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THE MEMPHIS ITWS CONVECTIVE FORECASTING COLLABORATIVE DEMONSTRATION*

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1. INTRODUCTION

Accurate, short-term forecasts of where thunderstorms will develop, move and decay allow for strategic traffic management in and around the aviation terminal and enroute airspace. Pre-planning to avoid adverse weather conditions provides safe, smooth and continuous air traffic flow and savings in both fuel cost and time. Wolfson, *et. al* (1997) describe the problem of convective weather forecasting for FAA applications.

In 1995, National Center for Atmospheric Research (NCAR), MIT Lincoln Laboratory (MIT-LL) and National Severe Storms Laboratory (NSSL) scientists and engineers agreed to collaborate on the development of a convective weather forecasting algorithm for use in airport terminal areas. Each laboratory brings special strengths to the project. NCAR has been developing techniques for precise, short-term (0-60 minutes) forecasts of thunderstorm initiation, movement and dissipation for the FAA over the past ten years and has developed the Auto-Nowcaster software. MIT-LL has been developing real-time algorithms for the Integrated Terminal Weather System (ITWS), including techniques for storm tracking, gust front detection, and calculating storm growth and decay (as part of predicting microbursts). NSSL has been working on the NEXRAD Storm Cell Identification and Tracking (SCIT) algorithm, and on understanding the predictive value of the storm cell information. Thus by using the latest research results and best techniques available at each laboratory, the collaborative effort will hopefully result in a superior convective weather forecasting algorithm. Our goal in the immediate future is to develop a joint algorithm that can be demonstrated to users of terminal weather information, so that the benefits of convective weather forecast information can be realized, and the remaining needs can be assessed.

As a first effort in the collaboration, the laboratories fielded their individual algorithms at the Memphis ITWS site. This paper gives an overview of our collaborative experiment in Memphis, the system each laboratory operated, some preliminary analysis of our performance on one case, and our plans for the near future.

2. THE MEMPHIS DEMONSTRATION

We selected Memphis as our preliminary test location because of the variety of summertime weather patterns, the computing and data infrastructure available through the MIT-LL prototype ITWS program (Evans and Ducot, 1994)., the expertise of the personnel there, and because we felt Memphis would be an appropriate airport for an eventual live demonstration of a prototype convective weather forecasting algorithm. A map of the Memphis TRACON showing radar and airport locations is provided in Figure 1

Our team received FAA go-ahead for the Memphis project quite late in 1996 (29 April). Thanks to tremendous effort on the part of the three laboratories, we had everything operating in Memphis by 1 July. The joint system, shown in Figure 2, operated every day that convective weather was near the Memphis airport. The demonstration

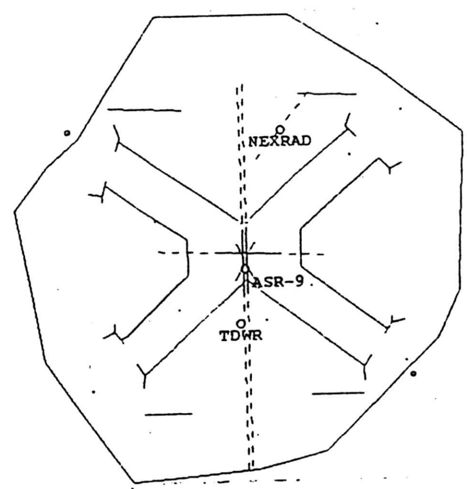

Figure 1. Outer boundary of Memphis TRACON, with airport runways (center), primary approach corridors (diagonal pathways), and the three weather radars. NEXRAD and TDWR are pencil beam Doppler radars with volumetric scans (6 min and 5 min update rates, respectively); ASR-9 is a fan beam radar with a 30 s update rate for the weather channel.

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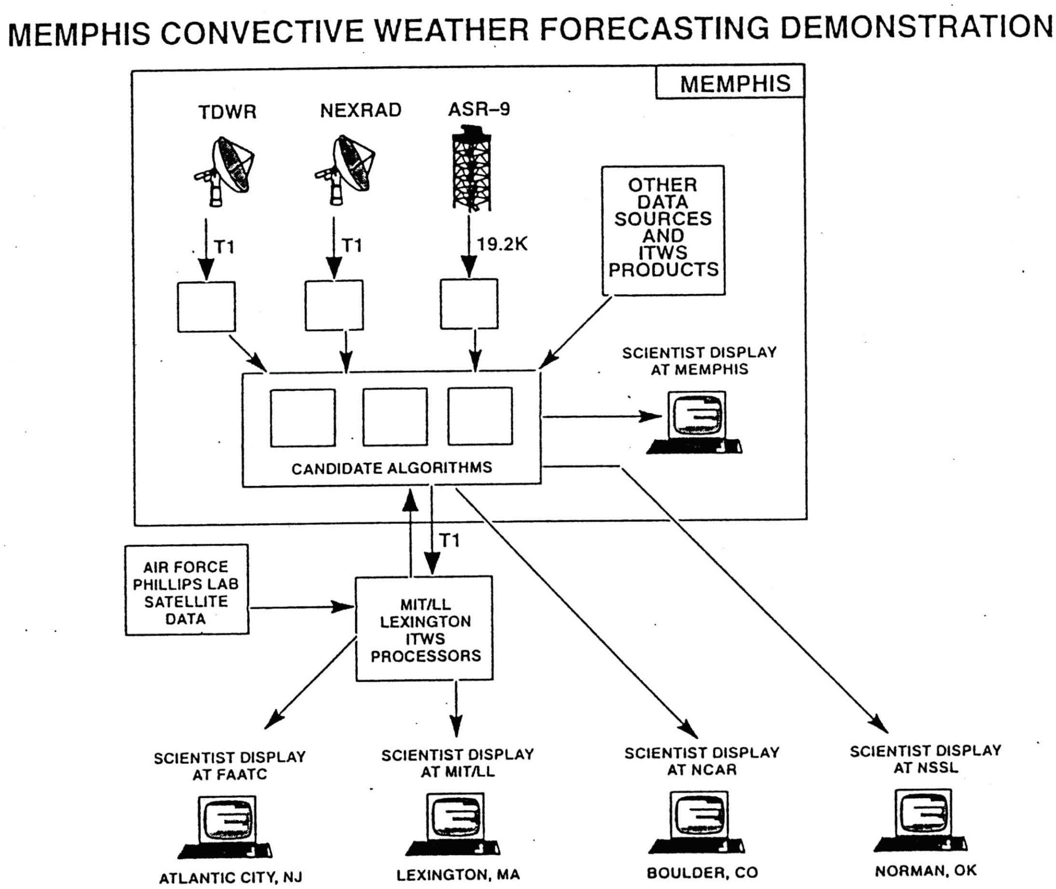

Figure 2. Schematic illustrating the Memphis collaborative convective forecast program. The "Candidate algorithms" represent the various algorithms fielded by the individual laboratories. Scientific displays were available at the FAATC, MIT/LL, NCAR, and NSSL.

was officially concluded on 30 September. (The system has been left in place so that we can exercise it over the winter, stage new versions of the software, and be ready for the springtime convection season.) The experimental convective weather forecast processes were placed on a separate network that communicated with the ITWS real-time network through only one relay, so there was no possibility of our experimentation impacting the provision of live data to users of the Memphis ITWS.

Since GOES-8 satellite data has not been part of the ITWS to date, we needed to acquire a real-time feed for our demonstration. The Air Force Phillips Laboratory (PL) on Hanscom Air Force Base has cooperated with a small company to operate a ground station, and downlink GOES-8 data directly. We installed fiber-optic cable between PL and MIT LL (also located on Hanscom AFB), provided a more capable workstation to PL to handle the extra load, and now receive the satellite data routinely at very little incremental cost.

Scientists at each laboratory could connect to the Memphis site through dedicated lines, and each lab had an analyst's display at their end for viewing the data. The FAA Technical Center also had an analyst's display so they could become more familiar with our technology in preparation for their role in future live demonstrations. NCAR provided their Cartesian Interactive Data Display (CIDD) to serve as the analyst's display, and we all found CIDD to be an excellent tool for algorithm analysis and refinement.

3. SYSTEMS FIELDED BY EACH LAB

A brief description of the systems each lab fielded in Memphis is given below.

3.1 NCAR Auto-nowcaster

Techniques for thunderstorm nowcasting have been proven in several field experiments, by allowing scientists to make forecast decisions in real time and then scoring the results (Wilson and Mueller 1993). Recent efforts have focused on automating these techniques. The Auto-nowcaster provides detailed forecasts of thunderstorm initiation, growth, movement and dissipation. This is done by applying forecast rules to various fields of data. These rules are based primarily on results from Wilson and Mueller (1993), Henry (1993), and Wilson and Megenhardt (1997). A detailed discussion about the actual Auto-nowcaster algorithm is given by Gould et al. (1993).

There are several processes that, when run together, make up the Auto-nowcaster (Figure 2). The processes fielded in Memphis are;

TITAN: a centroid storm tracker that works on 2 or 3-dimensional reflectivity data, handles cell merging and splitting, calculates storm trends (e.g., volume, mass, etc.), and makes predictions of storms based on the track and trends (Dixon and Wiener, 1993),

TREC: a method for determining the horizontal winds in clear air, using correlation tracking of radar signals (Tuttle and Foote, 1990),

MIGFA: the Machine Intelligent Gust Front Algorithm, developed at MIT LL, that uses a data level machine intelligence approach to combining evidence of gust fronts (Delanoy and Troxel, 1993),

COLIDE: an algorithm for detecting and extrapolating stationary boundary layer convergence lines,

Auto-nowcaster: the engine that combines outputs from the various algorithms using a rule based expert system (Gould et al. 1993) to produce a time and space specific thunderstorm forecast.

The Auto-nowcaster uses data from a single Doppler radar, satellite, surface mesonet stations and soundings to calculate its forecasts. Based on these input data, convergence line detections and extrapolations; information on existing storms (detections, extrapolations and characteristics); cumulus cloud detections and extrapolations; radar derived wind fields; stability fields; and model predicted convergence line characteristics are automatically generated (and also included in the database). So far data has been collected from Denver, Atlanta and Memphis.

3.2 MIT LL Growth & Decay Algorithm

Much of the work applicable to the thunderstorm forecasting problem that has taken place at MIT Lincoln Laboratory over the last five years has been in understanding the problem thunderstorms pose in the airspace system, estimating the benefits to users of forecast information, and developing techniques for ITWS, including correlation tracking of radar echoes, gust front identification, and direct detection of storm growth and decay for predicting microbursts. Many years' worth of multiple-sensor data from each of the ITWS prototype sites have been archived, and are available for new algorithm development. GOES-8 satellite data has only been archived since April, 1996, since it is not included in the IOC ITWS suite of sensors.

Figure 3 shows a block diagram of the Growth & Decay algorithm fielded by MIT LL in Memphis. The algorithm uses data from all three radars (NEXRAD, TDWR and ASR-9) for optimal performance and for reliability. For example, in producing a "Base Precipitation" map, the cone-of-silence over one radar is filled in with data from another. In the operational environment, it is often preferable that an algorithm continue to perform if a single data source is lost, even at somewhat degraded levels of performance, rather than simply shutting off. This increases reliability and user-confidence in the product.

The algorithm is completely pixel-based; no cell identification or cell-based trending takes place. Feature detectors operate on the raw data looking for physical signals indicative of growth and decay. Techniques used for calculating growth and decay are similar to those described by Wolfson, *et al.*, (1994), used in predicting microbursts. Both the advected Base Precipitation field from the current time, as well as the Previous Forecast (e.g., the 12-min forecast if computing the 18-min forecast) are used in each n-minute forecast (Figure 3, top). The Level-3 Probability uses statistical estimates of the probability a level 3 echo will exist in a given pixel at the forecast time based on past precip values and trends for that pixel. Gust front forcing is determined spatially by where a detected gust front has been (history) and where it is projected to be in the future. Bands of interest of different weight are applied to each interval of time ahead and behind the gust front, depending on how likely level 3 precip is to develop in that location. The combined interest images from the various feature detectors are weighted to make up the final forecast. The scoring functions at each forecast time interval, and the weights for combining the feature detectors, will be optimized using statistical methods.

MIGFA performance

Correctly detecting and extrapolating boundary layer convergence lines is critical to estimating future storm growth. The ITWS Machine Intelligent Gust Front Algorithm (MIGFA) was adjusted by MIT LL based on input from NCAR scientists, to detect weaker boundaries that were perhaps insignificant as operational wind shear haz-

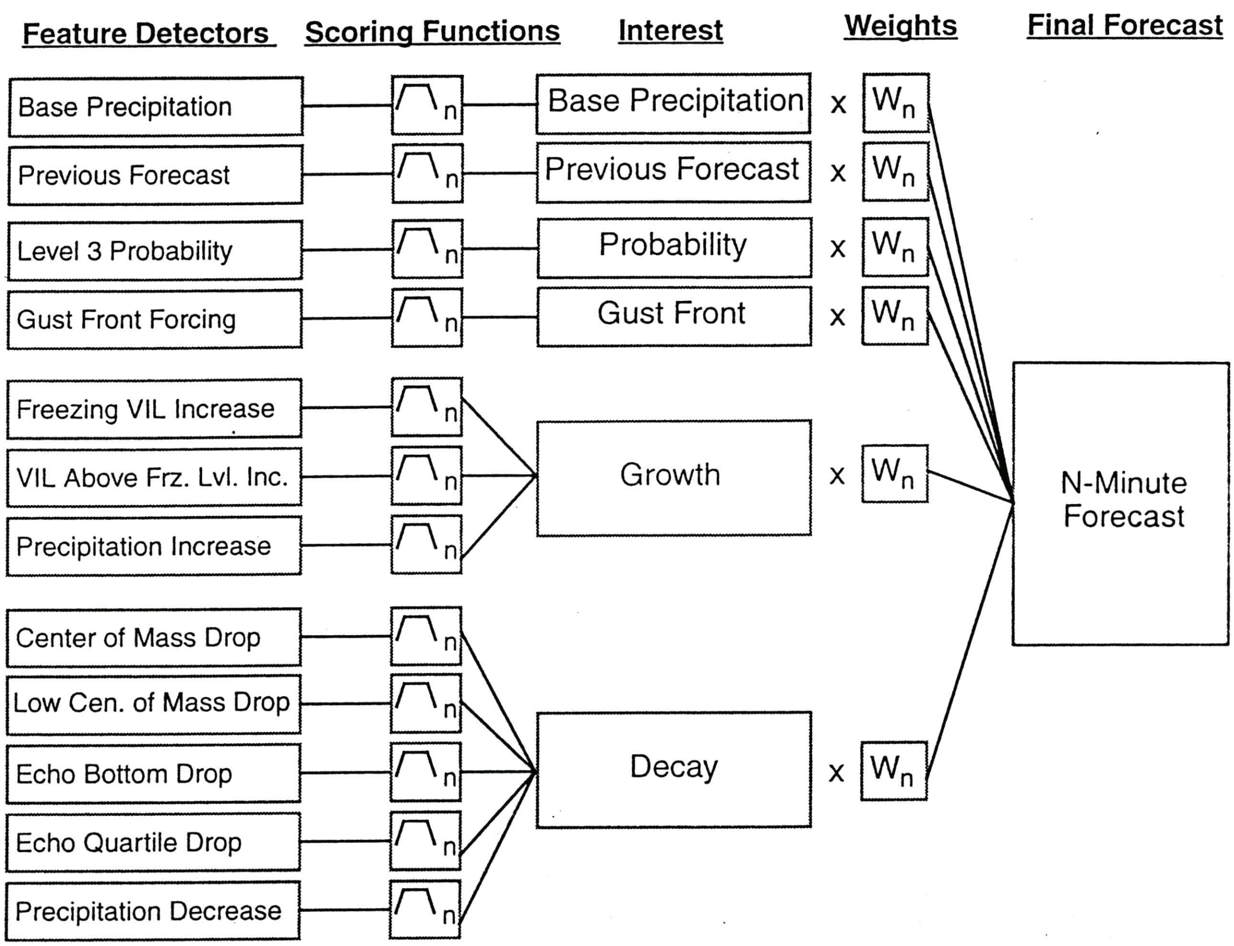

Figure 3. Block diagram of the Growth & Decay algorithm tested by MIT LL in Memphis in 1996. Feature detectors operate on the raw data to produce grids of "evidence", individual scoring functions are applied to the evidence for each "n-minute" forecast (subscript n), and the resulting interest images are optimally weighted to produce the best n-minute forecast.

ards but which, nevertheless, provided enhanced boundary layer forcing for clouds growing in their vicinity. We call this the "sensitized" version of the algorithm. Since both the TDWR and NEXRAD radar data is suitable as input to MIGFA, a study was undertaken to determine which radar provided better MIGFA results. Analysis of five cases from Memphis indicates that TDWR-MIGFA has a much higher PLD and lower PFA than the NEXRAD-MIGFA version. (NEXRAD's poor performance was largely due to clutter/AP contamination.

The decision to use TDWR would appear clear-cut, at least until individual cases are examined. Figure 4 shows the MIGFA detections at 2235 UTC on 7/26/96 in Memphis (case discussed in following section), when TDWR was experiencing bad second-trip contamination. This often happens, because the TDWR PRF is automatically selected each scan to minimize the second trip directly over the airport. Only the northwestern gust front is detected by both TDWR and NEXRAD, and they estimate quite different propagation speeds for it. All other gust fronts are detected by either one or the other radar. Our conclusion is that an ITWS Storm Growth & Decay algorithm will perform best if the sensitized MIGFA is run on data from both radars, and the results combined.

3.3 NSSL NEXRAD SCIT Algorithm

NSSL has developed a set of convective weather hazard detection algorithms [called the Severe Storm Analysis Package (SSAP)], that includes the Storm Cell Identification and Tracking (SCIT) algorithm, Mesocyclone, Tornado, and Hail Detection Algorithms, and the Damaging Downburst Prediction and Detection Algorithm (Eilts, *et al.*, 1996). The SSAP analyzes the velocity and reflectivity fields to determine the 4-dimensional structure of thunderstorms. Some examples of parameters that are diagnosed are time trends of:

a) the height of maximum reflectivity,

b) the strength of circulation,

c) the probability of severe hail, and

d) the VIL.

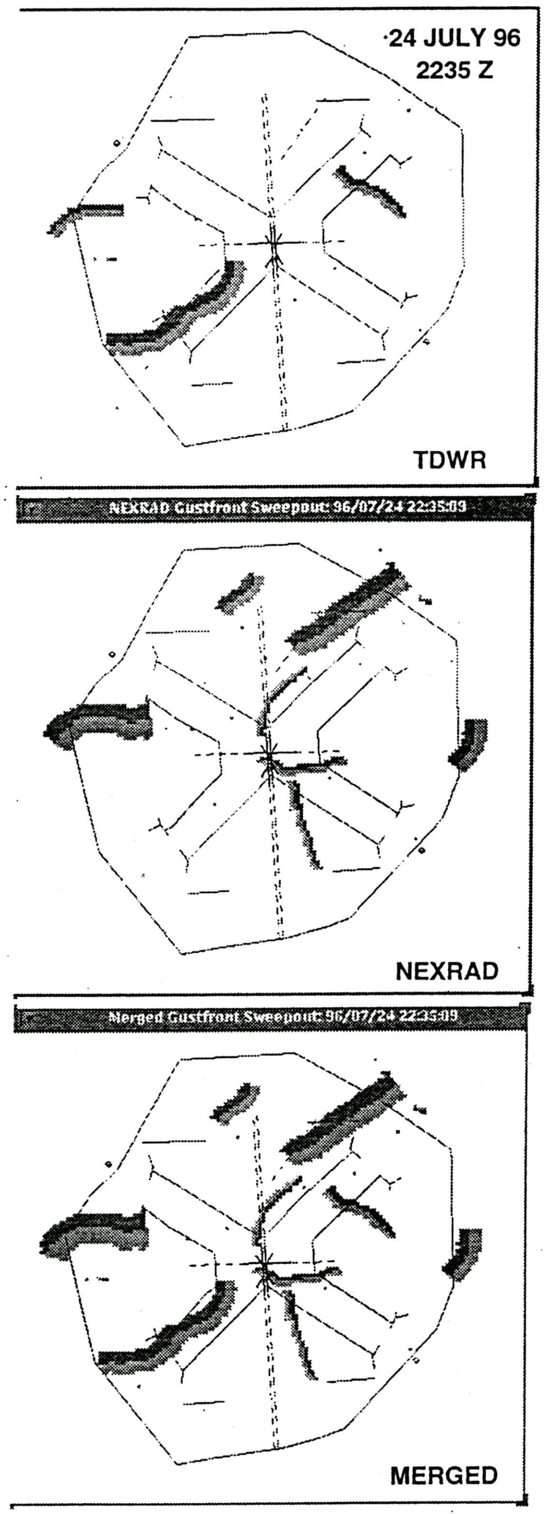

Figure 4. Gust fronts as detected by sensitized MIGFA at 2235 UTC on 24 July 96 in Memphis. The top figure shows fronts detected by TDWR, the middle by NEXRAD, and the bottom, the result of merging the two. The dark band for each gust front shows the current location projected out 5 min, and the light band, the position projected 5-10 min.

These parameters are used to provide forecasters insight into cell evolution, and as input into rule bases, neural networks, and empirical techniques to estimate the severity or longevity of a given thunderstorm (Marzban and Stumpf, 1996)

As part of the analysis of data from the Memphis demonstration, we are examining output from the SSAP to determine which parameters that we diagnose are related to storm lifetime. For example, one hypothesis is that if a significant circulation is associated with a storm cell, that cell is more likely to be long-lived than other similar storms in a similar environment. The same could be true for storms that produce large hail, or that have certain reflectivity or velocity signatures. We are examining numerous parameters from the algorithms to determine which ones have a strong correlation to the life cycle of a given thunderstorms.

4. PERFORMANCE ON 24 JULY 1996

A Memphis case from 24 July 1996 has been selected for preliminary assessment of the forecast algorithm capabilities. The thunderstorm activity on this day was intense with slow-moving thunderstorms impacting the TRACON region for over an hour. Crowe, *et al.* (1997) present an analysis of the impact this weather event had on Memphis air traffic. There was good storm development in association with convergence boundaries located southwest, southeast and northeast of the airport. Gust fronts from these systems collided over the airport, causing strong vertical development and convection initiation in the TRACON. We chose the time period that encompass the strongest development on the airport (2200 to 2330; all times are in UTC) for analysis. We first illustrate the Auto-nowcaster capabilities by examining different feature detectors at a single forecast time (2230). We then assess the performance of the Auto-nowcaster and Growth & Decay algorithms for the full 1.5 hr interval.

4.1 Auto-nowcaster Performance at 2230

An interest field of the lifting areas, which are based on the 30 minute automatic boundary extrapolation locations, is shown in Figure 5a. The light grey areas correspond with the highest interest values and represent areas of strong surface convergence (based on it's proximity to the extrapolated convergence lines). The black polygons in these figures represent the automated 30 minute forecasts.

The light grey areas in Figure 5b are areas of radar-detected cumulus congestus and towering cumulus clouds. For this example, these clouds are defined as radar echoes ranging from 20 to 40 dBZ and located between 3 and 6 km above msl.

Thirty minute extrapolations (based on past trends of size and location) for small (e.g. volumes < 400 km^3) and large (e.g. volume ≥ 400 km^3) thunderstorms are shown in Figure 5c and d, respectively.

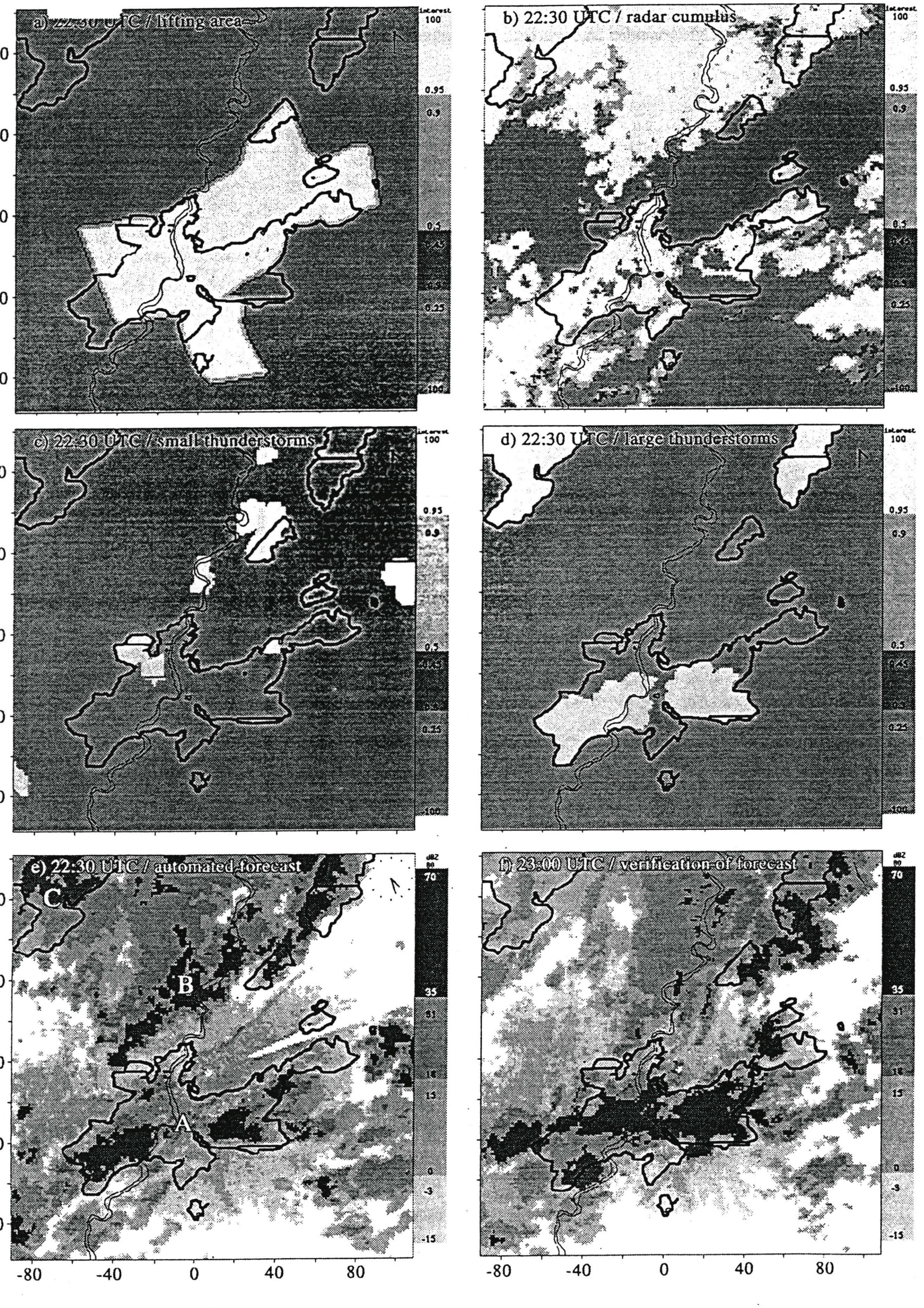

Figure 5. An illustration of Auto-nowcast capabilities based on a Memphis, TN case from 24 July 1996 at 2230. The Auto-nowcaster fields used to generate the forecasts are shown in a-d. Surface reflectivity fields at forecast issue (2230) and verification (2300) times, along with the Auto-nowcaster forecast, are shown in e and f, respectively.

The automated forecasts in this example were generated by combining the fields in Figure 5a-d, using relatively simple forecast rules applied at each 1 km grid point. Based on these rules, a forecast was issued for any area expecting large storms (light grey area in Figure 5d). The small storms (light grey area in Figure 5c) were forecast to dissipate unless they were located near areas of surface convergence. In other words, forecasts were generated only for areas where the light grey areas in Figure 5a and c overlap. Thunderstorm initiation and growth was predicted for areas where cumulus congestus and towering cumulus were co-located with the surface convergence (e.g. light grey regions in Figure 5a and b) overlap.

Surface reflectivity fields at forecast issue (2230) and verification (2300) times, along with the Auto-nowcaster forecast (black polygons), are shown in Figure 5e and f, respectively. Three main areas of interest (labeled A, B and C in Figure 5e) are observed in these figures. Region A shows strong growth and little movement during this 30 minute time period. The Auto-nowcaster does a good job of forecasting the new storm growth, represented by the amount of thunderstorms (e.g. reflectivity echoes ≥ 35 dBZ or the darker shaded areas) located within the forecast area. Part of the new growth was predicted by the storm extrapolation algorithm (refer to Figure 5d) but the Auto-nowcaster increased that area because cumulus clouds and small thunderstorms were located near boundaries indicating a strong possibility for additional growth and/or storm initiation.

A southwest to northeast line of thunderstorms was observed at the forecast issue time (region B). The southwestern part of the line dissipated, and the northeastern part grew by the valid time. The Auto-nowcaster does a good job of dissipating the southwestern part of the line by dissipating the small thunderstorms that are extrapolated into a region where there is no surface convergence. The northeastern part of the line is not forecast as well because the storm extrapolation algorithm does not reflect the strong growth in this area and the Auto-nowcaster does not forecast the growth because the automated boundary detection algorithm did not detect convergence lines in this area.

Region C shows an area of stratiform precipitation that was identified by the storm extrapolation algorithm as a large thunderstorm. Because this area was identified as a large thunderstorm it was not eliminated by the Auto-nowcaster. Work is currently being done to develop rules that will better eliminate these stratiform regions.

4.2 Statistical verification

A statistical evaluation is currently underway to assess the performance of the algorithms (Auto-nowcaster and Growth & Decay routines) and determine which forecast techniques are the most significant. Forecasts from Memphis datasets are being created at 6, 12, 18, 24 and 30 minute intervals. We currently plan to use two different data fields as truth: 1) areas of level 3 precip as depicted by the ASR-9 radar (for FAA applications, given pilots regularly deviate around level 3 weather), and 2) reflectivity ≥ 35 dBZ at 1 km above ground level as depicted by the NEXRAD radar (primarily useful for verifying quantitative precipitation forecasts). The preliminary evaluation presented below is based on the following forecast experiments:

Persistence:	No change from conditions at forecast time.
Extrapolation:	Extrapolate storm location using past motion. This is equivalent to the SEP algorithm used in ITWS (Chornoboy, et al., 1994; although results may vary if different trackers are used).
Auto-nowcaster Rules:	All rules were used, but no numerical model results were incorporated.
Growth & Decay:	Radar growth and decay feature detectors, plus probability trending. No gust front forcing was used.

Figure 6 shows statistics for persistence (solid curve), storm extrapolation (dotted curve), and the Growth & Decay feature detectors (dashed curve) from 2200 to 2330 on 24 July 1996. "Truth" is the area of level 3 in the Base Precipitation map. The average POD and PFA values for the 90 min period are shown for the 6, 12, 18, and 24 min forecasts. The forecast PODs are significantly better than either persistence or extrapolation, and the PFAs are no worse. Thus, the addition of growth and decay alone represents a valuable improvement over ITWS SEP.

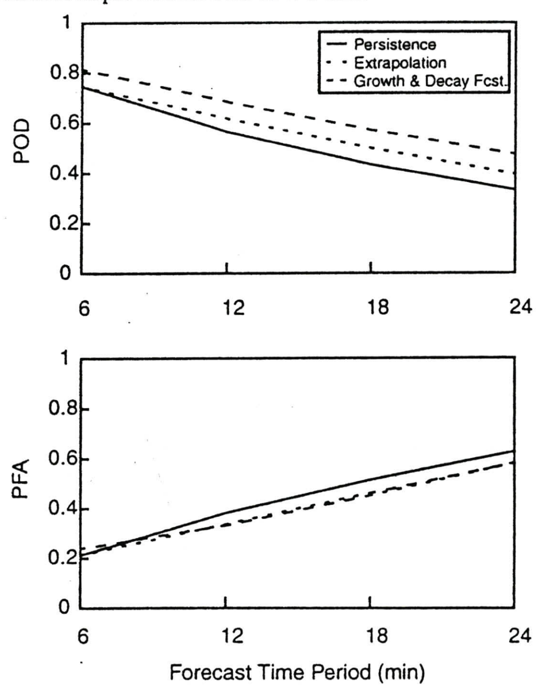

Figure 6. Average POD and PFA statistics for persistence (solid curve), storm extrapolation (dotted curve), and 6, 12, 18, and 24 min Growth & Decay forecasts (dashed curve) from 2200 to 2330.

Figure 7 shows different statistics for persistence (solid curve), storm extrapolation (dotted curve), and the 30-min auto-nowcast (dashed curve), for the forecast period 2200-2330. "Truth" is the area ≥ 35 dBZ at 1 km AGL. The POD and PFA values are shown at the verification times, 30 min later. The results for this case show that, while the POD values for the Auto-nowcast rules are better than persistence and extrapolation with trending, the PFA values are slightly worse. One of the major goals in the near future is to reduce the PFA for the Auto-nowcast rules.

In all statistics reported, the comparison with truth was done on a pixel-by-pixel (binary) basis. This produces statistics which are easy to understand and compare, but it does not produce numbers that are related to the *value* of the forecast for air traffic purposes. For example, if we look at a pixel map of the binary score for a forecast cell, and use colors to indicate "hits" (correct forecast), "misses" (failure to forecast), and "false alarms" (incorrect forecast), we can see that most misses and false alarms surround the region of hits (Figure 8). This could be due to an insignificant error in the storm motion estimate, perhaps due to quantization.

To arrive at a score that better matches the utility of the forecast to aviation, MIT LL derived a "fuzzy scoring" methodology that looks in a kernel (e.g., 3x3 - a pixel and its 8 nearest neighbors, or 5x5 - a pixel and its 24 nearest neighbors) for hits, misses, or false alarms. We can ask that one, two, three, or more pixels in the kernel be present to give credit to the central pixel. To illustrate the effect this has on the scores, we have tabulated the Growth & Decay statistics below for the binary scoring method, and a 5x5 kernel where 1 pixel overlap is required. The "fuzzy" scores better match one's subjective impression of the forecast

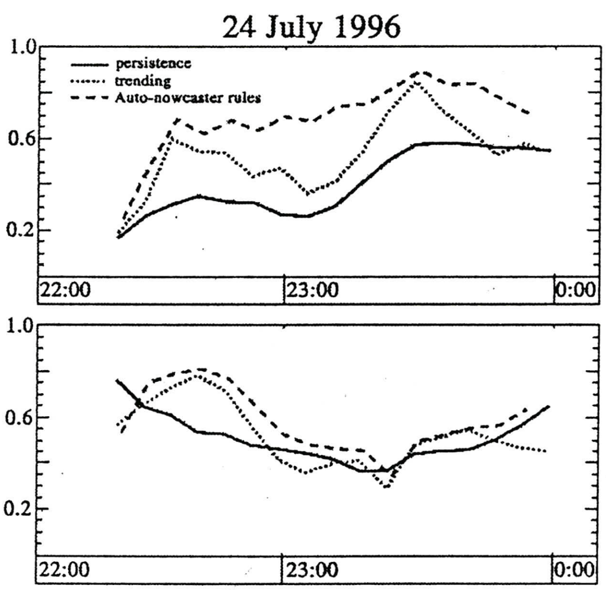

Figure 7. Statistics for persistence (solid curve), storm extrapolation (dotted curve), and the Auto-nowcaster 30-min forecasts (dashed curve) from 2200 to 2330. The statistics are plotted at the verification time, 30 min later.

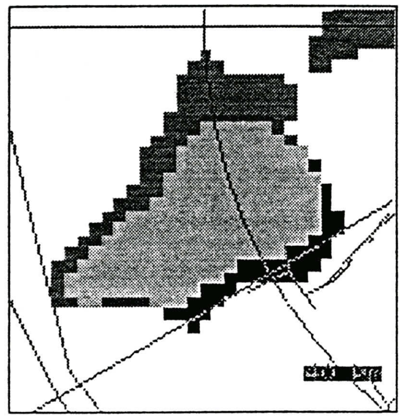

Figure 8. Forecast cell score, with light grey indicating hits, black - misses, and dark grey - false alarms.

when images such as that in Figure 8 are viewed. Whenever the POD rises sharply, and the PFA falls sharply, between the binary and fuzzy scoring methods as it does here, it is an indication that the errors fall in a thin margin around the correctly forecast pixels.

Table 1: Binary vs. fuzzy scoring results for MIT LL Growth & Decay algorithm.

FORECAST LEAD TIME	BIN POD	BIN PFA	FUZ POD	FUZ PFA
6 min	81	24	96	5
12 min	68	33	87	13
18 min	57	45	77	24
24 min	48	58	68	38

5. FUTURE WORK

We have selected an initial 5 Memphis cases for joint analysis, out of a possible 20 or so candidates. Our goal is to select cases that 1) represent a spectrum of convective weather types, 2) have complete data from all pertinent sensors, 3) impacted the Memphis airport and/or air traffic operations, and 4) were poorly forecast by the ITWS Storm Extrapolated Position (SEP) algorithm. We adopted the latter criteria to test our skill on cases where current methodologies fail, and where the need for, and benefit from, an algorithm that incorporates storm growth and decay is greatest.

The forecasts generated by the algorithms shown here are only as good as the rules and data ingested into them. We believe increased accuracy is required before we demonstrate a Convective Weather Forecast product to aviation users. Because the Auto-nowcaster and the Growth & Decay systems are modular in design, enhancements to various algorithms that create interest fields can be made in an efficient manner and then combined into the final forecast to increase the forecast accuracy. Our current list of research and algorithm development topics includes: 1) cloud classification and growth, 2) dynamics of boundary-layer convergence lines, 3) improved use of thunderstorm extrapolations and characteristics, 4) statistical optimization of the feature detectors and corresponding weights used to compute a combined forecast field, and 5) statistical verification of the forecasts themselves.

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7. ACRONYM LIST

CIDD	Cartesian Interactive Data Display
COLIDE	COnvergence LIne DEtection
ITWS	Integrated Terminal Weather System
LL	Lincoln Laboratory
MIT	Massachusetts Institute of Technology
NCAR	National Center for Atmospheric Research
NSSL	National Severe Storms Laboratory
PL	Air Force Philip's Laboratory
PRF	Pulse Repetition Frequency
SCIT	Storm Cell Identification and Tracking
SEP	Storm Extrapolated Position
SSAP	Severe Storms Analysis Package
TDWR	Terminal Doppler Weather Radar
TITAN	Thunderstorm Identification, Tracking, Analysis, and Nowcasting
TREC	Tracking Radar Echo by Correlation

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