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ATC-347

Roadmap for Weather Integration into Traffic Flow Management Modernization (TFM-M)

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16. Abstract

This report provides recommendations for aligning new Collaborative Air Traffic Management Technologies (CATM-T) with evolving aviation weather products to improve NAS efficiency during adverse (especially severe) weather conditions. Key gaps identified include

1. Improving or developing pilot convective storm avoidance models as well as models for route blockage and capacity in severe weather is necessary for automated congestion prediction and resolution.
2. Forecasts need to characterize uncertainty that can be used by CATM tools and, explicitly forecast key parameters needed for translation of weather products to capacity impacts.
3. Time based flow management will require substantial progress in both the translation modeling and in predicting appropriate storm avoidance trajectories. Near term efforts should focus on integration of the Traffic Management Advisor (TMA) with contemporary severe weather products such as the Corridor Integrated Weather System (CIWS).
4. Human factors studies on product design to improve individual decision making, improved collaborative decision making in “difficult” situations, and the use of probabilistic products are also essential.
5. Studies need to be carried out to determine how well en route and terminal capacity currently is being utilized during adverse weather events so as to identify the highest priority areas for integrated weather-CATM system development.

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ABSTRACT

This report provides recommendations for aligning the phased implementation of new Collaborative Air Traffic Management Technologies (CATM-T) with evolving capabilities for diagnosing and forecasting aviation-impacting weather conditions. This “weather integration” is needed to improve the operational utility of a number of planned TFM tools during severe weather so as to improve safety and reduce delays.

The key components of this roadmap analysis were the projection of the expected evolution of operational weather forecast capability based on efforts underway or planned, and the assessment of the weather input needs of current and evolving TFM tools such as Airspace Flow Programs (AFP) and time based flow management [e.g., Traffic management advisor (TMA), departure flow management (DFM)].

Principal recommendations include:

- Improving or developing pilot convective storm avoidance models for all phases of flight is very important for nearly all envisioned functional TFM capabilities. These models will determine which severe weather parameters (e.g., radar reflectivity metrics, storm echo tops and storm growth regions) should be generated by the weather forecast algorithms.
- Developing and validating models for route blockage and capacity in terminal and en route airspace also needs to be accomplished in the near term.
- The NextGen goal of migration to time based flow management will require substantial progress in many different areas including quantitative prediction of storm avoidance trajectories that are compatible with maintaining a feasible level of complexity in managing aircraft-to-aircraft separation. Given the many technical challenges in achieving such progress, we suggest that a near term study be conducted of the feasibility of integrating the CIWS system with TMA based on the insights gained from the ad hoc solutions to severe weather operations that are being developed by the current TMA users.
- Human factors studies in areas such as design of integrated products to improve decision making, improved collaborative decision making between different ATC facilities and airlines, and the use of probabilistic products will also be essential. The ongoing studies of the use of probabilistic ceiling/visibility forecast products at SFO should provide useful insights that can be applied to other types of adverse weather.
- Studies need to be carried out to determine how well en route and terminal capacity is being utilized during adverse weather events so as to identify the high priority areas for integrated weather-ATM research and development. This would also provide a quantitative metric for the effectiveness of TFM in adverse weather.

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1. INTRODUCTION AND SCOPE

This report provides recommendations for aligning the phased implementation of new Collaborative Air Traffic Management Technologies (CATM-T) with evolving capabilities for diagnosing and forecasting aviation-impacting weather conditions and for translating the weather forecasts into forecasts of impacts on NAS operations. This "weather integration" is needed to improve the operational utility of a number of planned TFM tools during severe weather.

The key components of this roadmap analysis are:

1. Projection of the expected evolution of operational weather forecast capability based on efforts underway or planned (especially in the FAA Aviation Weather Research Program and National Weather Service). Capabilities assessed will include forecast accuracy (versus look-ahead-time), the capability of the forecasts to support quantitative "airspace impact" assessments and, the ability to characterize forecast uncertainty in a manner that facilitates various modes of decision making (e.g., from manual to fully automated decision support);

2. Assessment of the weather input needs of current and evolving TFM tools [e.g., System Enhancements for Versatile Electronic Negotiation (SEVEN), Airspace Flow Program (AFP), Departure Flow Management (DFM)] and assessing how the specifics of the weather products (e.g., spatial and temporal resolution, accuracy, uncertainty metrics) will affect their utilization for TFM);

3. Recommendations for the evolution and time alignment of evolving weather and TFM tools including the identification of dependencies, risks and decision points.

An important component of the road map analysis has been the identification of "gaps", i.e., needed TFM or weather capabilities that do not appear to be covered in current work plans.

In this introductory section, we will provide some background material for this study including a brief summary of some recent studies related to weather-TFM integration and then conclude with a description of the structure of the reports.

1.1 WEATHER IMPACTS ON TFM IN THE NAS

The procedure changes and operational adjustments made to maintain safety during adverse weather have a major impact on the capacity of the U.S. National Airspace System (NAS). Airport operations rates are reduced to account for adverse surface winds, wind shear, low cloud ceiling or visibility conditions, degraded runway braking action and thunderstorms affecting terminal approach or departure paths. In en route airspace, thunderstorms may block jet routes or require significant flow-rate reductions, turbulence may effectively remove some flight levels from operational use and icing conditions may impact lower altitude operations for some classes of aircraft.

U.S. airports typically schedule for fair weather operations such that it is necessary to invoke traffic flow management initiatives (TMIs) when adverse weather reduces the capacity to less than the demand[1]. In cases where a non-convective weather impact is localized to the airport, objective estimates for the associated operations rate reductions are often available because the weather results in defined changes in runway configuration and/or aircraft spacing on approach or departure from the runways[2]. Ground delay programs have proven to be an appropriate traffic flow management mechanism for management of situations where the arrival demand exceeds the arrival capacity and, there is a well defined procedure Flight Schedule Monitor (FSM) by which customers can optimize their share of the available arrival capacity.

As a specific example, independent parallel approaches to San Francisco's International Airport's (SFO) Runways 28 RL must be suspended when cloud ceiling height is less than 2500 ft. This requires an increase of nearly a factor of two in average in-trail separation between landing aircraft and a corresponding arrival rate reduction from 60 to 30 per hour. Ground delay programs (GDPs) for SFO are routinely implemented in circumstances where cloud ceiling is forecast to remain below the threshold for independent parallel approaches during peak demand periods. A well defined procedure exists for allocation of SFO arrival slots to various airlines and the airlines can optimize their use of the arrival slots (e.g., by delaying or cancelling one flight so that a different higher priority flight can utilize an arrival slot allocated to the airport). Low ceiling/visibility conditions, synoptic changes in runway winds, and other airport capacity factors such as sheared winds aloft (leading to compression), wet runways or snow typically change fairly slowly such that setting GDP program rates is generally relatively straightforward and can be adjusted in real time based on operational experience.

By contrast, TFM decision making for convective weather (which is the principal cause of the summer delays shown in Figure 1-1) is very difficult and, despite a number of advances in traffic flow management capability, major FAA-customer initiatives (e.g., the S2K programs) and aviation weather products since 2000, NAS delays associated with severe weather have been comparable to or higher than those in 2000 as shown in Figure 1-1.

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[1] This US policy is rather different from that European policy of scheduling to the airport IMC capacity and forgoing the possible use of the additional airport capacity that is typically available under VFR flight rules and procedures.

[2] The FAA Airport Capacity Benchmark Report (2004) and local procedures provide explicit quantitative estimates for the reduction in capacity associated with low ceiling and visibility conditions as a function of the operational runway configuration at major airports.

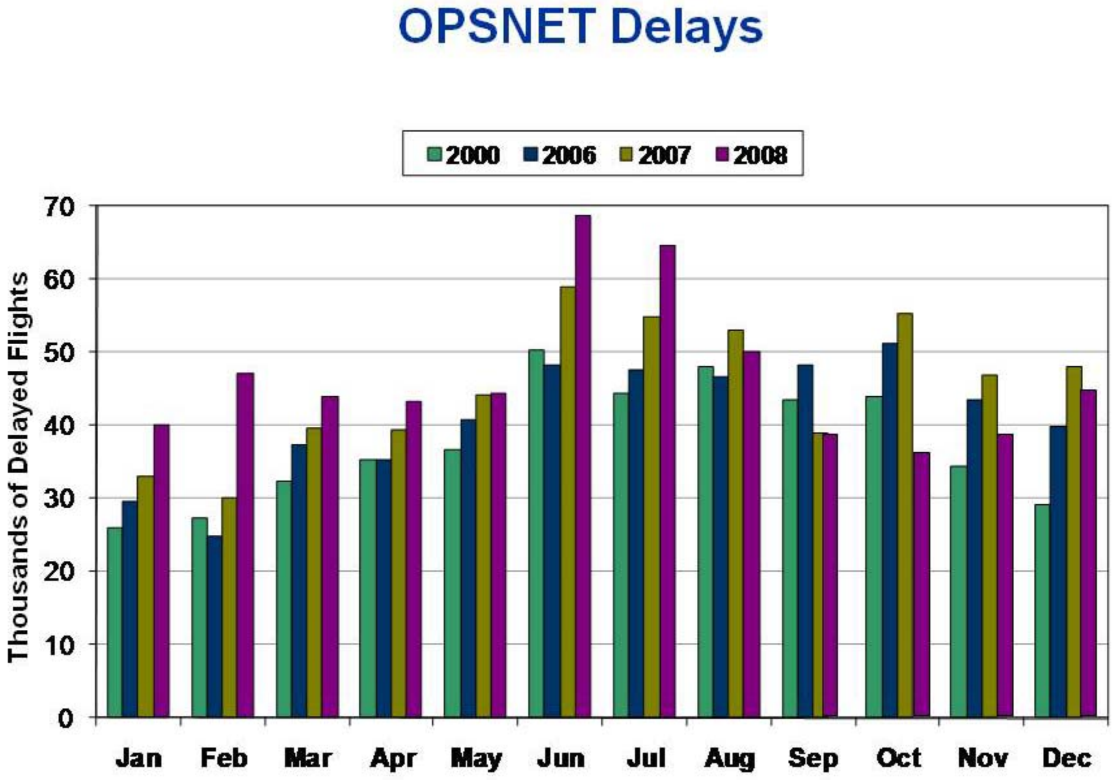

Figure 1-1. U.S. air traffic delays as measured by the FAA Air Traffic Operations Network (OPSNET) data base. OPSNET counts the number of delays of 15 minutes or more in a single Air Traffic Control (ATC) facility (including ground holds at the departure airport). 2008 had the greatest number of OPSNET delays of any of the years shown through August of the respective years; 2007 had previously set an all time record for OPSNET delays. The traffic at major airports in 2005 through 2008 was typically 7-8 % lower than the traffic in 2000. The number of ARTCC operations for 2007 were essentially unchanged from 2000. Traffic management system (TMS) delays accounted for about 5/6 of all OPSNET delays in the summer of 2008 with APFs and GDPs accounting for about half of the summer 2008 TMS delays.

The FAA is also concerned that anticipated increases in air traffic will result in much worse convective weather season delays by 2014 (Hughes, 2006).

The intensity of hazardous precipitation and turbulence associated with thunderstorms varies rapidly in space and time. Thunderstorm forecasts with the look-ahead-times (≥2 hour) needed to coordinate strategic traffic management initiatives (TMI) usually do not have the precision needed to determine which specific NAS resources (runways, arrival or departure transition areas, jet routes) will be impacted. Thus the impact on operations is inherently dynamic with a high degree of uncertainty on the future state of the system.

Pilots and ATC have considerable discretion in the tactical responses they choose to maintain safe separation from the storms. Although airline policies state their pilots maintain defined buffer-distances from all thunderstorms, these distances may be difficult to determine in real time and may be altered in practice to deal with the realities of the operational situation. The ability of

ATC to modify flows to avoid the thunderstorms varies greatly with the operational setting and circumstances[3]. Differences in terminal and en route operating paradigms, the density of jet routes and the extent to which flow modifications require coordination across sector and/or center boundaries are important factors in determining the effective capacity impact of the convective weather and in accomplishing traffic flow adjustments. No explicit guidelines (akin to the capacity benchmarks for IMC conditions at airports) currently exist for the capacity impact of convective weather.

Consequently, current traffic management initiatives during convection are based on best judgment of the personnel in the affected ATC facilities, the Air Traffic Control System Command Center (ATSCC) and airline operations centers as to the capacity impacts and appropriate traffic management initiatives (TMIs).

In view of importance of convective weather impact mitigation and, the current lack of operational integrated weather-TFM decision support tools, this weather roadmap focuses on weather-TFM integration associated with convective weather.

1.2 PAST STUDIES RELATED TO THE INTEGRATION OF WEATHER INTO TFM

1.2.1 National Academy study of weather forecasting accuracy for TFM

Under FAA sponsorship, the National Research Council (NRC) of the National Academy of Sciences conducted a workshop on weather forecasting accuracy for TFM in 2002. The workshop was then reviewed by an external independent set of reviewers and published in 2003 (NRC, 2003). The principal objectives of the workshop were to:

(1) Recommend approaches and strategies to obtain 2-6 hour accurate forecasts of regions of convective weather;
(2) Suggest scientific enabling strategies;
(3) Examine the best way to present the forecast information; and
(4) Suggest appropriate verification techniques.

The workshop participants viewed the FAA’s initial accuracy specification (Pd 80%, Pfa 20%) as unrealistic. Instead, it was suggested that the FAA should seek a 50% improvement in 2–6 hour forecast skill in 3–5 years and another 50% increase in the next 5 years.

The workshop participants noted that accurate predictions 2–6 hours in advance are very difficult due to both initial condition uncertainty (both in the boundary layer and aloft) and modeling uncertainties (e.g., microphysics, heating, cooling, boundary and surface layers).

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[3] For example, Rhoda and Pawlak (2002) found that on many occasions, aircraft landing at Memphis and Dallas were observed to penetrate very high reflectivity storms when within 10 n mi of the airport.

The report suggested that there was a predictability "wall" for convective forecasts at less than 3 hours lead time for all but very strongly forced synoptic situations[4], and suggested that the most promising long term approach would be ensemble forecasts from convection resolving (e.g., 1 km grid size) models run over continental–scale domains. The workshop recognized that having the computational capability to run such grids was probably a decade in the future and suggested an interim hybrid approach which is rather similar to the Consolidated Storm Prediction for Aviation (CoSPA) approach which will be discussed in Section 2.

The workshop recommended that the forecast products be designed to facilitate use by ATC personnel and airlines so as to predict capacity impacts, route blockage, and fuel loading. In particular, convective storm features such as spatial coverage, organization, height, strength, state of development and lightning needed to be related to key operational factors such as route availability and the capacity of en-route sectors and terminals. It was also suggested that the FAA have a robust "tactical" convective weather decision support capability in addition to the "strategic" TFM capability that was the principal focus of the workshop.

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[4] Dr. Andrew Crook of NCAR suggested that single cells might be predictable for 10–60 minutes, large thunderstorms 1–2 hours, strong squall lines 2–3 hours and large mesoscale convective systems for 6 hours and noted that about 80% of the convective activity is associated with the first two type of convective weather. Figure 1-2 shows the type of convective storms observed in the Northeast in 2002 as well as a typical spatial pattern for each type of convective storm.

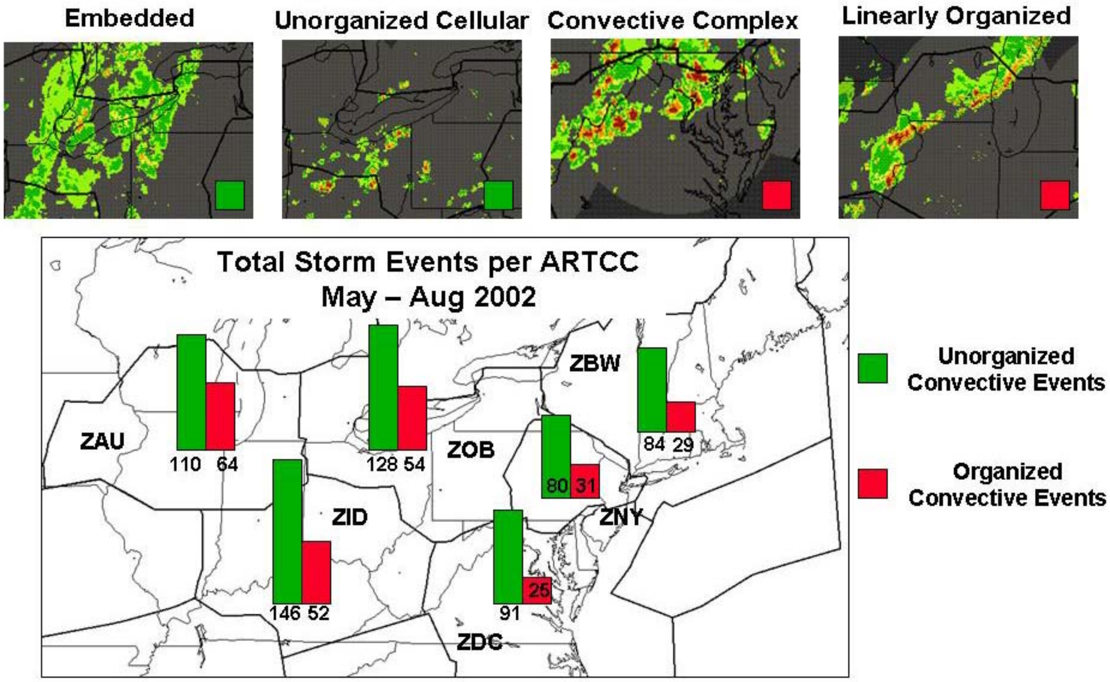

Figure 1-2. Typical spatial patterns of convective weather in the Northeast and their frequency during 2002. The "unorganized" situations are particularly hard to predict more than an hour in advance.

1.2.2 FAA R&D Advisory Committee (REDAC) study of weather-ATM integration

A two year study by the Weather – ATM Integration Working Group (WAIWG) of the National Airspace System Operations Subcommittee, Federal Aviation Administration (FAA) Research, Engineering and Development Advisory Committee (REDAC) provides a useful framework for considering weather-TFM integration as well as some germane recommendations. The WAIWG concluded (FAA REDAC, 2007) the following:

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

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

- Much of today's convective weather delay appears to be avoidable if improved forecasts and ATM decision support tools could be developed[5].
- The solution to the overall ATM decision making problem is to develop integrated weather-ATM decision tools (Figure 1-3) where weather information and forecasts are translated from words, pictures or probabilities into quantifiable airspace capacity impact values which are then appropriately incorporated into ATM processes and technology.

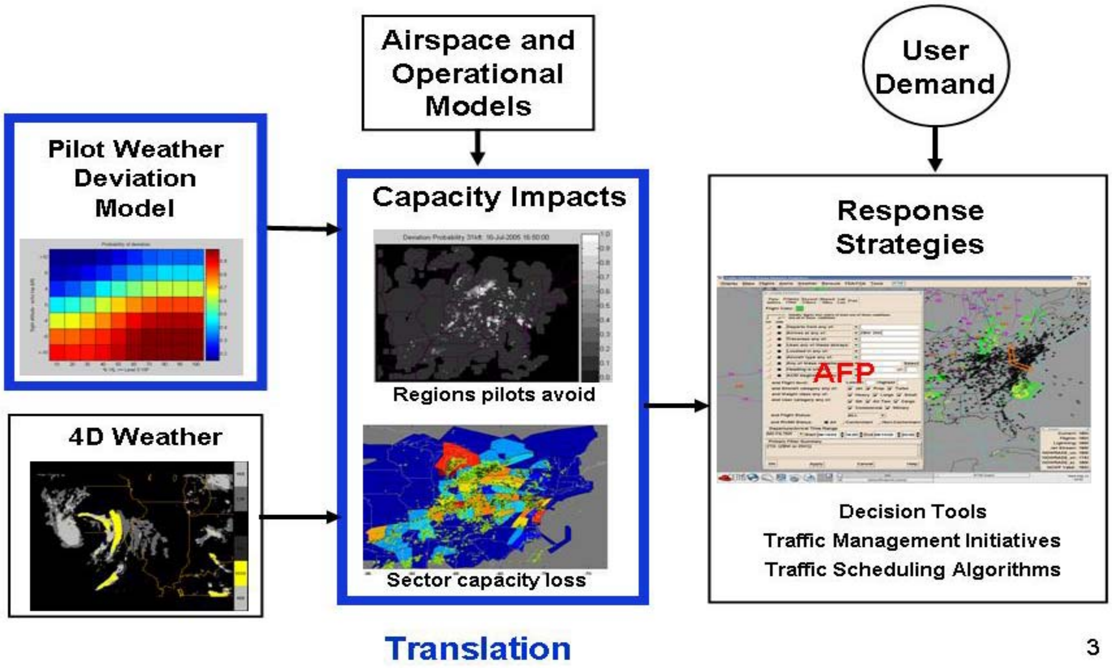

Figure 1-3. Weather – ATM Integration Architecture recommendation by REDAC WAIWG. Weather forecasts must be translated into capacity impact forecasts by considering both pilot preferences for storm avoidance and airspace and ATC operational constraints (dark blue boxes), and then used to generate ATM decision support.

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[5] This WAIWG conclusion was based on the analysis of three convective weather events using an automated congestion resolution algorithm operating on sector capacity estimates derived from measured CIWS reflectivity and echo tops data (Robinson, Moser, and Evans, 2008).

The structure of this report is as follows. Section 2 summarizes aviation weather product development activities that are likely to contribute to enhanced Traffic Flow Management capability in the next 7 years, while Section 3 considers the ability to transfer those weather products to TFM and customer systems. Section 4 is an overview of current research developing approaches to translating weather measurements and forecasts into airspace capacity impacts. Section 5 presents a recommended alignment of weather forecast and CATM-T capability development. Section 6 discusses the human factors elements of achieving a robust, timely decision process for addressing adverse weather impacts. Section 7 summarizes our findings and recommendations.

2. AVIATION WEATHER DIAGNOSIS AND FORECAST CAPABILITIES

This section provides our assessment of anticipated progress in the development of operational aviation weather diagnosis and forecast capabilities over the next 7 years (that is 2009–2016). The FAA Mission Needs Statement for Aviation Weather MNS #339 (June 2002) addressed key gaps in technology and the associated investment packages needed to mitigate various weather-related problems in the NAS. These problems were categorized as primarily safety-oriented, or related to efficiency and delays, and an "Alignment Score" was produced for each of these (see Table 2-1 below).

In Sections 2.1 and 2.2, we revisit MNS #339 to update recent scientific progress in the primary Aviation Weather categories, and to estimate future capabilities. Efforts to improve the dissemination of these weather products to operational decision makers and automation systems are discussed in Section 2.3.

TABLE 2-1

Aviation Weather Investment Packages Sorted by Alignment to FAA Goals

(MNS #339)

Investment Packages	Shortfalls	Target Agency Goals	Alignment Score
Thunderstorm (TS) Impact Mitigation	Current state of the atmosphere and forecast state of the atmosphere products may not be generated, may lack accuracy and resolution, may not be disseminated to users, or may not be available to all users in an acceptable format	Safety and Efficiency (delays)	10
In-flight Icing (IFI) Impact Mitigation	Current state and forecast state of the atmosphere products lack accuracy and resolution and is not be disseminated to users in a graphical format that does not require meteorological interpretation.	Safety	7.4
Obstruction to Visibility (OTV) Impact Mitigation	Current and forecast state of the atmosphere products lack accuracy and resolution, may not be disseminated to users, or may not be available to all users in an acceptable format.	Safety and Efficiency (delays)	6.5
Wind Shear (WS) Coverage Expansion	Detection and forecasting of low-level wind shear may need improvement and more airports need the detection and forecast capabilities.	Safety	4.1

Investment Packages	Shortfalls	Target Agency Goals	Alignment Score
Non-convective Turbulence Impact Mitigation and Winds Aloft (NCT&WA) Optimization	Current and forecast Non-convective Turbulence and Winds Aloft products may not be generated, may lack accuracy and resolution, may not be disseminated to users, or may not be available to all users in an acceptable format.	Safety and Efficiency (Delays, fuel savings)	3.7
Mitigation of Snow and Ice (SI) Impact on Ground Operations	Current and forecast Snow and Ice products may lack accuracy and resolution, may not be disseminated to users, or may not be available to all users in an acceptable format.	Safety and Efficiency (delays)	3.5
Efficient Airport Reconfiguration (EAR) in Response to Wind Changes	Current and nowcast wind shift changes products do not exist and is not disseminated to users in an acceptable format.	Efficiency (delays)	2.4
Wake Vortex (WV) Mitigation	Current wake vortices location and movement product does not exist and is not disseminated to users in an acceptable format.	Efficiency (delays)	0.7

It should be noted that although the table above only aligns wake vortex mitigation with Efficiency (delays). However, wake vortex encounters in the terminal area when an aircraft is not on final approach or initial departure can be a significant safety concern as was exemplified in the American Airlines flight 587 accident at New York on 12 November 2001 (see, e.g., http://en.wikipedia.org/wiki/American_Airlines_Flight_587).

2.1 THUNDERSTORM DIAGNOSIS AND FORECASTING

Recent work on thunderstorm depiction and forecasting has included a move away from purely summer thunderstorms, to recognizing that both summer and winter storms can occur simultaneously, and any storm analysis / forecast system needs to handle both accurately. It also includes the Collaborative Storm Prediction for Aviation (CoSPA) initiative. In 2006 the upper management of FAA operations planning insisted that the different summer and winter forecast systems, with different depictions of storms, local, regional and national coverage, human-generated and automated forecast creation, all be brought under one single consolidated system called CoSPA (Wolfson, et al., 2008). The Corridor Integrated Weather System (CIWS) [Evans and Ducot, 2006], with its 0–2 hr forecasts, represents the first component of CoSPA. The Aviation Weather Research Program is funding research and demonstrations that integrate with CIWS and extend this forecast lead time out to 8 hours.

2.1.1 Current state of the atmosphere

(a) Corridor Integrated Weather Systems

The Corridor Integrated Weather System, now with CONUS coverage, is funded primarily by FAA System Operations, with algorithm development support from the Aviation Weather Research Program. It provides weather decision support for en route traffic managers to assist in tactical adjustment of traffic flows during severe weather events. CIWS provides a depiction of storms (Figure 2-1) with the following characteristics:

Precipitation[6], Winter Precipitation[7] and Echo Tops[8]

- 1 km resolution, 2.5 min update rate
- Includes motion compensation of all radar data to a common time
- Includes NEXRAD, TDWR and Canadian radar data
- 2D mosaics
- Latency less than 1 min

Background available: Satellite (Visible and Infrared, from GOES E and W)

Overlays available:

- Lightning ground strike data (6-min avg.)
- Precipitation Growth & Decay Trends (diagnosis)
- Storm Motion (speed and direction)
- Echo Tops Tags

(b) Integrated Terminal Weather System (ITWS)

The ITWS provides weather decision support for terminal traffic managers to assist in tactical adjustment of traffic flows when thunderstorms impact the terminal area. ITWS provides the weather depictions shown in Table 2-2.

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[6] Precipitation is represented by VIL: vertically integrated liquid water, in VIP levels

[7] Winter Precipitation includes snow-mix-rain designation via color-coding.

[8] Echo Tops is the height in Kft of the 18 dBZ surface, in Kft.

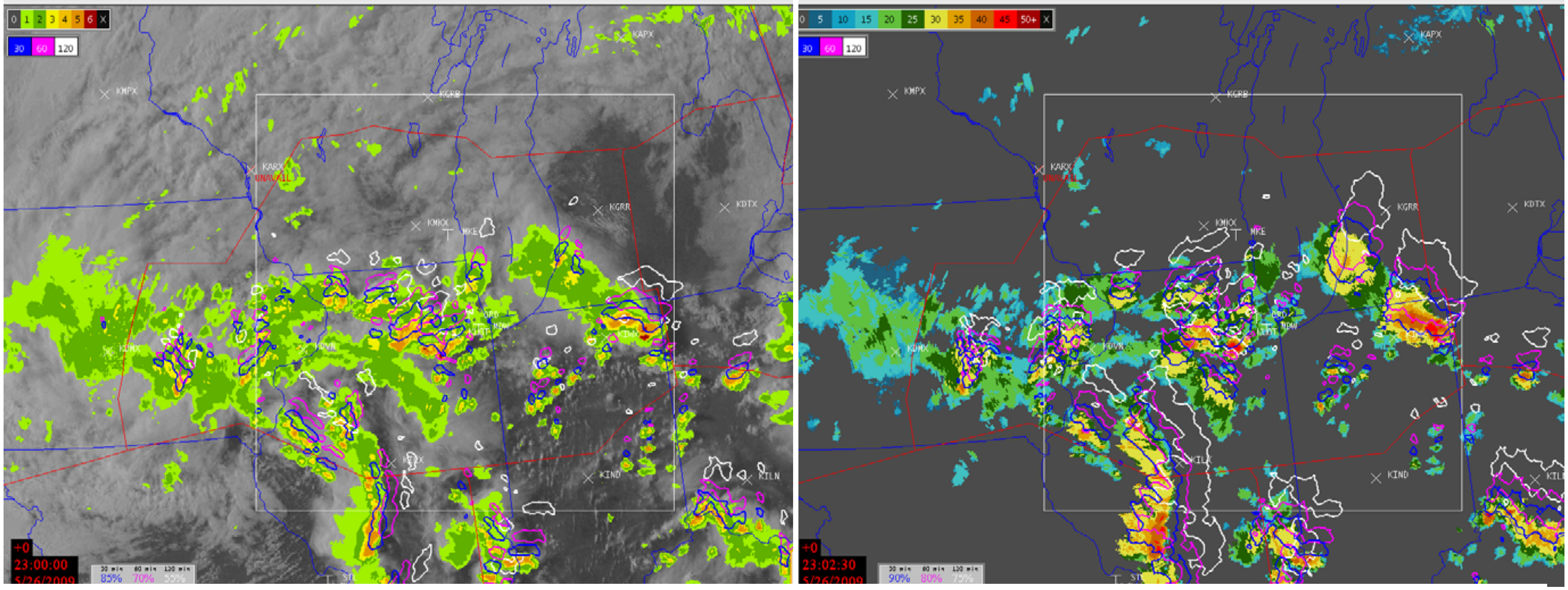

Figure 2-1. CIWS real time precipitation (left) and echo tops (right) products. The contours show the projected locations of strong precipitation (VIP level 3) and echo tops (30 kft) regions 30, 60 and 120 minutes in the future. Boxes in lower left hand are recent past forecast accuracies in the region covered by the white box in the respective figures.

The ITWS ASR-9 weather reflectivity product updates much more rapidly than does either the ITWS NEXRAD/TDWR mosaic or the CIWS NEXRAD/TDWR/Canadian mosaic. This is possible due to the rapid scan rate of the ASR-9.

The ITWS wind shear depictions are operationally used by both the terminal TFM managers and the ATCSCC to determine when tactical TMIs need to be implemented to address the loss of airport capacity due to wind shear phenomena (e.g., a first tier ground stop might be needed if a significant holding pattern arises as a result of loss of an arrival runway due to microburst impacts).

It should be noted that the ITWS terminal winds product has been found to be useful in gaining approval for GDP programs at the NY TRACON (N90) to address the arrival capacity constraints due to vertical wind shear aloft in the terminal area which leads to problems with compression on final approach (Allan, et al., 2001).

TABLE 2-2

ITWS Weather Depiction Product Update Rate[1] and Technical Performance[2]

Product	Data Sources	Product Update Interval (min[3])	Product Spatial Resolution (nmi[3])	Typical Performance
Microburst detection	TDWR[3]	1	1	$P_d{}^3 > 0.95$, $P_{fa}{}^3 < 0.05$
Microburst prediction	TDWR, MDCRS[3], Soundings, ASOS[3]	2.5	---	$P_d \approx 0.3 P_{fa} < 0.1$
Gust Front detection	TDWR	5	1	$P_d \approx 0.7$, $P_{fa} \approx 0.1$
Gust Front current location	TDWR	1[4]	1	----- -----
Wind Shift	TDWR, LLWAS[3]	5	---	Wind to within ± 8 knots, ± 30° 60% of time for wind shifts > 15 knots[6]
Airport precipitation	TDWR	1	0.13	----- -----
TRACON precipitation	ASR9 mosaic[5]	0.5	0.5	----- -----
Long Range precipitation (200 nmi)	NEXRAD and TDWR[3]	5	0.5	----- -----
Storm Motion	Precip source	1– 5[7]	---	Within 10 knots for 90% of storms moving faster than 10 knots
Storm Cell information (hail, severe storm, echo tops, lightning)	NLDN[3], NEXRAD	1-5[7]	---	-----
Terminal Winds	TDWR, NEXRAD, MDCRS, RUC[3]	5[4]	Vertical: 50 mb[3] Horizontal: ≤1 nmi within the TRACON and ≤18 kft[3]; ≤5 nmi outside the TRACON or >18 kft	-----
Tornado Vortex Signature	NEXRAD	5	0.5	
Ribbon display alerts and active runways. Runway winds	TDWR, LLWAS	0.15[8]	---	-----

Product	Data Sources	Product Update Interval (min[3])	Product Spatial Resolution (nmi[3])	Typical Performance
Lightning within 20 nmi of airport	NLDN	0.083	0.25	NLDN detects 80-90% of cloud-to-ground lightning[9]

Table 2-2 Footnotes:

1 Unless noted otherwise, update rate is nominal because the actual update is triggered by an external sensor.

2. Performance results from Klingle-Wilson (1995) unless otherwise noted.

3.

min	minutes
nmi	nautical mile
TDWR	Terminal Doppler Weather Radar
P_d	Probability of Detection
P_{fa}	Probability of False Alarm
MDCRS	Meteorological Data Collection and Reporting System
ASOS	Automated Surface Observing System
LLWAS	Low Lever Windshear Alert System
NEXRAD	Next Generation Weather Radar
NLDN	National Lightning Detection Network
RUC	Rapid Update Cycle
mb	millibars
kft	thousands of feet

4. Update rate is clock-driven.

5. ASR reflectivity is quality checked against TDWR and Next Generation Radar (NEXRAD) data.

6. Performance requirement for accuracy of predicted wind shift.

7. Update interval is a function of the underlying precipitation product.

8. At Low Level Wind shear Alert System (LLWAS) expanded network (NE) airports, TDWR derived alerts are integrated with LLWAS NE alerts. The Ribbon display alert update at a rate consistent with the fastest update rate associated with the input sensors. Runway winds are provided by an LLWAS (when available) or, by the center field anemometer.

9. Cummins et al. 1998 and Idone et al. 1998.

(c) Three dimensional (3D) reflectivity mosaics

Three dimensional reflectivity mosaics are of increasing operational interest due to the NextGen initiative to provide 3D gridded weather depictions. The NOAA NSSL 3D reflectivity mosaic system is partially funded by FAA AWRP. This system currently primarily provides data for quantitative estimation of precipitation for NWS flood forecasting, but the 3D representation of storms provides the basic data needed for vertical cross-sections of storms along a flight path, and for initializing high resolution numerical models capable of assimilating radar data. Ingest of the 3D reflectivity mosaic data into the ADDS Flight Path Tool is planned for FY09. Use of the 3D mosaic to initialize the experimental 13-km RUC model run at NOAA GSD in Boulder will also take place in FY09. (This is the parent model for the experimental High Resolution Rapid Refresh nest used for CoSPA 2-8 hr forecasts.) Characteristics of the NSSL 3D reflectivity mosaic are as follows:

1 km resolution, 5 min update rate, 31 vertical levels with 0.25 – 1.0 km spacing
Does not include motion compensation
Includes NEXRAD and TDWR data
Latency <15 min over 90% of the time
Separate Canadian radar 3D mosaic
Data received post-archive, approx 20 min latency
VIL and Echo Tops available as derived products, in metric units and linear scales
Satellite (Infrared only), rain gauge data, and RUC model grids available

CIWS aviation-oriented mosaics can be generated from NEXRAD Level II base radar data, from the NEXRAD product level (Level III) high resolution VIL and Echo Tops, or potentially from the NSSL 3D mosaic. Research to compare the NSSL 3D mosaic derived products with the CIWS products has been proposed to the AWRP, but has not yet been funded.

Casual comparison shows that the two mosaics potentially could be made quite comparable, although the data quality editing, motion compensation prior to mosaicing, grid update rate and overall processing latency are all potentially significant issues that need to be considered. While it is desirable for a "clean" NextGen architecture to have a single US and Canadian radar mosaic, extending the very large NSSL 3D mosaic to meet CIWS timing, storm location accuracy and latency specifications will not be without significant cost, so the benefits of use of a single mosaic for all products will require considerable study.

(d) Other convective weather depictions

(i) ADDS web page

The NWS Aviation Digital Data Service (ADDS) web page has a "Convection" tab, under which the National Convective Weather Detection (NCWD) product can be found. This product development was also funded by the FAA Aviation Weather Research Program, but was frozen in 2006 so as to focus the available resources on the CoSPA development. NCWD offers a depiction of convection that begins with the 4-km resolution Unisys VIL product and removes all stratiform rain (showing only the highly convective areas, but eliminating significant heavy rain, and for the most part hurricanes, and winter storms). It also uses a non-standard 6-level color map and coarsely quantized VIL values. Lighting is incorporated in the VIL measurement in an ad-hoc fashion (Iskenderian, 2008). Latency of the NCWD, produced operationally at the NOAA Aviation Weather Center, is 7–10 min.

(ii) Weather and Radar Processor (WARP)

The WARP provides satellite, NEXRAD composite and layer composite reflectivity mosaics, and computer model data, as well as alphanumeric data at ARTCCs. The layered composite reflectivity products on the WARP displays are also used as weather radar overlays on en route Air Traffic Controllers, Display System Replacement (DSR) or radar displays. The WARP has remote display terminals in the areas and at the TMU.

The local ARTCC-centered NEXRAD mosaics are updated whenever any radar in the designated coverage region updates. No motion compensation adjustment of other radars is made prior to re-mosaicing. The centralized WARP mosaic of individual ARTCC mosaics is updated every 5 min. The WARP layers typically go from the surface to 24 kft, 24 kft to 33 kft, and above 33 kft. A coarse echo tops mosaic is also generated (Moosakhanian, et al., 2005).

The WARP composite reflectivity mosaics are not viewed as appropriate for translation into capacity impacts due to the many data quality problems associated with the maximum composite reflectivity (Robinson, et al., 2002). These mosaics also often depict echoes in the wrong place during fast moving storms because of the lack of motion compensation (Stobie et al., 2008; Ahlstrom and Dury, 2007)

The WARP also displays the NCWF-1 1-hr convective weather forecast (as overlay contours), now considered to be superseded technology.

(e) Expected enhancements in convective weather depiction capability (2008–2015):

Work on convective storm depiction over the next 7 years includes:

- processor-based and algorithmic improvements in radar data quality;
- lightning flashes converted to proxies for VIL & ET in quantitative fashion, and combined with VIL & ET mosaics as a safety back-up in case of degraded or lost radar coverage;
- dual polarimetric measurements from NEXRAD for precipitation type assessment (removal of bright band and other non-weather artifacts, robust hail detection, etc.),
- incorporation of NWS safety-related storm information such as the probability of hail and the tornado vortex signature,
- incorporation of NWS Fronts, with improved update rate, and runway wind shift estimates,
- convective induced turbulence detection and depiction.

2.1.2 Convection forecasting

(a) Current convective weather forecasts

The current convective weather forecasts that could generally be accessed by a traffic flow decision maker in 2008 (e.g., via dedicated displays or, via the WWW) are summarized in Table 2-3. A principal near-term objective of the Collaborative Storm Prediction for Aviation (CoSPA) multi-agency research program is to reduce the number of such forecasts to a single forecast that covers 0–8 hours.

The CIWS 0–2 hr forecasts of both precipitation (including winter precipitation with the rain/mix/snow depiction) and radar echo tops have been selected as the baseline 0–2 hr consolidated forecast products to be supported by the Aviation Weather Research Program as a part of CoSPA. They provide aviation-oriented high resolution tactical forecasts for both en route and terminal applications. The current CIWS 0–2 hour forecasts include:

(1) explicit calculation of storm growth and decay trends,
(2) improvement in the motion vectors and advection schemes,
(3) prediction of convective initiation through the combination of improved representation of surface forcing (fronts), environmental forcing (environmental stability) and the use of satellite data,
(4) inclusion of winter precipitation and tracking of the rain/snow line, and
(5) a radar echo tops forecast [Wolfson and Clark, 2007; Dupree et al., 2006].

Figure 2-1 showed an example of the CIWS real time reflectivity product with contoured overlays that show the expected location of high reflectivity regions 30, 60, and 120 minutes in advance. More commonly, the user view the CIWS forecasts in a time animation (“movie loop”) format.

TABLE 2-3

Comparison of 0–12 Hour Storm Forecast Systems

Product	Key Features of product	Local, Regional, National	Update Rate (min)	Spatial resolution (km)	Lead Time (hours)	Loop Interval (if animated) (min)	Human Involvement (Yes/No)	Deterministic or Probabilistic
Convective SIGMET Issued by: Aviation Weather Center, NWS Intended customers: Pilots, controllers, Traffic Flow Managers	Severe or Embedded Thunderstorms occurring for more than 30 minutes Line of thunderstorms Area of active thunderstorms	Regional	60	Any occurrence	2	N/A	Yes	Deterministic forecast of coverage >40%
CCFP Issued by: Aviation Weather Center Intended customers: Airlines(dispatch and ATC coordinators) Traffic Flow Managers (ATCSCC, ARTCC,ATCT), NBAA	Collaborative Effort	National	120	Must be an area > 10,290 km^2 or line > 111 km (with > 40 dBZ, > 25Kft)	2,4,6	N/A	Yes	Deterministic forecast of coverage (25, 50, 75%) incl. forecaster confidence
International SIGMET Issued by: Aviation Weather Center Intended customers: Dispatch, Airline planners	Obscured Embedded Frequent Squall line	Hemi-spherical	240	10,290 km^2 except obscured, embedded, and squall line which have no minimum	4	N/A	Yes	Deterministic
CWA(Center Weather Advisory) Issued by: CWSU Meteorologists Intended customers: same as convective SIGMET	Unscheduled weather advisory	Regional	As needed	Any occurrence	2	N/A	Yes	Deterministic
NCWF-1 Issued by: Aviation Weather Center on ADDS Intended customer: Meteorologists and Aviation Users	Convection tracked using Titan with 1-hr extrapolation	National	5	Storm scale	1	N/A	No	Deterministic

Product	Key Features of product	Local, Regional, National	Update Rate (min)	Spatial resolution (km)	Lead Time (hours)	Loop Interval (if animated) (min)	Human Involve ment (Yes/No)	Deterministic or Probabilistic
NCWF-2 Issued by: Currently experimental on ADDS Intended customer: Meteorologists and Aviation Users	Convection tracked using Titan VIL based RUC model output and lightning data included	National	5	4	2	30	No	Probabilistic
NCWF-6 Issued by: Currently experimental Intended customer: Meteorologists and Aviation Users	Blends extrap-based and model fcst of convection	National	15	4	6	60	No	Probabilistic
TCWF Issued by: FAA ITWS Intended customer: Air Traffic, Airlines	VIL-precip Winter mode Growth and Decay Fuzzy Logic based with NEXRAD, TDWR and RUC inputs	Local	VIL, ET 2.5 min Fcsts of VIL 5 min	1	1	10 [30 min in past to 1 hr in future]	No	Deterministic
CIWS 0–2 hr Forecast Issued by: FAA Concept exploration prototype system Intended customer: Air Traffic, Airlines	VIL-precip and Echo Tops Fcst Rain/snow line Winter mode Growth and Decay Fuzzy Logic based with multiple inputs (including NEXRAD, TDWR, CanRAD, RUC, STMAS, 1-min ASOS, lightning and satellite data)	Regional	VIL, ET 2.5 min Fcsts of VIL, ET 5 min	1	2	5 [1 hour in past to 2 hrs in future]	No	Deterministic and Probabilistic

Development continues in evaluating other forecasts (below) to determine which elements should be preserved in the CoSPA forecast that will be discussed subsequently:

1) The AutoNowcaster, developed primarily under AWRP funding which ended in 2006 in favor of the CoSPA system, and which is currently being studied under NWS funding as a platform for incorporating human forecaster input into the short-term automated forecasts.

2) The NWS Aviation Digital Data Service (ADDS) web page has a "Convection" tab, under which the National Convective Weather Forecast (NCWF) can be found. The NCWF is also available on WARP. The NCWF is a forecast of only convective storm features (i.e., no stratiform precipitation). NCWF offers a depiction of convection that begins with the 4-km resolution Unisys VIL product and removes all stratiform rain (showing only the highly convective areas, but eliminating significant heavy rain, and for the most part hurricanes, and winter storms). It also uses a non-standard 6-level color map and coarsely quantized VIL values. Latency of the product, produced operationally at the NOAA Aviation Weather Center, is ~7–10 min.

   On a separate experimental web page hosted by NWS ADDS (http://weather.aero), the NCWF-2 is available under the "Convection" tab. NCWF-2 also forecasts only the convective storm features, but this experimental version provides a probabilistic forecast that has been shown to be unreliable in that the probabilities are incorrectly calibrated (Seseske et al., 2006). The NCWF product development was also funded by the FAA Aviation Weather Research Program, but was frozen in 2006 to focus the available resources on the CoSPA development.

3) The ITWS Terminal Convective Weather Forecast (TCWF) provides a 0–1 hour forecast derived from NEXRAD data. The TCWF display format is similar to the CIWS display format. Key differences are that CIWS offers a forecast out to 2 hours, and the TCWF does *not* include explicit display of storm growth and decay trends, recent improvements in the storm motion vectors and advection scheme, improved representation of surface forcing (fronts) and environmental forcing (environmental stability), the use of satellite data and tracking of the rain/snow line, and a radar echo tops forecast. Given that TCWF has no near term plans for additional advances in forecast accuracy, it would seem that TFM applications would principally focus on the use of the CoSPA as opposed to the TCWF (even for terminal TFM systems).

4) The Convective SIGMET (Slemmer and Silberberg, 2004) shows subjectively drawn polygons, lines, and circles depicting convection based on the following criteria[9]:

   - Severe thunderstorms due to:
     a. Surface wind greater than or equal to 50 kt
     b. Hail at the surface greater than or equal to ¾ inches in diameter
     c. Tornadoes

   - Embedded thunderstorms

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[9] http://www.faa.gov/avr/afs/afs400/ac00-45e.pdf

    - A line of thunderstorms
    - Thunderstorms producing precipitation greater than or equal to heavy precipitation affecting 40% or more of an area at least 3000 square miles.

5) The Collaborative Convective Forecast Product (CCFP) forecasts are produced through a collaborative process between forecasters from the National Weather Service (NWS) Aviation Weather Center (AWC) and meteorologists from airlines, Center Weather Service Units (CWSU), and the Meteorological Service of Canada. After the collaboration process, the final forecasts are issued by the AWC. The forecasts, issued with 2-, 4- and 6-hr lead times, are polygons that delineate areas of intense convection and thunderstorms. Minimum requirements for the issuance of a CCFP forecast polygon includes an area of at least 3,000 square miles with convective coverage of at least 25% coupled with echoes of at least 40 dBZ, and also a coverage of at least 25% with echo tops of 25,000 ft and higher. There are three possible coverage categories for CCFP forecasts: sparse (25–49% coverage within a polygon), moderate (50–74%), and solid (75–100%).The confidence is defined as the forecaster's confidence that convective weather will occur and meet CCFP minimum requirements within the forecast region.

(b) Forecast accuracy

The technical performance of the convective forecast is a key factor in both TFM decision making and the weather-TFM roadmap planning. Two types of accuracy metrics are currently being actively investigated:

- Spatial coincidence between forecast field (e.g., reflectivity or echo tops) and actual field (e.g., reflectivity or echo tops) (i.e., pixel overlap scoring), and
- Capacity forecast accuracy scoring.

1. Pixel overlap scoring

CIWS provides real time spatial coincidence metrics for the accuracy of the CIWS forecast based on a comparison of the forecast with the actual weather (e.g., comparing the 60 minute forecast issued an hour ago to the actual weather at this time) for a time window of N minutes[10]. Figure 2-2 shows how the forecast field is compared to the actual weather field at the valid time for the forecast. The numerical user score comparison metric is not a straight 1 km pixel-by- 1 km pixel comparison. Rather, a scoring window is passed over the 1 km grids of forecast and actual weather fields to classify each pixel as a "hit", "miss", "false alarm" or, "correct no weather". The size of the scoring window (in pixels) and number of pixels within the scoring window for which the actual weather level is ≥ forecast weather level vary with the forecast lead time as illustrated in Figure 2-3.

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[10] Users can also view an overlay of the 30-, 60- and 120-minute CIWS forecasts that are valid at the current time on the current weather so as to better understand the nature of the spatial errors in the forecasts.

The forecast accuracy score is the critical success index (CSI):

CSI= # of “hit” pixels /(# “hit” pixels + # “false alarm” pixels + # “miss pixels”) (2-1)

Note that “false alarms” result in a lower CSI with no credit being given for correctly forecasting regions where the actual weather was less than the forecast weather level.

The forecast accuracy scores for 2007 and 2008 for the CIWS JFK “home” - a square region whose main diagonal is roughly from Washington DC to Boston (centered on the NY airports) - are shown in Figure 2-4. We see that the accuracy scores for the 2 hour forecast are generally much lower than those of the 30- and 60-minute forecasts even though the 2-hour forecast scoring criteria is much less stringent than the 30- and 60-minute accuracy criteria. As was suggested by the NRC report (NRC, 2003), the 2-hour forecast is only reasonably accurate for strongly forced synoptic situations such as squall lines. The forecast accuracy scores for select days in 2007 are shown in Figures 2-5 through 2-7 categorized by weather type. The weather type was categorized into three categories; cluster, cellular, and line by an experienced meteorologist.

Given the significant variability in the accuracy scores that are observed for a given CIWS forecast lead time, the question then arises as to the time consistency of the accuracy scores on a given day (e.g., if the accuracy scores for a given forecast have been high, does that mean that the just issued forecast score will also be high). This is important because one can envision rather different TFM strategies in a given situation depending on the accuracy of the current forecast.

In Figures 2-8 to 2-10 we compare the accuracy scores for the various CIWS forecasts with the accuracy score at the time a forecast was issued[11]. For the 30 minute forecasts, there seems to be fairly good correlation between the two scores.

For the 60 and 120 minute forecasts, there is clearly much more variability between the recent past forecast accuracy and the accuracy of the forecast that has just been issued.

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[11] Again, the accuracy score for a forecast at the time the forecast is issued is the accuracy of the previous forecasts that were valid at the issuance time. The question posed here is akin to the question of how well past performance of a stock market mutual fund is at predicting the near term performance of that mutual fund.

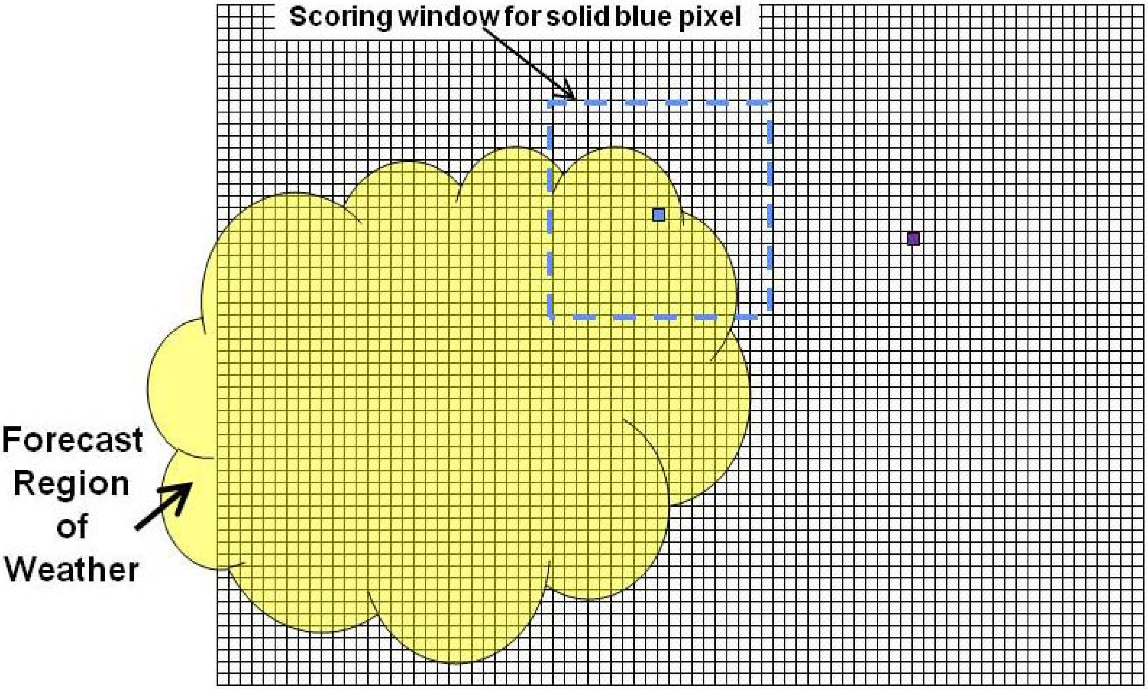

Figure 2-2. Computation of CIWS forecast accuracy scores for display. For each pixel within the region of forecast weather (e.g., the solid blue pixel), the actual weather at each pixel within a scoring window is determined. If the number of pixels in the scoring window with a weather level ≥ the forecast threshold (T) is greater than a threshold (NT), the pixel is scored as a "hit". Otherwise, the pixel is scored as a "false alarm". Partial credit (0.5 hits, 0.5 misses) are given for cases where the number of pixels in the scoring window whose weather level ≥ the next lowest forecast threshold (e.g., T-1) exceeds NT. Pixels outside the region of forecast weather (e.g., the purple pixel) are scored by a similar process. If the number of pixels in the scoring window with an actual weather level ≥ the forecast threshold (T) is greater than the threshold (NT), the pixel is scored as a "miss."

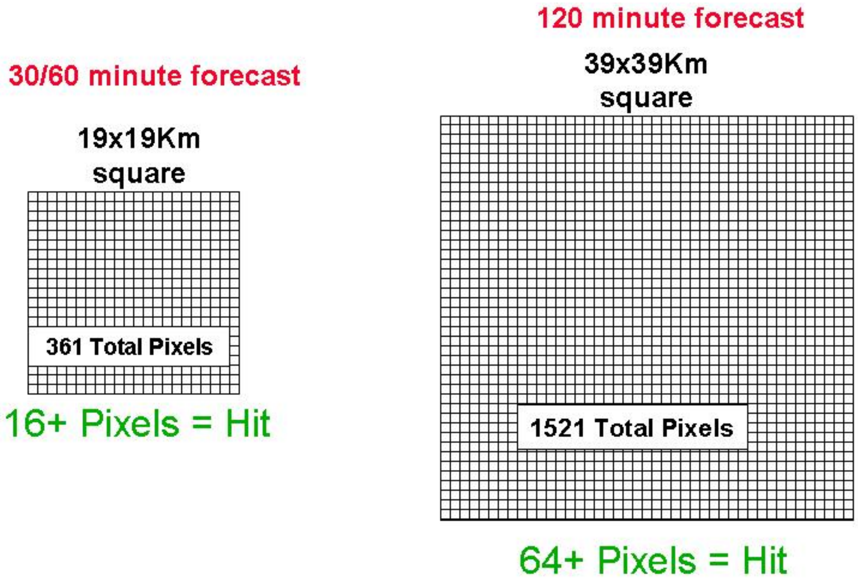

Figure 2-3. Scoring boxes and criteria for a correct "hit" used to generate the various CIWS forecast accuracy scores.

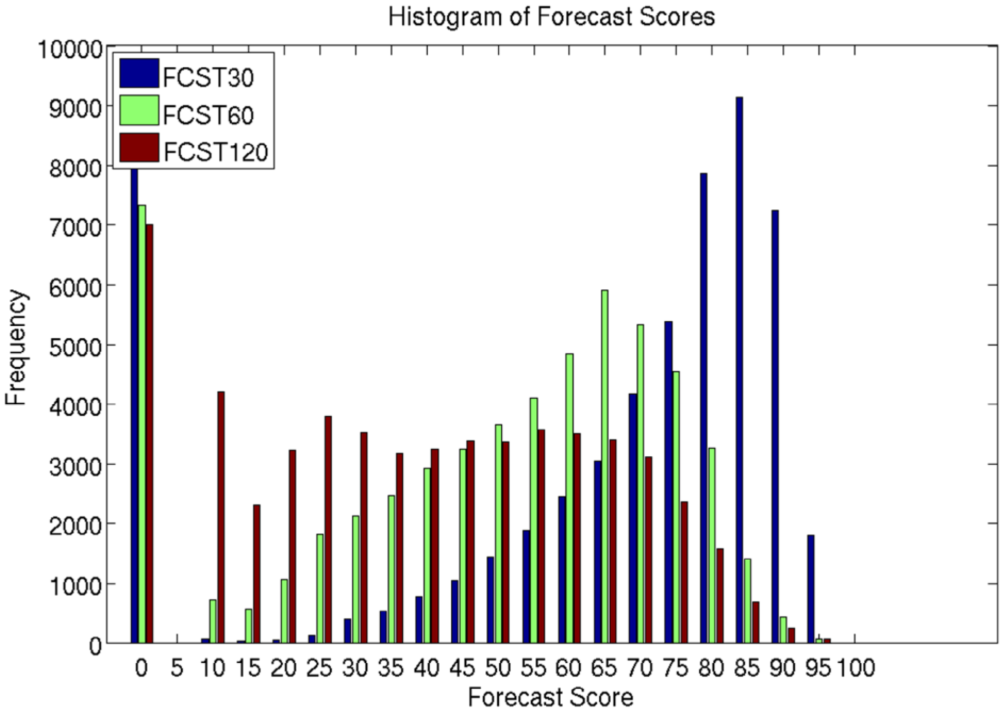

Figure 2-4. Frequent distribution of CIWS forecast scores for region near JFK for 2007 and 2008. Dark blue is 30 minute forecast, green is 60 minute forecast, and brown is 120 minute forecast.

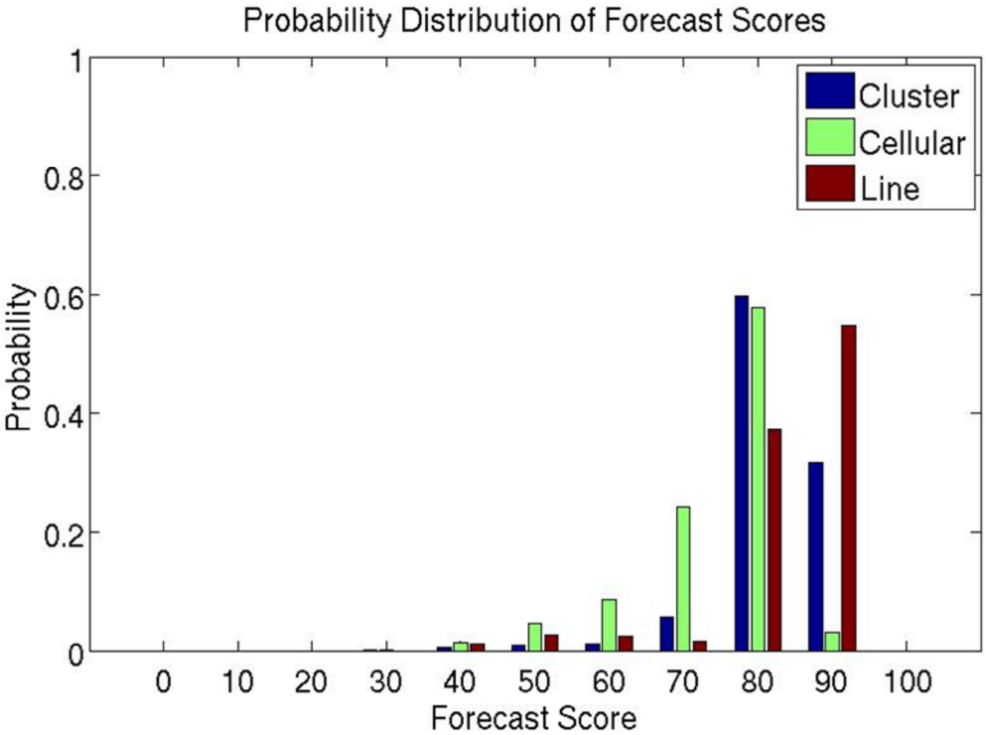

Figure 2-5. Probability distribution of CIWS 30 minute convective forecast accuracy scores as a function of storm type.

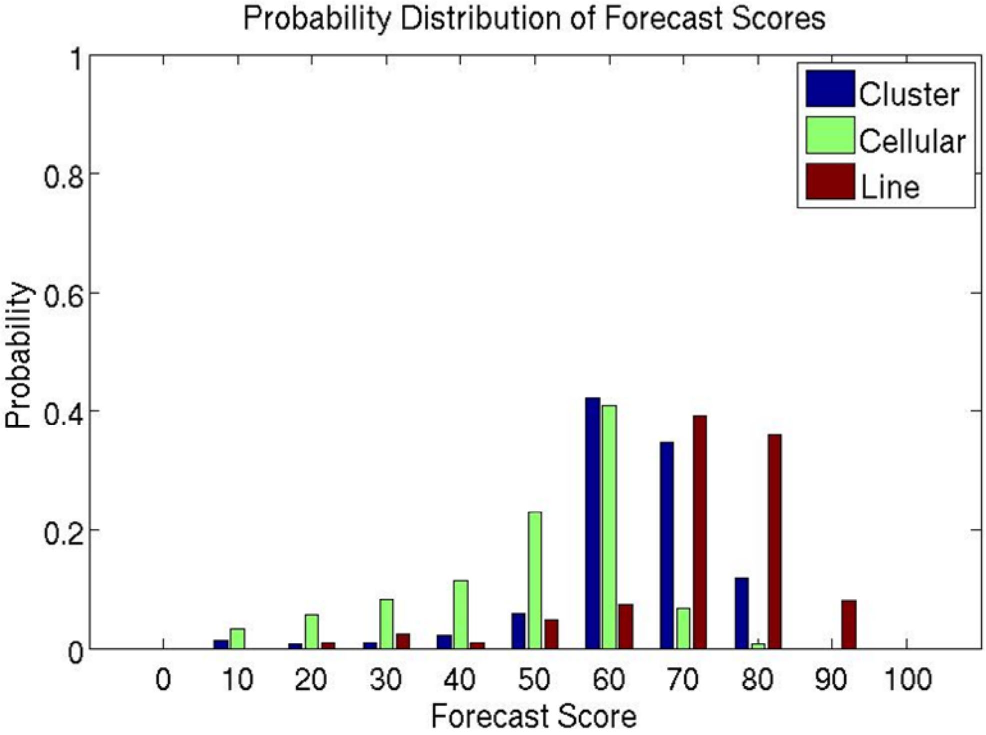

Figure 2-6. Probability distribution of CIWS 60 minute convective forecast scores as a function of storm type. Skill is highest for cell clusters and squall lines.

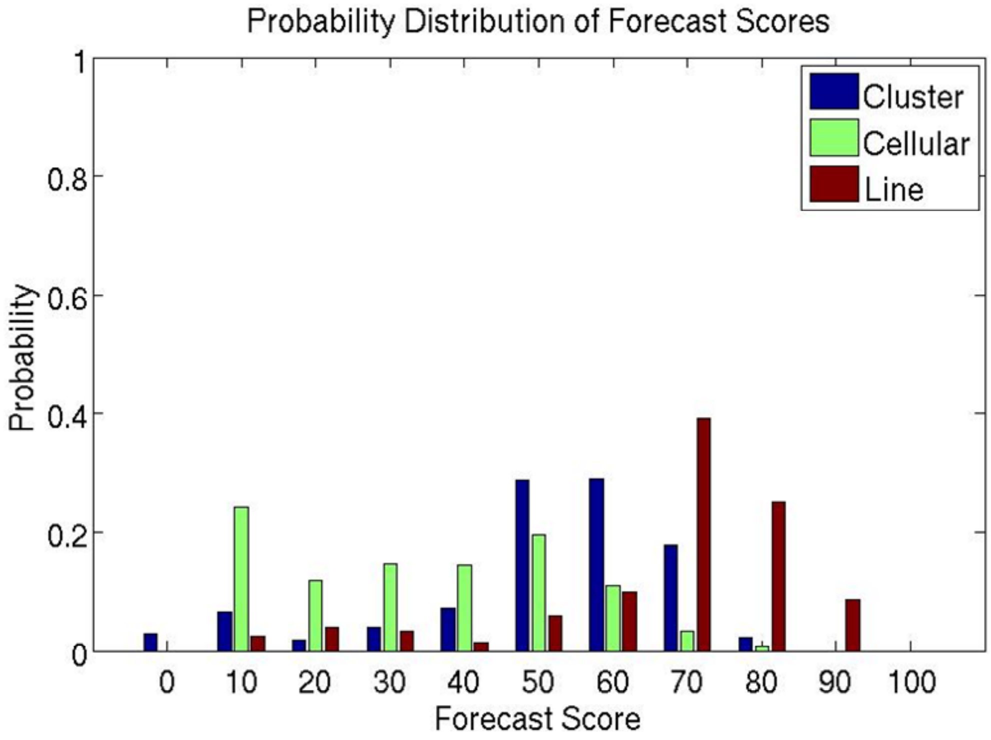

Figure 2-7. Probability distribution of CIWS 120 minute convective forecast scores as a function of storm type. Skill is high only for squall lines. However, most of the cluster scores are > 50%.

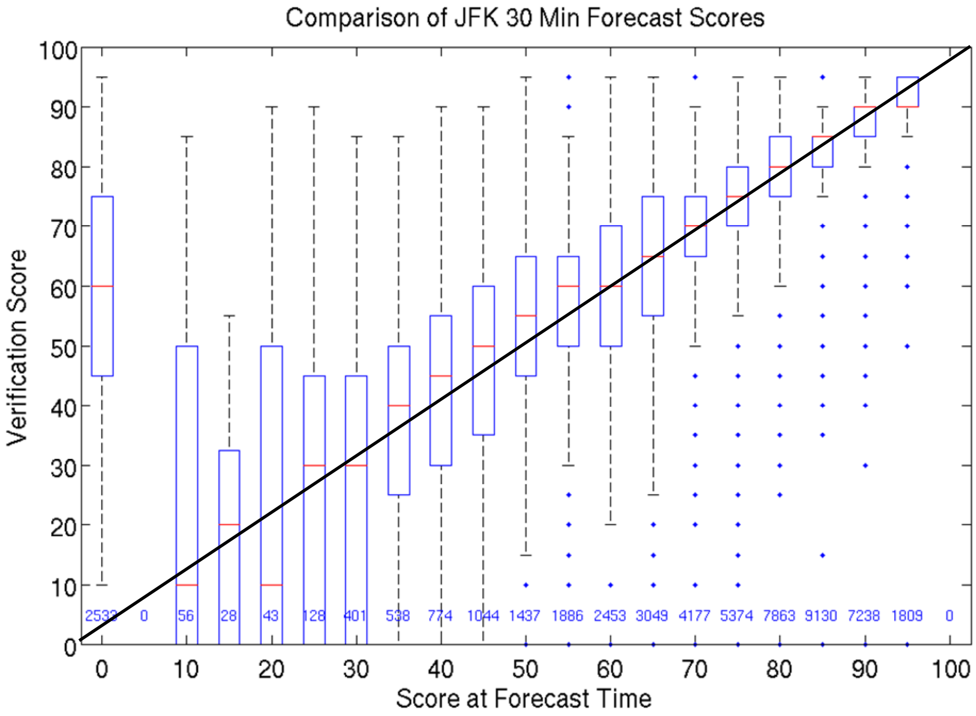

Figure 2-8. Accuracy projected for a 30 minute forecast at the time the forecast was issued versus the actual accuracy score for that forecast(scored at the forecast valid time) for a region along the east coast. Most of the forecast accuracies were in excess of 60%.

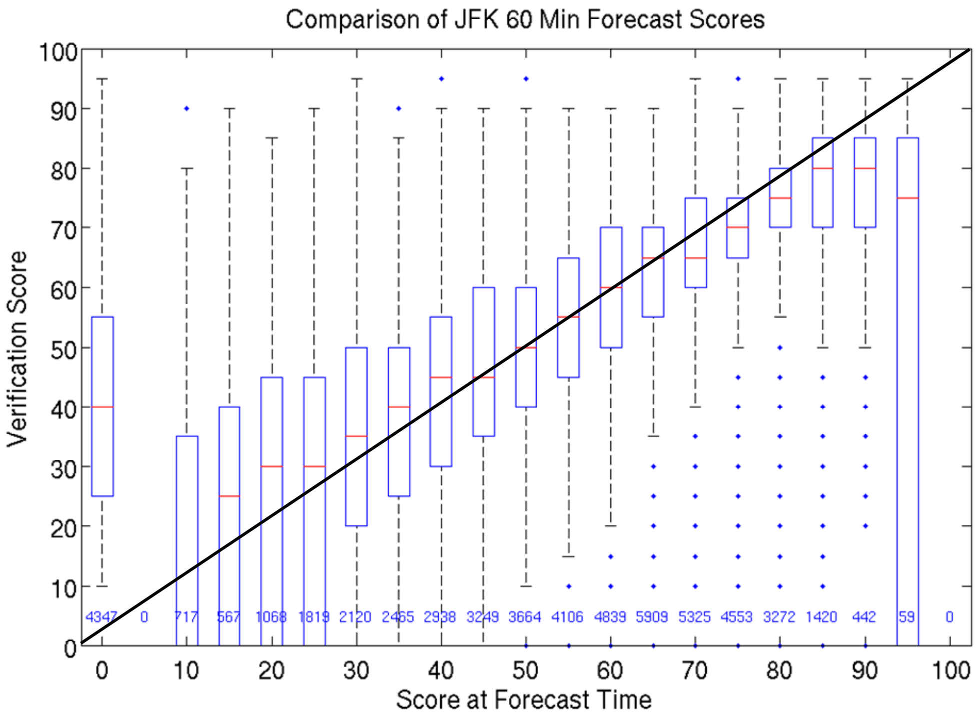

Figure 2-9. Accuracy score for a 60 minute CIWS forecast at the time the forecast was issued versus the actual accuracy score of that forecast (scored at the forecast valid time). Most of the forecast accuracies were in excess of 40%. If the accuracy score at the time of forecast was high (e.g, >60%), the accuracy of that forecast generally is high as well.

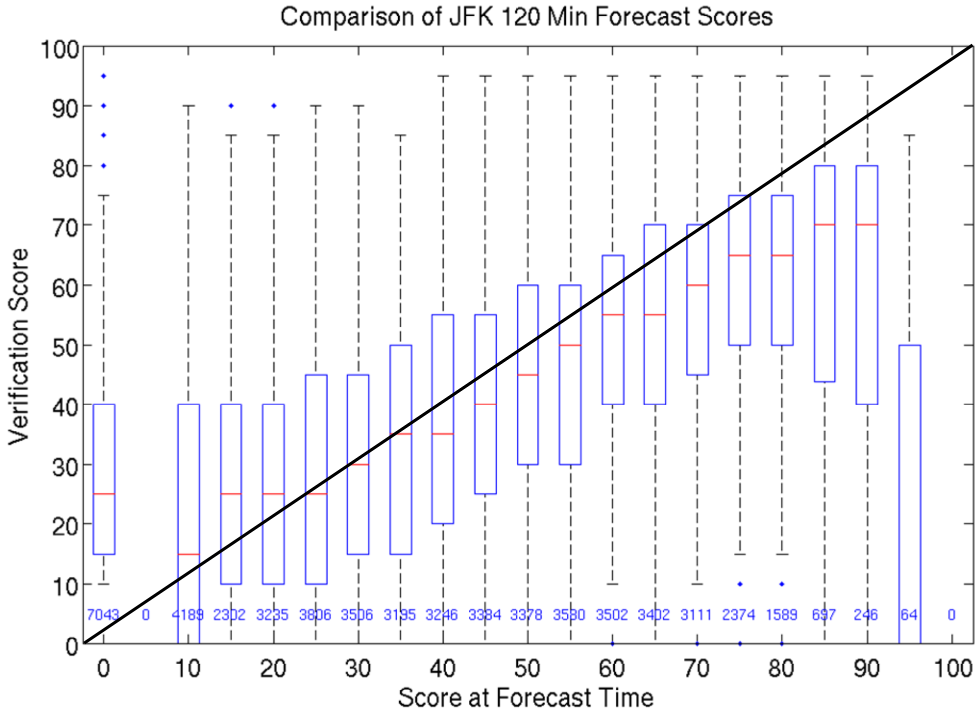

Figure 2-10. Accuracy score for a 120 minute CIWS forecast at the time the forecast was issued versus the actual accuracy score of that forecast (scored at the forecast valid time). The overall accuracies are much lower than for shorter lead time forecasts as is the ability to forecast the accuracy of the current forecast based on past forecast accuracies. There is a tendency for regression to the mean when either the past forecast accuracy was high or lower than average. Still, if the accuracy score at the time of forecast was high (e.g., >60%), the accuracy of that forecast is generally is high as well.

It is hard to judge from the CIWS forecast accuracy scores alone the skill of the various CIWS forecasts at correctly forecasting storm impacts on a given location. In appendix A we show a number of specific storm cases where the reflectivity forecasts have been scored on a "hit-miss" basis as indicated in Figure 2-2 along with the corresponding CIWS forecast accuracy scores. The 30 and 60 minute forecast plots provide insights on forecast accuracy score needed to accomplish medium spatial resolution TFM decision making (e.g., impacts on a 4 corner TRACON arrival fix or group of closely spaced departure routes). The 120 minute forecast plots provide insights on the forecast accuracy scores needed to accomplish larger scale TFM decision making (e.g., small TRACON impacts).

There is also a substantial literature on scoring of the CCFP on the basis of the spatial coincidence between the CCFP and actual field (e.g., reflectivity with a cloud-to-ground lightning activity adjustment) [e.g., Kay, et al., 2006, Seseske and Hart, 2006]. The actual measured radar reflectivity data on a 4 km spatial grid is regridded to a 40 km spatial grid using a maximum pixel criteria (i.e., a 40 km grid scale pixel = maximum reflectivity of the 100 4 km pixels contained within the 40 km grid scale pixel)[12]. The radar reflectivity of the 40 km pixels is then compared to the CCFP region to produce performance statistics. Given that the CCFP is not viewed as an appropriate long term approach to 2–8 hour forecasting for weather-TFM integration, we will not provide further details on the current CCFP forecast performance in this document.

2. *Capacity forecast accuracy scoring*

Work is underway to translate the CIWS forecast uncertainty into capacity forecast uncertainty. In Section 4.1, we review the very active research to translate convective weather information into capacity impacts and then discuss the current status of work in translating weather forecast uncertainty into capacity impact uncertainty.

However, it should be noted that the notion of characterizing forecast accuracy in terms of ATC impacts dates back at least to 1983. In Figure 2-11, we show a figure from an early paper by Lincoln authors on storm tracking for aviation that suggests scoring forecasts on their ability to correctly forecast route blockage.

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[12] (Kay, et al., 2006) note that this regridded operation increases the effective coverage of the weather by as much as a factor of 6.

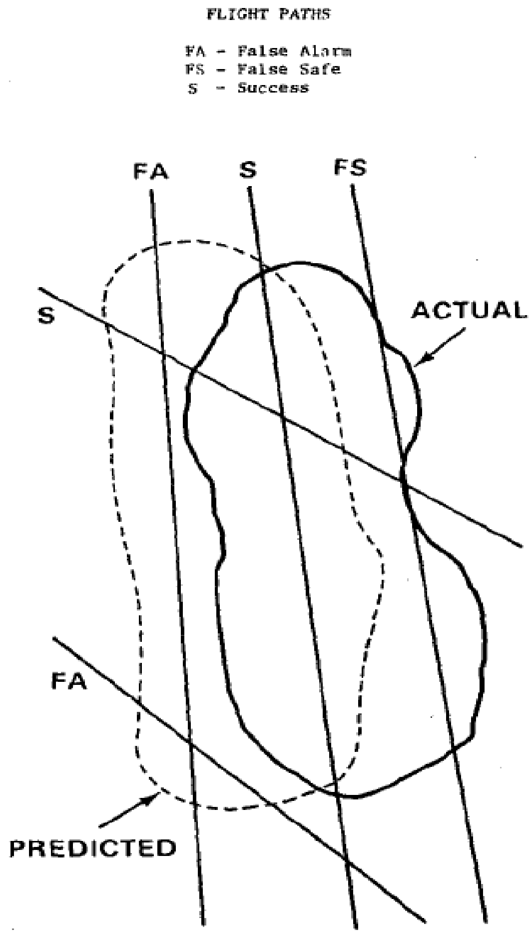


Figure 2-11. Scoring of convective weather forecasts in terms of the accuracy in forecasting route impacts (Brasunas and Merritt, 1983). S indicates successful route impact forecasts, FA indicates route impact false alarms, and FS indicates a missed route impact. Actual storm spatial extent is the solid contour; dashed contour is the forecast storm spatial extent.

Figure 2-12 illustrates on the relationship between forecast velocity and storm shape errors and errors in route blockage. We see that the route blockage errors go up significantly when the storm cross route velocity is small. Hence, if the routes in a given region tend to have a preferred spatial orientation, it is important to consider the storm mean velocity in translating weather forecast uncertainty (e.g., velocity errors and/or storm spatial extent errors) into route blockage uncertainty.

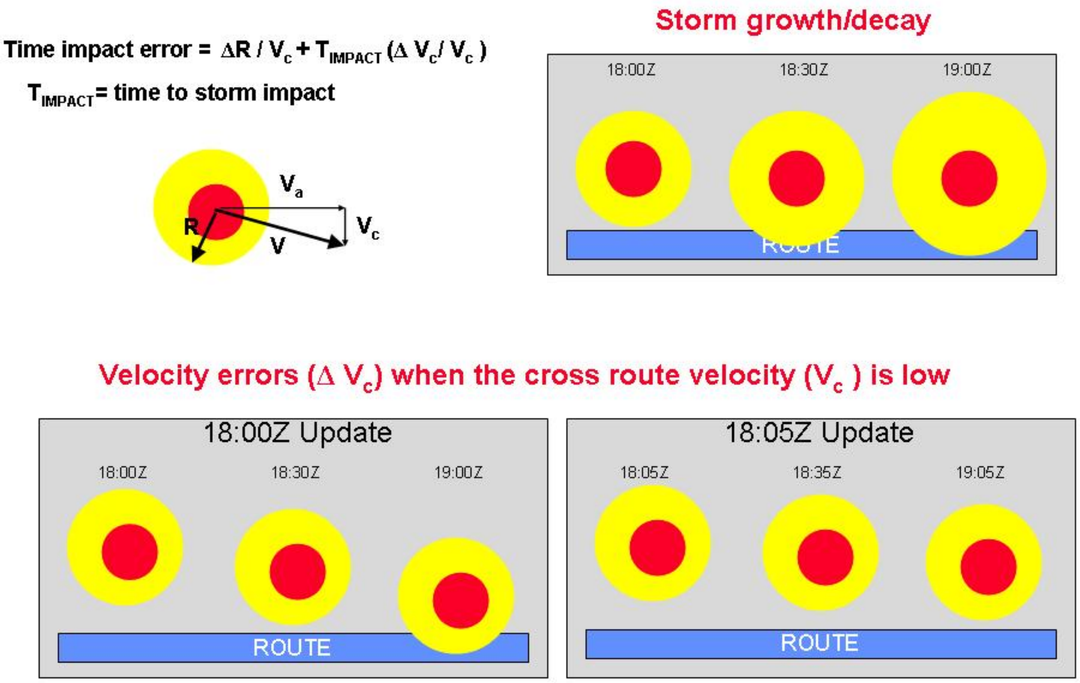


Figure 2-12. Illustration of the impacts of errors in storm size and cross route velocity errors on route blockage computations. When the cross route velocity (V_c) is small, predictions of route blockage and time of route blockage are very sensitive to small changes in either storm extent (ΔR) or cross route velocity (ΔV_c).

(c) Expected enhancements in convective weather forecast capability (2008-2015)

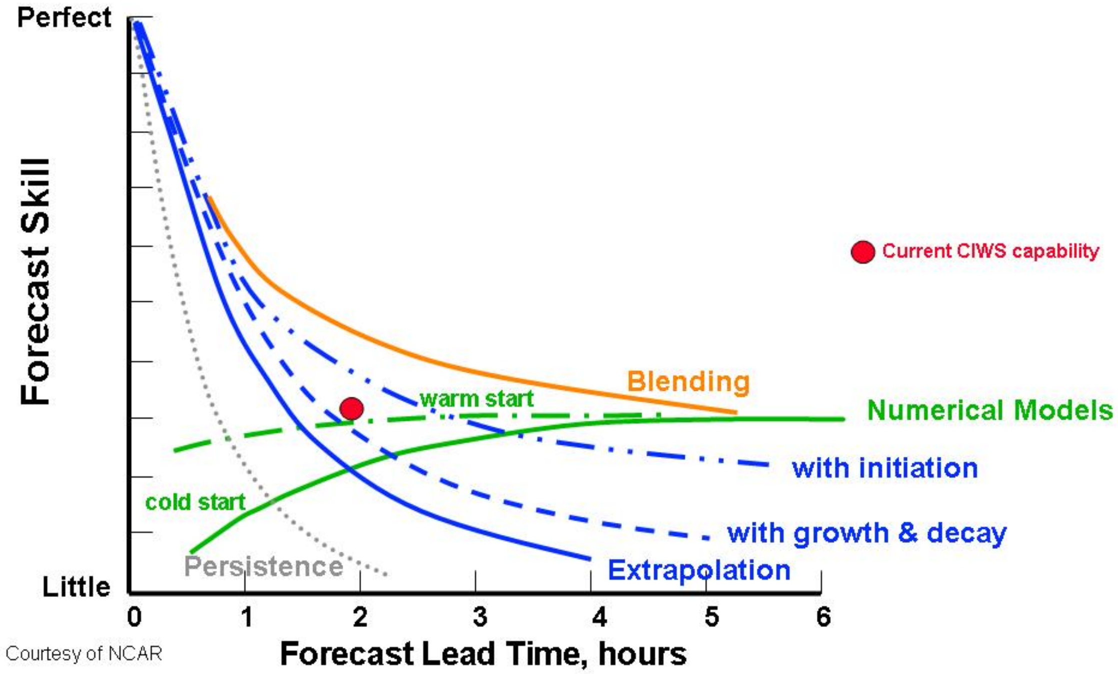
The current vision [see (Wolfson, et al., 2008)] is that CoSPA will use different meteorological processing techniques to generate the convective forecasts at various lead times as shown in Figure 2-13. The short lead time (CIWS based) forecasts (0–2 hour) rely heavily on tracking and advection of weather radar reflectivity data. The NOAA Space-Time Mesoscale Analysis System (STMAS) (Xie et al., 2005) gridded analyses of surface winds, temperature, dew point, etc. are used within CoSPA to produce very high quality stability fields (e.g., Convective Available Potential Energy), convergence fields, and are used for detection of atmospheric fronts. The STMAS data are used together with satellite data and weather radar data to forecast convective initiation of storms for the 0–2 hour forecasts.

The longer lead time (> 2 hour) forecasts rely heavily on incorporation of numerical modeling results, and the blending of those results (Pinto, et al., 2006) with the extrapolation-based heuristic models used for 0–2 hr forecast. The initial CoSPA 2–8 hr forecast will have 3 km spatial resolution with 15 minutes time resolution and be updated every hour.

The CoSPA 2–8 hour forecasts should be significantly more accurate than the current RUC 13 km forecasts as a result of the much higher spatial resolution (which offers the possibility of resolving some relatively large scale convection such as squall lines and large thunderstorms), more frequent updates, and the use of weather radar data to initialize the model runs (this should reduce the model “spin up” period and allow for much better blending of the model results with the 0–2 hour CIWS based forecasts.

The spatial grid size for the CoSPA 2–8 hour forecast is still a factor of three greater than the 1 km suggested by the NRC panel (NRC, 2003). This greater resolution was dictated by both computational hardware cost considerations (reducing the grid size by a factor of three could increase the computation load by a factor of 81), the inability to measure the initial atmospheric conditions (especially, surface temperature and humidity) at a corresponding high spatial resolution[13], and the need to conduct scientific research on high resolution storm modeling algorithms.

Improving forecast performance at longer lead times will involve use of these higher resolution numerical models and blending techniques. The cross-over forecast lead time and blending region will trend closer to current time as NWP systems begin to assimilate data from Doppler weather radars.



Courtesy of NCAR

Figure 2-13. Technology to be used for CoSPA as a function of the lead forecast time.

A key question in developing a weather-TFM roadmap is when various CoSPA forecast capabilities will become available such that the forecasts could be interfaced to ATM algorithms on at least an experimental basis.

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[13] Higher spatial resolution offers the possibility of more accurate forecasting of the growth and demise of individual convective storms. However, since the actual dynamic processes associated with convection are very sensitive to the initial atmospheric conditions, having a more precise storm dynamics computation will not necessarily yield more accurate forecasts if the initial atmospheric conditions are uncertain.

Two types of demonstrations are planned for CoSPA: 0–2 hour tactical forecast demonstration and a 2–8 hour strategic forecast demonstration.

Because the 0–2 hour tactical forecast is already well along its development path, an experimental operational platform has already been established through the CIWS program that would be used to carry out tactical weather-TFM demonstrations in the near term.

The 2–8 hour CoSPA forecast research is not as mature and therefore it is necessary to provide a separate research level demonstration platform. Here an experimental demonstration is defined as a prototype that is viewable by operational personnel during ATC events. A research demonstration is a demonstration that runs 24/7 but is viewed by research and FAA management personal only and is not used in regular operations.

Research demonstrations can and should be interfaced to TFM decision support tools to insure that the unique operational TFM needs are being addressed. As the research demonstration platform becomes hardened it could transition to an experimental operational demonstration that could be interfaced to TFM tools for a demonstration. The goals for IOC 2013 are outlined in Table 2-4.

TABLE 2-4

Planned CoSPA Demonstrations (2008–2012)

CoSPA Demos	2008	2009	2010	2011	2012
New 0–2 hr Forecast Products	Precip includes satellite data quality editing; Forecasts capable of CONUS coverage	2008 + Probabilistic Forecasts, Wx Avoidance Field Forecasts (WAFs), Lightning in Precip Mosaic, NWS Fronts	2009 + Statistically Optimized 0-2 hr Forecasts; TFM Scoring Metrics, Snow Liquid Water Equivalent Forecasts	2010 + Improved data quality and forecasts, NWS Initiation Regions; Begin legacy forecast comparisons	CoSPA Operational Prototype in service
0–2 hr Domain	CONUS	CONUS	CONUS	CONUS	CONUS
Type of Demo	Prototype	Prototype	Prototype	Prototype	Operational
Purpose	Tactical TFM	2008 + Couple w/ Decision Support Systems (e.g., RAPT)	2009 + other TFM DSS; Terminal Deicing Situational Awareness	2010 + NextGen cost / benefits based on joint use technology	NextGen IOC
Who Will View?	CIWS Users, Developers, Sponsors, TFM Collaborators	2008 + Private Vendors?	2009 + NNEW Distribution	2010 + NWS Centers and WFOs	NextGen “4D Wx Cube” Authorized Users
NWEC Gates				Begin NWEC Process	Deployment
New 2–8 hr Forecast Products	Precip only; 2-6 hrs	2008 + Echo Tops; 2-8 hrs; increase lead time to 8 hrs	2009 + Precipitation Phase (snow-mix-rain), TFM scoring metrics;	2011 Echo Tops and Probability Forecasts	WAF Forecasts. CoSPA Operational Prototype in service
2–8 hr Domain	NE Corridor	NE Corridor	CONUS*	CONUS*	CONUS*
Type of Demo	Research	Prototype	Prototype	Prototype	Operational
Purpose	TFM Strategic Planning and Collaborative Decision Making	2008 + Couple with research on Wx-ATM Integration	2009 + Couple w/ TFM Decision Support Models	2010 + NextGen cost savings based on joint use technology	NextGen IOC
Who Will View?	Developers and Sponsors only	2008 + CIWS Users + TFM Collaborators	2009 + NNEW Distribution	2010 + NWS Centers and WFOs	NextGen “4D Wx Cube” Authorized Users
NWEC Gates				Begin NWEC Process	Deployment

*CONUS only if significant new investment is made. Otherwise, continues only in NE Corridor.

2.2 CEILING AND VISIBILITY (C&V) DIAGNOSIS AND FORECASTING

2.2.1 Current atmospheric diagnosis

Low ceiling and visibility conditions at pacing airports are generally the principal consideration in non-convective airport TFM decision making. At such airports, the current state is typically provided by a combination of Airport Weather Observing Systems (AWOS), Automated Surface Observing Systems (ASOS) and Runway Visual Range (RVR) sensors. The data provided by these sensors is generally adequate for assessing airport capacity constraints with the noticeable exception of SFO where the principal constraint is horizontal visibility between aircraft at approximately 1000 ft. AGL on closely spaced parallel runway final approach paths (as opposed to RVR or ceiling as measured at the airport). Hence, at SFO, the determination of the slant range visibility determination is made via pilot reports.

2.2.2 Forecasting

The capacity-related component (as opposed to safety considerations) of the C&V research has been focused on terminal-specific forecasts of meteorological parameters that restrict capacity. Capacity restrictions are fairly well codified with respect to individual airports and runway configuration as a function of ceiling/visibility levels such that an accurate deterministic forecast can be directly translated to an operating capacity. However, the current Terminal Area Forecasts (TAFs) have been difficult to translate into airport capacity estimates because the forecasts were generally not tied to airport specific criteria. Additionally, the accuracy of the TAFs suffers in tactical time frame, during transitional periods when the forecasts are unable to keep pace with rapidly changing conditions.

Initial research by the FAA AWRP to provide a much more accurate and useful forecast for TFM planning focused on Ground Delay Program (GDP) decision support at SFO to cope with summer marine stratus clouds in the approach zone. Marine stratus clouds preclude paired SFO visual approaches and reduce arrival rate capacity by a factor of two. The restrictive weather is well-defined (persistent poor slant range visibility between about 700 ft AGL and 2500 ft AGL), occurs on a daily cycle, and has a well-defined and relatively isolated operational impact. An SFO optimized forecasting solution was implemented through development of a forecast model suite which required deployment of specific sensors to provide key data inputs for some of the forecast algorithms. The final product of the prototype system was initially a deterministic forecast of the transition time to full arrival capacity. This was then adapted to provide a probabilistic representation of full arrival capacity by key operational target times associated with periods of high scheduled arrival demand.

The marine stratus forecast (Ivaldi, et al., 2006; Clark, 2002) at SFO has been a success meteorologically:

1. the forecast of most likely marine stratus dissipation time outperforms climatology on average by:

    a) about 12% for the pre-dawn forecast (e.g., 13Z), and

    b) about 35% for forecasts issued during the morning hours (e.g., 15Z) based on data from 2003–2005. During 2005, high confidence morning forecasts of the dissipation time provided a 53% improvement over climatology, and

2. the automated objective probabilistic forecasts of clearing by key operational target times, namely 17, 18, 19, and 20Z, have been shown to statistically reliable.

To illustrate the accuracies achieved: the SFO system produced 136 forecasts in the three-year period 2003–2005 with a 90% or greater probability of clearing before 17Z or 18Z that verified 94% of the time. Of the 8 forecasts that did not verify, 7 had an offset time of less than 30 minutes.

The impact of the system forecast guidance on SFO TFM is discussed in detail in Section 4.2. Although the probabilistic capacity forecast has been shown to have accurate probabilities, the practical application (and, actual delay reduction achieved) has been very different from what was envisioned.

Ceiling and visibility forecasting to support TFM decision making would benefit from development of a more general forecast solution that could be applied to key capacity restricted airports within the NAS. Efforts have been initiated in this area; current AWRP research focuses on a C&V analysis system that is heavily reliant on spatial interpolation, with this technology also being extended to address forecast needs based on numerical model forecasts and statistical techniques. A parallel technology was also initiated which insulates the analysis and forecast problem from the limitations associated with interpolation of an observation field that comprises significant horizontal discontinuities, namely those associated with the boundaries of cloud decks and fog formations. This technology makes use of statistical correlations between predictands (visibility and ceiling height) and observations that are available at a high space and time resolution (e.g., satellite, radar, model forecast fields). A distinction is made between restrictive C&V conditions that are transient from those that are stationary, with tracking and advection applied accordingly to provide a smoother prediction field, more suitable for short term prediction of terminal area conditions. Funding for this forecast approach was suspended by FAA AWRP and apparently will not be resurrected in FY09.

2.3 WAKE TURBULENCE

Turbulence associated with wake vortices generated by arriving and departing aircraft poses a safety risk to other nearby aircraft, particularly lighter planes. This risk is mitigated by rigorous aircraft separation standards imposed when wake turbulence avoidance is a concern. The FAA is investigating application of wind-dependent procedures for improved arrival and departure operations that safely reduce spacing restrictions to allow increased airport operating capacity. The current focus is on procedures that allow for increased departure rates from Closely Spaced Parallel Runways (CSPR). These procedures are referred to collectively as Wake Turbulence Mitigation for Departures (WTMD).

An important component of WTMD is a Wind Forecast Algorithm (WFA) being developed by MIT Lincoln Laboratory. The algorithm is designed to predict when runway crosswind conditions will remain persistently favorable to preclude transport of aircraft departure wakes into the path of aircraft on parallel runways. The algorithm has two distinct components for predicting the winds at the surface (10 m) and aloft (up to 350 m, the nominal height at which departing aircraft diverge from the runway centerline on ascent). The surface component forecast applies a statistical approach using recent observations of winds from 1-minute ASOS observations. The winds aloft component relies on the 2 to 4 hour wind forecasts from NCEP's Rapid Update Cycle (RUC) model.

Real time proof-of-concept demonstrations of WTMD have been conducted at St. Louis Lambert International Airport (STL) and Houston Bush Intercontinental Airport (IAH). The system is currently under consideration for operational deployment at ten U.S. airports with closely spaced parallel runways that would realize a significant operational benefit in departure capacity. There is also consideration for extending the concept to include single runway operations, and for arrival runways.

The WTMD will increase departure capacity on individual runways when the runway winds are favorable. Since there generally are tradeoffs between arrival and departure rates at airports [e.g., the "Gilbo curves" (Gilbo, 1993)], a higher departure rate would in theory offer the possibility of increasing the airport arrival rates on a weather adaptive basis. However, the current WTMD surface wind forecasts do not have a long enough look ahead time (e.g., at least 2 hours) to reliably forecast when a higher arrival rate could be used in a GDP.

2.4 SURFACE WIND FORECASTS

Sudden changes in airport runway configuration may be required during local convective weather activity as a result of wind shifts, hazardous wind shear on runways or final approach/departure corridors, or intense precipitation in these same areas. These conditions are transient and, at best, are accurately predicted no more than 30 minutes in advance of their operational impact. Figure 2–14 illustrates the operational impacts of a major wind shift at Chicago O'Hare airport during 2006. In this instance, thunderstorm blockage of arrival and departure routes from the airport exacerbated the impact of the wind shift.

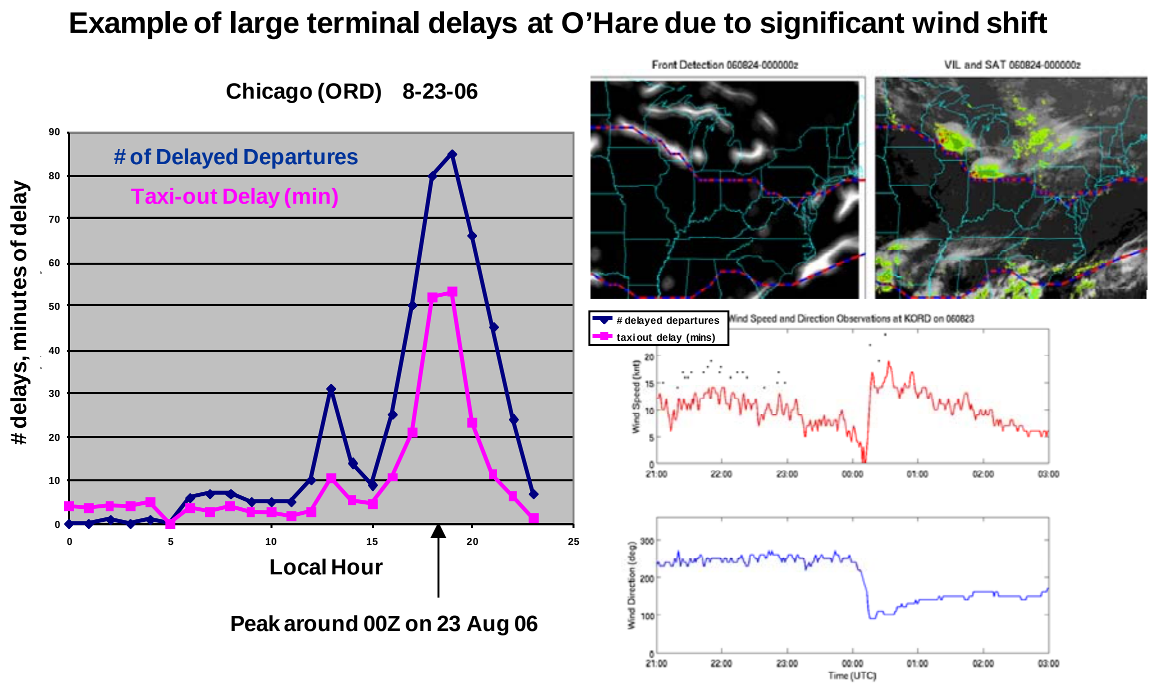

Figure 2-14. Terminal delays at ORD due to thunderstorms and a significant airport wind shift.

The current runway winds forecast capability does not adequately support airport surface TFM:

(i) Accurate "look-ahead times" for relevant phenomena are short. ITWS microburst wind shift predictions are generally provided only 20 minutes in advance of their airport impact. These runway impact "look ahead times" are comparable to aircraft taxi-out times.

(ii) Airport wind shift accuracy is imperfect. As an example, the TDWR/ITWS wind shift probability of detection is roughly 0.7 and probability of false alarm is 0.1 with large variation seasonally and geographically.

Current practice at many airports is to wait until the wind-shift occurrence is confirmed (for example visually through blowing dust or using airport wind sensors). At high-density airports, the associated delay in adjusting surface movement to account for the necessary runway reconfiguration significantly increases the impact of the wind shift.

If the airport reconfiguration is such that a capacity impact will occur, the question then arises as to whether a GDP will be warranted (or, an existing GDP needs to be modified). The ITWS does not currently provide runway winds forecast lead times sufficient to support decision making for GDPs to manage reduced arrival capacity due to sub optimal runway configurations. For GDP recovery, a reliable one hour lead time forecast of surface winds would provide a useful operationally capability since close in ARTCC flights (e.g., internal and first tier) could be released immediately and the GDP then adjusted for the new rate if a continued GDP was necessary.

At this point in time, major airport traffic managers typically seek to obtain an estimate of future airport surface winds based on local observations (e.g., winds at other "upstream" airports and surface sensors near the airport) and perhaps discussions with the CWSU at the pertinent ARTCC.

Research work underway under the AWRP program to forecast surface fronts may be useful for generating automatic longer lead time runway winds forecasts. However, there is no active research on this topic at this time other than the wake vortex winds forecast effort [14]discussed above. Hopefully, the A/DMT initiative discussed in section 5 will provide an impetus for improving the ITWS runway winds forecasting capability.

2.5 TURBULENCE

Under a NASA Research Announcement (NRA), Metron Aviation, Inc. (Herndon, VA), Science and Technology in Atmospheric Research Institute (STAR)[15] (Boulder, CO), and Mosaic ATM (Mountain View, CA) considered the possible impacts of many different types of non-convective weather on TFM. The principal non convective weather concerns[16] for TFM in en route airspace were Clear Air Turbulence (CAT) (e.g., from the jet stream or mountain waves) and en route icing.

As a part of NRA research, a number of ARTCCs were surveyed to gather information about non convective weather impacts from clear air turbulence and in-flight icing that impacted TFM decision making and, summarized the current state of research at forecasting these phenomena. Much of the description here is derived from the material presented at NASA workshops put on by the NRA participants.

ARTCC comments obtained by the NRA:

- ZTL - Turbulence will sometimes cause a/c to avoid rough altitudes. Too many a/c in the same altitude stratum will cause sector volume issues that would need to be controlled by MIT

- ZTL - Increased controller workload due to extra pilot/controller communications = Reduced capacity, restrictions.

- ZJX - Winter Jet Stream patterns often produce very high upper winds, often causing an increase in turbulence. Often this limits the usability of a block of altitudes, thereby reducing the volume of A/C that can be moved through airspace.

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[14] The wake vortex winds forecast effort is focusing on non convective weather situations owing to the difficulties in forecasting convectively induced wind changes.

[15] STAR personnel are staff from the National Center for Atmospheric Research (NCAR) working for a limited liability corporation (LLC) to get around NASA constraints on FFRDCs participating in NRAs.

[16] Volcanic ash was noted as a potential hazard, but the frequency of volcanic as a significant TFM concern has historically been very low or non existent.

- ZOB - Turbulence can render some altitudes unusable, compressing the volume into less vertical airspace

No analysis was made of the annual frequency of TMIs to address turbulence in the NRA study nor, whether there was a significant “avoidable” delay associated with the current use of TMIs to address CAT.

A past TMO at ZOB who is a consultant to Lincoln Laboratory noted that CAT is primarily of concern in the en-route level flight phase. Transitioning traffic often vacates the problem area quickly enough to be able to proceed and, have fewer options to be able to complete their flight plan than planes in level flight. The ZOB experience was that TMI’s from CAT are rare as most instances are handled with changes in flight level alone. However, with widespread affect (4 flight levels or more) compression in the sectors below or above the impacted area could become saturated enough to require MIT/AFP implementation.

Clear air turbulence (CAT) is difficult for pilots to detect, since there are no visible cues that suggest when and where CAT will be encountered along the flight path. It is also difficult to detect at en route flight altitudes with weather radar, since there is little return from clear air and the scale of turbulent eddies is generally smaller than radar gate volumes. Because CAT cannot be sensed remotely, the location of CAT and the determination of its impact on aviation has relied on pilot reports (PIREPs) of turbulence encounters. Unfortunately, PIREPs are subjective; the location and degree of turbulence reported (light, moderate, heavy or severe) are based on the judgment of the pilot and subject to significant error (Schwartz, 1996). The severity of the turbulence experienced is also dependent on the characteristics of the aircraft. Finally, the timeliness of PIREP reporting and distribution is not always reliable. There can be significant latency between the time of a CAT encounter and the time that the PIREP is made.

In-situ measurements of turbulence and automated reporting of Eddy Dissipation Rate (EDR) from instrumented aircraft provide a recently deployed alternative turbulence reporting mechanism that addresses the many shortcomings of PIREPs. Data from instrumented commercial aircraft from several carriers (United and starting in 2008, Delta and JetBlue) are being used to develop and validate models for the prediction of CAT.

The Graphical Turbulence Guidance [GTG; Abernathy, Sharman and Wiener (2008)] product from the Aviation Digital Data System (ADDS) provides an hourly forecast for CAT that predicts severity of turbulence, based on a set of CAT predictors derived from the 13 km NOAA Rapid Update Cycle Model (RUC) that correlate well to PIREPs. GTG provides diagnostics and forecasts (1, 2, 3, 6, 9 and 12 hour) at 36 flight levels. The GTG is distributed as a graphical map showing CAT severity (none, light, moderate or severe). The ADDS flight planning tool provides a graphical depiction of the CAT that is predicted to occur along a user-supplied flight trajectory. The ADDS tools are intended to assist pilots and dispatchers in planning routes. GTG is currently being enhanced to incorporate in-situ measurements into its prediction model.

2.6 IN-FLIGHT ICING

ARTCC comments obtained by the NASA NRA (discussed in Section 2.5) were as follows:

- Indianapolis Center (ZID) - When aircraft encounter icing, compression occurs as they move to find better conditions. Additionally, when icing is present, the ability to hold airborne aircraft is impacted and may require expanded MIT to accommodate aircraft.

- Chicago Center (ZAU) - Reduces our capacity for holding aircraft. This could result in expanded TMIs to prevent possible holding.

- Atlanta Center (ZTL) - When icing is reported in certain areas, additional MIT restrictions are utilized to minimize/prevent airborne holding. The facility cannot accept as many aircraft as normal because holding in icing conditions is not advisable

- Cleveland Center (ZOB) - Normally, icing affects arrival aircraft and arrival fix holding patterns resulting in less usable airspace which can lower the airport AAR

The annual frequency of TMIs to address in-flight icing was not determined in the NRA study, nor whether there was a significant avoidable delay that resulted from the current use of TMIs to address in-flight icing.

A past TMO at ZOB who is a consultant to Lincoln Laboratory noted that icing is primarily of concern in the en-route level flight phase (including holding patterns near arrival fixes). Transitioning traffic generally passes through the problem area quickly enough to be able to proceed and, have fewer options to be able to complete their flight plan than planes in level flight.

Icing impacts in en route airspace are limited primarily to flights that spend significant periods of time at low altitudes near the freezing level where atmospheric conditions are likely to result in icing. These flights include propeller, turbo-prop, regional jet services and possibly longer-range flights that are holding in en route airspace. Two icing products – the Current Icing Product and the Forecast Icing Product (CIP / FIP) – are currently available from ADDS. CIP and FIP provide hourly updated, three-dimensional fields of icing severity (none, trace, light, moderate or heavy) and probability of icing (ranging from 0 to 85%) with a 20km horizontal resolution and 1000 ft vertical resolution. CIP and FIP are currently distributed via the Web as graphical maps that depict icing levels and probabilities. They are intended for use as planning tools that pilots and dispatchers consult in developing their flight plans. CIP and FIP are not currently being translated into explicit partitioning of airspace into passable and non-passable regions.

3. WEATHER DATA DISSEMINATION

Many of the high-level capabilities envisioned for NextGen drive a need for improved, system-wide access to data. In order to provide the necessary flexibility, data must be dynamically discoverable and available on-demand using spatial, temporal, and product type filtering criteria. From the perspective of weather-related applications, one of the primary goals is to provide a common operational picture, where controllers, Traffic Managers, Airline Operations Center personnel and pilots alike can access and visualize observed and forecasted weather conditions. From the traffic flow management perspective, it is important that any weather data dissemination capability meshes seamlessly with the equivalent capability for other aeronautical information, including flight plans and aircraft tracks.

Within the FAA, work in the data dissemination area is proceeding at a number of levels. At the physical network level, the FAA Telecommunications Infrastructure (FTI) program is working to provide robust, IP-based connectivity to the majority of data producers and consumers on the private FAA Wide-Area Network (WAN). At the next level, the System-Wide Information Management (SWIM) program is defining and/or providing a set of core capabilities and associated standards that will be shared by all FAA data producers and consumers. At the highest level, individual FAA programs will leverage SWIM core capabilities and standards as they move forward, achieving a certain level of interoperability via the use of a shared infrastructure.

Programs relevant to weather include existing programs such as ITWS, CIWS, and WARP, as well as the more recent NextGen Network-Enabled Weather (NNEW) program. NNEW is in essence a weather-specific infrastructure program that augments SWIM’s core capabilities, providing additional shared services to the weather community-of-interest (COI) as a whole. The sections below discuss progress with respect to NNEW in more detail.

A key question for the TFM R&D program is when the various TFM research decision support efforts and the operational TFM system need to commence acquiring weather data via the NNEW program, and whether new functional capabilities would be obtained when this transition occurs.

3.1 NEXTGEN NETWORK-ENABLED WEATHER (NNEW) BACKGROUND

The NNEW program focuses on the distribution of weather data in the NextGen environment. At the conceptual level, weather data from a variety of sensors and computer models can be envisioned as residing in a ‘4D Weather Cube’, providing access to end users as well as automated decision support systems. This is illustrated in Figure 3-1. Note that the 4D weather cube encompasses *all* weather data available to FAA users. Within the cube, particular domains (or weather data subsets) exist to serve certain purposes. Perhaps the most important domain from the perspective of controllers and pilots is the Single Authoritative Source (SAS) domain. This domain comprises the official set of products used for active control of aircraft, and is the key subset of the weather cube relevant to the goal of a common operational weather picture.

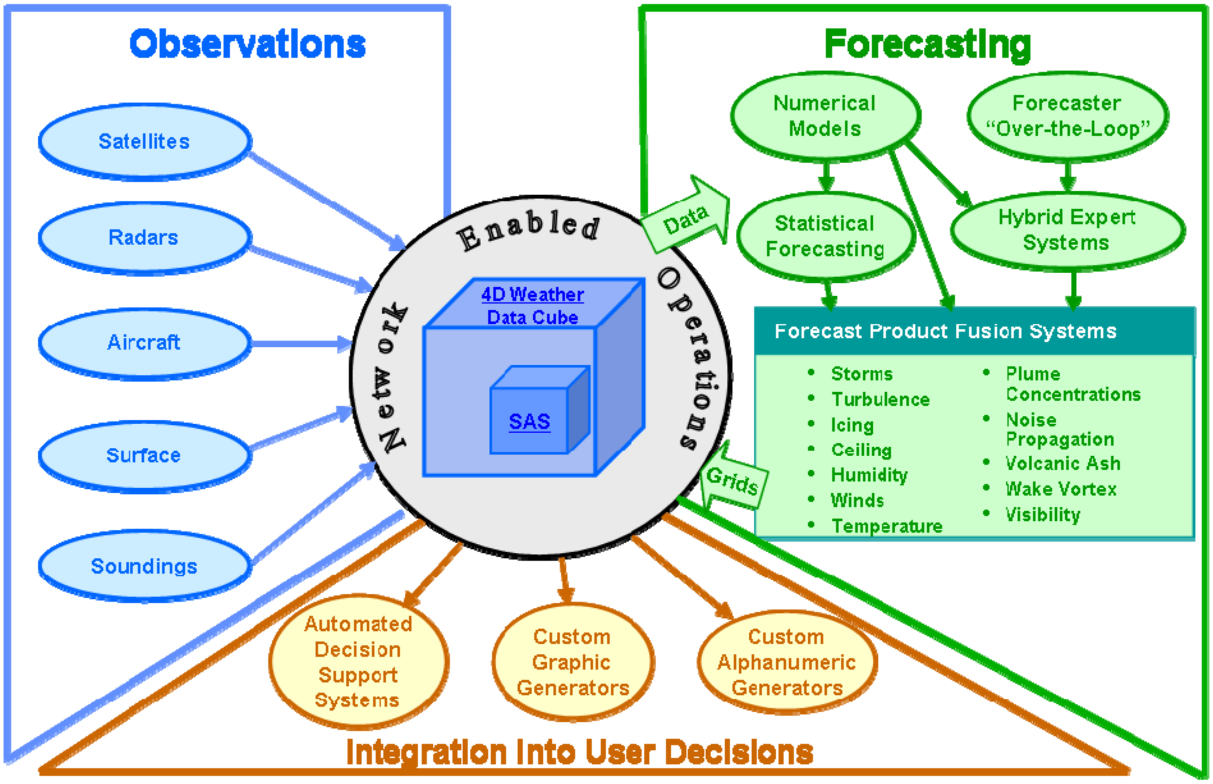

Figure 3-1. Weather Cube Data Producers/Consumer.

At the conceptual level, the weather cube depicted in Figure 3-1 has the appearance of a single, centralized data store. It is important to realize that at the actual implementation level, the 4D weather cube is envisioned as a distributed data store. Data residing in multiple locations will be federated together to form the 'virtual 4D weather cube', providing the appearance of a single entity to data consumers while simultaneously providing the scalability and fault-tolerance benefits of a more distributed architecture.

The NNEW program plan can be separated into two phases, a preliminary research and development phase running from 2007 to 2010, and a follow-on implementation phase beginning in 2010 and culminating in an Initial Operating Capability (IOC) in the 2013 time frame. The current R&D phase can be broken down into the following main focus areas:

Service-Oriented Architecture (SOA) for the Weather Cube. NNEW, like SWIM, is based on the SOA concepts at its core. Though common cross-domain data access services are desirable from an interoperability perspective, the sheer volume of data associated with weather products affects the design of services as well as the overall distributed database topology (e.g., number of 'hubs' and 'spokes' in the deployed system).

SOA Foundational Standards. Assess the utility of commonly-specified SOA standards (XML, HTTP, SOAP, WSDL, ebXML) in the context of weather data dissemination.

Some of these standards are still maturing, and best practices for using them in demanding high-volume real-time data access scenarios are still emerging.

Standard Weather Data Formats. A number of data formats exist in the weather domain, some with a design focus of small data size (GRIB, BUFR), and others with a focus on generality and ease-of-use (XML-based formats, NetCDF/HDF). The former typically represent older formats, designed at a time when data size was more of a limiting factor than it is today. Assessment of the tradeoffs involved between the various formats is needed in order to establish the necessary best practices. In addition, not all weather data are easily expressed using existing formats. In those cases, new data schemas must be established.

Data Access Services. Assess standard data access services and determine gaps that need addressing for NNEW use cases. The focus is on two data access service 'families' – services specified by the Open Geospatial Consortium (OGC) and services specified by the DOD (JMBL). Additional services based on syndication feed standards (ATOM, RSS) are also being considered for the more 'lightweight' data access use cases.

Demonstrations. Periodic NNEW-specific demonstrations are conducted as proof-of-concept for the standards being developed, adopted, and refined by the NNEW program. NNEW is also expected to contribute to a number of other NextGen demonstration initiatives over the life of the program.

The overall methodology being used for the R&D phase of the program is illustrated in Figure 3-2. A set of broad-based use cases is generated and analyzed along with existing architectural guidance to produce a candidate architecture that addresses the needs of the use cases. A set of candidate SOA technologies is selected to implement the architecture, and a demonstration is conducted. The process is iterative, with the results of each demonstration providing the necessary feedback for the next iteration. Results from each iteration are shared not only between members of the NNEW team, but with other weather-related programs and the SWIM and FTI 'foundational' programs.

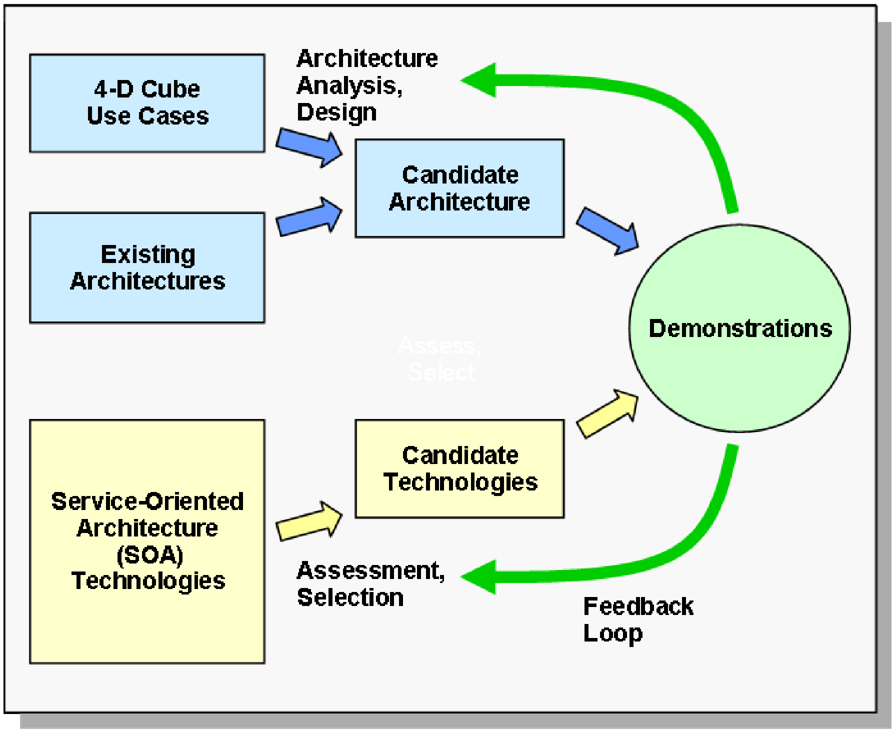

Figure 3-2. NNEW Development Methodology.

3.2 NNEW PROGRAM TIMELINE

The NNEW schedule is shown in Figure 3-3 with the R&D phase depicted in yellow and the follow-on implementation phase depicted in green. The work on representation and dissemination of gridded data products has been largely completed, and the focus has now shifted to the definition of the standards to be used with non-gridded data sets, as well as the registry/repository to allow for dynamic discovery of data sets.

Given that a number of requirements for NNEW will build on top of capabilities provided by the SWIM and FTI programs, an effort has been made to schedule the work items shown so as to minimize duplication of effort. Deferral of service-level security and monitoring until the 2009 time-frame, for example, is intended to allow the SWIM program the time to fully define the SWIM ‘container’ concept to be used to help implement these functions. Given the overall complexity of NextGen, some harmonization efforts will certainly be required downstream, but in general, the COIs and links between the various programs in the weather community are in-place to avoid a ‘stove-piped’ development approach.

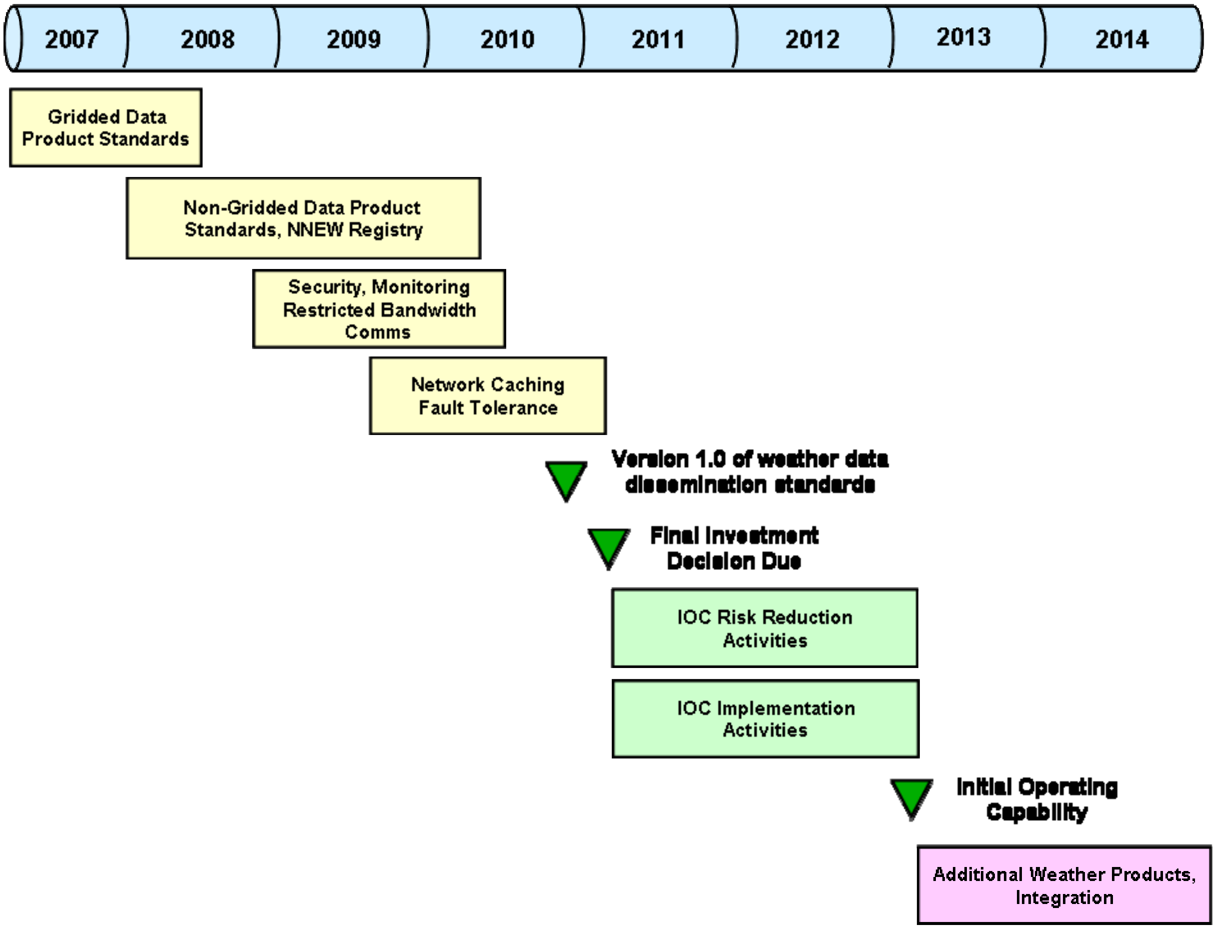

Figure 3-3. NNEW Development Timeline, 2007-2014.

3.3 NNEW DEMONSTRATION STATUS

The first formal demonstration of NNEW capabilities was successfully conducted in December, 2007 at the NCAR facility. For the demonstration, a set of 10 different gridded data products residing at NCAR, NOAA, and MIT Lincoln Laboratory was published on the open Internet using a common Web Service, and displayed on a shared Java-based client application. The datasets and their associated service endpoints were discoverable via a single ebXML-based registry/repository. The Web Service used (the OGC Web Coverage Service, or ‘WCS’) allowed the client to access data using simple spatial and/or temporal queries, returning only the data the client was interested in rather than always returning a CONUS-sized gridded data set This demonstration served as the first example of a 4D weather cube implemented using OGC data access services.

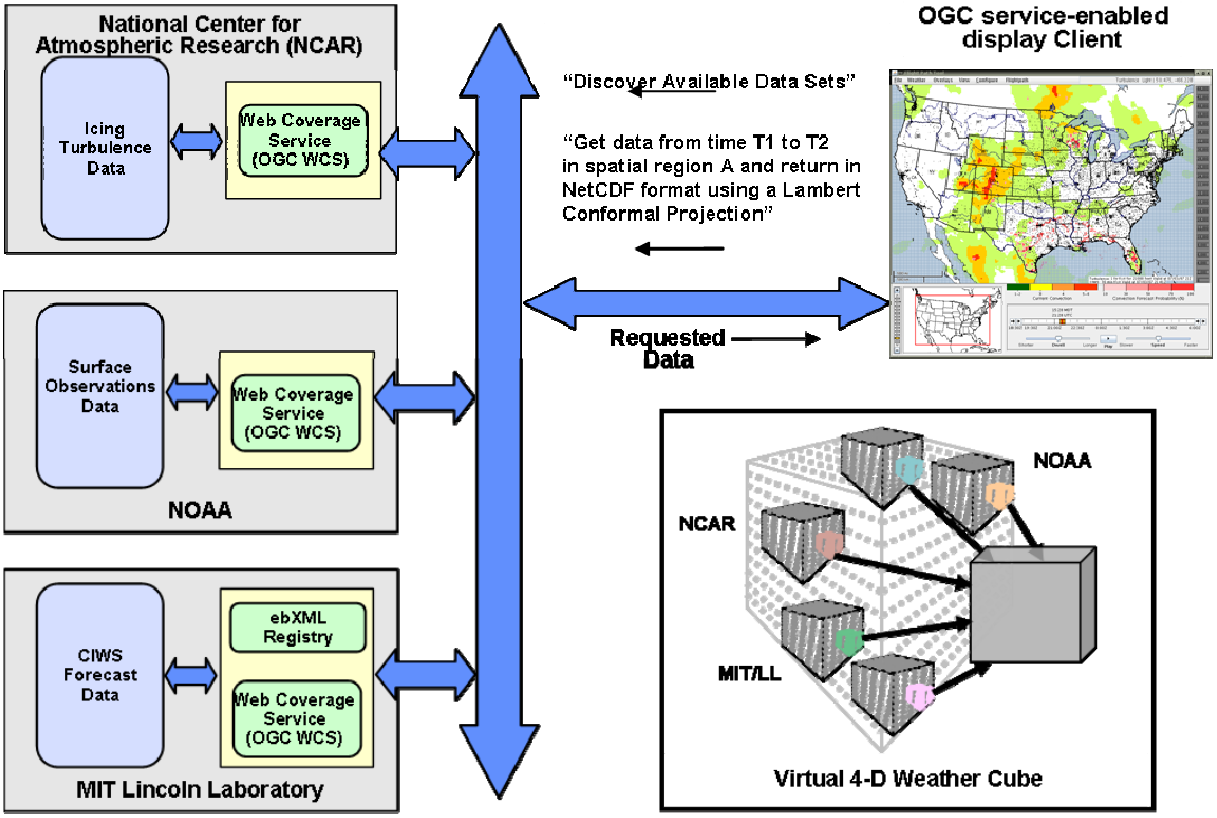

Figure 3-4. System architecture for 2007 NNEW demonstration.

It is worth noting that the majority of standards used for the 2007 NNEW demonstration are the same standards being adopted by the FAA and Eurocontrol for aeronautical information as well as weather. For example, the Aeronautical Information eXchange Model (AIXM) is based on OGCs Geography Markup Language (GML), and access to AIXM data is envisioned to occur using the OGC Web Feature Service (WFS) standard. This is highly relevant to the TFM community, as maximizing cross-domain interoperability between weather data and other types of data will greatly simplify the development of TFM applications. The use of these standards should also provide a high degree of interoperability with the international community.

In October 2008, NNEW is embarking on an interoperability experiment with the U.S. Aeronautical Information Management (AIM) community that will last about 7 months. This is being done in the context of the latest Open Geospatial Consortium (OGC) Interoperability Demonstration[17].

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[17] See http://www.opengeospatial.org/standards/requests/50 for a description of this demonstration.

3.4 NNEW FUTURE DIRECTIONS

At the conclusion of the R&D phase, a set of standards to be used for distribution of weather data within the FAA will move beyond draft status and be formalized. At that point, implementation activities related to the Initial Operating Capability (IOC) are scheduled to commence. The exact process to be used for implementation of IOC is not yet known, but it is reasonable to assume that the implementation work will leverage some of the R&D 'leave-behinds' produced by the Laboratories. In recognition of this, work done at the Laboratories will conform to certain quality measures, such as common coding conventions and support for unit tests. It is anticipated that follow-on risk-reduction efforts at the Laboratories will be conducted as needed to ensure that the implementation phase proceeds efficiently.

Integration with non-weather systems is not a core activity defined in the R&D phase of the NNEW program. Efforts related to integration will, however, be occurring during both the R&D phase and the follow-on implementation phase. One natural venue for integration work will be 'demonstrations of opportunity' that are conducted in the coming years. A current example of such a venue is the 'Airport of the Future' demonstration to be conducted in Florida during the latter portion of 2008.

The role of NNEW in these integration activities will be to provide the weather standards foundation for demonstration participants, as well as a variety of proof-of-concept net-centric weather data feeds. Lessons learned from these external demonstrations will be incorporated back into the NNEW architecture in the same manner as results from NNEW-specific demonstrations.

An important question for TFM modernization is to determine at what point should the TFM program consider use of the NNEW developed interfaces to obtain weather data and products.

The current expectation is that CIWS data will be available in NNEW-compatible data formats in 2009. Volpe is already working to access the CIWS utilizing these formats in conjunction with early versions of NNEW-compatible data access services. NNEW data access mechanisms (e.g., registry, discovery, query, etc.) will continue to mature during 2009, providing access to CIWS and a number of other weather data sources with a reliability appropriate for nearer-term TFM R&D activities. The expectation is that both NNEW and SWIM will have a full-up initial operational capability before 2013.

Though additional work remains for both the NNEW and SWIM programs with respect to weather data formats and dissemination mechanisms, there has been substantial progress made to date establishing the basic framework. As mentioned above, the framework shares much of the same infrastructure with that being adopted by the Aeronautical Information Management (AIM) community, providing inherent benefits with respect to integration of weather and surveillance data.

The expectation is that a TFM- transition to NNEW/SWIM data access mechanisms sooner rather than later will result in significant cost savings due to the availability of modern software support tools (i.e., the SWIM service container software) and a reduced need for downstream software modifications to achieve end-state NNEW/SWIM compatibility. We therefore recommend that the TFM program have a FY2009 technical interchange meeting with the NNEW/SWIM programs to determine a near term course of action.

4. CURRENT RESEARCH ON TRANSLATING WEATHER PRODUCTS INTO CAPACITY IMPACTS

In this section, we consider the state of art in translating weather products into capacity impacts. We will first consider en route airspace (which has been the principal focus of quantitative modeling to date) and then consider terminal airspace.

4.1 WEATHER CONDITIONS AFFECTING EN ROUTE OPERATIONS

4.1.1 Translation of convective weather forecasts into forecasts of NAS capacity impact

The term "capacity impact" can have a number of different characterizations depending on the particular TFM operational decision support application. In the table below we summarize some of the key characterizations for various TFM applications.

TABLE 4-1

"Capacity" Characterizations and the Corresponding TFM Applications

Characterization	TFM application (s)
Regions of airspace which pilots will avoid	Time based trajectories for time based flow management (e.g., TMA, EDC, the Metron DFM prototype) and weather avoidance tools (e.g., FEA, FCA, SEVEN). A key input to other quantitative characterizations of capacity discussed below.
Route availability	Arrival and/or departure route based automated congestion prediction [e.g., Route Availability Planning Tool (RAPT), DFM]; en route flow management; may be a key input to other quantitative characterizations such as Airspace Flow Programs or sector occupancy.
Bi- or uni-directional flow through a region	Automated airspace congestion [e.g., Airspace Flow Program (AFP) throughput rate forecasting]
Sector occupancy (# of aircraft in a spatial region in a given time period)	Automated congestion prediction and resolution algorithms (e.g., PACER, SEVEN)

For each of the above characterizations of capacity, one may also distinguish between the various portions of en route airspace of concern. The three airspace categories of greatest interest are:

a. Departure Transition – This could be seen as overlapping with some point within terminal, but here is meant to imply ARTCC airspace from the departure fix to the en-route portion of flight.

b. Arrival Transition – This is from Top of Descent in ARTCC airspace to the boundary with terminal airspace (i.e., arrival fix), but again could logically be extended to some point within terminal airspace.

c. En-Route – Operation of flights at or near the intended cruise altitude.

For purposes of exposition, we will discuss each of the topics in Table 4-1 separately.

(i) Characterization of capacity constraints by determining the regions of unusable airspace (e.g., "weather avoidance field")

Pilot avoidance of regions of airspace is directly applicable to time based metering of aircraft where one is concerned about estimating the impact of the convective weather on aircraft flight trajectories. Models for determining whether or not pilots will seek to avoid certain portions of the airspace, the deviation distance from avoidance regions and preferred weather avoidance strategies are also essential for determining capacity impact.

A number of recent studies have been carried out under NASA funding on the relationship of pilot decision making for level flight in en-route airspace on convective storm penetration versus deviations [DeLaura and Evans, 2006; Chan et al., 2007; DeLaura, et al., 2008a].

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

In the most recent study of pilot behavior in avoiding convective weather (DeLaura, et al., 2008a), only one of the five best predictors of deviation identified by a Gaussian classifier algorithm was not related to echo top height. Prediction errors were greatest for trajectories whose flight altitude were near or slightly below the echo top height, and the differentiation between 'benign' echo tops and those that pilots avoid remain a major challenge in convective weather avoidance modeling.

It may be surprising that commonly used measures of precipitation intensity (maximum VIL, composite reflectivity, etc.) did not provide additional deviation prediction skill beyond what is available in the echo top fields. However, for flights at en route cruising altitudes, regions of heavy but low-topped precipitation are readily over flown. Where heavy precipitation is due to vigorous convective activity, both high VIL and high echo tops are present. Echo top heights alone can explain observed pilot behavior in both circumstances. Note that in other phases of flight – departures and arrivals in the terminal area or transition from terminal area to en route airspace – aircraft are traversing different altitudes and pilots have different concerns that may be more closely related to precipitation intensity measured by VIL.

Translation of weather forecast gridded spatial fields into forecasts of regions of airspace that pilots will seek to avoid is straightforward if the forecasts include the key predictors of deviation (e.g., VIL and radar echo tops). The resulting fields of probability of pilot deviation have been termed weather avoidance fields (WAF) [e.g., (DeLaura and Evans, 2006)]. The WAF validation has been accomplished by determining how well the WAF predictions of pilot deviations agree with actual pilot behavior using weather-flight profile data sets that were different from the data sets used to develop the WAF predictors

Other areas of research identified in (DeLaura, et al., 2008a) include:

1) Development of an improved deviation detection algorithm to enable the creation of large scale trajectory and deviation databases for modeling and validation studies,

2) Consideration of upper level winds, storm dynamic structure features and cloud features determined from satellite data as possible deviation predictors,

3) Review of existing data such as echo top trends and storm motion data to ensure that predictors based on these products were well-chosen, and

4) Consideration of human factors, such as cockpit information, pilot training, and company policy as factors in predicting deviations. The cockpit information factors might include specific flight-related operational information such as time of day, storm illumination, behavior of other pilots in the area, etc.

Although the detection of turbulence associated with thunderstorms by use of Doppler spectrum width from NEXRAD has been treated as a separate entity from convective forecasting in the FAA AWRP, we recommend that these NEXRAD spectrum width turbulence detection outputs:

1) be treated as one of the convective storm predictors in the generation of weather avoidance fields rather than utilized independently, and

2) the AWRP conduct research to relate the spectrum width derived turbulence regions to storm 3D structural features and environmental winds

This is because a very major effort is being put forth in CoSPA to develop reliable short term tracking of storm movements. These, in turn, would be applicable to providing advection based forecasts of convectively induced turbulence that take into account storm growth and decay.

Another factor that could potentially be significant in improving the ability to accurately predict storm pilot deviation decisions is providing ground derived weather and airspace congestion products to the cockpit.

It was noted by the test pilots for the flight tests reported in DeLaura et al., (2008a) that it is not easy to estimate the altitude of storms relative to the aircraft at distances of 20–40 miles. Hence, some variability in pilot deviation behavior may arise from differing subjective estimates of what might be required to fly over a cell. Ground derived storm information such as storm tops, an indication of which storms are growing or decaying, and explicit turbulence severity forecasts might help in achieving more consistent deviation behavior between different pilots.

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

It should also be noted that relatively well validated pilot storm avoidance models have been developed thus far only for level flight in en route airspace. These models need to be extended to consider both the arrival and departure transition regions in en route airspace. For example, departures climb at much steeper elevation angles than the typical arrival. Also, both passengers and cabin attendants are seated with seat belts on during climb out whereas cabin attendants may be in the aisles during the initial descent phase. Hence, one might imagine that the pilot desire to avoid convective turbulence could be higher for arrivals than for departures. On the other hand, since pilots of descending aircraft are unaware of what sort of weather is hidden beneath the cloud cover, they may be willing to descend into areas that pilots of departing aircraft will avoid, since they can see the weather as they climb up to the cloud level.

Since many near term convective weather-ATM integration system capabilities involve flights that are in arrival and/or departure transition airspace, it clearly will be necessary to extend the pilot response modeling analysis to these other flight regimes early on in the 2008–2015 time period. This modeling will also be applicable to usage of current TFM decision support tools (e.g., TMA) during convective weather.

(ii) Characterization of capacity constraints by blockage of principal routes

TFM control is often executed using miles-in-trail (MIT) spacing between aircraft on a route or, at an arrival or departure fix and, by manipulation of flows (especially, starting and stopping the use of a fix or route). The Route Availability Planning Tool (RAPT) [DeLaura and Allan, 2003, DeLaura et al., 2008b] utilizes route segment blockage forecasts to determine when aircraft can depart an airport on a given route. Experience with RAPT has shown that convective weather impacts in the adjacent en route airspace are a significant factor in departure management. Since MIT and flow start/stops on a route are principal mechanisms used to manage traffic flows and mitigate the impacts of convective weather in en route airspace, the estimation of route impacts is clearly germane as a characterization of convective weather impact on “capacity” in en route airspace.

A number of areas for research in en route departure transition and level flight route blockage algorithms arising from the RAPT real time testing in 2007 are discussed in DeLaura et al., (2008b). They found that RAPT performance was best in circumstances where convection was embedded in larger regions of stratiform or low level precipitation. RAPT performed poorly in regions where route impacts were due to weather characterized by a large spatial gradient in the VIL or echo top prediction fields caused by small, strong isolated cells or the leading edge of intense convection. Work is underway to address these deficiencies in the RAPT route blockage model by using the weather avoidance field (WAF) to determine route blockage as opposed to an ad hoc combination of storm reflectivity and echo tops fields.

There is an urgent need to better understand the relationship between route blockage, route topology and transitional airspace capacity in the presence of convection. Research is needed to characterize how traffic managers handle situations such as storm impacts on merge and crossing points, ascending and descending flights, and arrival and departure fixes. Some issues associated with modeling the impact of storms on departure fixes will be investigated as a part of the studies of how the RAPT algorithms (which currently reflect the atypical arrival and departure fix geometry of the NY TRACON) should be modified to allow RAPT to be used at “conventional” 4-corner TRACONs.

Research is also needed to understand the interaction between route blockages in neighboring routes in transitional en route airspace where routes are densely packed. For instance, in their evaluation of RAPT performance in 2007, DeLaura, et al., (2008b) noted that capacity on New York departure routes that were relatively clear of weather impacts could be adversely affected when busy nearby arrival routes in ZNY airspace were blocked by convection.

Thus far, little work has gone into developing ATC impact models for arrival transition airspace. An important feature of arrival flows for major airports is the merging of flows near the arrival fixes as shown in Figure 4-1. Studies of the controller workload [e.g., Histon et al., (2002)] have found that such merge points are significant factors in workload. At this point, we do not know what the implications are for arrival flows if storms impact a merge point as opposed to blocking routes well away from a merge point.

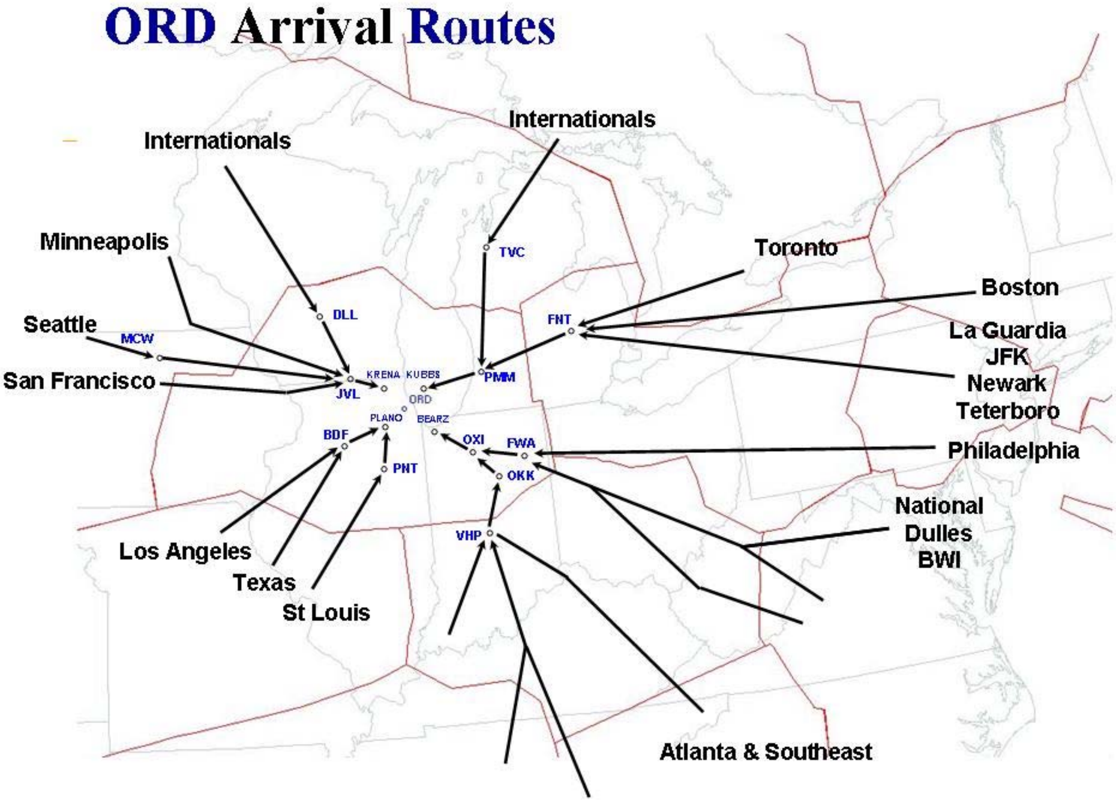

Figure 4-1. Arrival flow structure for the Chicago O'Hare Airport. Note the multiple merge points.

(iii) Characterization of capacity constraints as a reduction in the maximum number of aircraft that can safely be handled in a region

In the TFM literature, "capacity" typically is characterized by the maximum number of aircraft that can be safely handled in a region per unit time due to controller workload (and wake vortex) constraints[18]. The Enhanced Traffic Management System (ETMS) characterizes the capacity by the number of aircraft that may be in a sector over a given period of time (i.e., sector occupancy) in determining when TFM managers should be alerted as to a possible traffic overload.

However, there is no standard metric for the maximum number of aircraft that can be safely handled in a region due to controller workload. Complexity studies [Histon, et al., 2002, Song, et al., 2006] emphasize the importance of the geometry of principal traffic flows in a sector and factors such as:

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[18] NASA and MITRE have characterized workload by metrics that go well beyond sector occupancy. However, the published papers to date on characterizing the capacity constraints that arise with convective weather impacts [e.g., Wanke and Greenbaum, (2007), Song, et al., (2007)] have all used sector occupancy as the metric for capacity.

- the Major Flow through a sector and its size
- Number of Flows: The number of flows through the sectors that have at least two aircraft.
- Number of Merging Flows
- Number of Climbing Flows
- Number of Descending Flows
- Number of Crossing Flows

in determining complexity.

A key research issue at this point is how to predict sector occupancy during convective weather. There are two basic approaches that have been discussed in the literature to date: (1) ignoring all or most of the details of traffic flow within a sector (e.g., flow distribution, maximum flow, merges, and crossing points) within a sector, or (2), applying the complexity considerations used in fair weather to convective weather

Examples of the first approach include estimating sector usage in convective weather by a linear function of the fractional coverage of the sector by high reflectivity weather (Zobell, et al., 2006). Estimating sector usage for unidirectional flow in a sector by a fluid flow argument (specifically, a max-flow, min-cut theorem from the mathematical literature) that focuses on the narrowest available region that is at right angles to the traffic flow (i.e., akin to an obstruction in a pipe) (Mitchell, et al., 2006). Song, et al., (2007) have used the model by Mitchell, et al., (2006) to predict unidirectional flows in several principal directions through a sector.

An example of the second approach is the model discussed in (Martin, 2007) which predicts the reduction in sector occupancy by determining which specific routes in a sector are blocked and, what fraction of the normal traffic in the sector operates over the blocked routes. By far, the most successful model in terms of matching the sector usage of today's NAS is the model discussed in Martin (2007).

Figure 4-2 shows a typical result of the validation testing for Martin's model. We see that the error distribution peaks at zero error with the bulk of the errors within plus or minus three aircraft. Reasons for the major differences between the predicted and actual sector usage are discussed in Martin (2007); a principal cause of overestimation of the traffic within a sector was the impact of storms on other sectors surrounding the sector under study. The model typically underestimates capacity in sectors where air traffic control has sufficient flexibility to define improvised traffic flows that avoid weather and do not interfere with adjacent traffic flows.

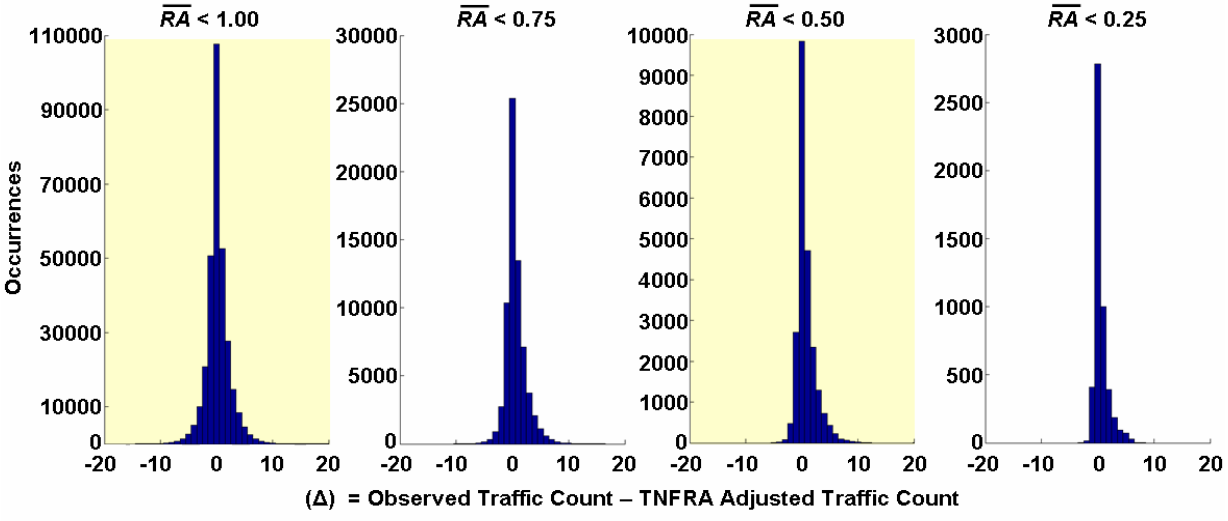


Figure 4-2. Comparison of estimated one minute traffic counts in 406 sectors within the Corridor Integrated Weather System (CIWS) domain using traffic normalized route blockages computed from CIWS 3D storm data and the actual observed one minute traffic counts for 27 July 2007 convective weather event. RA is the fraction of routes within a sector that were blocked at the time of measurement [From Martin (2007)].

Figure 4-3 shows a typical result for the high altitude capacity loss at several points in time over a one hour period due to convective weather in the Northeast U.S. computed by using Martin's model. This time-space variability of sector capacity loss in convective weather is clearly a major challenge for effective TFM. For example, flow patterns that were feasible at 1700 UTC would need to be significantly altered by 1730 UTC. At 1700 UTC, the convective weather impact on sectors along the East Coast is minor, and therefore represents alternative routes for excess traffic from the Midwest. By 1745 UTC, those East Coast sectors have been significantly impacted by convective weather while the Midwest impacts have also changed significantly. Hence, there would need to be significant changes in the traffic flows between 1700 UTC and 1800 UTC with significant coordination between the various ATC facilities.

The results in Figure 4-3 suggest that efficient and high-quality short lead time TFM is needed to handle the rapid/space time variations in sector capacity. Realistically, 2–8 hour convective forecasts coupled with capacity translation may only provide an estimate of a space/time average capacity loss in a region such as Figure 4-3. Hence, there will need to be extensive tactical adjustments even if the time-space average sector capacity loss was accurately forecast.

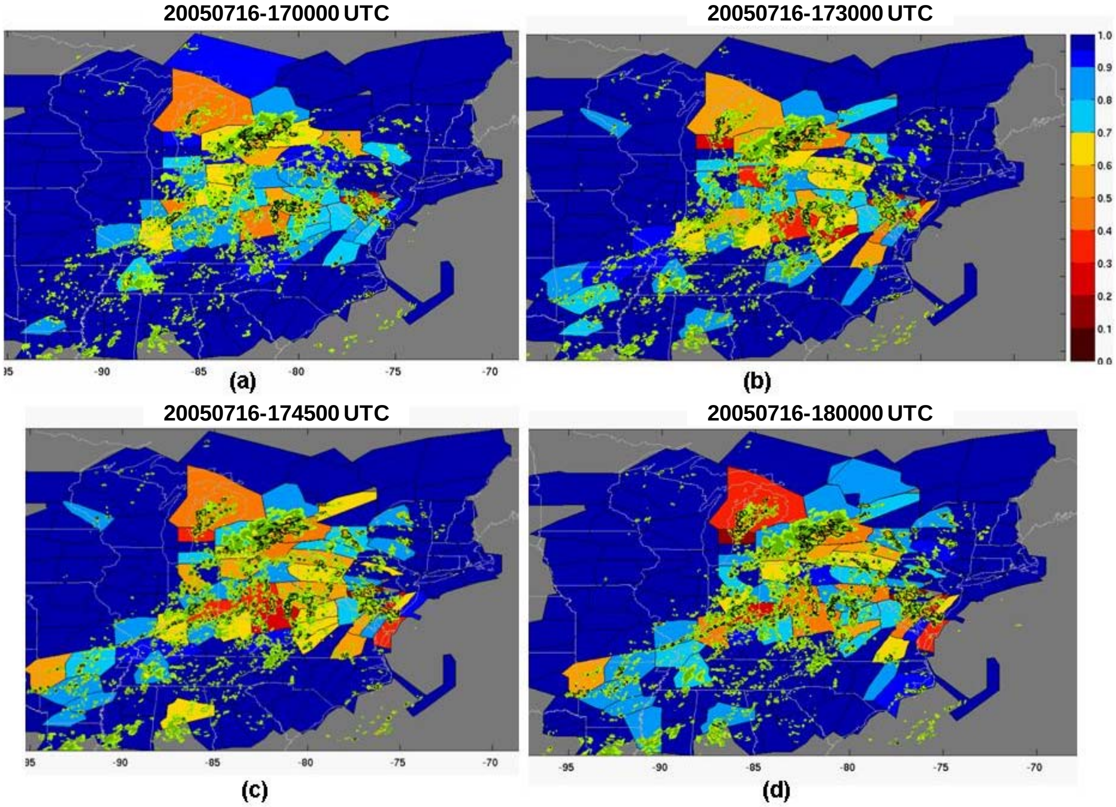


Figure 4-3. "Capacity" loss due to convective weather in the Northeast quadrant of the U.S. at (a) 1700 UTC, (b) 1730 UTC, (c) 1745 UTC, and (d) 1800 UTC on 16 July 2005. Overlaid atop capacity loss estimates is CIWS precipitation. The color bar in the upper right corner indicates effective capacity of a sector as a fraction of the sector fair weather capacity (dark red is fully "blocked" while dark blue is fully "open"). The "capacity" characterization here is sector occupancy.

(iv) Characterization of capacity constraints by reduction in the uni- or bi-directional flow through a region such as an AFP

A major new TFM tool for management of convective weather impacts is the airspace flow program (AFP) which typically constrains the flow per unit time through a region in en route airspace (FAA 2006). A preliminary study to estimate AFP reductions by forecasting the blockage of major routes that cross an AFP [analogous to the approach used in Martin (2008) to estimate sector occupancy by determine which principle routes in a sector are blocked] is discussed in Robinson, et al. (2008c). Figure 4-4 shows the two most common AFPs used operationally in 2006 (AFP-5 which constraints east bound flights along the Great Lakes Corridor and AFP-8 which constrains northbound flights through the northern end of ZDC).

Figure 4-5a and 4-5b show the initial comparisons of the actual throughput for AFP05 and AFP08 for three different storm events from 2006 with the actual traffic through the respective AFPs. The blue curve shows the fair weather flows on a typical weekday. We see that the AFP05 traffic increases significantly at about 1800 GMT (1100 local time); this significant increase arises from the morning west flights arriving in the area east of Chicago. By comparison, the fair weather

AFP08 traffic (from Washington, DC, the southeast and Florida) is much more uniform during the day.

When model estimates of throughput are less than the observed traffic:

1. weather impacts or route blockages are overestimated by the model,
2. AFP-delivered traffic demand exceeds the fair-weather demand used by TNFRA, or
3. some combination of the two occurs.

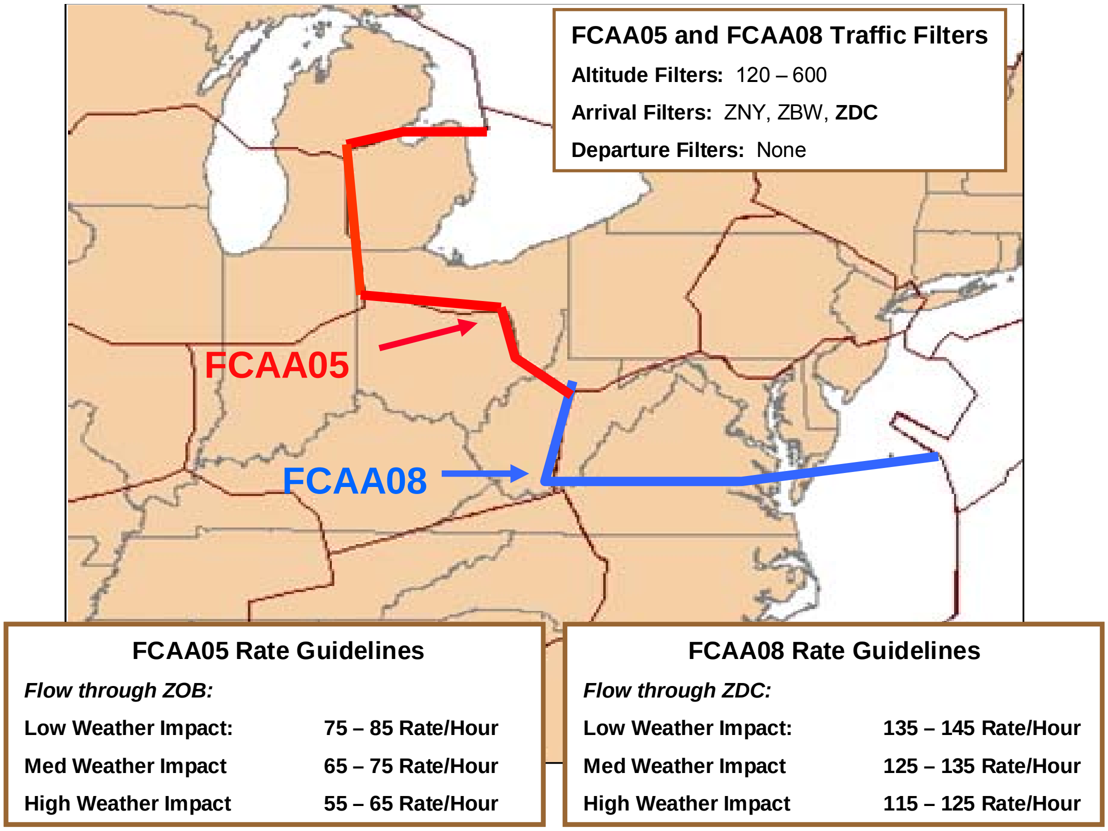
When model estimates of throughput are greater than the observed traffic:

1. weather impacts or route blockages are underestimated,
2. weather or volume impacts outside the analysis domain are reducing traffic demand,
3. under-utilized capacity exists within the domain, or
4. some combination of the three has occurred.

Examination of the FCAA05 and FCAA08 time series indicate that the route blockage based model for estimating impacts on AFP throughput (red) compares well to the observed trend in actual AFP throughput (green). Only in the 27 June 2007 case involving FCAA08 do we see a prolonged interval (1700 – 0400) of the model overestimating the weather impact on throughput across the AFP. In that case, actual traffic compares better with the maximum possible throughput (black curve) estimate. It is postulated that, in this case, the prolonged increase in actual throughput is the result of more traffic being directed south of weather impacts affecting FCAA05, consequently increasing the traffic directed through the FCAA08 domain. An inspection of the coverage, location, and severity of convection during the 27 June 2007 event shows that, given the dearth of available airspace in the A05 region, nominal FCAA05 traffic would have had to route through FCAA08 airspace to reach the airports in the northeast, increasing observed A08 traffic throughput during this event.

Cases where the projected throughput was in excess of the actual throughput represents situations where there evidently was available capacity that was not utilized. Such underutilized capacity has been observed in both the RAPT testing [Robinson, M., DeLaura, R., Evans, J. and S. McGettigan, (2008a)] and in studies of "avoidable" delay [Robinson, M., Moser, W. and J. Evans, (2008b)].

The multiple parallel lanes approach discussed in Mitchell, et al. (2006) could in theory be used to estimate AFP throughputs. However, that algorithm assumes many more planes could be handled in a sector than is feasible today. Hence, the practical utility of such "lane packing" estimates when plane-to-plane separation is accomplished manually is unclear. No comparisons between the AFP throughput predictions by "lane packing" models with actual AFP throughput have been published to date. If automated aircraft separation does mature, the algorithm discussed in Mitchell, et al. (2006) would warrant detailed analysis and validation as an alternative approach to AFP throughput estimation.



FCAA05 and FCAA08 Traffic Filters

Altitude Filters: 120 – 600

Arrival Filters: ZNY, ZBW, **ZDC**

Departure Filters: None

FCAA05 Rate Guidelines

Flow through ZOB:

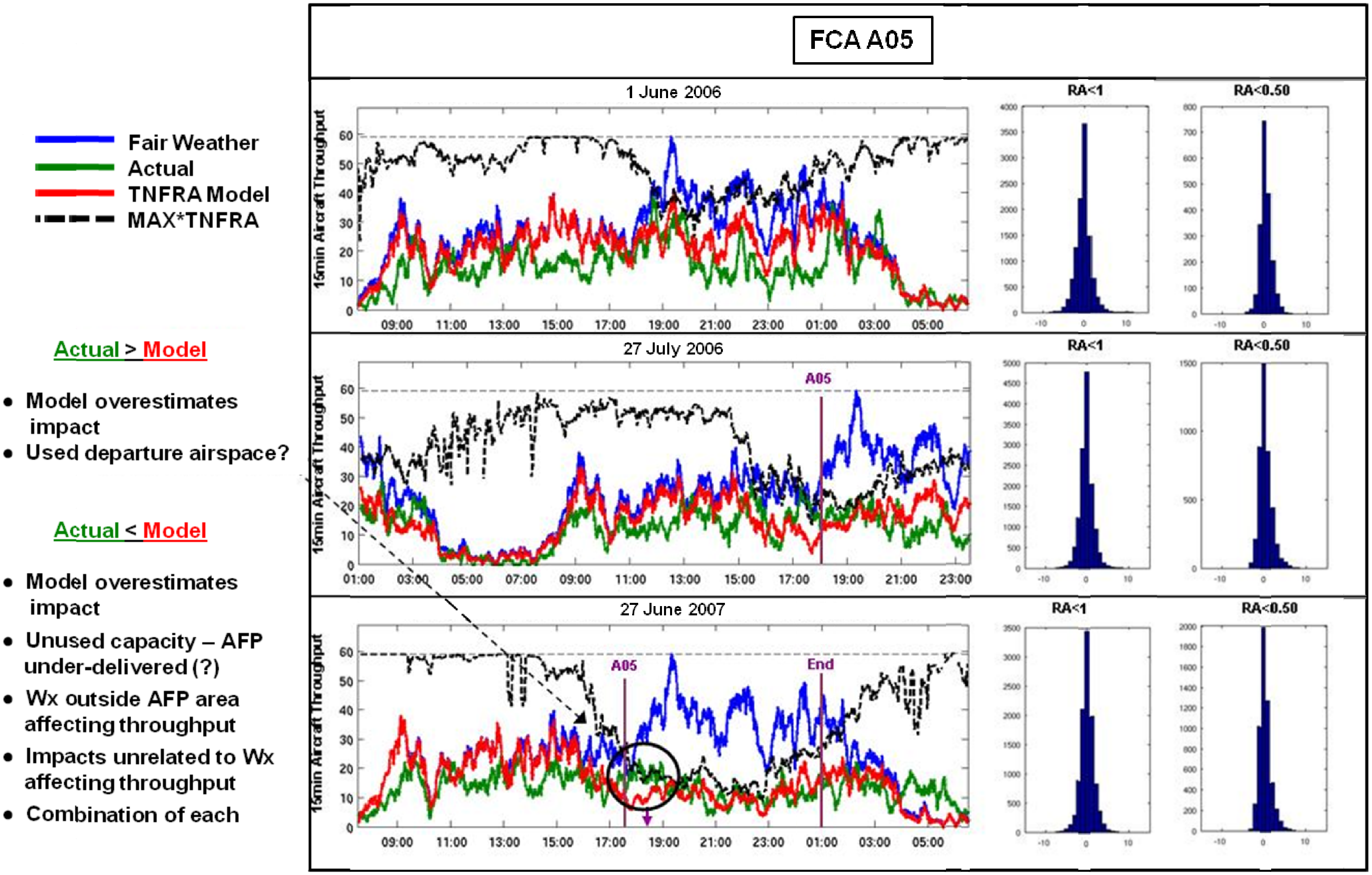
Low Weather Impact:	**75 – 85 Rate/Hour**
Med Weather Impact	**65 – 75 Rate/Hour**
High Weather Impact	**55 – 65 Rate/Hour**

FCAA08 Rate Guidelines

Flow through ZDC:

Low Weather Impact:	**135 – 145 Rate/Hour**
Med Weather Impact	**125 – 135 Rate/Hour**
High Weather Impact	**115 – 125 Rate/Hour**

Figure 4-4. Location, traffic filters, and rate guidelines for Airspace Flow Programs (AFPs) FCAA05 and FCAA08. Note that these two AFPs are unidirectional (i.e. they control only traffic into the Northeast portion of the NAS.



Actual > Model

- Model overestimates impact
- Used departure airspace?

Actual < Model

- Model overestimates impact
- Unused capacity – AFP under-delivered (?)
- Wx outside AFP area affecting throughput
- Impacts unrelated to Wx affecting throughput
- Combination of each

Figure 4-5a. AFP05 throughput estimates compared to the actual 15 minute throughput across FCAA05 for the three high impact weather events: 01 June 2006, 27 July 2006, and 27 June 2007. The green line represents the actual 15 minute AFP filtered throughput that occurred on each of the three weather impacted days. The blue line represents the throughput estimate derived by summing the 15 minute route maximum of the three fair weather days centered at each one minute time steps. The red line in the time series represents the forecast of actual throughput based on route blockage. The thick black dotted line is the throughput relative to the single value maximum observed fair weather throughput (thin dashed line) and is meant to represent a measure of potential achievable capacity given weather impacts in the AFP domain. The histograms on the right hand side are the sample distributions of the difference between a route's actual throughput and the route blockage (RA) estimate of throughput. Positive differences indicate that the route blockage overestimated the weather impact on a route's throughput at any given time; negative differences indicate the underestimates. The first column of histograms (left side) shows the occurrence distribution of these differences over all instances where route blockage indicated some weather impact (RA<1.0). The second column of histograms (far right) compares the differences for cases with greater weather impact (RA<0.50).

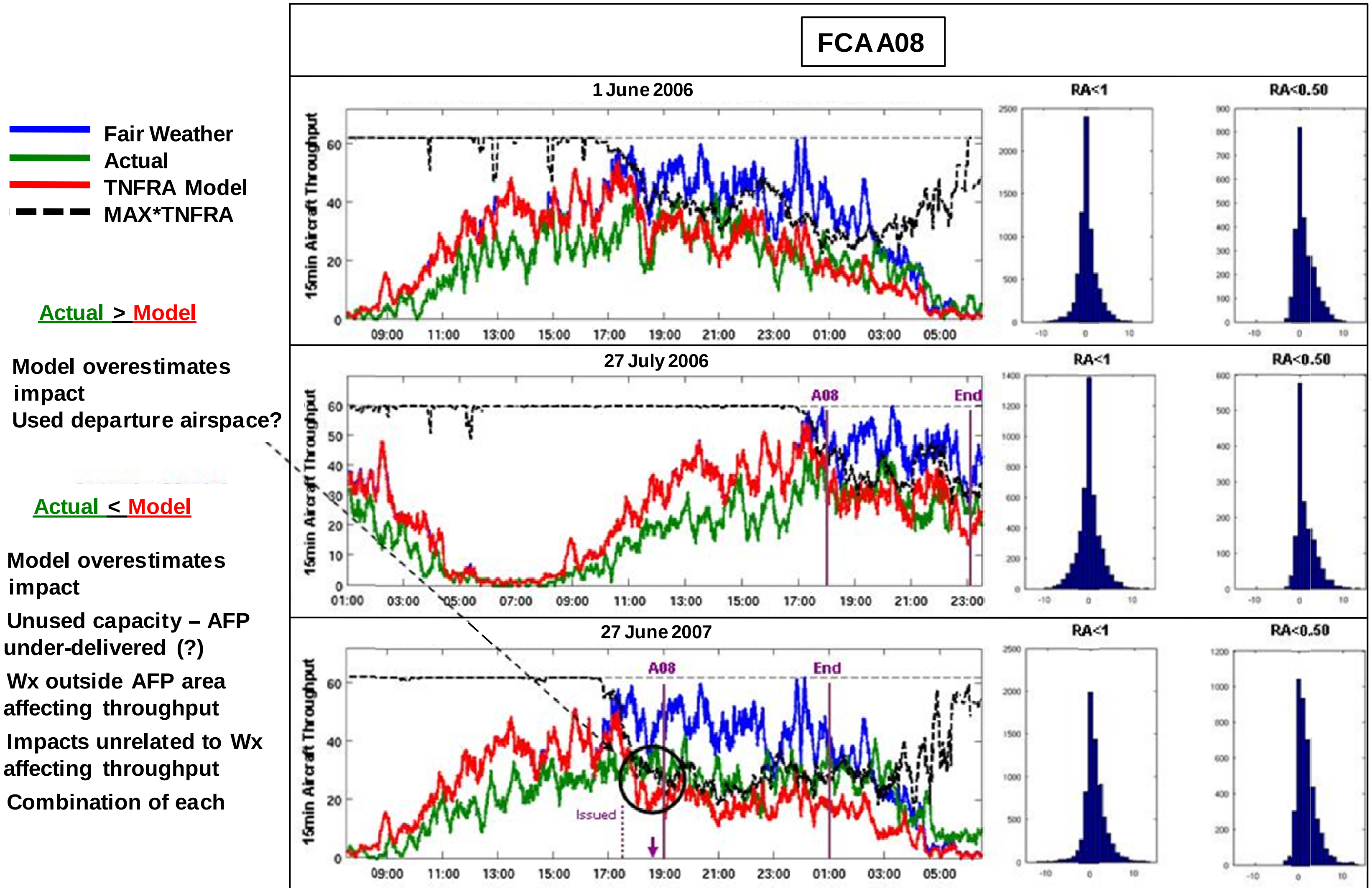


Figure 4-5b. AFP08 throughput estimates compared to the actual 15 minute throughput across FCAA08 for the three high impact weather events: 01 June 2006, 27 July 2006, and 27 June 2007. The green line represents the actual 15 minute AFP filtered throughput that occurred on each of the three weather impacted days. The blue line represents the throughput estimate derived by summing the 15 minute route maximum of the three fair weather days centered at each one minute time steps. The red line in the time series represents the forecast of actual throughput based on route blockage. The thick black dotted line is the throughput relative to the single value maximum observed fair weather throughput (thin dashed line) and is meant to represent a measure of potential achievable capacity given weather impacts in the AFP domain. The histograms on the right hand side are the sample distributions of the difference between a route's actual throughput and the route blockage (RA) estimate of throughput. Positive differences indicate that the route blockage overestimated the weather impact on a route's throughput at any given time; negative differences indicate the underestimates. The first column of histograms (left side) shows the occurrence distribution of these differences over all instances where route blockage indicated some weather impact (RA<1.0). The second column of histograms (far right) compares the differences for cases with greater weather impact (RA<0.50).

Capacity estimation models must be able to identify circumstances where improvised traffic flows are feasible, estimate the capacity achievable on those flows and account for the impacts of their usage on nearby traffic flows. Further research is needed to support the development of such models. Improved validation techniques are also needed, especially where capacity models suggest that achievable capacities are greater than observed traffic counts. Simulations and stochastic modeling techniques may be applied to both the development and validation of capacity models, but care must be taken to ensure that the simulations sufficiently reflect operational reality.

(v) Uncertainty in estimates of convective weather impacts

Uncertainty in forecasts of convective impact arises from several sources: weather forecast uncertainty, errors in translation and capacity models and the variability in judgment and risk tolerance among pilots, air traffic controllers and managers, etc. In the translation research described in the preceding sections, impacts have been estimated using known weather, so the observed uncertainty is the result only of translation errors or human variability. The effects of weather forecast uncertainty on the predictions of convective weather impacts have not been explored in depth.

Expressions of weather forecast uncertainty must be structurally compatible with weather impact models so that the impact models can translate weather uncertainty into capacity uncertainty. Most of the models for weather forecast uncertainty were developed to support human forecasters, not the emerging models for translation into aviation impact. Consequently, generally accepted weather forecast uncertainty models that can be readily translated into impact uncertainty do not yet exist.

We will now briefly review the status of research in this area.

1. Spatial coincidence between forecast field (e.g., reflectivity or echo tops) and actual field (i.e., pixel overlap scoring)

When the meteorological community discusses probabilistic forecasts for regions of precipitation, they are typically talking about a spatial map that shows the probability of precipitation (or, radar reflectivity) above some threshold at a given location at the forecast valid time. This quantitative metric was a significant improvement over subjective characterizations such as “chance of showers” since the probabilities can be verified experimentally by analysis of many different storm events.

However, probability of the radar reflectivity (or echo tops or other metrics such as WAF) exceeding some threshold at a given location at the forecast valid time cannot be readily converted into a probabilistic statement of capacity impact because:

1. the capacity impact typically depends on the spatial distribution of the convective weather in a region, and
2. the statistical correlations between weather occurring at nearby locations is critical to determining the likelihood of various local spatial distributions of weather.

For example, the CCFP provides a probability ('high', 'medium' or 'low' confidence) that 'convection' will cover certain percentages of the pixels in a region and provides an estimate of the likely range of the top quartile echo top (Fahey and Rodenhuis, 2004). However, because CCFP does not provide any information about the spatial characteristics of that coverage (other than for "solid lines"), this expression of forecast uncertainty provides no useful information to translation models.

To illustrate, if 25% coverage were in the form of a linear convective complex (e.g., such was shown in Figure 1-3) the certainty of impacts on east-west routes is likely to be very high and quite different than the likelihood of impacts on routes aligned southwest to northeast. If that 25% coverage is made up of several widely scattered cells, the uncertainty in impacts is likely to be very high, due to the difficulty of predicting the location and timing of small cells with much precision.

Because weather impacts are highly dependent on the spatial organization of the weather and its interaction with the underlying route structure, knowledge of the spatial correlation of forecast pixels is essential in estimating the effects of forecast uncertainty on capacity impacts. Such correlation information is not well known for current forecasts of convective weather. Even if the spatial correlation of the forecast pixels is well known, the problem of calculating impact probabilities over a flight trajectory, route or ATC sector is extremely difficult because of the enormous number of conditional probabilities that must be taken into account.

2. *Route blockage based assessment of convective forecast uncertainty.*

Given that blockage of routes is an operationally useful characterization of capacity impact in RAPT, and that route blockage appears to be useful in estimating AFP throughput and sector occupancy (e.g., modified MAP thresholds), characterizing forecast uncertainty in terms of route blockage uncertainty is an obvious approach that is being very actively investigated currently. Figure 4-6 shows an approach currently under active investigation at Lincoln Laboratory.

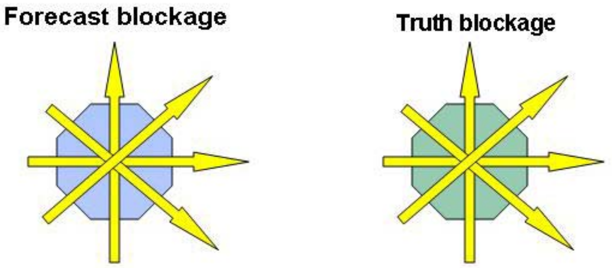


Figure 4-6. Approach to characterizing route blockage uncertainty. The blockage of routes in different directions is determined for both the forecast and the actual verification weather. This assessment of route accuracy would be accomplished over a square grid of evaluation points (e.g., separated by 10 km).

The en route blockage computation would consider both reflectivity and echo tops forecasts and data converted to weather avoidance fields (WAF). Figure 4-7 shows a preliminary example of scoring 15 minute and 60 minute CIWS convective forecast in terms of WAF and route blockage for aircraft at 31 kft.

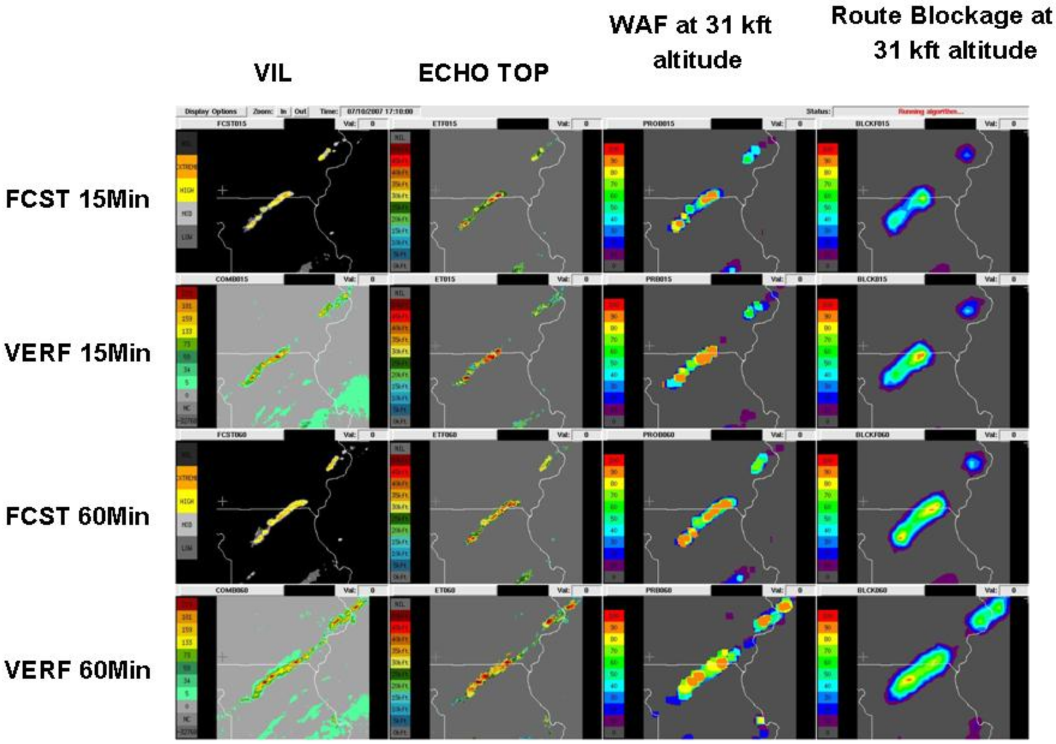


Figure 4-7. Example of scoring CIWS 15- and 60-minute forecasts of reflectivity (VIL) and radar echo tops in terms of weather avoidance field (WAF) and route blockage at 31 kft. The performance of the route blockage determination at 31 kft for the 60 minute forecast appears to be comparable to the 15 minute forecast accuracy.

For short lead time forecasts (e.g., 0–2 hours), one can envision a sector specific summary of recent past performance at forecasting route blockage. For example, if the bulk of the routes in a sector were oriented from southwest to northeast (as is the case in the northern portion of ZDC), then route blockage forecast accuracy for that route orientation would be given the highest weight in the route blockage accuracy score.

To handle the case where a sector S has had no recent convective weather impacts and/or the spatial distribution of the convective weather is spatially inhomogeneous (e.g., isolated convection in front of an approaching synoptic front), the accuracy score could be based on regions that are currently experiencing the convective weather that is forecast to move into S. One could then go through an analysis similar to that shown in Figures 2-8 to 2-10 to determine if route blockage accuracy scores based on past weather provide useful information on the accuracy of the current forecast.

3. Ensemble techniques used to characterize capacity forecast uncertainty.

The fact that the impact models described above in this section were based on known weather means that one can calculate an impact estimate for each member of an ensemble-based probabilistic forecast, since each member represents a possible specific weather outcome (akin to a deterministic forecast). A probabilistic forecast of capacity impact can then be explicitly calculated based on the ensemble of impacts calculated from the specific weather outcomes[19]. This would be particularly helpful for time based flow algorithms that would be concerned about the range of flight times a plane is likely to experience between two points (e.g., between the plane's current position and an arrival fix).

If this ensemble modeling approach is followed, it is important that the ensemble forecast members are representative of the range of possible outcomes. A major concern is that there is very little literature or practical experience with ensemble techniques for the time-space scale envisioned for the CoSPA 2–8 hour forecasts. For example, the various ensemble sample functions are often generated by running a numerical model at various start times (to generated different initial conditions) and/or running several different versions of the model with the same initial conditions. If there are N different sample functions generated, the probability of each is typically set to 1/N with no experimental substantiation that these probabilities are realistic.

Another major concern is that numerical models typically do not give realistic depictions of the weather at the start up time for a model run. In particular, the numerical models used to generate ensemble sample functions typically would not agree with the current weather at the start of the model run unless the numerical model algorithms can be modified to continually ingest a high resolution 3D characterization of the current state of the atmosphere (e.g., from weather radar data).

An alternative approach for generating validated ensemble sample functions for the 0-2 hour time region would be to characterize the storm forecast errors (e.g., velocity, cell size, cell shape) and then use Poisson modeling techniques [e.g., such as were used in Mitchell, et al. (2006) to synthesize spatial weather patterns] to account for new storm growth. An important, but difficult challenge, in utilizing this approach is to obtain ensemble functions that are realistic both in space and time (e.g., pseudo randomly generated new storms need to exhibit realistic storm growth and decay characteristics for the type of weather present on a given day).

Finally, while the provision of forecasts of capacity impacts of convective weather – even with well-calibrated uncertainty information – provides air traffic managers with information that is critical to decision making in convective weather, the question of how decisions should be made using this information depends on several factors including the risks and benefits of potential outcomes, the training and cognitive 'mindset' of the decision makers, the collaborative environment in which decisions are made, etc. The use of probabilistic forecasts in decision making is covered in greater detail in Section 5.3 below.

4.1.2 Translation of non convective en route weather impacts into capacity impacts

Under the previously mentioned NASA Research Announcement (NRA), Metron, Science and Technology in Atmospheric Research Institute (STAR), and Mosaic ATM were to consider how

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[19] A recent paper (Steiner, Mueller, Davidson and Krozel, 2008) proposed and illustrated this approach.

one might translate the forecasts of turbulence or icing into capacity impacts. As yet, there have been no results presented as to how such a translation would be accomplished.

Both in-flight icing and clear air turbulence from jet streams or mountain waves are typically slowly changing in space and time. Hence, today's TFM system can typically adapt to these constraints using current practices based on human judgment.

If automated congestion/prediction algorithms need to operate in situations where these phenomena would be of operational concern, then significant research would be needed to determine appropriate threshold parameters to utilize. This is particularly challenging for in-flight icing since it is the combination of duration of flight in such conditions and intensity of icing that is of concern (that is, the presence of conditions that could yield in-flight icing would not necessarily be a "no fly" zone unless it were severe icing likely to affect traffic along a particular route for an extended period of time).

4.2 WEATHER CONDITIONS AFFECTING TERMINAL OPERATIONS

4.2.1 Translation of convective weather forecasts into forecasts of terminal capacity impact

The conceptual approach to characterizing "capacity" in terminal airspace when there are convective weather impacts appears to require a different set of characterizations from those used in en route airspace.

TABLE 4-2

Terminal "Capacity" Characterizations and Corresponding TFM Applications

Characterization	TFM application (s)
Regions of airspace which pilots will avoid	Time based trajectories (for time based flow management). A key input to other quantitative characterizations of capacity discussed below
Arrival and departure fix impacts	Time based trajectories (for time based flow management); en route flow management, DFM, TMA
Terminal area arrival and departure route availability	Arrival and/or departure route management [e.g., Route Availability Planning Tool (RAPT), DFM]; a key input to other quantitative characterizations such as airport arrival and departure rates and en route management for flows to the terminal area
Runway arrival and departure rates	Automated congestion prediction (e.g., GDP management) and resolution algorithms (e.g., PACER, DFM)

(i) Characterization of capacity constraints by determining the regions of unusable airspace (e.g., a "terminal weather avoidance field")

The initial study on pilot avoidance of storms (Rhoda and Pawlak, 1999) was funded by NASA as a part of the CTAS program and focused on storm avoidance in the terminal area. It was noted that arriving pilots generally deviated around VIP level 3 composite reflectivity and ASR-9 reflectivity storms when near the arrival fixes, but generally penetrated all storms when within approximately 10 nmi of DFW. A subsequent study in Memphis (Rhoda and Pawlak, 2002) found similar behavior in the terminal area. However, departure storm avoidance behavior was not examined nor was a quantitative model developed that covers the entire region from arrival fix to airport surface.

Since the late 1990's, NASA has not funded research on pilot weather avoidance models for the terminal area and has not given any indication of interest in conducting such research in the near term.

The en route derived weather avoidance models will need considerable modification for terminal applications. Key factors that need to be considered include the following:

- Radar echo tops may be an indicator of a severe storm that is more likely to be avoided, rather than a key factor in determining whether the plane can fly over the storm
- Heavy precipitation reaching the ground may be a key factor for terminal storm avoidance whereas it is not germane for en route storm avoidance
- Squall lines may result in much greater likelihood of storm avoidance than isolated cells
- Factors such as terminal low-altitude turbulence, wind shifts, low ceiling and visibility, and icing conditions need to be considered,
- Wind shear activity (e.g., microbursts and gust fronts) is paramount.

As a result of the last factor, access to ITWS and Weather Systems Processor (WSP) wind shear alert information may be needed to carry out the pilot avoidance modeling studies.

Since forecasting terminal capacity is very important for some TFM applications (see the discussion in Section 7), the FAA TFM program will have to make a determination of how the necessary research on this topic should be conducted (e.g., as research funded and conducted directly by the TFM program or, directed by the FAA AWRP or, directed by NASA). It may be useful to have high level R&D program discussions between the FAA TFM program, FAA R&D, and NASA on this topic given that terminal pilot storm avoidance models will be needed for a number of the NextGen envisioned capabilities.

(ii) Translation of weather impacts on arrival and departure fix usage

Research needs to be conducted on the relationship between weather impacts on arrival and departure fixes as a function of the weather coverage of those fixes. The effective spatial extent of the arrival and departure fixes at New York is essentially the same as the width of the en route routes which are typically very narrow (M. Robinson, personal communication).

Terminals that have “four corner” fixes typically have fairly wide departure fixes that include several departure routes. Dallas can handle parallel arrival routes over a single arrival fix. Detailed case studies are needed to determine what the effective “maneuvering region” is for these much wider arrival and departure fixes.

The Potomac TRACON arrival and departure fixes may also be a special case akin to New York.

(iii) Translation of weather impacts into use of arrival and departure routes in the terminal area

We have observed major differences in the flexibility of ATC in terminals to handle significant deviations around storms versus the handling of flight deviations in transitional en route airspace or at transitions between different ARTCCs.

As a consequence of this greater flexibility in terminal areas, characterizing weather impacts on capacity by looking at impacts on the normal routes is less likely to be successful as an approach to terminal capacity assessment than it has been in en route airspace. When storms that pilots will not fly through are impacting the final approach segment or initial departure segment, then it is likely that the runway usage will cease. However, given the results of Rhoda and Pawlak, (2002), it is not clear how often storms truly prevent flight penetrations near the airport if the region of very heavy precipitation is relative small in spatial extent.

(iv) Translation of weather impacts into runway arrivals and departures per unit time

From a TFM viewpoint, the desired metric for characterizing terminal capacity impacts by convective weather will be the arrival and departure rates. However, it is also clear that the research to determine appropriate pilot storm avoidance models and route usage models for the terminal areas must be accomplished before arrival and departure rates can be forecast.

4.2.2 Translation of ceiling/visibility forecasts into terminal capacity impacts and use for TFM GDP decision making

At SFO, the problem of translating conventional ceiling and visibility sensor readings into an estimate of whether or not the horizontal visibility at about 1000 ft AGL was such that closely spaced parallel approach operations could be conducted was avoided by the use of ATC facility records of the times at which pilots reported that the visibility was such that side-by-side approach operations could be successfully conducted. Another major advantage of the SFO situation also was that there are many such low ceiling/visibility events every year from a weather phenomena that is quite consistent from day to day in its physical characteristics (e.g., top and bottom of the stratus clouds), and that the ATC facility kept records of the side-by-side times.

By contrast, when winter storms cause low ceilings and visibility at SFO, it is not clear that there is an effective algorithm for determining from sensor measurements whether the horizontal visibility along the descent paths is adequate to determine whether closely spaced parallel approach operations can be successfully accomplished.

It will be necessary to determine for each pacing airport that has an operationally significant number of low ceiling/visibility events that result in GDPs whether the operationally significant conditions can be deduced from readily available sensor readings as opposed to pilot reported conditions. If pilot reported conditions are a significant cause of such events, then it will be necessary to start accumulating an appropriate data base of these reports if there would be an operational benefit (e.g., planning) from accurate forecasts of capacity impacts due to low ceiling and visibility.

Even if the low ceiling/visibility weather forecasts can be successfully translated into forecasts of airport capacity changes, achieving operational success in the manual use of probabilistic terminal ceiling/visibility forecasts for GDP decision making has proved difficult.

Ivaldi, et al. (2006) summarized the possible SFO TFM decision maker actions based on the forecasts and operational consequences as follows:

"There are several ways in which the SFO forecast could influence traffic flow decision making for SFO:

- The first is to avoid a GDP if ceilings and visibilities are forecast to improve prior to arrival rates exceeding acceptance rates.
- Second would be to cancel a GDP proactively, once initiated, if confidence was high that clearing would occur prior to the arrival rate exceeding the acceptance rate.
- A third possibility is to maintain the GDP, but gradually increase the acceptance rate at some agreed upon time prior to clearing, based on the confidence of the forecast.

Each of these decisions carries with it a level of risk. Obviously the first option carries the greatest risk but also the greatest potential benefit to the NAS and the traveler. However if the forecast is wrong, the Oakland Center will be dealing with vectoring many aircraft into a holding pattern and most likely invoking a ground stop. The second option carries with it a reduced benefit, as well as a reduced risk, as less aircraft would be in the air to manage. The third option carries with it even less risk, but also reduced benefit, as it is dependent on the rate at which the acceptance rate is increased prior to clearing."

There have been very few events in which a GDP was cancelled proactively. The current FAA policy is to add two hours to the burn off time to arrive at a GDP cancellation time. Since the vast majority of stratus events dissipate well before 2 hours after the projected burn off time, most of the projected benefit from the forecast is not being achieved.

In cases where there is a (subjective) "high confidence" that burn off will occur at a given time (from discussions between the Oakland CWSU, the Monterey NWS and United Airlines meteorology), an intermediate (e.g., 45 per hour) arrival rate is used for the last two hours of the GDP. This partially reduces the number of landing slots that were not utilized, but still leaves a significant "avoidable" delay.

We have identified three key problems in the operational utilization of what appears to be a technically very successful probabilistic forecast:

1. the ARTCC operational users are very concerned about the possibility of too many aircraft holding in the Oakland ARTCC airspace,
2. the traffic flow management unit personnel do not have academic training or practical experience at using probabilities for decision making, and
3. important forecast information that would be needed to apply standard techniques for decision making under uncertainty were not being provided to the users in the current SFO forecast.

In Section 6, we discuss an initiative in the use of probabilistic/risk management techniques for TFM as an important near term research that will help in the operational use of such techniques for a number of different TFM applications.

5. ROADMAP FOR ALIGNMENT OF WEATHER PRODUCT AND TRAFFIC FLOW MANAGEMENT CAPABILITY DEVELOPMENT

This section considers the needed alignment between evolving weather diagnosis and forecast products and Traffic Flow Management decision support capabilities. We consider appropriate time phasing of the weather and TFM capabilities, the impacts of technical limitations in both areas, and the specific content of the weather information required to support the TFM concepts. Where appropriate, we will recommend studies, data analysis and/or field evaluations needed to address critical issues.

In order to structure this section, we will follow the outline of capabilities defined in the report "Inventory and Initial Assessment of CATM-T Work Package 2 Candidate Capabilities" (Geffard, et al., 2007). For brevity, this report is hereafter referred to as "CATM Report 2007".

5.1 WEATHER INFORMATION REQUIREMENTS FOR COLLABORATIVE INFORMATION EXCHANGE

CATM-T Collaborative Information Exchange concepts deal with information exchange between FAA Traffic Management personnel and NAS customers (e.g., airline operations center personnel), Traffic Management and Air Traffic Controllers, and between Traffic Managers. At a high level, the information to be shared involves:

(i) status of airports and NAS flows as affected by both "static" conditions (e.g., special use airspace) and more dynamic situations (congestion, weather);

(ii) flight-specific status and intent.

5.1.1 Information Exchange between Traffic Management and NAS Customers

During the mid- to late WP2 time frame (2012–2015) it assumed that the NAS customer will be able to submit to TFM multiple, priority-ordered flight plan alternatives for each flight during both pre-departure planning and airborne flight phases. It is assumed that the customer will determine the selected alternatives and their priorities based on information from TFM describing the location and probability of congestion that aircraft are expected to encounter based on their early-intent flight plan. The customer, will in fact, be able to use this information to "distribute" the expected impact of TMIs amongst their affected flights so as to minimize the overall disruption to their operations. For example, delay on "critical" flights could be traded off to other less critical flights. The "System Enhancements for Versatile Electronic Negotiation (SEVEN)" concept under development by Metron Corporation can be viewed as a prototype for this capability[20].

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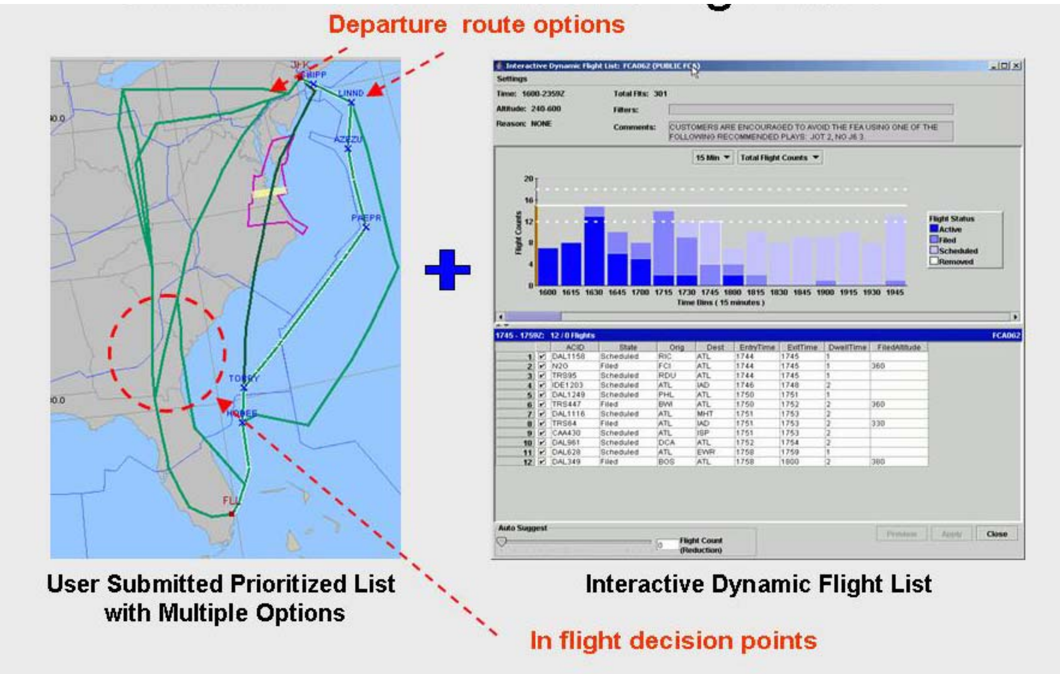
[20] Integrated Collaborative Routing (ICR) could be viewed as a precursor to SEVEN in that ICR allows a customer to fly a customer identified alternative flight plan when TFM has determined that reroutes around an area are necessary. However, ICR does not currently support multiple customer generated alternative routes.

Figure 5-1 shows an example of the multiple flight plan alternatives that might be envisioned for a flight from New York to Fort Lauderdale (FLL) when convective weather may occur both near New York and in southern Florida. The TFM system would be able to choose between the various flight plans prior to take off and then modify the routing to FLL later in the flight when shorter lead time, more accurate information was available on the weather capacity impacts near FLL.



Interactive Dynamic Flight List: FCA062 (PUBLIC FCA)

Time: 1600-2359Z
Altitude: 240-600
Reason: NONE
Total Flts: 301
Filters:
Comments: CUSTOMERS ARE ENCOURAGED TO AVOID THE FEA USING ONE OF THE FOLLOWING RECOMMENDED PLAYS: JOT 2, NO J6 3

1745 - 1759Z: 12 / 0 Flights FCA062

		ACID	State	Orig	Dest	EntryTime	ExitTime	DwellTime	FiledAltitude
1	☑	DAL1158	Scheduled	RIC	ATL	1744	1745	1	
2	☑	N2O	Filed	FCI	ATL	1744	1745	1	360
3	☑	TRS95	Scheduled	RDU	ATL	1744	1745	1	
4	☑	IDE1203	Scheduled	ATL	IAD	1746	1748	2	
5	☑	DAL1249	Scheduled	PHL	ATL	1750	1751	1	
6	☑	TRS447	Filed	BWI	ATL	1750	1752	2	360
7	☑	DAL1116	Scheduled	ATL	MHT	1751	1753	2	
8	☑	TRS84	Filed	ATL	IAD	1751	1753	2	330
9	☑	CAA430	Scheduled	ATL	ISP	1751	1753	2	
10	☑	DAL961	Scheduled	DCA	ATL	1752	1754	2	
11	☑	DAL628	Scheduled	ATL	EWR	1758	1759	1	
12	☑	DAL349	Filed	BOS	ATL	1758	1800	2	380

Figure 5-1. Illustration of the capability of System Enhancements for Versatile Electronic Negotiation (SEVEN) to provide flexibility for both departure and arrival routing when there is a possibility of severe weather both near the NY departure airport and near the destination (FLL). The customer provides multiple options for the flight. Traffic managers can assess the impact of various flight plan options on system congestion using an Interactive Dynamic Flight Lists (IDFL) and choose an option from the customer submitted list that provides weather avoidance and meets airspace capacity constraints. Changes to the filed flight plan are executed automatically and do not require coordination with the customer or other facilities.

The utility of this concept when it is used to mitigate weather impacts on NAS customers will vary substantially from case to case, depending on the skill of the weather forecasts (which is a function of the type of weather and the look-ahead-time needed), the ability to accurately estimate NAS resource constraints from these forecasts, and the sophistication of the customer's process for utilizing this information to define and prioritize alternatives for the impacted aircraft. At minimum, we believe that the TFM weather information system supporting this concept should provide the following capabilities.

(1) The phenomenology and severity of the predicted weather constraint should be identified (e.g., convection, turbulence, ceiling/visibility or runway winds limitations at an airport).

(2) The observing and/or forecast systems used to determine the constraint should be identified, and the “raw” meteorological observations/forecasts provided by these systems should be available as an optional source of information for the NAS customer. This provides customers the ability to potentially improve their operational processes through use of private-sector aviation weather forecasting services.

(3) Quantitative, time-varying forecasts of the reduction in NAS resource availability due to the weather should be provided. Appropriate metrics may are discussed in Section 4.

(4) Useable estimates of the uncertainty in NAS resource availability should be provided. Again, considerations in providing these uncertainty estimates are discussed in Section 4.

5.1.2 Information Exchange between Traffic Management and Air Traffic Control Personnel

During the mid-late term WP-2 time frame (2012–2015) collaboration between traffic control management and terminal/en-route controllers will be characterized by an increasing level of automated transfer of information on NAS resource constraints and flight-specific TMI implications. Automated execution of TFM reroutes will be expanded to include airborne flights and traffic-managers will be able to efficiently communicate flight-specific TMI information to controllers. Controllers will have explicit, graphical information on TFM-imposed flow constraints.

Relative to weather-related constraints, the required information content of the TFM-to-ATC communications is largely a subset of those defined in the preceding subsection. ATC personnel do not require detailed information on the source of the weather constraint predictions, nor would they have time or expertise to evaluate “raw” meteorological input data. Tower/TRACON supervisors and En Route area managers would, however, benefit from broad-area depictions of weather-related constraints in place, forecasts of future constraints and an effective means of collaborating with their facility’s Traffic Management unit in developing tactical response strategies for these constraints. The benefits of collaboration between en route Area Managers and the TMU have been well-documented during our CIWS facility observations (Robinson, Evans and Hancock, 2006).

The case of the tower controllers warrants some additional discussion given that much of today’s “avoidable” delay is associated with departures during severe weather. One of the major surface management problems noted in the RAPT operational evaluation Robinson et al. (2008) is the need to anticipate airside impacts on departures when managing the departure traffic on the airport surface. Unfortunately, it has been difficult thus far to experimentally determine the benefits of common situational awareness between tower controllers/TMs, TRACONs and enroute facilities due to difficulties and delays in providing RAPT/CIWS displays at major airports in NY and Chicago. Work underway in the FAA and NASA is directed at improving tower decision support services, including a more integrated approach to arrival, departure and surface traffic management. This work, discussed below in Section 5.4, may significantly improve the airport surface management process.

Controller personnel require graphical weather overlays on their radar screens relative to "safety-of-flight" weather phenomena and indeed, any phenomena that are likely to result in pilot requests for deviation from their nominal flight trajectory. Current controller displays of weather data show only precipitation location and intensity as determined from weather radar reflectivity measurements. An expanded set of weather information on controller scopes will be needed as a result of improvements in our ability to very accurately predict the future position of storms in the next 20–30 minutes, and diagnose turbulence, icing and non-convective wind shear phenomena.

5.1.3 Information Exchange amongst Traffic Management Personnel

Enhanced coordination between TM personnel at terminal and en route facilities and the ATCSCC will be enabled in the WP2 time frame through provision of shared weather-constraint information as described above. It is anticipated that sharing of local "know-how" in dealing with weather constraints will facilitate appropriate regional and national-scale traffic flow planning. Traffic management personnel at local levels will be able to assess customer preferences relative to the weather constraints, approve or disapprove these and in the latter case, develop joint alternative recommendations for the customer.

The shared weather information requirements for this concept are similar to those required for TM-NAS customer information exchange as described in Section 5.1.1. In addition, however, national TM personnel should have improved visibility into weather constraints affecting the tactical environment in key en route and terminal facilities. This requires a "drill down" capability showing fine-grained weather constraint maps, relevant local TMIs and traffic flows.

Reroute planning in accordance with NAS customer preferences will require that TMs utilize an inter-facility planning capability that fully integrates common weather constraint information. An integrated, national-scale source of common weather information is required for this function with sufficient spatial and temporal resolution to assess weather impacts at national, regional and local levels. The CoSPA and NNEW programs described in Chapters 2 and 3 of this report are directed towards achieving this capability.

5.2 WEATHER INTEGRATION INTO ENHANCED CONGESTION PREDICTION

More accurate predictions of NAS resource congestion (en route sector, airspace flow evaluation area, and airport) are a major focus of future Traffic Flow Management concepts. Traffic managers use congestion predictions to establish the type, timing and scope of TMIs. Because of the uncertainty in today's predictions, TMs often implement highly conservative strategies as a hedge against worse-than-forecast conditions.

Uncertainty in future resource congestion arises from both inaccuracies in estimating future demand, and from very limited capability to predict the future capacity of NAS resources during adverse weather. Demand predictions today do not even fully account for the impact of currently approved TMIs (for example MIT or arrival fix restrictions), and certainly do not attempt to estimate the impact of future TMIs that may be imposed as new weather constraints develop. Quantitative, dynamic predictions of resource capacity are not currently available and as a result, TMs must subjectively estimate the impacts of adverse weather on future airport operations rates and en route airspace capacity.

5.2.1 CIWS Overlaid on Current Traffic Display

In the initial WP2 time frame (2010–2011) CIWS weather forecasts will be integrated with the traffic display to allow TMs to visualize the impact of the weather on major routes, sectors and other airspace volumes. The display of CIWS product information on traffic management displays (as opposed to being provided on separate CIWS displays) will significantly enhance traffic flow decision making in adverse weather because traffic flow and weather information will now be available on a single display. Additionally, this transition will free up display space at crowded facilities and, provide CIWS products to some decision makers that could not easily view the CIWS demonstration system displays due to facility space restrictions. Additionally, TMUs and area managers in ARTCCs west and south of the northeast quadrant of the United States will obtain access to the CIWS products.

5.2.2 CIWS Overlaid on Future Traffic Display

In the initial WP2 time frame, CIWS weather forecasts will be integrated with the "future traffic display[21]" to allow TMs to visualize the impact of the weather on the specific flights that are expected to be traveling on major routes, sectors and other airspace volumes. This should assist the TM in determining which flights to move or conversely, when to cancel currently active TMIs that may no longer be needed. Use of more explicit mappings of the weather diagnoses/forecasts into constraint estimates, such as the WAF described previously, would further enhance the operational utility of the future traffic display. Use of the CoSPA forecast described in Section 2

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[21] The "future traffic display" as demonstrated at MITRE allows the users to visualize the projected positions of aircraft in the future. By manipulating a slider at the bottom of the traffic display, the user can see the TFM projected positions of all aircraft at that time in the future. Since the CIWS forecasts include spatial maps of forecast weather reflectivity and radar echo tops, the background weather maps on the traffic display would change as the slider position is changed.

should facilitate extension of this concept to longer (0–6 hour) look ahead times in the mid-WP2 time frame (2012–2013).

Given that:

(i) there are a number of different characterizations of “capacity” that are operationally useful in different situations (Section 4.1.1.1), and
(ii) TMs are very experienced with assessing the current workload associated with management of a convective weather event in their facility by viewing an overlay of current traffic on current weather spatial maps,

we strongly recommend that this option of CIWS forecasts overlaid on the future traffic display be experimentally assessed as quickly as possible since it offers the potential of significant increases in the (already high) operational benefits associated with the CIWS products.

5.2.3 Sector Demand Prediction

Probabilistic resource demand predictions must model not only currently approved TMIs but the likely effects of future TMIs that will be needed in response to weather constraints that are worsening or may not yet have developed. To properly model these future flow restrictions, a NAS-wide model accounting for time-varying future resource capacities and total (scheduled and pop-up) demand is needed. Since the skill of the demand and weather constraint predictions will generally improve rapidly for shorter look-ahead times, this model must cycle rapidly (~ twice per hour) in order to take advantage of the improving information on future constraints. Development of such a real-time model that fully integrates state-of-the-art weather predictions, weather-impact translations and traffic demand forecasts is a major undertaking that does not appear to be adequately supported in the current weather and TFM research portfolios.

5.2.4 Resource Capacity Prediction

“CATM Report 2007” states that CIWS forecast data will be used in the WP2 time frame to predict the reduction in expected resource capacity. Further, for each resource and each look-ahead-time, the probability distribution function of the capacity will be determined by TFM. The authors speculate that this may be implemented for en route sectors as a reduction in the Monitor Alert Parameters (MAP), based on the weather coverage, route blockage or other considerations.

Realizing a robust capacity prediction capability will require major effort in at least three areas.

(1) Continued progress in diagnosing and forecasting relevant weather phenomena over the 0–8 hour time scales needed for TFM is essential. As described in Section 2, the authors believe that “low hanging fruit” in this area involves research focused on extending the look-ahead-time for convective weather forecasts to 6–8 hours, and on improved 0–2 hour “nowcasts” of turbulence and airport weather conditions (ceiling and visibility, winds, winter precipitation) that effect capacity.

(2) Validated models for translating the weather information into quantitative resource constraint metrics are required. Research in this area is in its infancy. For airspace constraints, the authors believe that approaches based on algorithms for reduction of sector MAPs are problematic. MAPs are widely recognized to be subjectively determined and inconsistent across the NAS, even during nominal conditions. Scaling of MAPs to account for weather impacts must account for the directionality of major flows within a sector and, that the associated weather blockage that may be quite different for different major flows as illustrated in Figure 5-2[22].

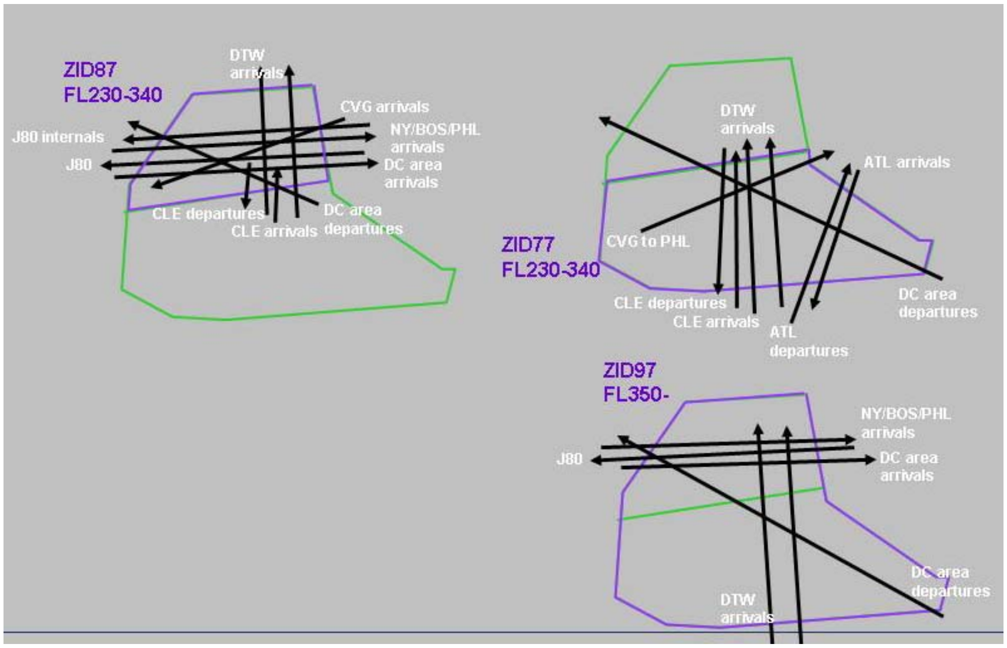

Figure 5-2. Illustration of major differences in the directionality of major flows within en route sectors in ZID. Note that convective weather could block one or more major flows (e.g., DTW arrivals and DC area departures) without significantly impacting other major flows (e.g., NY/BOS/PHL/DC arrivals). Hence, use of a fractional reduction in sector occupancy (e.g., a modified MAP threshold) to determine fractional reductions in major flows may not be warranted in many cases.

Objective models for airspace capacity during both nominal and off-nominal conditions are likely to be more useful (e.g., Welch et al., 2007; Martin et al, 2007; Song et al., 2007) but these approaches must be integrated, validated and adapted as necessary to future, more automated ATC paradigms. Augmented research on the impacts of non-convective weather phenomena (turbulence, icing) on airspace capacity is needed, as is a more comprehensive capability for predicting weather impacts on future airport operating rates (see Section 4).

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[22] The past TMO at ZOB suggested to us that sector occupancy (the parameter used for the ETMS monitor alerts) observed in convective weather typically reflects restrictions in principal flows through the sector as opposed to being an independent quantity from which one could infer the rates in the principal flows.

(3) Viable methods for estimating and conveying the uncertainty of future resource capacity predictions must be defined. This will require tightly coupled effort involving the meteorological forecasting and ATM research communities. The authors believe that "ensemble" approaches are most likely to be effective – that is a set of discrete weather forecasts will be developed that span the expected range of future scenarios, and these will be translated individually to associated estimates of capacity constraints on specific NAS resources. From these ensembles, appropriate metrics and visualizations of uncertainty can be transmitted to automated decision support tools and TMs.

5.2.5 Route Blockage and Route Congestion Prediction

In the WP2 time frame, route blockage will be determined for airport departures and arrivals and for transition and high-altitude en route operations. This capability will expedite Departure Flow Management, in-flight rerouting and arrival management. While these concepts are based on the Route Availability Planning Tool (RAPT) already in operational use at NYC airports, considerable effort is needed to adapt the concept to departure operations at other airports, to integrate it with other information on departure constraints (surface and downstream) and to extend it to en route and arrival operations.

A major first step is to develop flight-specific route blockage prediction capability which is tied to the aircraft trajectory ("wheels up time", arrival-time at flight path "way points") and to an efficient capability to determine viable alternatives when the filed route of flight is blocked by adverse weather.

Route congestion prediction will require the additional development of algorithms for translating "partial blockage" scenarios into estimates of required Miles (or Minutes) in-trail constraints. The approach described by Martin et al. (2007) for calculating the impact of partial route blockage on route throughput could be interpreted in terms of increased miles-in-trail restrictions although the authors do not discuss this point explicitly nor show any experimental data to confirm this interpretation. Significant additional research is needed to determine what transpires operationally in route usage when the route availability determined by Martin et al. (2006) is intermediate between 0 and 1.

More generally, there is an urgent need to validate the route blockage models for airspace usage (e.g., storm impacts on routes, merge points, use of adjacent routes carrying traffic in a given direction[23] when one of those routes is blocked) under various degrees of intersections by weather avoidance fields (WAF).

The RAPT concept needs to be expanded to explicitly forecast when arrivals deviating into departure airspace will become an operational constraint to departures. There are two research items that need to be considered:

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[23] For example, note that the DTW arrival traffic in Figure 5-2 is proceeding on adjacent routes.

1. Since arrivals descend much more gradually than departures climb, arrivals may be at lower altitudes in en route airspace than an adjacent departure flow whose flights have all ready reached their en route cruise altitude. Studies need to be conducted to see if pilot deviation model for descending arrivals is different from the en route constant flight altitude deviation model used in RAPT.
2. Also, there needs to be a determination of whether there are actually arrivals on the adjacent route (e.g., from analysis of the ETMS flight data).

Given that arrivals deviating into departure airspace have been a significant factor in RAPT not achieving the possible departure delay reduction (Robinson, et al. 2008a), adding this capability to RAPT should be a high priority.

Another significant need is to provide an enhanced capability for tactical adaptive, incremental traffic routing as a complement to “strategic” flight planning that requires much higher accuracies in 2-8 hour convective forecasts than seems achievable in the near term (Evans, 2001). This was recommended by the REDAC WAIWG (REDAC, 2007). Figure 5-3 (from a presentation of the WAIWG report to the REDAC) shows an example of such tactical adaptive, incremental traffic routing.

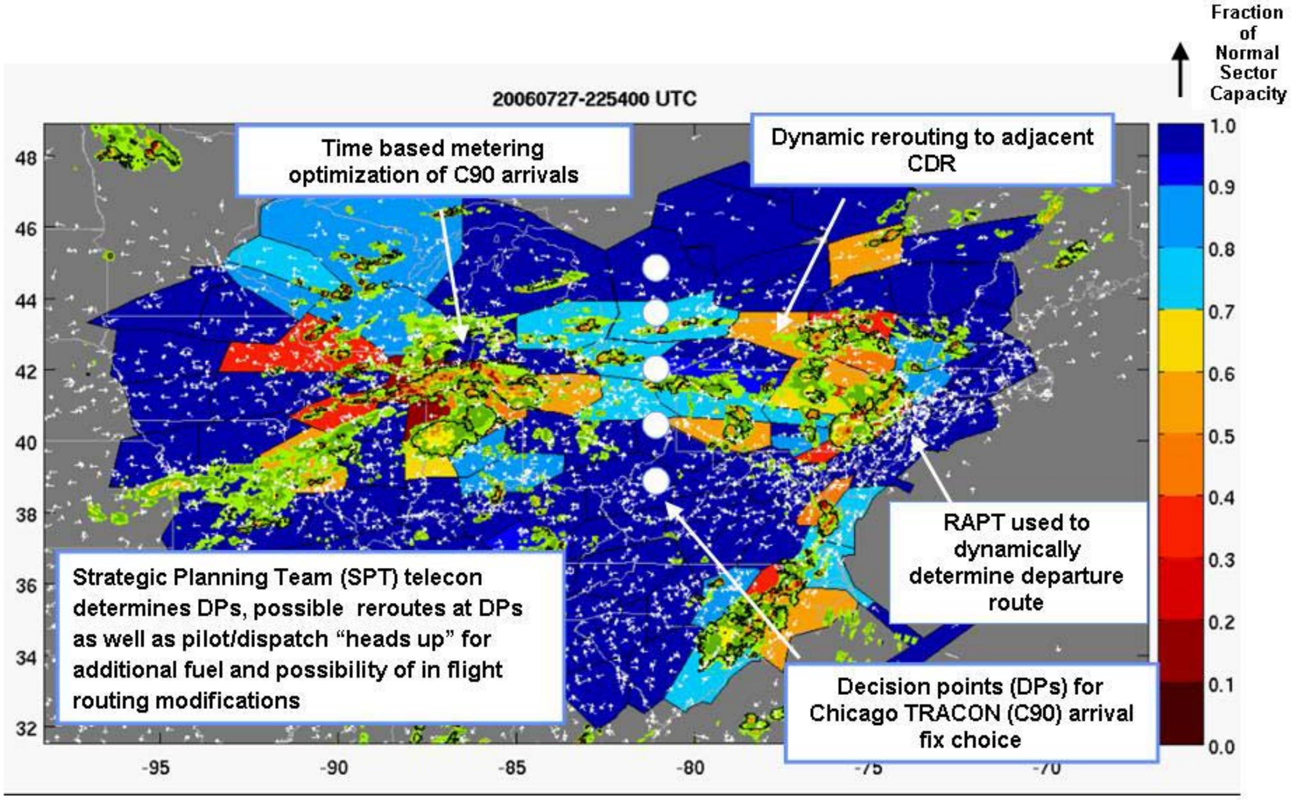

Figure 5-3. Example of tactical adaptive, incremental traffic routing for a flight from LGA to ORD when there is convective weather both near New York and Chicago. Intermediate decision points were determined in a strategic planning teleconference[24]. Concept SEVEN allows the filed flight routing to include multiple flight options with branches at the decision points (DPs) to the various arrival fixes into the Chicago TRACON. The Traffic managers at the ARTCCs containing the various DPs (ZOB or ZID in the case illustrated) can assess the impact of various arrival fix flight plan options on system congestion (in their ARTCC and ZAU) using an Interactive Dynamic Flight List (IDFL) and choose an arrival fix option from the customer submitted list that provides weather avoidance and meets airspace capacity constraints. Automated congestion resolution decision tools could offer a specific recommendation for routing to an arrival fix. A significant advantage of using predetermined DPs is that the DP locations can be chosen to coincide with standard fixes and procedures developed to reduce the workload associated with each flight reroute.

The tactical adaptive, incremental capability illustrated in Figure 5-3 also is consistent with the use of the tactical AFP throughput forecast algorithm that was shown in Figures 3-3 and 3-4 in Section 3.1.1.1. It appears technically feasible to convert the CIWS forecasts into estimates of AFP throughput and use the approach shown in Figure 5-3 to handle the tactical adjustments needed when the forecast AFP throughput is less than the in flight demand. Also, the approach

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[24] The decision points (DP) shown in Figure 5-3 are on a straight line for purposes of exposition; in practice, the DPs would be spaced irregularly around a roughly north-south line to reflect facility workload constraints.

used to forecast AFP throughput could be used to forecast throughput rates for "overlap AFPs" under investigation currently by the CDM Flow Evaluation Team (FET).

A critical next step in evaluating the operational applications and benefits of this AFP throughput forecasts will be to exercise the route blockage/flow-rate restriction model with CIWS forecast products [as opposed to actual VIL and Echo Tops data used for the results reported in (Robinson et al. 2008)]. The use of specific TMIs for appropriately modulating demand through AFP regions, based on guidance from the AFP throughput model, needs to be modeled and assessed for multiple real weather case scenarios. This work would benefit from the participation from operational Traffic Management subject matter experts (SMEs). To the extent possible, benefits of the dynamic AFP rate concept would be assessed relative to actual NAS operations on the case days considered. This research work should be accomplished in close collaboration with the work underway by the CDM Flow Evaluation Team (FET) to develop "adaptive AFP" concepts.

5.3 WEATHER INTEGRATION INTO AUTOMATED AIRSPACE CONGESTION RESOLUTION

Automated airspace congestion resolution concepts build on improved customer information exchange and enhanced congestion prediction capabilities to provide automated assistance to TMs in developing and executing reroute and delay programs.

In the WP2 time frame (2010–2015) TFM automation will disseminate probabilistic demand and capacity predictions for all monitored NAS resources to TMs and NAS customers. TMs will specify flow evaluation areas (FEA) indicating the airspace volumes where demand may need to be reduced, and will notify customers via a Planning Advisory. After customers review this information and submit prioritized flight preferences, TMs will use the Automated Airspace Congestion Resolution capability as an aid in resolving the predicted congestion. TMs can guide the automated solution via input on preferred resolution strategies (ground delay vs. rerouting), special guidance for individual airports, maximum ground delay and maximum distance increase for reroutes.

In the initial phase of WP-2 (2011–2014), the current FAA plan is to implement an initial Automated Airspace Congestion Resolution (AACR) capability in which the TMs will identify the FEAs and then the automation will propose a single, one-time resolution that will attempt to resolve the congestion that arises from the FEA all at once.

In the post WP2 time frame, TFM automation will identify the congestion problems and candidate FEAs and will propose incremental resolutions that maintain congestion risk at an acceptable level, while retaining the flexibility to modify or expand the resolutions as the future demand and constraint situation evolves. This approach will presumably reduce the number of flights affected by the initial TMIs. Thus if the congestion problem turns out to be less severe than originally forecast, the overall impact on customer operations will be reduced.

5.3.1 Weather Integration into Phase 1 (WP2 Time Frame) Automated Airspace Congestion Resolution

An efficient “one time” automated congestion resolution would require high-fidelity forecasts of the weather out to 0–6 hours as well as accurate translation of these forecasts into capacity impacts.

Although multi-hour CoSPA forecasts of convection will be introduced during the initial WP2 time frame (see Table 2-4), it is highly uncertain at this writing as to whether their accuracy (or the accuracy of necessary weather-capacity impact models) will be sufficient to support such one-time resolutions. In addition, errors in the capacity forecasts will translate into uncertainty about what future flow constraints will be necessary. This uncertainty in turn will result in errors in demand prediction that will also make one time, automated congestion resolution strategies very problematic.

For the CATM WP-2 assessment of Collaborative Automated Congested Resolution (CACR) benefits accomplished in the spring and summer of 2008, the MITRE analysts acting as the TM had perfect knowledge of the severe weather date and time and locations[25]. The FCAs were hand-drawn and were meant to “encompass the weather areas plus a large margin.” The operational benefits of CACR were determined by comparing the delays for the CACR determined weather mitigation plan to the plans that were manually determined by the MITRE analysis given the same FCA shapes. No comparison was made to the delays that were experienced on the actual day from which the weather events were determined (in which planes may have well flown through the FCA region).

Clearly, there is a need to have more realistic scenarios used for validating and refining the CACR capability scheduled for implementation in 2014. These scenarios would need to consider handling of uncertainty in the future capacity impacts including handling of situations where the FCAs determined at one point in time are subsequently found to be in the wrong locations such that traffic must be rerouted repeatedly. The timing of updates to the CACR-generated plan is also a potentially significant parameter as is the handling of terminal capacity impacts. Unfortunately, until the CoSPA 2–8 hour forecast becomes experimentally available, it may be difficult to carry appropriate scenarios to validate the initial CACR concept.

Our view is that in the 2010–2015 time frame, the major emphasis should be on improving the performance of human TMs through the provision of increasingly high quality information on future constraints. This capability will fall out of the enhanced information exchange and congestion prediction thrusts described previously, and will lead to both better NAS operational

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[25] Weather events on two days were considered. On the first day, sector occupancy reductions determined using the Martin (2007) model was determined from the actual CIWS weather. On the second day, the CIWS 2-hour forecasts of storm reflectivity and radar echo tops were converted to sector capacity reductions using the Song (2007) model. The resulting maps of sector capacity reduction were used as an input for the human generated FCAs.

performance and "real-world" experience with strategies for exploiting the enhanced information to improve congestion resolution.

We recommend that proposed concepts for these Phase 1 congestion resolution strategies be vetted through analysis and HITL simulations using realistic projections for future weather forecast capabilities. This should be accomplished as a precursor to any investment decision in this area to quantify the frequency with which the automated congestion resolution produces substantive investment decisions.

5.3.2 Weather Integration into Phase 2 (Post WP2 Time Frame) Automated Airspace Congestion Resolution

Wanke et al. (ATM2007 conference) describe an adaptive, incremental congestion resolution concept representative of the capabilities that are planned for the post-2015 time frame. These will exploit anticipated capabilities in that time frame for highly efficient reroute planning and execution for pre-departure and in-flight aircraft. Thus the initial scope of TMIs and the number of aircraft affected can be limited with the knowledge that more aggressive strategies can be implemented quickly if severe weather constraints develop over critical NAS resources.

Although there are many details of this concept to be worked out, in broad terms it aligns well with evolving automated, operational weather forecast capabilities. Relevant weather forecast capabilities will include:

(i) forecasts of parameters necessary to accurately assess the impact of the weather on airport or airspace capacity. Storm height (or radar echo top) and broad area estimates of turbulence potential are examples of such parameters;

(ii) frequent updates incorporating new weather observations and numerical model runs so as to continually provide the congestion resolution algorithms with the most accurate constraint information available for each look-ahead time;

(iii) multiple look-ahead-times (nominally 15 minute or smaller intervals) for each forecast update so that the effects of candidate TMI strategies can be assessed in detail;

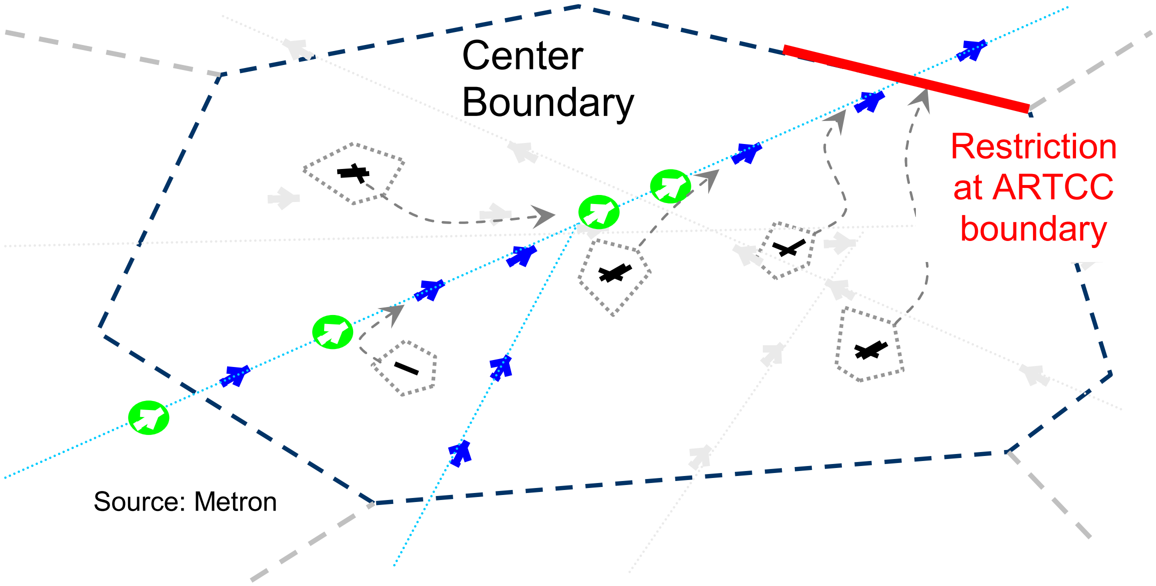
(iv) "scenario-based" representations of forecast uncertainty for each look-ahead-time so that TMI strategies can be developed and evaluated in relation to the range of possible capacity constraints.

It is likely, we believe, that with continuing development effort operational forecasts such as CoSPA will achieve usable capability in all of these areas in the post WP-2 time frame.

5.4 WEATHER INTEGRATION INTO DEPARTURE FLOW MANAGEMENT (DFM)

Departure flow management deals with the efficient movement of aircraft from their gates to the active runway, the timing and sequencing of departures so as maintain runway throughput and departure fix loading, and timing of departures so as to avoid conflicts when merging into overhead aircraft flows (particularly when MIT are in effect). Congestion constraints further downstream are also important in managing departures since it may not be possible to clear aircraft for takeoff if en route facilities along their route of flight are overloaded as illustrated in Figure 5-4.

Figure 5-4. Illustration of operation of DFM (from CATM Report 2007). Green symbols indicate available slots in overhead stream.



Source: Metron

Considerable effort is underway as of this writing to develop concepts for integration of weather information into DFM. One needs to consider weather impacts on the departing flights and the flights that are in the overhead stream.

5.4.1 Departing aircraft weather constraints

The prototype Route Availability Planning Tool (RAPT) in operation at New York utilizes CIWS forecasts of storm intensity and height to compute the time intervals where departures from a specific airport will be impacted by storms along specific departure routes. This operational tool incorporates many elements of the weather integration paradigm discussed earlier in this report (frequently updated, automated forecasts of relevant weather parameters, and "translation" of these forecasts into time varying determinations of the availability of a specific NAS resource, in this case a departure route).

Ongoing RAPT work is directed at improving the weather blockage models, developing usable metrics for the uncertainty of the route blockage estimates and extending the concept of operations to less rigid departure route structures than those in use in the NYC airspace where RAPT is being prototyped. As was noted in Section 4.2.1, there is a need to develop and validate a pilot weather avoidance models for terminal areas as well as developing and validating models for terminal airspace usage when impacted by convective weather.

Operational testing of RAPT has illustrated the need for a more integrated departure management process which covers surface movement, rapid reroute planning when the filed route for an aircraft on the surface becomes blocked by weather, integration of overhead stream and downstream sector constraints into the departure planning, and much-improved information exchange involving tower, TRACON and ARTCC controllers and TMs. Weather information requirements for this more integrated departure management process include:

(i) nowcasts of airport weather conditions that affect runway usage and airport operations rates (storms, wind shear, wind shifts, winter precipitation, ceiling and visibility changes). These will support proactive replanning of surface operations so as to minimize runway throughput losses and recovery time when major weather changes occur;

(ii) nowcasts of weather conditions (temperature, precipitation rate and type) that affect de-icing holdover time;

(iii) nowcasts of weather conditions that affect gate and ramp operations (lightning, winter precipitation, intense precipitation or hail);

(iv) accurate gridded wind data and short term forecasts (0–30 minutes) to support trajectory planning from the runway through the departure fixes and transition airspace. These data should extend from the surface to flight level, with horizontal and vertical grid spacing to be established based on analysis of the trajectory modeling requirements[26];

(v) highly reliable wind estimates (effectively measurements) and short-term forecasts (0–20 min) extending from the surface to approximately 1000’ AGL to support wind-dependent wake turbulence departure procedures (see Lang et al., ATM2005). Ongoing wake turbulence research will develop analogous arrival procedures which will facilitate both arrival and departure operations at some airports during appropriate conditions. These require reliable wind estimates to approximately 6000’ AGL and must extend outwards approximately 6 nmi from the airport.

(vi) Forecasts of convective parameters (intensity, height, turbulence) necessary to evaluate departure route availability and to assess the uncertainty associated with these evaluations. The 0–2 hour look-ahead-times provided by CIWS forecasts have proven to be useful for this function although longer forecast horizons would be valuable;

(vii) Diagnoses and forecasts of weather conditions that may change the rate and/or routes at which arrivals can be brought into the airport. Examples of such conditions include icing conditions, turbulence in holding areas, vertical wind shear (Allan, et al. 2001) and storms blocking major arrival flows to an airport. Operation of the RAPT prototype at New York has shown that when major arrival routes are blocked, the stream of arrivals can deviate into departure airspace which in turn prevents departures from using that airspace (Robinson, et al. 2008a).

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[26] The prototype DFM developed and operated by Metron utilizes RUC 3D gridded winds and the trajectory models used in the current TFM system.

A possible vehicle for addressing the above weather factors in improving departure operations is a set of automation-assisted, tower user support tools collectively designated as the Arrival/Departure Management Tool (A/DMT) Weber, et al. (2009).

A/DMT integrates information from a variety of systems (including airport surveillance) and decision support tools to create a comprehensive data base characterizing arrival and departure demand, relevant airport operating parameters and surface/airspace constraints that may affect capacity, efficiency and safety. This data base will be used to develop and manage an integrated plan for active and scheduled arrival and departure operations at the airport, based on 4D-trajectory assignments.

In particular, A/DMT will provide decision support for tower controllers working traffic from the en route environment to the gate, and for departure movements from the gate to the tower/TRACON handoff to en route control. It will also assist traffic management functions in the tower, TRACON and overlying ARTCC by providing integrated information on constraints and demand.

The vision is that A/DMT will integrate the TFM constraints provided by the Departure Flow Manager (DFM) with weather constraints, wake vortex constraints, runway occupancy constraints, surface congestion constraints and airline constraints to determine the best departure route and associated departure time for each flight. For each aircraft subject to TFM restrictions, DFM would provide a list of departure times for each such aircraft that ensures compliance with the constraints. The A/DMT receives lists of possible departure times from multiple sources [e.g., DFM, Route Analysis and Planning Tool (RAPT), airlines, surface congestion model], and combines them to determine the set of time windows that each flight can depart to satisfy all constraints. A/DMT provides the window of times for each aircraft for display to the ATCT Controllers. The ATCT Controller selects a departure time from the range in the window, and sends this selected time (and the range of available times) back to DFM in the ARTCC.

The communications and displays in the tower would be accomplished by Tower Flight Data Manager (TFDM) which is a new terminal local area network that will establish a highly capable data collection and processing architecture for tower operations. TFDM will consolidate functionality provided today by systems such as Flight Data Input/Output (FDIO), Electronic Flight Strip Transfer System and the Airport Resource Management Tool. TFDM will drive a versatile tower-user display suite consisting of a surface surveillance display, a terminal traffic display, an extended electronic flight strip or “flight data report (FDR)” display, an airport information display and an airport systems status display.

The combination of an upgraded ITWS could provide the wind shear, winds and wind shift information discussed above (albeit the current ITWS surface winds forecast capability is not adequate in terms of lead time for forecasts and the ability to forecast non-gustfront induced changes). The plan is for the CoSPA to provide both the forecasts of precipitation (including snow) and convective storm impacts.

5.4.2 Overhead traffic weather constraints

If convective weather is present in the terminal area and/or ARTCC illustrated in Figure 5-3, there is a good likelihood that the overhead streams of traffic may also be impacted by convective weather. In particular, when flights deviate around storms such that their flight trajectories no longer correspond to the flight trajectory expected by the DFM software, the DFM computation of flight time from the airport to fit into the overhead stream (or, arrive at a metering fix) will not be accurate. As a result, the departing aircraft might not fit into the expected slot in the overhead stream or at the metering fix.

Since the DFM functions that involve departure time adjustments to fit aircraft into the overhead stream are a particular instance of time-based flow management, there will be a need to conduct research on how a time-based flow management system can successfully operate in convective weather. The research and development process needed to accomplish this will be discussed in the next section.

5.5 WEATHER INTEGRATION INTO TIME-BASED ARRIVAL FLOW MANAGEMENT (TMA)

Although neither arrival flow management nor the Traffic Management Advisor (TMA) were addressed in the "CATM Report 2007", it is logical to consider this function in this roadmap since TMA is in operation at several locations that are frequently impacted by convective weather and hence could be used for experimental testing of concepts.

TMA determines the probable time of arrival of aircraft in en route airspace to an terminal area arrival fix and then determines how much a plane needs to be sped up or slowed down to yield an appropriate sequence of arrivals over that arrival fix[27]. The desired change in aircraft arrival time to the arrival fix is provided to en route controllers who then accomplish speed and/or trajectory changes such that the plane passes over the arrival fix at the desired time. The required arrival fix time adjustment is continually updated as the plane proceeds to the arrival fix to provide closed loop control.

The TMA software currently assumes that an aircraft will fly the normal fair weather trajectory. If the plane deviates from the expected flight profile so much that the computed time difference between the desired arrival time at an arrival fix and the current expectation is too large to adjust (especially, when the plane will be quite late in arriving), then the only recourse would be to modify the time sequence of aircraft over the arrival fix. An important feature of the current TMA software is the "freeze horizon" which is typically a range ring from 200 nmi to 400 nmi around the airport inside which the time sequence of aircraft over an arrival fix is frozen.

It is our understanding that TMA can be operated in some cases where there is limited convective impacts in the en route airspace of concern to TMA. If the storm impacts are limited to the area

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[27] The time sequences of aircraft over the various arrival fixes are coordinated so as to yield an appropriate sequence of aircraft landing on the various runways assuming the aircraft fly the expected flight profile from the arrival fix to the runway.

near one or more arrival fixes, aircraft scheduled for those fixes which are outside the "freeze horizon" can be transferred to a different arrival fix and TMA will resequence them. If a small number of aircraft deviate around storms such that TMs could:

(i) accurately estimate the additional flight time to the arrival fix, and
(ii) determine that there would be a suitable arrival fix time slot associated with the extra flight time,

then in theory it might be possible to manually resequence the planes.

However, if large numbers of aircraft are deviating around storms and it cannot be determined manually what the extra time of flight will be and what sequence order is appropriate, then the current practice is to shut down the operation of TMA and revert to the previous manual control methods.

Research needs to be conducted on methods of making TMA more useful in convective weather. Key elements of the required research include:

1. Convective weather events need to be analyzed to determine the fraction of time that convection impacts the region between the "freeze points" and the arrival fixes without also impacting the arrival routes within the TRACON.
2. If it appears that an operationally useful capability can be achieved by only improving TMA capability when convection is impacting the ARTCC (as opposed to both the ARTCC and terminal), development of a pilot weather avoidance model for descending aircraft in en route airspace is clearly a first step
3. The ability of TMA to consider non standard routings from the principal jet routes to arrival fixes (e.g., routes that might be manually drawn around a FCA using the CATM phase 1 reroute assessment utility) needs to be investigated.

We have recommended manual input of routes as opposed to automatically generated routes around storms (e.g. routes generated by algorithms of the type described in Krozel, et al., 2004) since it appears that the current automatic route generation algorithms do not consider complexity in determining merge points (Histon, et al., 2002) whereas humans would consider controller complexity.

Extensive testing of various modifications to the TMA software using data sets from the current TMA sites (e.g., ATL, DFW, or IAH) seems essential. Given that NASA Ames was the principal research organization for the development of the TMA algorithms, and has been the principal source of funding to date for development of pilot weather avoidance models, it would seem logical for the FAA to conduct discussions with NASA to determine if Ames would be interested in investigating near term modifications to the TMA algorithms to provide some enhancement in the ability to use TMA in convective weather.

In parallel, the FAA should utilize existing experienced TMA sites with significant convective weather impacts (e.g., ZTL) as locations to conduct exploratory investigations of how the ATL traffic managers could utilize CIWS weather products (and WAF fields) in determining approaches to extending the ability to use TMA with slight or moderate convective weather impacts. Since the controllers play a key role in the overall operation of TMA (by "closing the feedback loop" to achieve the desired arrival times at arrival fixes), it would be very important for the ZTL areas to have access to the CIWS products (and, additional experimental products that might be developed out of the interaction between TFM weather researchers and the ZTL operational community).

5.6 WEATHER INTEGRATION INTO INTEGRATED TIME-BASED FLOW MANAGEMENT

Integrated Time-Based Flow Management (ITBFM) will provide traffic managers an improved capability to develop, execute and adjust a common and integrated departure-to-arrival schedule for all aircraft that supports both TFM objectives and, to the extent possible, NAS customer preferences. The vision is that this capability will integrate or replace today's separate, uncoordinated and sometimes conflicting time-based metering restrictions (GDP, EDCT, AFP) to provide a more consolidated strategy for NAS resource management.

Although ITBFM can be viewed as extension to the time-based flow management concepts embodied in DFM, the need for a departure-to-arrival schedule plan imposes a considerably broader set of requirements relative to weather information. In the discussions above, we note that there is a considerable difference between the Metron DFM prototype and TMA to accomplish what appear to be quite similar functions of achieving a desired arrival time at an location (arrival slots or metering fixes for DFM; arrival fix for TMA): the DFM prototype functions essentially as an open loop system that relies on the controllers to manually determine if a flight's trajectory needs to be adjusted to merge into traffic at the desired aircraft in trail spacing whereas the TMA software seeks to arrive at the arrival fix at a specific time.

As a consequence of these differences, there may well be differences in the details of the weather forecast translation into ATC impacts for DFM versus TMA.

Hence, it will be important to determine the anticipated mode of operation for ITBFM so as to determine if there are additional weather-to-capacity translation issues that need to be considered in achieving an operationally useful ITBFM.

For example, RAPT and the Metron DFM prototype are basically not concerned about forecasting departure rates. Rather, they simply attempt to optimize the departure rate for the sequence of planes that is ready to depart. One might be able from the current RAPT timelines to infer a departure rate for the next 30 minutes. But, such a short duration rate estimate would hardly be helpful for ITBFM and/or GDPs due to convective weather in the terminal area.

A major problem is forecasting arrival or departure rates at an airport an hour or more in advance is that the circumstance where the greatest capacity rate impact is likely to occur is when storms are over or very near the airport (e.g., within 5 nmi). Achieving high accuracy multi-hour forecasts of storms impacts over such a relatively region for anything other than strong synoptic squall lines is a very difficult challenge.

It may well be that the operational concepts for ITBFM may have to be adjusted to have a much more limited scope of operation (e.g., use of TBFM over relatively short look ahead intervals such as an hour) during convective weather. We recommend that early on in the ITBFM development that there be simulations with representative convective weather data sets so as to address concerns at the outset rather than attempting to add on fixes to a deployed system such as will have to be accomplished with TMA.

6. HUMAN FACTORS INVESTIGATONS

Thunderstorms in congested airspace present a very difficult traffic flow management (TFM) cognition challenge for a number of reasons:

- En route and terminal capacities are significantly reduced by phenomena that are difficult to predict in advance.
- Developing and executing convective weather impact mitigation plans is difficult when actions taken in response to the weather disruptions in one spatial region may cause significant air traffic management problems in another spatial region. The task is further complicated by the fact that plans must be developed and executed quickly to take advantage of short lived opportunities.
- Convective weather often presents unique management problems, since there may be subtle differences between any two weather events that pose particular decision-making challenges and there are no agreed-upon approaches (akin to the controller's handbook) for traffic management of convective weather impacts.

Recent real time observations at Northeast ATC facilities during Severe Weather Avoidance Plan (SWAP) events by personnel from the W.J. Hughes Technical Center and MIT Lincoln Laboratory (Robinson, DeLaura, Evans and McGettigan, 2008a) have identified a number of major difficulties in timely, effective development and implementation of tactical traffic management initiatives (TMIs) during SWAP:

1. Both individual and group decision making were often observed to be less than optimal,
2. There were significant problems in ascertaining the current status of the various routes and fixes (e.g., open, closed, usable with significant miles-in-trail restrictions), and
3. Handling of uncertainty in weather forecasts and forecasts of departure route blockage was also a very significant problem.

Despite the importance of the TFM decision-making to the overall NAS operations, there are very few published studies of the TFM decision-making process during convective weather.

Research in the area of decision-making in difficult environments by Gary Klein (Klein, 1998) and others offers several concepts that seem applicable to improving TFM severe weather decision making, (including models for decision making by individuals, the importance of shared situational awareness and interpretation of team phenomena).

We outline in Sections 6.1 and 6.2 some focused initiatives to investigate experimentally improving individual and team traffic flow management decision making focusing on use of the ongoing RAPT testing at New York for the initial studies. Assessing the benefit of these initiatives quantitatively would be an important component of the studies.

However, at New York, the RAPT operational evaluation (Robinson, et al, 2008a) found there are other traffic flow management issues – in particular, poor real time common situational awareness of the NAS status (e.g., which routes and fixes are available and what constraints currently exist on the use of available capacity assets) - that would definitely hinder achieving the desired movement in performance metrics. In Section 6.3, we recommend a local initiative to significantly improve NAS status common situational awareness.

Use of probabilistic information for decision making has addressed in military and business applications for a number of years and there is an extensive literature on statistical decision theory and risk management. However, recent events in the U.S. housing loan and debt securities industries have abundantly demonstrated that risk management approaches based on inadequate probability characterizations[28] can lead to very significant problems. Accomplishing a full risk assessment for convective weather TFM plans is very, very difficult technically due to the difficulty in determining the probability and costs for various possible outcomes of possible TFM actions. Rather, we recommend focusing human factors work on a much simpler problem which is GDP management at SFO where the FAA can take advantage in this area already underway under NASA funding. This is discussed in Section 6.4

6.1 IMPROVING INDIVIDUAL DECISION MAKING

The real time observations in the CIWS and RAPT testing (Robinson, et al., 2006; Robinson, et al., 2008a) and the results of (Klein, 1998) strongly suggest[29] that decision making by traffic flow managers in congested airspace are best represented by a “recognition-primed decision” (RPD) model (Figure 6-1) in which the decision-maker makes an intuitive assessment assignment of the current situation to an analogue past problem and then evaluates various possible actions according to a mental simulation of possible outcomes. A set of expectancies, relevant cues, plausible goals and typical actions are used in the recognition process. Also shown in Figure 6-1 is an assessment of the applicability of the RPD model to convective weather TFM decision making based on the work of (Klein, 1998) and the CIWS/RAPT operational use observations.

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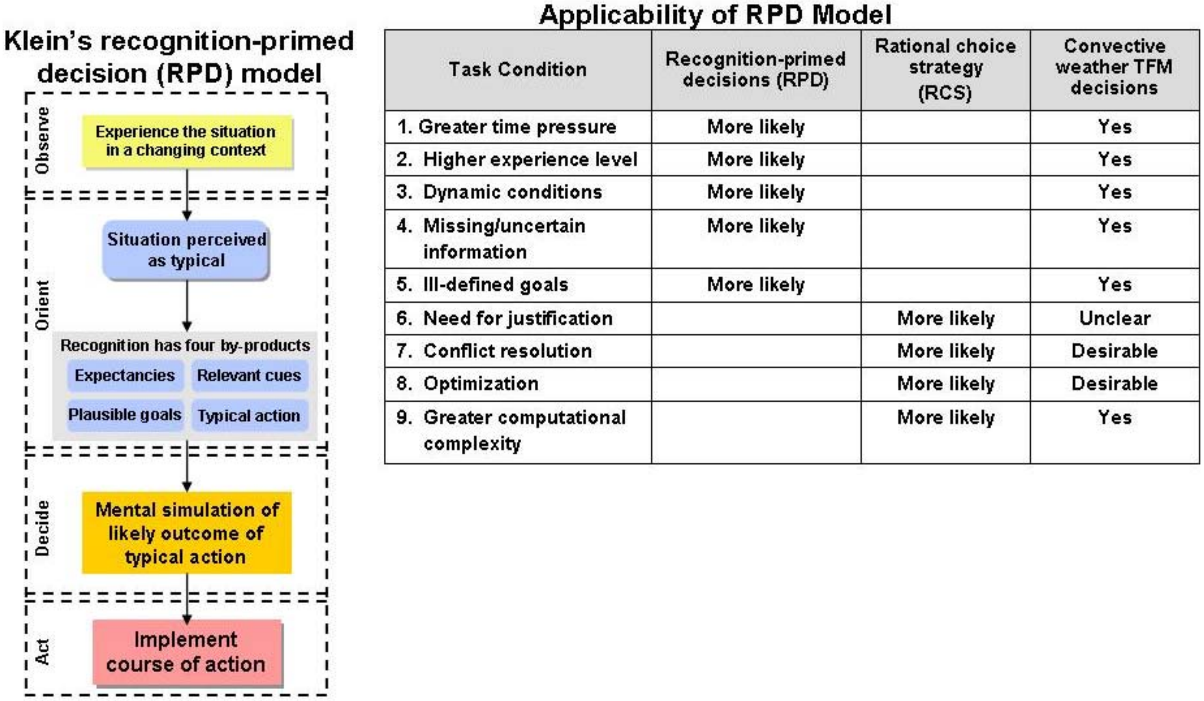
[28] A very readable general literature discussion of the problems that can arise in risk management when statistical correlations between different events are ignored was written by Taleb (2005). This topic of independent vs correlated events is quite germane to TFM use of some forms of probabilistic convective weather forecasts (especially, probability of convection at a given point in space).

[29] A much more detailed discussion of the basis for the above assertion is provided in Evans, et al. (2007).



Applicability of RPD Model

Task Condition	Recognition-primed decisions (RPD)	Rational choice strategy (RCS)	Convective weather TFM decisions
1. Greater time pressure	More likely		Yes
2. Higher experience level	More likely		Yes
3. Dynamic conditions	More likely		Yes
4. Missing/uncertain information	More likely		Yes
5. Ill-defined goals	More likely		Yes
6. Need for justification		More likely	Unclear
7. Conflict resolution		More likely	Desirable
8. Optimization		More likely	Desirable
9. Greater computational complexity		More likely	Yes

Figure 6-1. Recognition-primed decision model and an assessment of its applicability to tactical TFM decision making during severe weather versus the "classical" rational choice strategy (RCS) model. The delineation between RPD and RCS models as a function of task condition is from (Klein, 1998).

As a consequence of this decision model, there is a significant challenge in gaining acceptance for improved, alternative ways of accomplishing effective weather TFM (e.g., the RAPT and/or new procedures for TFM during SWAP) because the decision-makers will tend to prefer approaches for solving problems that have become readily-recognizable and intuitive. Another major problem in individual TFM decision making during SWAP is handling of the uncertainty in the capacity impact of weather that arises from uncertainty in the convective weather forecasts as well as uncertainty in pilot reaction to the weather.

We recommend that the FAA commence a program to investigate use of scenario based techniques for training of individuals as a means of building greater confidence in new operational procedures [e.g., the use of routes with significant miles-in-trail restrictions (e.g., 50–100 nmi) as opposed to routes either being fully open or fully closed] that are possible to use with enhanced decision support systems such as RAPT. A key element of this training will be techniques for recognizing situations where the forecasts of ATC impact are highly reliable so that proactive TMIs can be utilized with a high degree of confidence in success.

Two types of metrics will be used to assess the results of this initiative: conventional human factors metrics of user confidence in their ability to make better decisions and a reduction in the frequency of missed opportunities [e.g., such as were documented by (Robinson, et al., 2008a).]

If such a program were to be carried out at New York focusing on departures from the NY airports, the real time observations at NY in 2007 and 2008 will provide the baseline for the missed opportunities metric. At other locations, it would be necessary to develop a baseline for missed opportunities. The use of a post analysis automated congestion resolution tool together with capacity impacts determined from measured weather data (Robinson, et al., 2008b) would seem applicable.

6.2 IMPROVED TEAM DECISION MAKING

Collaboration between multiple facilities (e.g., tower, TRACON, ARTCC) and between different decision makers within a facility (e.g., TMU and areas in an ARTCC) is essential for expediting departures during SWAP (Davison and Hansman, 2001). Techniques utilized successfully in other "difficult" decision making environments (e.g., military, firefighting) should be assessed to determine specific approaches that would be utilized to improve team decision making during SWAP. It is expected that this training will involve the use of scenarios derived from past SWAP cases.

If such a program were to be carried out at New York focusing on departures from the NY airports, the real time observations at NY in 2007 and 2008 will provide the baseline for the missed opportunities metric. At other locations, it would be necessary to develop a baseline for missed opportunities. The use of a post analysis automated congestion resolution tool together with capacity impacts determined from measured weather data (Robinson, et al., 2008b) would seem applicable. Additional metrics (e.g., reduced time to accomplish coordination on a TMI) should also be considered.

At this point, there are no FAA metrics which assess the ability of various facilities to work together cooperatively to improve TFM tactical decision making. Delay statistics are not an adequate metric for this purpose given the difficulty in normalizing delays to account for differences in weather, demand, and/or strategic TFM initiatives. The feasibility of providing ongoing near real time tracking of missed tactical opportunities as a metric for assessing (and rewarding) more effective multiple facility team decision making should be investigated.

6.3 IMPROVED REAL TIME AWARENESS OF NAS STATUS

A major hindrance to achieving an improved ability of individuals and different facilities functioning as a team to make traffic flow decisions is the poor common situational awareness of the current NAS status during SWAP. When individuals do not consider the possibility of operationally effective TMIs due to a misunderstanding regarding NAS status and/or spend an inordinate amount of time determining the NAS status, bottom line improvements in operational effectiveness are very difficult to achieve.

The FAA TFM program is in the process of providing access to a real time data base of NAS status via the National Traffic Management Log (NTML). However, it is unclear how well the NTML data base will be updated during SWAP events due to the very high stress levels and, the data is not available in a graphical form. Verifying that the NTML data base is accurate for routes and fixes used for traffic to and from the northeast will be accomplished on an experimental basis by having the NY TRACON (N90), ZNY, and the adjacent ARTCC enter real time changes in the status of arrival and departure routes using a point and click Web based applications. Additionally, real time evaluation of flight tracks and filed routes (from ETMS) would be conducted to determine if a route that appeared to be open was not being used even though there was a demand and the route was not blocked by convective weather. This local data base will be used to generate a graphical depiction of the current constraints on the RAPT display as well as routes whose usage seemed to be at variance with its status.

Since the RAPT display is available at all of the key facilities that handle traffic to and from the New York airports as well as the ATCSCC and airlines, this graphical display will significantly improve common situational awareness and reduce the number of times where appropriate TMIs were not implemented. The graphical display of constraints will provide a “discovery” option wherein a viewer can determine which facility last changed the status of a route or fix.

Additionally, the differences between the NTML real time status and the status determined from the combination of NTML and “hot line” will be provided to TFM management so that they can determine the best procedures to insure that the NTML real time status is as accurate as possible.

The execution of this task will involve approximately 4 person-months of software engineering on the RAPT display and approximately a person-year of technical assistant time for the real time “hot line” monitoring. When the “hot line” is not active (e.g., no SWAP is in effect), the technical assistants would analyze past operational data to generate quantitative metric results.

Two types of metrics will be used to assess the results of this initiative: a reduction in the number of times where misunderstandings on the current NAS status are observed and, a reduction in the frequency of missed opportunities for departures from the NY airports. The real time observations at NY in 2007 and 2008 will provide the baseline for both of these metrics. Decision makers will be interviewed at the end of each summer’s demonstration to determine their assessment of the real time NAS status display and recommendations for future enhancements.

6.4 RESEARCH ON USE OF PROBABILISTIC FORECASTS

The use and, misuse of probability information in decision making has been covered in a number of popular books [see, e.g., Taleb (2005), Gigerenzer (2007)]. Although there is a very substantial literature on rational decision making when given probabilistic information, most decision makers use much more subjective approaches to use of probability information. Thus, a major issue that needs to be addressed is how probabilistic information could best be used by operational TFM decision makers.

First, we consider the possibility of applying standard rational decision making techniques to a classical TFM problem: ending a GDP proactively using a probabilistic forecast. We then discuss some of the issues that arise in extending such an approach to convective decision making.

(a) Rational decision making using probabilistic forecasts

Making decisions using well defined probability forecasts (i.e., probabilities that can be manipulated by the standard rules for probability use) involves the application of statistical decision theory which is a relatively well understood area conceptually.

The essential components (see, e.g., Chernoff and Moses, 1959) are:

- the available actions (e.g., GDP parameters)
- the possible states of nature (e.g., the marine stratus dissipation times)
- the consequence of actions for a given action that is taken when nature has some state (e.g., amount of delay, the number of aircraft in a holding pattern)
- the probability of the various possible states of nature, given some measurements (these probabilities for various states would be generated by e.g., the SFO forecast algorithm), and
- the strategy used to choose between the actions given the forecast probabilities.

It should be noted that there is an extensive literature on optimizing GDP parameters given a probabilistic forecast of the future capacity [Mukherjee and Hansen (2005) show contemporary results as well as providing references to the past literature]. These studies did not explicitly consider the cost to air traffic personnel from too many aircraft in a holding pattern (e.g., if the GDP was ended proactively in error). In addition, they generally assume that the costs and benefits could be expressed by a combined metric such that one could optimize the GDP parameters using an expected loss criteria.

If one sets about to convert the SFO marine stratus forecast information into information more directly tailored to the consequence of a given action that is taken when nature has some state, one finds quickly that a key factor, the probability distribution of extremely late dissipation times (e.g., the cases where the dissipation time was after the 90% forecast time), was not being provided to the decision makers.

This, coupled with the difficulties in relating the forecast probabilities to trading off possible outcomes for various strategies, lead us to consider instead providing a decision theory-based presentation for the forecasts.

Specifically, we suggest that there needs to be a substantially different, risk management based, approach to presentation and use of the SFO probabilistic weather forecasts:

1. The operational decision makers (e.g., the FAA traffic flow managers in consultation with key airlines) need to be provided the expected consequences of various actions (i.e., GDPs) given the probability distribution of expected dissipation times. This operational consequences-oriented presentation would include key factors such as expected average delays, expected unnecessary "avoidable" delay, average holding time, and the probabilities of various numbers of aircraft (e.g., 10, 20 or 30) in airborne holding within the Oakland ARTCC for various GDP options.
2. Much more attention needs to be paid to how to mitigate the risk of rare late stratus dissipation events that would cause an excessive number of holding aircraft. There are at least two options for such risk mitigation: improved use of the daytime forecasts (e.g., 15Z) to modify a GDP that was put into effect in the predawn period

(e.g., 13Z), and developing a fair and equitable system by which SFO-bound planes in a holding pattern would be diverted to an alternative airport in the event that the number of holding aircraft exceeds an agreed upon threshold. It should be noted that the diversion option would have to be developed collaboratively with the airlines.

NASA Ames and the Monterey, CA NWS forecast office are funding an initiative to explore how the SFO GDP decision making might be improved. This effort could benefit by a stronger interface to the ATCSCC and the customers. This SFO initiative offers the FAA a low cost opportunity to conduct research on how the NextGen vision for TFM accomplished using probabilistic forecasts might be used operationally.

(b) Decision making using probabilistic forecasts when "rational" decision making seems improbable.

The San Francisco stratus forecast decision making seems simple:

(1) very limited number of possible states and relatively few actions, and

(2) the outcomes analysis was relatively straightforward

but achieving operational benefits has been hard to achieve. Applying this approach to convective weather decision making problem is daunting by comparison since

a. the number of possible weather states – the storm spatial pattern as a function of time – is enormous

b. the number of possible actions is very large as well, and

c. the probability structure of various possible weather states is poorly understood.

As a consequence, the decision maker will probably have to resort to ad hoc simplifications. The question is how should the information on uncertainty be presented to the users given that ad hoc simulations will have to be made? For example, if the uncertainty were captured in 10 ensemble sample functions, should the user see a rapid animation (or, overlay) of these various results or should they be collapsed into a single probability map? One needs to develop a methodology for comparing the decisions made using these different representations of uncertainty.

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7. SUMMARY

In this section, we summarize key dependencies between TFM capabilities, weather forecasts and the weather-to-capacity translation algorithms that need to be addressed if the desired TFM-M capabilities are to achieve a useful operational capability in the desired time frame. This dependency analysis results in three key findings:

1. "Gaps" in current aviation weather product development that should be addressed if the weather products are to be readily used for improved TFM. Significant gaps in the current aviation weather research program include inadequate effort to characterize forecast uncertainty in terms that can be exploited by future TFM concepts, and inadequate research on forecasting key parameters (e.g., storm echo tops) that are very important for translation,

2. "Gaps" in joint aviation weather/ATM research on translating meteorological variables into quantitative measures of operational impact; and

3. "Gaps" in the conceptual basis and/or details of TFM decision support tools associated with operations in severe convective weather

that need to be addressed if the desired near term (e.g., WP2) TFM operational capabilities are to be achieved in a timely manner.

First, we should observe the importance of significantly improving the operational capability for tactical (e.g., < 2 hour) TFM decision making and implementation. The bulk of the convective weather in the high delay Northeast quadrant of the NAS is "unorganized" (Figure 1-2) which is hard to forecast accurately greater than 60 minutes in advance (Figures 2-4 through 2-10 and Appendix A) and the expectation (Figure 2-13) is that this will continue for a number of years.

Key components of improving tactical TFM decision making during convective weather include:

- Integrated weather-TFM decision support to reduce the cognitive workload for traffic managers and improve common situational awareness,
- Dramatic improvements in the ability to modify flight plans to address changes in the convective weather impacts (e.g., SEVEN and improvements in airborne rerouting),
- Dramatically reducing the amount of multi-facility coordination required for individual flight routing decisions,
- Increased attention to human factors issues related with TFM decision making in the ARTCCs, TRACONs and towers, and
- Developing metrics for effective tactical TFM decision making so that good performance can be recognized and rewarded.

The current 2-hour forecasts often show significant skill at forecasting squall lines impacts at relatively coarse spatial resolution (e.g., 20–40 nmi). Procedures should be developed to take advantage of the situations where these forecasts are accurate. If the CoSPA developers are able to achieve a similar performance for squall lines with 2–8 hour forecasts, this would then offer the possibility of much more accurate guidance for key strategic decisions such as determining AFP parameters (e.g., spatial domain and rates) provided that:

1) the long term forecasts include forecasting of key weather parameters for translation of the weather forecasts into "capacity" impact forecasts, and
2) the weather to capacity translation algorithms have been developed and validated.

The plan of attack in the "gap" analysis is to work backwards from the desired functional capabilities. We first outline candidate dates for various TFM functional capabilities. Then, we consider what is needed in the way of weather impact to capacity impact translation to achieve those capabilities. We then consider what is anticipated in the way of weather forecast capability.

In Table 7-1 we show dates for various functional TFM capabilities based on the CATM-T WP2 report (Geffert, et al., 2007) and, our assessment of feasible dates for capabilities not discussed in the CATM-T report.

Table 7-2 shows the dependencies between the various functional TFM capabilities, the convective forecasts, and various aspects of weather to capacity translation. From Table 7-2, we see that:

1. Improving or, developing pilot storm avoidance models for both en route and terminal is important for nearly all envisioned functional capabilities. This could be accomplished by the FAA aviation weather research program (on grounds it is similar to understanding icing and turbulence impacts on aircraft), or by the FAA TFM program or by NASA (who is already supporting research in this area). These models are also critical for the NextGen envisioned Reduce Weather Impact (RWI) initiative.

2. The research results on pilot storm avoidance models are very important for determining what weather parameters should be forecast by the weather forecast algorithms. The principal immediate need for 0-2 hour forecasts is the decay of the echo tops forecast. However, if storm 3D geometric features (e.g., growth, decay, storm structure downwind of the winds aloft) turn out to be very important, that would create additional requirements for the CoSPA forecast.

   The current 2–8 hour convective forecasts do not include an echo tops field forecast. Hence, the planned CoSPA demonstration in 2011 will be a very important milestone in the development of a 2–8 hour forecast which can be translated to generate strategic estimates of airspace capacity. In view of the importance of better guidance for strategic TFM decision making (e.g., determining AFP locations and throughput rates), we recommend that the TFM program establish experimental interfaces to the CoSPA 2–8 hour forecasts that include echo tops forecasts starting in 2009 so that the TFM uses of these forecasts are addressed early on in the development cycle.

3. Developing and validating models for route blockage (both terminal and en route) and sector capacity are also very important for nearly all TFM functional capabilities and the RWI initiative. Managing research in this area would seem to principally be an FAA TFM program and NAS Operations Planning responsibility since a key issue is how traffic managers and controllers utilize airspace. NASA recently has only supported capacity research associated with the NextGen fully automated aircraft-to-aircraft separation.

4. ITBFM is seen to require modeling progress on nearly all fronts as well both types of forecast. Hence, the implementation time for a robust convective weather capability is likely to be much later than was shown in Figure 7-1. Rather, it would seem desirable to first focus on limited domain applications of time based metering.

5. Given the many technical challenges in developing time-based metering algorithms that can automatically determine a controller workload feasible flight trajectory when a plane deviates around a storm, we strongly suggest that a near term study be conducted to see what sorts of ad hoc solutions are being developed by the current TMA users to provide some TMA capability during convective weather impacts. At the September 2008 CDM semi-annual meeting, it was announced that a traffic manager at ZTL was conducting such investigations. Providing the ZTL traffic managers with full access to CIWS and having researchers work with the ZTL traffic managers would seem to be a low cost, potentially high payoff investment.

6. Human factors investigations such as outlined in Chapter 6 will be an "enabling technology" that is likely to be critical to actually achieving significant operational benefits from the various TFM functional capabilities discussed in Tables 7-1 and 7-2.

We also recommend that there be a parallel effort to study the extent to which the current NAS weather delays have an "avoidable" component that can be attributed to strategic and tactical TFM decision making.

7. Operations research studies are needed to assess realistic benefits for proposed CATM-T concepts given projected future weather forecast capabilities.

For example, the current operational concepts for collaborative rerouting concepts such as Integrated Collaborative Rerouting (ICR) and System Enhancements for Versatile Electronic Negotiation (SEVEN) assume that:

i. FAA personnel can reliably determine the regions of airspace that flights will have to route around, and
ii. airline operations center personnel can prioritize ground delay and reroute options based on multi-hour (e.g., at least 3 hour) look-ahead thunderstorm forecasts.

In many situations (e.g., weakly forced, disorganized convection), uncertainty at the time of flight planning as to where and when the weather impacts will occur will inhibit the ability to usefully prioritize alternate flight options. Studies are needed to determine how often these concepts can be applied, given storm-type climatology in different parts of the NAS.

TABLE 7-1

Candidate Dates for Various TFM Functional Capabilities

CATM capability	Pre WP2 2009	Initial WP2 2010-11	Mid WP2 2012-13	Late WP2 2014-15	Post WP2
Enhanced congestion prediction		CIWS on Traffic Display CIWS on Future Traffic Display RAPT*	RAPT (NY PHL) Tactical AFP fcst En route blockage fcst	RAPT (P90, C90)	
Automated airspace congestion management		SEVEN CACR phase 1		CACR phase 2	
Arrival flow management	TMA	TMA*			
Departure flow management			A/DMT DFM TMA/EDC		
Integrated TBFM			TMA/EDC SEVEN?		
Post event analysis tool suite		Weather analysis for procedures	"avoidable" delay analysis		

Notes:
Dates shown are first date that a given capability becomes operationally available.
RAPT* - forecasts when arrival flows are likely to deviate into departure route airspace

P90, C90 – Potomac and Chicago TRACONs

TMA* - has enhanced capability to provide useful operational capability in convective weather

TMA/EDC– gate-to-gate TMA

TABLE 7-2
Pilot Weather Avoidance Model

Capability	**L**	**C**	**D**	**Arr**	**Dep**	**Arpt**	**Route blockage**	**Sector occupancy**	**Airport capacity**	**Storm avoidance trajectory**	**0–2 hr fcst**	**2–8 hr fcst**
Enhanced congestion prediction												
CIWS on TD and FTD	P	P	P	P	P						Y	
RAPT	Y		Y		Y		Y				Y	
RAPT*	Y	Y	Y		Y		Y				Y	
Tactical AFP rate fcst	Y	Y	Y				Y				Y	
Strategic AFP rate fcst	Y	Y	Y				Y					Y
En route blockage	Y	Y	Y				Y				Y	
Automated airspace congestion management												
SEVEN	Y	Y	Y	Y	Y	Y	Y	Y	Y		Y	Y?
CACR phase 2	Y	Y	Y	Y	Y	Y	?	Y	Y		Y	Y
Arrival flow management												
TMA*	Y	Y		Y			Y	?		Y	Y	
Departure flow management												
DFM prototype	Y		Y		Y	Y	Y	?	?	Y	Y	
A/DMT	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y?
Integrated time based flow management (ITBM)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Post event analysis of "avoidable" delay												
Maturity of model or forecast	H	L	M	L	L	L	M-L	M	L	L	M	L

Notes:
P – CIWS weather depiction and forecasts need to include the key weather parameters (e.g., storm reflectivity, radar echo tops) identified in storm weather avoidance modeling research
En route domains: L – level flight C – climbing D – descending
Maturity of route blockage model is M only for level flights in en route airspace
Route blockage "capacity" model includes both en route and terminal domains in most cases (AFP and en route blockage are en route only)

Benefits for augmentations to the concepts of operation for systems such as SEVEN (e.g., the decision making infrastructure supporting large-scale, adaptive rerouting of aircraft in flight) should be assessed. For example, as we noted in section 5, SEVEN could either be used as:

a) a strategic planning aid (the focus of much of the HITL testing to date), or,

b) the infrastructure (e.g., multiple flight options pre-approved by airline dispatch and an efficient real time mechanism for making mid flight adjustments to the flight plan) for in flight reroutes to reflect better information on arrival terminal convective weather impacts.

8. Some basic conceptual approaches to TFM automated congestion prediction and resolution need to be reconsidered in the context of convective weather operations

The generation of demand predictions used in automated airspace congestion resolution (AACR) needs to account for weather-related impacts relative to “schedule-based” demand. Reductions in airport departure rates and airborne re-routing around storms will significantly change airspace loading and these actions may not be fully captured by TMI’s known at the time the demand forecasts are made. Achieving more accurate future demand predictions may ultimately require a system-wide model capturing at least macroscopically the likely flow-rate reductions caused by forecast weather.

Another important issue for AACR research is the need to determine whether the concept of characterizing airspace capacity by a scalar sector occupancy metric (e.g., the “modified” MAP threshold) is adequate to insure continuity of major flows (see the discussion in Section 5.2.4). This might be accomplished in conjunction with an effort to see if more recent work on controller workload indicators were to be incorporated into the traffic display characterization of sector/airspace capacity. Developing a TFM concept for considering workload constraints and major flow continuity simultaneously is not a trivial undertaking and hence, an aggressive research program needs to be inaugurated early in the WP2 time frame if derivatives of PACER are to be operationally deployed in the mid WP2 time frame.

9. The FAA should investigate the use of routine “avoidable” delay analyses as a means of characterizing TFM operational performance as well as developing a business case for additional weather-TFM capabilities. The RTCA/S2K FAA/airline Customer Perspective Metrics Working Group [CMWG; Boone et al. (2006)] has for several years been studying how to more accurately measure how the system is performing from a customer perspective. One of the three key areas identified by the CMWG is resource utilization which the CBWG defined as “the safe and efficient use of available airport or airspace capacity.” To date, the CBWG has not developed a quantitative metric for measuring capacity utilization.

Robinson, et al. (2008b) has described a model to assess how available airspace capacity could have best been utilized during convective weather events. The Weather-ATM Capacity Utilization (WACU) model utilizes time-varying capacity reduction estimates (generated by translating the measured CIWS products into capacity estimates) and an automated congestion resolution algorithm to automatically generate broad-area ATM strategies that optimize the use of available capacity. Output from the WACU model include a quantitative estimate for “avoidable” and “unavoidable” delay, as well as individual flight tracks that can be reviewed in a playback mode and compared with actual traffic flows to assess individual TFM decisions. The WACU essentially is operating with perfect forecasts, so the results must be analyzed to ascertain which elements of the “avoidable” delay correspond to infeasible forecast accuracy. However, the initial experiments with WACU (Robinson, et al. 2008b) have shown that much of the “avoidable” delay was associated with not taking advantage of well forecast tactical opportunities[30].

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[30] (Robinson et al. (2008a) discuss many of the impediments to successful tactical TFM decision making in New York.

GLOSSARY

ADDS	Aviation Digital Data Service
AFP	Airspace Flow Program
ASOS	Automated Surface Observing Systems
ATSCC	Air Traffic Control System Command Center
AWC	Aviation Weather Center
CAT	clear air turbulence
CATM-T	Collaborative Air Traffic Management Technologies
CCFP	Collaborative Convective Forecast Product
CIWS	Corridor Integrated Weather System
COI	community-of-interest
CoSPA	Consolidated Storm Prediction for Aviation
CSI	critical success index
CSPR	Closely Spaced Parallel Runways
CWSU	Center Weather Service Units
DFM	Departure Flow Management
EDC	Early Display Capability
FAA	Federal Aviation Administration
FCA	Flow Constrained Area
FEA	Flow Evaluation Area
FSM	Flight Schedule Monitor
GDP	Ground Delay Programs
GTG	Graphical Turbulence Guidance
ITWS	Integrated Terminal Weather System
LLC	Limited Liability Corporation
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCWD	National Convective Weather Detection
NRA	NASA Research Announcement
NRC	National Research Council
NSSL	National Severe Storms Laboratory
PACER	Probabilistic, Automation-Assisted, Congestion Management for En Route
RAPT	Route Availability Planning Tool
REDAC	Research, Engineering and Development Advisory Committee
RVR	Runway Visual Range
SAS	Single Authoritative Source

SEVEN	System Enhancements for Versatile Electronic Negotiation
STAR	Science and Technology in Atmospheric Research Institute
TAF	Terminal Area Forecasts
TCWF	Terminal Convective Weather Forecast
TFM	Traffic Flow Management
TMA	Traffic Management Advisor
TMIs	traffic flow management initiatives
WAIWG	Weather – ATM Integration Working Group
WAN	Wide-Area Network
WARP	Weather and Radar Processor
WFA	Wind Forecast Algorithm
WTMD	Wake Turbulence Mitigation for Departures

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APPENDIX A
EXAMPLES OF CIWS ACCURACY AT FORECASTING REGIONS OF SIGNIFICANT STORM REFLECTIVITY

In the body of this report, we provided seasonal statistics for the frequency of various CIWS forecast accuracy scores. As was noted in Section 2, these scores are determined using score boxes and criteria (Figure 2-3) that are much coarser than the 1 km intrinsic resolution of the CIWS reflectivity and echo tops products. In this Appendix, we show a number of specific storm cases where the reflectivity forecasts have been scored on a “hit-miss” basis both:

(1) as shown in Figure 2-2 and,

(2) with 1 km scoring boxes

along with the corresponding CIWS forecast accuracy scores. These plots provide some perspective on the implications of a given forecast accuracy score for various spatial scales of TFM decision making (e.g., impacts on an airport, TRACON or group of closely spaced routes).

Given the importance of the Northeast corridor in overall NAS delays, a number of these examples are cases where weather was in the CIWS “JFK home” region shown in Figure A-1.

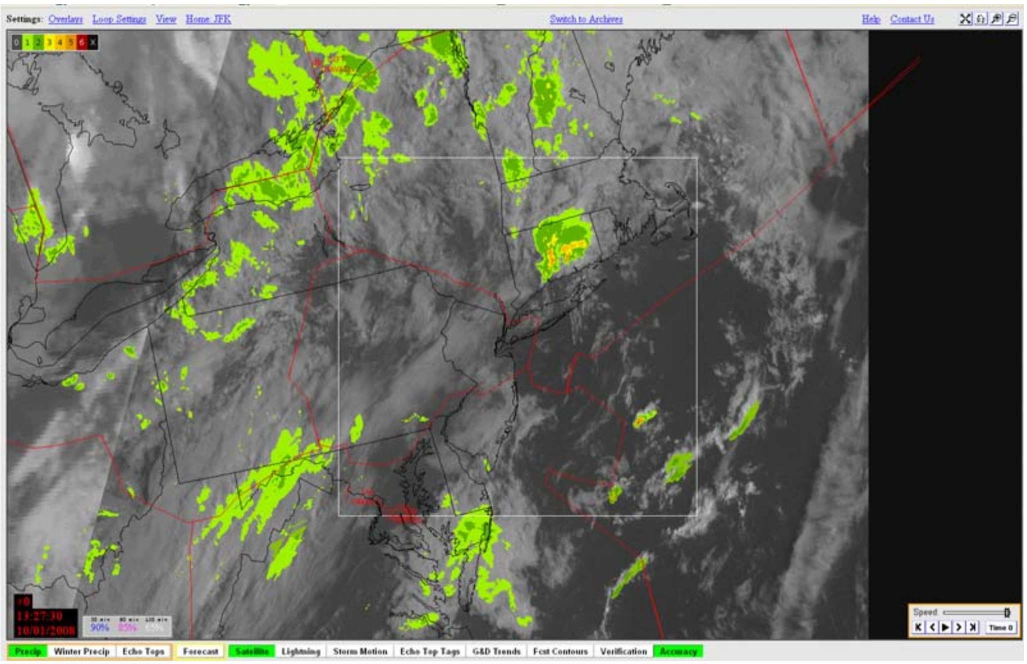


Figure A-1. White box is the spatial domain used to generate CIWS forecast accuracy scores for “JFK home” region.

A number of different examples are shown in Figures A-2 through A-13 for 30, 60 and 120 minute CIWS forecasts. The differences between the “hit-miss” scoring with the scoring boxes shown in Figure 2-2 and 2-3 and 1 km box scoring warrants some discussion. Comparing results for the same user accuracy scores (e.g., Figure A-3 to Figure A-11), we see that the 1 km scoring tends to show red and blue areas either next to each other, or, with a green region between them. This arises from errors in the storm advection velocity. Regions in Figures A-10 through A-13 which are predominantly red are situations where storm decay was not accurately forecast. Conversely, regions that are predominantly blue are situations where storm growth was not accurately forecast.

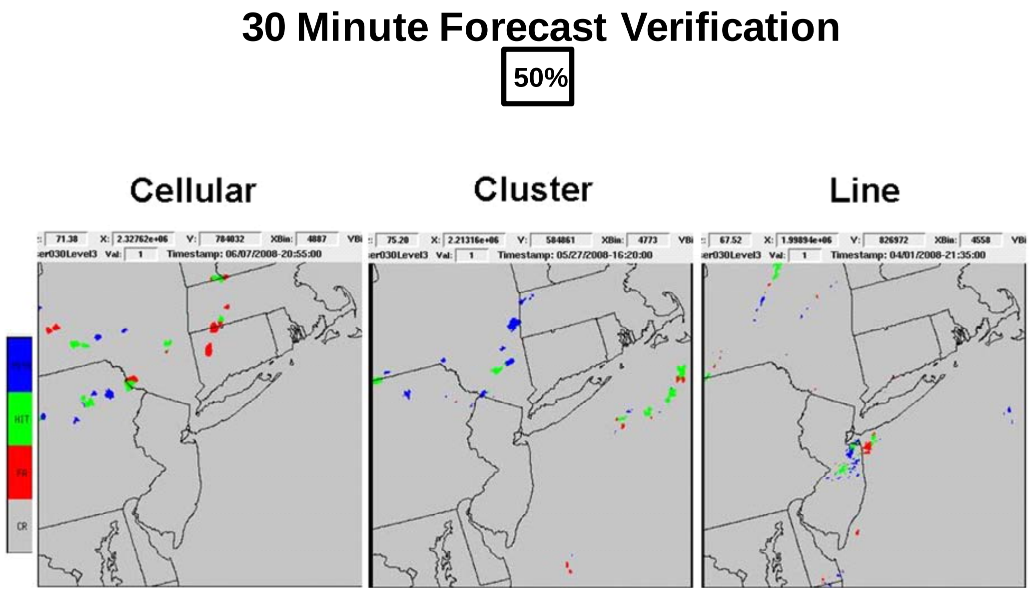
We see that the ability to accurate forecast storm impacts at:

(i) moderate spatial resolution (e.g., region near an airport, groups of closely spaced routes) with the 30 and 60 minute forecasts and,

(ii) coarse resolution (e.g., TRACON region) with the 120 minute forecasts

is generally poor for user scores below 50% and very poor for scores of 20% to 30%. Conversely, user accuracy scores of 70% or greater generally are situations where CIWS can forecast storm impacts at the above indicated scales.

Forecasting storm impacts at the level of closely spaced individual routes (e.g., the RAPT New York route widths are approximately 30–50 km) seems to be possible for high scores (e.g., above 70%) at 30 and 60 minutes albeit it is also clear that the user score alone does not insure accurate route impact scores in all portions of the forecast accuracy scoring region (e.g., the “JFK home” region shown in Figure A-1).



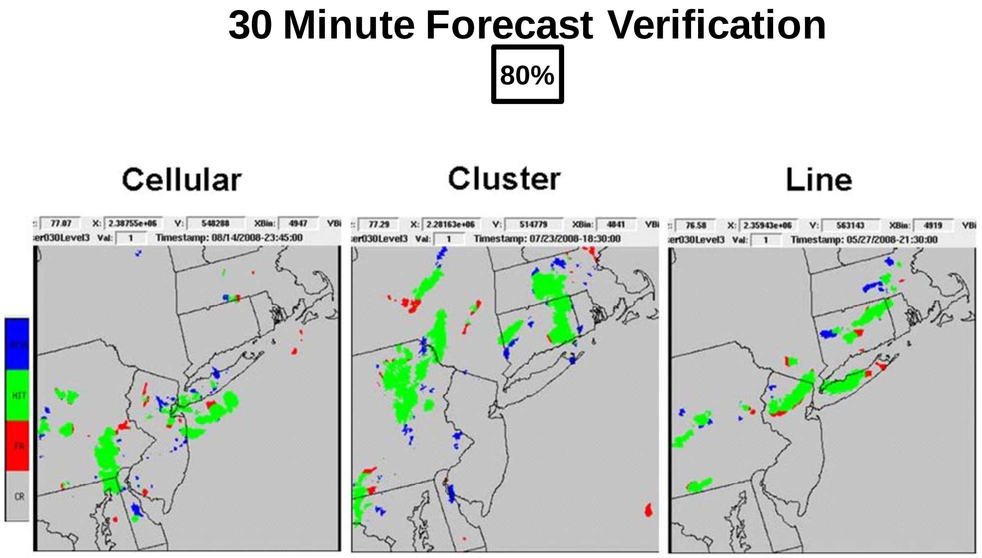
30 Minute Forecast Verification

50%

Cellular

Cluster

Line



30 Minute Forecast Verification

80%

Cellular

Cluster

Line

Figure A-2. Examples of 30 minute CIWS forecast verification with 19 km box scoring (per Figures 2-2 and 2-3). Green are regions of VIL ≥ VIP level 3 equivalent reflectivity that were correctly forecast; reds are false alarms and blues are misses. The vast majority of the 30 minute forecast scores are above 50% (see Figures 2-4 and 2-5).

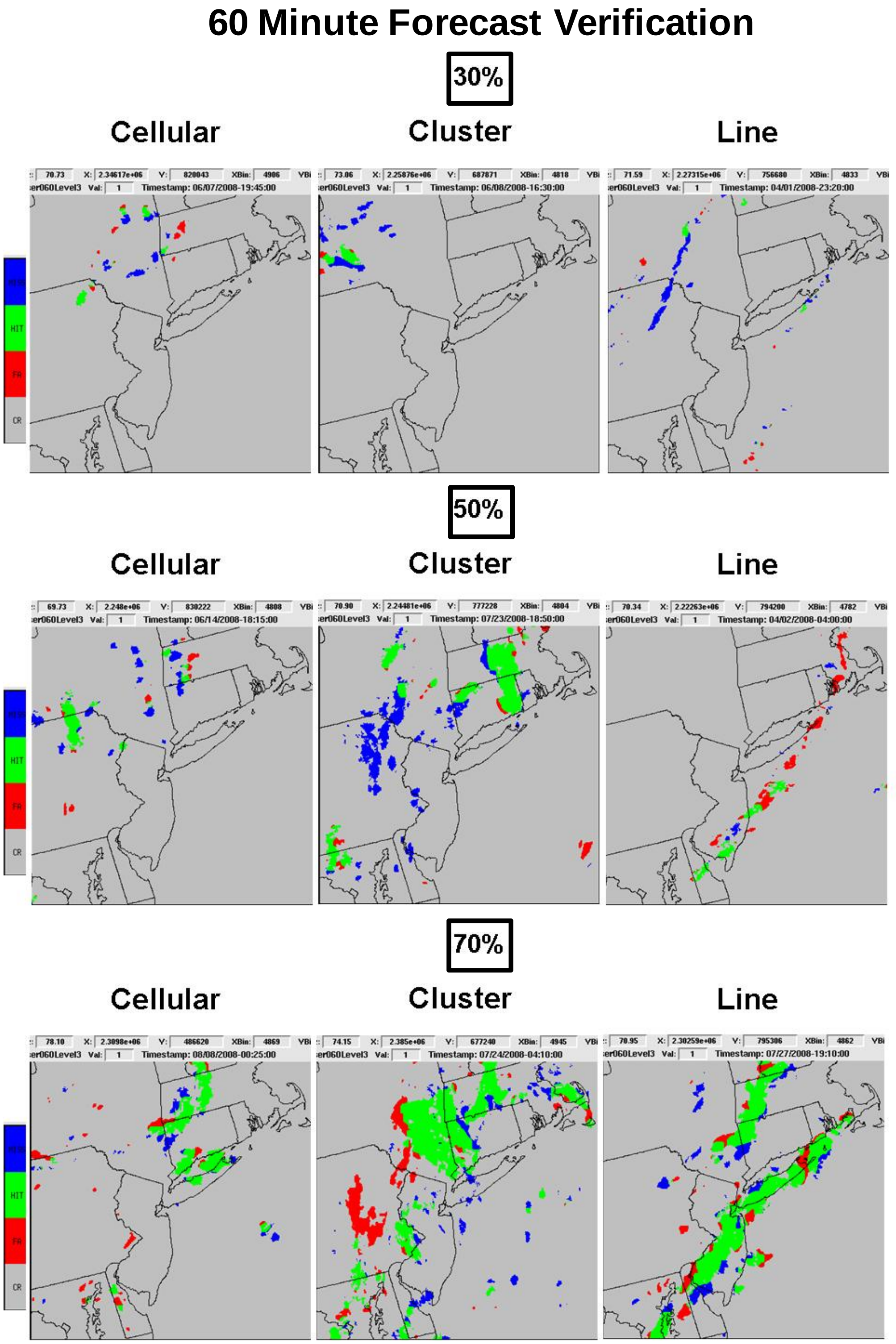


Figure A-3. Examples of 60 minute CIWS forecast verification with19 km box scoring (per Figures 2-2 and 2-3). The vast majority of the 30 minute forecast scores are between 30% and 80% (see Figures 2-4 and 2-6).

120 Minute Forecast Verification

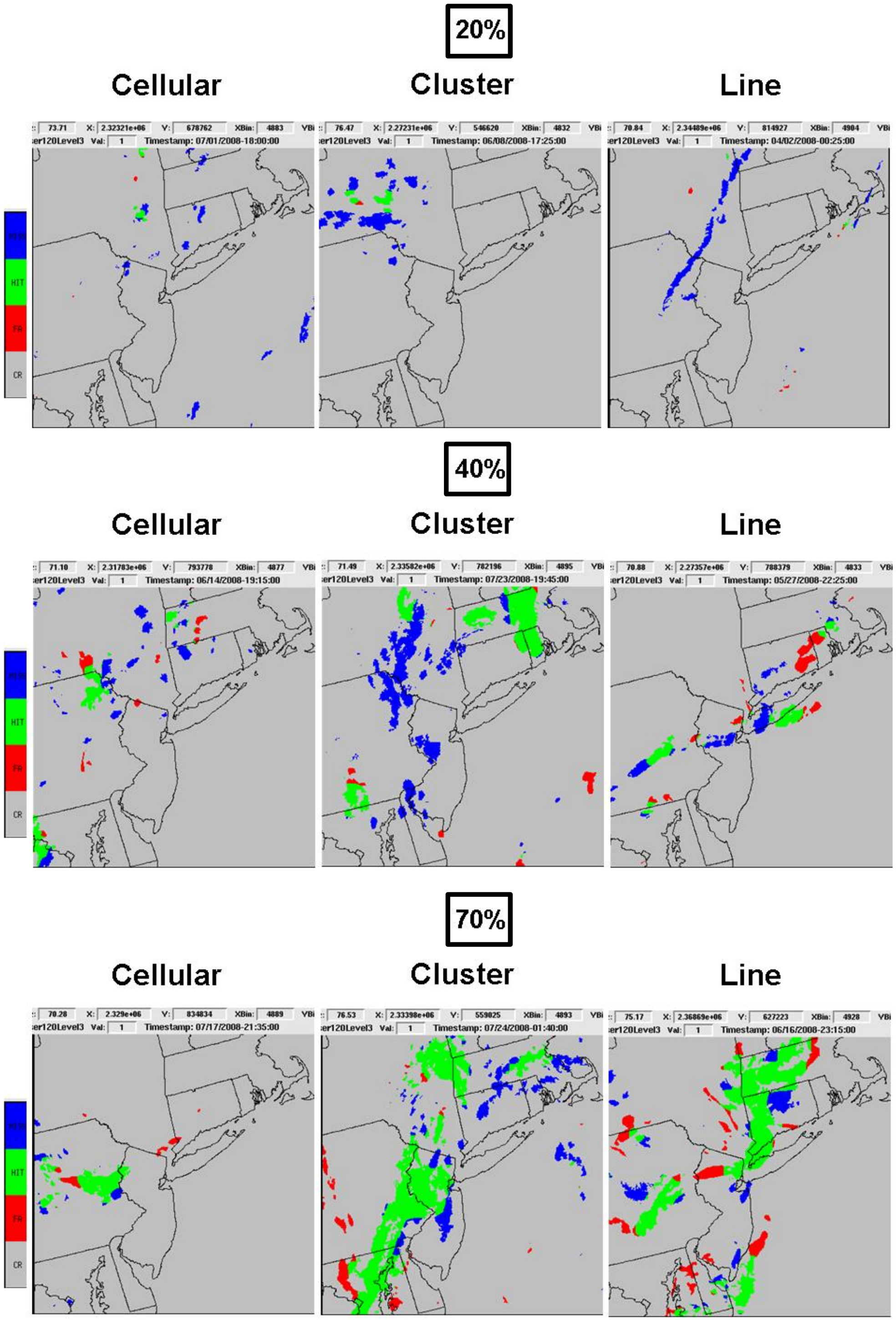


Figure A-4. Examples of 120 minute CIWS forecast verification with 39 km box scoring (per Figures 2-2 and 2-3). The vast majority of the 120 minute forecast scores are between 20% and 80% (see Figures 2-4 and 2-7).

120 Minute Forecast Verification

Squall Line

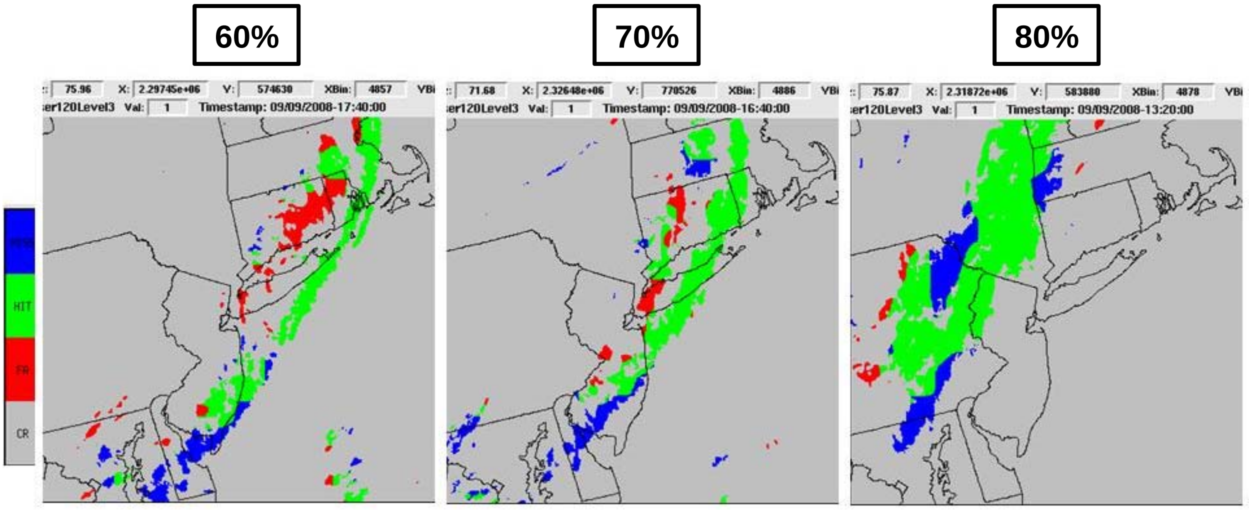


Figure A-5. Examples of 120 minute CIWS forecast verification with 39 km box scoring (per Figures 2-2 and 2-3) for three different accuracy scores on squall lines. The 120 minute forecast scores are highest for squall lines (Figure 2-7).

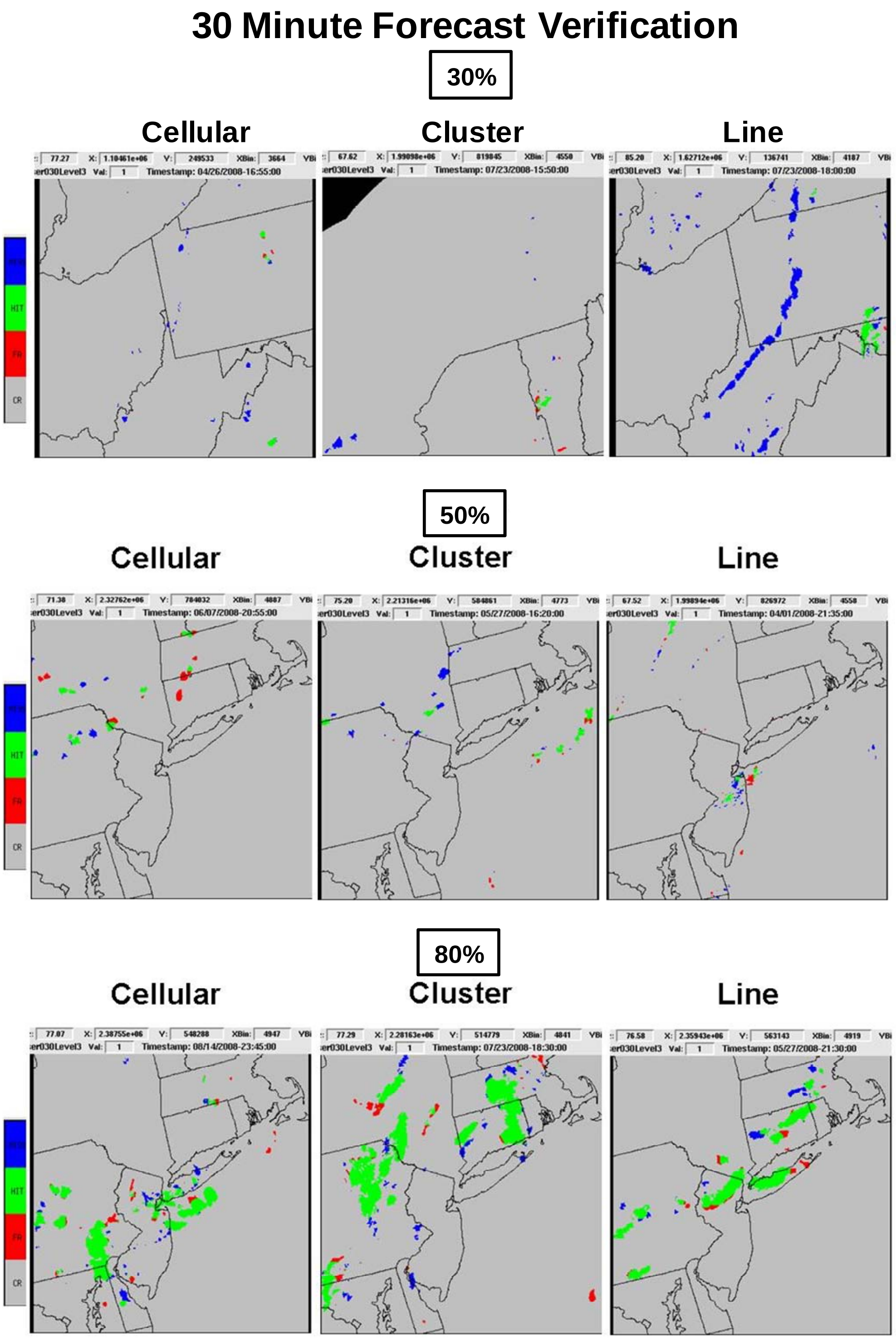


Figure A-6. Additional examples of 30 minute CIWS forecast verification with 19 km box scoring (per Figures 2-2 and 2-3). Corresponding forecast accuracy scores are shown above each plot.

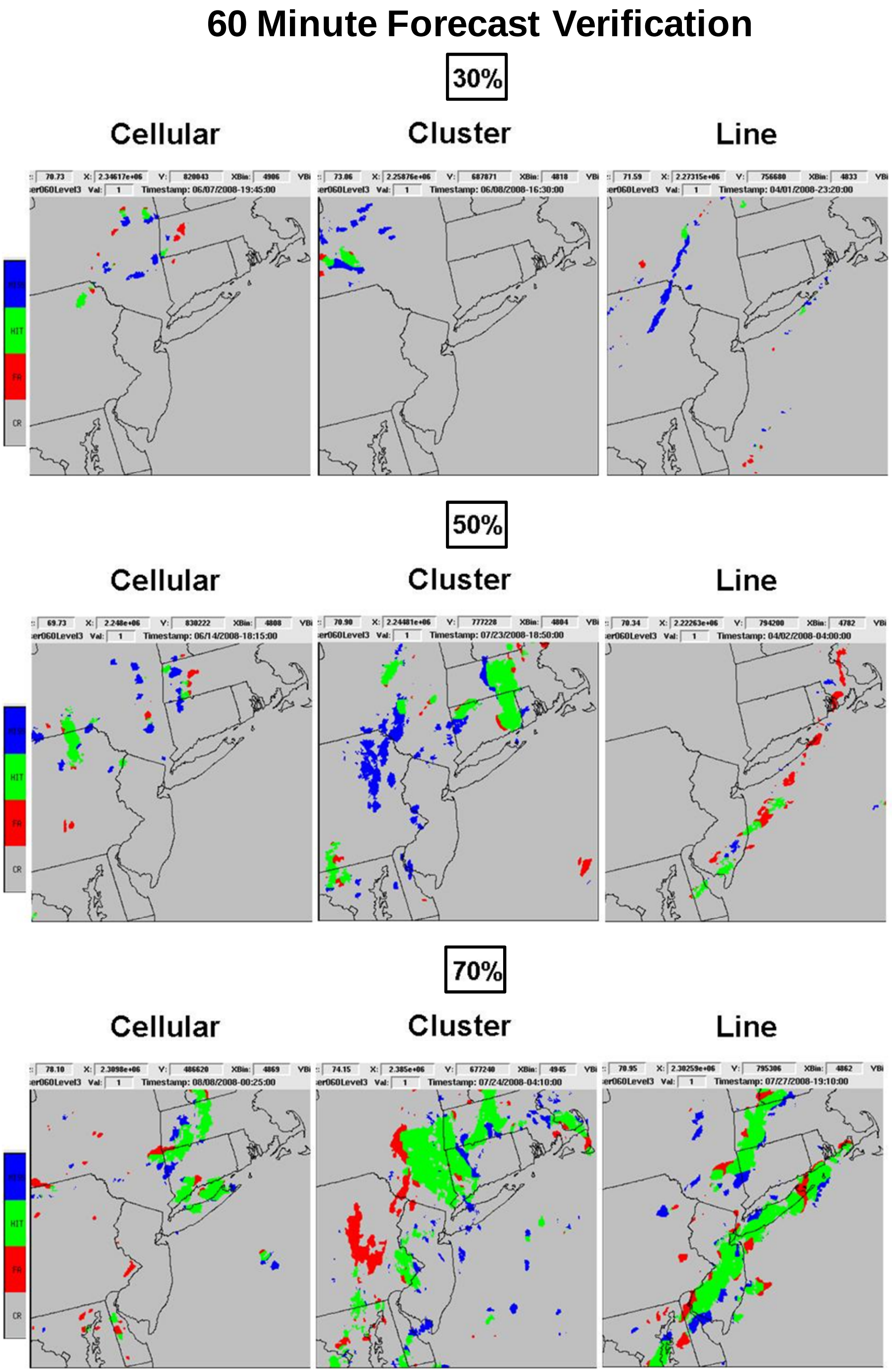


Figure A-7. Additional examples of 60 minute CIWS forecast verification with 19 km box scoring (per Figures 2-2 and 2-3). Corresponding forecast accuracy scores are shown above each plot.

120 Minute Forecast Verification

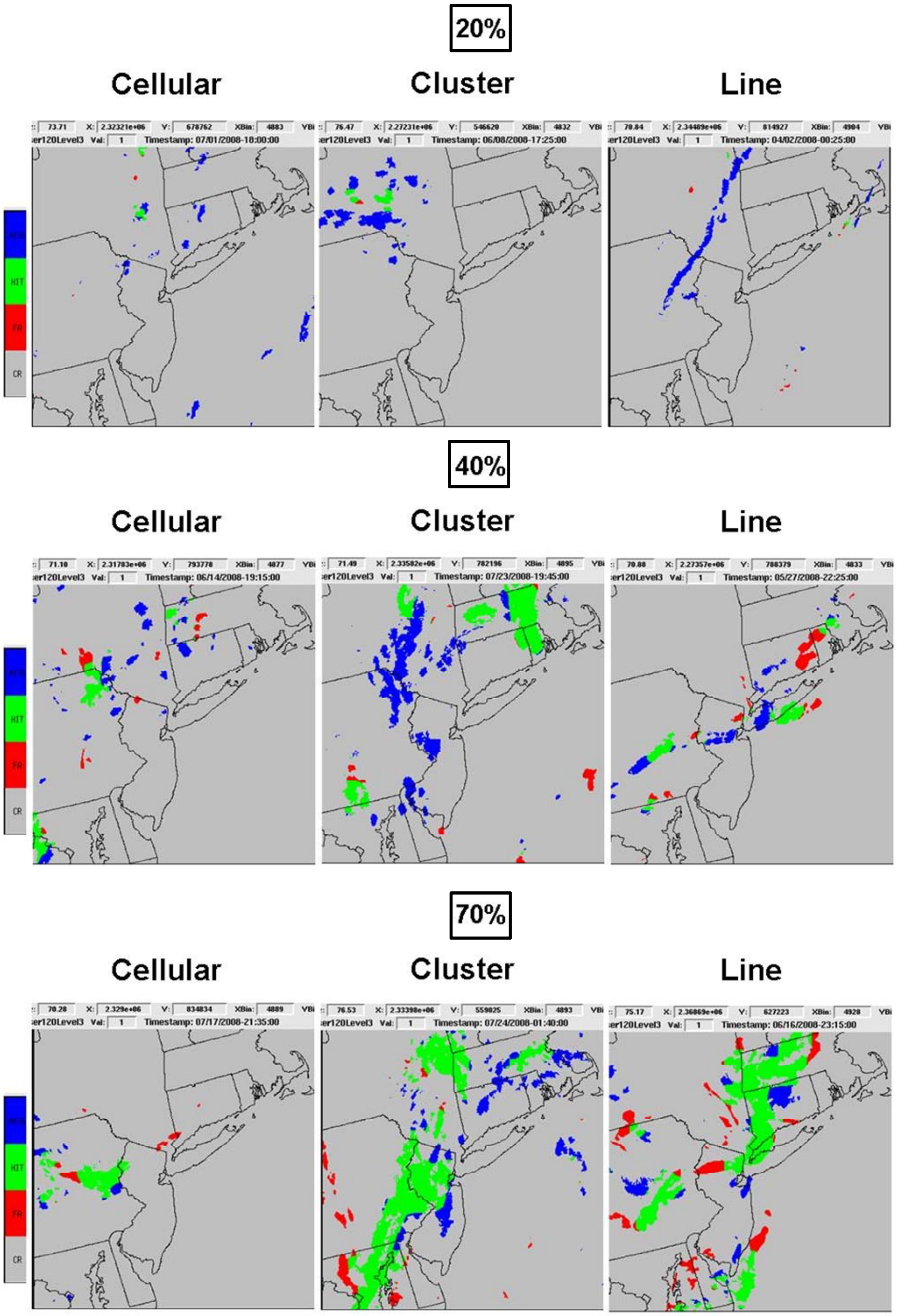
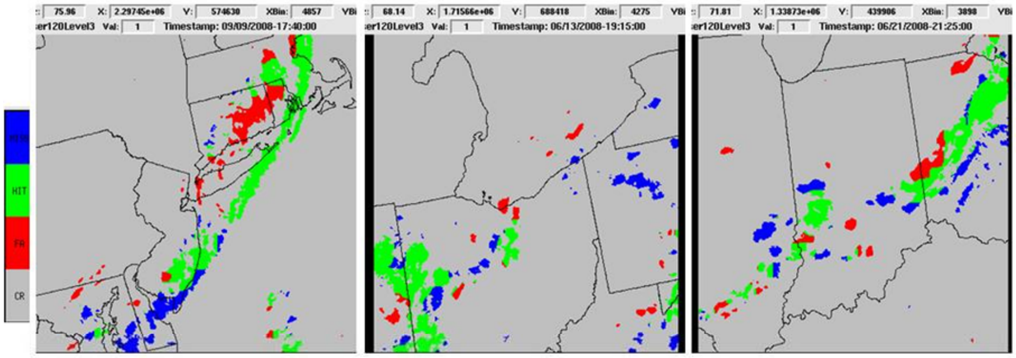


Figure A-8. Additional examples of 120 minute CIWS forecast verification with 39 km box scoring (per Figures 2-2 and 2-3). Corresponding forecast accuracy scores are shown above each plot.

120 Minute Forecast Verification

Squall Line

60%



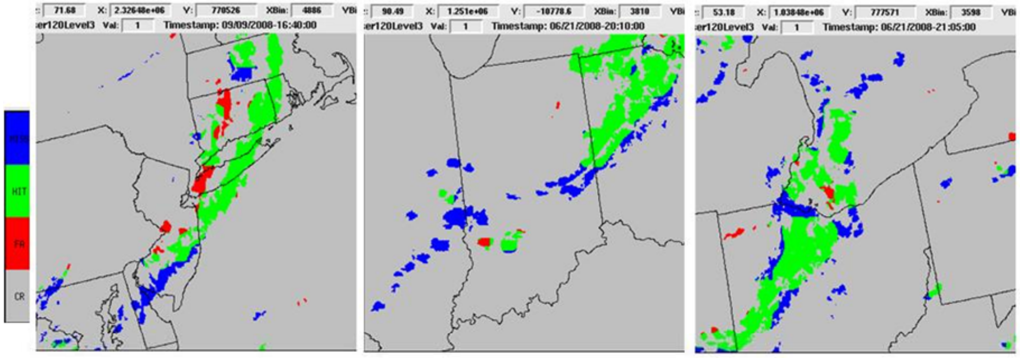
: 75.96 X: 2.29745e+06 V: 574630 XBin: 4857 VBi
er120Level3 Val: 1 Timestamp: 09/09/2008-17:40:00

: 68.14 X: 1.71566e+06 V: 688418 XBin: 4275 VBi
er120Level3 Val: 1 Timestamp: 06/13/2008-19:15:00

: 71.81 X: 1.33873e+06 V: 439906 XBin: 3898 VBi
er120Level3 Val: 1 Timestamp: 06/21/2008-21:25:00

Squall Line

70%



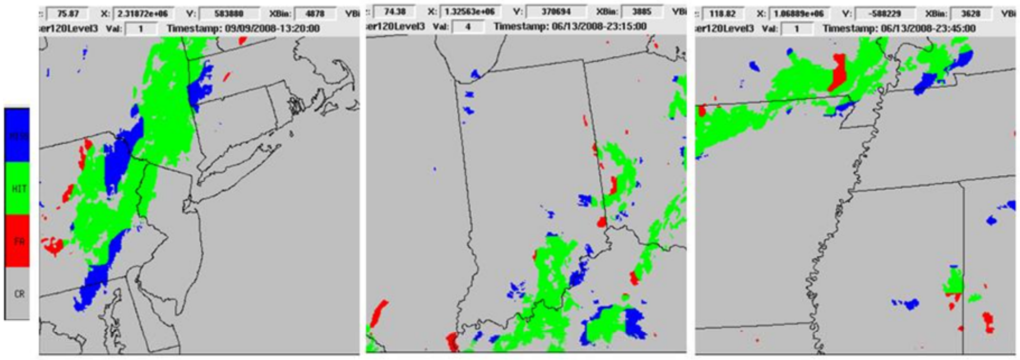
: 71.68 X: 2.32648e+06 V: 770526 XBin: 4886 VBi
er120Level3 Val: 1 Timestamp: 09/09/2008-16:40:00

: 90.49 X: 1.251e+06 V: -10778.6 XBin: 3810 VBi
er120Level3 Val: 1 Timestamp: 06/21/2008-20:10:00

: 53.18 X: 1.03848e+06 V: 777571 XBin: 3598 VBi
er120Level3 Val: 1 Timestamp: 06/21/2008-21:05:00

Squall Line

80%



: 75.87 X: 2.31872e+06 V: 583880 XBin: 4878 VBi
er120Level3 Val: 1 Timestamp: 09/09/2008-13:20:00

: 74.38 X: 1.32563e+06 V: 370694 XBin: 3885 VBi
er120Level3 Val: 4 Timestamp: 06/13/2008-23:15:00

: 118.82 X: 1.06889e+06 V: -588229 XBin: 3628 VBi
er120Level3 Val: 1 Timestamp: 06/13/2008-23:45:00

Figure A-9. Additional examples of 120 minute CIWS forecast verification with 39 km box scoring (per Figures 2-2 and 2-3). Corresponding forecast accuracy scores are shown above each plot.

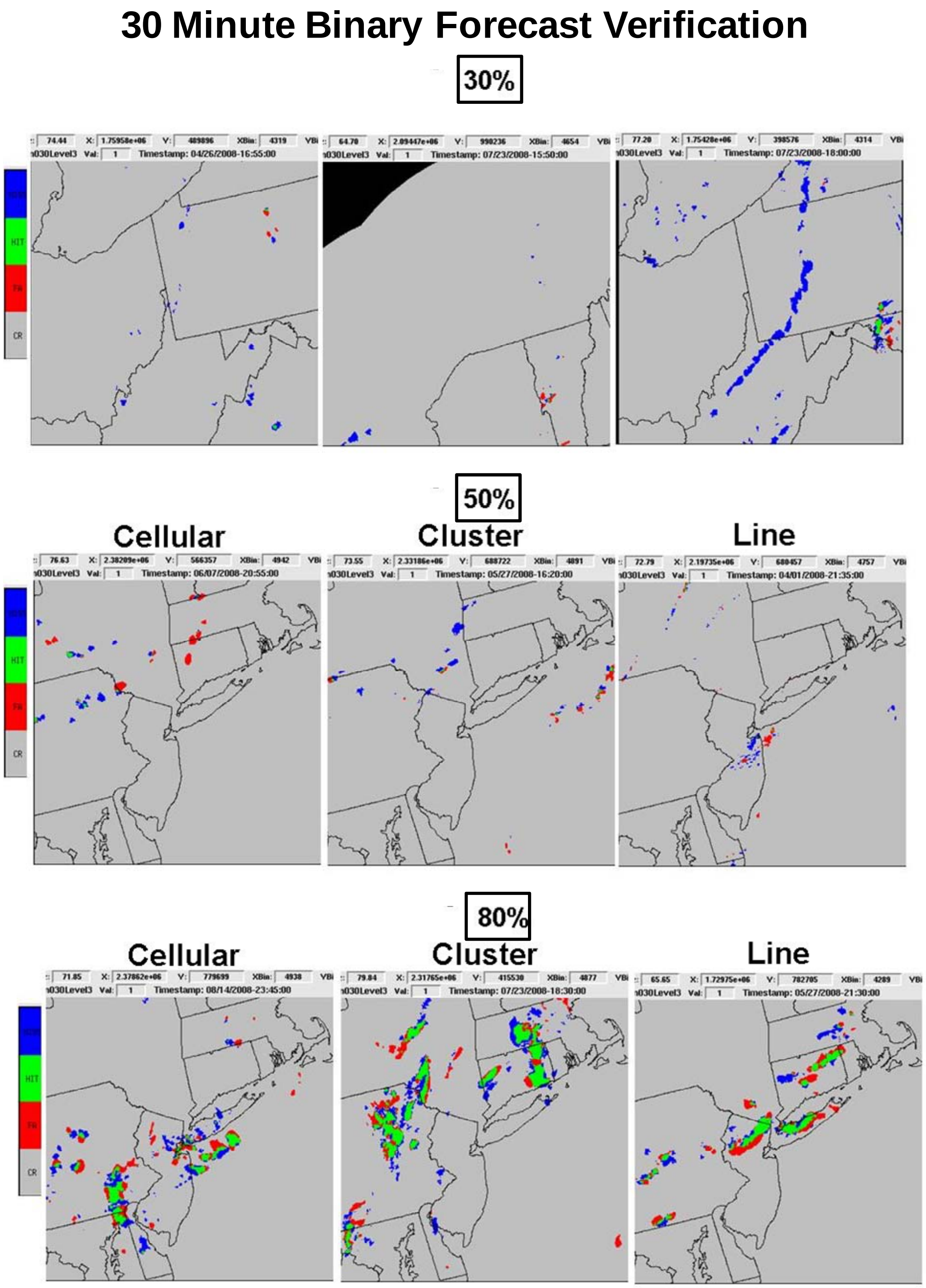
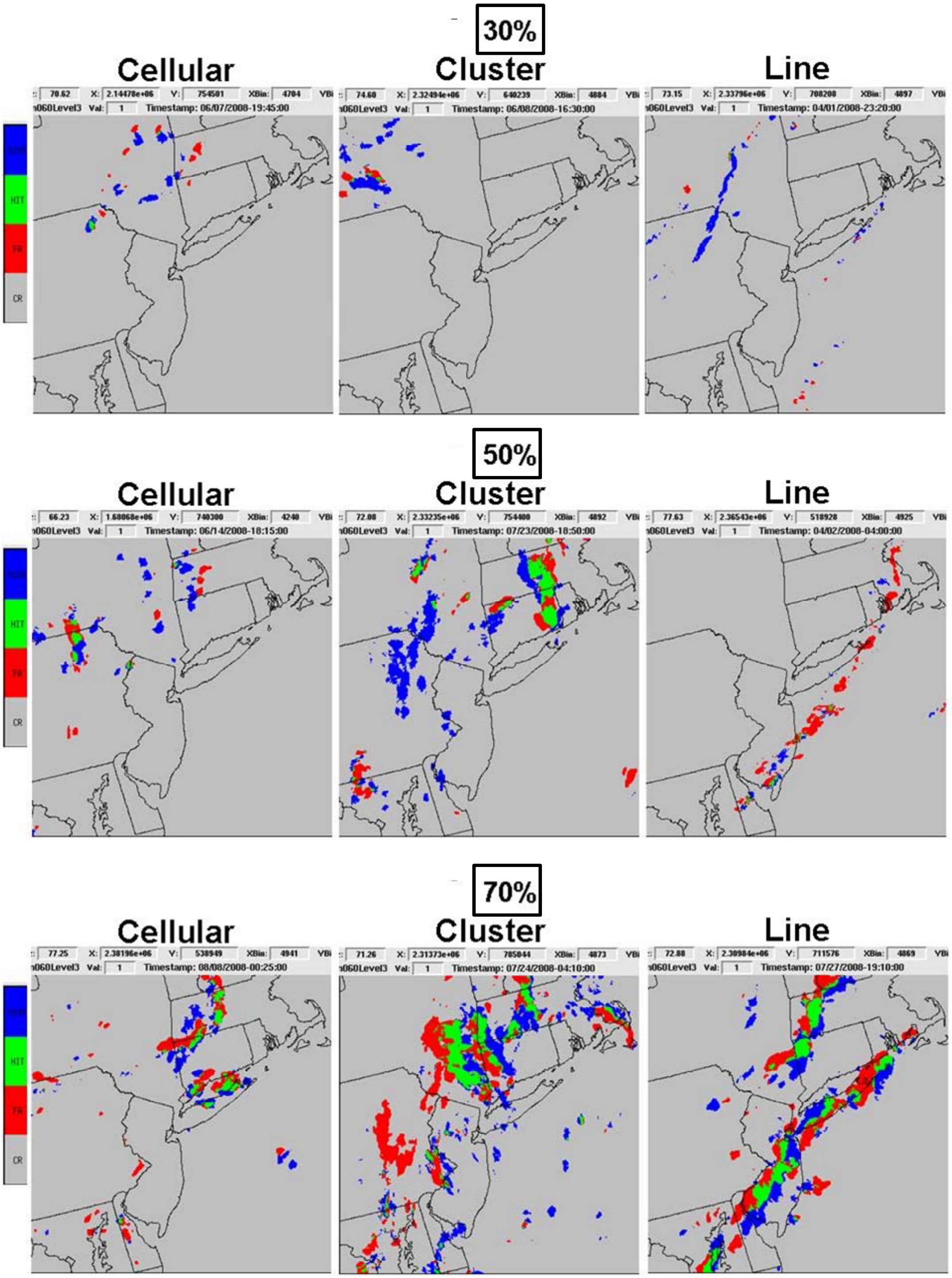


Figure A-10. Examples of 30 minute CIWS forecast verification with 1 km box scoring (scores above each plot are forecast accuracy scores per Figures 2-2 and 2-3). Green are regions of VIL ≥ VIP level 3 equivalent reflectivity that were correctly forecast; reds are false alarms and blues are misses. The vast majority of the 30 minute forecast accuracy scores are above 50% (see Figures 2-4 and 2-5).

60 Minute Binary Forecast Verification


30%

Cellular — Cluster — Line

50%

Cellular — Cluster — Line

70%

Cellular — Cluster — Line

Figure A-11. Examples of 60 minute CIWS forecast verification with 1 km box scoring (scores above each plot are forecast accuracy scores per Figures 2-2 and 2-3). The vast majority of the 60 minute forecast accuracy scores are between 30% and 60% (see Figures 2-4 and 2-5).

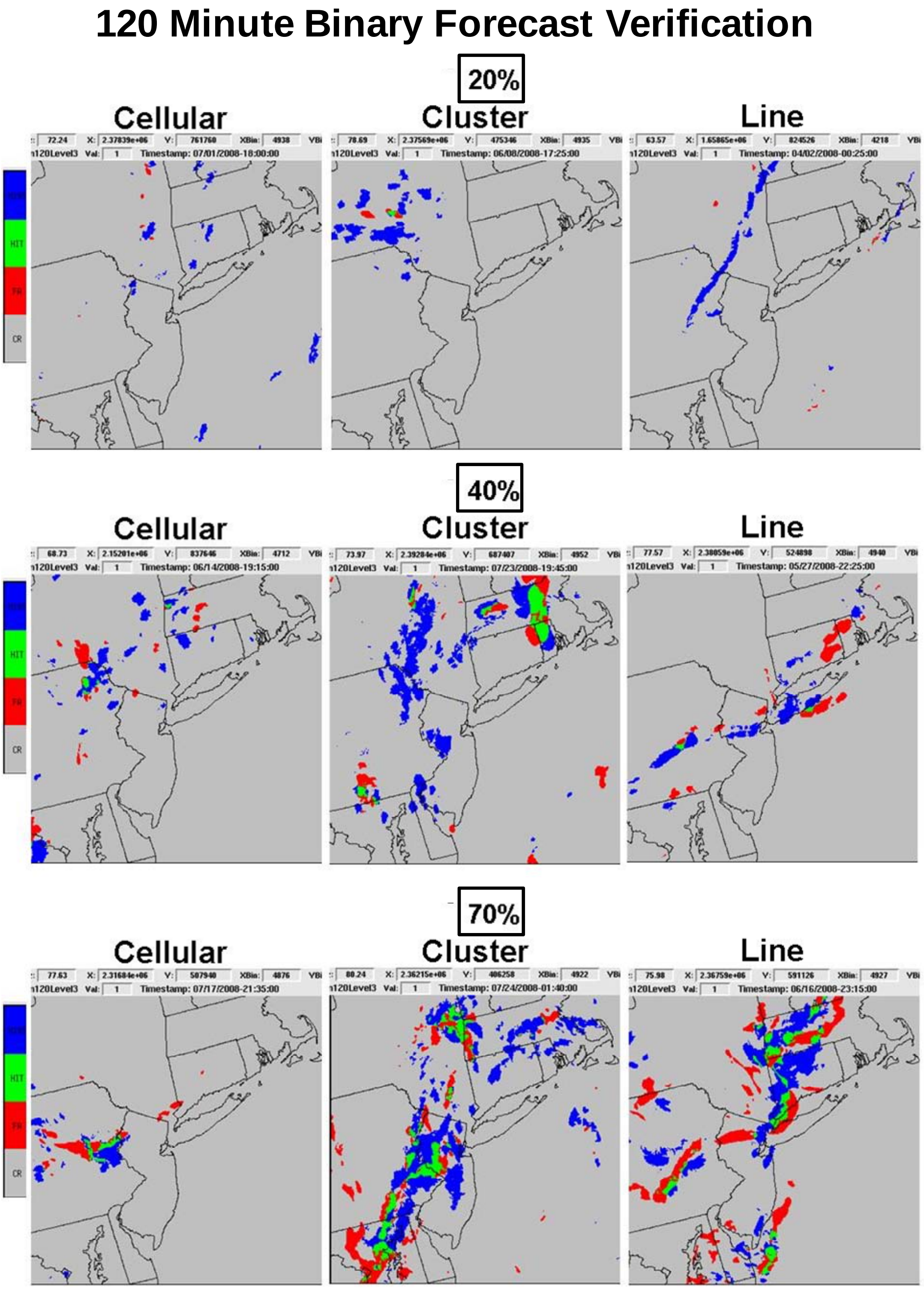
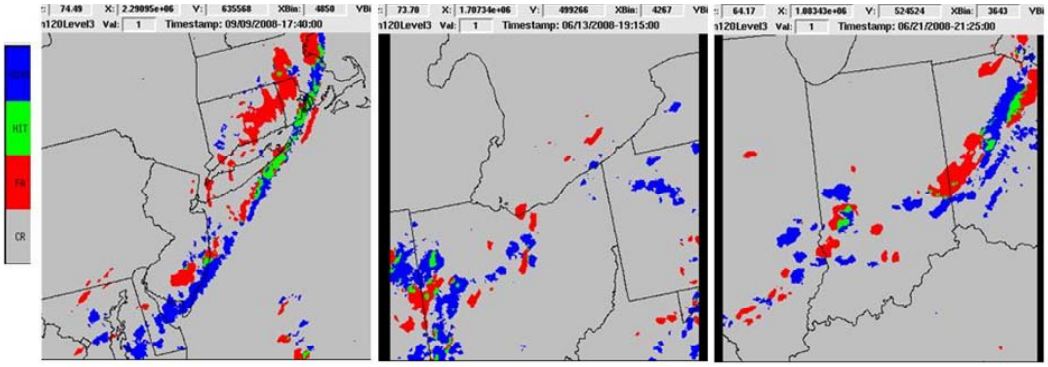


Figure A-12. Examples of 120 minute CIWS forecast verification with 1 km box scoring (scores above each plot are forecast accuracy scores per Figures 2-2 and 2-3).

120 Minute Binary Forecast Verification

Squall line

60%



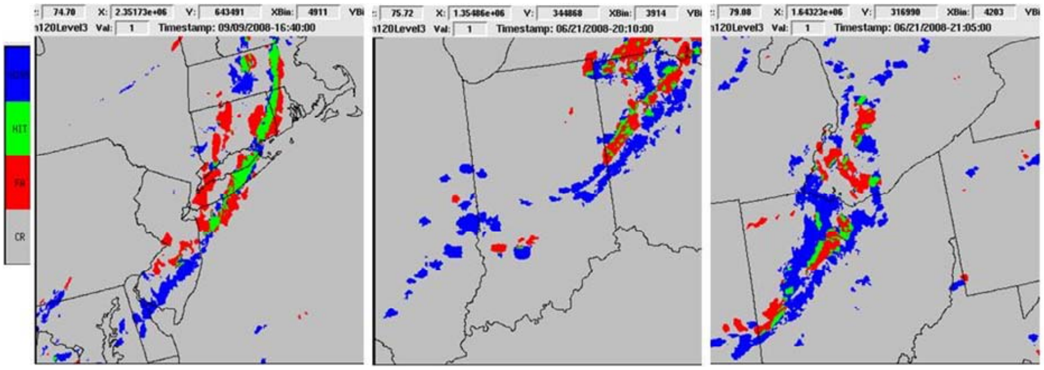
74.49 X: 2.29095e+06 Y: 635568 XBin: 4850 YBi
n120Level3 Val: 1 Timestamp: 09/09/2008-17:40:00

73.70 X: 1.70734e+06 Y: 499266 XBin: 4267 YBi
n120Level3 Val: 1 Timestamp: 06/13/2008-19:15:00

64.17 X: 1.08343e+06 Y: 524524 XBin: 3643 YBi
n120Level3 Val: 1 Timestamp: 06/21/2008-21:25:00

Squall line

70%



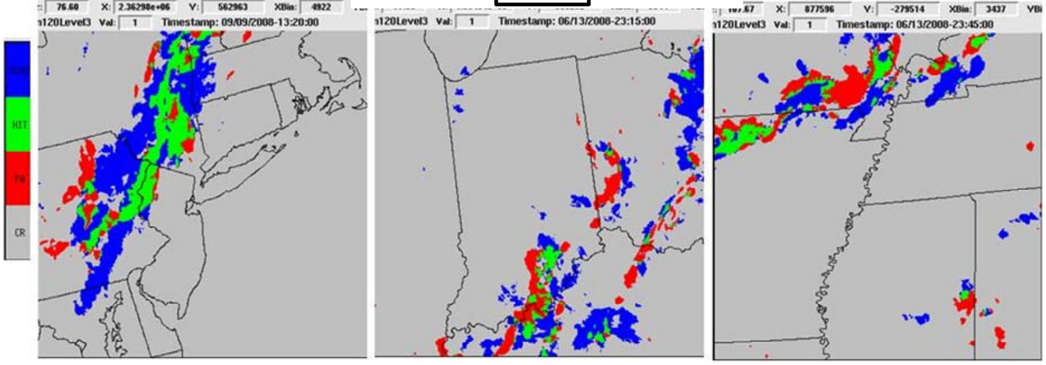
74.70 X: 2.35173e+06 Y: 643491 XBin: 4911 YBi
n120Level3 Val: 1 Timestamp: 09/09/2008-16:40:00

75.72 X: 1.35486e+06 Y: 344868 XBin: 3914 YBi
n120Level3 Val: 1 Timestamp: 06/21/2008-20:10:00

79.08 X: 1.64323e+06 Y: 316990 XBin: 4203 YBi
n120Level3 Val: 1 Timestamp: 06/21/2008-21:05:00

Squall line

80%



76.60 X: 2.36298e+06 Y: 562963 XBin: 4922
n120Level3 Val: 1 Timestamp: 09/09/2008-13:20:00

n120Level3 Val: 1 Timestamp: 06/13/2008-23:15:00

X: 877596 Y: -279514 XBin: 3437 YBi
n120Level3 Val: 1 Timestamp: 06/13/2008-23:45:00

Figure A-13. Additional examples of 120 minute CIWS forecast verification with 1 km box scoring (scores above each plot are forecast accuracy scores per Figures 2-2 and 2-3).