps between storms would open and close. Without the high update rates from the ASR9/ARSR4 sensors[5] and, lacking explicit predictions of cell growth and decay forecasting, the initial CIWS was less operationally effective in reducing delays when planes were far from airports. On a number of the summer 2001 storm cases difficulties in rerouting planes dynamically due to the lack of ATM support tools (see the discussion below), and the lack of airline access to the products for much of the summer also reduced the delay reduction achieved.

As a result of the summer 2001 operational experience, the CIWS demonstration in 2002 will seek to extend the forecast periods out to two hours through explicit growth/decay forecasting, expand the coverage as shown in fig 8 and, integrate the CIWS with contemporary ATM decision support systems.

4. Tactical Air Traffic Management Support for Convective Weather

Air traffic management tools that can utilize the tactical weather decision support products are critical to improved handling of traffic when there is convective weather in congested airspace. Key issues include reducing controller workload, unambiguously identifying regions of airspace that pilots will seek to avoid and, addressing the traffic flow management consequences of tactical rerouting to avoid convective weather.

[4] VIL is a measure of the liquid water mass held aloft over a point on the ground. Hence, it is a measure of both the vigor of the storm updrafts and, of the water content of storms. VIL is much less susceptible to ground clutter and anomalous returns from wet snow flakes than the more commonly used radar reflectivity (e.g., dBZ or VIP levels)

[5] Access to the ASR-9 and ARSR-4 sensor data was delayed by labor union issues associated with the use of researcher operated experimental demonstration systems at FAA facilities.

A. ATC workload reduction

A major problem in executing a highly adaptive, flexible approach to handling of convective en route weather is the controller and TFM workload associated with coordination and filing of flight path amendments. For example, analysis of a high delay case at EWR by J. Clarke of MIT found that there were major delays for departures in a case where routes were available due to problems in coordinating reroutes between three en route centers (Hansman, 2001). Our observations of traffic handling in the CIWS domain in the summer of 2001 found that the flight path amendment problem becomes particularly acute when reroutes must be coordinated across multiple sectors and ARTCCs.

Rerouting would be far simpler if there were electronic flight strip coordination tools that check for conflicts and traffic flow management constraints automatically. Both the User Request Elevation Tool (URET) developed by MITRE and the "Direct To" tool developed at NASA Ames significantly improves the capability to reroute planes; but has not yet been interfaced to convective weather decision support systems nor integrated with TFM tools such as Collaborative Routing Coordination Tool (CRCT). Based on the CIWS experience in 2001, we believe that it is important that tools such as URET and "Direct To" be extended to work over multiple ARTCCs[6] and, between TRACONs and ARTCCs if the available opportunities to advantageously reroute aircraft are to be more fully utilized.

B. Traffic Flow Management

In congested airspace, traffic flow management (TFM) constraints become particularly important when convective weather has reduced the capacity of various routes and sectors thus increasing the demand on other routes and sectors. Hence, determining the viability of candidate reroute strategies would be greatly facilitated by appropriate TFM decision support tools.

The CRCT has been effective at key en route centers in assessing the impacts of reroutes on downstream traffic flow management (TFM) systems. However, at this point, the CRCT software in use does not extend across multiple ARTCCs. CRCT currently requires the users to input the areas of weather impacts and, does not automatically generate sets of solutions for the projected weather impacts. NASA Ames is developing TFM coordination tools that will handle multiple ARTCC impacts; but these have not yet been evaluated in an operational FAA facility.

C. Algorithms for generating reroute strategies

When applied to rerouting for convective weather, the automation and TFM decision support tools discussed above principally provide "impact analysis" tools for human generated strategies. It has become clear that automatic algorithms are needed to aid in the development of convective weather reroute resolution strategies. There are three key capabilities that are needed:

a. Determining reroutes for individual flights that consider the time varying impacts of weather on various possible routes
b. Allocation of flights to available routes consistent with controller workload constraints (e.g., sector capacities) and aircraft conflicts and,
c. Handling the uncertainty in the location and severity of the convective weather in the future.

An algorithm for generating tactical rerouting strategies given present and projected locations of storms has been developed and is being marketed by the Preston Group for use by airline dispatch (Klein, 2001). Arnab Nilin is studying the single aircraft reroute problem in his PhD thesis (paper at this conference). However, neither of these tools has been interfaced to automation nor TFM decision support systems.

A very important research issue for the development of rerouting systems is achieving a quantitative understanding of en route pilot preferences in convective weather avoidance similar to that developed for the terminal area by Rhoda and Pawlak (1997). Key factors include the relative altitudes of the storm tops and aircraft, stage of development of the storm, lightning activity, and the availability of nearby alternative routes.

The en route airspace capability to handle a given set of flights expeditiously cannot be

[6] URET has demonstrated integration between 2 ARTCCs.

characterized by a scalar capacity and a scalar demand. This allocation of planes to capacity constrained elements (e.g., routes, sectors) of en route airspace is currently under investigation in a number of universities.

We propose the development of "stochastic" route generation/TFM /automation systems which can handle the uncertainty in convective weather impacts on capacity and routes much as stochastic optimum control theory is used for aircraft control. Virtually all of the automation and TFM system development to date has assumed perfect knowledge of the future for the duration of aircraft flights whereas the actual situation (recall figs. 3-5) is that significant uncertainty in convective weather impacts will exist in many cases between the time a flight plan is filed and the time that the plane lands at the destination.

The challenge here is the development of a stochastic model that can:

1. address the space/time correlation for convective weather of various types, and
2. smoothly transition to a largely deterministic model for short prediction times (e.g., 30 minutes) and,
3. be matched to route optimizing algorithms

The approach suggested above could be viewed a centralized paradigm for route planning that sharply conflicts with current decentralized approach where each airline dispatcher generates flight plans more or less independently and in which there is some degree of conflict resolution through FAA/airline discussions. This centralized approach with automation tools generating candidate reroute approaches by operation on automatically generated forecasts seems essential if the uncertainty in weather impacts is as severe as indicated in Figure 5.

This heavily automated rerouting capability is principally needed in highly congested airspace. In less congested airspace where there is much more flexibility to reroute individual aircraft with minimal or no traffic flow management constraints, the current approaches would probably suffice. How these two approaches might jointly exist in the air system in different regions might be a candidate near term for the large scale US air system simulation proposed for the NASA AvSTAR program.

5. Summary and recommendations

Convective weather has become a major cause of US aviation delays due to the major effective capacity reductions that are caused by thunderstorms. Convective activity is a particularly difficult challenge in congested airspace because both aircraft conflicts and traffic flow management issues must be resolved in fairly short time frames due to the difficulties in predicting the storm impacts more than 30-60 minutes in the future. We propose a major improvement in the tactical decision support capability by a combination of improved weather predictions together with automation and traffic flow management tools to generate and evaluate rerouting options on an ongoing basis.

A foundation for the rapid development of such tactical capabilities exist through the introduction of weather systems such as ITWS/CIWS, URET, “direct to” and CRCT. The success to date in tactical delay reduction with ITWS at major terminal areas suggests that a major en route initiative would also be very cost/effective. However, there will need to be significant improvements in the current weather prediction and automation/traffic flow management capabilities to provide en route convective delay reductions that are comparable to the terminal delay reductions.

In particular, we highlight the need to accomplish multi-ARTCC flight path amendment and traffic flow management coordination as well as the development of algorithms for automatic reroute generation in cases where the availability of routes is characterized stochastically for times > 30 to 60 minutes in the future.

We also recommend that operations research studies be carried out to assess how much delay in the current system when convective weather occurs would be avoidable given perfect forecasts and optimized rerouting. These studies would help to bound the potential delay reduction that could be achieved and, highlight the weather prediction and ATM decision support capabilities that would have the greatest potential for achieving significant delay reductions.

Refere nces

Allan, S., S. Gaddy and J. Evans, "Delay Causality and Reduction at the New York City Airports Using Terminal Weather Information Systems" Massachusetts Institute of Technology, Lincoln Laboratory, Project Report ATC-291, 16 February 2001.

Evans, J.E., and E.R. Ducot, "The Integrated Terminal Weather System (ITWS)", Massachusetts Institute of Technology, *The Lincoln Laboratory Journal*, Vol. 7, No.2, fall 1994.

Meyer, R. "Improvements in terminal area aviation weather operations: ITWS-a user friendly system", Journal of ATC, April-June 2001, pp. 13-16.

Hansman, J. Presentation at Workshop on Airline and National Strategies for Dealing with Airport and Airspace Congestion. (University of Maryland, March 15, 2001)

Klein, S. Presentation at Airline Dispatch Federation annual meeting (Washington, DC, Oct. 2001).

Rhoda, D. and M. Pawlak, "An Assessment of Thunderstorm Penetrations and Deviation by Commercial Aircraft in the Terminal Area", Project Report NASA/A-2, June 1999, MIT Lincoln Laboratory

Wolfson, M.M, B.E. Forman, R.G. Hallowell, and M.P. Moore, "The Growth and Decay Storm Tracker," American Meteorological Society 79th Annual Meeting, Dallas, TX, January 1999.

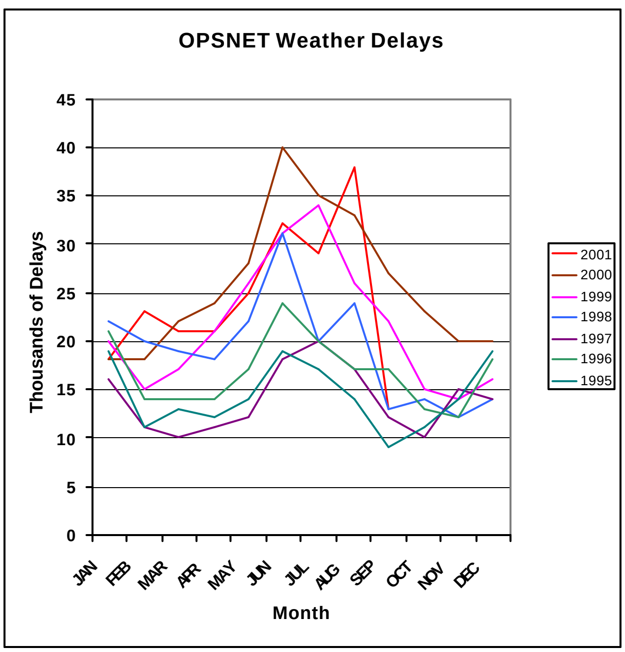

Figure 1. Weather related delays in US air system by month. Increased delays in fall of 2000 reflect over scheduling at La Guardia airport. Weather delays account for 65-70% of US delays. The major growth in delays has been in months characterized by convective storms.

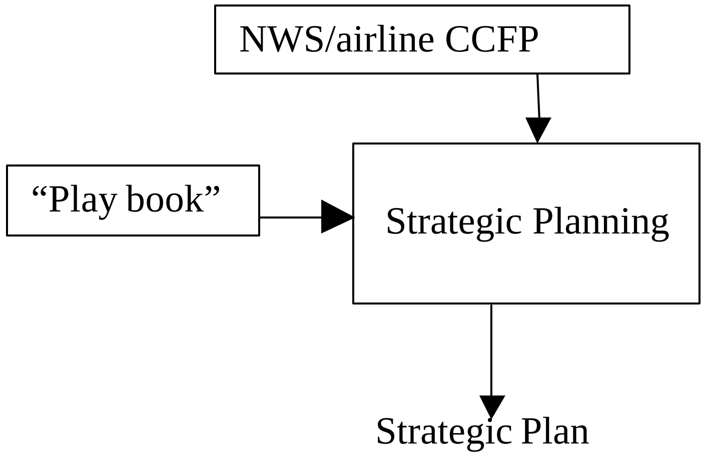

Figure 2. Collaborative process used to generate strategic plans every 2 hours; Collaborative Convective Forecast Product (CCFP) 2, 4 and 6 hour forecasts are issued every 4 hours. "Play book" are responses to hypothesized impenetrable weather.

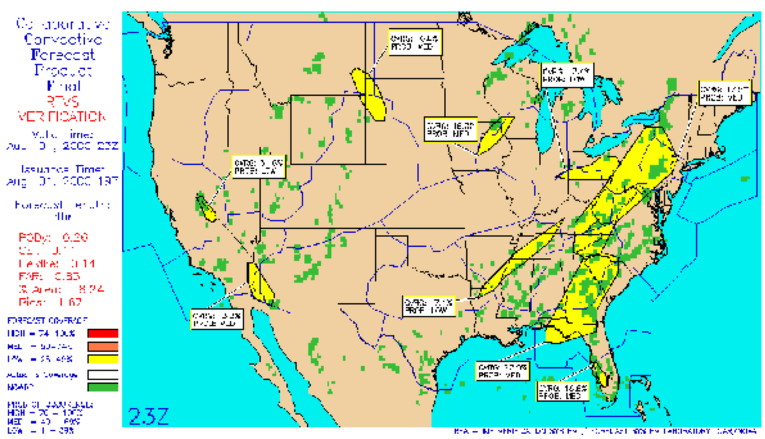

Figure 3. CCFP vs. actual VIP level-3 weather on 1 August 2000. Yellow polygons are areas where predicted coverage was 25–49%. Probability of weather occurring at forecast time was 20-50%.

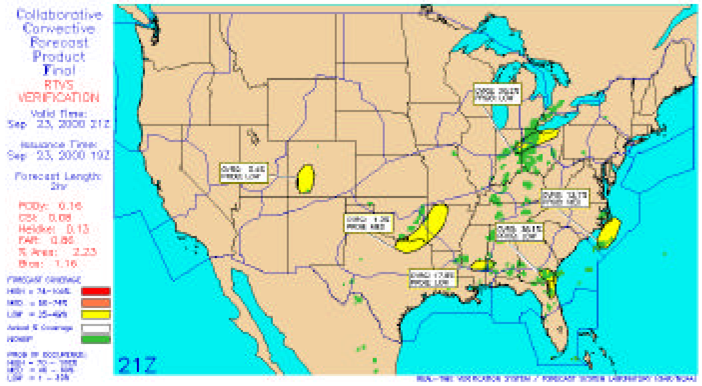

Figure 4. Example where actual weather (green areas) was more widespread than forecast (polygon is forecast). Forecast coverage was 25-49% for all polygons.

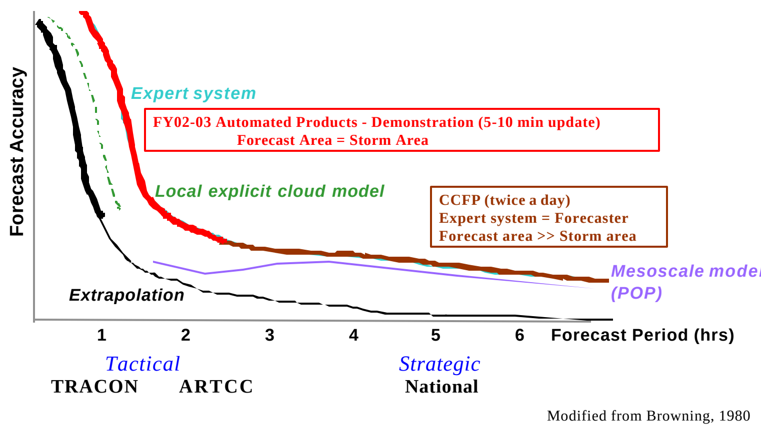

Figure 5. Projected storm cell prediction accuracy by FAA Aviation Weather Research (AWR) convective weather product development team.

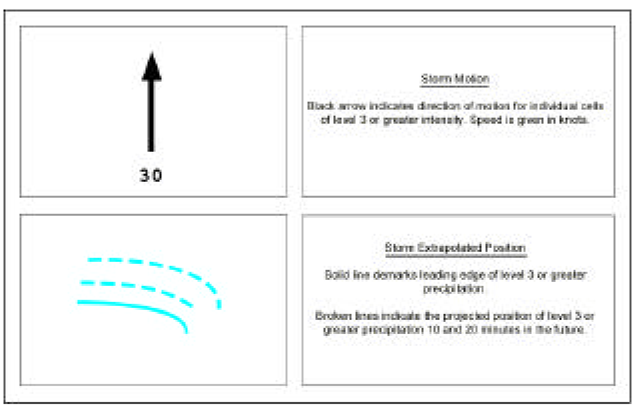

Figure 6. Depiction of storm motion and extrapolated positions by ITWS.

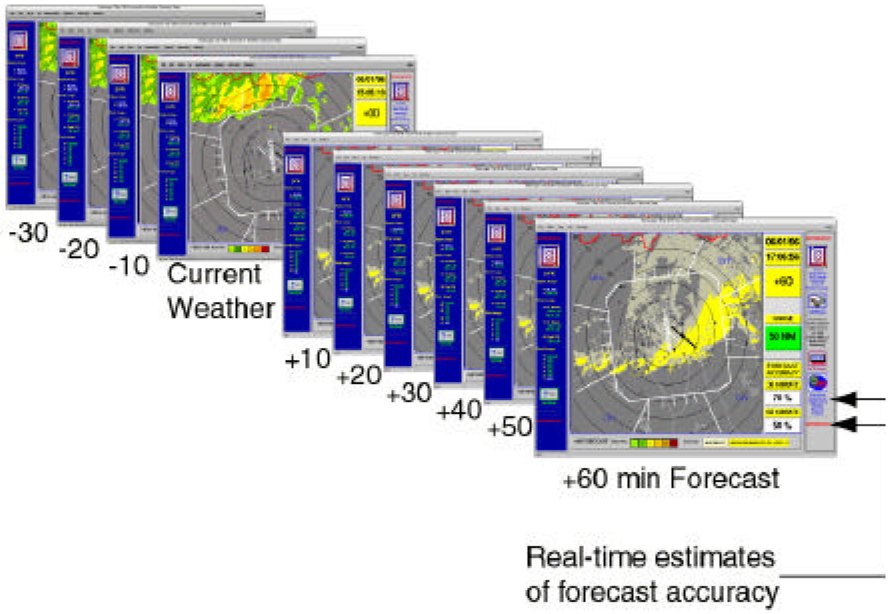

Figure 7. Terminal Convective Weather Forecast display. The light areas in the forecast windows (+10 to +60 min) indicate moderate and high probability of "level 3" weather (typically heavy rain). The continuous forecast loops from the past 30 minutes to the forecast time (30 or 60 min in the future). Various time subsets can be looped. Users can also select a stationary display of any forecast time. The accuracy of the forecast is continually updated in real time, based on pixel overlap criteria, and displayed as soon as it is available.

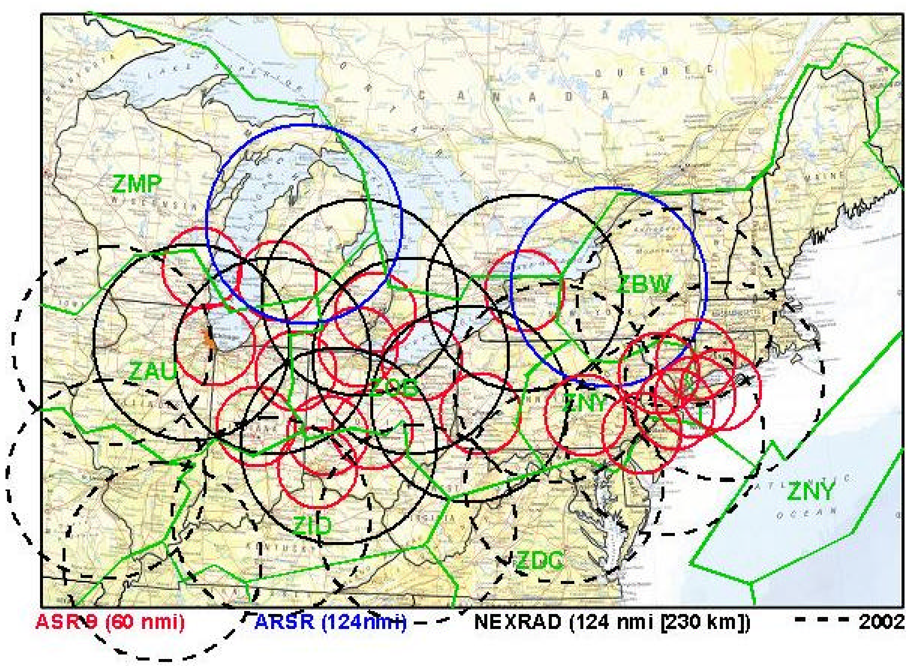

Figure 8. Coverage of sensors for Corridor Integrated Weather System (CIWS) concept exploration in 2001-02. Large circles are NEXRADs or ARSR4s: small circles are ASR9s. Solid large circles are NEXRADs used in 2001. The two northern large circles are ARSR4s. Dashed black circles are additional NEXRADs to be used in 2002. Not shown are TDWRs at many of the ASR9 locations.

Biography

Jim Evans has 30 years of personal experience in air traffic control and the aviation system. For the past 20 years, he has been developing new aviation weather decision support systems. This has included heading the Lincoln Laboratory programs to develop the Terminal Doppler Weather Radar (now at 43 major airports), the Integrated Terminal Weather System (ITWS), and the Corridor Integrated Weather System (CIWS). His current professional interests include operations research on the aviation system when impacted by adverse weather as well as environmental sensing and prediction. He has authored over 50 publications in refereed journals, conference proceedings and book chapters (including "Use of Terminal Weather Information Systems in Airline Operations," a chapter in the Handbook of Airlines Operations, Editors, Butler, G. and Keller, M., McGraw Hill, 2000). He is a FAA representative on the NEXRAD weather radar Technical Advisory Committee (TAC). Prior to working on aviation weather decision support systems, he was project lead on Lincoln studies of the Microwave Landing System (MLS) including supporting the US delegation to the ICAO All Weather Operations Panel. He received all (SB, SM and PhD) his degrees from the Massachusetts Institute of Technology (MIT). He is currently a senior staff member at MIT Lincoln Laboratory and a visiting scholar at the University of California, Berkeley.