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5.12 FAA TERMINAL CONVECTIVE WEATHER FORECAST ALGORITHM ASSESSMENT *

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1. INTRODUCTION

Air traffic delay due to convective weather reached historically high levels in 1999, as passengers blamed airlines and airlines blamed the FAA for the massive inconveniences. While coordination between the FAA's System Command Center and the regional centers and terminals can be expected to improve with the FAA's new initiatives, it is clear that air traffic management and planning during convective weather will ultimately require accurate convective weather forecasts. In addition to improving system capacity and reducing delay, convective forecasts can help provide safer flight routes as well. The crash of a commercial airliner at Little Rock, AR in June 1999 after a one-hour flight from Dallas/Ft. Worth illustrates the dangers and potential tactical advantage that could be gained with frequently updated one-hour forecasts of convective storms.

The Terminal Convective Weather Forecast (TCWF) product has been developed by MIT Lincoln Laboratory as part of the FAA Aviation Weather Research Convective Weather Product Development Team (PDT). Lincoln began by consulting with air traffic personnel and commercial airline dispatchers to determine the needs of aviation users (Forman, et. al., 1999). Users indicated that convective weather, particularly line storms, caused the most consistent problems for managing air traffic. The "Growth and Decay Storm Tracker" developed by Wolfson et al. (1999) allows the generation of up to 1-hour forecasts of large scale, organized precipitation features with operationally useful accuracy. This patented technology represents a breakthrough in short-term forecasting capability, providing quantitative *envelope* tracking as opposed to the usual cell tracking. This tracking technology is now being utilized in NCAR's AutoNowcaster (Mueller, et al., 2000), the National Convective Weather Forecast running at the Aviation Weather Center (Megenhardt, et al., 2000) and by private sector meteorological data vendors.

The TCWF has been tested in Dallas/Ft. Worth (DFW) since 1998, in Orlando (MCO) since 1999, and in New York (NYC) since fiscal year 2000 began. These have been informal demonstrations, with the FAA William J. Hughes Technical Center (WJHTC) assessing utility to the users, and with MIT LL modifying the system based on user feedback and performance analyses. TCWF has undergone major revisions, and the latest build has now been deployed at all sites. The TCWF is now in a formal assessment phase at the Memphis International Airport as a prerequisite to an FAA operational requirement. The FAA Technical Center will make a recommendation on whether TCWF is suitable for inclusion in the FAA's operational Integrated Terminal Weather System (ITWS), which has an unmet requirement for 30+ minute forecasts of convective weather. Memphis was selected for the TCWF Assessment since it has not been exposed to the forecast product during prior demonstrations. Operations began on March 24, 2000 and operational feedback is being assessed by the FAA Technical Center (McGettigan, et al., 2000) and MCR Corporation is performing a quantitative benefits assessment (Sunderlin and Paull, 2000).

This paper details the refined TCWF algorithm and display concept, gives examples of the operational impact of terminal forecasts, and analyzes the technical performance of the TCWF during the early stages of the Memphis Assessment.

2. ALGORITHM BACKGROUND

The initial design of the TCWF algorithm and display were both governed by user interviews conducted in DFW and MEM before initial demonstrations began. The product provides animated loops of 10-minute incremental forecasts out to 1 hour, using a 2 level probability map showing regions of moderate and high probabilities of level 3 and greater weather. Typically, pilots try to avoid level 3 and greater weather since it is the most threatening to aviation. Unique features of the TCWF display include animation of the real-time forecast, window manipulation, real-time forecast accuracy scoring, and forecast updates every 5-6 minutes (update time of the NEXRAD). Detailed analysis of the demonstrations (Hallowell, et al., 1999) as well as user feedback from DFW, MCO, NYC, and the airlines revealed areas for improvement and ultimately led to the TCWF algorithm redesign. These refinements will be discussed in detail in a later section. Table 1 illustrates the ongoing demonstrations.

Table 1: TCWF Ongoing Demonstrations

Year	Location	Prediction Time
1998	Dallas/Ft. Worth	30-60 min
1999	Dallas/ Ft. Worth Orlando New York	30-60 min
2000	Dallas/Ft. Worth Orlando New York *Memphis*	30-60 min *Formal Assessment*

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3. ALGORITHM METHODOLOGY

The TCWF uses NEXRAD wide-band radar data to create two-dimensional Cartesian files of 1-km full resolution Vertically Integrated Liquid (VIL) water using the NEXRAD VIL algorithm. VIL images are then remapped into "interest images" using an equation developed by Lincoln Laboratory (Troxel & Engholm, 1990). This conversion is made to represent the standard VIP levels so either Terminal Doppler Weather Radar (TDWR) or Airport Surveillance Radar–9 (ASR-9) weather channel data could be used in addition to or in place of the NEXRAD.

Wilson (1966) showed that strong, "large-scale" storms are more persistent with time than small-scale storms. Since large-scale features move differently from single cells, images of extracted "large-scale" weather features are then generated using a rectangular spatial filter, effectively a 2-D low-pass filter. This filter is designed to match the larger, more elongated features within the image (i.e., line storms and/or more organized events) while diminishing the smaller scales. A variation of the Fast-Fourier Transform (FFT) methodology suggested by NSSL (Lakshmanan, 2000) was employed to speed up the filtering step (complex FFT vs. real FFT). The ITWS Cross-Correlation Tracker (Chornoboy, et al., 1994) is run on these filtered images to generate pixel-by-pixel motion field estimates at a 1km resolution. (See the Appendix for a full list of Tracker parameters.) This finer resolution is essential to obtain accurate forecasts when slow-moving airmass or small-scale storms predominate, but also improves forecast accuracy on large-scale organized storms. The 1km grid of vectors is used to create two forecast products:

- TRACON (440km x 440km) at 1km resolution
- 200nm (640km x 640km) at 2 km resolution

Real-time 30- and 60-minute forecast accuracy scores are displayed for both the TRACON and the 200nm forecast products.

4. ALGORITHM REFINEMENTS

The current TCWF algorithm includes refinements that proved to be necessary based on the previous site demonstrations. The MCO demonstration was the most instrumental in diagnosing areas for improvement. The Orlando weather regime consists of daily airmass thunderstorms in the summer months, which unfolded both algorithm and display issues that needed to be addressed. The following two major modifications were made:

1. The new 1km resolution was implemented, requiring the FFT method for computational speed. TCWF would often forecast excessive motion for quasi-stationary storms. Studies revealed that the underlying 4km-grid resolution was too coarse. The Growth and Decay Storm Tracker was forced to choose either 0 or 1 pixel motion over the 12-minute correlation interval for the slow moving storms. The choice of 1 pixel (4 km in 12 minutes) led to erroneous rapid motion. Figure 1 illustrates the differences in forecast maps and vectors at 4km and 1km resolutions.
2. Cosmetic improvements were made to the forecasts. The TCWF forecast map shows regions of moderate and high probability of level 3 and greater precipitation up to 1-hour in the future. Clearly, it is not possible to forecast 1km resolution features out to 1-hr with the tracker technology. Without smoothing, a 1km scale graininess remains. The images are now smoothed using a binary dilation plus mean filter combination (Figure 2). This process increases user scores (detailed in later section) by ± 2 or 3 points and increases the bias, defined as the ratio of forecast pixels to truth pixels.

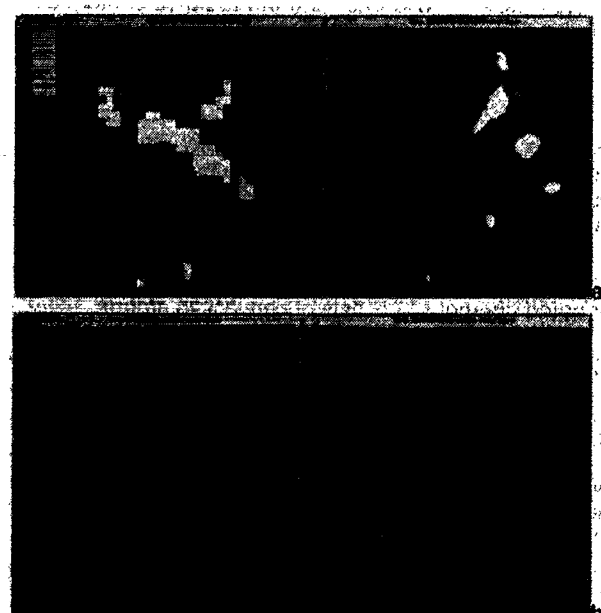

Figure 1. Illustrates the improvements made in MCO on 10 June 99 to TCWF by changing from 4km resolution to 1km resolution. The left hand side is the 4km resolution while the 1km resolution is depicted on the right. (a) Shows the 60-min forecast; light gray showing high probability of ≥ level 3 weather, and moderate probability denoted in the darker gray. (b) These images show the Tracker vector motions. The 1 km resolution avoids the bizarre vector motions shown in the 4 km resolution.

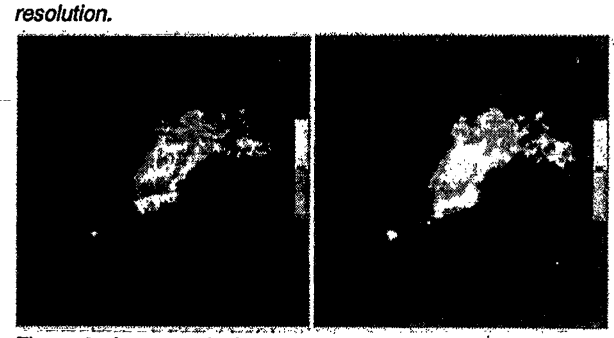

Figure 2. An example from NYC. The image on the left is the forecast prior to any smoothing operations. The forecast on the right shows the cosmetic improvement after smoothing.

5. SCORING

The TCWF provides its own performance evaluation in real time, after waiting 30-mins and 60-mins for "truth." Several components of the scoring system have changed since the algorithm was first deployed. The three main scoring issues are listed below.

1. Initial DFW interviews determined that users desired a forecast that is accurate to within 5nm (10km) and 10 minutes of the actual weather. The TCWF scoring looks in a 10km radius around each point to determine if the forecast pixel is a "hit," "miss," or "false alarm." As the demonstrations continued, users reported that the forecast was performing better than the scores indicated and so the "User" Scoring Technique was designed to better match their perceptions. The method allows partial credit (25%) for moderate probability forecasts. This new method was added to the TCWF scoring for demonstrations at all of the site locations.
2. When the TCWF was converted to a 1km resolution from a 4km resolution, an optimization study was done to select the size and pixel match criteria to best match the 4km scores. The study revealed that a scoring box radius of 9km (19km x 19km box) with 8 verifying pixels provided the best match.
3. Previously, TCWF only reported one score based on the entire long-range grid. On one occasion, air-mass storms dominated the MCO TRACON while a line storm moved into the long-range view. Users who had selected the TRACON view were given high forecast accuracy scores because of the organized line, which did not reflect the poorer air mass performance that they were seeing. Comments on this issue were heard through user interviews. "All MCO TRACON and ZJX ARTCC users want to see accuracy scores for the range being shown. Therefore, scores should be calculated for the 50nm range as well as the 200nm range" (FAA Tech Center, 1999). In the current algorithm, a 30 and 60 minute forecast accuracy score is produced for both the TRACON forecast product and the 200nm product.

Another scoring issue arose during the ongoing demonstrations. Currently, TCWF only scores level 3 and greater weather, and winter storms in particular have sparse level 3 pixels. Analysis has shown that TCWF storm tracks have been excellent and scores would have been helpful if calculated on the level 2 forecasts. This scoring issue will be addressed in the future.

6. FORECAST DISPLAY

In the first TCWF algorithm build, all users had web based displays. Table 2 shows the dates that each of the sites were upgraded with the new build of the algorithm, including the resolution change and the new display concept. Now, TCWF images are disseminated to users in two ways: through a dedicated display and a web based display. There are two types of dedicated displays: one used by Air Traffic Control (ATC) users, the TCWF-only integrated display (used in the TRACON and ARTCC) and one for non-ATC users, the ITWS/TCWF integrated display, used by the airlines with dedicated ITWS connections. All other users are able to access the information from a web (HTML) page.

The dedicated display used by ATC has many similarities to the ITWS display. It has all of the safety features of the ITWS display (status colors and alert information at the top) with only the Forecast product available for viewing (Figure 3). The purpose of this is to give the users a display similar to what they would see if the product were to be integrated into the ITWS system. Typically, this display sits aside the ITWS display in the facilities, and the ITWS display remains unchanged.

Table 2: Dates that the TCWF Algorithm and Display were Updated at Each of the Sites.

Site	Date of Upgrade
Memphis	March 24, 2000
Orlando	April 26, 2000
Dallas	April 29, 2000
New York	May 8, 2000

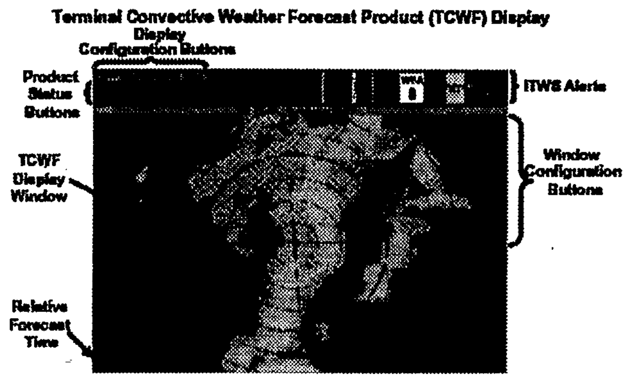

Figure 3. An example of the TCWF-only situation display for ATC users. ITWS alerts are identical to those on the operational ITWS prototype display for safety reasons. Only TCWF windows can be displayed, but full ITWS SD functionality (pan, zoom, overlays, etc.) is available.

Non-ATC users have fully integrated ITWS/TCWF displays. This is to familiarize these particular users with the integrated display which could be deployed as part of ITWS in the future. A wider monitor is used to provide room to display the additional product.

Other users such as airline dispatchers and meteorologists can access the TCWF product from the internet either via a password protected site at LL or via CDM-Net. These users are able to view TCWF information from Memphis as well as from the other demonstration sites. Table 3 lists the users of TCWF for the ongoing demonstrations at all of the sites, and Figure 4 illustrates the product dissemination configuration.

7. MEMPHIS ASSESSMENT

The Memphis International Airport was selected for the TCWF Formal Assessment since it was not exposed to the forecast product during prior demonstrations. The Assessment is being done for the following reasons:

1. Demonstrate the utility of a 1-hour forecast product and have the FAA's W.J. Hughes Technical Center assess whether the product addresses user requirements and is suitable for inclusion in ITWS.

2. Perform analysis on the new 1km resolution product and determine what parameter optimizations or other changes need to be made to the algorithm.
3. Gather feedback from the users on the new display concept.

Table 3: List of the dedicated TCWF for ITWS users. The site location and users of the display are noted along with the display type. "TCWF" denotes a forecast only display and "Integrated" denotes the TCWF product integrated on the ITWS display.

Site	Display Type	Setup	Location
DFW	TCWF	TRACON	Dallas/Ft. Worth TRACON TMC
DFW	TCWF	Center	Dallas/Ft. Worth ARTCC, TMU Position
DFW	TCWF	Center	Dallas/Ft. Worth ARTCC, CWSU Position
DFW	TCWF		Flight Service Station (Ft. Worth)
DFW	Integrated	Airline	American Airlines
DFW	Integrated	Airline	American Eagle Airlines
DFW	Integrated	Airline	Southwest Airlines
MCO	TCWF	TRACON	Orlando TRACON - Supervisor
MCO	TCWF	TRACON	Orlando TRACON - Traffic Manager
MCO	TCWF	Center	Jacksonville ARTCC - TMU
MCO	TCWF	Center	Jacksonville ARTCC - CWSU
MEM	TCWF	TRACON	Memphis TRACON
MEM	TCWF	Center	Memphis ARTCC - TMU
MEM	TCWF	Center	Memphis ARTCC - CWSU
MEM	Integrated	Airline	Federal Express
MEM	Integrated	Airline	Northwest Airlink
NYC	TCWF	TRACON	New York TRACON
NYC	TCWF	Center	New York ARTCC, TMU position
NYC	TCWF	Center	New York ARTCC, CWSU position
NYC	Integrated		New York Office of Emergency Management
ALL	Integrated	Multi	FAA's W.J. Hughes Technical Center
ALL	Integrated	Center	ATC System Command Center
ALL	Integrated	Airline	Northwest Airlines
ALL	Integrated	Airline	Delta Airlines
ALL	Integrated	Airline	Delta Express
ALL	Integrated	Airline	Continental Airlines
ALL	Integrated	Airline	United Airlines

Figure 4 illustrates the real-time connections to the MEM users. For example, the TRACON, ARTCC, Federal Express, and Northwest Airlines all have dedicated displays that they receive via leased phone lines. Other Users such as other airline dispatchers & meteorologists can receive the information via the Lincoln Web Server in Lexington, MA. Although the website is restricted, information regarding TCWF and other Aviation Weather projects can be found at: http://www.ll.mit.edu/AviationWeather.

8. RESULTS

The TCWF product has been running in Memphis since March 24, 2000. Operational benefits and feedback continue to be gathered and addressed. Highlights from a few early season events are listed below including a weather synopsis as well as TCWF performance.

March 25th. An approaching weak cold front brought convection to the area. Initial convection was isolated but a well-organized arc rapidly formed along a convergence boundary, which tracked eastward toward the airport. TCWF accurately depicted both the timing and the motion of the storms. As the convection became well organized, the forecast accuracy scores peaked at 90% for 30 minutes and 80% for 60 minutes and remained extremely high for several hours until the storms weakened and became more disorganized. The CWSU meteorologist used TCWF during the afternoon weather briefing while the TRACON Supervisor used the product as an aid in routing a plane from Memphis to Jackson, MS.

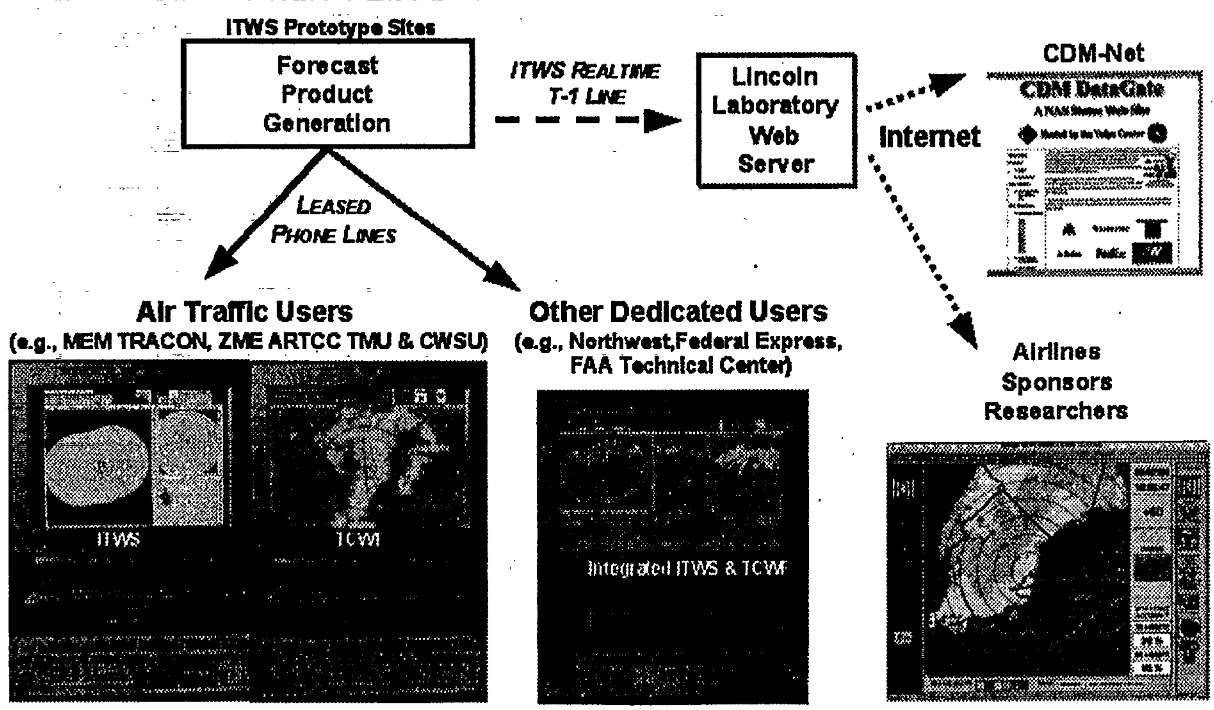

Figure 4. TCWF product dissemination flow chart. Examples of the TCWF displays used by ATC, Airlines, and internet users.

April 7th. During the afternoon, isolated thunderstorms developed to the north of the TRACON along the warm front. Later, this activity organized into a WSW/ENE line (with up to level 6 cells) that affected the northern airways. The strongest cell within the line (west of the airport) formed into a bow echo and produced golf-ball size hail. As the squall line/bow echo approached the airport, intensities weakened. The TCWF product generated moderately-high forecast accuracy scores throughout the mission. Scores rose quickly as the line developed and peaked at 95% for 30 minutes and 80% for 60 minutes. Northwest Airlines used ITWS and TCWF to supplement their weather briefings and to aid in determining gaps in case their planes were caught on the east side of the line. The TMU used the forecast product to help determine the timing of the airport impact and plan the arrival push accordingly.

May 9th. An approaching cold front brought the chance for severe weather. The Memphis area was under a Tornado Watch through the evening hours. Convection began to organize into a line and heavy precipitation impacted the TRACON during the Northwest Airlines arrival push. The TCWF product was highly accurate for this event. Forecasts correctly depicted which cells would impact the runways and which would affect the arrival/departure corridors. Scores peaked above 90% for 30 minutes and 80% for 60 minutes, remaining high for the majority of the mission (Figure 5). Northwest reported that up to 6 diversions were saved based on the ITWS/TCWF products. The TCWF product further helped the TMU to determine which gates would be the first to open so they could route traffic proactively towards those gates. The TRACON used the products to help minimize holds, regulate flow with the ARTCC and land more planes prior to runway closure.

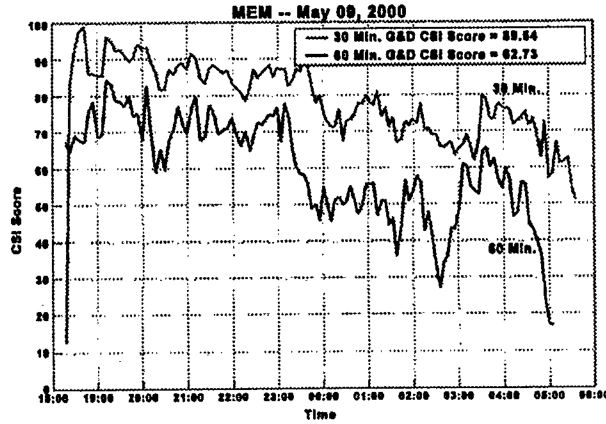

Figure 5. Time series plot of 30-minute scores (upper, grey) and 60-minute scores (lower, black) for Memphis weather event on May 9, 2000.

Although only a few results are presented in this paper, the Assessment will continue through the summer months and more complete results will be presented at the Conference.

9. USER FEEDBACK

User feedback from previous demonstrations led to many changes with the algorithm and display concept. The users received reference guides explaining the features of the TCWF display as well as contact information in case the need arises to call either a MIT/LL field site staff member or someone at the Lexington office. Table 4 illustrates the changes proposed for the TCWF display while training at the MEM ARTCC. Feedback continues to be gathered and addressed throughout the assessment.

Table 4: Suggested TCWF display changes gathered from user feedback.

Proposed TCWF Display Changes			
Change	**Suggested by**	**Date**	**Possible Solution**
Dwell Time Control on Loop selection for TCWF	MEM CWSU	3/30/00	Loop selection to include both a first and last frame pause time
Precipitation level filtering for past/current weather	MEM CWSU	3/30/00	Precipitation button would exist as additional window configuration button, "P" on TCWF window to allow precipitation level filtering

10. FUTURE WORK

The Memphis Assessment formally began on March 24, 2000 and results will continue to be gathered and analyzed during the convective season. Not only will algorithm performance be evaluated, but ideas for algorithm enhancement will be examined.

Currently, TCWF is a tracking algorithm and the team is studying ways to incorporate explicit storm growth and decay into the algorithm. Quantifying features of growth and decay is important in capturing the early stages of storm development as well as the dissipation phase. The team is now developing feature detectors with these capabilities.

ACKNOWLEDGEMENTS

TCWF site demonstrations, including the Formal Assessment in Memphis, would not be possible without help from several individuals at Lincoln. Lexington staff assisted in both hardware and software issues while the field site staff helped with training and interacting with the users, gathering operational feedback and performing data analysis. Their ongoing efforts are greatly appreciated.

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Kathy Carusone	Mark Isaminger	Brad Crowe	Richard Ferris	Duane Grant
Patrick Pawlak	Erik Proseus	Dave Miller	Darin Meyer	Steve Gaddy
Doug Piercey	Ben Boorman	Justin Shaw		Shawn Allan
Paul Morin				
Ed Griffin				

APPENDIX

Tracker Parameters	
Correlation box size	28 km x 28 km
Use histogram for tracking levels: Number of levels Percentiles (%)	 6 (60,70,80,90,95,99)
Minimum correlation for valid vector	.55
Min/Max valid weather in correlation box (%)	10/90
Speed limit (largest allowed vector)	120 km/hr
Global constraint	± 70 degrees in direction
Local time weight	70% prior vector and 30% current vector
Global time weight	25% prior global vector and 75% current global vector
Criterion for accepting local vectors based on global vector	Local direction within ±70° of global direction

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ADDS is being developed by NCAR Research Applications Program (RAP), NOAA Forecast Systems Laboratory (FSL), and NWS Aviation Weather Center (AWC) under the auspices of the FAA Product Development Team for the Aviation Gridded Forecast System (AGFS). Funding for ADDS is provided by the FAA Aviation Weather Research Program (AWRP): http://www.faa.gov/aua/awr/.

For additional information refer to paper 3.5 (page 85) entitled *"Recent Enhancements and Plans for the Aviation Digital Service."* The cover was prepared by FSL and sponsored by the FAA AWRP.

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